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Ultralow power all-optical diode in photonic crystal heterostructures with broken spatial inversion symmetry

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We experimentally realize an all-optical diode in a photonic crystal heterostructure with broken spatial inversion symmetry. The physical mechanism is attributed to bandgaps only for certain wavevectors and the transition between different electromagnetic Bloch modes, without any nonlinearity and high power requirement. An ultralow photon intensity of 50 kW/cm^2 and an ultrahigh transmission contrast of over 10^3 are reached simultaneously. Compared with previous reported all-optical diodes, the operating power is reduced by seven orders of magnitude, while the transmission contrast is enlarged by two orders of magnitude. This approach may open a way for the study of integrated photonic devices. © *2011 American Institute of Physics*. [doi:10.1063/1.3617433]

Recently, photonic crystal all-optical diode has attracted great attention due to its great potential applications in the fields of optical computing, optical interconnection networks, and integrated photonic circuits. Analogous to its electronic counterparts, nanoscale all-optical diode has nonreciprocal transmission properties. Two key characteristics for nanoscale all-optical diode are low operating power and high transmission contrast, which is defined as the ratio of maximum transmission in one direction to the corresponding transmission in the reverse direction. Though various schemes have been proposed theoretically to demonstrate all-optical diode in nonlinear and magnetic photonic crystals with broken time reversal symmetry,[1–9] very high operating threshold intensity of the order of 100 GW/cm^2 or strong magnetic field are needed experimentally due to relatively small nonlinear susceptibility and magneto-optical coefficient of conventional materials.[10–13] Moreover, the achieved transmission contrast is very low, usually less than 90.[10–13] Recently, Serebryannikov and Ozbay pointed out that it is possible to achieve unidirectional transmission of light in a photonic crystal structure having a non-symmetric configuration, i.e., breaking the spatial reversion symmetry, without any nonlinearity or high power requirement.[14,15] Subsequently, Hwang *et al*. reported a low-power all-optical diode by combining the photonic bandgap effect and the unique interface properties of asymmetric liquid-crystal photonic bandgap heterostructure.[16] Cakmakyapan *et al*. also reported a low-power all-optical diode in an asymmetric metallic grating heterostructure with a subwavelength slit at the microwave frequencies, which can also be realized in the visible and near-infrared range.[17] The large size of liquid crystal is unsuitable for the practical integration applications.

The aim of this letter is to study how to realize a low-power and high-contrast nanoscale photonic crystal all-optical diode suitable for the practical on-chip integration applications. For this purpose, we adopt a nanoscale integrated two-dimensional photonic crystal heterostructure composed of component photonic crystals 1 and 2, which have the same lattice constant but the different air hole size. This makes the central frequency of the photonic bandgap of component 1 different from that of component 2. Two component photonic crystals have photonic bandgaps only in certain directions. Component 1 acts like a "diffraction unit," which can bring about the rotation of photonic wavevector due to the strong refraction effect in the heterostructure interface. Component 2 acts like an "optical filter," which permits or prohibits the transmission of certain electromagnetic modes. The frequency of the incident light is selected at the pass band of component 1 but within the stop band of component 2. For the leftward incidence case, the incident light firstly enter component 2. The incident light will be reflected completely by component 2 due to the stop band effect in the Γ-X direction. While for the rightward incidence case, the incident light first enters component 1. The incident light can propagate through the component 1 because the frequency of the incident light is situated in the pass band of component 1 in the Γ-X direction. Then, the wavevector of the incident light is rotated to a direction with no photonic bandgap for component 2 due to the strong refraction effect in the heterostructure interface. So, the incident light can propagate through the photonic crystal heterostructure for the rightward incidence case, and the nonreciprocal transmission is reached. The reason lies in that components 1 and 2 have photonic bandgap only in certain directions, which makes that the photonic bandgap is only for certain wavevectors.[18] The photonic bandgap only prevents light from propagating in certain directions with specified energies.[19] Therefore, a nanoscale all-optical diode can be realized without any optical nonlinearity and high power requirement.

