Coupling light to periodic nanostructures

Driessen, E.F.C.

Chapter 3

Asymmetry reversal in the reflection from a two-dimensional photonic-crystal slab

The measured, angle-dependent, reflection spectra of a 2-D GaAs photonic-crystal slab consist of an asymmetric peak on top of an oscillating background. At large angles of incidence ($> 70°$), the asymmetry of the peak is observed to flip for *p*-polarized light. We explain the observed spectra with a Fano model that includes loss and interference between a resonant waveguide component and direct Fresnel reflection of the layered structure. We show that the reversal of the asymmetry of the line is due to a change in sign of the direct reflection at Brewster's angle.

This chapter is based on E. F. C. Driessen, D. Stolwijk, and M. J. A. de Dood, *Asymmetry reversal in the reflection from a two-dimensional photonic crystal*, Opt. Lett. **32**, 3137–3139 (2007).

3.1 Introduction

Optical reflectivity measurements of two-dimensional photonic-crystal slabs are a relatively easy way to characterize the properties of these slabs. The wavelength dependent spectra show a number of features related to the leaky waveguide modes of the slab [19,20]. A lot of effort has been devoted to calculating these spectra by rigorously solving Maxwell's equations, using scattering matrices [21,22], Green's functions [23] and finite difference time domain methods [19,24]. Although being able to reproduce the spectra, these calculations do not give physical insight into the origin of the spectral features. Therefore it is important to develop simpler models that can explain the measured resonances. Such models are an important diagnostic tool for fabricated structures and can facilitate the first design of a photonic crystal structure.

In this Chapter, we present reflection measurements on a 2-D photonic-crystal slab. We study the line shape of a resonance in this spectrum, as a function of the angle of incidence. The asymmetry of the (Fano) line shape [29,30] in the reflection spectra is observed to change for p-polarized light. Our observations can be described with an extended coupled mode theory, linking the reversal of asymmetry to the change of sign of the Fresnel reflection coefficient of the layered structure. This change of sign occurs at Brewster's angle.

3.2 Experiment

The photonic crystal in this study was fabricated in GaAs using e-beam lithography and reactive ion etching. It consists of a square lattice of 1000×1000 holes with radius $r \approx 100$ nm and lattice constant $a \approx 320$ nm. Figure 2.1(a) shows a scanning electron microscope (SEM) image from the top, and Fig. 2.2(a) a cross-section (made with a focussed ion beam). Due to details of the fabrication process, the cross-section of the holes consists of two slightly tapered parts, as can be seen in figure 2.2(b). The holes become wider until a depth of ~ 600 nm, and then narrow down until a depth of $1.5 - 2$ μm.

We measured the specular reflection from the photonic crystal along the Γ-X direction [indicated with the arrow in figure 2.1(a)], as a function of the angle of incidence from 25° to 80° in steps of 2.5°. 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 ~ 2 nm. The numerical aperture (NA) of the incoming beam was limited to NA < 0.04. The spot size on the sample was ~ 100 μm. We measured the spectra for both polarizations, but show only the results for p-polarized light.

Reflection spectra for angles of incidence of 50, 70 and 80° are shown in figure 3.1. The spectra show a large, asymmetric peak, on top of an oscillating background. By changing the angle of incidence, the peak shape in figure 3.1 changes from asymmetric with a tail on the red side (a), to symmetric (b), to asymmetric with a tail on the blue side (c).

