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Low-loss propagation in photonic crystal waveguides

L. O'Faolain, X. Yuan, D. McIntyre, S. Thoms, H. Chong, R.M. De La Rue and T.F. Krauss

The fabrication and characterisation of high-quality silicon membrane photonic crystals are reported. The etching process was carefully optimised to give holes with very smooth and vertical sidewalls, resulting in propagation, with a minimum loss of 4.1 ± 0.9 dB/cm in a single line defect (W1) waveguide.

Introduction: Propagation below the light line in photonic crystal (PhC) waveguides is theoretically lossless. Any deviation from the perfect crystal, however, acts as a scattering source, resulting in loss. Additionally, as operating below the lightline requires the use of high-refractive-index contrast materials, the scattering from these defects is particularly strong, placing very stringent requirements on the fabrication process. Recently, however, many of the problems have been solved in the silicon system, with Vlasov *et al.* and Notomi *et al.* [1, 2] successfully achieving sub-10 dB/cm propagation losses for W1 photonic crystal waveguides. In this Letter, we report W1 photonic crystal waveguides with an equal level of performance and highlight some of the issues that must be addressed in achieving such low propagation losses.

Fabrication: The devices were fabricated on a SOITEC silicon-on-insulator wafer, consisting of a 220 nm-thick silicon guiding layer and a 1000 nm-thick silica buffer layer on a silicon substrate. The photonic crystal pattern was defined in ZEP-520A electron beam resist using a Leica EBPG5 electron beam writer and a 600 µm writefield. Given that the longest waveguides measured in the present work approach 2 mm in length, a large writefield is important for reduction of the impact of stitching errors. The pattern was transferred into the silicon layer directly, without an intermediate hardmask layer, using low power (20 W), low DC bias (−205 V), reactive ion etching (RIE) with a combination of SF_6 and CHF_3 gas (50:50 mix). This etching regime exhibits low selectivity, which necessitates the use of a relatively thick (350 nm) resist layer. On the other hand, the low selectivity also minimises the sidewall roughness otherwise caused by micro-masking. The remaining resist was then removed by soaking in trichloroethylene; plasma-ashing was not used, since no hard mask was present to protect the silicon surface. Windows were opened in the photoresist above the photonic crystal regions and the silica cladding beneath the patterned silicon was selectively removed using dilute hydrofluoric acid (1:10 with water).

The conditions used at various stages in the fabrication process were monitored so as to control factors such as pattern quality, sidewall angle, sidewall roughness and under-etching. The processes were carefully refined and optimised to yield very high quality structures (Fig. 1*a*). The PhC lattice period and filling-factor were carefully chosen so as to ensure a wavelength range in which operation below the light-line was possible. A lattice constant of $a = 430$ nm and a hole diameter of 240 nm were used, corresponding to an r/a (radius/period) ratio of 0.279. Such a relatively small hole diameter is conducive to a larger operating bandwidth below the light-line and to lower propagation losses [1].

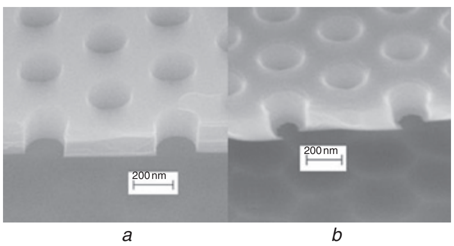

Fig. 1 *Sidewall profile of photonic crystal holes*
a Etching quality of very low-loss waveguides (< 10 dB/cm)
b Etching quality of higher loss (here: 105 dB/cm) waveguides, featuring small rims at bottom of hole, highlighting the fact that small defects can have considerable effects on losses

Results: The device loss was determined for a set of W1 waveguides ranging from 0.1 to 1.89 mm in length. Transmission spectra were measured for each length using an amplified spontaneous emission (ASE) source and the loss was determined from the difference between each spectrum. Fig. 2 shows transmission and loss spectra for devices with a period of 430 nm. Fig. 3 shows transmission against length for the wavelength at which the lowest loss was obtained. A number of well-known features of the W1 defect waveguide can be recognised: the W1 mode transmission-edge occurs at a wavelength of 1.56 µm; its shape is rounded owing to the reduced efficiency of coupling into the slow light regime that occurs just before cutoff. The loss increases towards the slow light regime owing to the increased light-matter interaction. The loss therefore reduces with decreasing wavelength as the group velocity increases. The position of the light-line is also clearly evident from the dramatic drop in transmission for the 1.89 mm-long device relative to the 0.1 mm-long device at 1.49 µm wavelength. For short lengths, the loss above the light-line has less of an impact [3]. At a wavelength of 1.52 µm, we observed a minimum loss of 4.1 ± 0.9 dB/cm.

