Digital waveguide adiabatic passage part 2: experiment

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Abstract: Using a femtosecond laser writing technique, we fabricate and characterise three-waveguide digital adiabatic passage devices, with the central waveguide digitised into five discrete waveguidelets. Strongly asymmetric behaviour was observed, devices operated with high fidelity in the counter-intuitive scheme while strongly suppressing transmission in the intuitive. The low differential loss of the digital adiabatic passage designs potentially offers additional functionality for adiabatic passage based devices. These devices operate with a high contrast (> 90%) over a 60 nm bandwidth, centered at ~ 823 nm.

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OCIS codes: (230.7370) Waveguides; (130.3120) Integrated optics devices.

References and links

1. Introduction

Spatial Adiabatic Passage [1–4] is the spatial analog of the Stimulated Raman Adiabatic Passage (STIRAP) protocol [5]. It is a three-state transfer framework where the coupling between states is varied to effect transfer of population from one state to another, by means of an intermediate unpopulated state. This framework is remarkably flexible and resilient to variations in implementation, leading to numerous applications in the optical domain. It has been applied directly in the design of broadband optical couplers [6–8] and optical frequency conversion [9]. The versatility of adiabatic passage has also been demonstrated in the development of optical splitters [10–12], frequency filtering [13] and optical photonic gates [14].

Recently, studies have explored adiabatic control strategies that employ digital (or piecewise) control schemes instead of continuous parameter variation [15–18]. Though the condition of adiabaticity formally requires continuity, these studies have shown that adiabatic-like behaviour is maintained. These findings provide additional flexibility when designing adiabatic passage devices, particularly in cases where precise control of the coupling coefficients is difficult.

In this paper, we use the digital adiabatic passage framework and apply it to the optical waveguide domain. We fabricate digital waveguide adiabatic passage devices where the central state has been digitised into five discrete waveguidelets. The device designs were optimised using numerical modelling, and then fabricated using a femtosecond laser direct-write inscription technique over a range of writing powers. These devices were characterised and shown to possess a highly transmissive configuration reminiscent of conventional adiabatic passage. Additionally in the opposite configuration, the transmission was strongly suppressed. This suppression is a key characteristic of the digitisation itself. High contrast operation (> 90%) is maintained over a 60 nm bandwidth about ~ 823 nm.

2. Digital adiabatic passage

The theory of digital adiabatic passage is treated in detail in [19]. In its simplest form, a system consisting of three identical coupled waveguides \{\langle a \rangle, \langle b \rangle, \langle c \rangle\} can be described by the
Hamiltonian:
\[ H = \begin{bmatrix} 0 & \Omega_{ab} & 0 \\ \Omega_{ab} & 0 & \Omega_{bc} \\ 0 & \Omega_{bc} & 0 \end{bmatrix}, \quad |E_0\rangle = \frac{\Omega_{bc}|a\rangle - \Omega_{ab}|c\rangle}{\sqrt{\Omega_{ab}^2 + \Omega_{bc}^2}}. \tag{1} \]

where the eigenstate \( |E_0\rangle \) is the so-called dark-state of \( H \). Here, \( \Omega_{nm} \) is the coupling between the \( n^{th} \) and \( m^{th} \) waveguides and only nearest neighbour coupling has been assumed. This eigenstate \( |E_0\rangle \) is completely composed of states \( |a\rangle \) and \( |c\rangle \) and is not directly dependent on the coupling coefficients \( \Omega_{nn} \), but on their ratio. The process of adiabatic passage corresponds to the use of this eigenstate: starting with the coupling coefficients such that \( \Omega_{bc} \gg \Omega_{ab} \) and slowly varying them such that \( \Omega_{ab} \gg \Omega_{bc} \) at the end of the device, transport is effected from \( |a\rangle \) to \( |c\rangle \). Due to the ordering of the coupling, this is commonly called the counter-intuitive coupling scheme. When the coupling order is reversed (corresponding to launching light in \( |c\rangle \) for the same coupling order), this is known as the intuitive coupling scheme, and leads to non-adiabatic oscillations, although, with central state detuning can lead to bright-state adiabatic passage [20].

As the name suggests, digital adiabatic passage devices are realised by digitising the central waveguide of standard waveguide adiabatic passage into several parallel elements which we term waveguidelets. For ideal systems with equal propagation terms or no direct next nearest neighbour \((a−c)\) coupling, the effective \( a−c \) hopping rate [18, 19] dictates the ideal segment length:
\[ L_{opt} = \pi \left( \frac{\Omega_{ab}^2 + \Omega_{bc}^2}{2} \right)^{-1/2}. \tag{2} \]

By using Eq. 2 to digitise the adiabatic passage devices, the counter-intuitive and intuitive coupling behaviour of conventional adiabatic passage is maintained. This is demonstrated in Fig. 1.

