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Low loss propagation in slow light photonic crystal waveguides at group indices up to 60

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Abstract

We have designed slow light photonic crystal waveguides operating in a low loss and constant dispersion window of $\Delta\lambda = 2$ nm around $\lambda = 1565$ nm with a group index of $n_g = 60$. We experimentally demonstrate a relatively low propagation loss, of 130 dB/cm, for waveguides up to 800 μm in length. This result is particularly remarkable given that the waveguides were written on an electron-beam lithography tool with a writefield of 100 μm that exhibits stitching errors of typically 10–50 nm. We reduced the impact of these stitching errors by introducing "slow–fast–slow" mode conversion interfaces and show that these interfaces reduce the loss from 320 dB/cm to 130 dB/cm at $n_g = 60$. This significant improvement highlights the importance of the slow–fast–slow method and shows that high performance slow light waveguides can be realised with lengths much longer than the writing field of a given e-beam lithography tool.

Keywords: Slow light; Photonic crystal waveguides; Loss; Dispersion

1. Introduction

The phenomenon of slow light in photonic crystal (PhC) waveguides is rapidly turning into an essential paradigm in linear [1] and nonlinear [2–12] photonics; it enables the realisation of compact modulators [13,14] and substantially increases the efficiency of nonlinear effects [2] over a broad bandwidth range [3]. The key to this functionality is the ability to engineer the dispersion and achieve the "flatband" condition, i.e. a dispersion band that features a section of low and constant group velocity. This type of dispersion relationship can be achieved, for example, by altering the size and/or position of the boundary holes in a line defect PhC waveguide or by a judicious alteration of the waveguide width [15–18].

In the absence of loss, the performance of such a flatband slow light waveguide is limited by its group index and bandwidth, e.g. a group index of $n_g = 30$ and $\Delta\lambda = 15$ nm at $\lambda = 1550$ nm [18]. Within these constraints, increasing a given delay or nonlinear enhancement would simply require increasing the length of the waveguide. Unfortunately, propagation losses also increase with group index and provide the ultimate limitation to the slow light enhancement that can realistically be achieved. Opportunely, our dispersion engineering technique also provides a handle on propagation loss, giving rise to the concept of "loss engineering"; loss engineering affords the reduction of

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backscattering losses, and we have so far been able to demonstrate significant loss reductions up to group indices of $n_g = 37$ [19].

How much further can his concept be pushed, however? Are we able to achieve slow light waveguides with group indices of $n_g = 50$ and beyond, and achieve low loss at the same time?

In this paper, we demonstrate that group indices up to $n_g = 60$ can be achieved in practise, and furthermore, we describe a fabrication technique that allows us to achieve these results on a conventional electron-beam lithography system with a limited writefield. This technique has the potential to get the similar results as those achieved on more expensive electron-beam machines with larger writefields [19,20].

2. Design and fabrication

We use electron-beam lithography on a converted electron microscope to fabricate the PhC waveguides. By carefully minimising imperfections such as sidewall roughness and lithographic inaccuracies, typical values of disorder are now on the order of 1 nm [21]. The remaining limitation of the electron-beam writer is the limited writing field of 100 μm. Waveguides that exceed this length require the "stitching" of multiple fields together using interferometric control, which can be performed with an accuracy of typically 10–50 nm. For waveguides operating in the relatively fast light regime around $n_g = 5$, stitching errors of this magnitude only have a limited impact on the performance, and we typically achieve losses on the order of 10 dB/cm [22], compared to the 4 dB/cm we have reported for devices written on a high-end machine with a writefield of 1.2 mm [23]. In the slow light regime, however, due to the enhanced light-matter interaction, the optical mode becomes much more sensitive to imperfections and the stitching errors have a much stronger impact, as we will show below.

The waveguides were designed according to the principles outlined in [19], with the dual goal of achieving a flatband dispersion around a group index of $n_g \approx 60$, suitable for nonlinear applications, as well as achieving low loss operation. The desired dispersion is achieved by judiciously moving the lines of holes adjacent to the channel waveguide [18], while the propagation loss can be reduced by controlling the field on the hole sidewalls. This method of "loss engineering" can significantly reduce the backscattering coefficient in a limited group index range [19], thereby overcoming the typical n_g^2 scaling of backscattering [24]. Accordingly, and for operation in the 1550 nm window, we chose a lattice period of $a = 416$ nm and a hole radius of 120 nm. The first and second rows of the lattice are shifted by $s1 = -42$ nm and $s2 = 20$ nm, respectively [18,19].

