

Toward photonic-crystal metamaterials: Creating magnetic emitters in photonic crystals

M. L. Povinelli,^{a)} Steven G. Johnson, and J. D. Joannopoulos

Department of Physics and the Center for Materials Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

J. B. Pendry

Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BU, United Kingdom

(Received 19 November 2002; accepted 11 December 2002)

In this work, we explore the possibility of designing photonic crystals to act as magnetic metamaterials: structures that exhibit magnetic properties despite the nonmagnetic character of their constituents. The building blocks of a magnetic material are microscopic magnetic dipoles, and to create a synthetic analog we employ point-defect modes in a photonic crystal. We begin by identifying a point defect mode in a three-dimensional crystal whose local field pattern resembles an oscillating magnetic moment. By analyzing the far-field pattern of the field radiated from the defect, we prove quantitatively that such modes can be designed with a primarily magnetic character: over 98% of the emitted power goes into magnetic multipole radiation. Unlike the constituents of natural para- and ferromagnetic materials, these synthetic magnetic emitters can be designed to operate without losses even at optical frequencies. © 2003 American Institute of Physics.
[DOI: 10.1063/1.1544428]

The concept of designing electromagnetic “metamaterials,” synthetic structures that exhibit effective properties different from those of their constituent materials, has sparked interest as a means of achieving physical behaviors not found in naturally occurring materials or composites. The realization of negative refraction, for example, may allow for a class of optical effects and devices.^{1–3} Here we consider how metamaterials can be constructed within a photonic-crystal system. Previous work in two-dimensional (2D) systems has developed an effective medium theory to show that magnetic resonances can lead to a negative effective magnetic permeability, or μ .⁴ Here, we use point-defect modes to create magnetic resonances in a three-dimensional (3D) photonic crystal. Photonic crystals are periodic dielectric structures with a forbidden frequency range, the band gap, in which light cannot propagate. For frequencies in the gap, light is confined near defects in the structure, which can be designed to have desired frequency and polarization characteristics. We suggest that these defects might be used as building blocks for a type of metamaterial: photonic crystals with combinations of point defects chosen to give rise to various, desired properties. In this letter, we identify building blocks for obtaining magnetic behavior in a nonmagnetic dielectric system, quantitatively demonstrating that point-defect modes can be designed to have a magnetic character.

We choose a three-dimensional photonic-crystal structure that is composed of a stack of alternating layers that mimic 2D TE- and TM-polarized photonic crystals. By creating defects in these layers, the local field pattern and symmetry of the state can be made to resemble either an oscillating magnetic or electric moment, corresponding to the TM

and TE polarizations, respectively. In this letter, we focus on a point defect that resembles a magnetic moment. We show that such a defect can be incorporated into a finite crystal so that the structure becomes a magnetic emitter: nearly all of the radiated power goes into magnetic, rather than electric, multipole terms, as determined by a multipole decomposition of the far field. This magnetic emitter, unlike an oscillating current loop (a familiar magnetic dipole source), can be designed to operate even at optical frequencies, where naturally occurring materials have an insignificant or very lossy magnetic response. We believe that such defects are promising building blocks for constructing a type of metamaterial that exhibits magnetic behavior in a previously inaccessible frequency range. Moreover, because the 3D crystal that we study also supports defect states that resemble electric moments, it could provide a useful infrastructure for designing metamaterials with ferroelectric-like properties.

The crystal structure that we study, described in detail in Ref. 5, has a large, complete, band gap of around 20% of the midgap frequency for Si/air structures, and is comprised of two types of alternating layers, rod layers and hole layers. Rod layers are formed by triangular lattices of dielectric rods in air, while hole layers are formed by triangular lattices of air holes in dielectric. It has been shown in Ref. 7 that defects can be designed to be almost completely TM or TE polarized in the midplane of the layer by working within a single rod or hole layer, respectively. In order to create a defect with magnetic character, we select the TE polarization (magnetic field perpendicular to the midplane of the layer) and increase the radius of a single hole from its bulk value of $0.414\bar{a}$ to $0.5\bar{a}$, where $\bar{a}$ is the nearest-neighbor spacing in either a hole or rod layer. Cross sections of the electromagnetic field mode for this defect in the bulk crystal, computed in the standard manner,⁶ are shown in Fig. 1. The defect mode resembles the field of an oscillating magnetic moment