3. Model parameters

To simulate the device, model parameters were heuristically obtained from previous work [21]. For a detailed discussion of the theoretical methods used to generate the digital adiabatic passage device see [19]. Both model parameters describing the refractive index difference between cladding and core refractive indices \( \delta \), and the \( 1/e \) width \( \rho \) of the Gaussian graded waveguides were varied in the software package BeamPROP until they gave a suitably good fit to the experimentally obtained mode field diameters and coupling curves. Rigorous 3D field propagation simulation was then performed to obtain the coupling lengths. This simulation was carried out using an in-house developed propagation tool based on the eigenmode expansion method [22]. Optimised lengths were found by inferring the coupling between guides from the beat length of two-waveguide systems. Although the eigenmode expansion is highly efficient, it is not able to model scattering losses. Accordingly, once a suitable design was chosen, the geometry was input into BeamPROP for accurate analysis of the scattering. Device parameters used in simulations can be found in table 1 and a simulation at these optimal parameters in the counter-intuitive and intuitive directions can be found in Fig 1.

4. Implementation

The waveguides in all devices herein were fabricated using an ultrafast laser inscription technique [23]. The output of a Ti: Sapphire oscillator (Femtolasers GmbH, FEMTOSOURCE XL 500, 800 nm centre wavelength, 5.1 MHz repetition rate, <50 fs pulse duration) was focused into a borosilicate substrate (Corning Eagle2000) at a depth of 170 \( \mu \)m using a 100x oil immersion objective lens. The sample was translated with respect to the beam focus using Aerotech motion control stages with 10 nm precision. Our combination of writing parameters lies within the
Table 1. Device parameters used in all calculations herein. All waveguidelets are aligned at $y = 0$ and $|a>, |b>_{1}, |c>$ all begin at $z = 0$. The waveguide’s center is given by $x$. All waveguidelet pairs $|b>_{i+1}$ and $|b>_{i}$ are separated in $z$ by 7.5 mm to increase the total length to 70 mm to further demonstrate digitisation. $\rho$ is the $1/e$ length of the Gaussian profile waveguides and $\delta$ is the difference between core and cladding indices. For details about the model parameters see [19].

| Waveguidelet | $|a>$ | $|b>_{1}$ | $|b>_{2}$ | $|b>_{3}$ | $|b>_{4}$ | $|b>_{5}$ | $|c>$ |
|--------------|------|-----------|-----------|-----------|-----------|-----------|------|
| $L_{opt}$ (mm) | N/A  | 5.5824    | 9.2295    | 10.3775   | 9.2295    | 5.5824    | N/A  |
| $x$ ($\mu$m)  | 10.00| -2.00     | -0.75     | 0.00      | 0.75      | 2.00      | -10.00|
| $\rho$        | 1.6 $\mu$m | 1.4994 | $\delta$ | 0.0056    | $\lambda_{opt}$ | 800 nm |

cumulative heating regime of refractive index modification [24] in which consecutive pulses are absorbed within the focal volume before the dissipation of energy into the bulk of the material, leading to a refractive index modification dominated by thermal effects. The thermal mechanism of the refractive index modification causes both the peak contrast and physical size of the waveguide to increase with the amount of absorbed energy [25]. This allowed the index profile of the written waveguides to be controlled by varying the writing pulse energy. The writing pulse energy was iterated between 28.5 and 34 nJ in 0.25 nJ steps at a constant sample feedrate of 1500 mm/min. With these writing parameters, we designed our devices for optimal operation at $\lambda = 800$ nm.

The design of the fabricated adiabatic passage devices is shown in Fig. 2(a). The total device length including spaces is 70 mm. The input and output states $|a>$ and $|c>$ consist of straight waveguides spaced by 20 $\mu$m. This choice was made so that there would be negligible direct coupling between the outer waveguides. The central waveguide $|b>$ was digitised into 5 waveguidelets that were written by modulating the laser output with a fast RTP pockels cell. A taper is observed at the start of the waveguidelet, as the threshold for index modification, due to

![Fig. 1. Beamprop simulation of transport in structures designed in table 1 in the (a) counter intuitive and (b) intuitive directions. Images are taken at the $y = 0$ slice. In the counter-intuitive scheme, the small populations in the intermediate guides make the design tolerant to scattering losses from improper segment length, conversely the very high population in the intuitive direction makes these highly sensitive devices. Spaces of 2.5mm where added between waveguidelets to highlight digitisation.](image-url)
cumulative heating, is gradually reached after illumination by the laser pulses. On the other hand, the sudden turning-off of the laser at the waveguidelet end leads to a rapid transition away from the thermal regime and the formation of a bulbous void [26] as shown in Fig. 2(b). These features are expected to introduce asymmetric losses in the device for the forward and backward launch directions, indicated in Fig. 2(b).

