Design and fabrication of a photonic crystal directional coupler for use as an optical switch

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Abstract. *We have designed and fabricated closely spaced photonic crystal waveguides in the silicon-on-insulator material system for use as an optical switch. By providing a slow-light region, the switch can have a total length of just 5µm. The design incorporates a silica overlayer, thus providing a robust solution suitable for integration.*

Introduction

Directional couplers are made up of two optical waveguides that are brought close enough together for their respective optical modes to interact. This interaction splits the modes into odd and even symmetry supermodes and allows the transfer of power between the waveguides. Light in the directional coupler is split between the odd and even supermodes of the coupled system, and the difference in propagation constants of the two supermodes is equivalent to a difference in the optical path length – a relative phase difference accumulates as light propagates through the directional coupler.

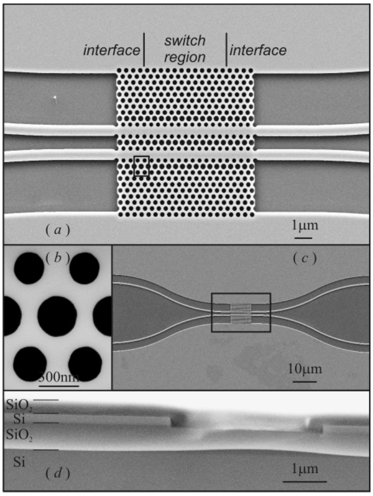

Figure 1: (a-c) Scanning electron micrographs of photonic crystal directional coupled etched into the silicon, before silica infilling. (a) shows the design of the switch, which has a length of $12a$ = 4.9 µm (the central region, as marked). At the input/output, interface regions of a stretched photonic crystal lattice with a slightly different bandstructure to the central switching region are used to couple light from the slab waveguides into the switching regions. (b) shows detail of the three hole sizes used for engineering the bandstructure. (c) shows the on-chip layout: s-bends are used in order to separate the slab waveguides to prevent interaction between them. (d) A cross-section of the SOI wafer after etching and silica infilling.

An optical switch requires a relative phase difference of π between the two supermodes of the coupled system, equivalent to the requirement $\Delta n\, L = \lambda/2$, where Δn is the index change needed to actuate the switch, L is the length of the switch and λ is the wavelength of light. Usually, values of Δn achievable in linear materials are small – for example, the thermo-optic effect in silicon will provide $\Delta n = 1.8\times10^{-4}$/K – and hence L must be large. However, by using closely spaced photonic crystal waveguides as the directional coupler, the dispersion of the coupled waveguide system can be engineered. Providing a slow region adds a new dimension to the problem – the effective interaction can be increased whilst maintaining a small footprint.

We recently demonstrated a compact, low-power optical switch based on a photonic crystal directional coupler in silicon [1]. In [1], the dispersion of the supermodes of the coupled system where engineered through a control of the hole sizes in the photonic crystal waveguides. Switching was demonstrated using the thermo-optic effect, with a 30 dB discrimination ratio between the output states achieved with an index shift of only 4×10^{-3}. The engineered slow-light region meant that the switch had a length of just 5 μm, or only a few wavelengths of the light, and the switching energy was estimated to be less than 200 pJ. The switch in [1] was based on a membrane slab geometry, where the substrate is selectively etched away from beneath the photonic crystal regions to form an air-bridge; this provides a vertically symmetric structure required for the decoupling of orthogonal polarisation states in the photonic crystal waveguides, and it also increases the contrast between the photonic crystal slab and its cladding, providing stronger index confinement. This contribution considers similar photonic crystal directional couplers to those in [1], but rather than use the membrane geometry, we have designed and fabricated the photonic crystal to be infilled with a silca overlayer. The silica overlayer provides a vertically symmetric structure and is a more robust solution compared to the membrane geometry. The post-photonic-crystal-etch processing of other device components (for example, electrical contacts or integrated microheaters) needed to drive the switch is simplified, as they can be placed directly over the photonic crystal regions with no increase of the optical losses.

Design and fabrication

The device presented here uses a photonic crystal directional coupler to switch light. The concept is based on that given in [2] – the sizes of several sets of holes are modified in order to engineer the dispersion properties of the waveguides. The geometry is shown in fig. 1. The holes in the rows of circles immediately adjacent to the waveguides have a smaller radius $r_1 = 0.31a$, whereas those in the rows immediately adjacent to this have the larger radius $r_2 = 0.39a$. All other holes have a radius $r_0 = 0.34a$. Ridge waveguides provide access to the interface regions, which consist of four periods of a "stretched" photonic crystal lattice, where the lattice constant in the direction along the waveguides is increased. This increase provides a slightly different dispersion in the interface regions as compared to the central region, which is designed to enable the efficient injection of light into the device; especially important in the slow light regime where large coupling losses can occur.

The switching length – the length at which the π phase change occurs – depends on the splitting of the odd and even modes: $L_{switch} = \pi/\Delta k$, where Δk is the difference in propagation constants of the two modes. The task is to provide a dispersion diagram that maximizes the change in L_{switch} for a minimum change in frequency – such a condition is met by providing a slow light region in the even mode. We have designed the directional coupler described above to provide such a region – the dispersion of the modes are shown in fig. 2(a), calculated by a 3D bandstructure method using the MIT Photonic-Bands Package [3].

