Dependence of extrinsic loss on group velocity in photonic crystal waveguides

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Abstract: We examine the effects of disorder on propagation loss as a function of group velocity for W1 photonic crystal (PhC) waveguides. Disorder is deliberately and controllably introduced into the photonic crystal by pseudo-randomly displacing the holes of the photonic lattice. This allows us to clearly distinguish two types of loss. Away from the band-edge and for moderately slow light (group velocity c/20-c/30) loss scales sub-linearly with group velocity, whereas near the band-edge, reflection loss increases dramatically due to the random and local shift of the band-edge. The optical analysis also shows that the random fabrication errors of our structures, made on a standard e-beam lithography system, are below 1 nm root mean square.

OCIS codes: (130.5296) Photonic crystal waveguides

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9. A 2D model makes some significant simplifications when applied to this problem- it cannot account for out of plane scattering and coupling to substrate modes. Complex interactions between the loss mechanisms cannot be ruled out, however, the model shows good agreement with the experiment (2nm difference in shifts), suggesting that these interactions do not have a significant effect. The small discrepancy is probably due to absence of these effects in the simulation.
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12. This analysis assumes that loss is disorder limited and that absorption (which would also scale with v_g) is negligible. This is reasonable in the SOI system at this wavelength.
13. This makes the non-trivial assumption that disorder does not change the group velocity. In order to verify this, we ran simulations of pulses propagating through the disorder. We found that up to the group indices where pulses break up due to dispersion (n>16), there was only minimal differences in group velocity between normal and disordered W1 waveguides.

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1. Introduction

The realization of devices exploiting the slow light effect has become an exciting topic of contemporary photonics research. Slow light leads to increased light-matter interaction, thereby enabling compact and low power switches and modulators [1,2]. Any linear interaction scales linearly with the slowdown factor, typically defined as the ratio of the group velocity over the phase velocity of a given waveguide system [3], whereas nonlinear interaction scales with the square of the slowdown factor [4]. Furthermore, tunability of the slowdown factor enables variable optical delay lines and memory elements, which are the key to all-optical signal processing. Slow light devices based on high-index contrast dielectric waveguides, such as coupled ring resonators and photonic crystals, have been identified as the most promising candidates for the realization of this exciting functionality [5].

Propagation losses and their dependence on the group velocity are of key concern; there is no justification for exploring the slow light regime if any advantage is immediately counteracted by excessive losses. In this context, several authors, especially Hughes *et al.* [6] have suggested that the loss in photonic crystal waveguides scales as the inverse square of the group velocity. This is due to the increased density of states in the slow light regime, as well as a backscattering component. The question in hand is then whether these two components can be separated and how strongly each component contributes to the loss. We address this issue by studying the propagation losses in W1 (single line of missing holes) photonic crystal waveguides as a function of deliberately induced disorder and group velocity. We study these losses below the light line, where the waveguide exhibits no intrinsic loss; any losses encountered are therefore extrinsic in nature, i.e. due to deviations from the ideal crystal, and leading to out-of-plane scattering or backreflection. We used a pseudo-random displacement of the hole positions in order to study the dependence of the waveguide properties on disorder, as shown in Fig. 1.

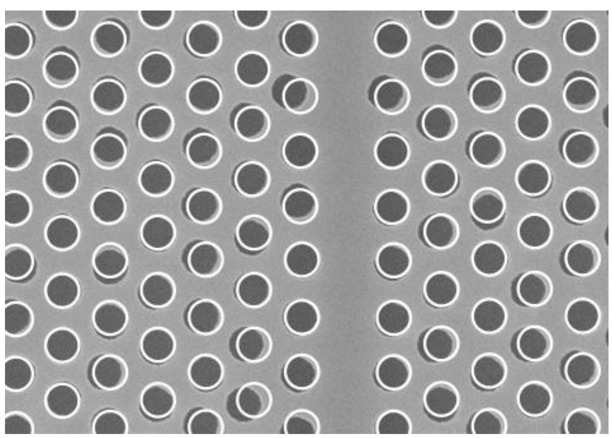

Fig. 1. An SEM image of a deliberately disordered photonic crystal- the ideal positions are shown in white. The root mean square value (RMS) of the deliberate disorder was 20nm. This device was made for demonstration purposes only- near zero transmission would be seen for such a level of disorder, while the disorder of a real device (up to 4.5 nm RMS) would not be discernible in such a picture.

