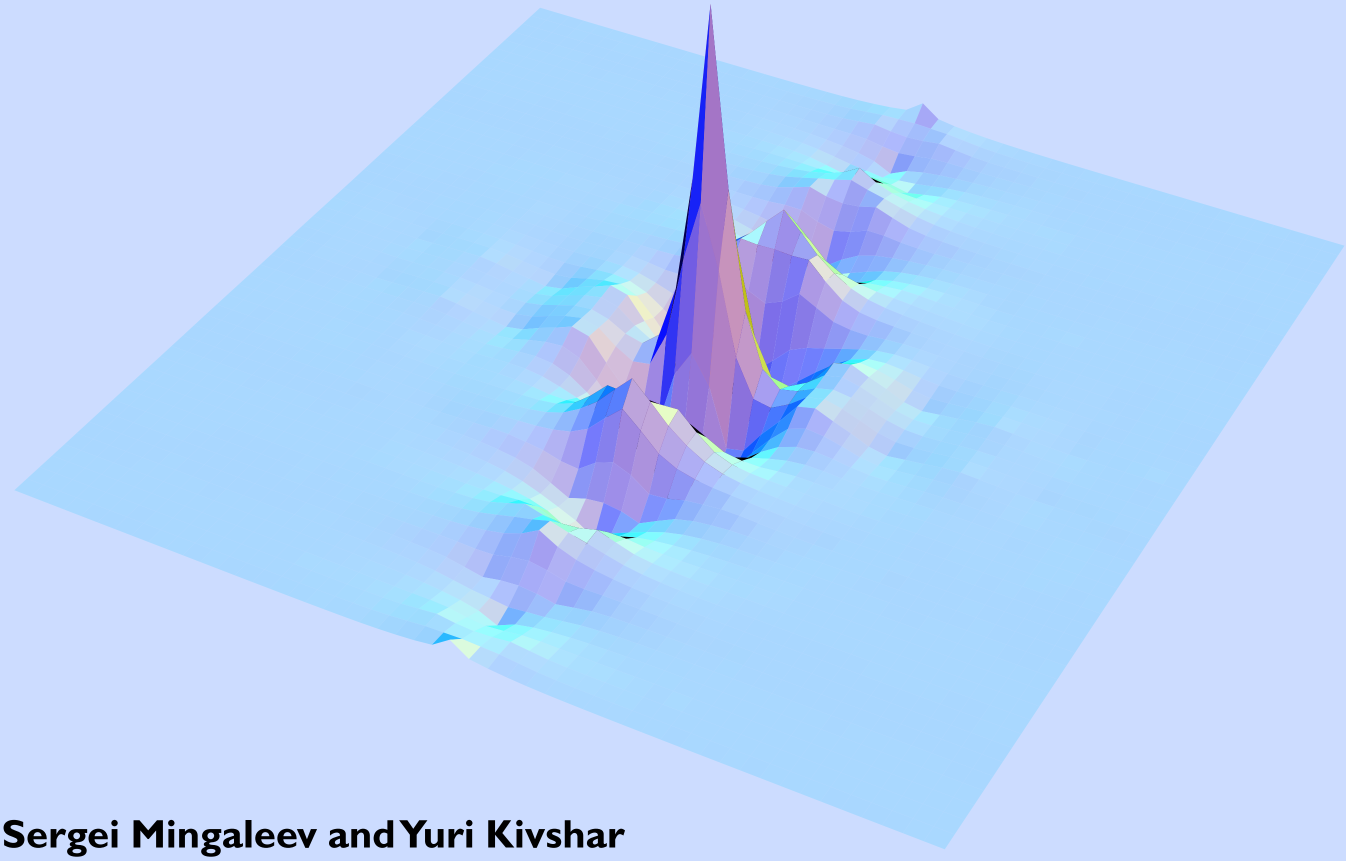
Nonlinear Photonic Crystals

Toward All-Optical Technologies



Sergei Mingaleev and Yuri Kivshar

Photonic crystals, an analog of semiconductors for light waves, are composite periodic dielectric materials that provide novel and unique ways to control many aspects of electromagnetic radiation. Harnessing the nonlinear properties of photonic crystals and photonic-crystal waveguides offers an opportunity to create the all-optical analogs of diodes and transistors that will one day enable the first all-optical computer to be built.

