Si-based Photonic Crystal Components: Relationship between Performance and Structural Disorder

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Abstract

We report recent achievements with our Si-based photonic crystal slab components. Using precise nanofabrication, we made a waveguide with a record low propagation loss (2 dB/cm). We investigated the loss mechanism in photonic crystal slab waveguides, where structural disorder plays an important role, and found that disorder also degrades the quality factor of photonic nanocavities.

1. Introduction

Photonic crystal (PhC) [1] is attracting widespread attention because of its novel optical properties and potential for use in nanophotonics [2]. Although a three-dimensional PhC can ideally achieve optimum characteristics [1], [3], it is still very difficult to make because the structure is too complicated for current nanofabrication technologies. Recently, photonic crystal slabs (PhCS) [4] have been actively studied as an alternative to the three-dimensional PhC. In a PhCS, three-dimensional light confinement is achieved by the photonic bandgap (PBG) in the in-plane direction and by index confinement in the vertical direction. The basic element, namely an array of vertical air holes or dielectric pillars, is highly compatible with current nanofabrication technologies. It has been shown that a suitably designed PhCS structure theoretically provides a lossless waveguide and a photonic nanocavity with a quality factor (Q) of around 10^7 [4], [5]. The advantage of the PhCS has been demonstrated experimentally by the fabrication of very-low-propagation-loss waveguides (6 dB/cm) [6] and ultrahigh (6×10^5) quality factor (Q) cavities with an ultrasmall modal volume [5], [7]. However, the factors restricting the waveguide loss and cavity-Q of actual structures were not well understood. These loss mechanisms must be clarified if we are to enhance PhCS device performance. We have focused on improving the preciseness of electron beam lithography to reduce fabrication-related disorder, which may have a considerable effect on PhCS loss characteristics. In this paper, we report our recent development of Si-based PhCS components for the optical communication wavelength regime including PhCS waveguides with a record low loss. We discuss the role of disorder in detail for the first time by carefully comparing theory and experiment.

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2. Low-loss photonic crystal waveguides and fabrication

Our Si-based PhCS fabrication process is shown in **Fig. 1**. We fabricated Si PhCSs from commercially available silicon-on-insulator (SOI) wafers whose Si and SiO_2 thicknesses were 205 and 3000 nm, respectively. Our PhCS structure consisted of a Si slab layer with triangular lattice of air holes and upper/lower air cladding. To define the PhCS structure we drew a pattern on a ZEP520 (ZEON) resist with a 100-kV JEOL electron beam (EB) writer and then transferred the resist pattern to an SOI layer using an inductively coupled plasma etcher. The SiO_2 layer under the PhCS was removed with buffered hydrofluoric acid. Here, the most important issue was to reduce the fabrication error. Scanning electron microscope (SEM) images of a fabricated PhCS are shown in **Fig. 2**. The vertical hole sidewalls were achieved by optimizing

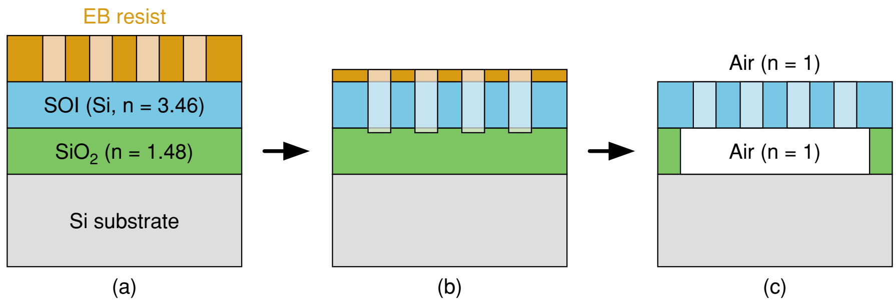

Fig. 1. Si-based PhCS fabrication process. (a) Patterning of EB resist with an EB writer. (b) Dry etching of SOI layer. (c) Wet etching of SiO_2 layer under-cladding.

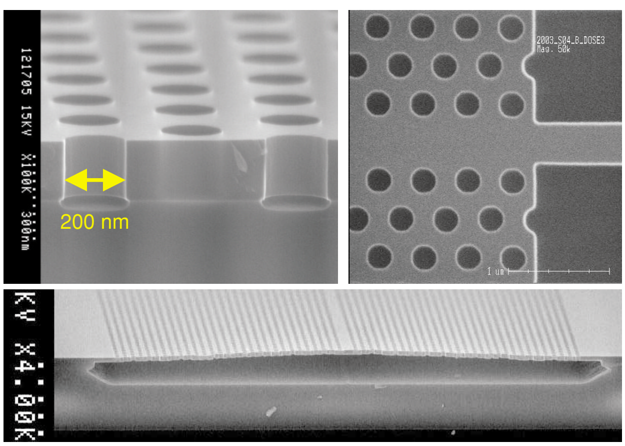

Fig. 2. SEM images of PhCS samples.