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2. Simulation

We first simulated the effects of deliberate positional disorder using two dimensional Finite Difference Time Domain (FDTD) software. We consider two situations- a W1 waveguide in which each hole has given a random displacement from the ideal, with the displacements forming a Gaussian distribution about zero with a root mean square value (RMS) of 5nm, and a normal W1 waveguide. The simulation results were found to converge for grid resolutions of 10nm or smaller (the software used, RSOFT FULLWAVE, has an averaging function allowing it to sample features smaller than the resolution grid). A 40µm long W1 waveguide device was simulated in both cases and included photonic wires for access.

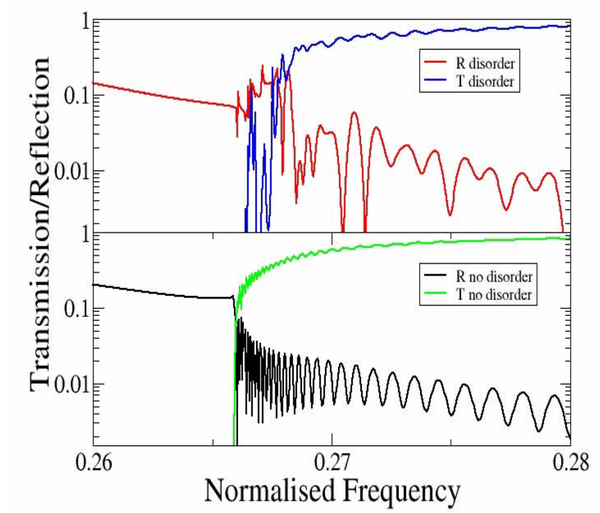

Fig. 2. The transmission and reflection characteristics (power) of a normal and disordered W1 waveguide. A significant increase in reflection can be seen for the disordered waveguide approaching the band-edge. No such increase is present in the normal W1. The calculated reflection is the back reflection into the guided mode of the access photonic wire and does not include off-axis scattering at the interface into free space (and thus the sum of the reflection and transmission does not equal one).

The results of the simulation are shown in Fig. 2. The transmission and reflection spectra of a normal W1 waveguide are shown by the green and black traces, respectively, and those of the disordered W1 by the blue and red traces. Away from the band-edge (frequencies greater than 0.27) the transmission and reflection of the two devices are roughly similar. As this 2D simulation cannot include out of plane scattering, scattering loss due to disorder is not observed, yet an important observation can be made: As the mode cut-off is approached, there is a sudden increase in reflection (by more than an order of magnitude) for the disordered waveguide causing the transmission to drop sharply. In the undisorderd device over the same range, there is only a slow increase in reflection due to reduced coupling into the slow light regime [7]. Significantly, this increase in reflection in the presence of disorder is not a smooth progression but makes an abrupt change near the cut-off.

Additionally, a study of the field distribution for light propagating in the high reflection regime of the disordered W1 shows that the reflection takes place over a relatively large spatial extent, approximately 10µm. This indicates that the reflection is not due to a cavity-like feature (accidentally created by the hole displacements) or coupling issues.

There are a number of possible causes of this reflection. As it is impractical to simulate such disordered devices in three dimensions [8], due to the need for fine resolution and long devices (so as to sample the disorder properly), we have taken an experimental approach to further examine this behavior.

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3. Fabrication

The devices were fabricated on a SOITEC Silicon-on-Insulator (SOI) wafer, consisting of 220nm thick silicon layer and a 1000nm thick silica layer on a silicon substrate. The photonic crystal pattern was defined in ZEP-520A electron beam resist using a hybrid RAITH ELPHY Plus/LEO Gemini 1530 electron beam writer, with a 2 nm pixel size, and then transferred to the silicon layer using low power (20W, 200 V DC bias) reactive ion etching with a combination of SF6 and CHF3 gas. The remaining resist was removed by soaking in trichloroethylene. Windows were opened in photoresist in the photonic crystal areas and the silica cladding beneath the crystals selectively removed using hydrofluoric acid.

