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HAL Id: hal-00878202

https://hal-iogs.archives-ouvertes.fr/hal-00878202

Submitted on 29 Oct 2013

Disorder-induced losses in planar photonic crystals

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The phenomenological approach introduced by Benisty *et al.* [Appl. Phys. Lett. **76**, 532 (2000)] to model out-of-plane radiation losses in planar photonic crystals with a low vertical refractive index contrast is extended to the case of in-plane disorder. The model is experimentally validated by means of optical measurements on GaAs-based structures. For the present fabrication techniques the disorder-induced contribution is found to be negligible compared with the other loss mechanisms. © 2006 Optical Society of America

OCIS codes: 130.0130, 130.3130, 230.3120, 250.5300, 290.5880.

Disorder-induced radiation losses can strongly limit the performances of planar photonic crystals (PhCs) in actual optoelectronic devices.[1–4] With the progress in lithography and etching, the effects of fabrication tolerances and imperfections are investigated to explore the limits of PhC structures. Disorder in the hole geometry can lead to a reduction of the bandgap size[1] and to an increase of radiation losses.[3,4] Several studies both on in-plane (i.e., random displacement from the ideal periodic lattice[3,4]) and on vertical (i.e., sidewall roughness[2]) disorder have been reported. In this Letter we show how disorder-induced losses in planar PhCs can be described by adapting the phenomenological model of Refs. 5 and 6. The model is experimentally validated and the relative contributions of intrinsic, depth- and disorder-induced losses are discussed.

In the seminal paper by Benisty *et al.*[5] a two-dimensional (2D) phenomenological approach was introduced to account for radiation losses in low-refractive-index-contrast planar PhCs. The out-of-plane scattering at the air holes is translated into an effective dissipation, i.e., into an imaginary dielectric constant ϵ'' in the air holes.[5] To first order, ϵ'' is the sum of three contributions:

$$\epsilon'' = \epsilon''_{\text{int}} + \epsilon''_{\text{fed}} + \epsilon''_{\text{dis}}, \tag{1}$$

where ϵ''_{int} accounts for intrinsic losses,[5] ϵ''_{fed} contains contributions from the finite etch depth or, more generally, from the hole sidewall shape,[6] while ϵ''_{dis}, accounting for disorder, is the parameter of interest here.

Concerning intrinsic radiation losses, for most practical cases, the general scaling law of Ref. 5 holds:

$$\epsilon''_{\text{int}} \propto \frac{n_2 \Delta \epsilon^2}{\lambda_0^3} w S \Gamma_1 \eta, \tag{2}$$

where λ_0 is the vacuum wavelength, w is the core thickness [see Fig. 1(a)], S is the area of the hole

cross section [see Fig. 1(c)], Γ_1 is the confinement factor of the guided mode,[5] and $\eta \cong 1 - \cos\theta$ [with $\theta = \arcsin(n_1/n_2)$] is the extraction coefficient from the core into the claddings.

An analytical expression can be derived for the effect of the finite etch depth,[6] i.e.,

$$\epsilon''_{\text{fed}} = \frac{4}{3}\pi^2 \frac{n_1(1 - n_1{}^2)^2}{\lambda_0^3} 2L_d S\Gamma, \tag{3}$$

where L_d is the decay length of the guided mode into the bottom cladding and Γ is the partial confinement factor, i.e., the overlap integral between $\zeta^2(z)$ and the underetched air hole region.

