Silicon Photonic Devices
Utilizing Lateral Leakage Behaviour

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Naser Dalvand

May 2014
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Abstract

Transverse magnetic (TM)-like modes of thin-ridge Silicon-on-Insulator waveguide can leak into radiating transverse electric (TE) slab modes in the lateral direction unless the waveguide width is maintained at a resonant, so called ‘magic’ width. The highly evanescent TM mode has a relatively low effective index and a strong longitudinal field component. The higher effective index TE slab mode, when rotated about the axis of TM propagation, can achieve both phase matching and non-zero overlap resulting in strong radiation without any perturbation. This TE radiation occurs in equal amounts on both sides of the waveguide. At the ‘magic’ width, there is destructive interference of radiation wave fronts resulting in low loss for the TM mode. Rather than viewing this leakage as a limitation, this thesis explores the ability to manipulate waveguides from low-loss guidance to efficient radiation and how this ability may present opportunities for new silicon photonic devices.

In this thesis, first a Silicon-on-Insulator waveguide structure is proposed which, when excited with TM guided light, emits controlled TE polarized radiation from one side of the structure only. The validity of the proposed structure is analysed using eigenmode expansion and supermode techniques. It is shown that care must be taken to select the gap between the radiating elements such that both the phase and the amplitude of the radiating modes are maintained along the propagation direction to achieve the desired directional control of radiation. Steps toward practical demonstration of the proposed structure are identified.

Transitions from low-loss ‘magic’ width to strongly radiating ‘anti-magic’ width thin-ridge silicon-on-insulator waveguides operating in
the TM mode, are analysed using a vector eigenmode expansion method for the first time to the best of my knowledge. It is shown that the transition produces a beam of TE radiation with a pattern which is strongly dependent on the geometry of the transition. It is shown that a controlled, highly coherent, and low-divergence TE beam can be emitted from a relatively compact linear taper. Methods for side lobe suppression are also analysed and avenues for more sophisticated beam shaping are identified drawing inspiration from leaky wave antennas.

Novel concepts for polarization splitter-rotator and wavelength selective devices are presented utilizing the lateral leakage in taper transition from ‘magic’ to ‘anti-magic’ width thin ridge Silicon-on-Insulator waveguides. It is shown that by utilizing a lens assisted taper as a TE beam collector, a very compact TM-TE polarization rotator-splitter with a large bandwidth (with a 0.24dB bandwidth of 100nm) can be realized. The dispersive characteristics of the TE beam emitted from a radiating taper structure is analysed with a film mode matching modal analysis, and based on this, a 4-channel wavelength de-multiplexer is proposed. It is numerically predicted that the proposed device would have relatively low propagation loss and cross-talk. Avenues to practical demonstration of the proposed structures are identified.

In summary, it is shown that the lateral leakage phenomenon can be used to design interesting new devices. It is shown that rigorous numerical tools introduced in this thesis can be effectively used to design such devices. This could enable designing and developing other topologies which might utilize lateral leakage such as sensors and hybrid integrated devices.
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Chapter 1

Introduction

Silicon photonics is a technology to realize different optical functionalities in silicon [1–6]. One of the key reasons for the use of silicon for future photonic integrated circuits is its compatibility with mature silicon integrated electronic circuit manufacturing. This compatibility with extensive existing infrastructure will enable mass production of silicon photonic devices. Another motivation is the good material properties of silicon as a platform for realizing optical devices [1]. Data transfer bandwidth and heat dissipation are two major obstacles facing integrated electronic technology presently [7]. Silicon photonics will allow using both the high computational capability of electronics and high communication bandwidth with low loss of photonics integrated on the same chip. Therefore, photonics brings new functionalities to electronic components such as low propagation losses, high bandwidth, wavelength multiplexing and immunity to electromagnetic noise.

Silicon photonics was pioneered by Soref during the 1980s [8, 9]. The main interest in silicon photonics emerged with the idea of having one chip containing all optical functionalities such as light generation, modulation, guiding, multiplexing, detection and amplification directly interfaced with electronics on the same chip with minimal additional fabrication cost per chip. Great progress has been made over the years to realize all optical functionalities in order to realize a photonic interconnect for the integrated silicon platform. Silicon photonics relies heavily on Silicon-On-Insulator (SOI) technology [10]. The major development of silicon photonics was started right after SOI was adopted by the mainstream
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CMOS industry. Realization of waveguides with very tight bend radii was made practical by the large index contrast between silicon and the buried oxide (BOX) layer. This huge index contrast is crucial for efficient packing of waveguides on a chip and miniaturization of various other optical components. Rib waveguides with the size of 5µm square were demonstrated where Silicon-on-Insulator was used. A little over 10 years ago, low loss silicon nano-wire waveguides and silicon photonic crystal waveguides were reported by Massachusetts Institute of Technology (MIT) [11]. The high index contrast led to sharp bends and reduced the footprint of many spectral filtering components such as ring resonators [12–14] and wavelength demultiplexers based on arrayed waveguide gratings (AWGs) [15, 16] or planar echelle diffraction gratings [17]. The coupling of light from a fiber into silicon nano-wires appeared as one of the early challenges due to huge modal size mismatch. This problem was solved by demonstration of the idea of inverted tapers [18, 19] which have been widely adopted and in parallel the grating couplers which being pioneered by IMEC-Ghent University [20].

On the active components side, the realization of active devices in silicon started in late 1990s with the hetero-growth of germanium on silicon which enabled the development of high-speed CMOS compatible photo-detectors [21, 22]. Shortly after the introduction of silicon nano-wires, as a step toward realizing light sources in silicon, optical gain in Er-doped silicon nanocrystal waveguides was observed and proof of concept amplification was demonstrated [23]. A high efficiency electroluminescent Er-doped device at the telecommunication wavelength of 1.54µm was demonstrated [24]. Raman gain in silicon waveguides was observed by researchers at University of California in Los Angeles (UCLA) [25] and based on that an optically pumped pulsed silicon Raman laser was demonstrated by the same team [26]. This was followed by the demonstration of a continuous-wave silicon Raman laser by Intel [27]. The first electrically pumped hybrid silicon evanescent laser was demonstrated by a team of researchers at University of California at Santa Barbara (UCSB) and Intel [28]. There have been introduced several state of the art modulator designs in silicon by different groups over the last decade. The design of an ultra-fast Mach-Zehnder waveguide modulator based on high-index contrast silicon split-ridge waveguide technology and electronic carrier injection was proposed by MIT researchers [29]. An ultra-compact (14µm length)
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A modulator operating at 1.5 Gb/s based on a ring resonator was demonstrated by researchers at Cornell University [30].

While most of the material published on silicon photonics operates in the tightly confined TE mode, many important functions are enabled by evanescent waveguides such as sensors [31, 32] and hybrid integrated active components [33]. For these components perhaps the TM mode is the most effective. Thus there is a case to study waveguides operating in the TM mode and also to consider structures that may convert the TM mode into the TE mode.

This brief overview of the advancement of silicon photonics over the last decades indicates that silicon photonics is a promising solution to develop low-power, high bandwidth technology for inter- and even intra-chip communications. Despite the tremendous progress in the field of silicon photonics over last decade, there are still plenty of opportunities for new designs in both passive and active components to achieve more efficient ultra-dense photonic devices and interconnection circuits for future communication bandwidth and computational needs.

1.1 Impetus and objective

The basic element in any integrated optic circuit is the optical waveguide. The most commonly used SOI waveguide structures are strongly confined strips and loosely confined ribs [1]. Figure 1.1 (a) shows the SOI rib waveguide. The high index contrast between the silicon core and silica cladding leads to highly confined modes which offer the advantage of tight bends with low loss. However, the field interaction with the waveguide cladding of these waveguides is limited. In some circumstances this confinement can be a disadvantage. For optical sensors or hybrid silicon devices where non-linearity or gain provided by the cladding material, a strong evanescent field is essential. Highly evanescent guiding can be achieved by using a thin film of silicon as the guiding layer and operating in the transverse magnetic (TM) mode [34, 35]. The strong refractive index discontinuity normal to the electric field enhances the field amplitude in the cladding both above the core and below core. In these thin film structures, lateral guiding is often provided by a weak, shallow rib structure to minimize propagation losses.
Recently, it has been observed that these thin, shallow ridge Silicon-on-Insulator structures exhibit strong width dependent propagation loss for the TM-like mode [36]. The width dependent loss is not present for the TE polarization. This width dependent propagation loss of the TM guided mode in thin ridge waveguide is due to the inherent lateral leakage of TM guided mode [36–39] into unguided TE radiation, even when perfectly smooth and straight. Figure 1.1 (b) shows a Schematic of the inherent TM/TE lateral leakage in thin ridge Silicon-on-Insulator waveguide. Apart from the TM mode guided by the shallow ridge, the thin silicon film also supports slab modes confined vertically but radiating laterally outside the ridge region. For waveguide geometries of practical interest, the effective index of the TM-guided mode is lower than that of the TE slab mode [36]. As a result it is possible for the guided TM mode to be longitudinally phase-matched to a TE slab mode which propagates at a significant angle to the guided TM mode. Under the phase-matching condition, the power of the guided TM mode can be coupled to the inherently phased-matched TE slab mode due to the index discontinuity at the shallow ridge walls. This coupling causes significant radiation loss of the TM guided light. However, at certain waveguide widths, and for particular wavelengths, the TE waves generated by this TM-TE conversion at each wall interfere destructively resulting in leakage loss cancellation and low loss propagation.

The TM-TE lateral leakage phenomena are undesirable in traditional pho-
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Figure 1.2: Schematic of a TM-TE polarization rotator-splitter utilizing lateral leakage in ridge Silicon-on-Insulator (SOI) platform.

tonic applications. The leakage causes optical propagation loss which limits the usefulness of the waveguide, and causes cross-talk between neighbouring components. For traditional integrated silicon photonic circuits, the leakage of the thin ridge waveguide must be avoided. The resonant cancellation of leakage is strongly dependent on both geometry and wavelength. It is thus very sensitive to perturbation. A recent paper [40] has proposed a technique to reduce this sensitivity using a dimple in the waveguide. My group at RMIT, in collaboration with Lehigh University, has shown that when thin, shallow ridge structures are used in more sophisticated structures (such as directional couplers [37]) that each mode of the structure exhibits different leakage behaviour. It is expected that when the thin ridge structure is used in more sophisticated longitudinally varying configurations, such as tapers and bends, new understanding will be required to overcome losses. It was also theoretically predicted that cylindrically symmetric shallow ridge disks can exhibit a new type of whispering gallery mode with wavelength dependent low-loss propagation at resonant radii [41]. In 2011, researches in University of California at Santa Barbara (UCSB) demonstrated a compact broadband TE pass polarizer in SOI ridge waveguides utilizing lateral leakage to
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eliminate one polarization [42].

Harnessing the strong TM/TE coupling and highly resonant transition from leaky to non-leaky behaviour, suggests an opportunity for new photonic devices. By making deliberate use of the leakage behaviour, novel components can be designed. For example, one of the components that is proposed, designed and analysed in this work is a compact TM-TE polarization rotator-splitter with a large bandwidth and ultra-low cross-talk. Figure 1.2 shows a Schematic of this device. Besides, manipulating and selectively enhancing radiation behaviour of waveguides is very common in microwave engineering, particularly for travelling wave antennas. By borrowing concepts from the fields of RF, microwave and antenna device engineering, this thesis will explore entirely new classes of photonic devices that exploit the lateral leakage mechanism. In this case, the objectives of this work are as follows. First objective of this work is to extend the understanding of the lateral leakage in thin ridge SOI waveguides and conceive designs that allow directional control of lateral leakage radiation. The second objective is to identify and/or adapt rigorous electromagnetic modeling tools to simulate the leaky TM light propagation through longitudinal varying thin ridge SOI structures. This problem is expected to be quite challenging due to the TM/TE polarization conversion at the waveguide step discontinuities and propagation of TE radiation at a significant angle to the propagation axis. The last objective is to design and analyze novel implementations of silicon photonic structures, specifically a polarization splitter-rotator and a wavelength multiplexer, that employ the studied phenomenon of lateral leakage in TM in SOI platform.

1.2 Thesis outline

In Chapter 2, a novel thin, shallow ridge SOI waveguide structure with directional control of lateral leakage radiation drawing analogy with Yagi-Uda antenna is presented. Most of the materials of this chapter has been already published in [43]. First, an overview of lateral leakage phenomena in thin-ridge SOI waveguides is presented. The lateral leakage mechanism of the TM-like mode in thin-ridge SOI waveguide is elaborated using a simple phenomenological model, and the experimental verification of the TM mode lateral leakage phenomenon is discussed.
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The next section reports the design and simulation of a range of SOI waveguide structures which when excited with TM guided light, emits TE polarized radiation with controlled radiation characteristics. The directional control of lateral leakage from thin-ridge SOI waveguides is represented by a simplistic optical ray diagram and analytically formulated. The proposed structure utilizes parallel leaky waveguides of specific separations. The radiation characteristics are controlled through choice of the phase of the excitation of these waveguides. To verify the validity of the proposed structures, the total field of the waveguide structure is simulated by superimposing the field distributions of the modes of individual waveguides excited with various phase differences. The coupling between the waveguides is simulated as the superposition of the super modes of the parallel waveguides together. These modal simulations are conducted using a rigorous full vector film mode matching technique. It is shown that the waveguides remain coupled even for significant separations and thus care must be taken to balance both the radiation loss and phase velocity of the supermodes involved. In this case, the investigation of the impact of phase and radiation mismatch between odd and even supermodes on single side radiation behaviour is presented.

In Chapter 3, the modelling of TM light propagating through longitudinal varying lateral leakage ridge SOI waveguide structures is presented. The modelling of this kind of structures has not been reported before and thus this is regarded as one of the main contributions of this thesis. Most of the materials of this chapter has been already published in [44]. The modelling of the leaky TM light propagation through such structures is found to be quite challenging due to the TM/TE polarization conversion at the waveguide step discontinuities and propagation of TE radiation at a significant angle to the propagation axis. Moreover, the nano-scale feature size of such waveguide structures along with relatively large dimension of the whole structure, because of the significant angle of TE radiation, make simulation of this kind of structures computationally very expensive. This thesis proposes a semi-analytical eigenmode expansion [45] method to rigorously simulate propagation of the leaky TM mode through longitudinally varying structures. In this chapter, first a review of most popular full-vector optical wave propagation simulation tools is discussed and they are compared with respect to their applicability to modelling of the lateral leakage in longitudinal varying thin-
ridge SOI structures. This is followed by an overview on the full vector eigenmode expansion wave propagation method which is chosen to simulate lateral leakage structures. The next section reports the analysis of an abrupt transition from low-loss ‘magic’ width to strongly radiating ‘anti-magic’ width ridge SOI waveguides operating in the TM mode using a vector eigenmode expansion method. The aperture field distribution and radiation pattern of emitted TE beam from such an abrupt transition is extracted and the beam characteristics, in terms of main radiation angle, field distribution and directivity are presented in detail. Then, the effect of ridge height on the leakage rate and consequently the beam characteristics are discussed by comparing three etch depth scenarios.

The abrupt transition is replaced by a linear taper from low-loss ‘magic’ width to strongly radiating ‘anti-magic’ width ridge SOI waveguides. The same eigenmode expansion simulation is used to simulate the taper structure. Comparison of the two simulations shows a major improvement in beam characteristics. It is shown that a directionally controlled and collimated TE beam with tailored beam shape can be emitted from a relatively compact linear taper. Methods for side lobe suppression are also analysed, and avenues to more sophisticated beam shaping are identified, drawing inspiration from leaky wave antennas [46].

In Chapter 4, novel concepts for polarization splitter-rotator and wavelength-selective devices utilizing directed and collimated lateral leakage beams are proposed, designed and analysed with a systematic procedure. The materials of this chapter have not been published yet, but I would expect to produce a publication based on these materials in the near future. The chapter starts with a detail study of the working principles of the proposed novel polarization splitter-rotator design utilizing lateral leakage. A combination of 3D full vector eigenmode expansion method and 2D finite-difference-time-domain (FDTD) method [47] is proposed and used to simulate the novel polarization splitter-rotator structure. This structure utilizes lateral leakage as the mechanism for TM/TE conversion where no polarization conversion occurs when the TE fundamental mode is launched into the structure. A lens-assisted taper is used to collect TE radiation, and the design principles and simulation method used to analyse this structure are elaborated. In the next section, a spectral analysis of the device is conducted by simulating the light propagation through the whole device for different wavelengths. The
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The proposed device shows relatively large bandwidth (with a 0.24dB bandwidth of 100nm). The device is designed to be very compact. Chapter 4 also proposes a 4-channel wavelength-division multiplexing (WDM) structure employing dispersive feature of lateral leakage. This structure combines the dispersive functionality of a laterally leaking taper, which separates different wavelengths of input light into beams at different angles and then a focal lens is used to focus the light down into a series of output waveguides channels. The proposed device is designed to operate over a broad spectral window around 1550nm with a 30-nm channel spacing. A combination of 3D full vector eigenmode expansion method and 2D bidirectional beam propagation method (BPM) [48] is proposed and used to simulate the light propagation through the whole structure. The filtering characteristics and propagation loss of the proposed device is presented in detail. The proposed device shows potentially low propagation loss due to the utilization of planar components with shallow ridge heights through dispersion and focusing mechanisms. Overall the chapter illustrates that the lateral leakage phenomenon can be used to design interesting new devices and that numerical tools can be effectively used to design such devices.

Finally Chapter 5 draws conclusions and sets a detailed and definitive direction for future work based on the findings of this thesis.

1.3 Publications

The work carried out during this thesis has led to a number of publications in international refereed journals:


This work was also presented in number of conferences:


Chapter 2

Thin-Ridge Silicon-on-Insulator Waveguides with Directional Control of Lateral Leakage Radiation

2.1 Introduction

As briefly discussed in chapter 1, TM-like modes of thin, shallow ridge SOI waveguide can leak into a radiating TE slab mode in lateral direction unless the waveguide width is maintained at a resonant, so called ‘magic’ width [36–38]. The highly evanescent TM mode has a relatively low effective index and a strong longitudinal field component. The higher effective index TE slab mode, when rotated about the axis of TM propagation, can achieve both phase matching and non-zero overlap resulting in strong radiation without any perturbation [38, 39]. Thus, no surface or sidewall roughness is required for this coupling. The phase matching of the guided TM and radiating TE slab modes means that radiation occurs only at a very specific angle to the propagation axis and in equal amounts on both sides of the waveguide. At the ‘magic’ width, there is destructive interference of radiation wave fronts resulting in low loss for the TM mode [38, 39, 52]. Rather than viewing this leakage as a limitation, the ability to manipulate waveg-
guides from low-loss guidance to efficient radiation presents opportunities for new silicon photonic devices.

This lateral leakage can be likened to a leaky waveguide antenna [53]. Drawing on this analogy with antennas, applications could be considered where this leakage is harnessed to transmit an optical signal between well separated waveguides through use of the unguided TE radiation. Before considering such a scenario, it is important that the characteristics of the radiation can be controlled and directed. For example, if one wished to transmit light efficiently between two adjacent waveguides, the radiation from the transmitting waveguide should emit from one side only.

