Photonic crystal slabs demonstrating strong broadband suppression of transmission in the presence of disorders

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Received April 28, 2004

We characterize the transmission spectra of out-of-plane, normal-incidence light of two-dimensional silicon photonic crystal slabs and observe excellent agreement between the measured data and finite-difference time-domain simulations over the 1050–1600-nm wavelength range. Crystals that are 340 nm thick and have holes of 330-nm radius on a square lattice of 998-nm pitch show 20-dB extinction in transmission from 1220 to 1255 nm. Increasing the hole radius to 450 nm broadens the extinction band further, and we obtain >85% extinction from 1310 to 1550 nm. Discrepancies between simulation and measurement are ascribed to disorder in the photonic lattice, which is measured through image processing on high-resolution scanning electron micrographs. Analysis of crystal imperfections indicates that they tend to average out narrowband spectral features, while having relatively small effects on broadband features. © 2004 Optical Society of America

OCIS codes: 120.2440, 230.4040, 050.2770, 230.5750.

In many applications dielectric mirrors are preferred over metallic mirrors because of their low loss at optical and infrared frequencies. High reflectivity from dielectric mirrors typically requires many layers of alternating dielectric constants. The multilayer nature and the dependence of the reflection band on the layer thicknesses make such structures difficult to incorporate into many optical components, especially devices based on microelectromechanical systems technology.

In this Letter we report on the experimental characterization of dielectric mirrors consisting of a single silicon slab with a periodic array of through holes, forming a square two-dimensional photonic crystal (PC) and experimentally verify that guided resonances[1–7] are effective despite the presence of disorders. The mirror is characterized in transmission; we compare the measurements with simulation results based on finite-difference time-domain (FDTD) simulations. The experimental data provide evidence that the structure is strongly reflective at certain wavelengths.

In the experiment we used an unpolarized tungsten-halogen lamp, coupled to a multimode fiber, as the light source. The output of the multimode fiber was imaged by a microscope objective with a magnification of 5 and a numerical aperture of 0.1 onto the PC. The transmitted light was picked up by an identical microscope objective that demagnified the spot onto a single-mode fiber, which was connected to an optical spectrum analyzer. Throughout the measurements we used a resolution bandwidth of 5 nm, obtaining a power level of less than 375 pW. The data were averaged over 50 successive measurements. The normalized noise level corresponds to a signal-to-noise ratio of, at best, 22 dB. This signal-to-noise ratio was the limit for the extinction in transmission that we could observe in this experiment.

The measured transmission spectrum of a crystal with relatively small holes is shown in Fig. 1. The crystal was designed to have a thickness of $t = 340$ nm with a hole radius of $r = 330$ nm at a pitch of $a = 998$ nm. The measured power was normalized to the power reaching the spectrum analyzer when there was no sample in the setup. The sample had a strong extinction in transmission down to 21 dB at wavelengths of ~1225 nm. The average extinction in the range

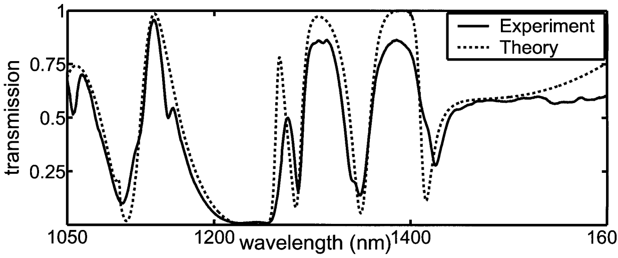

Fig. 1. Transmission spectrum of a PC slab with the following parameters: $a = 998$ nm, $r = 330$ nm, and $t = 340$ nm. The data are compared with a FDTD simulation for a normal-incidence plane wave on a sample with $a = 998$ nm, $r = 0.37a$, and $t = 0.335a$. The simulation data were resampled in the wavelength domain for a resolution bandwidth of 5 nm in accordance with the experiment.

0146-9592/04/232782-03$15.00/0

1220–1255 nm was 20 dB. By rotating a polarizer in front of the PC sample, we also verified that the spectra taken at normal incidence were polarization insensitive.

