PHYSICAL REVIEW B VOLUME 58, NUMBER 16 15 OCTOBER 1998-II

Superprism phenomena in photonic crystals

Hideo Kosaka
Optoelectronics and High Frequency Device Research Laboratories, NEC, 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan

Takayuki Kawashima
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan

Akihisa Tomita
Optoelectronics and High Frequency Device Research Laboratories, NEC, 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan

Masaya Notomi and Toshiaki Tamamura
NTT Opto-electronics Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa Prefecture, 243-01, Japan

Takashi Sato and Shojiro Kawakami
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan

(Received 4 August 1998)

Extraordinary angle-sensitive light propagation, which we call a *superprism phenomenon*, was demonstrated at optical wavelength in photonic crystals with three-dimensional-periodic structure fabricated on Si substrate. The propagation beam was swung from $-90°$ to $+90°$ with a slight change in the incident angle within $\pm 12°$. This effect together with wavelength sensitivity is at least two orders of magnitude stronger than that of the conventional prism. The incident-angle dependence including negative refraction and multiple beam branching was interpreted from highly anisotropic dispersion surfaces derived by photonic band calculation. These phenomena will be available to fabricate microscale light circuits on Si with LSI-compatible lithography techniques. [S0163-1829(98)51840-1]

Photonic crystals are artificial structures, which have a periodic dielectric structure with high index contrast, designed to control photons in the same way that crystals control electrons. Extensive efforts have been made in the search for structures that forbid propagation of photons within a certain range of energies (called a photonic band gap),[1–6] while also having an attractive energy dispersion (called a photonic band structure). This energy dispersion determines the refractive index being modified from the bulk constant. Recently, Lin *et al.*[7] demonstrated a highly dispersive prism by applying this index change in the radio frequency range. The angle modification, however, remained of comparable order to that of the conventional prism because they utilized the modification of *phase velocity*. In contrast, we here present ''superprism phenomena,'' where the light path shows a drastic wide swing with a slight change of the incident light angle owing to the strong modification of *group velocity*. In particular, the observed negative bending and multiple beam branching cannot be explained by the nonlinearity in the isotropic dispersion assumed in Ref. 7. We have interpreted these anomalies in terms of highly anisotropic dispersion contrary to their assumption. In addition, we observed extraordinary divergence of propagation beam as was propagating in a collimator or a lens, depending on the curvature of the dispersion surface. This demonstration is an important step towards enabling the eventual fabrication of extremely compact light circuits on Si. Such light circuits may be made with large-scale integrated circuit (LSI)-compatible lithography techniques.

The photographs in Fig. 1 show light paths inside a photonic crystal monitored from above. The light path swings from $+70°$ to $-70°$ as a result of a slight change of the incident angle from $+7°$ to $-7°$. Significantly, both paths show negative bending. If Snell's law is applied without regard to the photonic band anisotropy, this phenomenon implies a *negative refractive index*.

The photonic crystal was fabricated by depositing alternate layers of amorphous Si and SiO_2 on a patterned Si substrate having a hexagonal array of holes[8] (Fig. 2). The replication of the surface holes causes the three-dimensional (3D) structure, comprising alternately stacked triangular lattices of Si or SiO_2 disks, to be self-organized. This stacking structure, where the Si/SiO_2 *photonic atoms* in consecutive layers are directly above each other, is analogous to that of a graphite crystal. The self-organized crystallization on the Si substrate, which provides vertical alignment of the disks with a uniform shape and a high aspect ratio, is a great advantage compared to other fabrication processes such as that used to make artificial opals,[9,10] etching,[4,5,11–13] or micromanipulation.[14,15] In addition, the optically uniaxial geometry allows the assignment of either the TE-like mode (electric field parallel to the plane) or the TM-like mode (magnetic field parallel to the plane). We fabricated two kinds of samples with different lateral lattice constants ($a = 0.4$ and 0.32 μm) on the same wafer, with both samples consisting of a 20-pair stack with a layer pitch of 0.32 μm. A polarized light was incident onto the crystal from the edge. For the incident light, we used a vertical-cavity surface-emitting laser with $\lambda = 0.956$ μm, which corresponds to a normalized frequency Ω ($= \omega a/2\pi c = a/\lambda$) of 0.42 and 0.33, respectively, for the $a = 0.40$- and 0.32-μm samples.

