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Giant field localization in 2-D photonic crystal cavities with defect resonances: Bringing nonlinear optics to the W/cm^2 level

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We investigate the field localization properties in a 2-D photonic crystal cavity with defect resonances. Although based on a simple geometry, these resonances achieve extremely high quality (Q)-factors $\sim 10^8$. We provide an example of a chalcogenide glass (As_2S_3) photonic crystal cavity where all-optical switching at telecommunication wavelengths can be obtained for input intensity $\sim \text{W}/\text{cm}^2$ and local field intensity in the crystal well below the photodarkening threshold of the material. Copyright 2012 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1063/1.4739270>]

I. INTRODUCTION

The ability to confine light in extremely small volumes is crucial for enhancing many light-matter interaction phenomena such as surface enhanced Raman scattering,¹ quantum-dot² and quantum-well emission.³ Unfortunately light, differently from electrons for example, is difficult to localize in small volumes $\sim \lambda^3$ where λ is its wavelength, especially if long dwell times are necessary to enhance the interaction. In the last two decades a new class of materials has opened innovative venues to enhance light-matter interactions and in general to achieve photonic systems to manipulate light in an unprecedented way. Known as photonic crystals (PCs) or photonic band gap structures (PBGs),^{4–8} these materials can in general be described as structures in which scattering or diffracting elements are periodically arranged in such a way that their mutual distance is comparable with the wavelength of the incident light giving rise to allowed and forbidden band for photons in essentially the same way that semiconductors do for electrons. Among their numerous applications, we cite for example photonic crystal fibers,⁹ photonic crystal circuits¹⁰ and photonic crystal super-prism structures.¹¹ Regarding light confinement, 3-D PCs, such as “woodpiles”¹² or inverse opals,¹³ would be in principle the true way to arrive at a full localization, nevertheless they are in general difficult to fabricate. A viable alternative is to resort to 2-D PCs,^{14,15} i.e. structures made by periodically perforating a slab of dielectric material, although in this latter case only in-plane light confinement can be achieved and therefore out-of-plane losses may sensibly reduce the overall quality (Q)-factor of the resonances.^{16–18} In this paper we propose an extremely simple, yet powerful, design to achieve defect resonances in a 2-D PC cavity with extremely high Q-factor $\sim 10^8$. As an example we study a PC cavity made of a chalcogenide glass (As_2S_3). Chalcogenide glasses are characterized by high cubic nonlinearities and low two-photon absorption which makes them optimal candidates for all-optical switching devices^{19–23} in the telecommunication band. In particular we show the concrete possibility to achieve all-optical switching for input intensities at the W/cm^2 level and local field intensity in the PC well below the photodarkening threshold of the material.²⁴ We remark that although 2-D photonic crystal cavities have been widely studied in the past,¹⁵ our design is characterized by an extreme simplicity and moreover, as we will see in the following, defect

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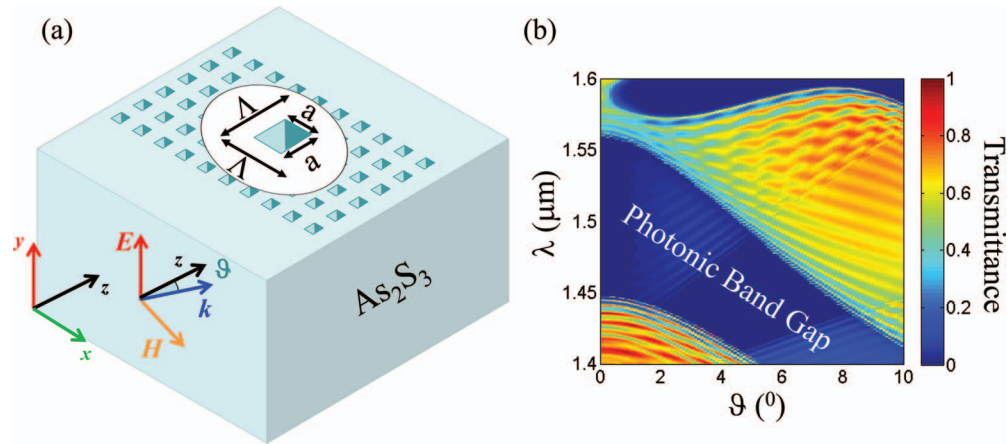