In this chapter, firstly the mechanism of lateral leakage loss for the TM-like mode in shallow ridge SOI waveguide is explained using a simple phenomenological model. It is followed by a review of the experimental verification of the TM mode lateral leakage phenomenon [36]. Rigorous full vector modal analysis of leaky TM-like mode in this kind of structure is then discussed [37]. By gaining insight from these and drawing analogy with antennas, a novel waveguide structure based on lateral leakage in thin, shallow ridge SOI waveguides is presented. This structure utilizes two parallel leaky waveguides that are excited with quadrature phase and separated by a quarter wavelength. The radiation from these two waveguides interferes constructively on one side and destructively on the other. To verify the validity of the proposed structures, the total field of the waveguide structure is simulated by superimposing the field distributions of the modes of individual waveguides excited with various phase differences. Then, the coupling between the waveguides is simulated as the superposition of the supermodes of the parallel waveguides together. These modal simulations are conducted using a full vector film mode matching technique [54]. It is shown that the waveguides remain coupled even for significant separations and thus care must be taken to balance both the radiation loss and phase velocity of the supermodes involved. To visualize the predicted radiation, the Poynting vector is calculated at each lateral and longitudinal coordinate, and it is shown that radiation can be resonantly enhanced or suppressed in different directions emanating from the waveguide structure. Steps toward practical demonstration of the proposed structures are identified.
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2.2 Inherent TM-mode lateral leakage in Silicon-on-Insulator waveguides

In this section, the mechanism of the experimentally verified lateral leakage loss for the TM-like mode in shallow ridge waveguide [34, 36] is explained using a simple phenomenological model. This is followed by rigorous full vector modelling based on film mode matching technique which were developed to analyse these structures.

Figure 2.1 presents a diagram of the cross-sectional structure of a thin shallow ridge and also the dispersion of the TE-like and TM-like fundamental modes of the silicon slab. The wavelength was set to $\lambda_0=1.55\mu m$. These modes cannot be considered as pure TE or TM since, as will become apparent, they interact to a greater or lesser degree and thus can only be considered TE-like or TM-like. For brevity, the terms TE and TM will be used here on in to mean TE-like or TM-like. Figure 2.1 (b) shows the Silicon-on-Insulator slab dispersion curve for both the TM and TE fundamental modes of the slab. For all ridge thicknesses, the effective index of TE mode is considerably higher than that of the TM mode. This implies that for paraxial waves, any possible conversion between TE and TM modes would be minimal as the longitudinal phase matching condition is not met. However, it is possible to achieve phase matching if the TM and TE modes are not paraxial, for example where the TM mode is propagating along an axis and the TE mode is propagating at some angle to this axis. Another important requirement for coupling is that the two modes to be coupled are non-orthogonal in the region of a perturbation. For the case of TE and TM modes propagating paraxially, modes will be orthogonal as for the TE mode the electric field is entirely in the horizontal axis with no component along the vertical or propagation directions and for the TM mode, the electric field is zero along this horizontal axis. However, due to the strong index contrast between silicon and air, the TM mode has a strong electric field component along the direction of propagation. Thus, if the TE mode is rotated such that it is phase matched to the TM mode, it may also have a significant electric field component aligned with the longitudinal field component of the TM and hence the TE and TM waves may no longer be orthogonal. For these two reasons it may be possible for TE and
TM modes to interact in high index contrast thin, shallow ridge waveguides.

Figure 2.2 (a) shows the phase matching diagram for TM/TE conversion at a step discontinuity. The term \( k_0 n_{TE} \) presents the propagation constant of the TE slab mode within the lateral cladding. The term \( k_0 N_{TM} \) presents the propagation constant of the TM mode within the core of the waveguide. As illustrated in Figure 2.2 (a), the propagation constant of the TM waveguide mode is much lower than that of the unguided TE slab mode. Since the TE slab mode is unguided, it can be rotated to any angle to the propagation axis (z-axis). As shown in Figure 2.2 (a), by rotating the unguided TE slab mode to a specific angle (\( \theta \)), the TM waveguide mode within the core and TE slab mode within the lateral cladding can be phase matched along the z-axis.

Figure 2.2 (b) presents a ray diagram of the leakage process in thin-ridge SOI waveguide. Since all of the waves have the same relative phase along the z-axis, the focus would be on phase in the lateral direction. At the bottom of the waveguide the guided TM mode (which is shown with solid line) is incident on the wall. The angle of incidence is such that TM total internal reflection occurs. However, when the TM mode bounces back and forth inside the waveguide, TM/TE conversion occurs at each ridge wall due to the step discontinuity. It has been shown that the TE transmitted and reflected propagating waves generated by TM/TE conversion at each step discontinuity have equal amplitude and \( \pi \) phase difference [37, 39]. At the left ridge wall, the TM mode generates additional transmitted and reflected propagating TE slab mode waves. The new transmitted TE wave, with a relative phase of \( \pi \), will be superimposed with the previous reflected TE wave that has moved across the waveguide width and gained a phase shift of \( k_{x,TE(\text{core})} \cdot W \). Therefore, if this phase difference between these waves, due to a single traverse of the waveguide core in the TE mode, is a multiple of \( 2\pi \), the TE waves will interfere destructively and the leakage loss will be cancelled. This leads to a width dependence for the leakage minima that satisfies a resonance-like condition [39] of \( k_{x,TE(\text{core})} \cdot W = 2\pi \), or alternatively stated [36]:

\[
W = \frac{m \cdot \lambda}{\sqrt{n_{TE(\text{core})}^2 - N_{TM(\text{core})}^2}}, \quad m = 1, 2, 3, \ldots \quad (2.1)
\]
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Figure 2.1: (a) Ridge waveguide geometry; (b) Slab mode indexes used in effective index calculations. The modal indexes for the guided TE-like and TM-like modes, respectively, lie intermediate between their slab values for slab thicknesses $t_1$ and $t_2$ [36].
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Figure 2.2: (a) Phase-matching diagram showing TM-like waveguide mode phase matched to a propagating TE slab mode in the lateral cladding; (b) Ray picture of the TM mode lateral leakage.
where \( n_{TE(\text{core})} \) is the two-dimensional slab effective index of the TE mode in the core while \( N_{TM(\text{core})} \) is the full three-dimensional effective index of the TM waveguide mode for the structure. It is evident from Equation (2.1) that significant leakage loss should be expected for the TM waveguide mode, except at precise, specific waveguide widths, so called ‘magic’ widths, which satisfying the resonance condition. The leakage loss will be greatly reduced for waveguides at ‘magic’ widths due to destructive interference of radiating TE waves.

A series of ridge waveguides with widths varying from 0.5 to 1.8\( \mu \text{m} \) increments with slab thickness \( t_1=205\text{nm} \) and \( t_2=190\text{nm} \) (i.e. a 15nm ridge height) were fabricated on an SOI wafer with a 2\( \mu \text{m} \) buried oxide (BOX) layer thickness at Lehigh university [34, 36]. Figure 2.3 (a) shows the atomic force microscope (AFM) profile of the waveguide surface as obtained using the thermal oxidation process [34]. Figure 2.3 (b) illustrates the total relative transmitted fiber-coupled power measured as a function of waveguide width for both the TE and TM input polarizations [36]. The wavelength was set to \( \lambda_0=1.55\mu\text{m} \). It is evident that the TE mode has a low net loss which is weakly dependent upon waveguide width, whereas the TM waveguide mode has a relatively high loss except at some specific waveguide widths (‘magic’ widths). These low loss waveguide widths were found to be \( W=0.72 \) and \( W=1.44\mu\text{m} \). It was shown that the ‘magic’ widths calculated using Equation (2.1) and TE and TM modal effective indexes obtained from a mode solver are in excellent agreement with the measured results presented in Figure 2.3 (b). It is also evident from Figure 2.3 (b) that the loss starts increasing gradually when the waveguide width departs from ‘magic’ widths.

To rigorously model the behaviour of the TM mode in shallow ridge waveguides, a full vector numerical analysis of these structures was employed using tools developed at RMIT University [37]. The full vectorial film mode matching method [37, 38] and finite element method (FEM) with perfectly matched layer (PML) boundary conditions [55] were employed to numerically evaluate the leakage loss of the shallow ridge SOI waveguides. The waveguide cross-section was divided into a number of uniform multilayer sections for the film mode matching method [54]. The waveguide field in each slab section was written as a superposition of normal modes, including guided and radiation modes for both TE and TM polarizations. The amplitude of the normal slab modes can be determined
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Figure 2.3: (a) AFM image of a waveguide formed using thermal oxidation; (b) Experimentally measured optical transmission (log scale) for the fundamental TE-like and TM-like modes for the waveguides [36].
by matching the fields of these sections at the ridge discontinuities and ensuring that the boundary conditions of Maxwell’s equations are satisfied [54]. The effective index of the mode was then calculated by applying the resonant condition to the eigenvalue matrix. The real and imaginary parts of the mode effective index represent the propagation constant ($\beta$) and attenuation constant ($\alpha$) of the mode, respectively. The propagation loss of the mode can be calculated from the attenuation constant. The problem is terminated above and below by perfectly conducting planes, such that the modes of each vertical slice form a discrete set. However, the computational window is fully open in the lateral direction. This makes film mode matching best choice among other numerical methods to model the lateral leakage devices.

Figure 2.4 shows the leakage loss of the TM mode as a function of the waveguide width of a straight waveguide (inset of Figure 2.4 simulated with film mode matching and FEM with PML [37]). As can be seen from Figure 2.4, both the
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FEM and film mode matching methods produce very similar results, providing confidence that this result can be trusted. The first two ‘magic’ widths obtained from the simulations are 0.71\(\mu\)m and 1.429\(\mu\)m. These ‘magic’ widths are in excellent agreement with the experimental results presented in Figure 2.3.

Figure 2.5 (a) and (b) show the vectorial components of the electric field distributions of the guided modes for waveguide widths of 1.2\(\mu\)m (‘non-magic’) and 1.429\(\mu\)m (‘magic’), respectively. As can be seen in Figure 2.5, \(E_y\) field component is a factor of 10 times smaller than the dominant \(E_x\) field. This illustrates the hybrid nature of the mode. Comparing the \(E_x\) (TM) components between the two cases it can be seen that the form of this field component is almost identical in the two cases. However, when comparing the \(E_y\) (TE) components, it can be
Figure 2.6: (a) Main angle of TE radiation as a function of waveguide width; (b) main angle of TE radiation as a function of slab thickness in lateral cladding.
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Figure 2.7: XY view of the 3D plot of loss of the fundamental TM mode of the ridge waveguide (with 220 nm slab thickness in the core) as function of waveguide width and ridge height [56].

seen that while there is strong, unbounded radiation in the ‘non-magic’ width case of Figure 2.5 (a), there is no evidence of such radiation in the ‘magic’ width case of Figure 2.5 (b). Similar radiation can be seen in the longitudinal field ($E_z$) of Figure 2.5 (a) since the TE slab radiation is propagating at an angle to the propagation axis ($z$-axis).

The TE slab radiation angle occurs where the TM mode in the core and the radiating TE slab mode in the lateral cladding are phase matched. This angle can be calculated by [36, 38, 56]:

$$\theta = \cos^{-1}\left(\frac{N_{TM\,(core)}}{n_{TE\,(clad)}}\right)$$  \hspace{1cm} (2.2)

where $N_{TM}$ and $N_{TE}$ are the effective indexes of the TM mode in the core and TE slab mode in the lateral cladding.
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Figure 2.6 (a) shows the TE slab radiation angle as a function of the waveguide width of a straight waveguide (inset of Figure 2.4). The effective index of the TM mode in the core is calculated using film mode matching. The TE radiation angle is calculated using Equation (2.2). The wavelength was set to $\lambda_0=1.55\mu m$. From Figure 2.6 (a), the TE radiation angle will decrease by increasing the waveguide width. The TE radiation angle variation is almost $1.7^\circ$ for waveguide width variation of $1.5\mu m$. The small sensitivity of the TE radiation angle to the waveguide width is due to the small sensitivity of the TM fundamental mode propagation constant in the core to the waveguide width variation. Figure 2.6 (b) shows the TE slab radiation angle as a function of the slab thickness in the lateral cladding. As can be seen in Figure 2.6 (a), the TE radiation angle will increase by decreasing the slab thickness in the lateral cladding. The TE radiation angle variation is almost $16^\circ$ for the lateral slab thickness of 100nm. The strong dependence of the TE radiation angle to the waveguide width is due to the dramatic change of the TM fundamental mode propagation constant in the core with respect to the lateral slab thickness variation. Figure 2.7 shows the XY view of a 3D plot of loss of the fundamental TM mode of this ridge waveguide as a function of waveguide width and ridge height as obtained using mode matching method [56]. The white portion on the top left corner in the plot corresponds to the region where the TM mode is at cut off. As can be seen in Figure 2.7, the TM mode loss as a function of waveguide width at a particular ridge height shows cyclic behavior as expected. The TM mode loss increases by increasing the ridge height at a ‘non-magic’ waveguide width. The TM mode loss for waveguides at ‘anti-magic’ width ($W=0.4$ and $1 \mu m$) is strongly dependent on ridge height, while it shows negligible dependence on ridge height for waveguides at ‘magic’ width ($W=0.73$ and $1.44 \mu m$).

2.3 Single side radiation device concept

Having reviewed the previous work on lateral leakage behaviour in thin-ridge SOI waveguides and gained insight from it, in this section, a waveguide configuration that radiates only from one side is conceived. To achieve this goal, it is proposed that two radiating waveguides can be excited with quadrature phase and placed...
Figure 2.8: X-Y cross section (a) of two identical and parallel SOI shallow ridge waveguides and plan view (b) of the structure showing the mechanism of the summation of the radiation of the two waveguides in both sides of the structure. Waveguide dimensions are shown.
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in parallel with an appropriate separation such that the radiation on one side is coherently cancelled. Figure 2.8 (a) and (b) shows the cross section and plan view of two parallel identical SOI shallow ridge waveguides. At this stage, it is assumed that evanescent coupling between the waveguides can be neglected. The fundamental TM mode of each of the two waveguides is excited with the same amplitude (A) but the excitation of the second waveguide has its phase shifted by Φ relative to the first waveguide. Figure 2.8 (b) illustrates the two TE waves radiating from each waveguide. Both TE waves propagate in the same direction but will have a relative phase that is dependent on the relative phase of excitation as well as the separation of the waveguides. The phase difference of the two equal components of TE radiation emanating from the right and left side of the structure can be written as:

\[ \Delta \phi_R = \Phi + k_0 n_{TE} d \]  \hspace{1cm} (2.3) \]

\[ \Delta \phi_L = \Phi - k_0 n_{TE} d \]  \hspace{1cm} (2.4) \]

where \( k_0 = \frac{2\pi}{\lambda_0} \) is the wavenumber of free space, \( n_{TE} \) is the effective index of the TE slab mode and \( d \) is the distance between the phase fronts of the TE waves exiting the two waveguides as illustrated in Figure 2.8 (b). To suppress the radiation on one side, the phase difference should be \( \Delta \phi = (2m + 1)\pi \), where \( m \) is an integer. If the fundamental modes of the two waveguides are excited with phase difference of \( \Phi = \frac{\pi}{2} \) and the separation of the two waveguides, \( S \) in Figure 2.8 (a), is chosen carefully such that \( k_0 n_{TE} d = 2m\pi + \frac{\pi}{2} \). Then, according to Equations (2.3) and (2.4) the phase difference between the TE waves radiating to the right will be \( \Delta \phi_R = (2m + 1)\pi \), while the phase difference between the TE waves radiating to the left will be \( \Delta \phi_L = 2m\pi \). If equal power radiates from each waveguide, then the radiation on the right side should coherently cancel while the radiation on the left side should coherently sum. Thus, in principle, the configuration of Figure 2.8 (b) should achieve single side radiation.
2.4 Simulation using superposition

Having conceived a structure that should provide single side radiation, this section now aims to investigate theoretically whether it will truly suppress radiation on one side. To rigorously model thin-ridge SOI waveguides with lateral leakage, a fully vectorial mode matching technique [54] was employed. Since the computational window in the film mode matching technique is completely open in the lateral directions, the lateral leakage can be simulated very accurately [37, 38]. To avoid treatment of the continuum of the radiation modes vertically, the ridge waveguide was placed between two perfectly conducting planes above and below the structure. These conducting planes were placed far enough from the waveguide, so that their effect on the waveguide was negligible.

The mode matching model was used to simulate the guided modes of the waveguide structure of Figure 2.8. The width of the waveguide was chosen to be $W=1\mu\text{m}$ to maximize TE lateral leakage radiation at a wavelength of $\lambda_0=1.55\mu\text{m}$ [36, 37]. The expected radiation angle of the TE light emitted from the waveguide core is $\theta=51.8^\circ$ to the $z$ axis.

Figure 2.9 (a) and (b) show the real and imaginary parts of the vectorial components of the electric field distributions of the guided TM-like mode of the thin-ridge waveguide. The TM-like mode of the waveguide is clearly strongly coupled to the radiating TE-slab mode. The TE radiation amplitude is symmetric on both sides of the waveguide. As a first approximation of the field that would be expected in two parallel thin, shallow ridge SOI waveguides, two identical instances of the field solutions presented in Figure 2.8 were simply superimposed, but with a lateral translation and an additional phase of $\Phi = \frac{\pi}{2}$ applied to the complex field profile on one instance. This simplistic approach of superposition ignores the effect of evanescent coupling between the waveguides.

Figure 2.10 (a) and (b) present the magnitude of $E_y$ for the left waveguide and the right waveguide respectively. The radiation into the TE mode is evident in both figures. The field ($E_y$) of right waveguide, as shown in Figure 2.10 (b), is identical to the left waveguide, but has been translated to the right by $4.58\mu\text{m}$ and has been advanced in phase by $\frac{\pi}{2}$. Figure 2.10 (c) presents the coherent superposition of the fields of Figure 2.10 (a) and Figure 2.10 (b). It is evident
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Figure 2.9: Electric field components of the guided mode of the waveguide of Figure 2.8 with width 1µm to maximize TE radiation at $\lambda_0=1.55\mu$m; (a) real component; (b) imaginary component.

that the coupling to the TE radiation is far stronger on the right side than it is on the left. This supports the reasoning that this structure should achieve single side radiation.

To examine the relationship between the field radiated to each side of the waveguide structure and the waveguide separation, the field distributions were calculated as a function of waveguide separation and the TE field was monitored on both sides of the structure. The locations chosen to monitor the field were at two symmetric locations to the left and right of the parallel waveguide structure. These two locations were vertically in the middle of the silicon core layer and had the same lateral distance to the center of the left or right waveguide respectively.

Figure 2.11 presents the radiated TE field amplitude on the left and right sides of the structure as a function of separation. It is clear that the TE radiation field amplitude measured at each side of the structure has a cyclic dependence on
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Figure 2.10: The magnitude of the y-component of the electric fields of the TM-like modes of (a) the original SOI waveguide; (b) the additional identical SOI waveguides with a 4.58 μm lateral translation and a $\frac{\pi}{2}$ phase shift and (c) the coherent superposition of these two modes.

the waveguide separation. For some waveguide separations, the TE radiation on one side is suppressed, while it is at a maximum on the other side. Figure 2.11 also shows the field amplitude predicted by Equation (2.3) and (2.4) using the relative phase between TE radiation from each waveguide. Excellent agreement is evident. Figure 2.10 and 2.11 illustrate through the use of superposition that it should indeed be possible to suppress the radiation from one side of the waveguide structure using appropriate waveguide separation and phase shift.

