Asymmetry reversal and waveguide modes in photonic crystal slabs

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ABSTRACT

The measured reflection spectra of two-dimensional photonic crystal slabs consist of an asymmetric peak on top of an oscillating background. For $p$-polarized light, the asymmetry of the peak flips for angles of incidence beyond Brewster’s angle. We explain the observed line shapes with a Fano model that includes loss and use a waveguide model to predict the resonance frequencies of the photonic crystal slab. Finite-difference time domain calculations support the model and show that the resonance due to a higher order mode disappears when the substrate refractive index is increased beyond $n_s = 2.04$. This is readily explained by the cut-off condition of the modes given by the waveguide model.

Keywords: Photonic crystals, Waveguides, Fano resonances

1. INTRODUCTION

Resonant optical structures, in particular photonic crystals embedded in a waveguide, form an important class of optical materials. These photonic crystal slabs contain a periodic arrangement of holes on a wavelength scale and allow control of the propagation of light guided in the plane of the waveguide.\textsuperscript{1} For example, they enable wavelength-dependent steering,\textsuperscript{2} strong coupling of atoms to a cavity,\textsuperscript{3} and enhanced non-linear optical effects.\textsuperscript{4}

A measurement of the reflectivity as function of the wavelength is a relatively easy way to characterize the optical properties of these slabs. At each angle of incidence, the reflectivity spectrum shows a number of resonant features related to coupling of incident radiation to a leaky waveguide mode of the photonic crystal slab.\textsuperscript{5,6} The reflection spectra can be calculated numerically by solving Maxwell’s equations using a scattering matrix approach,\textsuperscript{7,8} Green’s functions,\textsuperscript{9} or finite-difference time domain (FDTD) methods.\textsuperscript{5,10} Although these numerical solutions of Maxwell’s equations predict the right frequencies and quality factors of the resonances observed in the measurements, they do not give physical insight into the origin of the spectral features. Therefore, it is important to develop simpler models to explain the measured resonances. Such models can be used as a diagnostic tool for fabricated structures, and can facilitate the first design of a photonic crystal structure.

Here, we present reflection measurements on a two-dimensional (2-D) photonic crystal slab. We use an extended coupled-mode theory to describe the shape of the measured reflectivity spectra and the line shape of the resonant features. This theory explains the change in asymmetry observed when changing the angle of incidence as a result of the change of sign of the Fresnel reflection coefficient of the layered structure that occurs at Brewster’s angle. We use a waveguide model\textsuperscript{11,12} to predict the resonance frequencies of a photonic crystal slab and compare this model to FDTD calculations. The disappearance of modes from the spectra when increasing the substrate refractive index is explained by the model in terms of the cut-off condition of the guided modes.

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2. PHOTONIC CRYSTAL FABRICATION

The GaAs and AlGaAs photonic crystals in this study were fabricated using a combination of electron-beam lithography and reactive ion etching. A square lattice of 1000 \times 1000 holes, with a radius \( r \approx 100 \text{ nm} \) and a lattice constant \( a \approx 320 \text{ nm} \), was defined by electron beam lithography in a \( \sim 550 \text{ nm} \) thick layer of ZEP 520 positive tone resist\(^*\) on top of a \( \sim 300 \text{ nm} \) layer of silicon nitride. After development, the pattern was transferred to the nitride by reactive ion etching using a low pressure (\(< 8 \text{ \mu bar}\)) CHF\(_3\):Ar (1:1) plasma. The remaining ZEP resist was removed with an oxygen plasma.

The resulting hole pattern in the nitride serves as a mask for reactive ion etching of the (Al)GaAs with a chlorine-based plasma.\(^{13,14}\) In this process, the chlorine ions etch the (Al)GaAs, while the nitrogen is used to passivate the side walls. We used a power of 100 W, a pressure \(< 5 \text{ \mu bar}\), and a flow of 15 sccm BCl\(_3\) and 7.5 sccm Cl\(_2\), and varied the N\(_2\) flow to tune the profile of the side walls. The selectivity of the etching process is \( > 10 : 1 \), and the etch rate depends on the hole size and the nitrogen flow, i.e. \( \sim 200 \text{ nm/min} \) for holes with a diameter of 300 nm, and \( \sim 1 \text{ \mu m/min} \) for holes with a diameter of 1 \( \mu \text{m} \), with N\(_2\) added. Figure 1(a) shows a scanning electron microscope (SEM) image of the photonic crystal after the fabrication process. Figure 1(b) shows a cross section of the holes when using a plasma without N\(_2\) added, showing damage to the side walls of the holes. In Fig. 1(c), we added a flow of 10 sccm N\(_2\) to the plasma, resulting in straight holes. A slight curvature of the holes is observed in Fig. 1(c). The depth of this curvature depends on the hole size and is due to specular reflection of the ions from the slightly tapered nitride mask. This curvature is therefore not intrinsic to the process and straight holes as deep as a few microns can easily be achieved. In the final stage, we selectively removed the silicon nitride mask using the same CHF\(_3\):Ar reactive ion etch used to define the mask.