FIG. 1. (a) 2-D PC slab made of As_2S_3 for in-plane coupling of the incident radiation, i.e. the $\mathbf{k}$ -vector of the incident wave lies parallel to the (x,z) plane and forms an angle ϑ with the z axis. The PC is made by drilling holes of square section $a \times a$ arranged in a periodic array with periodicity Λ on both directions. The polarization of the electric field is along the y -axis, parallel to the axis of the holes. In our case $a = 450$ nm, $\Lambda = 900$ nm. The PC slab is finite along the z direction and has total length $L = N\Lambda$ with $N = 30$ periods, it starts at $z = 0$ and ends at $z = L = 27 \mu\text{m}$. We consider As_2S_3 be the input medium ($z < 0$) as well as the output medium ($z > L$). (b) Transmittance at the output medium in the (λ, ϑ) plane.

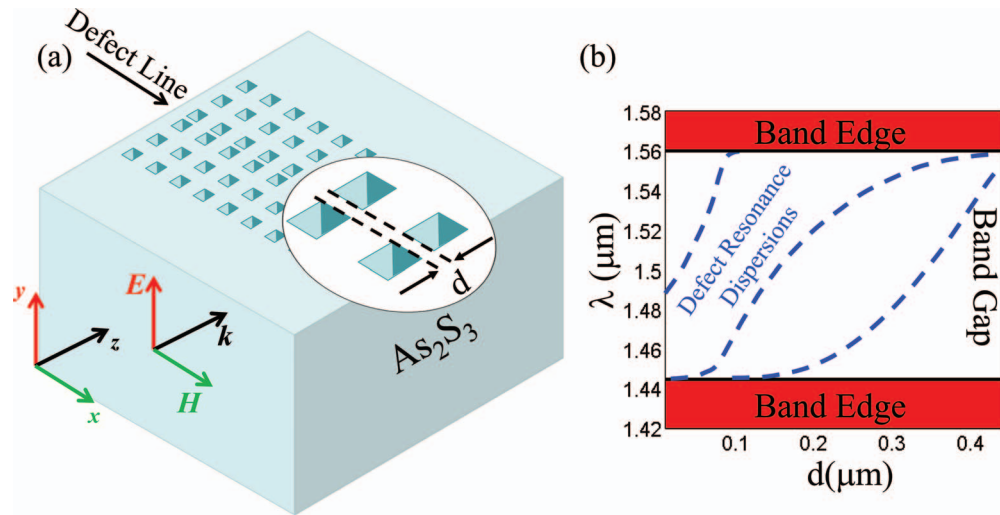


FIG. 2. (a) PC slab as in Fig. 1(a) but with a line defect of thickness d located at its center. (b) Dispersion at $\vartheta = 0$ of the defect resonances in the band gap vs. the defect thickness d .

resonances with consistent Q-factors can be achieved even when the holes filling factor is 50% or more. In Section II we detail the main results of our study followed by a discussion and in Section III we present our conclusions.

II. RESULTS AND DISCUSSION

We start our analysis by studying the transmitted power (transmittance) in the (λ, ϑ) plane for a 2-D PCs cavity as described in Fig. 1(a).

The numerical calculations have been performed by using an in house developed rigorous coupled wave theory, also called Fourier modal method (FMM), according to the recipe laid out in.²⁵ Fig. 2(b) shows that the structure admits a photonic band gap in the telecommunication range ($1.4 \mu\text{m}$ – $1.6 \mu\text{m}$), the refractive index of the As_2S_3 has been taken $n = 2.43$ according to the data reported in literature.¹⁹