The scattering losses are also expected to be asymmetric with respect to the intuitive and counter-intuitive configurations. The scattering is expected to be weak in the counter-intuitive configuration due to the dark-state. Conversely in the intuitive configuration, the central state is populated and the voids should scatter strongly, leading to a differential loss in the devices.

Each device was accompanied by a reference waveguide for transmission measurements and two waveguides with a 20 µm spacing to verify that direct coupling between states $|a\rangle$ and $|c\rangle$ is negligible.

5. Characterisation

Eleven of the devices fabricated are characterised below, written with writing powers between 28.75–31.5 nJ per pulse, corresponding to a refractive index variation of approximately $3 \times 10^{-4}$. These devices yielded coupling coefficients most consistent with modelling. In order to verify adiabatic passage behaviour in these devices, light at 808 nm was fibre coupled into the chip in the counter-intuitive configuration and the outputs measured.

The contrast ratio between the waveguide outputs is plotted in Fig. 3(a) as $P_c/(P_a + P_c)$, for each device in the counter-intuitive configuration. Here, $P_a$ and $P_c$ are the output powers of waveguides $|a\rangle$ and $|c\rangle$ respectively. The 11 devices tested showed little-to-no dependence on the writing energy over this range, and light was observed to have coupled across the device in the counter-intuitive configuration in almost all cases. These demonstrate insensitivity of the devices to the effective device length, characteristic of adiabatic passage designs. The largest source of variability is believed to be waveguide inhomogeneity due to the relatively large length of the devices. On average, 89% of the output is successfully coupled. Asymmetry in fidelity is also evident in the forwards and backwards directions, with a slightly greater fidelity in the backwards direction. This is easily explained by the position of the voids—in the backwards direction, each void is present at the beginning of the waveguidelet, where the light has yet to couple across and be scattered.

In order to characterise losses in digital adiabatic passage devices, the outputs of both waveguides were also summed and normalised against a straight reference waveguide written with the same power. This is shown in Fig. 3(b). Despite scattering losses arising from digitisation, the devices have an average transmission of 70%. If we assume a propagation loss of $(0.24 \pm 0.06)$ dB/cm, typical of laser written waveguides, and including facet losses, we obtain
Fig. 3. Characterisation at 808 nm. The contrast ratio is plotted as $P_C/(P_a + P_C)$ for the counter-intuitive configuration (a). The total transmission is also plotted as $(P_a + P_C)/P_{ref}$, for the counter-intuitive configuration (b) and the intuitive configuration (c). Insets show a CCD image of the voids at the end of the waveguidelets. The voids are shown to be bright and strongly scattering in the intuitive configuration, but dark in the counter-intuitive configuration where they remain largely unpopulated. Transmission is higher in the backwards direction in almost all cases. Mean (solid line) and standard deviation (dashed) have been indicated.

an insertion loss between 3.4–4.2 dB. In contrast, light launched in the intuitive configuration is consistently suppressed, transmitting an average of 12% of the light. This corresponds to an insertion loss between 11–12 dB. Without the dark state in the intuitive direction the waveguidelets become strongly scattering, as shown in the inset of Fig. 3(c). A slight difference in the forwards and backwards directions is also evident, with greater losses in the forwards direction for reasons discussed earlier in the paper.

Fig. 4. Spectral response of the devices are plotted, measured in the forwards direction. (a) Counter-intuitive contrast ratio plotted as $P_C/(P_a + P_C)$, and (b) the intuitive transmission plotted as $(P_a + P_C)/P_{ref}$. Note that the optimal operating wavelength is shifted from 800 nm (dashed) to be about 830 nm (shaded). It can be seen that the broad wavelength response in the counter-intuitive configuration coincides with a suppressed response in the intuitive configuration.