Figure 2 shows SEM images of photonic crystal samples that consist of a higher refractive index slab layer on top of a substrate with a lower index. The structure in Fig. 2(a) was fabricated in a GaAs substrate using a relatively low N\(_2\) flow, leading to incomplete passivation of the side walls. The lines in the figure indicate the resulting tapering of the holes. The undercut effectively defines a waveguide structure that was used in the optical measurements of Sec. 4.

The same reactive ion etch can be used to define high quality photonic crystals in a free standing membrane. Figure 2(b) shows a part of such a membrane structure consisting of 1000 \times 1000 holes (\( \sim 300 \times 300 \mu \text{m}^2 \)). To fabricate this structure, we used a GaAs substrate with a heterostructure consisting of a 1000 nm Al\(_{0.7}\)Ga\(_{0.3}\)As sacrificial layer, a 300 nm thick Al\(_{0.35}\)Ga\(_{0.65}\)As membrane layer, and a 100 nm thick GaAs capping layer to prevent oxidation. After transferring the photonic crystal pattern to the heterostructure, we selectively removed the GaAs capping layer, using a wet etch of peroxide and citric acid.\(^{15}\) In the last step, a wet etch with

\(^*\)ZEON corporation, http://www.zeon.co.jp
hydrofluoric acid was used to selectively remove the aluminium-rich sacrificial layer, thus creating the free-standing photonic crystal membrane in Fig. 2(b). Note that the curvature of the holes due to the tapered nitride mask occurs in the sacrificial layer in this case.

3. THEORY

The reflection spectrum of a photonic crystal slab typically consists of an oscillating background and a number of sharp resonances as shown in Fig. 4 and Fig. 6. The spectrum can be explained using a simple scattering model of a resonator coupled to a continuum of modes. The photonic crystal slab, that acts as the resonator, is depicted in Fig. 3(a), together with the input and output ports. Part of the radiation incident on the slab is diffracted into a leaky waveguide mode (blue dashed arrows), whereas another part is directly reflected and transmitted (black solid arrows). The radiation that is diffracted back from the waveguide mode interferes with the directly reflected and transmitted radiation, yielding the characteristic Fano line shape. In Sec. 3.1 we extend a temporal coupled-mode theory to include loss, and describe the reflection in terms of the parameters of the direct and resonant channels. After that, in Sec. 3.2, we introduce a waveguide model to predict the resonance frequency of the resonant channel.

3.1. Fano model including loss

To calculate the spectrum of the transmitted and reflected light, we proceed as follows. For each angle of incidence and wavelength, a scattering matrix links the amplitudes of the incident, reflected, and transmitted waves. The scattering matrix $S$ of the system is the sum of the scattering matrices of the direct and the resonant channel. The direct channel is described by a scattering matrix $C$, given by

$$\begin{pmatrix}
r_1 & t_{21} & \cdots \\
t_{12} & r_2 & \cdots \\
\vdots & \vdots & \ddots
ddend \end{pmatrix}$$

connecting the amplitudes of the modes (ports) on both sides of the slab. Without diffraction in the media above and below the guiding layer, the components of the scattering matrix are given by the Fresnel reflection and transmission coefficients for a homogeneous layered system. The contribution from the direct channel gives rise to typical oscillations in the reflectivity as a function of wavelength (Fabry-Pérot fringes). If diffraction occurs to modes propagating above or below the guiding layer, a more elaborate method is needed to calculate the matrix elements of $C$.