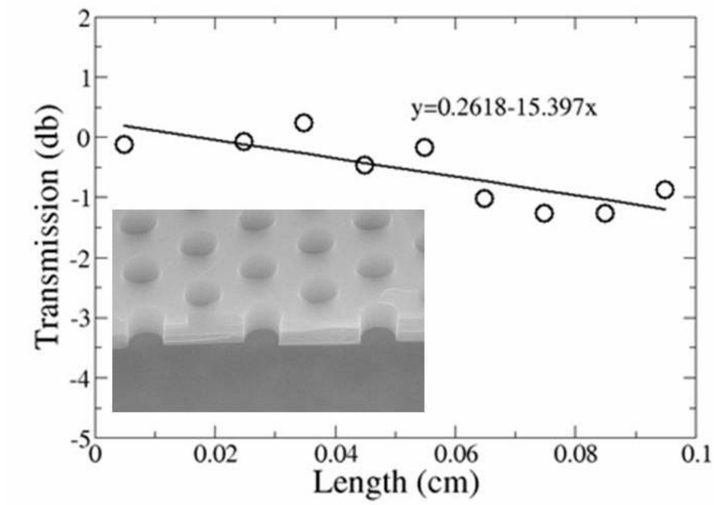

Fig. 3. Transmission through varied length w1 photonic crystal waveguides. The inset shows the etching quality corresponding to this measurement.

The conditions of the various steps in the fabrication process, such as pattern quality, sidewall angle, sidewall roughness and underetch, were carefully refined and optimized in order to achieve sufficiently low baseline losses prior to deliberately introducing disorder. Figure 3 shows the result of a series of transmission measurements through W1 photonic crystal waveguides with lengths varying between 50µm and 950µm. A value for the loss as low as 15dB/cm was obtained, demonstrating the high quality of the fabrication process.

4. Results and Discussion

Figure 4 shows the transmission spectrum for a 200µm long W1 waveguide. A 3D bandstructure was fitted to the data to obtain the group velocity as shown (to account for errors in determining the radii from SEM images (approx 2%), the r/a value was used as a fitting parameter to achieve an exact match). In the “fast” light regime, i.e. above a frequency of 0.27 c/a, one can observe densely spaced interference fringes, corresponding to the entire device length. Below 0.27 c/a, with the onset of the slow light regime, a substantial reflection occurs at the PhC waveguide interface [7] and the spectrum becomes more complex. In these devices, the photonic wire width at the interface with the photonic crystal was 550nm and the photonic wire terminated at center of the first hole of the photonic crystal and it did not prove possible to infer the group velocity in the PhC waveguide unambiguously from these measurements, although the change in fringe spacing is a clear indication for the group velocity changing.

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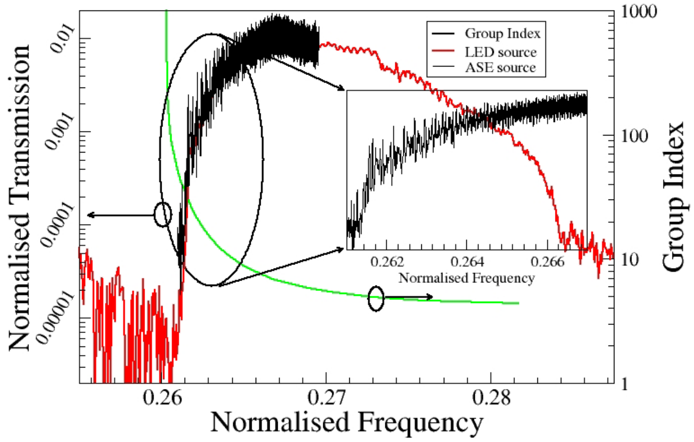

Fig. 4. The passband of the W1 waveguide (no deliberate disorder). A low power LED source was used to obtain the pink curve and a high power ASE source to obtain high resolution over a smaller range (the LED spectrum was scaled to match). The inset shows a close up of the high resolution fringes. The group velocity was determined from a 3D bandstructure (MPB) with r/a=0.28. The inset shows a close-up of the mode cut-off. While a change in fringe spacing is apparent, it is not possible to extract the group velocity from this data.