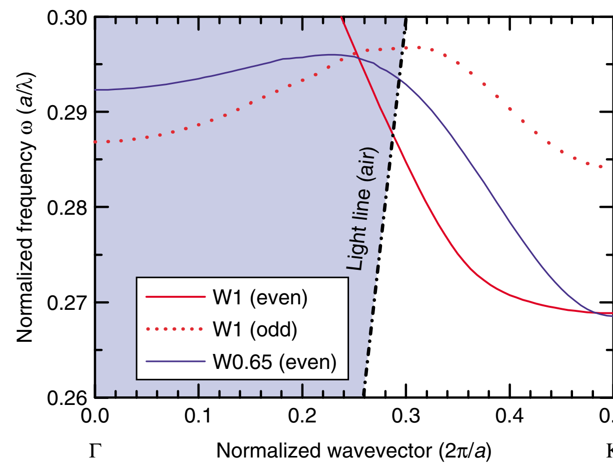

Fig. 3. Calculated band structure of waveguide mode for Si PhCS. The colored area is above the light line where the waveguide is leaky.

the dry etching conditions. The surface roughness of the hole sidewalls, determined by a statistical analysis of the SEM images, was less than 2 nm (root mean square (RMS)), namely the detection limit of our SEM. We believe that the samples fabricated in this study are the best-quality PhCSs reported to date. The crucial factors for minimizing roughness were optimization of the pattern data and the resist development process and suitable management of the proximity effect during electron beam lithography.

In this study, we investigated two types of line-defect PhCS waveguides: W1 and W0.65. The former was a simple one-row-missing line defect, and the latter was a width-reduced waveguide [8] whose line-defect width was 65% of the former. The photonic band structure of the waveguide mode for the two waveguides is shown in **Fig. 3**. The x-axis is normalized wavenumber in the Γ–K direction and the y-axis is normalized frequency $\omega = a/\lambda$ (*a*: lattice constant of photonic crystal, λ: wavelength). There are three important differences between W1 and W0.65. (1) In the vicinity of the low frequency limit (mode edge), W1 has a “slow light mode” where the group velocity of light can be smaller than c/100 (c: velocity of light in vacuum) [9], [10], corresponding to the nearly flat band in Fig. 3. (2) W0.65 has a broader low-loss transmission band than W1 considering the significant loss increase above the light line. (3) W1 has another waveguide mode with odd symmetry above the fundamental mode (even symmetry), whereas W0.65 has only one even mode with a high-frequency mode edge. We fabricated W1 (a = 432 nm) and W0.65 waveguides (a = 400 nm), where the hole radius was about 0.25a and the slab thickness was 0.48a. We measured the loss spectrum by comparing the transmittance of different length waveguides (cut-back method). The loss plot for W1 at a wavelength of 1550 nm is shown in **Fig. 4(a)**. The evaluated propagation loss was 2 dB/cm [11], which is the best value

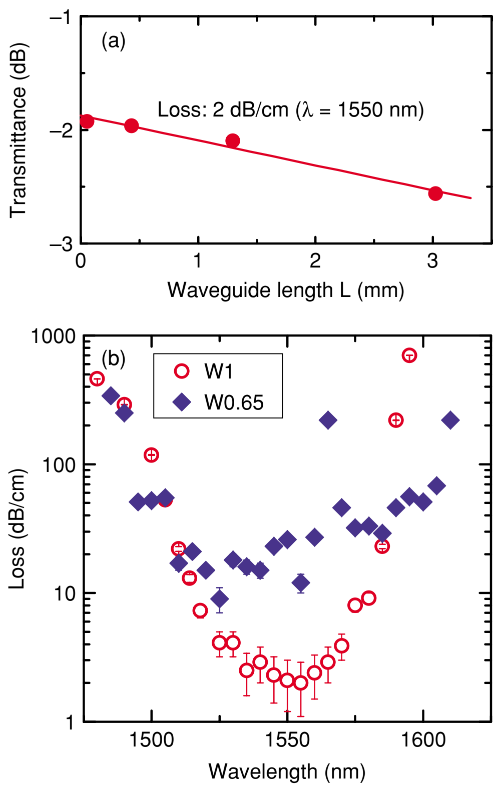

Fig. 4. (a) Loss plot of W1 waveguides at a wavelength length of 1550 nm. (b) Loss spectrum of W1 and W0.65 waveguides.