The resonant channel corresponds to a resonant coupling of the incident radiation to a leaky waveguide mode via diffraction from the periodic photonic crystal structure. For a fixed angle of incidence, the coupling to a specific waveguide mode $p$ occurs at a resonance frequency $\omega_p$ and is characterized by an escape rate $\gamma_p$. The
coupling to the waveguide mode is described by coupling constants $d_{j,p}$, where the index $j$ corresponds to the different ports coupling to the waveguide mode. The coefficients $\gamma_p$, $d_{j,p}$, and the matrix elements $C_{jk}$ are not independent. Time-reversal symmetry and energy conservation put the following constraints on the coupling constants\(^{17}\):

\[
\sum_j |d_{j,p}|^2 = 2\gamma_p, \\
\sum_k C_{jk}d_{k,p} = -d_{j,p},
\]

where the indices $j$ and $k$ refer to the different ports, and $C_{jk}$ are the elements of the direct transmission matrix connecting the different free-space modes. Equation (3) links the amplitude and phase of the coupling constants to the scattering matrix $C$ of the direct process.

The matrix elements of the scattering matrix $S$ for the combined system of direct and indirect coupling are given by

\[
S_{jk} = C_{jk} + \sum_p \frac{d_{j,p}d_{k,p}}{\iota(\omega - \omega_p) + \gamma_p},
\]

where $\omega$ is the angular frequency of the incident radiation. The reflection coefficients for the different ports are given by the diagonal elements of this matrix, and the transmission coefficients by the off-diagonal elements. It is important to stress that the equations derived here hold for the case of uncoupled waveguide modes only. For the modes to be uncoupled, it is necessary that the number of independent ports is larger than or equal to the number of waveguide modes.\(^{18}\)

Losses can be explicitly included in the description in this model, by discriminating between losses in the direct channel, due to absorption or surface roughness, and losses in the resonant channel. Losses in the resonant channel can also be due to scattering of the waveguide mode to ports that are not incorporated in the scattering matrix description.

Absorption losses in the direct scattering channel can be adequately described by using a non-unitary scattering matrix $C$ and the Fresnel coefficients of a layered system with complex-valued refractive index. This matrix can be renormalized by adding an extra port to the description. If we assume that the input in this extra port is zero, and that the loss port is not coupled to the resonator mode, then the scattering matrix $S$ includes a block matrix describing the normal input and output ports of the system, that is not influenced by the parameters of the loss port. This makes it possible to use Eqs. (2)-(4), while using a non-unitary scattering matrix $C$ for the direct channel.
Waveguide losses can be incorporated in a similar way, by extending the model with a loss port, which only couples to the waveguide mode. The direct scattering matrix for a two-port system with an additional loss port acquires the form

\[ C = \begin{pmatrix} r_1 & t_{21} & 0 \\ t_{12} & r_2 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \]

The loss rates \( \Gamma_p \) are incorporated in Eq. (2) in a straightforward way, by using the convention \( \sum_j |d_{j,p}|^2 = 2(\gamma_p + \Gamma_p) \), where the index \( j \) now runs over all ports.

For the symmetric case of two ports coupled to one leaky waveguide mode, symmetry requires that \( r_1 = r_2 = r \) and \( t_{21} = t_{12} = it \), where \( r \) and \( t \) are real. Moreover, the coupling constants to the ports should be equal, except for a plus or minus sign determined by the odd or even symmetry of the waveguide mode with respect to the mirror plane. The reflectivity in this case is given by

\[ R = \left| \frac{r + \gamma \mp it}{i(\omega - \omega_0) + \gamma + \Gamma} \right|^2, \]

where the \( \mp \) is determined by the even or odd symmetry of the mode.\(^{17}\) This expression gives the typical asymmetric Fano line shape. The reflectivity has a distinct zero if the loss rate \( \Gamma = 0 \). To reach 100% reflectivity, the direct process has to be lossless as well (i.e. \( |r|^2 + |t|^2 = 1 \)).

### 3.2. Waveguide modes

The model in the previous section gives a description of the line shape in the reflectivity of a photonic crystal slab, but it does not predict the resonance frequencies \( \omega_p \). As we will show in this section, it is possible to calculate the resonance frequencies and the waveguide modes for a photonic crystal slab using a simple model.\(^{11,12,19}\) In this nearly-free photon approximation, the waveguide is treated as a uniform slab with an effective refractive index that depends on the fill fraction of the air holes. For the TE waveguide modes, having the electric field in the plane of the slab, the dispersion relation for a uniform slab is implicitly defined as\(^{20}\)

\[ \sin(hd)\left(h^2 - pq\right) = \cos(hd)(p + q)h, \tag{7} \]

