Asymmetric light propagation based on semi-circular photonic crystals*

Wang Lin-Hui(王林辉)[a], Yang Xiu-Lun(杨修伦)[a]†, Meng Xiang-Feng(孟祥锋)[a], Wang Yu-Rong(王玉荣)[a], Chen Shou-Xiang(陈寿翔)[a], Huang Zhe(黄 哲)[a], and Dong Guo-Yan(董国艳)[b]

[a] *Department of Optics, Shandong University, Jinan* 250100, *China*
[b] *Department of Materials Science and Engineering, Tsinghua University, Beijing* 100084, *China*

(Received 27 April 2013; revised manuscript received 8 August 2013; published online 12 February 2014)

A new structure based on a semi-circular photonic crystal is proposed to achieve asymmetric light propagation. The semi-circular photonic crystal structure proposed in this paper is a deformation of a two-dimensional conventional square photonic crystal. Through the directional bandgap of the semi-circular photonic crystal, the light from one direction can transfer to the other side, but the light from the opposite direction cannot. A high contrast ratio is obtained by designing the constitutive parameters of the photonic crystal and choosing the suitable light frequency. This structure promises a significant potential in optical integration and other areas.

Keywords: semi-circular photonic crystal, asymmetric light propagation, optical integration

PACS: 42.82.–m, 42.82.Bq **DOI:** 10.1088/1674-1056/23/3/034215

1. Introduction

Photonic crystals (PCs) have attracted much attention in the optical integration field[1–7] since they were introduced by Yablonovitch and John.[8,9] Various structures of unidirectional light propagation based on photonic crystals have been proposed.[10–25] However, most of these previous approaches were based on nonlinear materials or metallic and magnetic-optical materials.[10–12,14,15] For instance, one-way electromagnetic waveguide formed at the interface between a plasmonic metal under a static magnetic field and photonic crystal[15] provides a frequency range in which only one propagating direction is allowed. In this frequency range, disorder-induced scattering is suppressed completely. However, nonlinear approaches require high-power input sources because small nonlinear susceptibility coefficient and metal inclusion accompanies optical losses, which can diminish light propagation.[24]

Numerous methods can achieve asymmetric light propagation based on photonic crystals without nonlinear optics or anisotropic materials. Wang *et al*. proposed a photonic crystal heterojunction diode[22,25] made of two kinds of square-lattice photonic crystals with different radii of dielectric rods. The unidirectional optical diode action is achieved via directional bandgap of the photonic crystals. Feng *et al*.[26] considered a two-mode waveguide with a spatially varying but time-independent dielectric constant, as well as numerically and experimentally obtained a one-way modal conversion effect. Fan *et al*.[27] showed that the structure in Ref. [26] is reciprocal in the sense that it has a symmetric scattering matrix. Therefore, such a structure cannot enable optical isolation. In addition, an optical isolator cannot be constructed by incorporating this structure into any linear and time-independent system described by materials with a scalar dielectric function. To achieve true optical isolation, the scattering matrix of the system must be asymmetric. Feng *et al*.[28] recognized that the one-way mode converter is Lorentz reciprocal and cannot be used as the basis of an optical isolator on its own.

Kurt *et al*.[24] presented a new approach to achieve asymmetric light propagation via graded photonic crystal waveguides. The horizontal period of the photonic crystal was changed linearly. The asymmetric light propagation was realized because of the bandgap structure of chirped photonic crystal waveguides.

In this paper, a new radial photonic crystal structure is proposed to achieve asymmetric light propagation. The PC structure is composed of several concentric semi-circles made up of dielectric cylinders. Numerous types of radial photonic crystals were proposed previously,[29–32] but some radial photonic crystals were one-dimensional.[29] Moreover, only the bandgap properties were considered.[32] The semi-circular photonic crystal structure proposed in this paper is a deformation of a two-dimensional conventional square photonic crystal. Properties of conductive band are mainly considered. Through the directional bandgap of the semi-circular photonic

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60907005, 10804063, and 51102148), the Natural Science Foundation of Shandong Province, China (Grant Nos. ZR2011FQ011 and ZR2010AM025), the Natural Science and Technology Program of Shandong Province, China (Grant No. 2011GGH20119), the Research Award Fund for Outstanding Young Scientists of Shandong Province, China (Grant No. BS2011DX023), the Science & Technology Bureau of Shenzhen City, China (Grant No. 0014632063100426032), and the Independent Innovation Foundation of Shandong University, China (Grant No. 2010TB019).