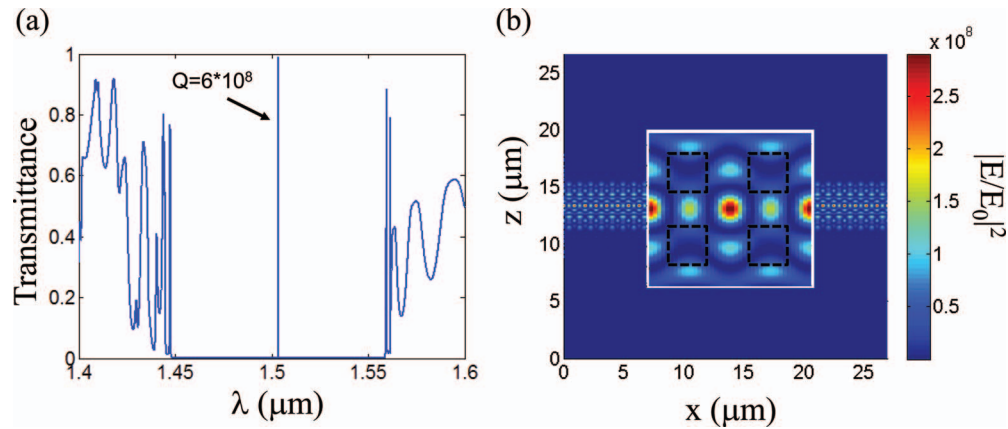


FIG. 3. (a) Transmittance at normal incidence vs λ for a PC slab with a line defect of thickness $d = 160$ nm. The defect resonance is located at the center of the gap with $Q = 6 \times 10^8$. (b) Cross sectional view of the electric field localization normalized to the incident field at the defect resonance. For the help of the eye, the inset shows a magnification of the field localization around the defect line. The black dashed squares indicate the position of the air holes.

In Fig. 2(a) we show the PC slab with a line defect of thickness d located at its center. It is noted that when $d = 450$ nm the structure degenerates into the perfect periodic one of Fig. 1(a). Fig. 2(b) shows the dispersion of the defect resonances in the band gap as function of the defect thickness d and it helps to design the appropriate structure tailored for our specific needs. We notice that at normal incidence and $d = 160$ nm the structure admits only one defect resonance located at the center of the band gap at $\lambda \sim 1.5 \mu\text{m}$.

Fig. 3(a) shows the transmittance vs. λ at normal incidence for the PC slab with a line defect of thickness $d = 160$ nm. As expected, and in complete agreement with the results of Fig. 2(b), we notice the sharp, Lorentzian line located at the centre of the band gap. The resonance possesses an extremely high quality factor $Q = 6 \times 10^8$. The Q has been calculated according to the standard formula $Q = \lambda/\Delta\lambda$ where λ is the central wavelength of the resonance and $\Delta\lambda$ its full width half maximum. In Fig. 3(b) we report a cross sectional view of the electric field localization, in particular the inset shows the detail of the field localization in a region around the defect line. It is noted the exceptionally strong energy squeezing along the defect line with peak field localization of the order of 3×10^8 . In Fig. 4(a) we show the transmittance vs. λ at normal incidence in the case of a thicker defect line ($d = 320$ nm). In this case the band gap contains two defect resonances, respectively characterized by a Q -factor of 1.6×10^8 and 4×10^6 . Figs. 4(b) and 4(c) report respectively the cross-sectional view of the field localization at the two resonances. In particular in Fig. 4(b) it is shown the field localization for the resonance with $Q = 1.6 \times 10^8$. It is noted that in this case the maximum field localization lies outside the defect line in contrast with the field localization of Fig. 3(b).

In order to show the potentiality of these defect resonances, in Fig. 5 we present a nonlinear calculation performed on the defect resonance already described in Fig. 3(a).

In particular we use the cubic nonlinearity of As_2S_3 $n_2 = 2.9 \times 10^{-18} \text{ m}^2/\text{W}$ ¹⁹ to obtain all-optical switching for input intensity at the level of $\sim 1 \text{ W}/\text{cm}^2$ as shown in Fig. 5(b). The local field intensity in this case will not exceed $\sim 0.5 \text{ GW}/\text{cm}^2$, i.e. well below the photodarkening threshold of the material.²⁴ The nonlinear calculation has been performed by extending the FMM method to the nonlinear regime using a mean field approach similar to that one reported in.²⁶ It is now worthwhile to point out that our theoretical predictions lack the inclusion of losses found in fabricated structures, such as vertical leakage, roughness, and non-vertical walls. These factors could raise the switching threshold by a few orders of magnitude. Nonetheless we would like to remark that our structure still maintains high Q defect resonances even when the dimensions of the air holes are consistently increased. At this regard, in Fig. 6 we show the defect resonances for the same structure as described in Fig. 2(a) except that the air holes have now dimensions $a = 540$ nm (Fig. 6(a)) and $a = 630$ nm (Fig. 6(b)).