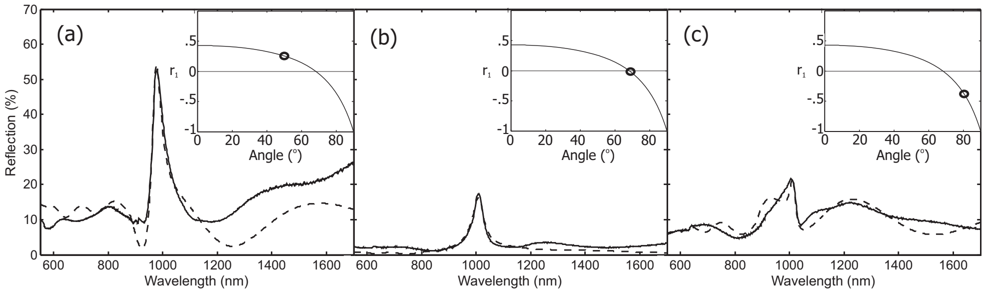

Figure 3.1. Experimental reflection spectra of the photonic-crystal slab for 3 angles of incidence: 50° (a), 70° (b) and 80° (c). The dashed lines are fits using the model discussed in the text. The insets show the reflection coefficient r_1 for an interface of air and $n_{\text{eff}} = 2.5$, as function of angle of incidence. The circles indicate the angle of the measurement.

3.3 Model

In order to explain our measurements, we extended the temporal coupled-mode theory in Ref. 30, by including an additional loss port. Light incident onto the photonic-crystal slab can be reflected through different channels: a non-resonant (direct), and a resonant loss channel. The direct channel corresponds to the Fresnel reflection of the layered system, while the resonant channel is created by coupling to a (leaky) waveguide mode. This waveguide mode has a well-defined dispersion relation and coupling at a specific frequency occurs via diffraction. The asymmetric Fano line shape can be explained by interference between the direct channel and the resonant channel. A loss port is added to include the effects of scattering from surface roughness and diffraction into the substrate. All input and output ports of the system are linked by a direct-scattering matrix C and a resonant scattering matrix U. Coupling of the resonant mode to the three different ports is described by the complex coefficients d_j.

The direct channel contains the reflection and transmission coefficients of the layered system. At each angle of incidence, we use Maxwell-Garnett's effective-medium theory [34, 35] to describe the photonic crystal layer as a birefringent layer with refractive index n_{eff}. We then calculate the Fresnel reflection and transmission coefficients [43] of the layered system shown in figure 3.2(a), incorporating the known refractive-index dispersion of GaAs [39], that includes absorption for wavelengths shorter than 950 nm. Taking the loss port into account, we write the scattering matrix for the direct process as

$$C = \begin{pmatrix} r_1 & t & 0 \\ t & r_2 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{3.1}$$

where r_1, r_2 and t are the (complex) Fresnel reflection and transmission coefficients for the electric field.

The resonant channel, due to the leaky waveguide, is formed by the photonic crystal layer. As pictured in figure 3.2(b), the incident light is partially diffracted into the waveguide and confined by internal reflection. The light that is diffracted back, interferes with the directly reflected and transmitted light (ports 1 and 2 in figure 3.2). The resonance angular frequency ω_0 is determined by the dispersion relation of the waveguide mode involved. The average lifetime in the waveguide is parameterized by an escape rate γ and is a function of angle of incidence. The scattering matrix describing the resonant channel is given by

$$U_{jk} = \frac{d_j d_k}{i(\omega - \omega_0) + \gamma}. \tag{3.2}$$

where ω is the angular frequency of the incident light.

In our experiment, the tapered form of the holes effectively ensures that there is a waveguide in the upper part of the photonic crystal layer. However, since the refractive index of the substrate is higher than the effective index of the photonic crystal layer, light propagating in the waveguide mode can still leak to the substrate without being diffracted. In order to incorporate these losses in the model, we added a third port to the scattering matrix [port 3 in fig. 3.2(b)]. In this relatively simple model, we assume that a fraction of the light is irreversibly lost by leaking out of the resonant channel. This is valid as long as losses in the resonant channel are much larger than losses in the direct channel. This generally holds when the losses in the direct channel are small, since in this case the interaction length for light in the resonant channel is much larger than that in the direct channel. The effect of adding a loss port is that the reflectivity no longer reaches 100% nor 0% as is the case for a system without loss [30].