For the past 50 years, the physics of semiconductors has played a vital role in information and communication technologies. Advances in the development of semiconductor heterostructures and integrated electronic circuits, underlined by the award of the first Nobel Prize of the New Millennium to Zhores I. Alferov, Herbert Kroemer, and Jack S. Kilby, led to the information technology revolution that has reshaped society. The advances achieved during the past decade suggest that the use of a new class of materials—*photonic crystals*—provides a way to achieve similar goals with light alone.[1–4] However, the analogy between semiconductors and linear photonic crystals cannot be pushed too far inasmuch as photons, in contrast with electrons, are not easily tunable. For this reason, it is crucial to turn to photonic crystals made of nonlinear materials, the transmission changes of which depend on the intensity of light. The unique properties of photonic-crystal waveguides and waveguide circuits formed in nonlinear photonic crystals would allow the creation of ultimate fast and compact all-optical switching devices with which light can be used for the manipulation and control of light itself.

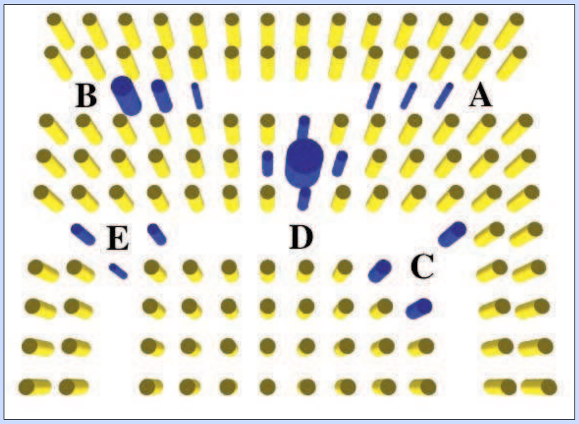


Figure 1. A photonic-crystal circuit with a set of embedded nonlinear defects (blue): A, symmetric and B, asymmetric optical filters; C, waveguide bend; D, channel drop filter; E, waveguide branch.

Switches, limiters, and optical diodes

To illustrate the basic ideas of nonlinearity-induced waveguide transmission, we consider the example of a two-dimensional (2D) photonic crystal created by a square lattice of dielectric rods. Such a crystal, recently fabricated in macroporous silicon[5] with a lattice period of $a = 0.57\mu\text{m}$ and a rod radius of $r = 0.18a$, has a large bandgap: the light with wavelengths between $2.26a$ and $3.31a$ cannot pass through the photonic crystal and thus is completely reflected. Removing a row of rods, one can create a customized photonic-crystal waveguide that can be used to guide light with wavelengths that are inside the bandgap. The transmission efficiency of such waveguides is high even for sharp bends.[6] Combining the waveguides with the embedded defects (installed or removed dielectric rods that break the perfect periodicity of the structure), one can create photonic-crystal circuits (see Fig. 1). The transmission properties of these photonic circuits can be accurately described by the effective discrete equations with long-range interactions.[7,8] Such photonic-crystal circuits can be used as sophisticated optical filters (some examples are shown in Fig. 1). If we do not take account for the nonlinear properties of photonic-crystal circuits, they cannot be used for all-optical signal processing. The nonlinearity of optical materials is essential if we wish to create nonlinear devices such as optical diodes, transistors, switches, and limiters. Let us assume that defects in a photonic-crystal circuit are made of a Kerr-type nonlinear dielectric (blue rods in Fig. 1). In this case, even the simplest system of identical nonlinear rods (device A in Fig. 1) exhibits bistable transmission.[9,10] The transmission of an asymmetric set of nonlinear defects (device B in Fig. 1), which does not depend on the propagation direction for low-intensity light, becomes highly asymmetric in the vicinity of resonant frequencies for large light intensities. Properly designed, such an asymmetric system can be used as an optical diode that exhibits unidirectional pulse propagation.[9]

