

# On-chip optical diode based on silicon photonic crystal heterojunctions

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**Abstract:** Optical isolation is a long pursued object with fundamental difficulty in integrated photonics. As a step towards this goal, we demonstrate the design, fabrication, and characterization of on-chip wavelength-scale optical diodes that are made from the heterojunction between two different silicon two-dimensional square-lattice photonic crystal slabs with directional bandgap mismatch and different mode transitions. The measured transmission spectra show considerable unidirectional transmission behavior, in good agreement with numerical simulations. The experimental realization of on-chip optical diodes with wavelength-scale size using all-dielectric, passive, and linear silicon photonic crystal structures may help to construct on-chip optical logical devices without nonlinearity or magnetism, and would open up a road towards photonic computers.

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**OCIS codes:** (230.1150) All-optical devices; (230.5298) Photonic crystals; (230.3240) Isolators.

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## 1. Introduction

Optical isolation is a long pursued object with fundamental difficulty in integrated photonics [1]. The need to overcome this difficulty is becoming increasingly urgent with the emergence of silicon nano-photonics [2–4], which promises to create on-chip large-scale integrated optical systems. Motivated by the one-way effect, considerable effort has been dedicated to the study of the unidirectional nonreciprocal transmission of electromagnetic waves, showing important promise in optical communications. These "optical diodes" include fluorescent dyes with a concentration gradient [5], absorbing multilayer systems [6], and second harmonic generators with a spatially varying wave vector mismatch [7]. An electro-tunable optical isolator based on liquid-crystal heterojunctions, showing nonreciprocal transmission of circularly polarized light in photonic bandgap regions, has been reported [8]. In another configuration using liquid crystals, linearly polarized light is used [9]. In addition to many attempts on magneto-optical materials [10–13], optical isolators have also been fabricated using nonlinear optical processes [14,15] and electro-absorption modulators [16]. A theoretical scheme of optical isolation achieved by dynamically inducing indirect photonic transitions in an appropriately designed photonic structure was reported [17]. Other reported optical isolators are generally based on photonic crystals (PCs), which are dielectric or metallo-dielectric structures with a spatial periodicity in their refractive index [18,19]. This periodicity affects the propagation of electromagnetic waves in the same way as the periodic potential in a semiconductor crystal affects electron motion by defining allowed photonic bands and forbidden bandgaps [19]. For example, a one-dimensional photonic crystal structure having a nonlinear optical response and a two-dimensional (2D) photonic crystal waveguide with an asymmetric array of nonlinear defect rods [20–22] are found to display nonreciprocal effects. In these cases, however, optical isolation occurs only for specific high power ranges or with associated modulation side bands. In addition, there have been works that aim to achieve partial optical isolation in reciprocal structures that have no inversion symmetry (for example, chiral structures). Until now, on-chip integration of optical diode still stays in theory, particularly in silicon.

An efficient routine to create optical diode is via time-reversal symmetry breaking [5–17, 20–22] or spatial inversion symmetry breaking [23, 24]. Both effects could lead to the optical isolation in any device where the forward and backward transmissivity of light is very much different. Recently a unidirectional sound propagation has been reported in sonic-crystal-based acoustic diodes with a completely linear system [25]. In this paper, we report a method for making unidirectional on-chip optical diodes based on the directional bandgap difference

of two 2D square-lattice photonic crystals comprising a heterojunction structure and the break of the spatial inversion symmetry. Simulations confirm the existence of a clear isolation effect in the designed heterojunction structure. We fabricate these on-chip optical diodes in silicon and the near-infrared experiment results show high-performance optical isolation, in good agreement with the theoretical prediction. This device may play the same basic role in photonic circuits as the electrical diode does in electronic circuits. It could further pave the way to achieve on-chip optical logical devices without nonlinearity or magnetism and bloom the photonic network integration.