where \( p, q, \) and \( h \) denote the transverse components of the wave vector in the different media. They are defined as \( q^2 = \beta^2 - (\omega^2/c^2) n_g^2 \), \( h^2 = (\omega^2/c^2) n_g^2 - \beta^2 \), and \( p^2 = \beta^2 - (\omega^2/c^2) n_s^2 \), where \( n_0, n_g, \) and \( n_s \) are the refractive indices of the top, guiding, and bottom layer, respectively, and \( c \) is the speed of light in vacuo. The condition for coupling to a waveguide mode is given by the diffraction condition

\[ \vec{k}_\parallel + \vec{G} = \vec{\beta}, \tag{8} \]

where \( \vec{k}_\parallel \) is the parallel component of the incident wave vector, \( \vec{\beta} \) is the parallel component of the wave vector of the waveguide mode, and \( \vec{G} \) is a reciprocal lattice vector of the photonic crystal. For normal incidence, this reduces to \( \vec{\beta} = \vec{G} \), which can be used to numerically find the resonance frequencies \( \omega_m \) from Eq. (7).

For simplicity, we calculated the reflectivity of an one-dimensional (1-D) array of slits, using a freely available FDTD package.\(^{21}\) The cross section of the structure used in these calculations is given in Fig. 3(b). The slab of thickness \( d \) and refractive index \( n_g = 3.5 \) contains an array of slits of width \( w \) and refractive index \( n_0 = 1 \). The array has a lattice constant \( a \) and we used \( w/a = 0.1 \) and \( d/a = 0.5 \). The substrate index \( n_s \) was varied between 1 and 3.0, and the reflection spectra were calculated at normal incidence for TE-polarized light (\( E \)-field parallel to the slits).

Figure 4 shows the reflectivity of the array as a function of frequency, for increasing substrate index \( n_s \). Two distinct resonances are visible on top of an oscillating background. The Fresnel reflection coefficient for the layered system can be fitted to the spectra, using an effective refractive index of the form\(^{10}\)

\[ n_g = c_0 + c_1\omega + c_2\omega^2, \tag{9} \]
Reflectivity of a 1-D photonic crystal slab, calculated using a FDTD method. The grating consists of air slits with \( w/a = 0.1 \) in a dielectric slab with \( d/a = 0.5 \) and refractive index \( n_g = 3.5 \), on top of a substrate with increasing refractive index. Two resonances are visible, on top of an oscillating background. The blue dashed line is a fit of a refractive index of the form described in Eq. (9) to the background. The resonance around \( \omega = 0.5 \) disappears for \( n_S > 2.0 \).

with \( c_0 \), \( c_1 \), and \( c_2 \) as only fit parameters. Typical values for the fit parameters are \( c_0 = 3.25 \), \( c_1 = 0.42 \), and \( c_2 = -0.21 \), yielding an effective index between 3.25 and 3.46. The result of the fit is shown as the blue dashed lines in Fig. 4. The effective index is close to the volume average of the dielectric constants\(^{22,23} \) for \( \omega < 0.5 \), but deviates for higher frequencies. This is due to the fact that for higher frequencies the wavelength becomes comparable to the lattice spacing and slit width.

At normal incidence, the resonances corresponding to a specific reciprocal wave vector \( \mathbf{G} \) are degenerate. Due to the grating, they are coupled and show an avoided crossing. A simple explanation of the fact that we only observe one of the resonances is given in terms of coupled mode theory.\(^{24} \) For a 1-D grating with a dielectric function that contains only one Fourier component, no avoided crossing occurs. The interaction that creates the avoided crossing is caused by the higher harmonics of the dielectric function \( \epsilon (\mathbf{r}) \). The coupling to these modes is determined by the relative phase of the Fourier components. For a 1-D square profile, the first and second harmonic are out of phase (\( \phi = \pi/2 \) in the notation of Ref. 24). This leads to zero coupling strength to the low-frequency mode, and as a consequence, the peaks in Fig. 4 are exclusively due to coupling to the high-frequency mode. This is confirmed by the calculation in Fig. 5(a), that shows a reflection spectrum for the 1-D grating with a substrate index \( n_S = 1 \), at an angle of incidence of \( 5^\circ \), calculated using a rigorous coupled wave analysis.\(^{25} \) In this figure, the lower-frequency resonances can be seen to appear as narrow resonances at \( \omega = 0.33 \) and \( \omega = 0.48 \).