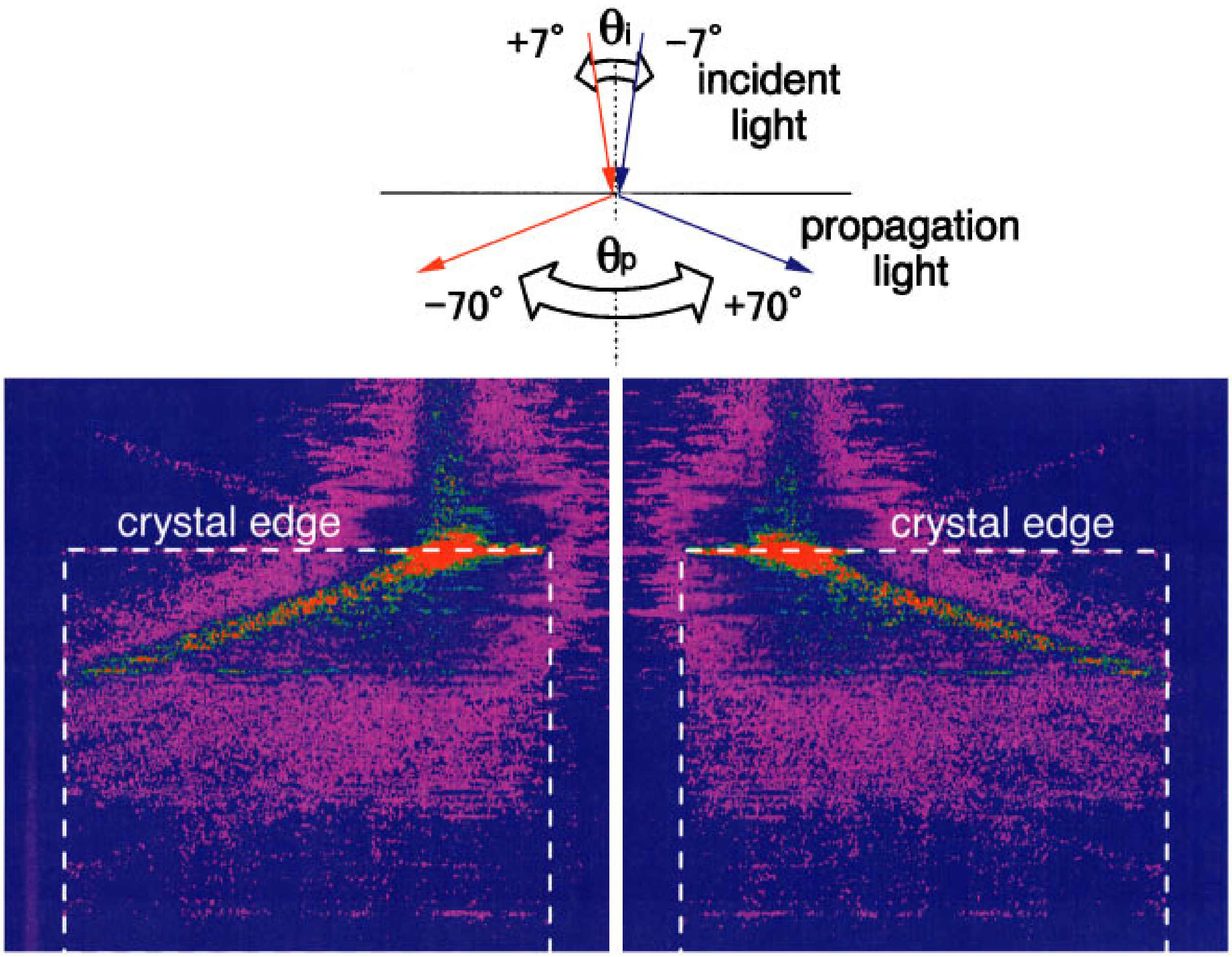

FIG. 1. (Color) Photographs showing light-beam swing inside the photonic crystal. The tilting angle of the incident light was slightly altered from $+7°$ (left) to $-7°$ (right). Both paths show negative bending. The incident light has a wavelength corresponding to the normalized frequency $\Omega = 0.33$ (defined later) with the TM polarization. The angles were measured from normal to the crystal edge ($\Gamma - M$ crystal direction). The crystal size is 500 μm$\times$500 μm.

To examine the anomalous phenomena described above, we measured the dependence of the propagation angles on the incident angle (Fig. 3). The propagation angles ranged from $0°$ to $+90°$ for $\Omega = 0.42$ and from $-83°$ to $0°$ for $\Omega = 0.33$, and showed a particularly sensitive dependence on the incident angle below $12°$. In addition, the doubly branched rays showed a totally opposite angular dependence. These features cannot be explained in terms of conventional crystalline optics because beam branching never occurs with either TE or TM polarization in conventional optically uniaxial crystals.