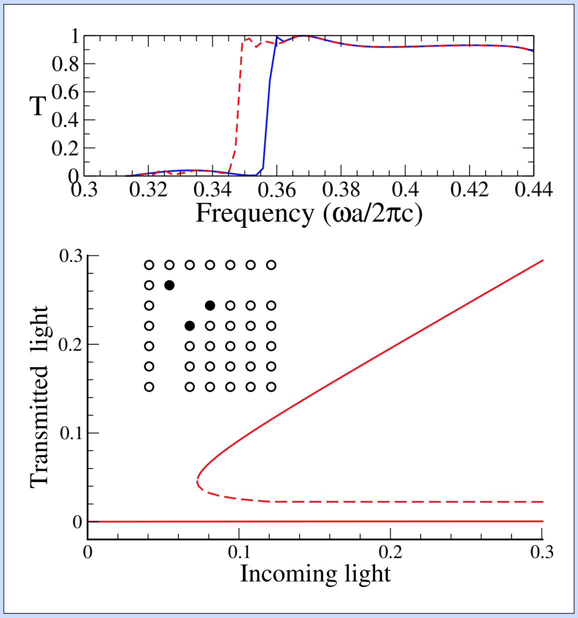


Figure 2. (*Top*) Transmission of a waveguide bend with three embedded nonlinear defects in the linear (solid) and nonlinear (dashed) regimes. (*Bottom*) Nonlinearity-induced bistable transmission through the waveguide bend shown in the inset (stable branches are represented by solid curves).

To gain better insight into the physics of nonlinear transmission and to demonstrate the significant potential of nonlinear devices based on photonic-crystal technology, we briefly discuss an example of a waveguide bend with three embedded defects made of Kerr-type nonlinear material with a dielectric constant of ε=7 (device C in Fig. 1). In the linear regime, this bend behaves as an optical threshold device that efficiently transmits guided waves with frequencies above the threshold frequency but completely reflects the waves with lower frequencies, as is shown in Fig. 2 (top) by the solid blue curve. When the light intensity increases, the threshold frequency decreases, which extends the transmission region [a red dashed curve in

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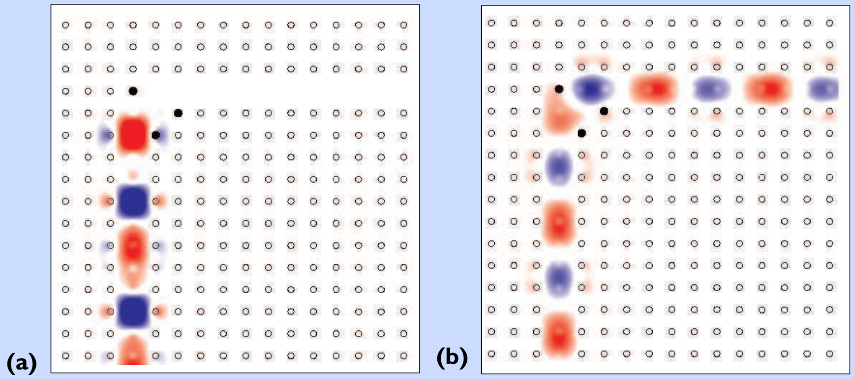

Figure 3. (a) Nonlinearity-induced reflection and (b) 100% transmission in an optical gate created by a bent waveguide with nonlinear defect rods (three black circles) as shown in Fig. 2.

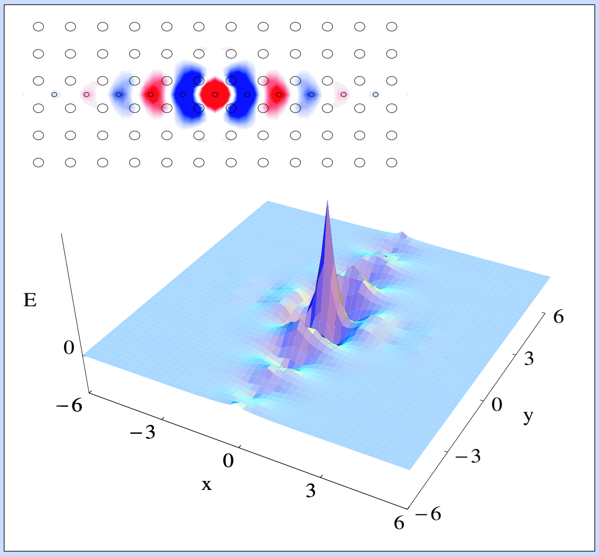

Figure 4. Top and 3D view of a nonlinear localized mode—discrete soliton—excited in a nonlinear photonic-crystal waveguide.