We adopted poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) as the matrix of the two-dimensional photonic crystal heterostructure. MEH-PPV powder with an average molecular weight of 200 000 (Sigma-Aldrich Company, USA) was dissolved in chloroform with a weight ratio of 1:150. The spin coating method was used to fabricate 600-nm-thick MEH-PPV films on silicon dioxide substrates. The linear absorption spectrum of the

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600-nm-thick MEH-PPV films is shown in Fig. 1(d). There is a wide linear absorption band from 200 to 580 nm. A focused ion-beam (FIB) etching system (Model DB235, FEI Company, USA) was employed to prepare the periodical patterns of the two-dimensional photonic crystal heterostructure in a 600-nm-thick MEH-PPV slab. The fabrication process was described in detail in Refs. 20 and 21. Scanning electron microscopy (SEM) images of the MEH-PPV photonic crystal heterostructure are shown in Figs. 1(a) and 1(b). The photonic crystal heterostructure consisted of two square lattice photonic crystals having the same lattice constant but the different air hole size. The lattice constant was 440 nm. The diameter of air holes was 220 nm for component 1 and 340 nm for component 2. There is an angle of 56° between the heterostructure interface and the horizontal direction. The photonic crystal region consisted of 25 blocks of photonic crystal heterostructure connected in line in the longitudinal direction. The length and the width of the patterned area were about 100 μm and 4 μm, respectively. The photonic crystal heterostructure was connected to two 600-nm-thick MEH-PPV optical waveguides with a size of 100 $\mu m \times 5$ mm. The transmission spectra of components 1 and 2 were calculated by use of the three-dimensional finite-difference time-domain (FDTD) method (using a commercial software RemCom XFDTD, version 6.4.18.2), as shown in Fig. 1(c). The refractive index of MEH-PPV was set at 1.83.[22] It is very clear that the transmission of 650-nm light is 100% and 0% for components 1 and 2, respectively. This indicates that the wavelength of 650 nm is in the pass band of component 1 and in the stop band of component 2.

To study the transmission properties of the MEH-PPV photonic crystal heterostructure, we used a transmission measurement system based on the evanescent-field coupling method.[20,21] A beam (with a pulse duration of 120 fs and a repetition rate of 76 MHz) from a femtosecond optical parametric oscillator (OPO) system (model Mira 900F, Coherent Company, USA), with an output power of 30 mW, was split into two beams with a ratio of 1:1. One beam was used as the reference light, which was used to monitor the laser fluctuations. The other beam was used as the probe light. The probe light was a transverse-electric polarized wave with the electric-field vector parallel to the MEH-PPV film. The probe light was collimated and attenuated by two apertures with a diameter of 100 μm before it was coupled into the photonic crystal by use of the evanescent-field. The 100-μm-diameter of the probe light was equal to the longitudinal size of the photonic crystal heterostructure, which ensures that all the probe light propagates through the photonic crystal region. The signal coupled out from the output waveguide was detected by a photo-diode, the output signal of which was extracted by a lock-in amplifier. The reference light was also recorded by use of a photon-diode connected to another lock-in amplifier. The output signals from two lock-in amplifiers were collected and analyzed by a computer. The photon intensity of the probe light propagating through the photonic crystal heterostructure was less than 50 kW/cm^2 due to the attenuation and the coupling losses. Owing to the limitation of the tunable wavelength range of the laser system, the transmission spectrum of the photonic crystal heterostructure was only measured from the wavelength range from 610 to 685 nm, as depicted in Fig. 2(a). The linear transmission was normalized to a reference MEH-PPV waveguide without the patterned region, which is a normal method widely used to study the transmission properties of two-dimensional photonic crystals.[23] It is very clear that the transmission of the 650-nm probe light was 70% for the rightward incidence case and 0.02% for the leftward incidence case. The transmission contrast reaches 3500, which is two orders of magnitude larger than that of the previous reports.[10–13] The measured results were in agreement with the calculated results by use of the three-dimensional FDTD method, as shown in Fig. 2(b). The photon intensity of the probe light propagating through the photonic crystal heterostructure was less than 50 kW/cm^2, which is reduced by seven orders of magnitude compared with that of the previous reports.[10–13] Moreover, the performance of the all-optical diode does not have any optical nonlinearity or high power requirement. Therefore, a nanoscale integrated photonic crystal all-optical diode with an ultralow-power and ultrahigh transmission contrast was realized. It is very clear from Fig. 2(a) that when the wavelength of the probe light changes from 640 to 660 nm, a transmission of 50% and 0.02% can be achieved for the rightward and leftward incidence case,