Examination of Figure 2.11 would suggest that the radiation suppression will be quite sensitive to waveguide separation and it might be expected that the initial phase of the two modes would be equally important. To quantify this sensitivity, Equation (2.3) and (2.4) were used to calculate the tolerance in initial phase and waveguide separation that would be required to maintain ≥20 dB radiation
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Figure 2.11: The magnitude (in Log scale) of the super-imposed radiation fields of identical modes at two symmetric fixed points ($y_1 = +8\mu m$ and $y_2 = -8\mu m$, $x_1 = x_2 =$ midpoint of the Si film) on right and left hand sides of both waveguides versus the gap ($S$) between the waveguides and the magnitude of the summation of the TE radiation waves as obtained from Equation (2.3) and (2.4) which account for the phase difference between the two TE waves.

suppression on one side. Figure 2.12 shows the radiated TE field amplitude on the left and right sides of the structure as a function of waveguide separation around central waveguide separation of $S=4.58\mu m$. As shown in Figure 2.12, the waveguide separation should be maintained within $\pm20nm$ to achieve $\geq20dB$ radiation suppression on one side which, while challenging, is within the range that can be achieved with modern CMOS processing. Figure 2.13 illustrates the radiated TE field amplitude on the left and right sides of the structure as a function of initial phase around central phase of $\Phi=\frac{\pi}{2}$. If the waveguide separation is set to $4.58\mu m$, to achieve $\geq20dB$ radiation suppression on one side, the initial phase needs to be kept within $\pm12^o$ which would be quite achievable practically.

The results of Figure 2.10 and 2.11 suggests that it should in principle be possible to configure two waveguides such that they radiate to one side only, however, this analysis has neglected the effect of coupling between the waveguides
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Figure 2.12: Fabrication tolerance in waveguide separation that would be required to maintain $\geq 20$dB radiation suppression on one side.

Figure 2.13: Fabrication tolerance in initial phase that would be required to maintain $\geq 20$dB radiation suppression on one side ($S=4.58\mu$m).
and this may be an important factor limiting the degree of suppression that can be achieved.

2.5 Simulation using supermodes

In Section 2.4, it was shown that by selecting the appropriate separation between two parallel waveguides and exciting the TM guided modes in the two waveguides with a \( \frac{\pi}{2} \) phase difference, the TE radiation can be enhanced on one side while it is suppressed on the other side of the waveguide structure. However, in the previous analysis, the evanescent coupling between two waveguides was ignored. This section aims to more rigorously model the radiation behaviour of two parallel waveguides by including the effect of coupling.

The behaviour of a coupled parallel waveguide structure can be rigorously represented as a superposition of the even and odd supermodes of the coupled structure [57]. It has been shown previously that mode matching can be used to effectively model coupled waveguide structures that exhibit lateral leakage [37].

In the present case, the aim is to excite the two parallel waveguides with modes of equal amplitudes and a \( \frac{\pi}{2} \) phase difference between them. This \( \frac{\pi}{2} \) phase difference between the light in each waveguide can be achieved by exciting the odd and even supermodes with a \( \frac{\pi}{2} \) phase difference.

Using the mode matching model, the eigenvalues and eigenvectors of the even and odd supermodes were calculated for different waveguide separations. Figures 2.14 (a) and (b) show the real and imaginary parts of the calculated effective indexes of the even and odd supermodes as functions of the waveguide separation. For separations of less than 3\( \mu \)m, the effective indexes of the odd and even modes become significantly different indicating strong coupling. For separations above 3\( \mu \)m, the odd and even mode effective indexes asymptote to approximately the same value indicating that coupling between the waveguides has significantly diminished.

Careful inspection of the real part of the effective index of both the supermodes for separations above 3\( \mu \)m reveals that this value actually oscillates with separation. This oscillatory behaviour is due to the coupling between the two waveguides through the minor TE radiation field component. This coupling is via the propagating TE wave rather than being evanescent and hence does not
Figure 2.14: Propagation constants (a) and losses (b) of the even and odd super-modes of the structure versus the waveguide separation.
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Figure 2.15: The magnitude of the y-component of the electric fields of the TM-like supermodes of the structure with 4.54 µm waveguide separation respectively: (a) even mode (b) odd mode; (c) The super-imposition of these two modes with a phase difference of $\pi/2$.

reduce with increasing separation.

The imaginary component of the effective index for the odd and even supermodes is presented in Figure 2.14 (b). This corresponds to radiation loss. The loss clearly oscillates as a regular function of separation. This suggests that if the waveguides are independently excited with equal power and are either in phase (even mode) or in anti-phase (odd mode) then there will be distinct waveguide separations at which the radiation of both modes is equal and hence the lateral leakage can be optimally suppressed. This oscillatory lateral leakage appears to be largely unaffected by the evanescent coupling at separations below 3 µm.

Figures 2.15 (a) and (b) present the magnitude of the electric field eigenvector calculated for the odd and even eigenvalues at a separation of 4.54 µm. Radiation
is clearly evident in both supermodes. Figure 2.15 (c) presents the coherent superposition of the odd and even supermodes of Figures 2.15 (a) and (b) with a relative phase shift of $\frac{\pi}{2}$.

As expected, the radiating TE field to the left is suppressed while the radiation to the right is enhanced. The impact of the waveguide separation on the amount of radiation that would be expected on the left and right sides was quantified by recording the magnitude of the field at symmetric locations in the centre of the silicon core layer to the left and right of the waveguide structure. Figure 2.16 presents the radiation recorded at these locations as a function of the waveguide separation. It is evident that the radiation oscillates from left to right. Complete cancellation on the left or right is only observed at separations where the amplitude of radiation of the odd and even modes is equal. These specific separations can be determined from Figures 2.14.
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It can be seen from Figure 2.14 that a separation of greater than 3\(\mu\)m is required to minimize the evanescent coupling between the two waveguides. Further, even for larger separations, due to the oscillatory nature of the real part of the effective index, only specific separations will result in equal effective indexes for both odd and even modes. Comparing Figure 2.14 (a) and (b) for large separations, it is evident that when the radiation is equal for the odd and even modes, the difference in the real parts of their effective indexes is greatest. Hence, it is not possible to have both the real and imaginary parts of the effective indexes of the odd and even supermodes equal simultaneously and thus some compromise must be made.

2.6 Impact of phase and radiation mismatch between odd and even supermodes

In the previous section, it was shown that even for large separations, both the radiation and the effective indexes of the odd and even supermodes of a laterally leaking waveguide pair would oscillate with waveguide separation. Further, it was shown that it was not possible to achieve equal radiation and phase velocity for the odd and even supermodes simultaneously and hence ideal radiation cancellation on one side of the structure is not possible along the entire propagation length. It was anticipated that with radiation balance, but phase mismatch, ideal cancellation would be achieved initially, but as the modes propagated this cancellation would oscillate from side to side as the supermodes accumulate phase difference. Conversely, if phase matching was achieved, but radiation was imbalanced, stable radiation behaviour would be observed as the modes propagated, but the cancellation of the radiation would be poor. To investigate this predicted behaviour and to explore possible compromises we simulated the evolution of the super-imposed odd and even supermodes and analysed the radiation.

To perform this analysis we used the supermodes of Section 2.5 with separations of 4.36\(\mu\)m (perfectly phase matched, but radiation imbalanced), 4.54\(\mu\)m (phase mis-matched, but perfectly radiation balanced) and 4.45\(\mu\)m (a compromise mid point with neither perfect phase match nor radiation balance). To advance
Figure 2.17: (a) Poynting vector magnitude of Y-Z cross section of the structure for waveguide separation of S=4.36µm; (b) Poynting vector magnitude at two symmetric fixed points to the right and left of the structure (y₁ = +8µm and y₂ = -8µm, x₁ = x₂ = midpoint of the Si-film) as a function of propagation distance in the z-direction for separation of S=4.36µm.
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Figure 2.18: (a) Poynting vector magnitude of Y-Z cross section of the structure for waveguide separation of $S=4.54\,\mu$m; (b) Poynting vector magnitude at two symmetric fixed points to the right and left of the structure ($y_1 = +8\,\mu$m and $y_2 = -8\,\mu$m, $x_1 = x_2 =$ midpoint of the Si-film) as a function of propagation distance in the $z$-direction for separation of $S=4.54\,\mu$m.
the modes along the propagation direction, the phase and amplitude of the two modes according to their complex propagation constants were simply adjusted. To quantify the radiation predicted on each side of the structure as a function of propagation distance, two positions on the left and right of the parallel waveguide structure were chosen and the Poynting vector at these points along the propagation direction were calculated. To visualize the propagation and radiation as the mode superposition evolved, the Poynting vector at each lateral and longitudinal coordinate was calculated.

Figures 2.17 (a), 2.18 (a) and 2.19 (a) show the power (Poynting vector magnitude) that would be expected throughout the entire structure as a function of propagation distance for separations of 4.36µm, 4.54µm and 4.45µm, respectively. In Figure 2.17 (a) the power does not couple between the waveguides, but there is no evidence of radiation cancellation on either side of the structure. This is expected due to the perfect phase match but imperfect radiation balance as can be seen in Figure 2.14 (a) and (b). Figure 2.17 (b) shows that the radiation is indeed equal on both sides of the structure. The magnitude of both the guided and radiated field reduces with propagation distance as expected since power will be lost due to radiation.

Figure 2.18 (a) shows strong coupling between the light confined in the two waveguides and initially strong cancellation of the radiating field on one side of the structure. However, as the light propagates, this cancellation rapidly degrades and towards the end of the propagation, the cancellation is observed on the other side of the structure. The coupling can be explained since the phase velocities of the odd and even modes are not equal. Figure 2.18 (b) shows the power radiated on each side of the structure and it is clear that initially the cancellation on the right side is near ideal, but rapidly degrades as the odd and even modes de-phase. Towards the end of the propagation the cancellation shifts to the other side. Attenuation of both the guided and radiating fields is again evident with propagation.

Figure 2.19 (a) presents the field evolution for the compromise situation. Here the coupling between the guided light is only subtle. Modest cancellation of the radiation at initial stages is also evident. Figure 2.19 (b) shows the power radiated to the right side is suppressed by about 20dB when compared to the
Figure 2.19: (a) Poynting vector magnitude of Y-Z cross section of the structure for waveguide separation of $S=4.45\mu m$; (b) Poynting vector magnitude at two symmetric fixed points to the right and left of the structure ($y_1 = +8\mu m$ and $y_2 = -8\mu m$, $x_1 = x_2 =$ midpoint of the Si-film) as a function of propagation distance in the $z$-direction for separation of $S=4.45\mu m$. 

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2. Directional Control of Lateral Leakage Radiation

left side. Importantly, this suppression is maintained for approximately 250µm of propagation. After this length, coupling begins to dominate.

The results of Figures 2.17, 2.18 and 2.19 show that while it is not possible to achieve ideal cancellation of radiation that is sustained over a long propagation distance, it is possible to strike a compromise where a reasonable degree of radiation cancellation can be maintained over some propagation distance. It should be possible to adjust the separation to trade propagation distance for improved suppression or vice versa. It may also be possible to design longitudinally varying structures that suppress coupling without compromising radiation suppression.

To practically implement this structure, a means of providing the initial $\frac{\pi}{2}$ phase difference between the excited waveguide modes must be found. This could be achieved by using the two outputs of a 3dB directional coupler. In addition phase modulators could be inserted between this directional coupler and the waveguide pair to fine tune the initial phase on the two waveguides. Active control of the phase of excitation may also enable dynamic manipulation of the direction of the radiation.

2.7 Conclusions

In this chapter, first a brief literature review on the concept of experimentally verified lateral leakage phenomenon in thin-ridge SOI waveguides and its rigorous modal analysis was presented. The remainder of the chapter then reported the first analysis of directional control of radiation for Silicon-On-Insulator thin-ridge waveguides with lateral leakage. The film mode matching method was employed to calculate the TM mode solution of the whole structure and the effective indexes for different gaps between the two waveguides. Both simple superposition and more sophisticated supermode analysis have been used to predict the radiation behaviour. Through this analysis it has been found that it is not possible to meet both the phase matching and radiation balance conditions required for ideal suppression of radiation on one side of the structure to be sustained over long propagation distances simultaneously. The evolution of superimposed supermodes as they propagate has been examined and it has been shown that it is possible to strike a compromise between phase-match and amplitude balance that
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allows modest radiation suppression to be sustained over reasonable propagation distances. This directional control of radiation could be used to transmit power to another well separated waveguide on one side of the structure through unguided TE beam propagating into free propagation region with almost no radiation lost to the other side.
Chapter 3

Thin-Ridge Silicon-on-Insulator Waveguide Transition and Tapers

3.1 Introduction

In the previous chapter, a thin-ridge SOI waveguide structure at the ‘anti-magic’ width which emits coherent radiation with directional control was presented. It was shown that exciting two parallel ‘non-magic’ width waveguides with identical TM mode inputs will result in symmetric TE radiation, as shown in Figure 3.1 (a). However, when two radiating waveguides are placed at an appropriate separation (S), and are excited with a quadrature phase difference, single-sided TE radiation can be achieved as illustrated in Figure 3.1 (b). This structure may be likened to an antenna. Drawing on this analogy with antennas, applications could be considered where this leakage is harnessed to transmit an optical signal between well separated circuits through use of the unguided TE radiation. The TE radiation emitting from the antenna and propagating through the free propagation region can be collected at a receiver and transferred into a waveguide using another antenna element or an adiabatic taper waveguide as illustrated in Figure 3.1 (b). To integrate such an antenna with an optical circuit, it would be necessary to design an effective transition from ‘magic’ to ‘anti-magic’ width.

Infinitely long and longitudinally invariant lateral leakage structures have been rigorously modelled previously [37–39]. However, despite a thorough literature
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search, there does not appear to be any previous report of modelling longitudinally varying lateral leakage structures. The TM/TE polarization conversion at the waveguide step discontinuities along with TE radiation at significant angle to the propagation axis, make the modelling of the light propagation through such structures quite challenging. Moreover, nano-scale feature size of such waveguide structures along with relatively large dimension of the whole structure because of the significant angle of TE radiation make simulation of this kind of structures computationally very expensive.

In addition to the challenging numerical computation, it is desired that such a transition should be as compact as possible, but it is predicted that if this transition is too abrupt, then the radiation angle will be significantly broadened by

Figure 3.1: (a) Plane view of parallel ‘magic’ to ‘non-magic’ width waveguide transitions with identical TM mode inputs yielding symmetric TE radiation; (b) Similar structure with phase shifted inputs showing directional control of radiation.
diffraction, and will develop nulls and side lobes. If the structure of Figure 3.1 (b) were to be used to transmit information across a silicon chip, it would be important that the radiating beam was highly directional with a well behaved pattern to maximize overlap of the TE beam wave-front with adiabatic taper shown in Figure 3.1 (b).

In this chapter, firstly a literature review of most popular full-vector optical wave propagation simulation tools is presented. This is followed with an overview on the eigenmode expansion wave propagation tool which has been chosen to simulate lateral leakage behaviour over longitudinally varying thin-ridge SOI structures. Finally, after establishing the simulation method, the transition from a ‘magic’ width to ‘anti-magic’ width waveguide is numerically investigated, and the predicted radiation behaviour is analysed in terms of its directionality and the beam pattern emitted from the transition.

3.2 Literature review of full-vector optical wave propagation methods

The simple waveguide transition from a non-radiating to radiating waveguide widths as shown in Figure 3.1 cannot be considered longitudinally invariant, hence it is expected that such a transition will exhibit more complex behaviour than has been reported previously for longitudinally invariant structures. To accurately simulate such a transition, a rigorous full-vector electromagnetic wave propagation simulator must be employed to account for the polarization coupling in these thin, shallow, ridge structures.

The most popular wave propagation methods is the finite-difference time-domain (FDTD) method [48, 58]. In FDTD, the only approximation that is made is that the field is broken up into discrete finite points in both time and space at which the differential form of Maxwell’s equations are enforced. This method was first described by Yee [47]. FDTD can be used for modelling electromagnetic scattering problems for open devices where the computation domain is surrounded by absorbing perfectly matched layer (PML) introduced by Berenger [59]. In FDTD, the time-domain electromagnetic-field equations are solved using finite-difference
techniques. By discretizing the spatial and time spaces using a staggered-grid approximation [47], Maxwell’s equations can be replaced by a system of finite-difference equations. This leads to a high requirement on computational resources such as speed and particularly memory, even for 2D problems. One option to simulate the sorts of lateral leakage structures illustrated in Figure 3.1 is FDTD, however the nano-scale ridge dimensions coupled with relatively long propagation lengths make this intractable. The finite element method (FEM) could be used as a wave propagation tool in essentially the same way that FDTD is used. However, FEM is usually done in the frequency domain rather than the time domain and involves a matrix solve, rather than simply multiplication and thus becomes geometrically more computationally expensive than FDTD in both memory and computation time with increasing numbers of unknowns.

Another popular wave propagation method is the beam propagation method (BPM) [60, 61]. The BPM is an approach to solve the monochromatic Maxwell’s equations numerically through use of a number of approximations. The mesh system used for BPM at a transverse cross section can be based on finite-difference [61] or finite-element [62] mesh systems. A commonly used boundary condition for BPM is the transparent boundary condition (TBC) [63] which enables BPM to model open structures by allowing radiation to freely escape from the computation domain. The conventional BPM uses the paraxial approximation by removing the second-order derivative of the field in the propagation direction from the system of wave equations [48]. This mainly allows simulation of structures with low refractive index contrast and wave propagation at small angle to the propagation axis. The restrictions of the paraxial BPM can be relaxed by using wide-angle BPM [64]. The most popular technique to implement wide-angle BPM is using Pade-based approximations for the second-order derivative term [65]. The conventional BPM is not inherently bi-directional as the first order derivatives only consider forward propagation, and the algorithm steps incrementally forward in both time and space assuming an approximate propagation rate in a single direction. Various methods can be used to address this issue by considering the coupling that happens for an incident wave at an interface along the propagation axis [66]. The constraints explained above would make BPM an unsuitable option for nano-structures with high index contrast. In terms of simulating leaky
thin-ridge SOI structures, similar to FDTD, BPM would also be computationally expensive due to the small dimensions but further, the significant angle of the TE radiation relative to the propagation axis breaks the paraxial approximation of traditional BPM.

Last but not least, are the semi-analytical wave propagation methods that operate in spectral domain and which are based on mode matching technique. The wave propagation method based on the mode matching is known as eigenmode expansion method (EME) [67]. Eigenmode expansion slices up a structure into layers in which the refractive index profile does not change along with propagation axis rather than using a uniform grid to discretize the structure like methods explained above. In each of these slices, the field is expanded in terms of the local eigenmodes (or modes) of that particular slice [45]. The boundary conditions are defined by the particular method used to locate the eigenmodes of each layer. Forward and backward propagation through a slice can be calculated analytically and expansion coefficients of the modes can be calculated by applying continuity conditions and through use of mode matching [45, 68]. These features make eigenmode expansion an inherently bidirectional method and the only approximation that is made is the truncation of the infinite number of modes into complete finite set of modes to make the method computationally practical. Eigenmode expansion generally requires only low computational resources as it is a semi-analytic method and provides an accurate solution to the full-vector form of Maxwell’s equations. These features make eigenmode expansion a good candidate to simulate nano-scale structures with high refractive index contrast. For modelling light propagation through leaky thin-ridge SOI waveguide structures, a full-vector eigenmode expansion method was chosen.