Fig. 2 (top)]. The resulting transmission as a function of input intensity [see Fig. 2 (bottom)] demonstrates a sharp nonlinear threshold character with an extremely low transmission of waves below a certain threshold intensity [see Fig. 3(a)], and the possibility of switching to a state with nearly 100% transmission above the threshold intensity [see Fig. 3(b)], so that the bend behaves as a tunable all-optical gate. Thus, effective nonlinearity-induced bistable transmission can be realized in basically linear photonic crystals with some nonlinear elements that can be used to control the resonant light transmission by a variation of the input light intensity. Other types of nonlinearity-induced bistable light transmission and switching have also been explored recently.[9, 10]

Discrete solitons as information carriers

Although the photonic-crystal circuits discussed above exhibit many interesting nonlinear transmission properties, their fabrication is hampered by the need to embed nonlinear impurities into an otherwise linear photonic crystal. This impediment can be obviated by fabrication of a complete photonic crystal from a single piece of nonlinear dielectric material. Moreover, this approach makes possible unique opportunities, such as the creation of nonlinear photonic-crystal waveguides. In this case, the nonlinear response of an optical material can lead to the self-localization of light in the form of nonlinear localized modes or discrete solitons,[11] and it would allow for the creation of almost ideal waveguide circuits for discrete soliton networks.[12] A simple example of the nonlinear photonic-crystal waveguide that carries nonlinear localized modes is shown in Fig. 4. Here the waveguide is created by the introduction of a row of additional rods of smaller radius into an otherwise perfectly periodic photonic crystal. All the rods are made from the same nonlinear dielectric material. The modes excited in such a waveguide can be localized along the waveguide direction and can remain trapped in the transverse direction because of Bragg reflection. Such a localized mode corresponds to a discrete spatial soliton.

By appropriate design, such as modification of the guiding properties of the corner bend of the waveguide, reflection losses that occur along very sharp bends (e.g., less than 90°) in 2D discrete soliton networks can be almost eliminated.[12] We could effectively achieve this result by introducing nonlinear defects at the bend corner, similar to the transmission shown in Fig. 2. In addition, by use of vector–incoherent interactions at network junctions, soliton signals can be routed at will on specific pathways.[13] In this way, the discrete solitons can be navigated anywhere within a 2D network of nonlinear waveguides. The possibility of realizing useful functional operations such as blocking, routing, logic functions, and time gating has recently been discussed in Refs. 12 and 13. By appropriate engineering of the intersection site, we could also improve the switching efficiency of the junctions in 2D discrete-soliton networks, which would allow us to design routing junctions with specified operational characteristics.

Quadratic photonic crystals

Nonlinear optics is traditionally discussed in terms of separate effects of quadratic [second-order or $\chi^{(2)}$] and cubic [third-order or $\chi^{(3)}$] nonlinearities. For example, $\chi^{(2)}$ the nonlinearity of noncentrosymmetric nonlinear crystals is responsible for such important optical effects as frequency conversion and optical parametric amplification, whereas $\chi^{(3)}$ nonlinearity is usually associated with the intensity-dependent refractive index (i.e., due to the Kerr effect), self-phase modulation, self-focusing, and optical solitons. Research in recent years has demonstrated that these two classes of optical effects could actually merge. In particular, it has been shown that $\chi^{(2)}$ nonlinearity could lead to strong ultrafast self-phase modulation through the cascading effect when the fundamental wave and its second harmonic are nearly phase matched. Such cascade nonlinearities are known to allow for many of the important optical effects—including soliton generation and propagation—that resemble the light self-action effects in $\chi^{(3)}$ media possible at much lower input powers.[14] These novel possibilities have led to increased interest in the application of $\chi^{(2)}$ materials in all-optical signal processing.