In order to examine the effects of disorder, deliberate positional variations were introduced into the PhC waveguides. Each hole was randomly shifted, such that the distribution of hole positions was, within experimental limitations, Gaussian about the ideal. The transmission as a function of RMS disorder was then measured, shown in Fig. 5.

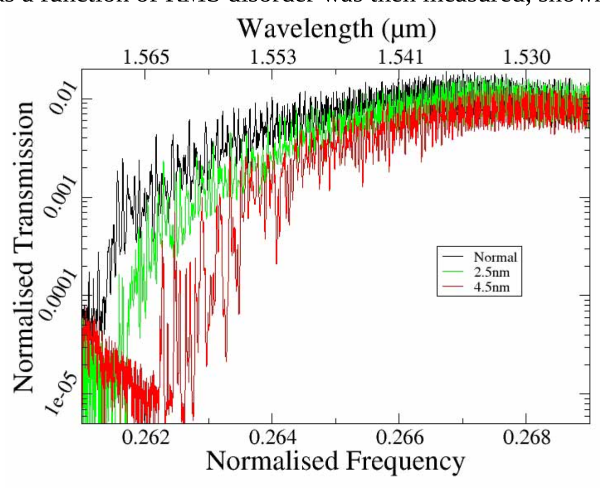

Fig. 5. Transmission through a 200µm W1 waveguide as a function of increasing disorder. The inset gives the RMS value of the deliberate positional variations.

There are two obvious effects: - the transmission drops steadily with increasing disorder and the W1 mode edge shifts to higher frequencies. The general drop in transmission can be explained by the increased loss due to out-of-plane scattering from the increased disorder. This is absent from Fig. 2, as the 2D simulation cannot account for the out of plane components and only the shift to higher frequency is present. The qualitative agreement with the movement of the mode cut-off between Fig. 2 and Fig. 5 is otherwise good. In the simulation for a RMS disorder of 5nm, the mode cut-off moves by 9nm (0.0015 in normalized frequency), while in the experiment, a shift of 11nm (0.0018) is observed for a RMS disorder

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of 4.5nm. The discrepancy with the 2D model is probably due to out of plane scattering which could cause an additional apparent movement of the mode cut-off.

The steady movement of the mode cut-off with increasing disorder in Fig. 5 suggests the origin of the phenomenon. The disorder locally modifies the lattice constant of the crystal, thereby changing the position of the W1 mode. Light of frequencies near the band-edge may then be transmitted by some portions of the crystal, but be partially reflected by others that have already been cut off due to the local variation in mode cut-off frequency.

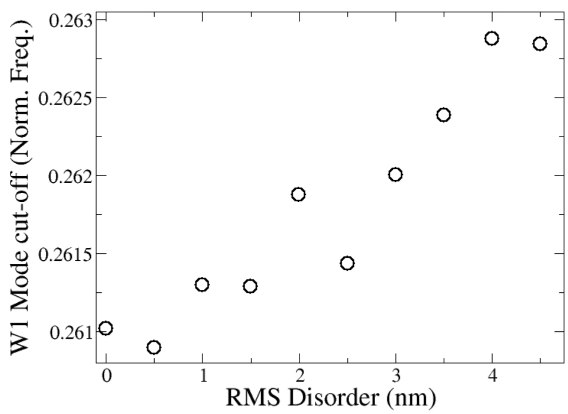

Fig. 6. W1 mode cut-off frequency with disorder. As the disorder increases the position of the W1 mode cut-off moves to higher frequencies.

Figure 6 shows the position of the mode cut-off (taken as the point where transmission is less than 1% of its maximum value) as a function of this disorder. With increasing disorder, it moves to shorter wavelengths with a near linear relationship. Intuitively, disorder creates regions of the crystal of different lattice constant. If these regions are of sufficient length then they dominate the transmission spectrum. Due to the nature of the Gaussian distribution of the lattice constants, most of the lattice will have a lattice constant close to the average and there is only a relatively small cumulative length where the lattice constant is far from the average. This gives rise to the very rounded nature of the transmission curves and the reduction in the threshold disorder with proximity to mode cut-off observed in Fig. 5.