3.3 Eigenmode expansion method overview

In this section, the main principles of the eigenmode expansion method are discussed. The eigenmode expansion wave propagation method starts with slicing up the structure into slices where the refractive index does not change in propagation direction as shown in Figure 3.2. In each slice of the waveguide, the optical field can be written as superposition of eigenmodes. The decomposition of the
optical field into eigenmodes is analogous to Fourier analysis. The eigenmodes are solutions of Maxwell’s equations where the optical refractive index does not vary in the $z$ direction. These modes can be written as:

$$E_i(x, y, z) = E_i(x, y)e^{-j\beta z}$$

assuming a monochromatic field that varies harmonically in time as $e^{j\omega t}$.

A finite number of guided modes or leaky modes can be found in a typical waveguide, but there is a spectrum of an infinite number of radiation modes. These radiation modes are not physical modes as they cannot be measured individually as without integrating over infinite space and time, they cannot be practically distinguished from one and other. However, including them in a wave propagation simulation is crucial as they carry power away from the waveguide core. To enable discretization of the radiation modes and in order to end up with a finite set of radiation modes, the computation domain must be surrounded with a terminating boundary condition. Theses modes can be located with using any
As explained before, any solution of Maxwell’s equations in each slice shown in Figure 3.2 can be written as a summation of a complete set of forward and backward propagating modes in that slice. Based on this fact and using the mathematical expression of the modes of each slice as given in Equation (3.1), the field in each waveguide slice shown in Figure 3.2 can be written as:

\[ E(x, y, z) = \sum_{i=1}^{N} \left( A_i E_i(x, y) e^{j\beta_i z} + B_i E_i(x, y) e^{-j\beta_i z} \right) \] 

(3.2)

where \( A_i \) and \( B_i \) are the forward and backward expansion coefficients which determine the amplitude of each the forward and backward propagating components of mode ‘i’, respectively and where \( N \) is the number of the modes in each slice. In a closed system, by including a finite, but sufficiently large number of modes, accurate approximation of the exact solution of Maxwell’s equations can be achieved.

To model the propagation of the light through a given structure, a relationship between the expansion coefficients of subsequent slices is needed. There are several methods which relate the expansion coefficients of the subsequent slices. The most robust and numerically stable method is the scattering matrix method [45, 67]. The scattering matrix between two subsequent slices can be calculated by imposing the continuity of the tangential components of the total field at the interface between them. This approach is called mode matching and requires calculation of the overlap integrals between both of the subsequent slices. The scattering matrix within each slice is a diagonal matrix since the modes propagating through a slice are orthogonal and there is no coupling between them. The overall scattering matrix of the whole longitudinally varying device can be derived simply by combining the scattering matrices of transitions across the interfaces between each subsequent slice and the transmission within each slice. This matrix gives the relationship between the mode coefficients of the modes of input and output slices. The overall scattering matrix of a device
such as one shown in Figure 3.2 is written as:

\[
\begin{bmatrix}
A_{\text{out}} \\
B_{\text{in}}
\end{bmatrix}
= \begin{bmatrix}
T_{\text{in}} & R_{\text{out}} \\
R_{\text{in}} & T_{\text{out}}
\end{bmatrix}
\begin{bmatrix}
A_{\text{in}} \\
B_{\text{out}}
\end{bmatrix}
\]  

(3.3)

where \(A_{\text{in}}\) and \(B_{\text{in}}\) are the forward and backward field coefficients respectively at input (leftmost slice). \(A_{\text{out}}\) and \(B_{\text{out}}\) are the forward and backward field coefficients respectively at output (rightmost slice). The components of the overall scattering matrix are \(T_{\text{in}}\) and \(T_{\text{out}}\) which are transmission matrices from left side and right side, respectively and \(R_{\text{in}}\) and \(R_{\text{out}}\) which are reflection matrices from the left and right sides, respectively.

One of the matrix elements of the scattering matrix is the transmission matrix at output waveguide slice (\(T_{\text{out}}\)) which is the amplitude transmission between the forward modes in the input and output slices. The elements of this transmission matrix are complex numbers, the square of the magnitudes of these elements represent the energy weight of the modes at the output slice. Suppose there is just one mode at the input slice which is the excitation mode with transmission amplitude equal to one and the amplitudes of all of the other modes are equal to zero, the transmission matrix gives the normalised energy distribution of the basis modes at the output waveguide section after light has propagated through the whole structure. Hence, it is obvious that once the scattering matrix of a structure is calculated, a great deal of information about not only the whole field but also the coupling of energy between the modes while light propagates through the structure can be extracted.

### 3.4 Abrupt transition from ‘magic’ to ‘anti-magic’ width

Having outlined the EME method in Section 3.3, it is now possible to use this method to start to analyse the longitudinally varying structures that are the topic of this chapter. The simplest of these structures is an abrupt transition from a non-radiating, ‘magic’ width waveguide to a highly radiating ‘anti-magic’ width waveguide. However, before this can be done, it will be necessary to develop in
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Figure 3.3: Cross section of a thin, shallow-ridge SOI waveguide.

more detail the approach used to simulate the many modes of various waveguide slices both for non-radiating and radiating cases.

3.4.1 Modes of the ‘magic’ and ‘anti-magic’ width slices

Figure 3.3 presents the cross-section of a thin, shallow ridge SOI waveguide. The silicon thickness was $h_c=220$ nm. The lateral leakage rate for waveguide at ‘anti-magic’ width will increase by increasing the ridge height to the point that the effective index of TM mode is not smaller than the TE slab mode in lateral cladding any more and the TM mode is no longer leaky [56]. The ridge height was selected to be $h_r=120$ nm to maximize the TE lateral leakage rate of the TM-like mode. This waveguide exhibits minimum radiation to the TE slab mode when the width ($W$) is a resonant ‘magic’ width of $W=0.73\mu m$ or $W=1.44\mu m$; and exhibits maximum radiation at anti-resonant ‘anti-magic’ widths of $W=0.4\mu m$ or $W=1\mu m$ [36, 56]. The main radiation angle occurs where the TM mode in the core and the radiating TE slab mode in the lateral cladding are phase matched.
This angle can be calculated by [36, 38, 56]:

\[ \theta_{\text{rad}} = \cos^{-1}\left(\frac{N_{TM}}{N_{TE}}\right) \]  

where \( N_{TM} \) and \( N_{TE} \) are the effective indexes of the TM-like and TE slab modes, respectively.

To run the EME simulation, it is not sufficient to only include a set of leaky and guided modes. The comprehensive set of guided, leaky and radiation modes is needed to model the power radiated away from the waveguide core for longitudinal varying waveguide structures. The number of the guided and leaky modes is finite in a standard waveguide structure, but the radiation of light is modelled by coupling to a continuous spectrum of an infinite number of radiation modes. As discussed in Section 3.3, to truncate the number of eigenmodes to a finite number (N), a boundary condition is needed to applied to the computation domain. An absorbing boundary condition could be applied by surrounding each uniform slice with a PML [45] along with perfect conducting walls. However, it is very time consuming as a large number of propagation constants of eigenmodes need to be searched in the complex plane for each uniform slice. Besides, the procedure is quite prone to failure due to a very complicated behaviour of the roots of the dispersion function of such leaky waveguide structures. In the approach used in this work, the waveguide structure was placed between perfect conducting walls. Consequently, propagation constants will be found on the real axis, not in the complex plane. This will speed up the root finding procedure very much. These conducting walls should be located far from the area of interest to minimize the reflection of the radiation field back into the problem.

To increase the accuracy of the simulation, care must be taken in choosing a set of modes for each slice that are likely to be a good representation of the field. To achieve this goal, it is necessary to have closer look at the basis set of the modes of the structure which is shown in Figure 3.3. A full-vector mode matching method [54, 69] was used to calculate the basis set of the modes. The wavelength was set to \( \lambda = 1.55 \mu \text{m} \). The mode profile of the TM fundamental modes of the lateral leakage structures at ‘magic’ and ‘anti-magic’ widths with open lateral boundary were shown in Figure 2.5 of Chapter 2.
Figure 3.4: Mode profile of different types of radiation (box) modes in thin-ridge SOI waveguide.
Figure 3.5: Mode profile of the major component of discretized TE slab radiation modes propagating away from the waveguide core at different angles to the z-axis in thin-ridge SOI waveguide.
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Figure 3.4 shows the mode profile of several different kinds of hybrid radiation modes in the structure shown in Figure 3.3. The computation window is surrounded with perfectly conducting planes, and its geometry is shown in Figure 3.4. Two mode profile in Figure 3.4 (a) and (b) represent major electric field components of fundamental TE and TM radiation modes of the lateral slab waveguide propagating away from the core of the waveguide at an angle. The mode profiles in Figure 3.4 (c) and (d) represent major electric field components of the TE and TM slab radiation modes of the lateral slab waveguide propagating away from the core of the waveguide at an angle. Figure 3.5 shows the major electric field components of the TE slab radiation modes shown in Figure 3.4 (a) propagating at different angles to the propagation axis in the thin-ridge SOI structure. The angle of each TE slab radiation mode can be calculated by using 
\[ \theta_{rad} = \cos^{-1}\left(\frac{N_m}{N_{TE}}\right) \], where \( N_m \) is the 3D effective index of the TE slab radiation mode and \( N_{TE} \) is the 2D effective index of the TE slab mode in the lateral cladding.

However, any perturbation along the propagation axis could give rise to coupling of power from the TM in the core of the waveguide to a continuous range of the TE slab radiation modes. In the EME simulation, these radiation modes are discrete. Figure 3.4 presents a selection of these discretised radiation modes and identifies the radiation angle that they represent. In the case where there is a longitudinal perturbation, then these modes will be significant as a sharp perturbation may make it possible to couple power to them even though they are not inherently phase matched to guided mode. The discretised spectrum of radiation modes shown in Figure 3.5 is of the best importance as the TE tail of leaky TM mode in thin-ridge structure is equivalent to one of these radiation modes. Consequently, not including complete set of these type of radiation modes will cause losing accuracy in simulating TM light propagating through this kind of structures.
3.4.2 EME simulation of abrupt transition from ‘magic’ to ‘anti-magic’ width

Having established the method for simulating the waveguide transitions, we now analyse first a simple, abrupt transition and then a linear taper from non-radiating to radiating widths.

Figure 3.6 (a) presents a plan view illustration of an abrupt transition from ‘magic’ width (W=0.73 µm) to ‘anti-magic’ width (W=0.4 µm) which maintains single mode propagation throughout. The structure was simulated using the EME model describe in Section 3.3 and using the modes in each slice described in Section 3.4.1. The input slice was excited with the fundamental mode of the ‘magic’ width waveguide at the input (z=0). The length of the ‘anti-magic’ width waveguide section was chosen to ensure that at the end of the aperture more than 99% of the power in TM-like mode should have radiated away. Using the attenuation coefficient, $\alpha$, of the ‘anti-magic’ width waveguide, as obtained from the imaginary part of complex propagation constant of the TM fundamental mode of the waveguide, it was found that the ‘anti-magic’ waveguide section should be longer than 10 µm.

The length of the ‘anti-magic’ waveguide section was set to L=22 µm. Figure 3.6 (b) shows the real part of the x-directed component of the simulated electric field. Only a small amount of x-directed field can be seen while the field is propagating in the TM mode of the ‘magic’ width waveguide from z=0 to z=2 µm. This is to be expected as the primary components of the TM mode are directed along the y- and z-directions. Once the width transition occurs (z=2 µm) there is a clear increase in the x-directed field intensity as the field couples into the TE component. The field radiates away from the waveguide at an angle of approximately $\theta_{rad}=45^\circ$ to the z-axis. Some divergence of the radiating beam is evident.

To further analyse the nature of the radiating beam, the x-directed field distribution immediately adjacent to the radiating waveguide, at x=0.53 µm, inset of Figure 3.6 (b), was plotted as is shown in Figure 3.6 (c). From z=0 to z=2 µm a constant, non-zero amplitude x-directed component is evident next to the ‘magic’ width waveguide. At the width transition (z=2 µm), the x-directed field rises.
Figure 3.6: (a) Plane view of a transition; (b) Real part of x-directed electric field of light propagating through the transition; (c) Absolute value of x-directed electric field just outside waveguide at x=-0.53µm along the z-axis.
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Figure 3.7: Normalized radiation pattern at x-y cross section at the right end of the aperture of join structure (Figure 3.6).

abruptly and then rises further (up to $z=3\mu m$) and then drops exponentially along the $z$-axis with some minor ripples evident.

The constant field from $z=0$ to $2\mu m$ is the evanescent field of the guided TM mode. The abrupt increase is due to the sudden coupling of TM guided field into TE radiating field at the width transition and the continued increase up to $z=3\mu m$ is due to continued coupling from the TM field in the core to TE radiation. The discontinuity in the field at the abrupt transition is due to the limitation of the number of the modes available in the EME simulation. The exponential decrease of field amplitude beyond $z=3\mu m$ is due to the continuous loss of power from the TM field in the core, which is the source. The ripples can be attributed to diffraction from the abrupt transition causing constructive and destructive interference of the radiating beam.

Having examined the field amplitude close to the source of radiation, the
nature of the radiated beam itself was analysed through examination of the examining the radiation pattern. The radiation pattern, in principle, could be calculated by taking the Fourier transform from of the aperture field distribution, near field, shown in Figure 3.6 (c). However, since propagation through each slice is essentially the same as taking the Fourier transform, it may be possible to extract the radiation pattern from the information already contained within the EME result. As can be seen the main angle of the radiation is almost $45^\circ$, thus, the the near filed could be considered as the field exiting through the output interface of the radiating slice. Based on the EME main principle introduced in Section 3.3, the total field at the output slice is the superposition of complete set of normalized modes with different amplitudes. The decomposition of the exiting field to normalized modes with different amplitudes is essentially Fourier analysis, converting the field from the spatial domain to the angular spectral domain. Therefore, by having the amplitude of the decomposed modes at the right end of the structure the radiation pattern can be calculated. From the EME simulation, the amplitude of each individual mode can be found from the scattering matrix. The amplitude distribution of discretized spectrum of the TE radiation modes exiting the eigenmode simulation window at $z=24\mu$m were extracted and the effective index of each TE slab radiation mode ($N_m$) was interpreted as an angle using $	heta_{rad} = \cos^{-1}\left(\frac{N_m}{N_{TE}}\right)$ where $N_{TE}=2.125$ is the effective index of the TE slab mode at lateral cladding. Figure 3.7 shows the normalized radiation power calculated from the scattering matrix at the exit interface of the slice as a function of the radiation angle. It can be seen in Figure 3.7 that most power is radiated at an angle $\theta_{rad}=44.5^\circ$. This is expected as it is the phase matching angle between the TM like mode and TE slab radiation as predicted by Equation (3.4). Side lobes which are $10.65\text{dB}$ and $9.01\text{dB}$ lower than the main lobe are evident. This relatively high side lobe level can be attributed to the step nature of the discontinuity. The beamwidth is defined as the angular range where the beam drops to half power [46]. The beamwidth of the TE beam in Figure 3.7 is $\Delta\theta=4.8^\circ$.  


3.5 The effect of leakage rate on radiation characteristics

In Section 3.4, the abrupt transition of the waveguide shown in Figure 3.3 (a) and 3.6 (a) with ridge height of $h_r=120\text{nm}$ has been modelled. It has been shown previously that the ridge height has direct impact on leakage rate [56]. It is anticipated that similarly altering the ridge height and hence the leakage rate will have a significant impact on the radiation patterns observed with a step discontinuity. In this section, same structure shown in Figure 3.3 and 3.6 (a) with different ridge heights will be modelled in order to investigate the effect of leakage rate on TE beam characteristics. One waveguide with smaller ridge height ($h_r=90\text{nm}$) and one with bigger ridge height ($h_r=140\text{nm}$) were chosen. In each case, the total silicon thickness of the core was maintained constant at 220nm and the ridge height was subtracted from this to form the lateral cladding. Figure 3.8 shows the loss of the leaky TM mode of the structure shown in Figure 3.3 as a function of waveguide width for ridge heights of $h_r=90\text{nm}$, $h_r=120\text{nm}$ and $h_r=140\text{nm}$. As illustrated in Figure 3.8, the lateral leakage rate rises by increasing the ridge height. This increase in the loss is to the point that the effective index of TM mode is no longer smaller than the TE slab mode in lateral cladding and TM mode is no longer leaky [56]. It is interesting to note that the widths that correspond to the ‘magic’ and ‘anti-magic’ widths are relatively insensitive to the ridge height, which is reasonable since the thickness of the core is the same in each case and would be expected that this core thickness would dominate the waveguide behaviour with the lateral cladding thickness being of only secondary importance.

Similar to Figure 3.6 (c), the x-directed field distribution immediately adjacent to the radiating waveguide (at $x=0.53\mu\text{m}$) with ridge heights of $h_r=90\text{nm}$ and $h_r=140\text{nm}$ is plotted as is shown in Figure 3.9 (a) and (b). From $z=0$ to $z=2\mu\text{m}$ it can be seen that a constant, non-zero amplitude x-directed component is evident next to the ‘magic’ width waveguide for both structures. At the width transition ($z=2\mu\text{m}$), the x-directed field rises abruptly and then rises further (up to $z=3\mu\text{m}$, for the structure with $h_r=90\text{nm}$ and up to $z=4\mu\text{m}$, for the structure with $h_r=140\text{nm}$). The x-directed field then drops exponentially along the $z$-axis.
3. Thin-Ridge SOI Waveguide Transition and Tapers

![Waveguide Width (µm) vs. Leakage Loss (dB/cm)](image)

Figure 3.8: The loss of the leaky TM mode of the structure shown in Figure 3.3 (a) versus the waveguide width for ridge heights of \( h_r = 90 \) nm, \( h_r = 120 \) nm and \( h_r = 140 \) nm.

for both cases. This drop is slow for the structure with \( h_r = 90 \) nm with some minor ripples evident as shown in Figure 3.9 (a). However, the x-directed field drops dramatically along the z-axis with major ripples evident in the structure with \( h_r = 140 \) nm.

Similar to results shown in Figure 3.6, the constant field from \( z = 0 \) to \( 2 \mu m \) is the evanescent field of the guided TM mode, and the abrupt increase in both cases (\( h_r = 90 \) nm and \( h_r = 140 \) nm) is due to the sudden coupling of TM guided field into TE radiating field at the width transition. The continued increase up to a point is due to continued coupling from the TM field in the core to TE radiation. By comparing the Figure 3.9 (a) and (b), it is evident that the abrupt increase of the radiated field for the structure with greater ridge height (\( h_r = 140 \) nm) is bigger than the one with lesser ridge height. It is because of the greater leakage rate for the structure with greater ridge height. The exponential decrease of field amplitude beyond the point that the radiated field hit maximum is due to the continuous...
Figure 3.9: The x-directed field distribution immediately adjacent to the join structure, shown in Figure 3.6 (a) at x=-0.53 µm, with ridge heights of (a) $h_r=90$ nm and (b) $h_r=140$ nm.
3. Thin-Ridge SOI Waveguide Transition and Tapers

Figure 3.10: Normalized radiation pattern at x-y cross section at the right end of the aperture of join structure shown in Figure 3.6 with (a) $h_r=90\text{ nm}$ and (b) $h_r=140\text{ nm}$.
loss of power from the TM mode. This drop is faster in the structure with greater ridge height because of the greater leakage rate. The ripples in both cases can be attributed to diffraction from the abrupt transition causing constructive and destructive interference of the radiating beam. Major ripples for the structure with greater ridge height \( h_r = 140 \text{ nm} \) implies more severe diffraction due to the greater leakage rate.