The fabrication of the devices proceeds as follows. A 350 nm thick layer of ZEP-520A is spun onto a SOI wafer supplied by SOITEC (220 nm ± 5 nm thick Si layer, 2 μm SiO_2 buffer) to act as a resist and etch mask. The patterns were generated by electron beam lithography, and, following development of the resist, transferred directly into the Si layer using low-power, low-DC bias reactive ion etching in a CHF_3/SF_6 gas mix, a process known to yield very low-loss photonic crystal waveguides [4]. A silica overlayer and the infilling of the etched structures is provided by a spin-on flowable oxide, which is hard-baked at 400°C for 3 hours. Figure 1 (d) shows an SEM of the cross-section of a slab waveguide after this process.

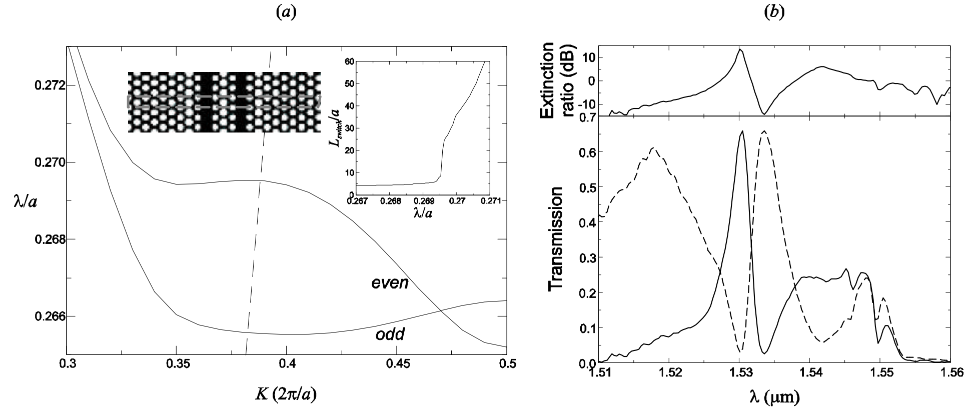

Figure 2: (a) Dispersion curves of the modes of the central section of the directional coupler switch, calculated using a 3D bandstructure method. The dashed line indicates the position of the lightline of the silica cladding. (Inset) The switching length, directly calculated from the bandstructure using the equation $L_{switch} = \pi/\Delta k$. (b) Measured transmission spectra (bottom) of the through port (dashed) and the cross port (solid) for the photonic crystal directional coupler after silicon infilling. The transmission axis is normalized to the mean transmission of several 3 μm wide slab waveguides on the same chip. Also shown (top) is the extinction ratio.

Results and discussion

In order to test our fabricated devices, we characterized them using an end-fire setup with a broadband LED source. Figure 2(b) shows the transmission spectra of both the through (dashed line) and cross (solid line) ports of the device, normalized to the mean transmission of several 3 μm wire waveguides on the same chip. Figure 2(b) also shows the extinction ratio of the output ports (top), defined as the ratio of power in the cross-port to that in the through-port. This extinction ratio varies from 14 dB at $\lambda = 1530$ nm to -14 dB at $\lambda = 1533$ nm. Such a spectral response makes the device an excellent prospect for switching applications, as it could be activated with a refractive index change of just 7×10^{-3}, which corresponds to a temperature shift of 38 K where the thermo-optic effect to be used.

Whilst the thermo-optic effect could be used to actuate the switch by using integrated microheaters, we believe that electronic tuning is more suitable for real applications [5], where switching speed is an important parameter. With suitably designed contacts, the small size of our device would afford an extremely low capacitance, which is essential for high-speed operation. As an example, the carrier-depletion type modulator recently demonstrated by Liu *et al* [6] affords effective refractive index changes in the low 10^{-4} range. Larger changes are predicted for our device due to the strong confinement of the optical mode in photonic crystal waveguides and the corresponding increased overlap with the depletion layer. Values of $\Delta n = 10^{-3}$ have, in fact, already been demonstrated with carrier-injection type devices based on photonic crystals [7]. Further optimisation of the switch design is required in order to access these small index changes, but the control over the dispersion offered by the photonic crystal directional coupler gives the flexibility of design in order to meet this requirement (the current design traded index change required for a greater bandwidth).

The on-chip insertion efficiency is around 65%, corresponding to an insertion loss of ~2dB. The insertion loss of this device is interesting: as can be seen from fig. 2 (a), much of the dispersion curves of the relevant modes of the switch lie above the silica lightline, and hence the index confinement in the silicon slab is lost and the modes become "leaky". This could be expected to significantly increase the insertion loss as compared to an equivalent membrane or air-bridge device. However, it can be seen that the insertion loss reported here is similar to the membrane devices in [1]. We attribute this to the ultra-short length of the device; losses above the lightline are proportional to the propagation length in the device. More devices would need to be tested in order to see if there is a statistically significant difference of the insertion loss between the two classes of device.

Conclusions

We have designed and fabricated a photonic crystal directional coupler for use as an optical switch. The design is for the SOI material system, and includes a silica overlayer and infilling of the etched pattern, which provides a robust solution suitable for post-processing steps. We have demonstrated that excess optical losses due to the lower silica lightline are small, and also that our device has good spectral characteristics for use in optical switching: a port to port extinction ratio which varies from ± 14 dB for a wavelength shift of 3 nm. Such a switch requires a temperature shift of 38K to be actuated by the thermo-optic effect.

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