^{a)}Electronic mail: mpovinel@mit.edu

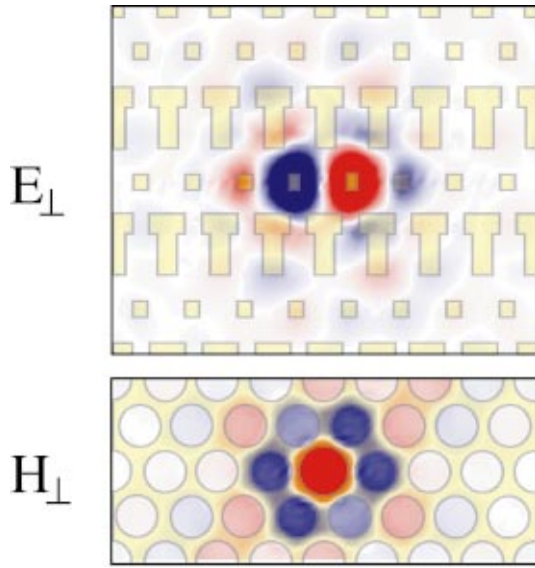


FIG. 1. (Color) Electromagnetic mode profiles for a magnetic-moment-like point defect in a 3D photonic crystal structure. The top and bottom pictures show, respectively, the electric and magnetic field components perpendicular to the plane. Red represents negative values and blue represents positive values; white corresponds to zero. The color map has been exaggerated. Yellow shading indicates dielectric material.

in several respects. The magnetic field in the midplane is almost completely (99%) polarized perpendicular to the plane,⁷ and the parity of the state is odd under inversion (the electric field is odd, while the pseudovector magnetic field is even). Moreover, the local field pattern of the mode resembles that of an ideal dipole, with some additional structure induced by the photonic crystal.

To determine the degree of magnetic character of the mode, we studied the properties of radiation from such a defect in a finite crystal. The coupling of light into radiation modes will depend on the mode profile at the crystal boundary. In order to preserve the dominant TE-like polarization of the mode, the crystal was cleaved close to the defect layer, resulting in a crystal that was three hole layers and two rod layers high, with the defect contained in the central hole layer. The radiation fields were calculated using 3D, full-vectorial, finite-difference time-domain (FDTD) simulations of Maxwell's equations⁸ with perfectly-matched-layer boundary regions at the edges of the computational cell.⁹ The defect mode was excited using a magnetic-dipole source at the center of the defect. The frequency, amplitude, and quality factor (Q) of the mode were extracted from the field decay after source turn-off, using a low-storage filter-diagonalization method.¹⁰ Figure 2 shows snapshots of the radiated fields for three different crystal radii: $r = 3.5\bar{a}$, $4.5\bar{a}$, and $5.5\bar{a}$; the corresponding Q values are shown in Table I. Notice that while the mode in the vicinity of the defect looks very similar for all three cases, the structure of the radiated fields changes, with the field amplitudes decreasing in the plane of the crystal for increasing crystal radius.

The magnetic character of the radiation mode was quantitatively determined by performing a multipole decomposition of the far field. For a generalized localized source distribution, the magnetic field in the radiation zone ($r \gg \lambda$) can be written (see Ref. 11):