## 2. Simulation and results

Figure 1(a) shows the schematic configuration of the original diode structure under study, which consists of two PC slab domains ( $PC_1$  and  $PC_2$ ) with the same lattice constant  $a$  but different air hole radii ( $r_1$  and  $r_2$ , respectively) comprising a heterojunction structure. These two PC regions stand at a silicon slab [grey area in Fig. 1(a)]. Each PC region has a square-lattice pattern of air holes [white holes in Fig. 1(a)], with the hetero-interface between  $PC_1$  and  $PC_2$  along the  $\Gamma$ -M direction. Here we set the two hole radii as a fixed ratio to the lattice constant  $a$ , which are  $r_1 = 0.24a$  and  $r_2 = 0.36a$  in order to simplify our discussion. These two composite PCs would comprise a pure PC region if  $r_1 = r_2$ . The light source is placed symmetrically aside the structure with two  $4a$ -wide ridge waveguides connecting the surface of the two PC regions. The whole area is surrounded by a perfectly matched layer.

We simulated the transmission spectra for a TE-like light signal transporting along the forward (from left to right) and backward (from right to left) direction using the three-dimensional finite-difference time-domain (3D-FDTD) method [26]. The refractive index of the dielectric slab was set to 3.4, corresponding to that of silicon at 1,550 nm. The slab thickness was  $h = 0.5a$ . Note that all geometric parameters are constant and normalized by the PC lattice constant  $a$ . Figure 1(b) shows the calculated forward (black line) and backward (red line) transmission spectra. The frequency is normalized by  $a/\lambda$ . It is clearly seen that there exists an isolation band ranging from 0.2649 to 0.2958 ( $a/\lambda$ ), where the forward transmission forms a peak with a transmissivity of about 6% while the backward transmissivity is down between 0.5% and 1%. The forward peak is located at 0.2793 ( $a/\lambda$ ), just in the middle of the isolation band. We define  $S = (T_F - T_B)/(T_F + T_B)$  as the signal contrast of the diode, where  $T_F$  and  $T_B$  denote the forward and backward transmissivity, respectively. The maximum  $S$  of this original diode equals 0.846 at the peak. Besides, there exists another isolation region from 0.2196 to 0.2649 ( $a/\lambda$ ), where the backward transmissivity is higher than the forward transmissivity. This structure thus shows an extraordinary phenomenon of unidirectional transport property. When we set the interface of the hetero-junction as normal to the  $\Gamma$ -X direction of both  $PC_1$  and  $PC_2$ , the simulation result shows no isolation phenomenon. This indicates that the isolation happens only when the hetero-junction is tilted.

The TE-like electromagnetic field distributions of the forward and backward transport of light at 0.2793 ( $a/\lambda$ ) are calculated in order to have a visual sight of the detailed characteristic of optical isolation [Figs. 1(c) and 1(d)]. In Fig. 1(c), light goes straight in  $PC_1$  and reaches the heterojunction interface. Then one part of light reflects at the junction and goes downward; the other part of light travels along the junction and diffracts into  $PC_2$ , which eventually outputs from  $PC_2$  into the connected waveguide. But in Fig. 1(d), light cannot go straight but separates into two  $45^\circ$ -direction paths, which fit the  $\Gamma$ -M direction of a square-lattice photonic crystal. Most of light is lost and there is little light reaching the output waveguide. It is thus the different choice of light path that leads to the difference between the forward and backward transmission.

