Fano lineshape reversal in the reflectivity spectra of photonic crystals transferred to a gel substrate

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We present a novel method to transfer freestanding photonic crystal membranes to a low refractive index substrate. These structures are optically flat and we compare their optical properties with those of freestanding membranes. The resonant coupling of light to leaky modes of photonic crystals leads to asymmetric Fano lineshapes in reflectivity spectra. For symmetric membranes the asymmetry of the lineshape reverses whenever the amplitude reflection coefficient of the background reaches zero. In contrast, we show that for asymmetric membranes on a substrate the asymmetry of a resonance can be reversed by angle tuning without reaching zero amplitude in the background.

Introduction

Ever since the introduction as materials that can inhibit spontaneous emission [1] or localize light [2], photonic crystals have been recognized as structures that are able to tailor the propagation of light [3]. These photonic crystals consist of a dielectric material arranged on a periodic lattice with a lattice constant comparable to the wavelength of light. Nowadays, photonic crystals find application in high Q, small mode volume cavities, in slow-light waveguides and numerous other applications that make use of the intriguing linear and nonlinear optical properties of photonic crystals.

We fabricate freestanding two-dimensional photonic crystal slabs with a square lattice of holes with a hole radius of 150 nm and a lattice constant a = 820 nm using a combination of e-beam lithography and reactive ion etching techniques. The holes are perforated in a 150 nm thick $Al_{0\ 35}Ga_{0\ 65}As$ membrane which covers an area of 300 300 μm^2. The edges of the membrane are attached to a GaAs substrate via a 1 μm thick $Al_{0\ 7}Ga_{0\ 3}As$ sacrificial layer. The measured refection spectra of this structure show dispersive, asymmetric (Fano) lineshapes superimposed on top of a slowly oscillating background [4, 5]. These dispersive features correspond to leaky modes of the structure. Unlike the truly guided modes which are confined to the photonic crystal slab by total internal reflection, the leaky modes can resonantly couple to external radiation via diffraction from the photonic lattice [6]. The characteristic Fano lineshapes result from the interference between the direct (non-resonant) contribution that contains slow Fabry-Perot oscillations for a uniform dielectric slab, and the indirect (resonant) contribution [6]. After measuring linear reflectivity spectra as a function of both the wavelength and the angle of incidence, the membrane is transferred to a transparent gel film [7] with a low refractive index of n_{gel} 1 4 on a standard microscope slide. The structure is gently placed on the gel and the GaAs substrate is carefully peeled off. The transfer to the gel eliminates the buckling of the membranes due to a small lattice mismatch between the $Al_{0\ 35}Ga_{0\ 65}As$ membrane and the GaAs substrate. As a result, an optically flat membrane that enables transmission measurements is created.

We show that the resonant features in the experimental reflectivity spectra are more prominent for the transferred membrane than for the freestanding membrane and we give the explanation for this. Furthermore, we study the asymmetry reversal of Fano lineshapes for p-polarized light for both structures. In the case of the symmetric structure (freestanding membrane), the asymmetry of the Fano lineshape reverses whenever the amplitude reflection coefficient of the background reaches zero. This occurs when the optical thickness of the slab is equal to $2m$ 1 λ 4 (Fabry-Perot condition), or when the angle of incidence is tuned through Brewster's angle for the slab in air. For the asymmetric structure (membrane on the gel), the amplitude reflection coefficient of the direct contribution does not reach zero and one would naively expect that the asymmetry of the Fano profile does not reverse in this case. However, we show that the Fano lineshape reversal occurs for the membrane on the gel as well, and we explain the underlying mechanism of the asymmetry reversal.

Leaky modes before and after the transfer

Figure 1 shows typical experimental reflection spectra for p-polarized light of the photonic crystal slab before (blue circles) and after (red circles) the transfer to the gel. The two resonances in the spectra are the p-polarized (0, 1) and (-1, 1) leaky modes. It is clear from the measured spectra that the resonant features for the membrane on the gel substrate are more prominent than those for the freestanding membrane. This effect is mostly in the background contribution for a wavy membrane on a highly-reflective GaAs substrate. The observed waviness of the membrane introduces variations in the distance between the substrate and membrane, which are much larger than λ 4. This creates strong variations in the reflected amplitude of the background contribution. Illuminating with a large spot is equivalent to averaging over all the substrate to membrane distances, and as a consequence the resonances in the reflection spectra for the freestanding slab have lower

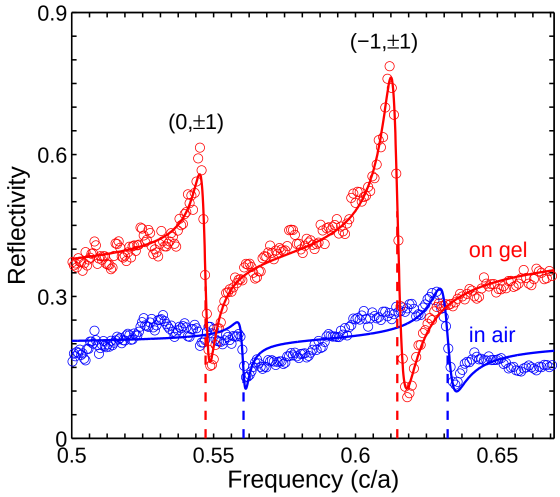

Figure 1: Measured reflection spectra of the slab suspended in air (blue circles) and transferred on the gel (red circles), for an incidence angle of 35 . The solid lines are obtained by fitting a Fano model (see the text) to the experimental data. The dashed lines indicate the center frequencies of the p-polarized (0, 1) and (-1, 1) modes, as determined from the fit.