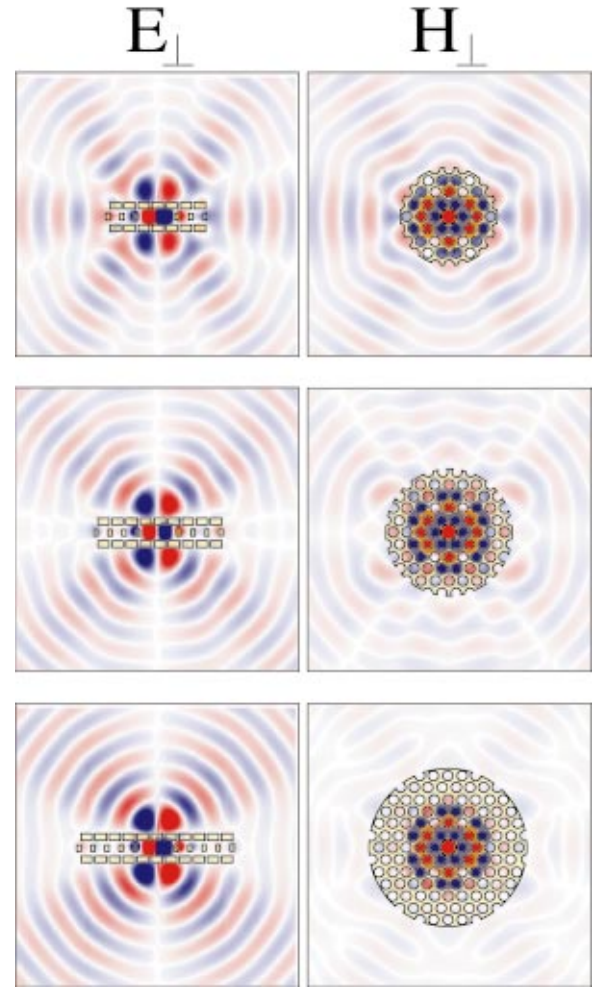


FIG. 2. (Color) Radiating point defect modes for three different cuts of the photonic crystal. The left- and right-hand columns show the electric and magnetic field components perpendicular to the plane, respectively. The colormap has been exaggerated to make the far-field radiation more visible. Yellow shading indicates dielectric material.

$$\mathbf{H}(r \gg \lambda) \cong \frac{e^{ikr - i\omega t}}{kr} \sum_{l,m} (-i)^{l+1} \times [a_E(l,m) \mathbf{X}_{lm} + a_M(l,m) \hat{r} \times \mathbf{X}_{lm}],$$

where the $\mathbf{X}_{lm}$'s are the vector spherical harmonics, given by $\mathbf{X}_{lm}(\theta, \phi) = 1/\sqrt{l(l+1)} \mathbf{L} Y_{lm}(\theta, \phi)$, and $\mathbf{L}$ is the angular-momentum operator, $1/i(\mathbf{r} \times \nabla)$. a_M and a_E are the magnetic and electric multipole moments, respectively, and each mul-

TABLE I. Quality factor Q and dominant multipole coefficients for the radiating point-defect states shown in Fig. 2. The radius of the photonic crystal is given by r ; $\bar{a}$ is the in-plane lattice constant of the crystal. M_{pwr} denotes the percentage of the total radiated power due to magnetic multipole terms.

	$r = 3.5\bar{a}$	$r = 4.5\bar{a}$	$r = 5.5\bar{a}$
Q	174	299	320
$ a_M(1,0) ^2$	5%	30%	37%
$ a_M(3,0) ^2$	50%	50%	50%
$ a_M(5,0) ^2$	8%	10%	8%
Any other $ a_M(l,m) ^2$	$\leq 3\%$	$< 1\%$	$< 0.5\%$
Any $ a_E(l,m) ^2$	$\leq 4\%$	$< 0.5\%$	$< 0.5\%$
M_{pwr}	79%	96%	98%

tipole radiates a time-averaged power of $\sqrt{\mu_0/\epsilon_0}/(2k^2)|a(l,m)|^2$. Using the orthogonality relations for the vector spherical harmonics

$$\int \mathbf{X}_{l'm'}^* \cdot \mathbf{X}_{lm} d\Omega = \delta_{ll'} \delta_{mm'},$$

and

$$\int \mathbf{X}_{l'm'}^* \cdot (\hat{r} \times \mathbf{X}_{lm}) d\Omega = 0,$$

we obtained the multipole coefficients a_M and a_E by numerical integration over a sphere near the boundary of the computational cell.

