Bandwidth engineering of photonic crystal waveguide bends

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An effective design principle has been applied to photonic crystal waveguide bends fabricated in silicon-on-insulator material using deep UV lithography resulting in a large increase in the low-loss bandwidth of the bends. Furthermore, it is experimentally demonstrated that the absolute bandwidth range can be adjusted in a post-fabrication thermal oxidation process.

Introduction: The planar photonic crystal waveguide (PhCW) has numerous potential applications because of its unique capability to control the propagation of light by utilising the photonic bandgap (PBG) effect [1, 2]. This effect allows the interaction between light and the PhCW to take place on a minute scale [3, 4]. Thereby, the overall size of optical components based on PhCW structures may be greatly minimised and, correspondingly, device packing density increased. Recent advances in deep UV lithography at 248 nm [5] have made mass fabrication of optical ultra-compact PhCW devices viable by employing existing fabrication methods commonly encountered in the semiconductor electronics industry.

Research has now reached a level where existing fabrication technologies allow manufacture of PhCW structures with low propagation losses [6–9]. Hence, there is presently worldwide focus on the design and fabrication of PhCW structures possessing adequate bandwidths. PhCW structures with 20–40 nm useful optical bandwidths have previously been demonstrated [3, 10, 11]. Recently, Borel *et al.* [12] have demonstrated that a new inverse design method, topology optimisation, can be utilised to dramatically increase the bandwidth of a PhCW component. However, some of the holes in these components have special sizes and shapes that currently cannot be manufactured using deep UV lithography and, thus, cannot currently be mass fabricated. Except for these topology-optimised structures, no bandgap-based PhCW components have been demonstrated with satisfactory performance in a broad wavelength range.

In this Letter, we present an alternative design strategy, which also leads to large bandwidths of PhCW bends, and that is suitable for fabrication utilising deep UV lithography. Furthermore, we demonstrate a simple experimental procedure employing thermal oxidation on how to tune the absolute position of the operational bandwidth for an already fabricated batch of samples.

Waveguide fabrication: The photonic crystal structures have been patterned using 248 nm deep UV lithography and transferred into a silicon-on-insulator material, with a 220 nm thick silicon-layer separated from the substrate by a 1 µm thick silica-layer, employing a standard anisotropic reactive ion etch. The fabrication procedure is described in detail in [5, 13]. The structures are defined in a triangular lattice of air holes extending through the top silicon-layer, with a lattice constant $\Lambda = 435$ nm and regular hole diameter $d = 0.53\Lambda$. This configuration gives a relatively large PBG below the silica-line [14] and allows TE-like singlemode propagation in the PhCWs. A missing line of holes in the ΓK direction of the triangular lattice forms the waveguides.

Bend design and results: Owing to the PBG effect in a PhCW component, light may be routed around sharp corners such as the simple 60° bends displayed in Fig. 1. Note that in each bend one hole has been displaced [14]. However, in singlemode operation, discontinuities in the straight PhCW introduce large reflections at the interface between different sections of the PhCW. Discontinuities may also excite higher-order modes that are not necessarily guided in the PhCW. As a result, the simple bends shown in Fig. 1 only have a ~40 nm bandwidth region with high transmission for TE-polarised light as can be seen from the spectrum in Fig. 2 (dashed curve). The measured transmission spectrum for the structure shown in Fig. 1 has been normalised to a straight PhCW of equivalent propagation length in order to extract the bend loss. The experimental characterisation setup has been described in detail in [6].