Increasing the relative size of the holes decreases the lifetimes of the guided resonances, so the deviation from the Fabry–Perot background occurs within a relatively wider range.[3] Figure 2 shows the measured transmission spectrum for a sample with larger holes (450 nm in radius). The measured transmission has two minima down to the noise level. A relatively low transmission with >85% extinction occurs at a wide interval of 1310–1500 nm, suggesting broadband reflection. PCs with larger hole sizes have the advantage of being less sensitive to fabrication-related disorders; furthermore, smaller lifetimes for the guided resonances are favorable for decreasing the effects of any optical loss mechanisms.[8]

The measured transmission is compared with FDTD simulations in Fig. 1. The simulation was carried out for a normal-incidence plane wave on an infinite array of holes. A dielectric constant for silicon of 11.7 was used throughout the simulation band. The crystal parameters were varied, and the best fit was obtained with the following values: $a = 998$ nm, $r = 0.37a$, and $t = 0.335a$. We observed good agreement between the measured data and the simulation results. It is important to note that the best fit was obtained assuming a lossless dielectric constant.

The angular spread of the optical field as a result of the finite spot size was small in our experiments (the $e^{-1/2}$ angular width being less than 0.85°), and the resonant bands in this angular range were close to flat,[9] so we did not expect the effects of the angular distribution to be significant in our measurements. Geometrical imperfections of the crystals are important, however, so we developed an image-processing code to quantify their effects. First, ~25 high-resolution scanning electron microscope images of different sectors of the lattice were taken so that the entire PC was covered. The code took these scanning electron microscope images as input, analyzed the lattice hole by hole (which in our case amounts to ~10,000 holes), then measured and calculated several statistical parameters, such as the mean ($\overline{x}$) and standard deviation (σ_x) of the hole radius, horizontal pitch, vertical pitch, and hole roundness. In this case roundness is defined by the form factor, which is $4\pi \times \text{area}/\text{perimeter}^2$. We calculated statistics for the PC of Fig. 1 for both the entire lattice (100 μm × 100 μm in area) and the more uniform central part (67 μm × 50 μm in area) where we took our measurements (Table 1). The thickness of the membrane did not vary significantly in the relatively small area in which the PC was defined.

The data show that the holes are very close to perfectly circular, especially in the central part. In our analysis, therefore, we do not consider any effects of imperfect hole shape. Because of the good fit between simulation and measurements, we expect the disorder in parameters r and a to have a perturbative effect on the ideal crystal spectrum.

The transmitted amplitude in the absence of disorder, for resonances sufficiently separated from each other, can be expressed as[3]

$$t = t_d - (t_d \pm r_d)\frac{\gamma}{i(\omega - \omega_0) + \gamma}, \qquad (1)$$

where t_d and r_d are the direct transmission and reflection coefficients and + and − correspond to even and odd modes with respect to the mirror plane parallel to the slab. The parameters γ and ω_0 are the half-widths and center frequencies of the guided resonances, which are determined by fitting them to the guided resonances isolated from the Fabry–Perot-type background. We separated the resonances from the simulation data by filtering out the fast-decaying direct transmission amplitude in the time domain and Fourier transforming to get the Lorentzian line shapes.

The deviations in a and r occur on a larger length scale (~10 μm) than the localization and travel lengths of the resonances (~1 μm). Therefore we can assume that our lattice consists of several smaller lattices. Consequently, in this model the total transmission is the sum of the transmissions of several lattices with parameters $\overline{x} + \delta x$, weighted by the normal distributions determined through the image-processing code. For a small change in either a or r, the center frequency of a guided resonance will shift slightly. Considering that the background and linewidth vary more slowly than the center frequency, the transmitted amplitude becomes

$$t' = \langle t \rangle = t_d - (t_d \pm r_d)\left\langle \frac{\gamma}{i(\omega - \omega_0) + \gamma} \right\rangle. \qquad (2)$$