visibility compared to the slab transferred to the gel.
A red shift of the resonances is observed after the transfer to the gel. From the fits of the Fano model [8] to the measured data (solid lines in the figure), we find a red shift of 2.5 and 2.8% for the 0 1 and 1 1 mode, respectively. Qualitatively this red shift can be understood from a nearly free photon picture [9]. The leaky modes are due to the folded mode of the slab waveguide with an effective refractive index. When the slab is placed on a substrate with a higher refractive index, i.e. gel instead of air, this effective refractive index increases and a red shift is observed. This conclusion is confirmed with FDTD simulations for an infinite slab with parameters identical to the experimental structure.

Asymmetry reversal of Fano lineshapes

Figure 2 shows the measured reflection spectra for various angles of incidence (grey symbols) for the freestanding membrane (left panel) and the membrane on the gel (right panel). In both cases, the asymmetry of the Fano lineshape of the *p*-polarized (-1, 1) mode is reversed by tuning the incidence angle. For the symmetric structure (air-slab-air), the leaky mode produces a nearly symmetric lineshape at an angle of incidence of 70 . Based on the reflectivity measurements for every 5 we estimate that the asymmetry reversal occurs at an angle of incidence of 71 1 , which corresponds to Brewster's angle for a uniform dielectric slab in air with a refractive index of n_{eff} 2 9 0 2. This is consistent with the effective refractive index of an infinitely long two-dimensional photonic crystal slab with parameters identical to the experimental structure at the asymmetry reversal of the *p*-polarized (-1, 1) mode. A fit of the Fano model to the calculated reflection spectra (scattering matrix calculation) for angles of incidence of 60 and 80 was used to estimate the dispersion of the effective refractive index of the photonic crystal slab [6]. For the asymmetric structure (air-slab-gel), the reversal of the asymmetry occurs at a much larger angle of 78 1 , compared to the symmetric structure. This is also

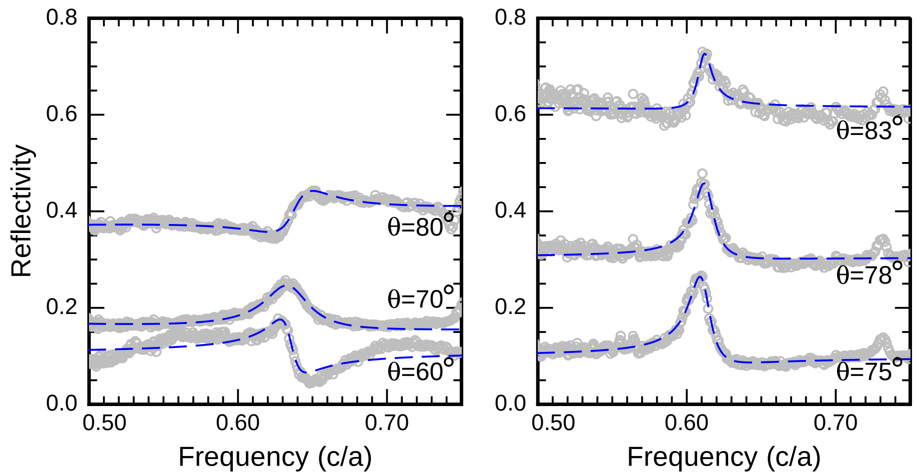

Figure 2: Measured reflection spectra for various angles of incidence (grey symbols) for the photonic crystal slab before (left) and after the transfer to the gel (right). The dashed blue lines are obtained by fitting the Fano model to the data. By tuning the angle of incidence the asymmetry of the Fano lineshape of the *p*-polarized (-1, 1) mode is reversed.

reproduced using a scattering matrix calculation. Moreover, a detailed inspection of the calculated reflection spectrum at the asymmetry reversal shows that the direct reflection is low, but doesn't reach zero.
To gain physical insight in the origin of the asymmetry reversal we applied a truncated two-port coupled-mode theory [8] to both the symmetric and the asymmetric photonic crystal slab waveguide, where the inputs and outputs of the system correspond to the reflected and transmitted modes. The asymmetry reversal occurs whenever the phase difference between the non-resonant (direct) and the resonant contribution is an integer multiple of π. Within this model, the phase difference is determined solely by the complex amplitude reflection and transmission coefficients of the layered system (air-slab-air or air-slab-gel). The coupled-mode theory agrees very good with both the experimental data and the numerical calculations, and shows that the asymmetry reversal for an asymmetric structure does not necessarily coincide with a zero in the amplitude of the direct (non-resonant) contribution.

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