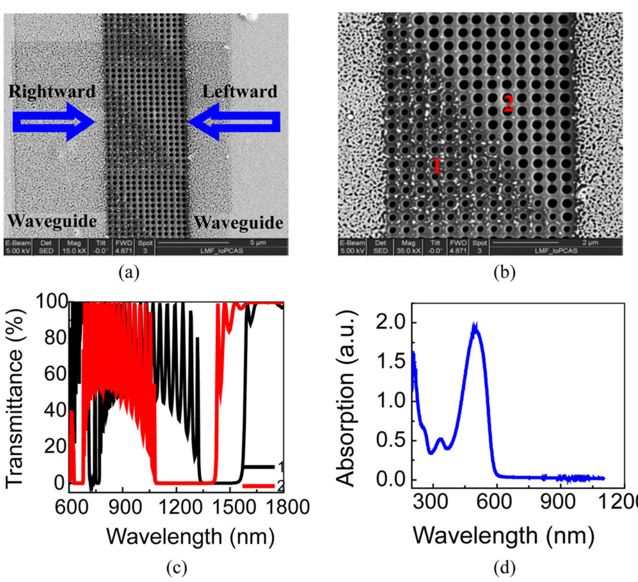

FIG. 1. (Color online) (a) Large-scale SEM image of the MEH-PPV photonic crystal heterostructure. The arrow indicates the propagation direction of the signal light. (b) Small-scale SEM image of the photonic crystal heterostructure. (c) Simulated transmission spectra of component 1 (right) and 2 (left). (d) Linear absorption spectrum of MEH-PPV films.

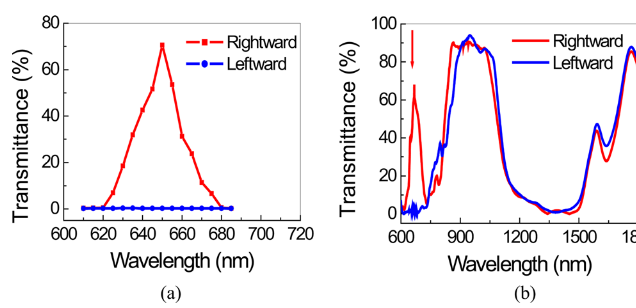

FIG. 2. (Color online) Transmission spectra of the MEH-PPV photonic crystal heterostructure (up is for rightward and down for leftward). (a) Measure results. (b) Calculated results.

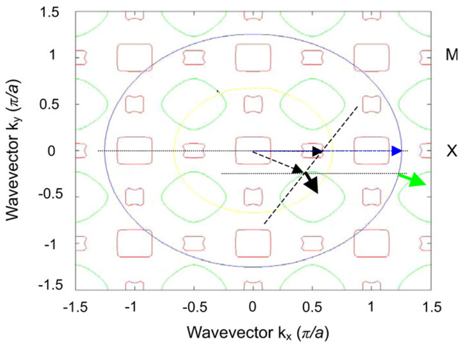

FIG. 3. (Color online) Constant -frequency contours of the photonic crystal heterostructure for the wavelength of 650 nm. The yellow and blue lines are the light cone in air and MEH-PPV, respectively. The red and green lines are the constant-frequency contours for components 1 and 2, respectively. The black and blue arrows represent the wavevectors in the component photonic crystals and the MEH-PPV optical guides, respectively. The thick arrows indicate the group-velocity directions.

respectively. High transmission contrast of 2500 can still be obtained. The operating bandwidth is much larger than the previous reports.[10–13]

To understand the physical mechanism of the unidirectional light transmission phenomenon, we calculated the constant-frequency contours of the photonic crystal heterostructure for the 650-nm incident light, as shown in Fig. 3. The large circular curve is the light cone in MEH-PPV. The rectangle- and square-shape curves are the constant-frequency contours for components 1 and 2, respectively. The thin arrows represent the wavevectors. The thick arrows indicate the group-velocity directions. For the leftward incidence case, the probe light enters into component 2 first. There is no corresponding Bloch mode existing in component 2, because the 650-nm probe light was located in the stop band in the Γ-X direction of component 2. The case is different for the rightward incident case. The wavelength of the probe light was in the pass band of component 1, and there are corresponding Bloch modes in component 1. The probe light can propagate through component 1. The probe light was strongly refracted in the heterostructure interface. Luo *et al.* have pointed out that the wavevector of the refracted propagating mode is determined by the conservation of the frequency and the wavevector component parallel to the heterostructure interface.[24] There is corresponding Bloch mode for the refracted light in component 2. Then the 650-nm incident light can propagate through the photonic crystal heterostructure.

In conclusion, we have experimentally realized an all-optical diode in a photonic crystal with broken spatial inversion symmetry. An ultralow photon intensity of 50 kW/cm^2 and an ultrahigh transmission contrast of over 10^3 are reached simultaneously, without any optical nonlinearity or high power requirement. This may offer an approach for the study of ultralow-power integrated photonic devices.

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