In order to fabricate waveguides of several 100 μm length according to this design, we need to minimise the impact of the stitching errors. To this end, we propose and demonstrate the principle of a "slow–fast–slow" (SFS) mode conversion interface that overcomes the stitching error limitation in the slow light regime and allows us to write much longer slow light PhC waveguides. Fig. 1 illustrates the idea for a single interface; we simply taper down the group index from the slow regime to the relatively fast regime of $n_g \approx 5$, where the stitching errors have much less impact. This taper is realised by increasing the hole spacing in propagation direction by 24 nm (Fig. 1), which is sufficient to alter the dispersion curve by the required amount. This method is based on the realisation that a fast–slow interface in the PhC waveguide system can have a transmission approaching unity [25,26], hence there is only little penalty associated with such a transition.

The waveguides were fabricated on a SOITEC silicon on insulator (SOI) wafer comprising a 220 nm thick silicon layer on a 2 μm thick silica buffer layer. The pattern was defined in ZEP520A electron beam

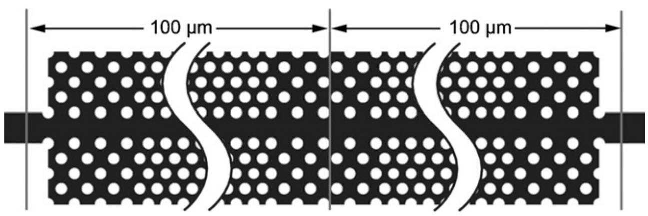

Fig. 1. Illustration of the SFS mode conversion interface in a 196 μm long slow light PhC waveguide. A 100 μm writing field is used in this example and the grey lines represent the writefield size. This is based on the mode conversion interface described in [25]. In the real structure, the increase of the hole spacing is 24 nm, and we used an interface region consisting of 12 unit cells at the ridge waveguide interface and one consisting of 24 unit cells around each stitching area.

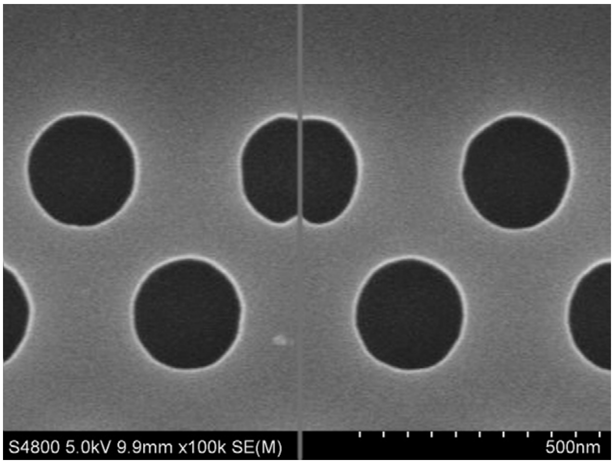

Fig. 2. SEM micrograph of the PhC structure at the writefield edge. The grey line represents the writefield boundary and a small deformation of the hole is apparent.

resist using a hybrid ZEISS GEMINI 1530/RAITH ELPHY electron beam writer at 30 kV with a pixel size of 2 nm and a writefield of 100 μm. The pattern was directly transferred into the silicon layer using reactive ion etching (RIE), with a combination of CHF3 and SF6 gases (50:50 mix). The fabrication process is very similar to that of [23]. Finally, the silica cladding was selectively removed by using buffered HF etch to create the membrane PhC waveguides. On-chip inverse taper mode converters with SU8 polymer waveguides were also added to enhance the injection efficiency [5,8,27].

3. Results

Fig. 2 shows an SEM micrograph of the completed PhC structure at the writefield boundary, which was taken for a device with a stitching error of only around 16 nm. Despite this small value, it is self-evident from the micrograph that additional scattering losses will occur at this interface.