†Corresponding author. E-mail: xlyang@sdu.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

crystal, light from one direction can transfer to the other side, but light from the opposite direction cannot. The structure is linear and passive. Therefore, the structure is essentially reciprocal. The asymmetric light propagation is achieved through simulation using multiple modes in the input and output ports. A higher contrast ratio is obtained. This structure has significant potential in optical integration and other areas.

2. Asymmetric transmission structure

In this paper, the proposed two-dimensional photonic crystal is a semi-circular photonic crystal with dielectric cylinders in air, as shown in Fig. 1(a). The semi-circular photonic crystal (SCPC) structure consists of several concentric semi-circles made up of dielectric cylinders. The positions of the dielectric cylinders in the X–Y plane for the SCPC are given by $R_{n+1} - R_n = a$ and $\theta_n = \pi/(2 \times n)$, where R_n is the radii of the N-th concentric circle, a is the lattice constant, θ_n is the angle between adjacent dielectric cylinders in the N-th concentric circle, $R_1 = a$, and $\theta_1 = \pi/2$. Therefore, the distances between two adjacent dielectric cylinders in every concentric semi-circle are equal. The value is $\pi/2$. The radii of the dielectric cylinders are $0.3a$. This SCPC structure presented in Fig. 1(a) can be regarded as the deformation of a standard PC, as shown in Fig. 1(b). The prototypical photonic crystal is a regular PC that has a rectangular lattice with a rod radius of $0.3a$. The periods of prototypical photonic crystal are a in the X direction and $(\pi/2) \times a$ in the Y direction. SCPC can be obtained by bending the upper and lower ends of the prototypical photonic crystal to the X direction. Crystalline Si (c-Si) is an attractive material because of its natural abundance and almost ideal bandgap. Thus, silicon is chosen as the material for the dielectric rods, and the dielectric constant is equal to 11.56 (i.e., $n = 3.4$).[33] In addition, the base material is air ($\varepsilon = 1$). The scale of SCPC is $14a$ in the X direction. In other words, the SCPC structure contains 13 concentric semi-circles. Given the desired conditions for the case study, we consider only the TM modes in this paper (the E field is parallel to the rods). The simulation software used is MEEP. The thickness of PML is set as 1. The resolution is set as 16.

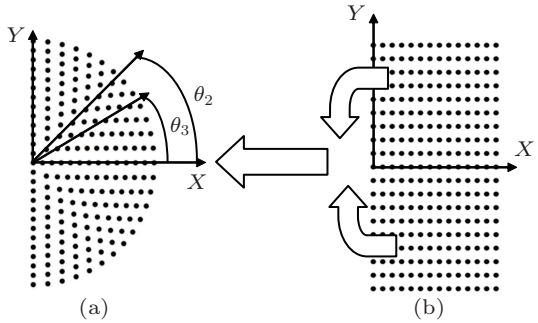


Fig. 1. (a) Semi-circular photonic crystal structure. (b) Prototypical photonic crystal.