Similar to Figure 3.7, Figure 3.10 (a) and (b) show the normalized radiation power as a function of the radiation angle for the abrupt transition waveguide with ridge height of \( h_r = 90 \text{ nm} \) and \( h_r = 140 \text{ nm} \), respectively. As can be seen the main angle of radiation is different for the two different ridge heights. This is because the main angle corresponds to the TM/TE phase matching angle which is directly dependent on the propagation constant of the TM mode at the core and
TE mode at slab, as predicted by Equation (3.4). Since for each different ridge height, the slab around the waveguide is etched to a different depth, it follows that the TE radiation in this slab will have an effective index that is different for each ridge height. Figure 3.10 (a) has side lobes 12.39dB and 13.87dB lower than the main lobe for structure and Figure 3.10 (b) exhibits side lobes that are 9.39dB and 6.563dB lower than the main lobe. These side lobe levels are correlated with the amount of ripple observed in Figure 3.9 (a) and (b) and it is evident that the height of the side-lobes and the degree of ripple increases with increasing ridge height and hence coupling rate.

To quantify the directivity of the TE beam emitted from the aperture in terms of the waveguide leakage rate and the aperture length, the beamwidth of the TE beams for waveguide structures with \( h_r = 90\text{nm} \), \( h_r = 120\text{nm} \) and \( h_r = 140\text{nm} \) were calculated as functions of aperture length and the results are presented in Figure 3.11. The aperture length is defined by the length of radiating waveguide at ‘magic’ width. Since the computational window is open along with propagation axis in EME simulation [45], the radiating aperture with the length of \( L \) can be defined with two consecutive abrupt transitions: first from ‘magic’ to ‘anti-magic’ width, then from ‘anti-magic’ back to ‘magic’ width. As can be seen in Figure 3.11, for each ridge height, as the aperture length is increased, the beamwidth drops rapidly. If this were a simple aperture, it would be expected that the beamwidth would be inversely proportional to the aperture length. The expected hyperbolic for this ideal Fourier aperture behaviour is illustrated in Figure 3.11 as dotted lines with a good fit evident for small apertures. As the aperture length increases, however, each of the beamwidths corresponding to the different ridge heights hits a minimum value and stays there. The fact that the beamwidth becomes independent of nominal aperture length is evidence that the aperture is being set by the fact that the amplitude of the TM mode that is exciting the TE radiation is depleted before the nominal end of the aperture, creating an effective aperture that is shorter than the nominal aperture. It would be expected that this aperture length would be shortest for the greatest coupling strength. It is clear from Figure 3.11 that the waveguide with the greatest ridge height reaches this plateau at a fare shorter aperture length than those with lesser ridge heights and hence coupling strengths. These results show that the
beamwidth follows the principles of Fourier analysis and also shows that the rate of attenuation of the TM source is a significant limiting factor. These findings suggest an opportunity for improving the properties of the radiated beam.

3. Thin-Ridge SOI Waveguide Transition and Tapers

3.6 Linear tapering from ‘magic’ to ‘anti-magic’ width

The analysis of the step discontinuity in the previous sections predicted high side lobe’s level and broad beamwidth. This was attributed to the abrupt step nature of the transition and relatively sharply peaked aperture field amplitude distribution. Following the principles of Fourier analysis, it should be possible to reduce the side lobe level and narrow the beamwidth by implementing a more gradual transition.

To test this hypothesis, the abrupt transition of Figure 3.6 (a) was replaced with a linear taper transition from ‘magic’ width (W=0.73\(\mu\)m) to ‘anti-magic’ width (W=0.4\(\mu\)m) as illustrated in Figure 3.12 (a), with ridge height maintained at h_r=120nm. The taper length was chosen so that at the end of the taper more than 99% of the TM mode power would be radiated away. It was found that this condition can be set if the taper length is longer than L=22\(\mu\)m. The length of the taper was set to L=22\(\mu\)m which is same length as of the ‘anti-magic’ waveguide in Section 3.4. The structure was simulated using the same method used for the step transition, however the taper structure was approximated as a sequence of 35 longitudinally invariant waveguide segments of equal length with incrementally decreasing width along the z-axis.

Figure 3.12 (b) shows the real part of the x-directed component of electric field that resulted when the fundamental TM mode was launched into the structure at z=0. Comparing to Figure 3.6 (b), the evanescent component of the TM mode is again evident from z=0 up to the point of transition, however, unlike Figure 3.6 (b), the field does not change abruptly at z=2\(\mu\)m where the taper transition begins. Instead, the TM mode continues to propagate up until about z=5\(\mu\)m where the TE radiation begins to become apparent. From this point on, the radiating TE field becomes stronger up to about z=12\(\mu\)m and then gradu-
3. Thin-Ridge SOI Waveguide Transition and Tapers

Figure 3.12: (a) Plan view of a linear taper structure, ridge height $h_r = 120\text{nm}$; (b) Real part of the $x$ component of electric field of light propagating through the linear taper structure; (c) Absolute value of the $x$ component of electric field just outside the waveguide core at $x = -0.53\mu\text{m}$ along the $z$-axis.
Figure 3.13: Normalized radiation pattern at x-y cross section at the right end of the aperture of the taper structure (Figure 3.12).

ally becomes weaker again with radiation completed at around $z=20\mu m$. The radiating beam is again at an angle of approximately 45° to the $z$-axis, but is significantly broader than that of Figure 3.6 (b) and appears to exhibit less divergence.

Similarly to Figure 3.6 (c), Figure 3.12 (c) shows the amplitude of the electric field just outside the waveguide core at $x=-0.53\mu m$. Unlike the case of abrupt transition of Figure 3.6 (c), the field amplitude is fairly symmetric, gradually increasing to a maximum value at approximately the middle of the taper and then decreases again toward the end of the taper.

Similarly to Figure 3.7, Figure 3.13 shows the radiation pattern as the beam exits the simulation window. The main angle of the radiation is approximately 41.7°. The side lobes are 22.55dB and 25.32dB lower than the main lobe and the beamwidth is $\Delta \theta=3.5^\circ$ which is significantly improved from the sidelobe levels of
10.65dB and 9.01dB and the beamwidth of $\Delta \theta = 4.8^\circ$ evident in Figure 3.7.

The main radiation angle of $41.7^\circ$ is slightly smaller for the linear taper. As discussed in Section 3.4, in the case of the step transition, the main radiation angle is set as the phase matching angle between the effective index of the TM mode of the radiating section and the TE slab radiation. In the case of the linear taper of Figure 3.12 (a), the effective index of the TM mode is actually changing over its length. Thus the radiation angle is actually also changing over the aperture. In this case, unlike the case of abrupt transition, the main radiation angle can be approximated with the phase matching angle, Equation (3.4), of lateral TE radiation tail of the leaky TM mode of the waveguide width of the taper at $z = 13\mu m$ where maximum TE radiation occurs as shown in Figure 3.7. The main angle value approximated with this approach is similar to the main radiation angle of $41.7^\circ$ observed in Figure 3.7.

The narrower beamwidth is due to relatively broad aperture field distribution (Figure 3.12 (c)) in comparison to the relatively narrow and sharply peaked aperture field distribution in the case of abrupt transition (Figure 3.6 (c)), and the reduced side lobes can be attributed to the relatively symmetric and gradual apodization of the field amplitude across the aperture. A more gradual transition and expanded aperture field distribution can be achieved by increasing the taper length. This would lead to a narrower beamwidth and further suppression for side lobe levels.

### 3.7 Aperture field distribution

It may not be immediately obvious why a linear taper should produce a field amplitude apodization of the form shown in Figure 3.12 (c). To illustrate why this apodization occurs, a vector mode matching method [54] was used to calculate the radiation loss as a function of waveguide width. The optical power remaining in the waveguide was also calculated as a function of length along the linear taper with using the EME method.

Figure 3.14 (a) presents the attenuation constant as a function of length along the taper. The waveguide width reduces linearly with length, but the attenuation constant ($\alpha$) does not increase linearly with reducing width, instead the atten-
Figure 3.14: (a) The leakage loss rate profile of the waveguide along the z-axis calculated with full-vector mode matching; (b) The intensity of the light at core at $x = 0$ along the z-axis.
uation increases almost sinusoidally as the waveguide width linearly decreases from ‘magic’ width to ‘anti-magic’ width. Figure 3.14 (b) presents the calculated intensity of the TM light in the waveguide as a function of the taper length. At the beginning of the taper, the TM power remains almost constant, as the loss increases in half way along the length of the taper, more and more of the TM power is lost, with the largest fraction of the TM power being lost at approximately half the taper length. Towards the end of the taper, even though the loss is greatest, most of the TM power has already been lost and thus the net power lost at the end of the taper reduces.

The TM power can be thought of as the source for the radiation. The attenuation constant \(\alpha\) is actually the efficiency with which the TM power is coupled to the TE beam and hence the field amplitude at the source of the TE beam can be envisioned as the product of the two functions depicted in Figure 3.14 with the net effect being the apodization of the radiation field amplitude as seen in Figure 3.12 (c).

### 3.7.1 Relationship between aperture field distribution and loss profile

It is clear that by introducing a simple linear taper between the ‘magic’ width and ‘anti-magic’ width waveguide segments, much more coherent TE radiation is achieved and the beam pattern of the TE radiation field can be controlled. This also implies that by engineering the taper profile desired aperture field distribution could be achieved. In order to design an appropriate taper profile for a desired radiation aperture, it would be convenient if there were a simple relationship between the profile of the desired radiation aperture, \(A(z)\) and the attenuation constant \(\alpha(z)\) which can be controlled by adjusting the taper width at any point \(z\). It is proposed that such an expression could be formulated by borrowing concepts from leaky wave antennas [46].

Due to the loss caused by lateral leakage, the power at the core of the waveguide along the propagation axis (\(z\)) for any geometry of the waveguide can be
written as [46]:

\[
P(z) = P(0) \exp \left[ -2 \int_0^z \alpha(\rho) d\rho \right]
\]

(3.5)

where \(P(0)\) is the power which is launched into the waveguide and \(\alpha(z)\) is imaginary part of the propagation constant (attenuation constant) of the waveguide structure along the propagation axis. For a uniform waveguide, the above equation reduces to:

\[
P(z) = P(0) \exp(-2\alpha z)
\]

(3.6)

Now, by taking derivative of Equation (3.5) with respect to \(z\) we have:

\[
\frac{dP(z)}{dz} = -2\alpha(z)P(0) \exp \left[ -2 \int_0^z \alpha(\rho) d\rho \right]
\]

(3.7)

by rearranging the above equation we have:

\[
-\frac{dP(z)}{dz} = 2\alpha(z)P(z)
\]

(3.8)

The desired outcome is a relationship between the radiation amplitude \(A(z)\) and the attenuation constant \(\alpha(z)\), independent of the power in the waveguide \(P(z)\). If it is assumed that all of the power lost from the core is converted into radiation, then the rate of change of power in the core can simply be related to the power of the radiation at the point as:

\[
|A(z)|^2 = -c \frac{dP(z)}{dz}
\]

(3.9)

where \(c\) is a constant of proportionality. Now combining Equations (3.9) and (3.8), we have:

\[
|A(z)|^2 = 2c\alpha(z)P(z)
\]

(3.10)
3. Thin-Ridge SOI Waveguide Transition and Tapers

by combining above equation and Equation (3.5), we have:

\[ |A(z)|^2 = 2cP(0)\alpha(z)\exp\left[-2\int_0^z \alpha(\rho)\,d\rho\right] \]  \hspace{1cm} (3.11)

Equation (3.11) shows the relationship between the aperture field distribution and the loss profile of the waveguide structure along z-axis. Based on Equation (3.11), the shape of the beam radiated from the waveguide structure can be approximated if the loss profile, \(\alpha(z)\) of the structure is known. This loss profile can be calculated explicitly using the full-vector mode matching mode solver on each slice of any arbitrary structure.

3.7.2 Prediction of the radiation aperture for a linear taper

Having derived a simple expression relating the radiation aperture to the loss profile, it will now be illustrative to apply this expression to the case of the linear taper that was analysed in Section 3.6. It is anticipated that it should be possible to produce a predicted radiation aperture directly from the attenuation coefficients of each slice of the taper that matches the observed field amplitude produced by rigorous simulation. To test this hypothesis, the aperture field distribution of taper structure shown in Figure 3.12 (a) calculated using Equation (3.11), the attenuation profile was as presented in Figure 3.14 (a), calculated by simply extracting the complex eigenvalues of the TM modes of each slide. Figure 3.15 presents the aperture field distribution calculated using Equation (3.11) with the parameters of Figure 3.14 (a). Figure 3.15 also presents the x-directed field distribution adjacent to the radiating taper waveguide (at \(x=-1.46\mu m\)) extracted from the EME model which was shown in Figure 3.12 (b). To have fair comparison between the formula and simulation results, the x-z cross section placed in the smallest distance from the radiating waveguide where the evanescent tail of the confined field in the core is negligible (at \(x=-1.46\mu m\)). As can be seen in Figure 3.15, the results from formula and eigenmode expansion simulation are well matched which proves that it is possible to accurately predict the aperture field distribution simply using Equation (3.11) and the eigenvalue parameters of
3. Thin-Ridge SOI Waveguide Transition and Tapers

Figure 3.15: The TE field adjacent to taper waveguide shown in Figure 3.12 (a) calculated with Equation (3.11) and absolute value of the x-component of electric field outside the waveguide core at x=-1.46µm along the z-axis.

each slice of the taper profile without needing to resort to the rigorous EME simulation.

3.7.3 Prediction of the required leakage profile for a desired radiation aperture

It has been shown in Section 3.7.2 that it is possible to accurately predict the aperture field distribution from a linear taper. It follows that provided that the structure is adiabatic, such that the power in each slice remains in the forward propagating fundamental TM mode throughout the propagation and if it is assumed that all of the power lost during propagation is converted into radiation, then it should be possible to predict the radiation aperture of a structure with any arbitrary loss profile. Given that it should be possible to predict the radiation
aperture of an arbitrary loss profile, it is proposed that it should also be possible
to reverse the process and extract the taper profile based on desired aperture field
distribution. By combining Equations (3.5) and (3.11), the loss profile along the
z-axis can be written as [46]:

\[ 2\alpha(z) = \frac{|A(z)|^2}{P(0) - P(L)} \int_0^L A(\rho) d\rho - \int_0^z A(\rho) d\rho \]  

Note that the proportionality coefficient \((c)\) has been cancelled out from both
sides of the equation. \(P(L)\) is the power remaining in the core of the waveguide
structure at the end of aperture. The power \(P(L)\) is limited to some non-zero
finite number due to the fact that in practice some finite attenuation coefficient
\(\alpha(z)\) can be achieved within any particular waveguide slice. Equation (3.12)
implies that with having desired amplitude distribution outside the radiating
waveguide structure, the loss rate profile needed along the axis of the propagation
can be extracted. Once the loss profile along the propagation axis is found, the
waveguide widths associated to the loss profile can be extracted from loss versus
waveguide width graph (which can be calculated from Mode Matching or FEM
mode solver for example Figure 2.4). It is obvious that taper designs are not
limited to linear geometries, indeed by engineering the taper profile, different
desired beam patterns could be achieved. As an example a Sinc aperture could
be designed to produce flat-top focal points and potentially beams that vary their
angles as a function of wavelength. Care must be taken in calculating leakage rate
along z axis using Equation (3.12) as very large leakage rate cannot be achieved
in practice. The analysis of such structure could be an extension of the work
carried out in this chapter.

3.8 Conclusions

In this chapter, the first analysis of a thin, shallow-ridge Silicon-On-Insulator
waveguide with transitions from a ‘magic’ width to an ‘anti-magic’ width has
been presented. Eigenmode expansion wave propagation method used to model
the transitions excited with fundamental TM mode. It has been shown that highly
collimated TE beam can be achieved by replacing abrupt transition from ‘magic’ width to ‘anti-magic’ width by a linear taper. This investigation considered only a linear taper. It is been shown that further improvements in radiation efficiency and resulting beam quality could be achieved by engineering the profile of the taper to apodize the radiation aperture. Borrowing concepts from leaky wave antennas, it has also been shown how it might be possible to design a taper profile that would produce an arbitrary radiation aperture.
Chapter 4

Thin-Ridge SOI Waveguides: Novel Concepts for Polarization Splitter-Rotator and Wavelength-Selective Devices

4.1 Introduction

In Chapter 3, the TE beam emitted from a thin-ridge SOI waveguide at ‘non-magic’ width operating in the TM mode was fully characterized in terms of main radiation angle, main lobe beamwidth and main lobe to side lobe level. It has been also shown that by using a linear taper profile for the waveguide transition from ‘magic’ width to ‘anti-magic’ width, a transmitted TE beam with almost Gaussian distribution can be emitted from the taper and transmitted into the free propagation region. The ability to control radiation from a waveguide could be an opportunity to create novel devices with applications in telecommunications and other fields. For example, the collimated TE beam emitted from the radiating taper structure could be collected with an adiabatic taper structure and form a polarization splitter-rotator.

Chapter 3 showed that the collimated beam produced by TM to TE conversion in a taper is emitted at a precise angle and that the main angle of TE radiation
is directly dependent on the effective index of TM mode at the waveguide core relative to the effective index of the TE radiation in the lateral cladding. It is known that due to the evanescence of the TM mode that the effective index of this polarization will vary significantly with wavelength due to waveguide dispersion. Conversely, due to the tight vertical confinement of the TE slab mode, the effective index of this polarization will be dominated by the silicon material and thus will be far less wavelength dependent. Thus, the main angle of radiation should be directly proportional to the free space wavelength. As a potential application, wavelength selective devices based on lateral leakage could be conceived in this platform. This dispersive feature of lateral leakage could find applications in de-multiplexing or sensing.

The design and analysis of such a polarization splitter device is introduced in Section 4.2. It is expected that the numerical analysis of a complete device will be hard to achieve with any single simulation tool and hence this section explores the use of combinations of tools with the fine and coarse spatial and spectral resolutions. A wavelength-division multiplexing (WDM) structure is introduced in Section 4.3 by combining the dispersive function of the TM/TE coupling mechanism in a thin-ridge SOI waveguide taper and using a lens to focus the TE light into a series of output waveguides.

4.2 Polarization splitter-rotator concept

It is well known that SOI nano-photonic platforms are very polarization sensitive because of structural birefringence [70–72]. It is very difficult to build polarization insensitive devices in this platform [73, 74]. A general solution to this problem is to use polarization diversity systems by using devices such as polarization beam splitters and polarization rotators [75, 76]. Different kinds of polarization beam splitters have been reported in the literature such as polarization beam splitters based on Mach-Zehnder interferometry, multimode interference and directional coupling.

Mach-Zehnder interferometers (MZIs) have been used extensively for optical modulators, optical sensors and spectral filters. They can also be used as polarization beam splitters by using the birefringence of the MZI arm waveguides.

One can improve the birefringence characteristics of the MZI arm waveguide by introducing extra stress [77], using highly birefringent materials such as III-V semiconductor compounds [78] or LiNbO$_3$ [79]. However, in each of above solutions the birefringence is poor and this will make the device very long. Besides, in terms of fabrication process none of these solutions are compatible with CMOS processing.