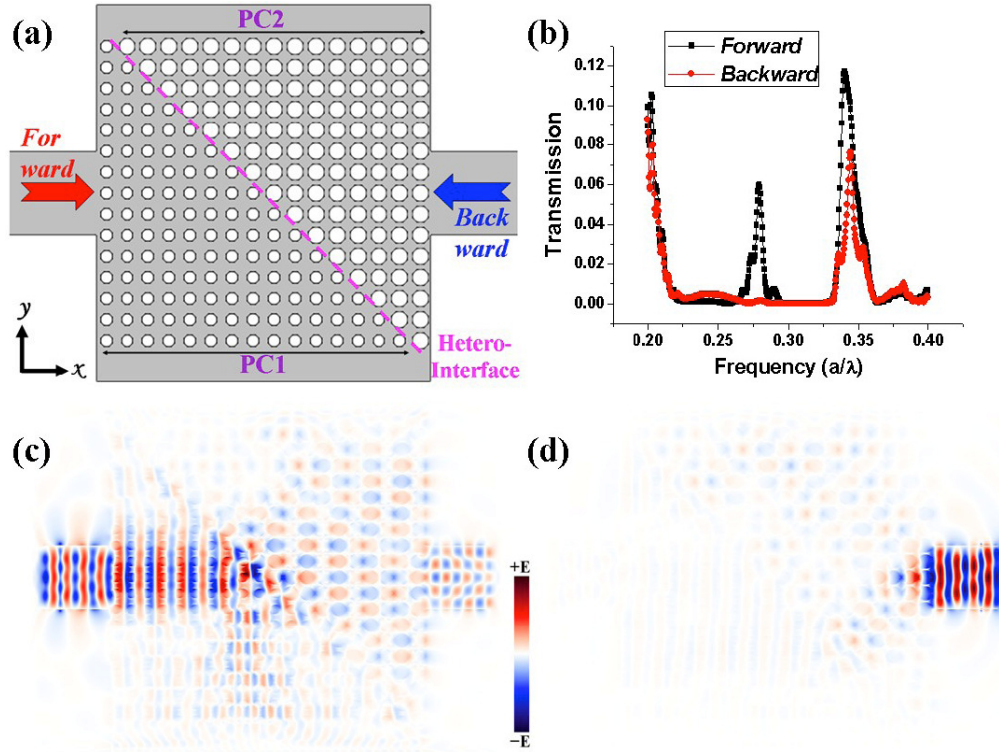


Fig. 1. (a) Schematic geometry of an original heterojunction optical diode formed by the interface (normal to the  $\Gamma$ -M direction) between two PC slabs (denoted as PC<sub>1</sub> and PC<sub>2</sub>) with different hole radii ( $r_1$  and  $r_2$ , respectively). (b) Simulated transmission spectra of the diode in the forward direction (the black line) and the backward direction (the red line). An input and output ridge waveguide has been used in the 3D-FDTD calculation. (c),(d) Calculated TE-like mode  $E_y$  field distribution at  $0.2793 (a/\lambda)$  in the forward and backward direction, respectively.

To have a deeper understanding of the isolation effect, we calculated the band diagram of the TE-like modes of these two PC slabs using the 3D-FDTD method. Figures 2(a) and 2(b) show the calculation results. The first band (even mode) in bulk PC<sub>2</sub> [Fig. 2(b)] is directional as the top mode frequency in the  $\Gamma$ -X direction ( $x$ -axis) is  $0.2345 (a/\lambda)$  but that in the  $\Gamma$ -M direction ( $45^\circ$ -direction) is  $0.3087 (a/\lambda)$ . Inside the region between  $0.2345 (a/\lambda)$  and  $0.3087 (a/\lambda)$ , the all-directional transparent region of PC<sub>1</sub> needs to be above  $0.2633 (a/\lambda)$  [Fig. 2(a)] in order to match the bottom mode frequency in the  $\Gamma$ -X direction of the second band (odd mode). These two modes in PCs are the basic working mode of the diode structure. Here the even and odd modes are defined with respect to the off-slab mirror-reflection symmetry  $\sigma_z$  of the field component  $E_y$ . In the region between  $0.2633 (a/\lambda)$  and  $0.3087 (a/\lambda)$  PC<sub>1</sub> is transparent in all directions, while PC<sub>2</sub> is transparent along the  $\Gamma$ -M direction but opaque along the  $\Gamma$ -X direction. Compared with Fig. 1(b), the isolation region [ $0.2649$  to  $0.2958 (a/\lambda)$ ] just coincides with the overlapped region between the directional bandgap of PC<sub>2</sub> and the all-directional pass band of PC<sub>1</sub>. This simple picture indicates that the current isolation effect involves two ingredients: (I) directional bandgap of PC<sub>2</sub> and (II) all-directional pass band of PC<sub>1</sub>. Noting that the structure does not obey the spatial inversion symmetry along the propagating direction, the principle of optical isolation can thus be summarized as follows:

- 1) Forward transport. When light goes across PC<sub>1</sub> as the odd mode and reaches the hetero-junction along the  $\Gamma$ -X direction, it cannot stay in the  $\Gamma$ -X direction in PC<sub>2</sub> further because of the  $\Gamma$ -X directional gap. But the hetero-junction is along the  $\Gamma$ -M direction, so light turns to the hetero-junction and diffracts as the even mode at any  $\Gamma$ -M direction into PC<sub>2</sub>, which passes through PC<sub>2</sub> and eventually outputs.