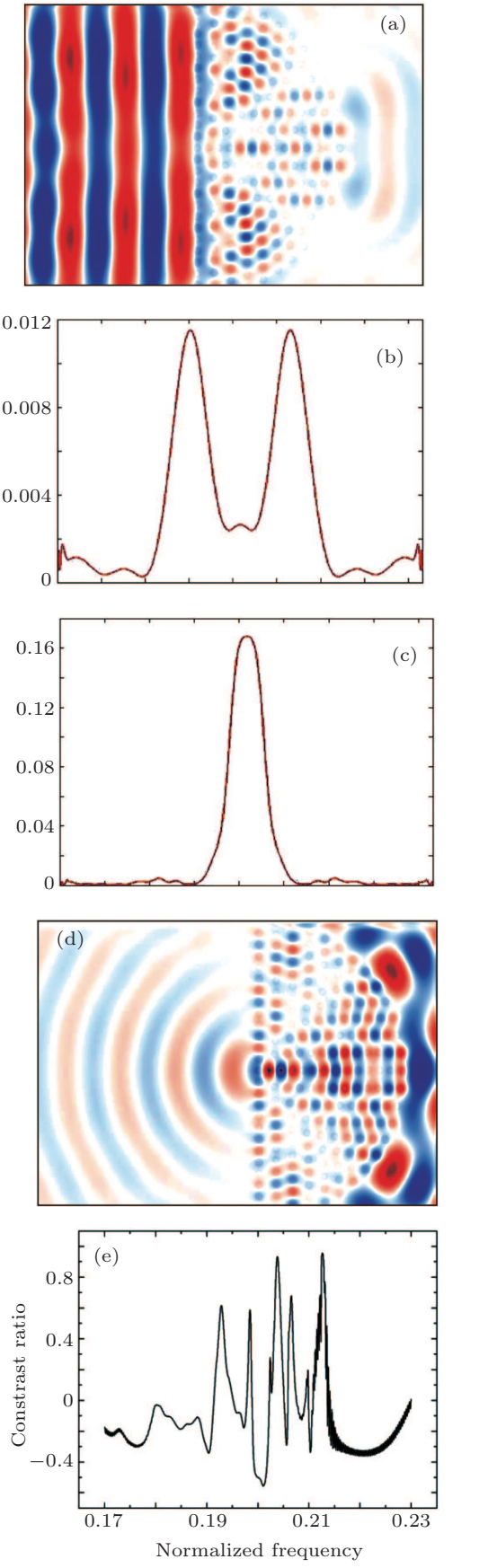


Fig. 2. (color online) (a) Time-domain snapshot of propagation of light from left to right. (b) Transverse field profile across the end face of the structure. (c) Transverse field profile across the front side of the structure. (d) Time-domain snapshot of propagation of light from right to left. (e) Spectral content of the contrast ratio. The frequency is $0.201(a/\lambda)$ and the angle θ_n is $\pi/(2 \times n)$.

The contrast ratio is defined to characterize the normalized difference between the two oppositely propagated waves.[24] $T = (T_{+X} - T_{-X})/(T_{+X} + T_{-X})$, where T_{+X} and T_{-X} represent transmission power propagating along the $+X$ (left-to-right) and $-X$ (right-to-left) directions, respectively. The positive and negative T denote the transmission direction. Figure 2(e) shows the spectral content of the contrast ratio and indicates several peaks. The SCPC structure can be considered as a deformation of conventional rectangular photonic crystals. However, the transmittances of SCPC at these frequencies are extremely low. The frequency is chosen as $0.201(a/\lambda)$ on account of the peak value in Fig. 2(e) and the transmittance. Figures 2(a) and 2(b) present a time-domain snapshot of light propagation from left to right and transverse field intensity across the end face of the structure, respectively. In addition, the time-domain snapshot of light propagation from right to left and transverse field intensity across the front side of the structure are illustrated in Figs. 2(d) and 2(c).

The difference of field distributions between two directions of light propagation is apparent. When propagating from right to left, light can transfer into the SCPC structure and propagate along the concentric semi-circle. Subsequently, the light spreads to the air at the end face of the structure. However, any light can hardly propagate into SCPC. When propagating from left to right, the light is inhibited to propagate in SCPC. The transverse field intensity distributions indicate the significant difference. The maximum intensity of the transmission light from right to left is approximately 0.17 (the amplitude of the incident light is 1), roughly 15 times stronger than the maximum intensity of the transmission light from left to right (0.011). Subsequently, the expected result is achieved in which asymmetric light propagation can be achieved through the SCPC structure, as shown in Figs. 2(a)–2(d).