Another way of realizing polarization beam splitters is to use conventional multi-mode interference (MMI) structure. These devices show relatively good fabrication tolerance in comparison to other types of the polarization beam splitter designs. MMI devices are based on the self-imaging effect [80]. To realise a polarization beam splitter based on MMI, the length of the MMI section needs to be chosen to be a multiple of the self-imaging length of TE and TM polarized modes simultaneously [71]. This makes the device quite long. The length of the device can be shortened by using cascaded structures [81] or the quasi-state imaging effect [82]. However in these cases, the devices still remain quite long, on the order of a few millimetres.

Another popular way to make polarization beam splitter devices is to use directional couplers [83–86]. To split two polarizations, the length of the device is chosen such that $mL_{TM} = nL_{TE}$ where $L_{TM}$ and $L_{TE}$ are coupling lengths for TM and TE modes respectively, $m$ and $n$ are integer numbers and are related with $m = n + k (k = 1, 3, 5, ...) \ [71, 83]$. This makes the device quite long even for high index waveguides like silicon nano-wires. To shorten the length of the device, asymmetric coupling mechanism have been introduced in which the strong cross coupling occurs for one polarization while the other polarization remains almost uncoupled. This can be achieved by introducing a dimple to one of the waveguides [87] or using bent waveguides [88] in the silicon nano-wire platform.

Realizing a polarization rotator is more complicated than a polarization beam splitter. In order to rotate the optical axis in a planar waveguide one needs to use asymmetric structures. Examples include off-axis double cores [76], bi-level tapers [89, 90], slanted cores [91, 92], or cascaded bent waveguides [93]. Each of these configurations suffer from complicated fabrication processes such as double etching with critical alignment requirements or exotic etching processes to realize a slanted side wall with a specific angle. It is desirable to have both polarization
rotation and polarization splitting functions simultaneously in one device. It is also desirable that the proposed device be compact and CMOS compatible. A polarization splitter-rotator based on silicon nano-wires was proposed by [94]. This device utilizes a structure combining an adiabatic taper and an asymmetrical directional coupler. The adiabatic taper acts as polarization rotator by effectively converting all of the power in the TM fundamental mode when it is propagating through the device to a higher order TE mode and then isolating this higher order TE mode from the fundamental mode using an asymmetric directional coupler. This device is compact, relatively broadband and CMOS compatible in terms of fabrication process but exhibits some small amount of cross talk.

As an alternative, this thesis proposes a compact and broadband polarization splitter-rotator which could be realised using the SOI platform. This proposed device utilizes the TM/TE conversion caused by linear tapering transition from non-radiating to radiating ridge waveguides developed in Chapter 3. This new design is proposed with the aim of achieving a device with better broadband performance and less cross-talk compared to the device introduced in [94].

### 4.2.1 Working principles

In Chapter 3, the compact linear tapering transition from ‘magic’ to ‘anti-magic’ widths was introduced. The TM/TE conversion and the TE beam emitted from the radiating structure shown in Figure 3.12 (a) was numerically investigated in terms of the main radiation angle, directivity and aperture field distribution. It was shown that a collimated, unguided TE beam with approximately Gaussian distribution can be generated using this taper structure. It was also shown that this beam will propagate as a well behaved approximately Gaussian beam through free propagation region.

Figure 4.1 (a) and (b) show the simulation results for the intensity of light propagating along the designed linear tapering from ‘magic’ to ‘anti-magic’ widths, illustrated in Figure 3.12 (a), which were calculated by using the eigenmode expansion (EME) method. It can be seen that mode conversion occurs for the input TM fundamental mode as expected, whereas there is no mode conversion when the TE fundamental mode launched into the structure.
Figure 4.1: Simulated intensity of the light propagating along the radiating taper (illustrated in Figure 3.12 (a)).

Figure 4.2: Schematic view of the proposed polarization splitter-rotator device: (a) the 3D view; (b) the plan view.
This structure can thus clearly operate as a polarizer, however in order to realise a compact polarization splitter-rotator, the radiated TE beams must be collected and concentrated into waveguides. To achieve this task, it may be possible to employ a lens-assisted focusing taper \cite{95} directed along the main angle of the TE radiation to collect unguided TE beam.

Figure 4.2 (a) and (b) show the three-dimensional and the plan views of the proposed compact polarization splitter-rotator, which consists of a radiating linear taper structure, similar to that illustrated in Figure 3.12 (a), and two identical lens-assisted focusing tapers. When the light travels along the radiating taper structure, the TM fundamental mode launched into the left end of the structure will be converted to the unguided TE slab mode and will propagate through the free propagation region as an approximately Gaussian beam at the main angle of $\theta_m$ to the z-axis. A pair of planar lens-assisted taper are placed to focus the light and taper it down to a pair of single mode nano-wire waveguides. Throughout this process the TE light is assumed to be confined vertically within the fundamental mode of the slab.

### 4.2.2 TE collecting lens-assisted taper design

The design procedure for a linear taper from ‘magic’ to ‘anti-magic’ width thin-ridge SOI waveguide was extensively discussed in Chapter 3. The rigorous modelling of the taper structure defined with 120nm depth etching of 220nm-thick silicon layer were also demonstrated in Chapter 3. Since the collimated beam quality for the structure analysed in Chapter 3 was deemed to be good, this structure is a good candidate to be used as a TE/TM converting device, therefore this same structure was chosen for use in this investigation.

As illustrated in Figure 4.2, a planar Plano-convex lens along with a focusing linear taper is proposed to focus the unguided slab TE light into a 450nm width single mode waveguide. As the first step toward the lens design, the lens facet width ($W_f$) should be chosen to be equal to TE beam waist which was approximated by $L \cdot \sin \theta_m$. Based on this, the lens radius (R) should not be smaller than the lens facet width divided by two to avoid the discontinuity. Basic lensing theory can be used to approximate the focal length of the lens. For
maximum coupling of focused light into the single mode nano-wire waveguide, the entrance to the waveguide needs to be placed at a distance equal to the focal length from the centre of the lens. The focal length of a plano-convex thin lens can be approximated by:

$$L_t = \frac{n_{fpr}R}{n_l - n_{fpr}}$$  \hspace{1cm} (4.1)

where $R$ is the radius of curvature of the interface of the plano-convex lens, and $n_{fpr}$ and $n_l$ are effective indexes of the free propagation region and planar lens slabs for TE mode, respectively. The central wavelengths is set to $\lambda=1.55\mu m$. The effective indexes of the free propagation region and planar lens slabs for the fundamental TE mode can be found using a simple 1D mode solver as $n_{fpr}=2.123$ and $n_l=2.827$, respectively. By knowing from Chapter 3 that the length of taper is $L=22\mu m$ and the main radiation angle is $\theta_m=41.5^\circ$, the beam waist is approximately $15\mu m$, therefore $W_f$ is set to $15\mu m$. Thus the minimum lens radius is set to $R=8\mu m$. By using Equation (4.1) and the effective indexes of the free propagation region and planar lens slabs, the focal length of $L_t=30.16\mu m$ is calculated for the lens with $R=8\mu m$. It is predicted that for the $R=8\mu m$ and focal length of $L_t=30.16\mu m$, most of the power should be focused and transferred into the nano-wire waveguide. However, this model ignores the possible effect of the numerical aperture (NA) of the lens and nano-wire waveguide mismatch on power transmission through the nano-wire where the focusing of the lens is too strong. Therefore, to test this hypothesis a rigorous simulation needs to be done.

Because of the large dimension of the whole structure along with nano-scale waveguide components, using 3D EME method or 3D FDTD for the whole device would be computationally intractable. An option would be to combine simulation of the radiating taper with the EME model introduced in Chapter 3 and then simulate the TE light propagation through the lens structure with using another method. Since the radiation is within the fundamental mode of the TE slab and the slab only supports a single mode in the TE polarisation, it is not possible for the lens facet to result in any excitation of higher order modes and it would not be expected that these facets could launch any significant radiation due to the high index contrast of silicon and the insulator. Further, since the TE beam is

Figure 4.3: 2D FDTD simulation of the power transmission of the lens-assisted taper as a function of the taper length ($L_t$) for different radii of curvature $R$ where the ridge height is $h_r=120\text{nm}$. (the wavelength was set to $\lambda=1550\text{nm}$)

incident on the lens facet at normal incidence, it is not possible for it to be phase matched with TM waves that might be generated at this interface. Therefore, by taking advantage of planar platform here, the effective index method can be used to reduce the 3D problem to 2D problem by assuming that all of the light remains in the fundamental TE mode in each region of the slab. Since significant Fresnel reflection is predicted at the lens facet, a bidirectional wave propagation tool must be used. Thus, 2D FDTD is used to simulate the lens-assisted taper.

To interface the 3D EME and 2D FDTD models, the TE beam emitted from radiating taper was approximated with a Gaussian distribution with beam waist of $15\mu\text{m}$. As it was shown in section 3.6, the TE beam emitted from radiating taper is highly directed and coherent, thus the phase profile of the TE beam was assumed to be same as a Gaussian beam. This Gaussian distribution was used as excitation field of the 2D FDTD simulation.

Figure 4.3 shows 2D FDTD simulation of normalized power transmission of
the TE light into nano-wire waveguide, which is termed the TE collecting efficiency of the lens, as a function of lens-assisted taper length ($L_t$) for different radius of curvature (R). For the minimum lens radius of R=8µm, more than 90% power transmission is achieved for a relatively narrow range of taper lengths, from $L_t=20\mu m$ to $25\mu m$. However, for a lens radius of R=9µm, more than 90% power transmission is achieved for a relatively broad range of taper lengths, from $L_t=25\mu m$ to $35\mu m$. The focal length calculated geometrically lies within this range. As is evident in Figure 4.3, for the smallest lens radius (R=8µm) the maximum transmitted power is smallest compared to the other lens radius designs. That is because when the lens becomes too strong, the numerical aperture (NA) of the lens is too large to match the single mode waveguide [95]. As the lens radius is increased, the lens focussing becomes weaker and the focal length becomes longer and the numerical aperture of the lens becomes smaller. As the numerical aperture becomes smaller, the coupling of power to the output waveguide becomes more efficient with greater than 90% of the power being transmitted for a broader range of taper lengths. Improvement in efficiency does not continue arbitrarily with further increases in lens radius. For the cases with larger lens radius, the main part of the loss is just the Fresnel reflection at the lens interfaces. The lens with the radius of R=10µm and taper with the length of $L_t=40\mu m$ was chosen in order to minimize the effect of NA and single mode nano-wire mismatch along with keeping the device footprint size as small as possible. The footprint of the proposed device is approximately $66.5\mu m \times 47.5\mu m$.

### 4.2.3 Assessing bandwidth and cross-talk performance

The fact that it is possible to efficiently and compactly collect the TE radiation using a lens and taper as described in Section 4.2.2 lends support to the proposal that a polarization splitter-rotator as depicted in Figure 4.2 may be feasible. However, when this configuration was proposed, it was compared to the implementation of [94] and it was proposed that this alternate approach may offer improved cross-talk and broader bandwidth. To assess whether this is the case, the full structure of Figure 4.2 must be analysed in terms of spectral response and in terms of cross talk.
In order to investigate the spectral properties of the proposed device, the effect of varying wavelength on the TM/TE conversion along the radiating taper structure must be studied. The polarization conversion efficiency can be calculated from the amount of power that remains in the leaky TM fundamental mode at the right end of the linear taper. The polarization conversion efficiency can be calculated as:

\[
PC_{TM\rightarrow TE} = \left( 1 - e^\left(-2\int_0^z \alpha(\rho) d\rho\right) \right) \times 100\% \tag{4.2}
\]

where \(\alpha(z)\) is imaginary part of the propagation constant (attenuation constant) of the TM leaky mode at the core of the taper structure. This attenuation constant varies as the width of the taper changes along the z-axis.

The polarization conversion efficiency of Equation (4.2) basically estimates the portion of field that leaves the waveguide. In order for the device to be broadband, then this relationship should be relatively wavelength insensitive. From Section 2.2, the imaginary part of the propagation constant \(\alpha(z)\), is also a function of wavelength due to the resonant nature of the waveguide ‘magic’ width. To calculate the wavelength dependence of Equation (4.2), the taper structure of Figure 3.12 (a) was re-analysed and the wavelength dependent attenuation constant \(\alpha(z)\) was calculated in each slice of the taper for a number of different wavelengths in the range of 1.5\(\mu\)m to 1.6\(\mu\)m. These were then used to calculate Equation (4.2) as a function of wavelength and the results are presented in Figure 4.4 (a).

As can be seen in Figure 4.4 (a), the polarization conversion efficiency at the right end of radiating taper is more than 99% for a broad range of wavelengths. This might seem surprising as the lateral leakage behaviour can be quite wavelength sensitive. However, the relatively wavelength independent result of Figure 4.4 (a) can be understood by recalling the fact that the phase velocity, determined by the real part of the propagation constant, of the leaky TM mode is quite sensitive to the wavelength, while the attenuation constant, imaginary part of the propagation constant, is not that sensitive to the wavelength variation. However, even this minor sensitivity of the attenuation constant to the wavelength variation can be reduced with introducing a dimple to the structure [40].
Figure 4.4: (a) polarization conversion efficiency for fundamental TM mode travelling through the radiating taper structure; (b) main angle of TE radiation as a function of wavelength.
Figure 4.5: The wavelength dependence of the designed polarization rotator-splitter when the input is TM (a) and TE (b) fundamental modes, respectively.
The relatively wavelength independent result of Figure 4.4 (a) also leads to the fact that the aperture field distribution of the taper is relatively wavelength independent since the power at the core determine the aperture field distribution, Equation (3.11), and this might have very small effect on shifting the centre of the radiation aperture along the taper.

So, having concluded that the location of the radiating beam along the taper is not varying significantly with wavelength, the remaining parameter is radiation angle. The optical wavelength will directly affect the main angle of radiation since the main radiation angle is directly related to the effective index of the TM leaky mode. The main angle of TE radiation as a function of wavelength can be calculated using Equation (3.4) and is shown in Figure 4.4 (b). As can be seen the main radiation angle variation is approximately 3° for wavelengths from \( \lambda = 1.5 \mu m \) to \( \lambda = 1.6 \mu m \).

Having calculated the amount by which the beam angle varies as a function of wavelength, it is now possible to examine how sensitive the collecting efficiency of the lens assisted taper will be to these changes in angle. To assess the impact of varying angle on collection efficiency, the Gaussian beam used to excite the 2D FDTD simulation of the lens assisted taper was adjusted on the range of 3° and the collection efficiency was assessed. This angle variation was used as the amount of angle tilt of the Gaussian excitation field in the 2D FDTD simulation of lens-assisted taper.

Figure 4.5 (a) shows the collecting efficiency of the lens assisted taper, the transmitted power at the cross port, when the input is the TM fundamental mode. As can be seen in Figure 4.5 (a), the maximum power transmission occurs for a central wavelength of \( \lambda = 1.55 \mu m \). The power transmission efficiency for this central wavelength is 94.7%. This is not surprising since this is the wavelength and angle at which the collecting lens was designed and should thus be considered the unperturbed result. It is evident that the power transmission drops when the wavelength departs from this central wavelength, but remains above 90% efficient across the full range of angles corresponding to wavelengths ranging from 1.5 to 1.6\( \mu m \). Thus, the efficiency varies by about 5% over the range from 1.5 to 1.6\( \mu m \) which is a variation of about -13dB. Thus, while it had been expected that the collection efficiency might be relatively sensitive to wavelength due to changes
of beam angle, the result shown in Figure 4.5 (a) implies that the transmitted power at the cross port is quite high for a wide range of the wavelengths.

Since the TE fundamental mode is effectively guided for all widths [36] the transmission of the TE should not depend on wavelength. To test this hypothesis, the TE fundamental mode was launched into the taper structure and the light propagation through the device was calculated with the 3D EME model introduced in Chapter 3. Figure 4.5 (b) shows the wavelength dependence of the transmission of the fundamental TE mode through the taper structure. This can be considered the 'through port' transmission of the polarization splitter-rotator. This model did not consider side-wall scattering loss which is likely to dominate. However, TE transmission at the through port should also be well over 90% for the whole wavelength range, potentially over 99% depending on scattering loss.

Regarding the cross-talk between the cross and through ports, as can be seen in Figure 4.4 (a), the polarization conversion efficiency at the right end of radiating taper is more than 99% for a broad range of wavelengths. This means that almost all the TM light at the core is converted to TE radiation and more than 20dB extinction ratio can be achieved for TM fundamental mode. This extinction ratio can be even improved by deliberately keeping the through-port waveguide at the ‘anti-magic’ width for a short length, on the order of tens of microns. In terms of the TE fundamental mode, ideally no TE power at the core should leak into the free propagation region at the main radiation angle and be collected by the lens-assisted taper. However, some TE light can be coupled to the lens assisted taper through scattering at the side wall roughness, but this would be expected to be far less than 1%.

In conclusion, From Figure 4.5 (a), the designed polarization splitter-rotator has large bandwidth which is more than 100nm for a variation of around -13dB and extinction ratio in excess of 20dB for both cross- and through-ports. This is potentially greater bandwidth and cross-talk performance for this proposed device compared to the polarization splitter-rotator introduced in [94].
Figure 4.6: 2D FDTD simulation of the power transmission of the lens-assisted taper as a function of the taper length ($L_t$) for different radii of curvature $R$ where the ridge height is $h_r=100$nm (the wavelength was set to $\lambda=1550$nm).

4.2.4 The impact of the ridge height on efficiency and footprint

In Section 4.2.3, it was shown that almost 95% polarization conversion efficiency could be achieved when the device works at the central wavelength. It was also shown that the footprint of such device would be approximately $66.5\mu m \times 47.5\mu m$. It was proposed that the efficiency was limited mainly by Fresnel reflections.

One method to reduce Fresnel reflections is to reduce the etch depth of the free propagation region. This will reduce the effective index contrast between the interior and exterior of the lens and, consequently will reduce the Fresnel reflections. To investigate the effect of the ridge height on the performance of the proposed polarization splitter-rotator, the etch depth of the structure of Figure 4.2 was reduced from the value of 120nm used in Sections 4.2.2 and 4.2.3 to 100nm. As the ridge height was reduced, the radiation strength from the taper would become less and thus the radiation should occur over a larger aperture. In fact,
from the process introduced in Section 3.5, it is found that the aperture length extends to 30\(\mu\)m so that at the end of the taper more than 99\% of the TM mode power has radiated away.

The beam direction for this taper is \(\theta_m=44.89^\circ\) and thus the width of the lens will be this aperture projected onto the angle of the radiation of the beam waist is \(W_f = L \cdot \sin \theta_m\) or \(W_f = 22.58\mu\)m. So, the minimum radius of the lens is set to \(R=11.5\mu\)m. The focal length of the lens can again be calculated from Equation (4.1) using the effective indexes of the interior and exterior of the lens. In this case the index of the interior of the lens is still that of the fundamental TE mode of a slab of thickness 220nm, \(n_l = 2.827\), however the exterior of the lens is the effective index of a slab of thickness 100nm which can be calculated using a simple 1D mode solver to be \(n_{fpr} = 2.292\). Again, similar to Section 4.2.2 and as predicted by Equation (4.1), it is anticipated that the smallest radius will give the shortest focal length. For the parameters above, substituting in \(R=11.5\mu\)m, \(n_l = 2.827\) and \(n_{fpr} = 2.292\) into Equation (4.1), the focal length of the lens will be \(L_f=49.3\mu\)m. This is significantly longer than the minimum focal length for the deeper etched case of Section 4.2.2. Similar to Section 4.2.2, this model neglects the possible effect of the numerical aperture (NA) of the lens and nano-wire waveguide mismatch on power transmission through the nano-wire where the focusing of lens is too strong.