The reason for the increase in reflection near the mode cut-off of a disordered W1 observed in Fig. 2 is now apparent. It is not, as such, due to disorder but rather the presence of a lattice constant shorter than the nominal lattice in the disordered device- this lattice reflects light that would otherwise be transmitted. Thus, reflection does not smoothly increase as the band-edge is approached (and light slows down) but it rapidly rises once a critical distance from the band-edge is reached. This is what we will refer to as "reflection loss" due to disorder-induced changes in mode cut-off.

In the experiments reported to date, it has not been possible to distinguish such effects [6] and a lumped loss comprising coupling into the counter propagating mode and out-of-plane scattering was reported. In contrast, due to our introduction of controlled disorder, the difference is now clearly evident, see Fig. 7. Away from the mode cut-off (corresponding to the data in the top left of the figure), the curves have a single, approximately quadratic, behavior. Closer to the mode cut-off, however, there is an abrupt drop in transmission above certain values of disorder. This threshold occurs at lower disorder values the closer to the mode cut-off we operate and is directly related to the shift of the mode cut-off shown in Fig. 5.

While the movement of the mode cut-off is clearly related to the disorder (Fig. 6) a quantitative explanation is non trivial. Experimentally, the mode cut-off is observed to move by 11nm (0.0018) for an increase in RMS disorder of 4.5nm. Naively, one would expect the

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cut-off to move proportionally to the wavelength/lattice constant ratio, i.e. roughly by a factor 4. As a similar shift is observed in the simulation [9], errors such as experimental bias are ruled out. A possible explanation for the discrepancy is the complex and random nature of disorder- for instance, if two disorder-induced shortened lattices were to occur consecutively, the effect is likely to be different than if they were distributed over the device.

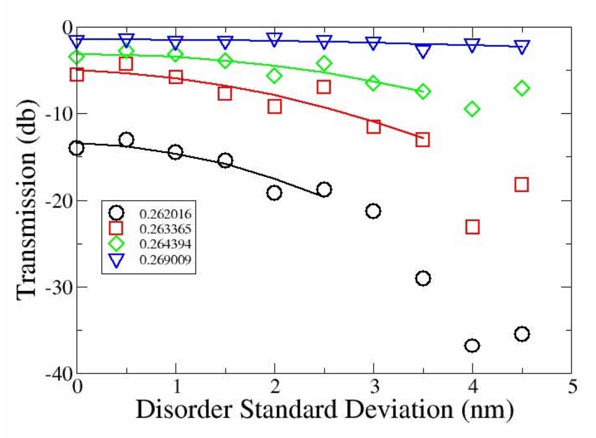

Fig. 7. Normalized transmission as a function of disorder at different spectral positions. (The data was averaged to smooth out the Fabry-Perot ripple). The inset gives the normalized frequency for each data set. The rise at the end (e.g. circles at 4.5 nm) is somewhat of an artifact- past cut-off, transmission slowly increases, particularly in the case of strong disorder. The intercept (parameter A in equation (1)) is determined by the coupling coefficient into the PhC waveguide, which is generally lower in the slow light regime. The lines correspond to the fits made using equation 1.

It has been reported by Gerace *et al.* [10] and Ferrini *et al.* [11], using a perturbative approach, that backscattering and out of plane scattering have a quadratic dependence on the level of disorder, (the physical origin for this being the Rayleigh scattering mechanism). If only our data points above the thresholds for reflection loss are considered, then a quadratic formula indeed provides a good fit, i.e. they agree with perturbation theory. The experimental behavior around and below cut-off is different, however, indicating a more complex and non-perturbative effect. From now on, we shall therefore distinguish between the below cut-off ("reflection") and the above cut-off ("transmission") regime.

In the transmission regime, we can fit the data points to the following formula, adapted from [10]

$$T = A - B(x + C)^2 \quad (1)$$

where T is the transmission, x is the deliberate positional disorder and A is the transmission for a W1 waveguide with no deliberate disorder, i.e. it accounts for coupling and loss due to sidewall roughness and non-deliberate disorder. B then gives the dependence of transmission on positional disorder. C is an offset in the x direction and should be the amount of non-deliberate positional disorder [12], i.e. the positional disorder induced by fabrication. In Fig. 7, the loss-disorder parameter B is plotted, for a number of frequencies approaching the mode-edge, against the corresponding group velocity calculated from the bandstructure [13]. NB Only data points above mode-cut-off, i.e. in the transmission regime, were considered in this analysis.