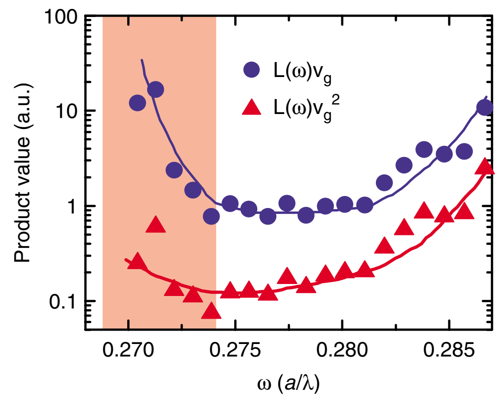

Fig. 5. Comparison of the frequency dependence of waveguide loss for v_g and v_g^2. In the shaded area, the dependence is approximately $(1/v_g)^2$.

yet reported for a PhC waveguide. Note that there was no increase in loss even at the longest waveguide (3 mm), which demonstrates that there is no technical barrier for millimeter-order PhCS waveguides. The loss spectra for W1 and W0.65 are shown in **Fig. 4(b)**. Both waveguides had a finite low loss bandwidth and that of W0.65 was the broader of the two, as suggested by Fig. 3. The loss of W0.65 (approx. 15 dB/cm) was much higher than that of W1, probably because there was considerable field seepage into the holes surrounding the waveguide, which increases the loss due to sidewall fluctuation among holes [12].

3. Loss mechanism of photonic crystal waveguides

We clarified that the loss spectra in Fig. 4 were determined by rich and complex loss physics. It has been predicted that out-of-plane loss (not related to scattering) takes place above the light line, but we found that the main loss factor in Fig. 4(b) was disorder-related scattering. Applying Fermi's golden rule to the scattering process, we derived a formula that shows that the loss depends on the local density of states (LDOS) of both the initial and final states [12]. Since the LDOS of the waveguide mode is proportional to $1/v_g$ (v_g: group velocity), the loss depends on $1/v_g$ for out-of-plane scattering and on $(1/v_g)^2$ for backscattering. The products of loss $L(\omega) \times v_g$ and $L(\omega) \times v_g^2$ for W1 are compared in **Fig. 5** [13]. We found that the loss was more closely proportional to $(1/v_g)^2$ than to $1/v_g$ in the vicinity of the low-frequency mode edge, which means that backscattering was dominant in this regime where v_g was very small. Although out-of-plane scattering loss has already been reported, this is the first report of the large contribution of backscattering in the slow light mode [9], [10]. This is important because low loss for slow light mode is essential for device applications such as an optical delay line. Inter-mode scattering in the multimode region was another reason for the increase in loss for W1 in the high frequency region because the upper odd mode had a large LDOS and a large loss due to the larger field distribution. Our physical concept also includes the idea that loss depends on the square of the RMS sidewall roughness [12]. This means that the waveguide was lossless if there was no disorder. Thus, we clarified that the complex loss characteristics of actual PhCS waveguides are determined by disorder, LDOS, and v_g. We even found Van-Hove-singularity-like loss peaks corresponding to the mode edge of waveguide mode [13].

We calculated the theoretical loss using the formula mentioned above [12] and compared the results with experimental loss spectra for an actual sample. **Figure 6** shows this comparison for a W1 sample

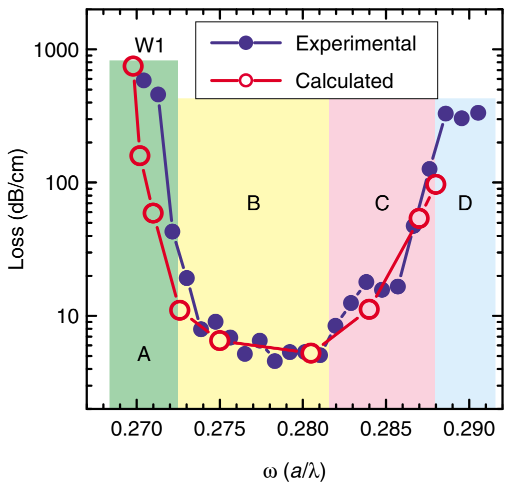

Fig. 6. Comparison of experimental and theoretical loss spectra of W1 waveguide.