The same phenomenological approach is used here to model disorder-induced radiation losses. Positional and geometrical in-plane disorder are considered [see Figs. 1(b) and 1(c)]. In this case out-of-plane losses
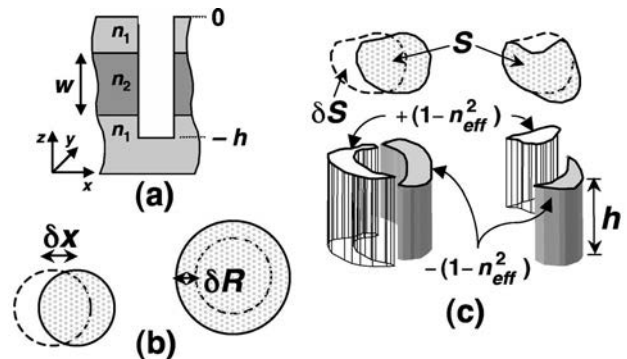

Fig. 1. Schematic of (a) a planar PhC etched through a vertical waveguide with a refractive index profile $n_1/n_2/n_1$ (w, core thickness; h, hole depth); (b) and (c) In-plane positional (left) and geometrical (right) disorder effects (x and R, hole position and radius; S, area of the hole cross section). The perturbation with respect to the periodic lattice is represented by plugs of dielectric constant $\pm(1 - n_{\text{eff}}^2)$ that extend down to the hole bottom h with a cross-section area δS.

can be evaluated considering the actual PhC as the sum of an ideal periodic array of evenly shaped holes plus a dielectric perturbation $\delta\epsilon = \pm(1 - n_{\mathrm{eff}}^2)$ that extends down to the hole bottom h with a cross-section area of $\delta|S| = 4R\,\delta x$ and $2\pi\delta R$ for positional and size (uniform expansion) disorder, respectively [see Fig. 1(b)]. The same approach as in Refs. 5 and 6 is adopted (see Appendix A), yielding

$$\epsilon_{\mathrm{dis}}'' = \frac{4}{3}\pi^2 \frac{n_{\mathrm{eff}}(1 - n_{\mathrm{eff}}^2)^2}{\lambda_0^3} w_{\mathrm{eff}} S \left(\frac{\delta|S|}{S}\right)^2 (1 - \Gamma)\eta'. \quad (4)$$

Moreover, for most etching techniques, h almost overlaps with the entire $\zeta(z)$, so that $\Gamma \ll 1$, $\epsilon_{\mathrm{fed}}''$ becomes negligible, and $1 - \Gamma \approx 1$.[7]

To validate the present model, planar PhCs consisting of a triangular lattice of air holes were etched through a nominally undoped GaAs-based vertical waveguide grown by molecular beam epitaxy ($w = 240$ nm).[8] At the wavelengths of interest [$\lambda_0 \approx 1050$ nm: $n_1 = 3.39$ (upper cladding) and 3.06 (bottom cladding), $n_2 = 3.48$] the effective refractive index of the fundamental transverse-electric (TE) guided mode is $n_{\mathrm{eff}} = 3.36$. Moreover, $w_{\mathrm{eff}} \approx 650$ nm, $L_d = 100$ nm, and $\Gamma_1 = 0.55$,[5] while $\eta \approx 0.50$ and $\eta' \approx 0.04$. The PhC structures were fabricated by electron beam lithography and reactive ion etching.[8] Simple eight-rows-thick PhC slabs were fabricated with a lattice period $a = 190-370$ nm ($\Delta a = 20$ nm) and $h \approx 1$ μm (i.e., $\Gamma \approx 10^{-4}$).[6] A strong in-plane disorder was deliberately introduced without any intentional disorder in the vertical direction by a nonoptimized transfer of the PhC pattern from the e-beam-written resist to the SiO_2 mask[8] [see the top and edge scanning electron microscopy (SEM) micrographs in the inset of Fig. 2(a)]. By using an internal light source technique[9] the absolute transmission through the PhC structures was measured along the ΓM direction as a function of the normalized frequency $u = a/\lambda_0$. The ΓM transmission spectrum is shown in Fig. 2(a) (solid curves) for the TE polarization. It was fitted by a 2D finite-difference time domain (2D-FDTD) model assuming n_{eff} as the matrix index.[9] Out-of-plane losses were included in the 2D model by adding ϵ'' in the holes.[6] The fit parameters were the air filling factor f and ϵ'', and the calculated spectra are shown in Fig. 2(a) (gray dotted curves). The values $f = 0.32 \pm 0.02$ (i.e., $S \approx 2 \times 10^4$ nm^2 for $a = 270$ nm) and ϵ''[exp.] $= 0.11 \pm 0.01$ were found. The latter value agrees well with the theoretical value ϵ''[th.] $= 0.115 \pm 0.005$ obtained from Eqs. (1)–(4) (see Table 1). The amount of disorder $\delta|S|/S = 0.2$ was found by the 2D Fourier analysis of the top SEM micrograph in Fig. 2(a), which allows the extraction of its both periodic and disordered components [Figs. 2(b) and 2(c), respectively]. Once the micrograph has been digitalized, the inverse transform of the periodic part of its Fourier transform yields the periodic PhC pattern, while the disordered component is obtained by subtracting the latter pattern from the total image. The very good agreement between the theory and the
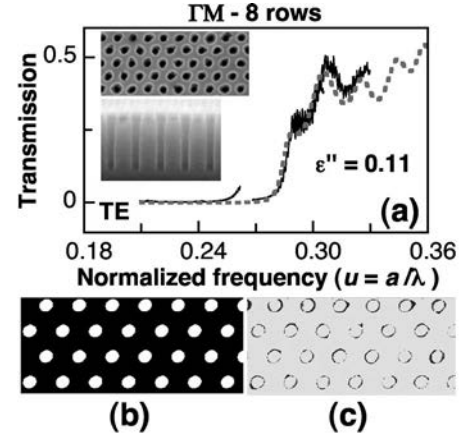