The results are shown in Table I. The absolute value of the multipole moments squared, $|a(l,m)|^2$, is expressed as a percentage of the total power radiated. For all three crystal structures, the largest multipole moments were magnetic with $m=0$ and $l=1, 3$, or 5 . As the crystal diameter increases, the strength of the $(1, 0)$ magnetic dipole term increases, while the strength of the $(3, 0)$ and $(5, 0)$ terms remains approximately fixed. This trend can be understood from the fact that the crystal must block radiation in the lateral direction, as seen in Fig. 2. As the $l=0$ component increases, it cancels the $l=3$ component to reduce the amplitude of the fields in the plane of the crystal. The percentage of the power that is emitted in magnetic multipole terms, M_{pwr} , is also given in the table. The power is mostly magnetic for all three crystals, with M_{pwr} increasing to a maximum of 98% for the largest crystal radius studied. Moreover, the crystal height was found to be an important parameter in determining the percentage of power that goes into magnetic radiation; increasing the height of the $r=4.5\bar{a}$ crystal so that it included nine hole layers significantly reduced M_{pwr} , from 96% to 60%.

The key to the magnetic nature of the radiation, we believe, is the primarily TE character of the mode in the midplane—in two dimensions, this would lead to purely magnetic radiation, and the only electric multipole components in 3D are due to the deviations from this TE character. Away from the midplane, the deviations take the form of $\hat{z}$ components of $\mathbf{E}$; these components can induce electric radiation, but that radiation is primarily in the lateral directions. Therefore, by increasing the lateral crystal size, we can substantially eliminate this radiation and increase the magnetic character, as observed in Table I. Conversely, as the vertical size is increased, deviations from TE character become more pronounced and consequently, the percentage of magnetic radiation is decreased.

Starting with a point defect in a bulk photonic crystal whose local field pattern resembles an oscillating magnetic moment, we have shown that the crystal boundary can be cut so that the radiation from the defect mode is almost completely magnetic. Unlike traditional magnetic sources, this magnetic emitter can be designed to operate even at optical frequencies. (In a practical implementation, the defect mode would be excited by shining light onto the crystal from an optical source. This process could be enhanced by incorporating a fluorescent dye within the crystal to absorb outside the band gap and emit at the frequency of the point-defect mode.) Using the point-defect mode that we study here as a building block, it may now be possible to design arrays of defects that yield magnetic bulk properties in photonic crystals; “ferromagnetic” and “antiferromagnetic” arrays, for example, can be created by operating at frequencies corresponding to wave vectors at the edge of the Brillouin zone, where adjacent defect states will have phase shifts of ~ 0 or $\sim \pi$. Creating defects within the rod layer of the 3D photonic crystal, which behave like electric multipoles, could similarly allow the design of ferroelectric and antiferroelectric arrays. Investigation of the properties of these defect complexes is a promising direction for future work.

This work was supported by DoD/ONR MURI Grant No. N00014-01-1-0803 and the MRSEC program of the NSF under Award Nos. DMR-9400334 and DMR-0213282. The authors would like to thank E. Lidorikis, S. Schultz, D. R. Smith, S. R. Nagel, and M. Yahyanejad for helpful discussions, as well as E. Lidorikis and C. Luo for recent improvements to the FDTD code.

¹V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968).

²R. A. Shelby, D. R. Smith, and S. Schultz, Science **292**, 77 (2001).

³J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).

⁴S. O'Brien and J. B. Pendry, J. Phys.: Condens. Matter **14**, 4035 (2002).

⁵S. G. Johnson and J. D. Joannopoulos, Appl. Phys. Lett. **77**, 3490 (2000).

⁶S. G. Johnson and J. D. Joannopoulos, Opt. Express **8**, 173 (2001); and references therein.

⁷M. L. Povinelli, S. G. Johnson, S. Fan, and J. D. Joannopoulos, Phys. Rev. B **64**, 075313 (2001).

⁸K. S. Kunz and R. J. Luebbers, *The Finite-Difference Time-Domain Methods* (CRC Press, Boca Raton, FL, 1993).

⁹J. C. Chen and K. Li, Microwave Opt. Technol. Lett. **10**, 319 (1995).

¹⁰V. A. Mandelshtam and H. S. Taylor, J. Chem. Phys. **107**, 6756 (1997); see also erratum, **109**, 4128 (1998).

¹¹J. D. Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, New York, 1999), Chap. 9.