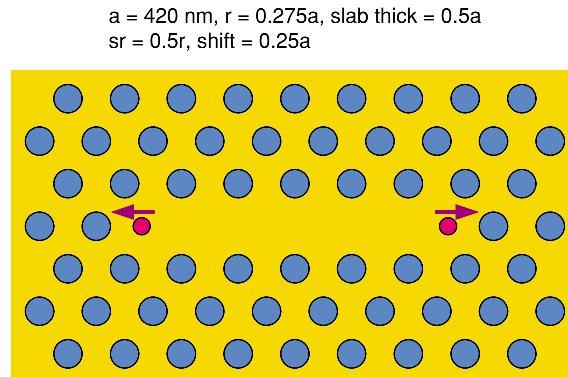

Fig. 7. The 4-point defect structure model used for FDTD simulation.

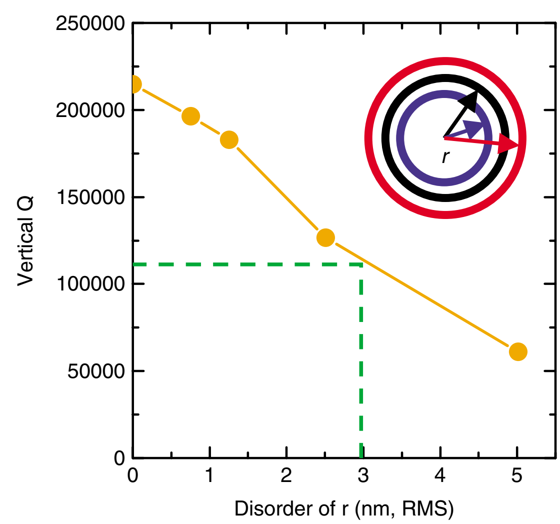

Fig. 8. Disorder dependence of cavity-Q as a function of the RMS hole radius obtained by FDTD.

[13]. The main loss mechanisms were: backscattering (A), out-of-plane scattering (B), intermode scattering (even to odd) (C), and intrinsic out-of-plane loss above the light line (D). Because the comparison was performed for an old sample whose RMS sidewall roughness was 3 nm, the loss (5 dB/cm) was slightly larger than the values shown in Fig. 4. We found that there was surprisingly good agreement between the calculation and experiment. Such good agreement was also obtained for a waveguide with a different structure without using a fitting parameter. This is the first demonstration of the precise quantitative calculation of the loss of PhCS waveguides. It should be noted that the good agreement was also assisted by the small uniform disorder in our samples.

4. Disorder in photonic nanocavities

It was not understood until recently why the experimental Q of a PhCS nanocavity is much less (about one order of magnitude) than its theoretical Q. The theoretical calculations were usually performed for ideal structures without disorder, so we thought that the disorder reduced the cavity-Q by increasing the loss in the same way as with waveguide loss. We performed a numerical study of the way in which the inter-hole disorder restricts the Q of PhCS nanocavities [11], [14]. We considered a four-point-defect cavity with a smaller, shifted hole (radius: 50%, shift: 0.25*a*) at each end of the defect [15] (**Fig. 7**). We calculated the Q of the cavity using the three-dimensional finite-difference time-domain (FDTD) method with an in-plane calculation area of 19 × 28 periods. The calculated vertical Q was 210,000 without disorder. We used a simple disorder model characterized by only the RMS deviation of the hole radii; i.e., intra- and inter-hole correlations were disregarded. The disorder dependence of cavity-Q as a function of the RMS of the hole radius obtained by FDTD is shown in **Fig. 8**. We found that for 3-nm inter-hole disorder, the vertical Q was reduced to as little as half the value without disorder, which is not far from the experimental Q (maximum: 70,000). This suggests that inter-hole disorder has a great influence on the Q of nanocavities. We were the first to report the large effect of inter-hole disorder although another group started to study disorder before us. Although we have not yet studied this issue in detail, perhaps the same scattering mechanisms that cause waveguide loss also reduce the Q values of nanocavities.

5. Conclusion

We have already obtained PhCS waveguides with dB/cm-order loss, which is sufficiently low for mm^2-order PhCS integrated circuits. Very recently, we developed a PhCS nanocavity with a new design whose experimental Q was over 10^6 for the first time [16]. This substantially increased Q value will enable us to reduce the coupling loss at cavities, reduce the channel interval for wavelength division multiplication devices, extend the light trapping time for optical memory operation, and decrease the operating power needed for optical switches. Although we must still overcome polarization dependence and chip-to-fiber coupling loss, the waveguide loss and cavity-Q no longer represent bottlenecks for photonic component applications. Our study of the loss mechanism revealed that the performance of PhCS components can be further improved by reducing structural disorder, which indicates that a PhCS is a promising candidate for a nanophotonics platform.

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