In this case, $\omega_0(\overline{x} + \delta x) = \omega_0(\overline{x}) + \Delta\omega(\delta x)$ is the center frequency for lattice parameters deviating by a small amount δr and δa from the mean values; the averaging

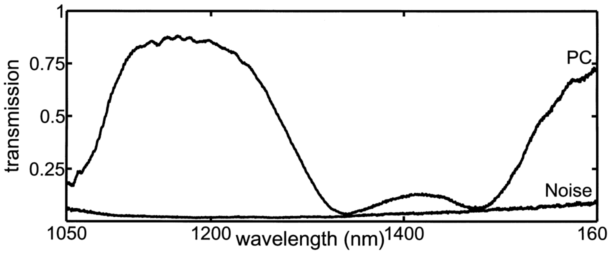

Fig. 2. Transmission spectrum of a PC slab with the following parameters: $a = 998$ nm, $r = 450$ nm, and $t = 340$ nm. An extinction in transmission with a value of >85% occurs for a wide interval of 1310–1500 nm, suggesting broadband reflection.

Table 1. Statistics for Geometrical Imperfections

Crystal	r (nm)	a_X (nm)	a_Y (nm)	Θ
Complete				
$\overline{x}$	330	999	996	0.93
σ_x	9.05	14.1	10.5	0.12
Central Part				
$\overline{x}$	331	999	996	0.95
σ_x	3.19	5.92	3.86	0.038

r, a_X, a_Y, and Θ denote radius, horizontal pitch, vertical pitch, and hole roundness, respectively.

is defined through the following normal distributions with zero mean and no mutual correlation:

$$\langle \delta r^2 \rangle = {\sigma_r}^2, \quad \langle \delta a^2 \rangle = {\sigma_a}^2,$$
$$\langle \delta r \rangle = \langle \delta a \rangle = \langle \delta r \delta a \rangle = 0. \tag{3}$$

Note that in the summation in Eq. (2) there is no additional phase factor for the individual Lorentzian resonances that are due to any optical path difference. This is because the measurement consists of imaging the demagnified near field.

For the following results normal distributions for the central PC were used, since it represents the measurement most accurately. The resonances corresponding to the dips at 1232, 1255, 1284, and 1416 nm were measured to have peak extinctions of 21, 20, 8, and 6 dB, respectively. Our approximate calculations predict that the deterioration of those resonances in the 5-nm resolution bandwidth will be 35, 20, 8, and 4 dB, which concur with the measured data and the noise floor at 22 dB. Therefore we can attribute the discrepancies between the calculated and measured transmission minima at 1232, 1255, 1284, and 1416 nm primarily to fluctuations in the pitch and radius of the crystal. The minimum at 1349 nm, however, has a measured extinction of 9 dB, whereas the calculations predict a value of 13 dB. This discrepancy is due to an additional measured resonance at 1340 nm. Band structure calculations reveal that this resonance is nondegenerate and hence is not coupled to outside radiation in a symmetric crystal.[3] Coupling to such resonances is possible if the symmetry is broken as a result of, e.g., disorder in the lattice. The simulations must include fabrication asymmetries to capture such effects of nondegenerate modes.

In conclusion, we have presented simulations and experimental verification showing that single-layer two-dimensional PCs can be used to create optical devices, such as filters and broadband reflectors. We also have shown that a frequency band with a large extinction can be made quite large. Analysis of crystal imperfections shows that they average out narrow resonances, decreasing the maximum transmission or reflection for a narrowband filter. On the other hand, the imperfections have a relatively small effect on broadband features. Consequently PC structures can be designed to have resonances with large extinctions that are insensitive to fabrication-related disorders, such as variations in pitch and hole size, making them useful for practical applications.

The authors acknowledge contributions from R. Belikov, K. Crozier, and K. Yu. This work was sponsored by the U.S. Army Research Laboratory under contract DAAD17-02-C-0101 and by the Stanford Network Research Center. A. S. Sudbø acknowledges support from the Norwegian Research Council. O. Kilic's e-mail address is okilic@stanford.edu.

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