To test the operating bandwidth, the devices were also characterised using a white light source (NKT Photonics SuperK Compact). The white light spectrum was narrowed down using a FGB25 colour filter to capture the spectral response of the devices between 700 nm and 900 nm. The
output was fibre-coupled to a USB4000 OceanOptics spectrometer. The devices shown were measured in the forwards direction.

The wavelength dependent performance of these devices is shown in Fig. 4. These were normalised against straight reference waveguides in order to remove the spectral shaping caused by the filtering and the white light source itself. In the counter-intuitive configuration (Fig. 4(a)), a high contrast region is consistently observed in a wavelength band centered around $\sim 830$ nm. This is shifted from the intended centre wavelength of 800 nm. Each device exhibits fidelity above 95% at its optimal wavelength. The devices also remain insensitive to small variations in writing power, reflected in the small shifts in optimal frequency.

The operational bandwidth with a fidelity above 90% is $\approx 60$ nm, after which the adiabatic passage-like behaviour rolls off on either side. This can be attributed to changes in the mode size and coupling strength. As a result, Eq. 2 is no longer satisfied, and the waveguidelets are no longer the appropriate length to facilitate effective adiabatic passage. At the short wavelengths, the behaviour is further complicated by the introduction of higher order modes, resulting in variations in the roll-off behaviour.

In the intuitive case (Fig. 4(b)), the opposite is observed. The transmission is suppressed in the wavelength band around 830 nm, and we observe that the optimal conditions for the counter-intuitive performance coincide with the conditions for maximal loss in the intuitive case. The average transmission is $< 5\%$. The increase in transmission at both longer and shorter wavelengths can then be attributed to the same effects discussed above: at wavelengths far from the optimal wavelength, the changes in coupling no longer allow Eq. 2 to be satisfied. In both cases, light oscillates between the waveguides, is more weakly scattered and is then observed at both outputs.

Switching the filter from the FGB25 to a set of long-pass and short pass filters allowed us to shift the spectral window and observe the roll off of the 30.5 nJ device shown in Fig. 5, chosen because it had the highest average transmission of all the FGB25-measured devices. The roll off of this device is smooth and is consistent with modelling [19]. The total transmission of this device using the new filter set up is also plotted in Fig. 5, where the transmission around 805 nm was omitted due to a normalisation error arising from the saturation of the spectrometer. Wavelength dependent loss is evident in this device, and is assumed to come from the scattering properties of the voids terminating the waveguidelets. On average, more than 80% of the light was transmitted across the spectrum tested.

The bandwidth of these devices, constrained by the effective $a - c$ hopping rate and the waveguidelet lengths, was measured to be narrower than predicted in [19]. Both this and the shift in the center wavelength suggests either a shift in the profile height parameter $\Delta$ or the width $\rho$, or that the Gaussian graded index model is an invalid approximation for estimating the refractive index profile. In principle, the bandwidth can be improved by increasing the number of waveguidelets and by removal of the spaces in between.

6. Conclusions

We have experimentally demonstrated digital adiabatic passage devices, using the design constraints investigated in [19], and fabricated using a femtosecond laser direct write technique. Despite the variability from device to device, as well as the wavelength dependent behaviour, the devices still strongly exhibit features characteristic of adiabatic passage. These features include robustness against variations in coupling, robustness against strong scattering losses in the central state, $|b\rangle$ (from both the digitisation and writing asymmetry), in the counter-intuitive configuration. Additionally, as a consequence of the digitisation process, these features are consistently accompanied by a suppression of the transmission the intuitive configuration. These characteristics suggest digital adiabatic passage may be a robust framework for designing photonic devices with novel applications.
Fig. 5. Second set of measurements taken of waveguide written at 30.5nJ, using band-pass filtering. (a) Contrast ratio $P_a/(P_a + P_c)$ as a function of wavelength. Shaded area corresponds to 95% confidence interval using bisquare method. The fitted equation is $\cos^2\left(2\pi(\lambda - \lambda_{opt})/\lambda_L\right)$ where $\lambda_{opt} = 823.00 \pm 0.17$ nm and $\lambda_L = 541.15 \pm 1.39$ nm. (b) Device transmission $(P_a + P_c)/P_{ref}$ as a function of wavelength. A section of the transmission around 805 nm has been omitted due to a normalisation error. In the optimum region, transmission typically lies between 75% to 95% (shaded in-image).

**Funding**

This research was supported by the ARC Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems (Project Number CE110001018) and was performed in part at the OptoFab node of the Australian National Fabrication Facility using NCRIS and NSW state government funding. A.D.G. acknowledges the ARC for financial support (Grant No. DP130104381).