Fig. 2.   (a) Measured (solid curves) and calculated (gray dotted curves) ΓM transmission spectra through eight-row-thick disordered PhC slabs for TE polarization: the value of the loss parameter ϵ'' is reported; the inset shows the top and edge SEM micrographs. (b) Periodic and (c) and disordered components of the top SEM image.

Table 1. Calculated and Measured Radiation Losses

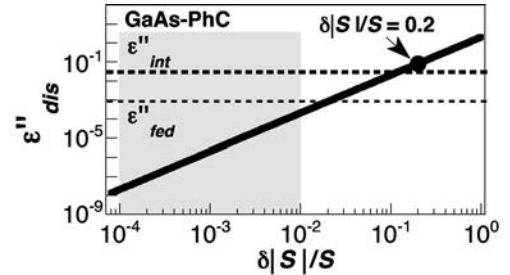|	Theory			Experiment
$\epsilon_{\mathrm{inf}}''$ [a]	$\epsilon_{\mathrm{fed}}''$	$\epsilon_{\mathrm{dis}}''$	ϵ'' [th.]	ϵ'' [exp.]
0.035 ± 0.005	0.001	0.08	0.115 ± 0.005	0.11 ± 0.01

[a] From Eq. (2) and Ref. 5.

Fig. 3.   Disorder-induced losses ($\epsilon_{\mathrm{dis}}''$) as a function of the disorder parameter $\delta|S|/S$ for GaAs-based PhCs. Circle: the disordered PhC shown in Fig. 2. Dotted lines and gray region: $\epsilon_{\mathrm{int}}''/\epsilon_{\mathrm{fed}}''$ and $\delta|S|/S$ values, respectively, for the present fabrication techniques of GaAs-based PhCs.

experiments validates the use of this model for the study of disorder-induced losses in planar PhCs.