Frequency mixing and generation is the important area in which photonic crystals can play a crucial role in cascading effects. For the quasi-phase-matching (QPM) technique, (a method for achieving phase matching between two or more optical harmonics), the importance of periodic structures is well known. A traditional QPM technique relies on 1D periodic modulation (with a period equal to the beat length) of the nonlinear second-order susceptibility, to compensate for mismatch between the wave vectors of the collinear fundamental and second-harmonic waves. Using nonlinear photonic crystals with 2D or 3D periodic modulation of $\chi^{(2)}$ susceptibility allows one to extend this concept into higher dimensions, as was recently predicted theoretically[15] and demonstrated experimentally,[16] for the first example of a 2D QPM nonlinear structure with hexagonal symmetry created in lithium niobate. Such a quadratic nonlinear photonic crystal allows for efficient (>60%) second-harmonic generation that uses multiple reciprocal lattice vectors of the lattice. More importantly, such 2D $\chi^{(2)}$ nonlinear structures can also provide an efficient means of simultaneous phase matching of several wavelengths,[17] which paves the way for experimental verification and practical implementation of the theoretical concepts based on parametric multistep cascading.[18,19]

Figure 5 shows an expanded view of the 2D quadratic nonlinear photonic crystal fabricated by Broderick *et al.*[16] Each hexagon in a plane is a region of domain-inverted material; the total inverted area comprises 30% of the overall sample area. Poling was accomplished by applying an electric field through liquid electrodes on opposite faces at room temperature. This kind of quadratic photonic crystal has a period that is suitable for noncollinear frequency doubling of 1536 nm, and it also allows for efficient quasi-phase-matched second-harmonic generation by use of multiple reciprocal lattice vectors of the crystal lattice. The second-harmonic light can be simultaneously phase matched by multiple reciprocal lattice vectors, resulting in the generation of multiple coherent beams.

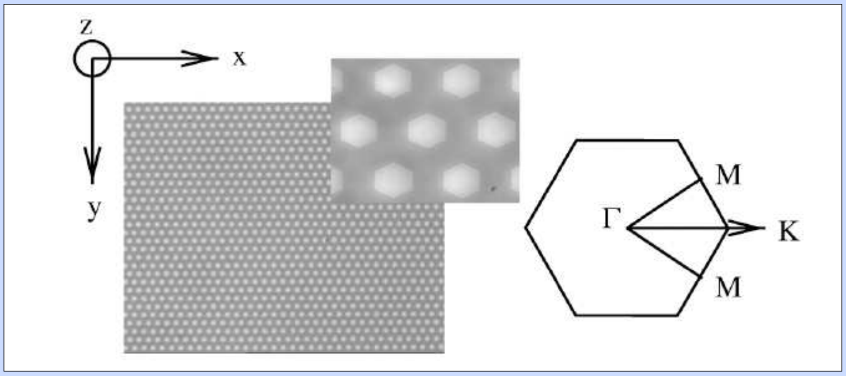

Figure 5. Hexagonally poled lithium niobate crystal and the first Brillouin zone. The period of the crystal, 18.05 μm, is uniform over the whole sample.[16]

Strictly speaking, such structures do not fit the classical definition of a photonic crystal[1] because they do not possess a bandgap in the limit of small intensities. However, the frequency spectrum gap is not crucial for the observation of many properties of nonlinear photonic crystals such as harmonic generation, and quadratic nonlinear crystals seem to be most suitable for the observation of numerous effects based on phase-matched parametric interaction. The technique is extremely versatile and allows for the fabrication of a broad range of 2D quadratic crystals, including quasi-crystals.

Concluding remarks

Many frontiers in this field remain to be explored. The use of nonlinear photonic crystals in all-optical devices and circuits is being actively researched from the viewpoint of both exciting fundamental physics and important industrial applications. We are fascinated by the enormous potential offered by the photonic-crystal concept: Many of the effects studied 10-15 years ago in nonlinear physics and nonlinear guided-wave optics can base their unique and unexpected manifestations on these novel materials. In particular, photonic crystals seem to be an ideal material for which many properties of discrete optical solitons can be engineered in a simple way. The slow group velocity of light in photonic-crystal circuits can dramatically increase the accumulated nonlinear phase shifts that are required for the efficient performance of an all-optical switch,[20] which should lead to a decrease in the size of many photonic devices that operate at much lower power. These advantages could be employed to design extremely small all-optical logical gates that could use readily available materials. It might also be possible to combine several thousands of such devices onto a chip of a few square centimeters.

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The references to this article appear on page 62, OPN's reference page.

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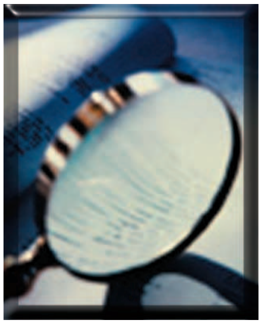

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