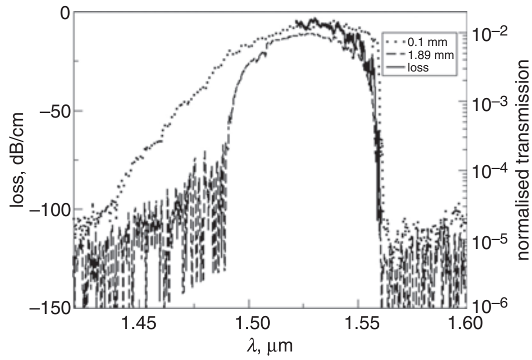

Fig. 2 *Dotted and dashed lines are transmission spectra through 0.1 and 1.89 mm-long W1 photonic crystals, respectively, made using optical spectrum analyser, together with broadband (250 nm spectral bandwidth) LED source (normalised from respective sources)*
Solid line is measured loss calculated from 5–6 devices in 0.1–1.89 mm length range, measured using ASE source (70 nm broad)
Details of measurement setup make error for measurements with LED source relatively larger

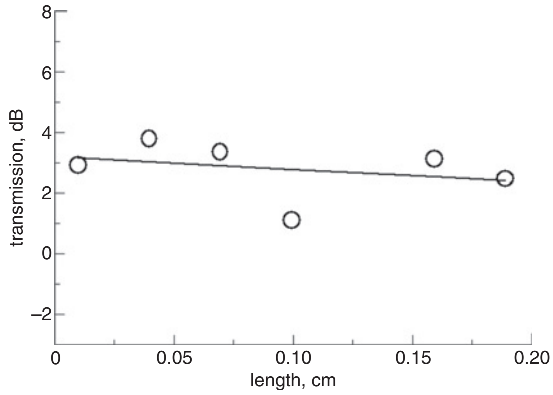

Fig. 3 *Propagation against W1 length at wavelength of 1.53 µm. The slope is 4.1 ± 0.9 dB/cm*
Large error is largely due to damage on 1 mm-long device, which resulted in reduced transmission

Interestingly, this work demonstrates that a simple RIE etching process is a viable method for etching of high-quality silicon membrane photonic crystals. Other, more involved, processes such as inductively coupled plasma (ICP) or electron cyclotron resonance (ECR) etching, that are more commonly used for such high-quality etching [1, 2], do not seem to offer any obvious advantages in this case. Despite its limitations, such as relatively strong coupling between the plasma generation and etching conditions, high-quality etching using RIE is still possible, given sufficient optimisation.

Fig. 1 gives an indication of how critical the etching quality is. Fig. 1*a* shows the sidewalls of holes for which the low losses discussed in this work were obtained. Fig. 1*b* shows holes for which the etch depth was fractionally too small, resulting in the formation of a lip or rim at the bottom of the holes. Holes with this shape scatter light very strongly; for the corresponding PhC channel guide, the lowest loss obtained was 105 dB/cm. Not only does such a sharp defect in the hole shape radiate light directly but also, by virtue of its small vertical dimensions, it is prone to large variations from hole to hole. This variation causes disorder that further increases the light-scattering [2, 4].

We believe that further optimisation of the etching process will allow the etching of smoother and smaller holes that will give reduced losses over a wider wavelength range [1]. Additionally, the use of a material with 2 μm buried oxide layer may further reduce the losses, as the mode tail will then extend less into the silicon substrate.

Conclusions: We have achieved very high-quality W1 photonic crystal waveguides, and believe that the most critical factor affecting propagation losses in such planar photonic crystals is the etching quality. Very smooth and vertical sidewalls are vital for the minimisation of scattering losses.

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