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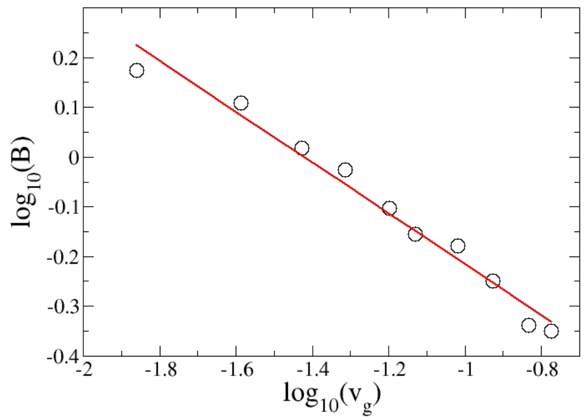

Fig. 8. The experimental dependence of the disorder parameter on the group velocity, plotted on logarithmic scales. A $1/vg^{1/2}$ dependence of parameter group velocity is the best fit (R^2 value of 0.972). The group velocity is derived from the bandstructure (Fig. 4).

Three different fits to this data were considered (and plotted on a log-log scale to demonstrate the power dependence clearly) - a $1/v_g$ dependence, which may be intuitively expected- the loss is proportional to the increased interaction of the mode with the disorder, due to the increased density of states, which is inversely proportional to v_g, a $1/vg^2$ dependence, as suggested in [6] and a $1/vg^{1/2}$ dependence.

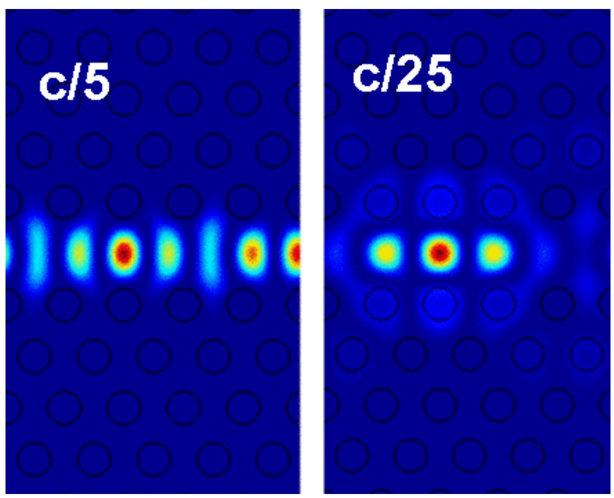

Fig. 9. $|H_z|^2$ field plots for light propagating in W1 at group velocities of c/5 and c/25. The expansion of the mode at low group velocity is evident even at c/25.

Surprisingly, the $1/vg^{1/2}$ dependence was the most satisfactory (Fig. 7). Its R^2 value is 0.972, rather close to the ideal fit of $R^2=1$, while the $1/v_g$ dependence gave a value of 0.905 and the $1/v_g^2$ a value of 0.672. Even in the absence of backscattering, one would expect the out-of-plane losses to scale as the inverse of the group velocity, since the loss is proportional to the increased interaction of the mode with the disorder. A possible explanation for this sub-linear nature of the dependence is that the mode expands in the slow light regime, see Fig 9. A larger mode has a lower intensity at the etched interfaces, resulting in a reduced interaction with roughness, which scales as E^2 at the scatterer [14]. In any case, it is clear that the loss dependence is sub-linear rather than super-linear, as long as we operate in the transmission

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regime. To cross-check, we also fitted all the data of Fig. 7, i.e. both in the transmission and the reflection regime, and obtained a $1/vg^2$ fit, in harmony with [6].

Interestingly, a weak dependence of the loss on group velocity was also reported by Vlasov et al. [7], who suggested that the dominant effect was coupling rather than propagation loss. This is also true in our case, where the A-coefficient (represented by the intercept with the y-axis in Fig. 5 that represents coupling loss) dominates over the disorder-induced loss, represented by the B-coefficient in equation (1), at the values encountered experimentally.