As can be seen in Fig. 4, the two resonances visible for \( n_S \leq 2.0 \) at normal incidence have opposite symmetry. This is consistent with the fact that these resonances are due to the first and second TE waveguide mode, respectively. For a refractive index \( n_S > 2.0 \), the second resonance is seen to disappear from the spectrum. We fitted Eq. (6) to the calculated spectra, using the refractive index obtained by the fit of the oscillating background as an input. The only fit parameters are the resonance frequencies \( \omega_0 \) and \( \omega_1 \), and the line widths \( \gamma_0 \) and \( \gamma_1 \). The resulting resonance frequencies are shown as the symbols in Fig. 5(b), plotted as a function of the substrate refractive index, and are compared to the numerical solution of Eq. (7) (red solid lines) obtained using \( n_g = 3.5 \). The calculated frequencies are below the points, because the waveguide model predicts the center frequency and does not take into account the avoided crossing. In fact, the data in Fig. 5(a) for \( 5^\circ \) angle of incidence show that the waveguide model correctly predicts this center frequency.

The disappearance of the resonance is also predicted by the waveguide model. The cut-off frequency of the \( m \)-th mode is given by\(^{20} \)

\[
\omega_{cm} = \frac{c}{2\pi d} \sqrt{n_g^2 - n_S^2} \left( m\pi + \arctan \sqrt{\frac{n_g^2 - n_S^2}{n_g^2 - n_S^2}} \right).
\]

This condition is drawn as the dashed blue line in Fig. 5(b) for the first two waveguide modes, calculated using
Figure 5. (a) Calculated reflectivity of the array of slits at 5° angle of incidence, for a substrate index $n_s = 1$. Two resonances that are not visible at normal incidence appear at $\omega \approx 0.33$ and $\omega \approx 0.48$. (b) Resonance frequencies of the Fano resonances as a function of the substrate refractive index $n_s$. The resonance frequencies can be predicted using a simple waveguide model (solid red line), with $n_g$ given by effective medium theory. This model does not include the avoided crossing between the two waveguide modes, and therefore calculates the average of the high-frequency and low-frequency resonances. The dashed blue lines correspond to the cut-off conditions of the $m = 0$ and $m = 1$ modes. The gray area indicates the parameter region where higher order diffraction into the substrate occurs.

an effective refractive index $n_g = 3.34$. Diffraction into the substrate occurs at a frequency $\omega_d$, where the propagation constant $\beta$ becomes equal to the length of the wave vector in the substrate. This leads to the condition

$$\omega_d = (k_{||} + G)/n_s. \quad (11)$$

The existence of diffraction orders at normal incidence is indicated by the grey area in Fig. 5(b). This corresponds to the situation where the transverse component of the wave vector in the substrate $p = 0$. The resonance frequency of the waveguide mode at cut-off is thus given by the intersection of Eq. (10) and Eq. (11).

It is important to mention here that although the assigning the different resonances to different modes is quite straightforward in the 1-D case, in the 2-D case TE-TM mixing will occur. The mixing between different modes induces avoided crossings between otherwise orthogonal modes, and causes TE modes to appear in the TM spectra, and vice-versa. This makes identification of specific peaks with specific waveguide modes more complicated.

4. REFLECTION MEASUREMENTS

We measured the specular reflection from the GaAs photonic crystal slab shown in Fig. 1(a) along the $\Gamma$-X direction (indicated with the arrow) as a function of the angle of incidence from $25^\circ$ to $80^\circ$. White light from a spectrally broad lamp was polarized and focused onto the sample. The specular reflection was polarization-filtered, imaged onto a fiber, and analyzed in a spectrometer with a spectral resolution of $\sim 2$ nm. The numerical aperture (NA) of the incoming beam was limited to NA $\leq 0.04$. The spot size on the sample was $\sim 100 \mu m$.

Reflection spectra for angles of incidence of $50^\circ$ and $80^\circ$ are shown in Fig. 6 for three different settings of the polarizers. Figures 6(a) and (d) show the spectra for the situation where both polarizers were set to a polarization perpendicular to the scattering plane (s-polarization). An asymmetric peak around a wavelength of $\sim 950$ nm is seen on top of an oscillating background and changes position with angle of incidence. A similar peak is seen in Fig. 6(b) and (e), where both polarizers were set to a polarization parallel to the scattering plane (p-polarization). In this case, the asymmetry of the peak is changed when tuning the angle of incidence from $50^\circ$ to $80^\circ$. The symmetry of the peak is the same for both polarizations at $80^\circ$ angle of incidence.
The Fano model described in Sec. 3.1 can be used to describe the observations. We use Maxwell-Garnett’s effective medium theory\textsuperscript{22, 23} to describe the photonic crystal layer as a homogeneous birefringent layer with an effective refractive index $n_{\text{eff}}$, incorporating the known refractive index dispersion of GaAs.\textsuperscript{27} This includes absorption for wavelengths shorter than 950 nm. With this effective index, we calculate the polarization- and angle-dependent Fresnel reflection and transmission coefficients of the layered system.