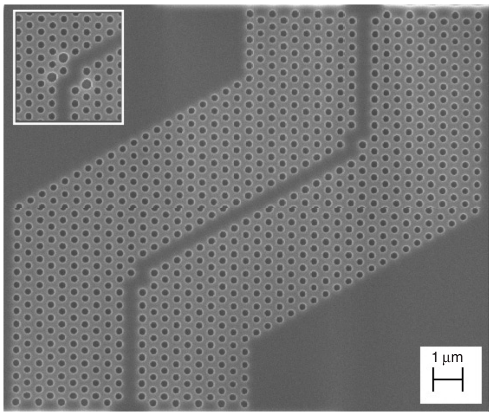

Fig. 1 *Scanning electron micrograph of fabricated structure containing 60° bends*

One hole displaced at each bend
Inset: Scanning electron micrograph of how each 60° bend modified to improve bandwidth. Note that in this case one hole displaced and three holes enlarged at each bend

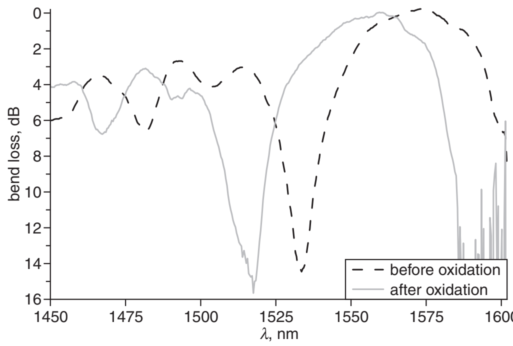

Fig. 2 *Measured loss per bend for simple fabricated structure shown in Fig. 1 before and after thermal oxidation*

To improve the bandwidth of the PhCW 60° bends, the bend geometry was modified as shown in the inset of Fig. 1. Note that in addition to the displacement of one hole, the diameter of three holes has now been enlarged at each bend. The enlarged holes have a diameter $D = 0.71\Lambda$. This design is based on inspiration from microwave engineering [15]. The normalised transmission spectrum for TE-polarised light for a 60° bend is obtained as before. The measured bend loss is displayed in Fig. 3 (dashed curve). Especially noteworthy is the ~85 nm bandwidth with low bend loss around ~1 dB and the square-like shape of the spectrum.

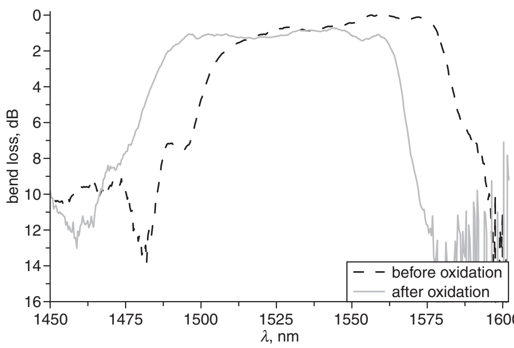

Fig. 3 *Measured loss per bend for fabricated structure shown in inset of Fig. 1 before and after thermal oxidation*

After the waveguide sample containing the above-mentioned PhCW structures had been fabricated and characterised, a thin layer (~10 nm) of oxide was thermally grown on top of the sample. Thereby, the thickness of the core silicon layer and the hole diameters both changed slightly. These small oxidation changes introduce a blue shift of the spectra as seen in Figs. 2 and 3 (solid curves). In our experimental conditions it is observed that ~1 nm of oxide blue shifts the spectrum about 1.3 nm. It is seen that the spectral shift induced by the thermal oxidation essentially keeps the spectral features intact and merely changes the wavelength scale. 3D finite-difference time-domain calculations [14] have confirmed the observed frequency shifts caused by the thermal oxidation.

This thermal-oxidation procedure can conveniently be used in concert with vertical grating couplers [11]. When a batch of PhCW components have been fabricated, the spectral features can be assessed using the grating couplers to characterise the samples before the wafer is cleaved and the samples are packaged. If necessary the spectral features for the full batch can be shifted utilising thermal oxidation.

Conclusion: Planar PhCW 60° bends have been fabricated in silicon-on-insulator material utilising deep UV lithography. A simple design method has been utilised to increase the bandwidth by more than a factor of two. The manufactured PhCW bends have been designed with sufficient tolerances for fabrication with standard deep UV lithography. Furthermore, it has been demonstrated that thermal oxidation can be used in a post-processing step to precisely blue shift the spectral features a required amount.

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