Figure 7 also contains further information. Since the parameter C in equation (1) represents the non-deliberate positional disorder, we can extract its value from the parabolic dependence, which has a maximum for $-x=C$. For our data, we can derive a value of C= (-0.1±0.5) nm, i.e. the non-deliberate, fabrication induced disorder is essentially zero within the experimental error (due the small slope of the curves near this maximum the error of the measurement is high- the negative value being unphysical. The error is taken as the standard deviation of the values of C obtained at different frequencies). Our method therefore constitutes a direct optical measurement of positional disorder in a 2-dimensional photonic crystal. Previous measurements, such as [15] were based on SEM imaging that suffers from a larger error, in excess of 1 nm. For 3D photonic crystals, alternative techniques of total diffuse transmission and enhanced backscattering can be applied [16], but their application to 2D systems is non-trivial. Our measurement therefore also demonstrates the ability of electron beam lithography to create high quality photonic crystal patterns.

While we have only considered positional disorder, the analysis can be generalized to the other forms, i.e. - radius, shape and roughness disorder. Disorder, whatever its form, creates deviations from the perfect lattice that can be considered as weakly scattering shells. The amount of scattering is then proportional to the Rayleigh cross sections of the shells and their density [15]. For low levels of disorder (<5%), to a good approximation, this product will be similar regardless of the origin of the scatterers.

5. Conclusion

Overall, we have clarified the contribution of disorder to the loss in photonic crystal waveguides as a function of group velocity, using both simulation and experiment. In agreement with other researchers, we observe a very dramatic increase in loss near the mode cut-off, but we provide a clearer picture of the individual components of the disorder-induced effects;

a) Out-of-plane scattering scales sub-linearly with inverse group velocity; while we do not fully understand the sub-linear (rather than a linear, as expected) dependence, we suggest this may be related to the enlarged size of the slow mode, which reduces the E^2 near the scattering centers [14]. As we have modeled the group velocity of disordered waveguides in the moderately slow light regime discussed here [13], we are confident of the group velocity values employed in the scaling. Above the mode cut-off and for group velocities faster than c/20, we observe this to be the dominant loss mechanism.

b) At very low group velocities, the coupling of light into the backward propagating mode by defects (backscattering) becomes very significant [6,17]. This is due to the high density of states in both the forward propagating and backward propagating modes in this regime. Backscattering loss scales as $1/ vg^2$ and only becomes dominant at very low group velocities (below c/100) [17]. We believe that we were unable to observe this effect, as the approach presented here is limited to group velocities above approx c/20.

c) Near the band-edge, disorder causes local variations of the lattice that shift the mode cut-off. This shift of the cut-off leads to strong reflections that act as a significant source of loss dominating over other losses. It should be noted that the nature of the model used in [10, 17] does not account for disorder-induced changes in mode cut-off and so this effect is not observed there.

Naturally, it is difficult to distinguish experimentally between backscattering (b) and reflection (c) losses, as both lead to a sharp decrease in transmission near cut-off. The nature of backscattering (i.e. that it becomes significant only at very low group velocities) and the

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fact that we observe a sub-linear dependence of loss in the moderate group velocity regime, however, leads us to conclude that reflection and not backscattering losses are responsible for the observed cut-off. These reflection losses have been ignored by previous analyses.

Our analysis suggests that, by operating away from the mode cut-off, there is a window of moderately slow group velocities (certainly down to c/20 as observed here, but possibly extending further), where slow light devices can be operated with relatively low loss.

This insight does not deflect from the fact that very high standards of fabrication accuracy need to be met in order to realize high quality photonic crystal waveguides, especially in the slow light regime. Even away from the band-edge, we show that positioning errors on the order of 1nm already become significant. We also show that such high positioning standards, i.e. within the experimental error of 0.5nm, can already be met with existing technology. The overall insight that loss scales sub-linearly with group velocity, and not with its square, as previously believed, is a strong indication that the future for devices exploiting the slow light effect in photonic crystals, such as compact modulators, switches and memory elements, is bright.

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