To observe the asymmetric propagation more intuitively, we determine the intensity distribution. Inspection of the intensity distribution for SCPC is presented in Fig. 3. Figures 3(b) and 3(c) are obtained by reducing the color scale of the part inside the boxes shown in Figs. 3(a) and 3(d), respectively. These boxes have the same scale. The intensity of light that reaches the rear surface shown in Fig. 3(b) is significantly weaker than the intensity of light reaching the front surface presented in Fig. 3(c).

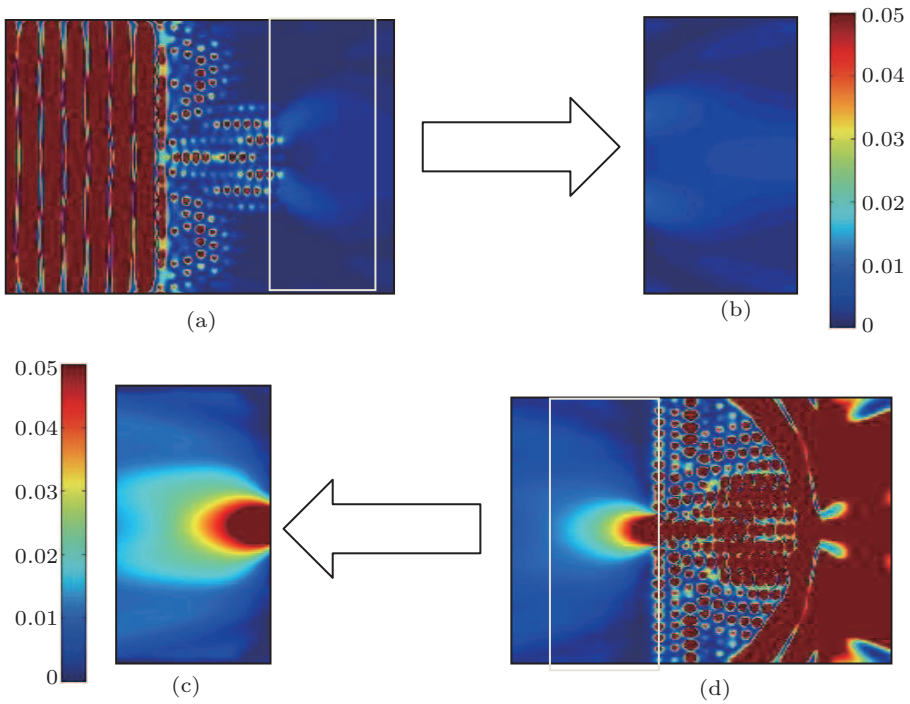


Fig. 3. (color online) Intensity distribution in SCPC when the frequency is $0.201(a/\lambda)$ and the angle θ_n is $\pi/(2\times n)$. (a) and (b) Light propagation from left to right. (c) and (d) Light propagation from right to left.

3. Parameter optimization

To obtain a higher contrast ratio, we consider the angle between adjacent dielectric cylinders θ_n and the radius of dielectric cylinder. Changing angle θ_n is equivalent to changing the length–width ratio of the standard PC. Table 1 shows the maximum contrast ratio of semi-circular photonic crystals with radii of $0.3a$ for different θ_n. The contrast ratio has the highest value when angle θ_n is $\pi/(5\times n)$. The peak value is

0.931. The frequency is 0.173, and the contrast ratio is 0.931.

Figure 4 illustrates the change of contrast ratio of semi-circular photonic crystals with different radii at a frequency of 0.173 when the angle between adjacent dielectric cylinders θ_n is $\pi/(5\times n)$. This figure also indicates that the maximum value of the contrast ratio appears when the radius of the dielectric cylinder is $0.3a$.

Table 1. The maximum contrast ratio for different θ_n.