Three sets of waveguides of length between 96 μm and 796 μm were fabricated in order to give a sufficient dataset for reliable loss determination via the cutback method. Waveguides without the SFS mode conversion interface were also fabricated for comparison. The results are shown in Fig. 3. We measured a group index of $n_g = 60$ over a bandwidth of $\Delta\lambda = 5$ nm around 1565 nm wavelength using Fourier transform spectral interferometry [28], and observe a 2 nm low loss window within this bandwidth. As explained in [19], this two-step increase in the loss window of a group index of $n_g = 60$ is given by the design, which is caused by backscattering rather than by the stitching error. The lowest loss in the $n_g = 60$ window is 130 dB/cm. Compared to the loss value of other slow light waveguides, e.g. 40 dB/cm for $n_g = 16$ [12] and 210 dB/cm for $n_g = 51$ [5], this value represents a significant improvement.

The same data can be plotted as propagation loss vs. group index, which is shown in Fig. 4 (red solid dots). For comparison, we also show the simulated losses based on the loss engineering code of [19] (solid line) and observe a non-perfect, yet remarkable agreement. This agreement indicates that the SFS interface design has overcome the loss issue incurred by the stitching error, and the loss value is mainly determined by the design of the slow light waveguide. Please note that there are no fitting parameters, i.e. we perform the calculation on the chosen design, assuming the same technology parameters (roughness, etc.) as in previous work [19]. Fig. 4 also shows the loss for a comparable

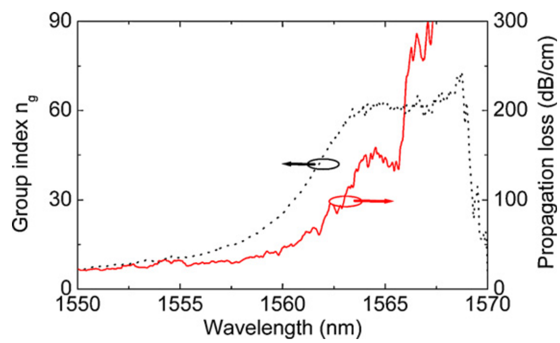

Fig. 3. Measured propagation loss (red solid line), and group index (black dotted line) of the slow light PhC waveguides with SFS mode conversion interface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

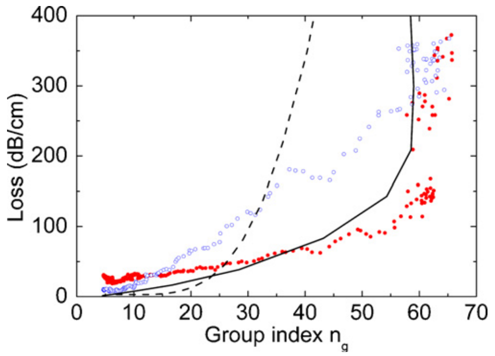

Fig. 4. Experimentally measured propagation loss of the slow light waveguide as a function of group index with (red solid dots) and without (blue open circles) SFS mode conversion interface. The solid line is the simulation result without any stitching errors. The dashed line shows the simulated results for a W1 waveguide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

W1 waveguide (dashed line, data taken from [19]), highlighting the impressive improvement afforded by our dispersion and loss engineered design.

Finally, we also compare the experimental results with those of comparable waveguides without the SFS interface (blue open circles). It is interesting to note that the SFS interfaces add some additional losses in the fast light regime, but these are more than compensated by the substantial improvement in the slow light regime. Note that, at a group index of $n_g = 60$, the propagation loss has been reduced from 320 dB/cm to 130 dB/cm, highlighting the success of the SFS scheme of minimising the impact of stitching errors.

4. Conclusions

In conclusion, we have developed a SFS mode conversion interface and have demonstrated that it is effective in reducing the scattering loss arising from lithographic stitching errors in slow light PhC waveguides. This approach enables the fabrication of low loss slow light waveguides on electron-beam tools with limited writefield, and will therefore benefit many researchers who do not have access to high-end tools with a large writefield. We have used the SFS approach to demonstrate slow light waveguides with a group index of $n_g = 60$ and with a performance that closely matches simulation. Losses at $n_g = 60$ have been reduced from 320 dB/cm without SFS to 130 dB/cm with SFS for waveguide lengths up to 800 μm using a 100 μm writefield. We have already demonstrated high efficiency four wave mixing (FWM) in 396 μm long slow light waveguides with a group index of $n_g = 30$ [8] using the same technique, as well as ultracompact all-optical XOR logic gates [11]. These successful demonstrations also show that the phase is not distorted by the SFS mode conversion interface design. By increasing the operating group index of these devices to ∼60, dramatically improved performance can be expected.

Acknowledgements

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