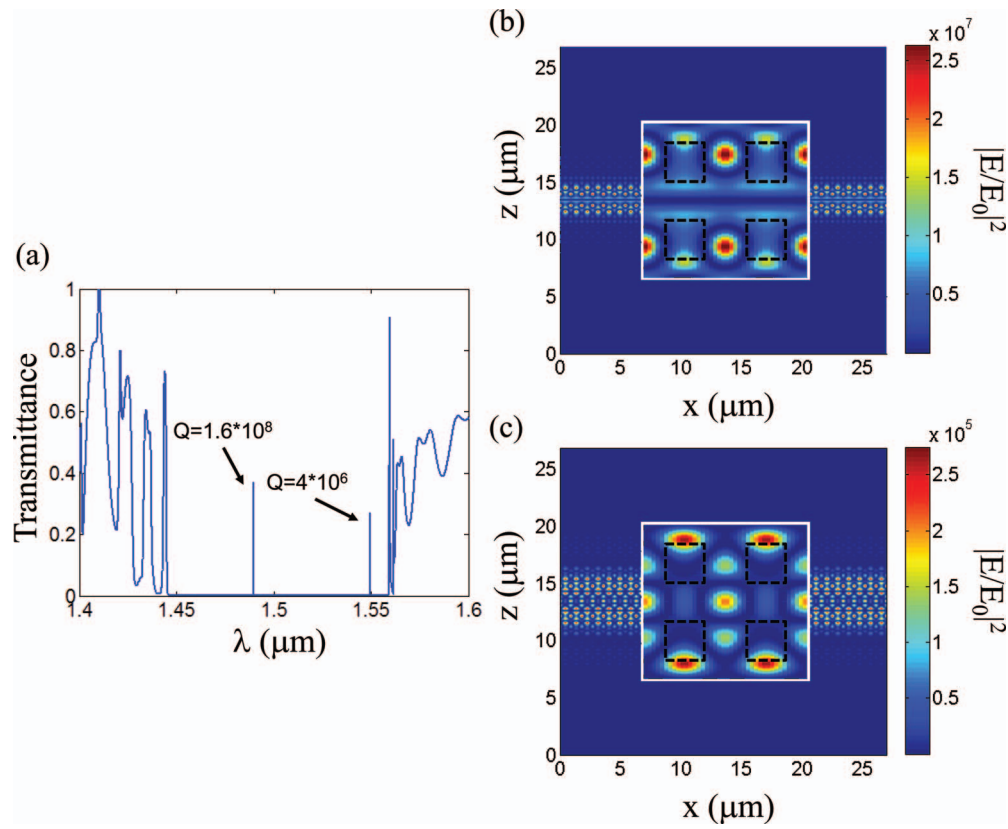


FIG. 4. Transmittance at normal incidence vs. λ for a PC slab with a line defect of thickness $d = 320$ nm. In this case there are two defect resonances in the gap respectively with $Q = 1.6 \times 10^8$ and $Q = 4 \times 10^6$. (b) Cross sectional view of the electric field localization normalized to the incident field at the defect resonance with $Q = 1.6 \times 10^8$. (c) Cross sectional view of the electric field localization normalized to the incident field at the defect resonance with $Q = 4 \times 10^6$. In both (b) and (c) the inset shows a magnification of the field localization around the defect line. The black dashed squares indicate the position of the air holes.

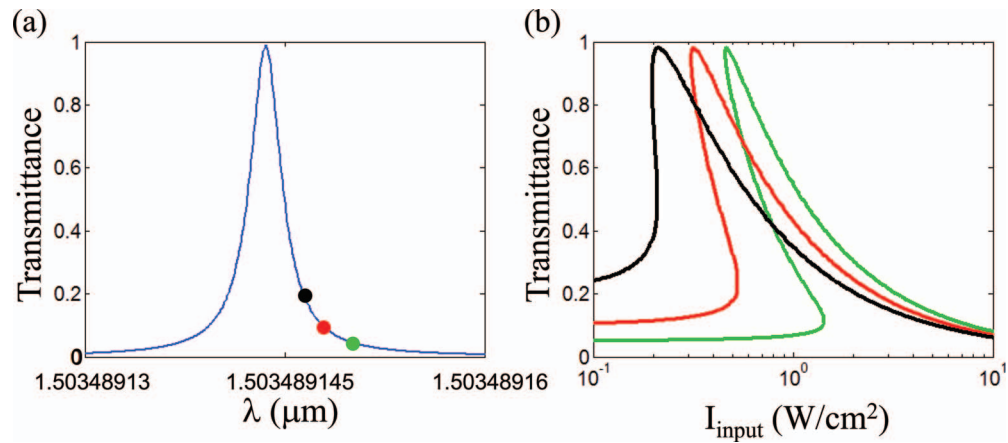


FIG. 5. (a) Magnification of the defect resonance of Fig. 3(a). The black, red and green dots respectively indicate the tuning condition of the impinging wave used for the nonlinear calculation. (b) Nonlinear transmittance vs. input intensity for the tuning conditions described in (a).