θ_n	Contrast ratio
$\pi/(2\times n)$	0.913
$\pi/(3\times n)$	0.825
$\pi/(4\times n)$	0.846
$\pi/(5\times n)$	0.931

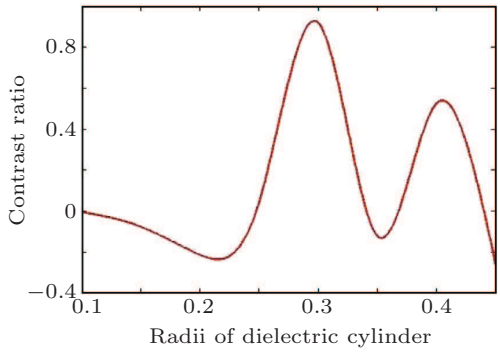


Fig. 4. (color online) Contrast ratio of semi-circular photonic crystals with different radii when the frequency is $0.173(a/\lambda)$ and the angle θ_n is $\pi/(5\times n)$.

The field distributions are simulated when the light at frequency 0.173 propagates through the SCPC at a dielectric cylinder radius of $0.3a$. The angle between adjacent dielectric cylinders θ_n is $\pi/(5\times n)$. Figures 5(a) and 5(b) illustrate the time-domain snapshot of light propagation from left to right and the transverse field intensity across the end face of the structure, respectively. The time-domain snapshot of light propagation from right to left and the transverse field intensity across the front side of the structure are presented in Figs. 5(c) and 5(d). When propagating from left to right, light can transfer into the SCPC structure, and propagate along the concentric semi-circle. Then, the light spreads to the air. Light can hardly propagate into the SCPC when the light propagates from right to left. In fact, even the light that has propagated into the SCPC is inhibited from propagating in the SCPC. The transverse field intensity distributions exhibit a significant difference. The maximum intensity of the penetrable light propagating from left to right is approximately 0.33 (the amplitude of the incident light is 1), roughly 30 times stronger than the maximum intensity of the penetrable light propagating from right to left. Subsequently, we obtain the expected result, in which asymmetric light propagation could be achieved by the SCPC structure, as shown in Figs. 5(a)–5(d).

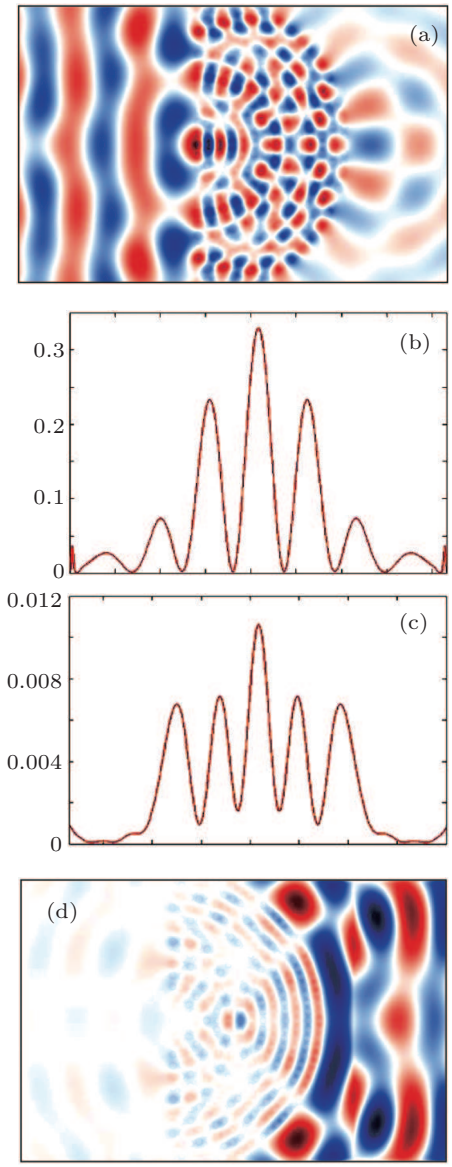


Fig. 5. (color online) (a) Time-domain snapshot of propagation of light from left to right. (b) Transverse field profile across the end face of the structure. (c) Transverse field profile across the front side of the structure. (d) Time-domain snapshot of propagation of light from right to left. The frequency is $0.173(a/\lambda)$ and the angle θ_n is $\pi/(5\times n)$.