In order to test the impact the shallower etch could have on the TE collecting efficiency of the lens-assisted taper, rigorous modelling of the structure is required. The modelling tool chosen for this investigation is the same 2D FDTD method used in Section 4.2.2 which assumes that all the power remains in the fundamental TE modes of the slab in each region and does not treat TE to TM conversion, and does not include scattering loss due to roughness, but does rigorously consider all of the effects above and also diffraction, beam expansion and reflections. To identify the impact of adjusting lens radius on TE collection efficiency, a number of lens radii were considered, \(R=11.5, 13\) and \(14\), and the length of the taper and hence the distance between the centre of the lens and the input of the nano-wire was scanned for each radius to numerically locate the focal point. The expected coupling efficiency was calculated using 2D FDTD for each lens radius and taper length combination.

Figure 4.7: The wavelength dependence of the device when the input is TM fundamental modes ($h_r=100\text{nm}$).

Figure 4.6 shows 2D FDTD simulation of normalized power transmission of the TE light into nano-wire waveguide as a function of lens-assisted taper length ($L_t$) for different radius of curvature (R) where the ridge height is $h_r=100\text{nm}$. More than 90% power transmission is achieved over a relatively broad range of taper lengths, from $L_t=34\mu\text{m}$ to $L_t=54\mu\text{m}$, with the minimum lens radius of $R=11.5\mu\text{m}$. In the cases of lens radius of $R=13\mu\text{m}$ and $R=14\mu\text{m}$, more than 95% power transmission achieved for taper lengths bigger than $48\mu\text{m}$ and $52\mu\text{m}$, respectively. Similar to the case of ridge height of $h_r=120\text{nm}$, for the smallest lens radius ($R=11.5\mu\text{m}$) the maximum transmitted power is smallest compared to other lens radius designs as the numerical aperture (NA) of the lens is too large to match the silicon nano-wire waveguide.

Having established that the optimal transmission efficiency for the case with a 100nm etch depth has a lens radius of $R=13\mu\text{m}$ and a focal length of $L_t=55\mu\text{m}$ it is now possible to use these values and examine the behaviour of the effect of angle of incidence of the TE beam. The footprint of this proposed device is

approximately $100\mu m \times 65\mu m$. As was discussed in Section 4.2.3, to test this the angle of the Gaussian beam waist input into the 2D FDTD model was adjusted over a range of angles from its nominal angle of $\theta_m = 44.89^\circ$ corresponding to wavelengths ranging from 1.5 to $1.6\mu m$ and the transmitted power at the cross port was calculated. Figure 4.7 shows the transmitted power at the cross port when the input is the TM fundamental mode. The peak transmission of 97.8% occurs at a wavelength of $1.55\mu m$, which is not surprising since this was the design wavelength which set the nominal angle of the lens. Over the full range of wavelengths from 1.5 to $1.6\mu m$, the the transmitted power at the cross port drops to 90% at either extreme.

It is interesting to note that despite the peak transmission for the shallower etch as shown in Figure 4.7 being 97.8%, which is higher than the peak transmission of 94.7% for the deeper etch shown in Figure 4.5 (a), the transmission when the angle or wavelength is varied is approximately the same in both cases. It is reasonable to expect that there would be a fundamental trade-off between the peak power efficiency and the wavelength band over which this peak power efficiency was sustained. The observed reduction in efficiency may simply be due to the small width of the lens being precisely the projection of the beam width and thus when the beam angle is adjusted (pivoting on the beam waste at the taper) causing the beam to not fully fill the lens. If this were the case, to remedy this situation a larger lens width would be required. For the same lens radius, an increase in lens width would increase the focal length proportionally resulting in a larger footprint.

By comparing the cross-port power transmission results for ridge height of 100nm and 120nm, the power transmission is increased for the case of 100nm ridge height. However, the footprint size of the device gets larger. It is understandable since the most of the power loss is due to the Fresnel reflection at the lens facet, so the structure with shallower etch depth shows larger power transmission. On the other hand, shallower ridge means that the lens is weaker and the radiating taper is longer, consequently the size of the device will be increased.

4.2.5 Summary

In this section, a novel concept for a compact polarization splitter-rotator was proposed. This structure utilizes lateral leakage as the mechanism for TM/TE conversion while no polarization conversion occurs for the TE mode. The input fundamental TE and TM light are separated by utilizing the fact that TE mode remains within the core while TM mode leaks into the TE slab mode in the free propagation region and is collected and focussed into the to TE fundamental mode of a nano-wire waveguide by using a lens assisted taper. The proposed device is relatively broadband and shows very low cross-talk since almost all TM power at the core is radiated to the TE slab mode at the end of the radiating component while practically all of the TE power remains in the core after propagation through the taper. This proposed device splits the converted transmitted power by half since the leakage occurs equally on both sides of the radiating taper. To guide all converted power into one collecting waveguide, this device could be integrated with the single side radiation device proposed in Chapter 2. Another solution would be to make one side of the waveguide acts like mirror by etching deep to the BOX.

4.3 WDM device concept

WDM devices can filter a broad spectrum of wavelengths directing each wavelength or wavelength band into a specific, spatially separated output channel simultaneously. The most popular and robust WDMs are array waveguide gratings (AWGs) [16] and echelle gratings [14]. These devices utilize a combination of wavelength dependent phase delays through the use of relatively long and precisely controlled propagation paths and free space focusing mechanisms to achieve the wavelength selection function.

In echelle gratings, the input waveguide is excited by multiple wavelengths simultaneously. The input waveguide is interfaced to a slab region (free propagation region) where the light beam expands and propagates until it is incident on the grating facet. A typical uniform planar grating would reflect all of the spectral components of an incident plane wave at different angles. However, in

In the case of the eschelle grating, the incident beam is from a point source and thus has a circular phase front. The grating is also circular and thus reflects and incoming expanding circular phase front into an outgoing contracting circular phase front, with each of the spectral components being reflected at a different angle. Hence, the concave grating diffracts, reflects and focuses the light beam into the output channels which are placed at specific points on the Rowland circle [96]. In these structures, the footprint scaling of the structure is inversely related to the wavelength spacing. Therefore, to have a narrower channel spacing, the spatial focusing resolution of the structure must be improved which leads to a larger free propagation region [16]. Compact echelle grating structures in Silicon have been presented in [17, 97, 98]. All echelle gratings require critically smooth vertical etching to realise the grating facets. This potentially increases insertion loss. However, overall insertion loss can be reduced by coating the grating facet by metal [98] or by using strong Bragg mirrors in the facet [14] to reduce Fresnel transmission loss.

In AWGs, instead of one free propagation region, two free propagation regions are used to expand and refocus the light into the channels separately. A number of waveguides with different lengths are used between the two free propagation regions to impose different wavelength dependent phase delay before refocusing in second slab region [99]. The footprint scaling of an AWG is determined by a combination of a few parameters including the number of wavelength channels and also the free spectral range (FSR) [14]. In [15], one of the first compact AWG device fabricated in Si platform was demonstrated. The overall insertion loss of the AWG is lower compared to equivalent echelle grating since the main source of the loss is because of the Fresnel reflection at the waveguide slab interface. This loss can be reduced through use of a shallow etched interface [100]. However, small fluctuations in the geometry of the photonic wire waveguides used to impose wavelength dependent phase delay can cause severe phase noise because of high index contrast, and this can cause higher cross-talk.

In Section 4.2, it was shown that the TM to TE coupling mechanism could be used to realise a polarization splitter-rotator device by converting a guided TM mode into a free space TE beam and focusing that beam into an output waveguide using a lens assisted taper. In analysing this device, it was found that

the beam direction was somewhat sensitive to wavelength due to the differential dispersion of the TM guided and TE radiated modes. This wavelength dependence was viewed as a limitation of the polarization converter, however, through understanding of the mechanisms that cause this wavelength dependence, it may be possible to harness this effect and exploit it for wavelength filtering. Hence this section explores the possibility of using the dispersive function of a TM/TE coupling mechanism in TM thin-ridge SOI waveguide at a ‘non-magic’ width to spatially separate different wavelengths from the input waveguide at the ‘magic’ width and then use a focal lens to focus the light into a series of output waveguides. Similar to echelle grating devices, the footprint of the proposed device is expected to be inversely related to the wavelength spacing. Like AWG devices, the whole structure could be realized by implementing a single shallow etch step. Therefore, it is expected that the overall insertion loss of the proposed device could be potentially low.

4.3.1 Working principles

It was shown in Section 4.2.3 that the main angle of radiation should be directly proportional to the free space wavelength. It is proposed that this dispersive feature could be utilized to conceive a WDM in this platform. A schematic structure of the proposed WDM is shown in Figure 4.8. As can be seen, the whole device could be defined in one etch step. Similar to the polarization rotator device design introduced in Section 4.2, the light is always confined vertically (along the y direction) within the fundamental mode of the slab waveguide. The input of the device is the wide end of a radiating taper which can be found at the the axial origin in Figure 4.8. At the input, the optical excitation includes several superimposed wavelengths simultaneously. The input excitation is in the fundamental TM mode of the taper, which starts at the ‘magic’ width and gradually tapers to strongly radiating non-magic width which converts the TM guided light into TE slab radiation. As shown in Section 4.2.3, the radiation angle of the beam will be somewhat wavelength dependent. The taper is designed to apodize the beam pattern and main radiation angle to achieve a collimated TE beam emitted from the structure and propagating through a 2D free space. After the collimated TE

Figure 4.8: Schematic view of the proposed WDM device: (a) the 3D view; (b) the plan view
light is emitted from the radiating taper structure and starts propagating through 2D free propagation region, a planar lens is placed to focus the light into output channels. The planar waveguide and lens designs of the proposed structure have the advantage of monolithic integration and could have potentially low insertion loss.

The focussing function of a lens can be considered as a Fourier transform between incident angle at the input to the lens to location at the Fourier plane of the lens. Thus, a highly collimated beam incident on the lens at a specific angle will be converted into a tightly focussed spot at a specific location on the Fourier plane. If the incident angle of the collimated beam changes, then the location of the focus on the Fourier plane will also change. Thus, since each wavelegth that is propagating within the taper is radiated at a different angle, the lens will focus these different wavelengths to different locations on the Fourier plane and hence they can be isolated using distinct output waveguides as illustrated in Figure 4.8, implementing the function of the WDM device. The tasks required in order to design the structure of Figure 4.8 can be divided as follows. First, the radiating taper must be designed and its dispersive characteristics must be modelled. Then, a focusing lens must be designed to efficiently focus the TE beams to output channels. Finally, the filtering characteristics of the whole device should be modelled and avenues to improve the filtering performance of the device can be identified.

4.3.2 Dispersive radiating waveguide structure design

Considering the functionality of the device depicted in Figure 4.8, the input to the radiating taper is fed by a waveguide which is non-radiating, being at the ‘magic’ width. However, it is known that, due to its resonant nature, the ‘magic’ width is somewhat wavelength dependent and hence for any given width of the input waveguide only one of the wavelengths would be confined at the ‘magic’ width, with the others experiencing some radiation, increasing rapidly with spectral separation from the resonant wavelength. Thus it is necessary to consider means to achieve effective low-radiation ‘magic’ width behaviour over a range of wavelengths. It has been shown that the wavelength range at which
radiation is suppressed can be broadened through the introduction of a dimple [40, 101]. Hence to ensure broadband suppression of the radiation at the input to the taper it is proposed that such a dimple be used on the input waveguide in this instance as well.

The primary finding of [40] is that the introduction of a dimple can extend the operation range of ‘magic’ width waveguides. However, it was also shown in [40] that when a dimple is added to an ‘anti-magic’ width waveguide, then the radiation strength can actually be enhanced. It is possible that this enhancement of radiation could be used to improve the performance of the radiating taper and thus it may be valuable to retain the dimple throughout the taper as well.

Section 4.2 showed that the radiating taper of Chapter 3 could be combined with a lens assisted taper to collect the TE radiation into an output waveguide. The efficiency of this collection was limited, in part, by the focusing nature of the lens, but ultimately was limited by the Fresnel reflections from the front facet of the lens. This Fresnel reflection was determined by the index contrast between the interior and exterior of the lens. It was shown in Section 4.2.4 that reducing the etch depth could improve the efficiency by reducing the Fresnel reflections and allowing a longer focal length lens to achieve higher efficiency.

Comparing the polarization converter of Figure 4.2 with the proposed WDM of Figure 4.8, it can be seen that while the device of Figure 4.2 has a single interface between the radiating taper and the collecting lens which could generate Fresnel reflections, the WDM device of Figure 4.8 has three such interfaces: the input facet of the lens, the output facet of the lens and the input facet of the collecting waveguides. Thus it would be expected that Fresnel reflection will be even more significant for the efficiency of the design of Figure 4.8 and hence it would be desirable to reduce the ridge height as much as possible in order to minimise these Fresnel reflections. However, by decreasing the etch depth the index contrast drops and therefore the lens becomes weaker. This leads to larger footprint.

On the other hand, Chapter 3 showed that the ridge height determined the radiation strength of the taper and, if a linear taper is selected and the condition is set that the taper should radiate away 99% of the guided TM mode, then as the ridge height is made smaller, the required length of taper to achieve 99% radiation...

![Figure 4.9: (a) Cross section of radiating ridge SOI waveguide; (b) Plan view of radiation linear taper structure.](image)

of the TM mode will become longer. This will cause a larger device footprint. Now, as shown in [40] while the introduction of a dimple can suppress radiation when the waveguide width is close to the ‘magic’ width, it can actually enhance the radiation when the waveguide width is close to the ‘anti-magic’ width. Thus, it should be possible to enhance the radiation efficiency of a taper with a shallow ridge height allowing a shorter taper to be defined reducing footprint, but while maintaining minimal Fresnel reflections.

Having discussed that it would be beneficial to insert a dimple at the start of the device in order to broaden the bandwidth of the ‘magic’ width input, and that it would be beneficial to retain the dimple over the length of the taper in order to achieve strong radiation with a shallow ridge height, it is now possible to consider what length of taper is required to realise the WDM device of Figure 4.8. As was shown in Chapter 3, the ridge height \( h_r \) and length of the taper determine the main characteristics of the TE beam emitted from the device. The beamwidth of the TE beam emitted from the structure could be one of the key parameters to reduce the crosstalk between the channels. The angular spread of the main lobe of the radiated TE beam for each individual wavelength channel should...
be less than the angular spacing between the adjacent wavelength channels to keep the crosstalk between the channels low. As the angular spread of the beam is directly related to how broad aperture field distribution is, the taper length should be selected long enough to minimize the beamwidth. On the other hand, the length of the taper is determined by the amount of TM power which remains in the core of the waveguide at the end of the taper.

Firstly, in order to design the taper it is necessary to analyse the modal response of the dimpled waveguide to assess the expected radiation characteristics as a function of width. A diagram of the dimpled waveguide is presented in Figure 4.9. Here the dimple width is chosen at $d=100\text{nm}$, the etch depth is set to $h_r=50\text{nm}$, the silicon slab thickness remains at $h_c=220\text{nm}$ and the width of the outer waveguide walls are varied. To investigate the leakage behaviour of the structure shown in Figure 4.9 (a), a full-vector mode matching mode solver was used to calculate the attenuation constant ($\alpha$) of the waveguide as a function of the waveguide width. Figure 4.10 shows the leakage loss of the TM-like mode as a function of the waveguide width of the structure illustrated in Figure 4.9 (a).

The inset is magnified view of the width range in which the minimum loss occurs for this waveguide structure. This waveguide exhibits minimum radiation to the TE slab mode when the width is at resonant ‘magic’ width of either $W=1.72\mu m$ or $W=1.9\mu m$. This double resonance is characteristic of the dimple waveguide and, in fact, the entire range form $W=1.7\mu m$ to about $1.91\mu m$ can be considered as being approximately at the ‘magic’ width [40]. This waveguide exhibits maximum radiation at anti-resonant ‘anti-magic’ width of $W=1.05\mu m$ [40].

Having determined the ‘magic’ and ‘anti-magic’ widths of the radiating taper, the length of the taper can be chosen. Figure 4.10 (a) presents a diagram of the taper structure with a constant width dimple running along its length. The length of the taper is determined by considering the amount of power that remains at the core at the end of the taper waveguide. The length of the taper is designed to ensure that at the end of the aperture more than 99% of the power in TM mode has radiated away. The amount of TM power that remains at the end of waveguide taper can be calculated by Equation (3.5). The procedure of calculating the remaining power is explained in Section 4.2.3. By using the power calculations introduced in in Section 4.2.3, the length of the taper was set to $L=140\mu m$. This length is far greater than the length of taper studied in Section 4.2, but as already discussed, such a long length is required to achieve a large aperture for the beam and hence a very narrow angular spread and thus a tight focal spot at the output to minimise cross-talk. The taper length is, however, far less than would be expected for a simple 50nm taper without a dimple enabling such a shallow rib to be used for this application without excessive device footprint.

Having determined the geometry of the radiating taper structure, its dispersive characteristics must be investigated. Before that the central wavelengths need to be assigned. In this design, the four wavelength channels are spaced by 30nm, and central wavelengths of 1.46, 1.49, 1.52 and 1.55\mu m were chosen.

The main TE radiation angle as a function of wavelength can be approximated using Equation (3.4) as was done in Section 4.2. In order to use this equation, a single effective index must be chosen for the TM mode, but the effective index varies as the waveguide width varies along the length of taper. It was shown in Chapter 3, that it was reasonable to approximate the effective index as the index half way along the taper as this is where the bulk of the field is radiated. Thus,

Figure 4.11: (a) Main angle of TE radiation as a function of wavelength; (b) Normalized radiation pattern for central wavelengths.
picking the point at 70\,\mu m along the taper where the width is W=1.385\,\mu m it is possible to calculate the wavelength dependent index of both the TM guided and TE slab modes and then use Equation (3.4) to estimate the radiation angle. Figure 4.11 (a) shows the main TE radiation angle as a function of wavelength. The main radiation angle increases as the wavelength is varied from 1.4\,\mu m to 1.6\,\mu m. The dispersive characteristic of the taper structure is evident and the angle of radiation varies from $\theta_m=43.62^\circ$ to $46.59^\circ$ over the wavelength window from $\lambda=1.46\,\mu m$ to $1.55\,\mu m$. The angular spacing between adjacent wavelength channels are $\Delta \theta_m(1.46\,\mu m \rightarrow 1.49\,\mu m)=1.07^\circ$, $\Delta \theta_m(1.49\,\mu m \rightarrow 1.52\,\mu m)=0.99^\circ$ and $\Delta \theta_m(1.52\,\mu m \rightarrow 1.55\,\mu m)=0.91^\circ$. Based on the calculated angular spacing between central wavelength channels, the beamwidth of the radiated TE beam for all channel wavelengths should be less than $0.91^\circ$ to minimize the crosstalk between them.