The photonic band structure, which determines the energy dispersion of a photons, was calculated using the plane-wave expansion method[16] [Fig. 4(a)]. Although the scaling is not perfect because the vertical lattice constant is the same for both samples, almost the same band structure was obtained for both samples. Refractive indices for Si and SiO_2 were set to the measured values (3.24 and 1.46, respectively) for the bulk condition and a hexagonal-rod shape was assumed in the calculation. Though the inversion symmetry prevents the occurrence of a complete three-dimensional band gap, the band structure shows a semimetallic pseudogap in the plane direction (a complete gap is obtained in the vertical direction) and exhibits strong anisotropy especially in the bands marked B, C, and D. The propagation inside the crystal is strongly affected by the dispersion anisotropy regardless of the completeness of the band gap. The dispersion surfaces at a constant frequency [Fig. 4(b)] also show strong anisotropy in a star shape at the center of Fig. 4(b) (the B band) or a bell shape at the corners (the D band). Exact band structures were used for obtaining these dispersion surfaces. The propagation direction is obtained as normal to the dispersion surface at the propagation wave vector—obtained under the continuity condition between incident wave vector k_i and propagation wave vector k_p for the tangential components parallel to the incident crystal edge $k_{p\parallel} = k_{i\parallel}$ [through momentum conservation; graphically illustrated in Fig. 4(b)]—because the group velocity is derived by

$$v_g = \nabla_k \omega(k).$$

The obtained angular dependence in the $\Omega = 0.42$ case (solid curves in Fig. 3) agrees well with the measurements (closed circles in Fig. 3), indicating that the characteristic angular dependence can be explained from the star-shaped dispersion surface. On the other hand, the angular dependence in the $\Omega = 0.33$ case (open circles in Fig. 3) can only be well explained by adjusting the tangential component as $k_{p\parallel} = k_{i\parallel}$

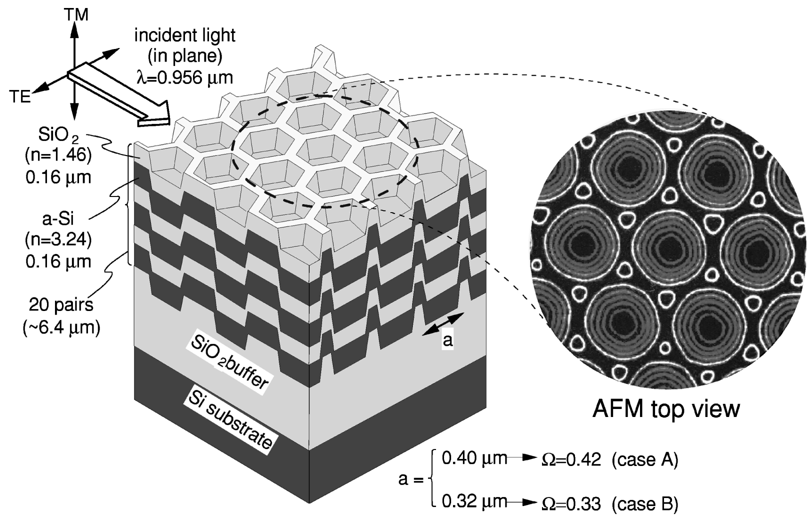

FIG. 2. Self-organized 3D photonic crystal with graphite structure fabricated on Si substrate. The stacking structure is analogous to that of simple hexagonal graphite. Two sets of amorphous-Si and SiO_2 photonic atoms, with refractive indices of 3.24 and 1.46, respectively, are contained in a unit cell. The lateral lattice constants ($a = 0.4$ and 0.32 μm) correspond to normalized frequencies Ω of 0.42 and 0.33, respectively, for the incident light with $\lambda = 0.956$ μm.

$-2\pi/3a$ (dashed curves in Fig. 3) from the bell-shaped dispersion surface. At present we do not clearly understand the origin of this modified momentum-selection rule, however, the locally excited surface mode[17] might be related.