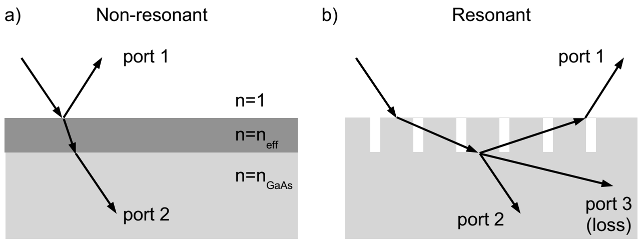

Figure 3.2. Model for the non-resonant (a) and resonant (b) channels in the model. The numbers indicate the different ports in the scattering matrix model. (a) The non-resonant channel is modeled by applying effective medium theory to the photonic-crystal layer and calculating the Fresnel reflection and transmission coefficients of the layered system. (b) For the resonant channel, the incident light is diffracted into a waveguide mode, which can diffract back to ports 1 and 2, but can also propagate into the substrate (port 3) constituting loss.

Time-reversal symmetry and energy conservation put the following constraints on the coupling constants d_j [30]

$$\sum_k C_{jk} d_k^* = -d_j \tag{3.3}$$

$$\sum_j |d_j|^2 = 2(\gamma + \Gamma), \tag{3.4}$$

where Γ is the loss rate from the resonant mode. Furthermore, the diffractive coupling to the resonant mode is assumed to be equally large on both sides of the photonic crystal slab (i.e. $|d_1| = |d_2|$). With these constraints, we can write the coupling constants d_j in terms of the Fresnel coefficients and the parameters ω_0, γ and Γ. The reflectivity $R = |U_{11} + C_{11}|^2$ for the system is then given by

$$R = \left| \frac{i\left[(\omega - \omega_0) r_1 \mp \gamma t\right] + \Gamma r_1}{i(\omega - \omega_0) + \gamma + \Gamma} \right|^2 . \tag{3.5}$$

After setting the fill fraction and the thickness of the photonic crystal slab once, the Fresnel coefficients are fixed and there are only three free parameters left in the model: the resonance angular frequency ω_0, and the loss rates γ and Γ.

The dashed curves in figure 3.1 show the best fit of the model to our data. Although the fits deviate on detail from the measurements, qualitatively all elements of the measurements are contained in the model. We attribute most deviations from the measurements to simplifications we made with respect to the vertical shape of the air holes. Also, Maxwell-Garnett effective medium theory is only valid when all relevant length scales in the system are much smaller than the wavelength. This condition is not fulfilled in our structure.

Using the model described here, one can understand the origin of the change in asymmetry of peak shape when changing the angle of incidence. Since the peak is a product of interference between a resonant Lorentzian line and a non-resonant direct contribution, the relative phase between these two contributions will determine the asymmetry of the resulting line shape.

The Fresnel reflection coefficient (r_1) for p-polarized light, for a dielectric interface, vanishes and changes sign at Brewster's angle. This is shown in the insets of figure 3.1, for an interface between air and a dielectric with $n_{\text{eff}} = 2.5$. It is exactly this change of sign that causes the line shape to vary from red-tailed asymmetric to Lorentzian at Brewster's angle to blue-tailed asymmetric for larger angles. For s-polarized light, we observed the line shape to be blue-tailed asymmetric for all angles of incidence, which confirms this explanation since the Fresnel reflection coefficient for s-polarized light is always negative.

The rough shape of the holes causes relatively broad spectral features that are easily resolved. The fact that we are able to describe our data with an extended version of a coupled mode theory and observe a change in asymmetry of the spectral line shows that the description is robust and also valid for less-than-perfect crystals.

3.4 Conclusion

In summary, the reflection spectra from a 2-D photonic-crystal slab show a large asymmetric peak on top of an oscillating background. With increasing angle of incidence, the asymmetry of the peak reverses. We explained all observations with a scattering matrix model [30] that is extended to include losses. The reversal of the asymmetry is a consequence of the change in sign of the Fresnel reflection coefficient when crossing Brewster's angle. The 'model gives good qualitative as well as quantitative agreement with the measurements, while having only three fit parameters describing the resonance frequency and lifetime of the resonant waveguide mode, and its losses.

Although the model does not predict the position of the resonances for a given structure, these can be estimated for the case of a true waveguide (i.e. $n_{\text{eff}} > n_{\text{subs}}$, with n_{subs} the refractive index of the substrate) [44, 45]. The model can easily be extended to incorporate multiple uncoupled waveguide modes, thus forming a powerful tool in explaining the observed phenomena in reflection spectra from 2-D photonic crystals.