Figure 4.11 (b) shows the normalized radiation pattern at the right end of the aperture (taper) for each of the central channel wavelengths. To extract the beam characteristics of TE beam radiated from the taper waveguide for these four central wavelengths, the EME method was used as described in detail in Section 3.6. It can be seen in Figure 4.11 (b) that most of the power is radiated at angles of $\theta_m=46.5^\circ$, $45.6^\circ$, $44.7^\circ$ and $43.8^\circ$ for wavelengths of $\lambda=1.46\,\mu m$, $1.49\,\mu m$, $1.52\,\mu m$ and $1.55\,\mu m$, respectively. The maximum beamwidth is found at the central wavelength of $\lambda=1.55\,\mu m$ which is $\Delta \theta_m=0.77^\circ$. This is much less than critical beamwidth of $\Delta \theta_m=0.91^\circ$ which is required to minimize the crosstalk between channels. The radiation angles are well matched with the modal analysis estimation shown in Figure 4.11 (a). Side lobes which are at least 21\,dB lower than the main lobes of all central channels are evident which is deemed sufficiently low that the side lobes will not contribute significantly to cross-talk.

### 4.3.3 Focusing lens design

Having designed and analysed the dispersive taper waveguide, the relatively broad TE beam emitted from the taper needs to be focused and imaged into the output waveguide channels. As shown in Figure 4.8, a planar circular lens was selected for this design. As the first step toward the lens design, the lens facet width

$(W_f)$ should be chosen to be equal to TE beam waist which was approximated by $L \cdot \sin \theta_m$. Based on this, the lens radius (R) should not be smaller than the lens facet width divided by two to avoid discontinuity. Basic lensing theory can be used to approximate the focal length of the lens. The center of the lens should be aligned with the middle of the taper length at the central main radiation angle $(\theta_c)$. The lens and dispersive taper spacing was chosen as 150$\mu$m.

The central main radiation angle $(\theta_c)$ was designed to be the main radiation angle of the TE radiation at a wavelength of $\lambda=1.505\mu$m which is the mid-wavelength between two adjacent central wavelength of $\lambda=1.49\mu$m and 1.52$\mu$m. This angle can be extracted from Figure 4.11 (a). The channel spacing was approximated as the product of the focal length of each central wavelength with the angular deviation of its main radiation angle from the main angle of each adjacent central wavelength. By decreasing the etch depth, the lens becomes weaker, thus the channel spacing is increased. The waist width of the focused TE beam at the focal point is directly proportional to the focal length of the lens and wavelength, and inversely proportional to the width of the TE beam. By decreasing the etch depth, the focal length of the lens increased, but the aperture length (width of the radiated beam) is increased. Thus, the change in the etch depth is expected to have negligible impact on the waist width of the focused TE beam. Therefore, the width of the facet of the output channels can be designed based on the channel spacing. In this case, larger channel spacing is expected to improve uniformity across the channels. In here, the output channel waveguides were designed to be adiabatic tapers. The width of the facet of the output channels was set to 7$\mu$m and the end width of the taper was set to 1$\mu$m. A set of optimised parameters of the device is summarized in Table 4.1.

4.3.4 Assessing the filtering characteristics of the device

Having designed and analysed the dispersive taper waveguide, and having designed and analysed the focussing lens and also designed the output channel waveguides, it is now possible to assess the performance of the assembled device. Because of the large dimension of the whole structure along with nano-scale waveguide components, using 3D EME method or 3D FDTD for the whole device
### Table 4.1: WDM device structure parameters

<table>
<thead>
<tr>
<th>Calculated parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Width ($x_1$) ($\mu$m)</td>
<td>~550</td>
</tr>
<tr>
<td>Device Length ($z_1$) ($\mu$m)</td>
<td>~550</td>
</tr>
<tr>
<td>Lens radius ($R$) ($\mu$m)</td>
<td>80</td>
</tr>
<tr>
<td>Central pointing angle ($\theta_c$) (degrees)</td>
<td>45.18</td>
</tr>
<tr>
<td>Lens and taper spacing ($S$) ($\mu$m)</td>
<td>150</td>
</tr>
<tr>
<td>Calculated Focal length for $\lambda=1460$nm ($\mu$m)</td>
<td>519</td>
</tr>
<tr>
<td>Calculated Focal length for $\lambda=1490$nm ($\mu$m)</td>
<td>509</td>
</tr>
<tr>
<td>Calculated Focal length for $\lambda=1520$nm ($\mu$m)</td>
<td>500</td>
</tr>
<tr>
<td>Calculated Focal length for $\lambda=1550$nm ($\mu$m)</td>
<td>491</td>
</tr>
<tr>
<td>Channel spacing (center to center) (1460nm→1490nm) ($\mu$m)</td>
<td>9.81</td>
</tr>
<tr>
<td>Channel spacing (center to center) (1490nm→1520nm) ($\mu$m)</td>
<td>8.75</td>
</tr>
<tr>
<td>Channel spacing (center to center) (1520nm→1550nm) ($\mu$m)</td>
<td>7.71</td>
</tr>
</tbody>
</table>

would be computationally intractable. Similar to Section 4.2, an option would be to model the radiating taper in advance using 3D EME and then model TE light propagation through the lens structure using another method. Since Fresnel reflection is predicted at the lens facet, a bidirectional wave propagation tool must be used here. However, unlike the case of Section 4.2, the Fresnel reflection at each facet predicted to be small, as the ridge height is only 50nm. Thus, 2D bi-directional BPM (BeamPROP, Rsoft [102]) can be used to simulate the lens-assisted taper. A transparent boundary condition was used in the lateral direction to avoid reflection of radiation leaving the simulation window back into the problem. To interface the 3D EME and 2D bi-directional BPM, the TE beam emitted from the radiating taper was approximated with a Gaussian distribution with beam waist as calculated in Section 4.3.3. This Gaussian distribution was used as the excitation field of the the 2D bi-directional BPM simulation.

To investigate the focusing performance of the lens, the field distribution of all wavelength channels along the average focal line of the lens was calculated.
Figure 4.12: The field distribution for central wavelengths along the focal line of $z=655\,\mu\text{m}$.

Figure 4.12 shows the field distribution of the four central wavelengths along the focal line of $z=655\mu\text{m}$. In this simulation the output waveguide channels were not included. The input field for the BPM simulation was approximated with a Gaussian field with waist size equal to double the lens radius. The peak of the field for different wavelengths is different because of the aberration due to the dispersion of the effective index of the lens and its surrounding slab region. This aberration manifests as slightly different focal lengths for each different wavelength and could be addressed by simply adjusting the location output channel waveguides to match the actual focal length. Side lobs are evident for all focused beams. This could be because of diffraction due to the limited size of the lens aperture. These side lobes are the main source of crosstalk between the adjacent central wavelengths channels.

At this stage, the output channels were introduced to the model to enable simulation of the focusing of the light into them. It was expected that for each of the
four central wavelength channels, most of the light would be coupled into the appropri-ate output channel. To investigate the filtering characteristics of the device, the power coupled to the output waveguide channels was calculated as a function of wavelength and plotted in Figure 4.13. The power of each wavelength channel was calculated at the end of the output channel pathway and normalized to the power of the Gaussian field excitation. The crosstalk between adjacent channels were found to be $(1.46\mu m \rightarrow 1.49\mu m) = -27.25\text{dB}$, $(1.49\mu m \rightarrow 1.46\mu m) = -24.74\text{dB}$, $(1.49\mu m \rightarrow 1.52\mu m) = -21.33\text{dB}$, $(1.52\mu m \rightarrow 1.49\mu m) = -23.57\text{dB}$, $(1.52\mu m \rightarrow 1.55\mu m) = -19.49\text{dB}$ and $(1.55\mu m \rightarrow 1.52\mu m) = -20.10\text{dB}$. The maximum cross-talk between adjacent central wavelength channels is $-19.49\text{dB}$. This cross-talk could be attributed to side lobes due to diffraction. Improvement to a nominal value of -20dB should be relatively straightforward with minor adjustment of the lens and/or taper geometry.

The loss predicted when the TE beam was focused into the output channels
can be extracted from Figure 4.13. The propagation loss for central channels are 0.35dB, 0.21dB, 0.32dB and 0.29dB for $\lambda=1.46\mu$m, 1.49$\mu$m, 1.52$\mu$m and 1.55$\mu$m, respectively. This loss could be due to Fresnel reflections from the input and output facets of the lens and also the input facet of the output channel waveguide. It could also be due to the finite efficiency of the coupling of the focussed TE beam into the output waveguide. The loss of around 0.3dB is relatively low. This low loss can be attributed to the shallow etching which defines the planar components. Hence, the proposed device shows the potential to work with very low overall propagation loss as the device takes advantage of shallow etched planar platform. It is also expected the device parameters, crosstalk and channel uniformity, to be exceptionally tolerant to the fabrication tolerant. The fabrication sensitivity analysis of the proposed device could be an extension of the work carried out in this section.

4.3.5 Summary

In this section, a novel concept for a wavelength selective device was proposed. This structure utilized lateral leakage as the mechanism to disperse the input TM multi-wavelength excitation into unguided TE beams which propagate into the free propagation region at different radiation angles. Then, the radiated TE light was focused into the output channels through use of a planar lens. The proposed device shows low propagation loss and relatively low cross-talk between the central wavelength channels. In addition the device could be realised using a single etching step. Similar to polarization splitter-rotator device, this device could be integrated with the single side radiation device proposed in Chapter 2 to guide all the power to one set of output waveguides in one side of the structure.

4.4 Conclusions

This chapter has presented two new device concepts. In the first section, a novel concept for a compact polarization splitter-rotator was presented. This structure utilized lateral leakage as the mechanism to convert guided TM light into a radiating TE beam, while while no polarization conversion occurred for the guided
TE mode. The device exhibited more than 95% converted power transmission from guided TM through conversion to radiated TE and then to collected TE via a lens assisted taper waveguide. The proposed device exhibited a relatively large bandwidth (more than 100nm for a variation in efficiency of less than -13dB). The whole device occupied a footprint of 67µm wide 47µm long. It has been shown that the size of the device was inversely related to the etch depth. By increasing the etch depth, the device size can be reduced at the cost of reduced transmission efficiency. Avenues to practical realization of this device were identified.

In the second section, a novel concept for a WDM device based on lateral leakage phenomena in thin-ridge SOI platform was developed. In this proposed device, lateral leakage was used as the mechanism to disperse the multi-wavelength excitation of the TM guided mode of a thin-ridge taper, into radiated TE beams which propagate into the free propagation region at different radiation angles. A dimple was introduced to the radiating taper to enhance the radiation efficiency of the taper with a shallow ridge height allowing a shorter taper to be defined reducing footprint, but while maintaining minimal Fresnel reflection loss. Through design and simulation of this WDM device, a maximum propagation loss of about 0.35dB has been predicted. The cross-talk was predicted to be around 20dB between each of the adjacent channels. The whole device occupied a footprint 1mm wide and 550µm long and can be defined using single step etching. It is also possible to make the device footprint below 800µm × 400µm by reducing the focal length of the focusing lens.

Overall, this chapter showed that the lateral leakage phenomenon can be used to design interesting new devices. The main challenge through the design and simulation of such devices was their full vector nature of modelling of nano-scale thin ridge waveguides along with relatively large footprint because of the significant angle of TE radiation. A combination of full vector 3D EME to accurately model TM/TE conversion at thin-ridge waveguide and 2D FDTD/BPM to simulate TE beam propagation through free propagation region was proposed and used to rigorously simulate the light propagation through polarization splitter-rotator and WDM devices. It was shown that rigorous numerical tools introduced in this chapter can be effectively used to design such devices. This could enable designing and developing other topologies which might utilize lateral leakage such

as sensors and hybrid devices.
Chapter 5

Conclusions and Future Work

5.1 Conclusions

The aim of this thesis was to harness lateral leakage in thin-ridge SOI waveguides to conceive new range of devices drawing inspiration from antennas. First analysis of directional control of lateral leakage radiation in SOI thin-ridge waveguides using rigorous film mode matching modal analysis was presented. This directional control of radiation could be used to transmit power to another well separated waveguide on one side of the structure with almost no radiation lost to the other side.

In SOI thin-ridge waveguides, harnessing the strong TM/TE coupling at the step discontinuity and highly resonant transition from leaky to non-leaky behaviour, suggests an opportunity for new photonic devices. The main challenge to achieve this goal was to model the longitudinal varying lateral leakage devices. Such simulation has never been reported before. The large dimensions of the whole device due to TE radiation into FPR at a significant angle combined with the nano scale features at the waveguide core and strong polarization conversion at the step discontinuity make using standard wave propagation tools such as BPM and FDTD intractable. This thesis has suggested the semi-analytical EME method to simulate such structures. The emitted TE beam was studied in terms of main radiation angle, directivity and aperture field distribution. It has been shown that by using a linear taper to transition the radiating waveguide from ‘magic’ to ‘anti-magic’ width, a highly collimated TE beam with almost
5. Conclusions and Future Work

Gaussian wave-front can be emitted from the taper structure.

As an application, this TE radiation was used to conceive a novel compact and broadband TM/TE polarization splitter-rotator in thin-ridge SOI nano-photonic platform. Moreover, a novel WDM design based on the dispersive characteristic of lateral leakage was developed and modelled. A dimple was introduced into the radiating taper structure to enhance the radiation loss in order to have a compact aperture while also keeping the etch depth shallow. This proposed device showed relatively low propagation loss as it takes advantage of planar platform and shallow etch depth. Overall, it was shown that the lateral leakage phenomenon can be used to design interesting new devices. The rigorous numerical tools introduced in this thesis might be used to design diverse devices and other topologies utilizing lateral leakage such as sensors and hybrid devices. In conclusion, the objectives laid out at the start of the thesis have been achieved and the next section presents a summary of each of these achievements.

5.2 Outcomes of this work

In Chapter 2, the first analysis of directional control of radiation for SOI thin-ridge waveguides with lateral leakage was presented. This structure consisted of two radiating waveguides and initially these were treated as being independent provided they were well separated. However, a significant finding of this chapter was that the waveguides remained coupled with distinct odd and even supermodes irrespective of their separation, even for very large separations. The film mode matching technique was used to calculate the TM mode solution of the whole structure and the effective indexes for different gaps between the two waveguides. Both simple superposition and more sophisticated supermode analysis were used to predict the radiation behaviour. Through this analysis it was found that it is not possible to meet both the phase matching and radiation balance conditions required for ideal suppression of radiation on one side of the structure to be sustained over long propagation distances simultaneously. The evolution of superposed supermodes as they propagate was examined and have shown that it is possible to strike a compromise between phase-match and amplitude balance that
allows modest radiation suppression to be sustained over reasonable propagation distances.

In Chapter 3, the modelling of TM light propagating through longitudinal varying lateral leakage ridge SOI waveguide structures was presented. The EME simulation of abrupt transition from non-radiating ‘magic’ width waveguide to radiating ‘anti-magic’ with waveguide was presented. The aperture field distribution of emitted TE beam from such abrupt transition was obtained and the beam characteristics in terms of main radiation angle and directivity was studied by extracting radiation pattern. The effect of ridge height, etch depth, on the leakage rate and consequently the beam characteristics was presented by comparing three etch depth scenarios. Linear taper transition from non-radiating ‘magic’ width waveguide to radiating ‘anti-magic’ width waveguide was simulated and TE beam characteristics was extracted. The comparison of TE beam characteristics emitted from the abrupt transition and the linear taper was presented, and large side lobe suppression achieved and the directivity improved. It was shown that unlike the abrupt transition which has a exponentially decaying radiation aperture, an almost Gaussian aperture field distribution can be achieved by the linear taper transition. The aperture field distribution of the linear taper structure predicted from analytical formulations borrowed from leaky wave antenna was compared with the EME simulations. The avenue to apodize the taper profile to tailor the beam to obtain a desired shape was discussed in detail.

In Chapter 4, a novel concept for polarization splitter-rotator design was introduced by using lateral leakage in ridge SOI waveguides. A collecting lens-assisted taper was designed to collect the Gaussian shape TE light emitted from radiating taper structure. The light propagation through this structure was simulated with using rigorous 3D EME and 2D FDTD methods. The spectral analysis of the device was studied by simulating the light propagation through the whole device for different wavelengths. The proposed device showed relatively large bandwidth (more than 100nm for a variation in efficiency of less than -13dB). The device was designed to be very compact. An avenue to reduce the propagation loss of the whole device due to Fresnel reflection at lens facet with having low impact on the footprint size of the device was presented. A novel concept for a WDM device was introduced by using the dispersive feature of lateral leakage in ridge
SOI waveguides. A waveguide which tapers linearly from ‘magic’ to ‘anti-magic’ width with a dimple in the middle of the structure was designed and used as dispersive radiating component. The wavelength dependent feature of the main TE radiation angle was thoroughly studied with film mode matching modal analysis. The beam characteristics of all four central channel wavelengths was analysed using an EME model. A circular planar lens was designed and used to focus the emitted light to output channels. Finally, the numerical prediction of the filtering characteristics and propagation loss of the proposed device was presented and the device showed relatively low cross-talk and propagation loss.

5.3 Suggestion for future work

The first and most obvious extension of the work carried out in this thesis would be experimental verification of devices introduced in this work. Advanced fabrication procedures involving nano-photonics like electron beam lithography (EBL) could be employed to enhance the device performance and reduce the impact of roughness on the beam characteristics.

The further work for single side radiation device introduced in Chapter 1 would be to integrated the parallel waveguides with an input device which splits the TM light into half and then created $\pi/2$ phase difference between the light propagating through the arms. This part of the circuit could be realized using a nano-wire platform. The nano-wire waveguides can be interfaced to a shallow ridge waveguide with an efficient transition between them [70].

As an alternative to the device introduced in Chapter 1, single side radiation could be achieved by making one side of the waveguide acts like mirror by etching deep to the BOX. The potential problem with this design would be the loss caused by high lateral index contrast on one side. This high index contrast increases the scattering loss due to side wall roughness and also makes the emitted TE beam characteristics more sensitive to fabrication parameters. To mitigate this loss a silicon dioxide layer could be used on top as upper cladding instead of air.

In terms of transition from non-radiating, ‘magic’ width, to strongly radiating, ‘anti-magic’ width, waveguides, more sophisticated taper profiles could be
designed by using the formulations presented in Section 3.7.3. In this case, the exact desired beam wave front could be achieved. To obtain a more collimated TE beam, one straightforward solution would be to use transition from ‘magic’ to ‘non-magic’ width waveguide instead of ‘anti-magic’ width waveguide to keep the phase variation along taper minimum. This could come up with the cost of larger aperture length. Alternatively, by introducing dimple to the taper structure less phase variation along with keeping the length of aperture smaller could be achieved. A more challenging solution to obtain more collimated TE beam would be to come up with a design which is able to keep the phase along the structure constant. This could be achieved by utilizing a periodic structure. The waveguide at the uniform part should be at ‘magic’ width, but the periodically modulated part which could be formed by transition from ‘magic’ to ‘non-magic’ width waveguides and vice versa makes the radiating component. This periodically modulation of radiating part of the structure could be achieved with the introduction of corrugations on the side walls of the waveguide core. However, the beam quality in such design could be prone to fabrication parameters.

Last but not least, the polarization splitter-rotator design could be integrated with single side radiation device introduced in Chapter 2 to guide all the converted power into one cross-port. The one side mirrored structure also could be used instead of symmetric taper structure introduced in Chapter 3. Regarding the wavelength selective device, the single side radiation orientations could also be used. The imaging accuracy of the device could be improved by both improving the beam quality using advanced apodization and radiation control such as the side wall corrugations discussed above. More imaging accuracy along with using more sophisticated lens designs like elliptical lens could shrink the footprint size of the device.
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