This is the first visualization of a light beam *inside* a photonic crystal, and it provides direct evidence of highly modulated band dispersion at an optical wavelength. Lin *et al.*[7] previously measured the prism effect in a photonic crystal and observed a 20% angle change resulting from a 40° incident-angle change when measured *outside* the crystal at a *millimeter-wave frequency*. They attributed this effect to the nonlinearity in the isotropic dispersion. Conversely, our observation showed a striking change, ranging from $-90°$ to $+90°$ (Fig. 3) with a slight change in the incident angle of 12° or less. This significant difference in the observations of Lin and our observations arises because the origin of the phenomena is essentially different; the origin of Lin's observation is phase velocity in contrast to group velocity in our observation. Furthermore, the strong anisotropy, unlike the isotropy assumed in Lin's work, creates a critical difference in direction between the phase velocity and the group velocity that accounts for the significant difference in the observed behaviors. To emphasize this difference, we call our observed behavior, ''superprism phenomena.'' In addition, the strong anisotropy causes strong interband coupling, which allows a modified momentum-selection rule in contrast with other analogous phenomena on planar waveguide gratings,[18,19] acoustic waves, and x-ray diffraction where the anisotropy is weak. Furthermore, the three-dimensional configuration might be essential to the visualization of light paths inside the photonic crystal. This is because the source of the observed light is likely to be a slightly out-of-plane component introduced by the vertical dispersion, which would be flat in two-dimensional photonic crystals. Not only the angle dependence but also the wavelength dependence shows sensitive behavior. We have observed that the propagation angle is changed by 30° when the wavelength is changed by 10 nm around 0.98 μm in the $\Omega = 0.33$ case. These effects are at least two orders of magnitude stronger than Lin's observation.

In addition to the superprism phenomena related to the propagation angle, we observed extraordinary divergence of propagation beam depending on the propagation angle. At the angles corresponding to the inflection points in the dispersion surface, the beam showed almost collimated propagation insensitive to the divergence of the incident beam (collimator case). Otherwise, the beam showed divergent propagation if the incident beam is slightly divergent (lens case). These phenomena are independent of the intensity of the incident light in contrast to the self-focusing phenomena in nonlinear materials.

The technological significance of these phenomena can be found in the fabrication of integrated optical devices such as planar light circuits or arrayed waveguide gratings. The critical issue here is that size of current devices must be at least

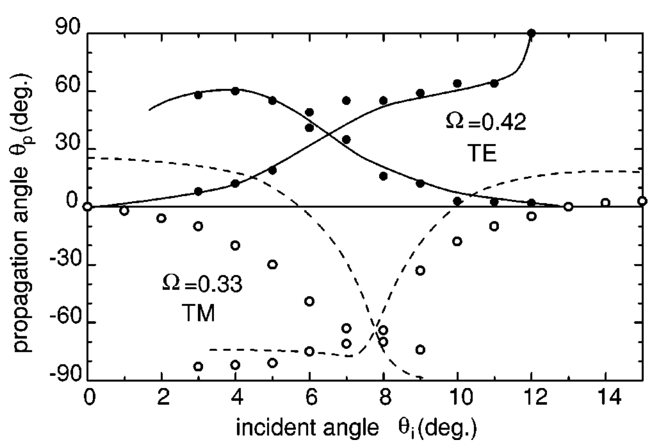

FIG. 3. The dependence of the propagation angles on the incident angle. The closed and open circles denote the cases for normalized frequency $\Omega = 0.42$ and 0.33, respectively. The solid and dashed curves were derived through an analysis of the photonic band structure (illustrated in Fig. 4).

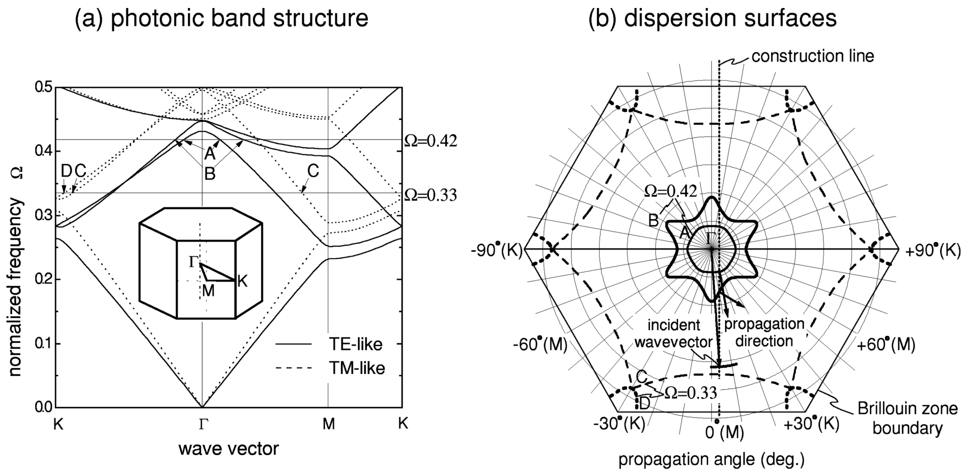

FIG. 4. Calculated photonic band structure (a) and the constant-frequency dispersion surfaces (b). We used 1258 plane waves for the expansion to ensure accuracy to within 1%. The solid and dashed curves denote the TE and TM mode, respectively. In (b), the normal vector at the intersection of the dispersion surface and the construction line (through the end of the incident wave vector and normal to the crystal edge) gives the propagation direction.