To observe the asymmetric propagation more intuitively, we obtain the intensity distribution. Inspection of the intensity distribution is presented in Fig. 6. Figures 6(b) and 6(c) are constructed by reducing the color scale of the part inside the boxes in Figs. 6(a) and 6(d). These figures have the same scale. The intensity of light that reaches the rear surface shown in Fig. 6(b) is considerably stronger than that of light that reaches the front surface presented in Fig. 6(c).

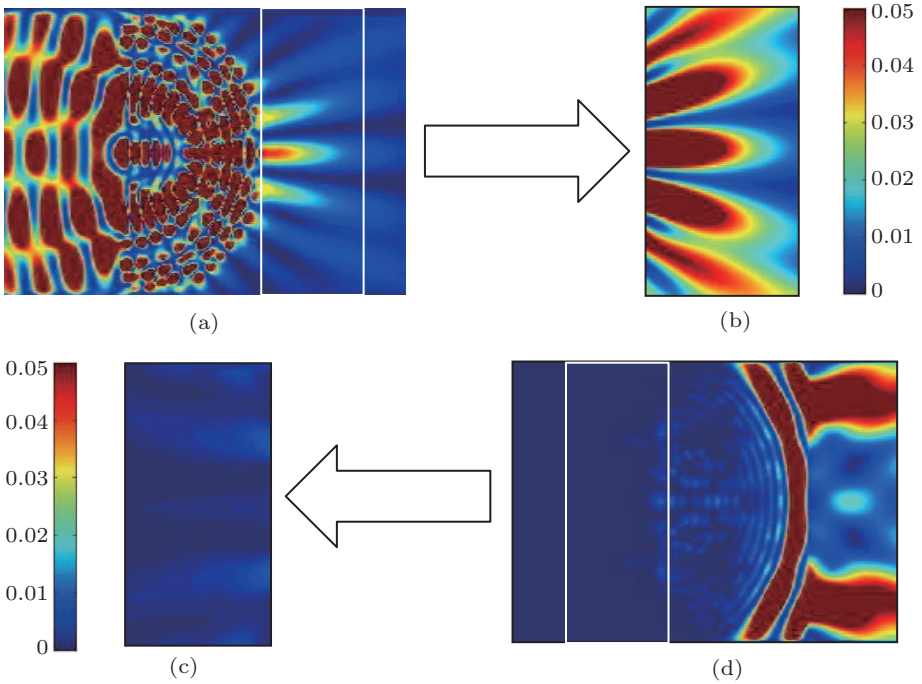


Fig. 6. (color online) Intensity distribution in SCPC when the frequency is $0.173(a/\lambda)$ and the angle θ_n is $\pi/(5\times n)$. (a) and (b) Light propagation from left to right. (c) and (d) Light propagation from right to left.

4. Conclusion

In this paper, a new structure is proposed to achieve asymmetric light propagation. This asymmetric light propagation structure is based on semi-circular photonic crystals without nonlinear optics or anisotropic material. The SCPC structure is composed of several concentric semi-circles made up of dielectric cylinders. The structure is linear and passive. In accordance with the Lorentz reciprocity theorem, any system with symmetry tensors of both permittivity and permeability always has a symmetry scattering matrix for defined modal ports. Therefore, any transmission from an incoming mode to an outgoing mode must be equal to that of the reverse case. Asymmetric light propagation is achieved because of the multiple modes in the input and output ports, as demonstrated by other studies.[22,24,26–28] Through simulation, the asymmetric light propagation can be realized via the SCPCs. The directional bandgap of the semi-circular photonic crystal causes the light from one direction to transfer to the other side, but not the light from the opposite direction. Study of the asymmetric light propagation may contribute to research on optical integration, implementation of practical optical rectifier-type devices, and other areas.