In Fig. 3, Eq. (4) is plotted as a function of the disorder parameter $\delta|S|/S$ for the investigated GaAs-based PhCs, thus providing a figure of merit for the minimization of the disorder contribution with respect to the other loss sources. The filled circle in Fig. 3 corresponds to the disordered PhC of Fig. 2 (i.e., $\delta|S|/S = 0.2$). The dotted lines in Fig. 3 indicate the values of $\epsilon_{\mathrm{int}}''$ and $\epsilon_{\mathrm{fed}}''$ calculated from Eqs. (2) and (3), respectively, for the best fabrication technologies presently available for GaAs-based PhCs (see also Table 1). These technologies also guarantee that $\delta R/R \approx 1\%$ and $\delta x/x \lesssim 0.5\%$.[10] Thus for typical GaAs-based structures ($a = 200-400$ nm and $f \approx 0.3$, i.e., $R \approx 60-120$ nm), $\delta|S|/S$ ranges from 10^{-4} to 10^{-2} for the

geometrical and positional disorder, respectively (the gray region in Fig. 3).[10] This results in disorder-induced losses that are negligible with respect to both intrinsic ($\epsilon''_{\text{dis}} \ll \epsilon''_{\text{int}}$) and depth-induced ($\epsilon''_{\text{dis}} < \epsilon''_{\text{fed}}$) losses.

In conclusion, a quantitative analysis of disorder-induced losses in low-refractive-index-contrast planar PhCs has been presented. For the present fabrication techniques of GaAs-based PhCs the disorder-induced contribution is found to be negligible with respect to the other loss mechanisms. Concerning high-refractive-index-contrast planar PhCs, we note that, to our knowledge, while there are several papers dealing with propagation losses in membrane-like line-defect waveguides with disorder,[11] little work has been done on simple PhC slabs on membranes. We believe that in such systems our phenomenological approach may be applicable and relevant for broad families of 2D PhC bands for which the assumptions on light extraction[5] are still valid and no singularity is present. These include low group-velocity modes above the light line (some of them having indeed low intrinsic losses near the Γ point due to cancellations that vanish in the presence of disorder). Nevertheless, based on the work on waveguides,[12,13] the case of slow group-velocity modes below the light line should be treated separately.

Appendix A

Disorder-induced out-of-plane losses are generated by the radiation of the polarization $P(x,y,z) = \pm \epsilon_0 (1 - n^2_{\text{eff}}) E(x,y,z) dx dy dz$ [where $E(x,y,z) = \psi(x,y)\zeta(z)$ is the separable electric field].[5,6] Following Ref. 6, the power radiated in the homogeneous medium of refractive index n_{eff} and then lost into the claddings can be written as[5,6]

$$P_{\text{rad}} = \frac{4}{3}\pi^3 \frac{c}{\lambda_0^4} \epsilon_0 n_{\text{eff}} (1 - n^2_{\text{eff}})^2$$
$$\times S\left(\frac{\delta|S|}{S}\right)^2 \int\int_S \psi^2(x,y)dx dy \left[\int_{-h}^0 \zeta(z)dz\right]^2 \eta',$$
(A1)

where c and ϵ_0 are the vacuum light speed and dielectric constant, respectively, and $\eta' \cong 1 - \cos\theta'$ [with $\theta' = \arcsin(1/n_{\text{eff}})$] is the extraction coefficient from the waveguide slab to the air. The approximation

$$\left[\int\int_{\delta S} \psi(x,y)dx dy\right]^2 \cong S(\delta|S|/S)^2 \int\int_S \psi^2(x,y)dx dy$$

is made.[6] The disorder-induced losses per hole can be represented as the dissipated power[5,6]

$$P_{\text{diss}} = \frac{1}{2}\epsilon_0 \frac{2\pi c}{\lambda_0} \epsilon''_{\text{dis}} \int\int_S \psi^2(x,y)dx dy \int_{-\infty}^{+\infty} \zeta^2(z)dz.$$
(A2)

Finally, for $h \gg w + L_d$, the effective width of the guided mode can be defined as

$$w_{\text{eff}} \cong \left[\int_h^{+\infty} \zeta(z)dz\right]^2 \Big/ \int_h^{+\infty} \zeta^2(z)dz$$
$$\cong \left[\int_{-\infty}^{+\infty} \zeta(z)dz\right]^2 \Big/ \int_{-\infty}^{+\infty} \zeta^2(z)dz.$$

Thus equating Eqs. (A1) and (A2) yields Eq. (4).

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