a few centimeters, which is limited by the bending angle of the waveguides. The application of the phenomena we observed promises to reduce the size by three orders of magnitude in area, and enable microscale light circuits. This reduction will be directly reflected in production costs. Also, the increased incident-angle sensitivity is unlikely to complicate the fabrication process. On the contrary, the nature of the band structure is more strongly affected by the lattice configuration than by the atomic form, which makes precise angle control easier than with etched mirrors or other equivalent devices. This nature is well suited to lithography techniques with an order comparable to that of LSI fabrication processes. On the other hand, Mekis *et al.*[20] have demonstrated a smart way to realize lossless sharp bending in photonic crystal waveguides by computer simulation. The realization of such an ideal structure, however, will require innovative fabrication technologies to attain a complete band gap, which is not needed with these superprism phenomena. In addition, the potential of multiple branching and wavelength sensitivity will inspire novel designs of functional devices such as wavelength-division multiplexers/demultiplexers. Also, three-dimensional light circuits might be realized by introducing vertical waveguides into this 3-D photonic crystal. These advantages should make optical products more affordable and practical for use in many consumer products, and also enable the widespread integration of optical devices with LSI devices.

We thank Osamu Hanaizumi, Yoshihiro Nambu, Yoshiyuki Miyamoto, Mineo Saito, Kohichi Izumi, Seido Nagano, Kimihiko Ito, and Hong-Wen Ren for discussions and support. We also thank Mitsuru Naganuma, Masaki Ogawa, Ikuo Mito, and Kennichi Kasahara for support.

[1] E. Yablonovitch, J. Opt. Soc. Am. B **10**, 283 (1993).
[2] C. M. Soukoulis, *Photonic Band Gap Materials* (Kluwer, Dordrecht, 1996).
[3] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, Nature (London) **386**, 143 (1997).
[4] T. F. Krauss, R. M. De La Rue, and S. Brand, Nature (London) **383**, 699 (1996).
[5] J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen, Nature (London) **390**, 143 (1997).
[6] S. Fan, P. Villeneuve, J. Joannopoulos, and E. F. Schubert, Phys. Rev. Lett. **78**, 3294 (1997).
[7] S. Lin, V. M. Hietala, L. Wang, and E. D. Jones, Opt. Lett. **21**, 1771 (1996).
[8] S. Kawakami, Electron. Lett. **33**, 1260 (1997).
[9] V. N. Bogomolov *et al.*, Phys. Rev. E **55**, 7619 (1997).
[10] S. G. Romanov *et al.*, Appl. Phys. Lett. **70**, 2091 (1997).
[11] P. L. Gourley, Nature (London) **371**, 571 (1994).
[12] D. Cassagne, C. Jouanin, and D. Bertho, Phys. Rev. B **52**, R2217 (1995).
[13] T. Baba and T. Matsuzaki, Jpn. J. Appl. Phys., Part 1 **35**, 1348 (1996).
[14] E. Ozbay, A. Abeyta, G. Tuttle, M. Tringides, R. Biswas, C. Soukoulis, C. T. Chan, and K. M. Ho, Phys. Rev. B **50**, 1945 (1994).
[15] S. Noda, N. Yamamoto, and A. Sasaki, Jpn. J. Appl. Phys., Part 2 **35**, L909 (1996).
[16] K. M. Ho, C. T. Chan, and C. M. Soukoulis, Phys. Rev. Lett. **65**, 3152 (1990).
[17] R. D. Meade, K. D. Brommer, A. M. Rappe, and J. D. Joannopoulos, Phys. Rev. B **44**, 10 961 (1991).
[18] P. St. J. Russell, T. A. Birks, and F. D. Lloyd-Lucas, in *Confined Electrons and Photons*, edited by E. Burstein and C. Weisbuch (Plenum, New York, 1995).
[19] R. Zengerle, J. Mod. Opt. **34**, 1589 (1987).
[20] A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. Lett. **77**, 3787 (1996).