References

[1] Liu H X, Li J, Li B, Cao L and Yuan B 2011 *Chin. Phys. B* **20** 017301
[2] Zhang X, Chen S W, Liao Q H, Yu T B, Liu N H and Huang Y Z 2011 *Chin. Phys. Lett.* **28** 084201
[3] Wu H, Jiang L Y, Jia W and Li X Y 2012 *Chin. Phys. Lett.* **29** 034203
[4] Zhou Y and Yin L Q 2012 *Chin. Phys. Lett.* **29** 064213
[5] Zhu Q Y, Fu Y Q, Hu D Q and Zhang Z M 2012 *Chin. Phys. B* **21** 064220
[6] Zhuang D X, Chen X Y, Li J J, Qiang Z X, Jiang J Z, Chen Z Y, Qiu Y S and Li H 2012 *Chin. Phys. Lett.* **29** 124201
[7] Chen S X, Yang X L, Meng X F, Dong G Y, Wang Y R, Wang L H and Huang Z 2013 *Chin. Phys. Lett.* **30** 054206
[8] John S 1987 *Phys. Rev. Lett.* **58** 2486
[9] Yablonovitch E 1987 *Phys. Rev. Lett.* **58** 2059
[10] Scalora M, Dowling J P, Bowden C M and Bloemer M J 1994 *J. Appl. Phys.* **76** 2023
[11] Tocci M D, Bloemer M J, Scalora M, Dowling J P and Bowden C M 1995 *Appl. Phys. Lett.* **66** 2324
[12] Lockyear M, Hibbins A, White K and Sambles J 2006 *Phys. Rev. E* **74** 056611
[13] Biancalana F 2008 *J. Appl. Phys.* **104** 093113
[14] Takeda H and John S 2008 *Phys. Rev. A* **78** 023804
[15] Yu Z, Veronis G, Wang Z and Fan S 2008 *Phys. Rev. Lett.* **100** 023902
[16] Serebryannikov A E and Ozbay E 2009 *Opt. Express* **17** 13335
[17] Serebryannikov A 2009 *Phys. Rev. B* **80** 155117
[18] Wang Z, Chong Y, Joannopoulos J D and Soljačić M 2009 *Nature* **461** 772
[19] Yu Z and Fan S 2009 *Nat. Photon.* **3** 91
[20] Cakmak A O, Colak E, Serebryannikov A E and Ozbay E 2010 *Opt. Express* **18** 22283
[21] Ye W M, Yuan X D, Guo C C and Zen C 2010 *Opt. Express* **18** 7590
[22] Wang C, Zhou C Z and Li Z Y 2011 *Opt. Express* **19** 026948
[23] He Z, Peng S, Ye Y, Dai Z, Qiu C, Ke M and Liu Z 2011 *Appl. Phys. Lett.* **98** 083505
[24] Kurt H, Yilmaz D, Akosman A E and Ozbay E 2012 *Opt. Express* **20** 20635
[25] Wang C, Zhong X L and Li Z Y 2012 *Sci. Rep.* **2** 674
[26] Feng L, Ayache M, Huang J, Xu Y L, Lu M H, Chen Y F, Fainman Y and Scherer A 2011 *Science* **333** 729
[27] Fan S, Baets R, Petrov A, Yu Z, Joannopoulos J D, FreudeW, Melloni A, Popovic M, Vanwolleghem M, Jalas D, Eich M, Krause M, Renner H, Brinkmeyer E and Doerr C R 2012 *Science* **335** 38-b
[28] Feng L, Ayache M, Huang J, Xu Y L, Lu M H, Chen Y F, Fainman Y and Scherer A 2012 *Science* **335** 38-c
[29] Chen J and Chen X 2011 *J. Opt. Soc. Am. B* **28** 241
[30] Carbonell J, Díaz-Rubio A, Torrent D, Cervera F, Kirleis M A, Piqué A and Sánchez-Dehesa J 2012 *Sci. Rep.* **2** 1
[31] Voloch N, Ellenbogen T and Arie A 2009 *J. Opt. Soc. Am. B* **26** 42
[32] Adibi A, Gauthier R C, Lin S Y and Scherer A 2008 *Proc. SPIE* **6901** 69011
[33] Dong G Y, Yang X L and Cai L Z 2010 *Opt. Express* **18** 16302