The red dashed lines in Fig. 6 show fits of the Fano model to the measurements. The only fit parameters were the resonance frequency $\omega_0$, the linewidth $\gamma$, and the waveguide losses $\Gamma$. We slightly adjusted the hole diameter of the holes for different angles of incidence, to get a better fit to the oscillating background. Although the fits deviate on detail from the measurements, qualitatively all elements of the measurement are contained in the model. We attribute most deviations to the simplifications we made with respect to the vertical shape of the air holes, and to the fact that Maxwell-Garnett’s effective medium theory only holds when all relevant length scales in the system are much smaller than the wavelength. In fact, the tapering of the holes is essential to observe the resonances. This ensures that there is an effective waveguiding layer in the top part of the photonic crystal structure.

The Fano model also gives an explanation for the change in asymmetry of the peak. Since the peak shape is determined by interference of a resonant and a direct channel, the relative phase between these two contributions determines the asymmetry of the resulting peak. The Fresnel coefficient $r$ for $s$-polarized light is always negative, but the Fresnel coefficient for $p$-polarized light vanishes and changes sign at Brewster’s angle. It is exactly this change of sign that causes the line shape to change when the angle of incidence is tuned to larger angles.\textsuperscript{28, 29} The fact that the asymmetry for $s$-polarized light is the same as for $p$-polarized light at large angles of incidence indicates that both peaks are due to coupling to a waveguide mode that is even in the center plane of the photonic crystal slab.

In Fig. 6(c) and (f) the reflection spectra of the photonic crystal slab is shown in a setup where the incoming light was $p$-polarized, and the collected light was $s$-polarized. A small Lorentzian-shaped peak can be observed in these spectra. The resonance frequencies obtained from the fits of the different measurements are not exactly...
identical for the same angle of incidence. This indicates that the peaks in Fig. 6(a), (b), and (c) are due to different waveguide modes. Since Fresnel reflection is polarization-maintaining for s- and p-polarization, the direct channel is filtered out by the second polarizer. This results in a resonant contribution only, explaining the Lorentzian line shape of the peak.\(^{30}\) The intensity of these peaks is low, because the symmetry of the lattice dictates that the polarization (s or p) is conserved upon transmission and reflection, as long as the wave vector \(k_{||}\) is along one of the symmetry directions of the lattice. The fact that we do observe a small peak demonstrates that our structure is less than perfect.

5. CONCLUSION

In summary, the typical asymmetric peaks on top of an oscillating background, observed in the reflection from a photonic crystal slab, are due to interference between a direct and a resonant reflection channel. The change of asymmetry of the observed peak for p-polarized light is caused by a change in sign of the direct reflection channel, around Brewster’s angle. The rough shape of the holes in our experiment causes relatively broad spectral features that are easily resolved. The fact that we are able to describe our data with a coupled mode theory and observe the change in asymmetry of the spectral line shows that the description is robust and also valid for less-than-perfect photonic crystals.

The frequencies of the resonances can be predicted using a simple waveguide model using the effective index of the guiding layer as only adjustable parameter. This model can be used to predict the disappearance of certain resonances from the reflectivity spectrum when changing the substrate refractive index. The predictions for waveguide cut-off of the second TE mode are confirmed by FDTD calculations of the reflectivity. The ability to control the coupling to specific modes can be an important design parameter for photonic crystal structures, if coupling to a specific mode is undesirable. Another possible application is to create an optical switch, where a change in the optical parameters of the guiding layer can be used to temporarily transform one of the guided modes into a leaky mode.

ACKNOWLEDGMENTS

We thank Steven Habraken for discussions, Paul Alkemade for making the cross-sectional SEM image, and Rob van der Heijden for help with sample fabrication. We acknowledge financial support from the Dutch Association for Scientific Research (NWO) and the Foundation for Fundamental Research of Matter (FOM).

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