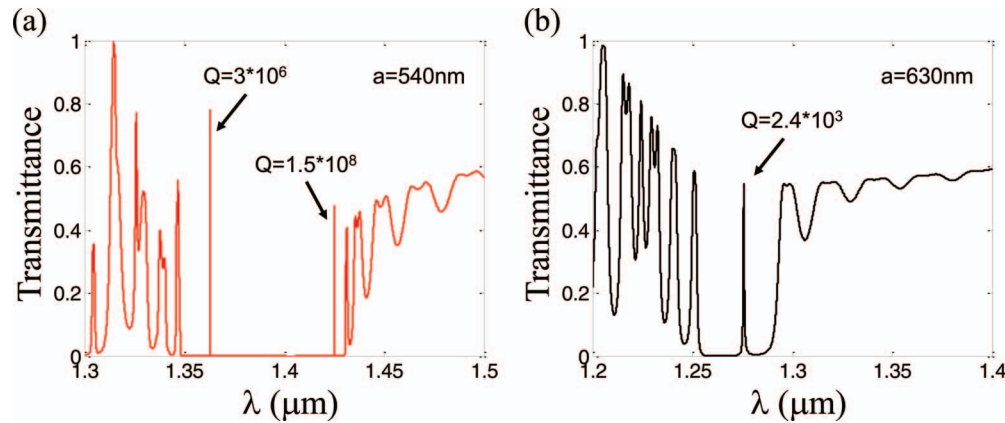


FIG. 6. Transmittance vs. wavelength at normal incidence for the same structure as described in Fig. 2(a) except that now the air holes have dimensions respectively $a=540\text{nm}$ (a) and $a=630\text{nm}$ (b). In the figures is also indicated the Q-factor of the defect resonances in the different cases.

The figures confirm that our structure is quite robust against an increase of the hole dimensions. Even in the extreme cases where the air filling factor reaches $\sim 50\%$ or more the structure still admits defect resonances with a consistent Q-factor.

III. CONCLUSIONS

In conclusion, we have studied the defect resonances in a 2-D photonic crystal slab and showed that extremely high Q resonances are available for nonlinear optical applications, even using simple designs to create the defect such as the one shown in this work. In particular we have presented the example of a 2-D PC made of a chalcogenide glass where all-optical switching is achieved at input power level of $\sim 1\text{ W/cm}^2$. Moreover, while here we have modeled, for simplicity, holes with square cross section, similar results are expected for holes with circular cross section of same area. A final note of caution is necessary at this point. As we have already made clear in the introduction, here we have studied the ideal case of perfect in-plane coupling. As a matter of fact, the absence of a complete band gap in the y-direction may cause out of plane energy leaking which ultimately hampers the efficiency of the defect resonance. Several designs have been suggested to mitigate this effect as reported in Refs. 16–18, for example. One way to avoid leakage might be to grow a multilayer omnidirectional reflector²⁷ on the top and on the bottom of the slab along the y-direction, for example. We may also expect that in the future more mature fabrication techniques will be available, allowing the deep perforation of the slab for many wavelengths which would therefore avoid once and for all the problem of out of plane leakage. Last, but not least, similar geometries could be explored in the THz regime. In this case, the structure, a slab of polymethylmetacrylate (PMMA) for example, should have a period of the order of $100\text{ }\mu\text{m}$, a defect line of thickness of the order of $15\text{ }\mu\text{m}$ and air holes of the order of $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$. The air holes can be fabricated by standard mechanical micro-drilling techniques, as in.²⁸ The mechanical method allows the precise and deep perforation of the slab reducing therefore out of plane leakage and providing extremely narrow defect resonances in the THz range for a variety of applications such as THz bio-sensing,²⁹ for example.

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