- 2) Backward transport. When light goes directly into PC<sub>2</sub> as the even mode, it turns to the two  $\Gamma$ -M direction paths which cannot convert to the odd mode of PC<sub>1</sub> in the  $\Gamma$ -X direction and eventually leak out so that it does not output.

Another point that should be explained is that the main diode structure is a quasi-diffraction structure with a PC heterojunction. The ridge waveguides attached to the PC heterojunction are only for experiment convenience. The band diagram of the TE-like modes of these two PC slabs (Fig. 2) not only gives us the directional bandgap difference, but also shows that every frequency has only one corresponding eigenmode distribution in the two PCs individually in the working frequency region of diode. All other input/output modes from the waveguide should first couple into/out of these two working eigenmodes, indicating the input mode pattern does not affect the diode property. We further find that the output mode conversion is output-waveguide-width related and the only reason is that it is caused by the coupling between PC<sub>2</sub> and output waveguide. This indicates that we can change the type or the shape of the output waveguide to improve the coupling but the diode effect remains the same. And due to its modular design, the mode conversion problem also can be solved by adding other modules. This character also shows the advantages in optical integration that it has no self-needed situation which could affect other devices and that it is easy to integrate with other devices.

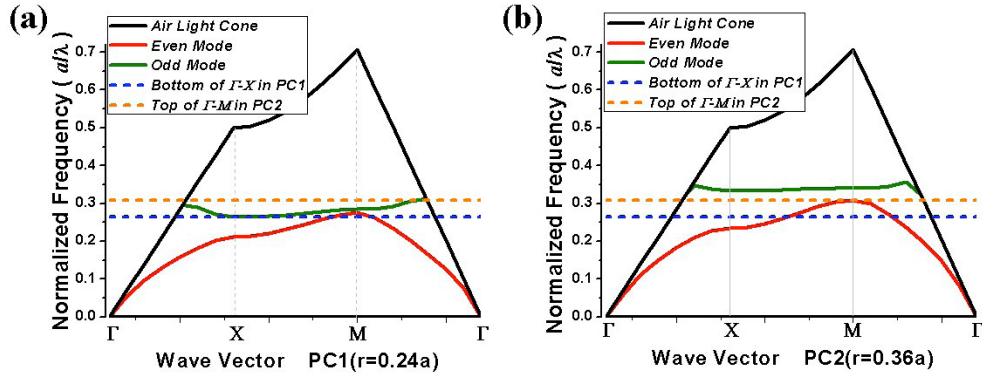


Fig. 2. (a) Calculated modal dispersion curve for PC<sub>1</sub> ( $r = 0.24a$ ). (b) Calculated modal dispersion curve for PC<sub>2</sub> ( $r = 0.36a$ ), in which the black line is the air light cone. The red curve denotes the first even mode, while the green curve denotes the second odd mode. The blue dashed line denotes the bottom frequency of the  $\Gamma$ -X directional odd mode [0.2633 ( $a/\lambda$ )] of PC<sub>1</sub> and the orange dashed line denotes the top frequency of the  $\Gamma$ -M directional even mode of PC<sub>2</sub> [0.3087 ( $a/\lambda$ )].

As we have known that it is the directional bandgap difference that causes the isolation effect, next we change the original diode into the revised structure [Fig. 3(a)] in order to ensure the backward transmission to be zero and to increase the magnitude of the forward transmission peak as much as possible. In Fig. 3(b) the isolation region still ranges from 0.2625 to 0.3050 ( $a/\lambda$ ). The simulation values of the backward transmission in the isolation region generally decrease a half compared with that of the original structure and at the same time the forward peak reaches about 13% of the input power at the frequency of 0.2834 ( $a/\lambda$ ). The maximum signal contrast  $S$  of the revised structure increases to 0.92 at the peak, which is near the value of the present electronic diodes. In addition, the region where the backward transmissivity is higher than the forward transmissivity is gone as the structure is no longer  $y$ -axis mirror symmetric. The TE-like electromagnetic field distributions of the forward and the backward transport of light signals are calculated [Figs. 3(c) and 3(d)]. It is clear that light signals are all guided out of the structure in the backward path [Fig. 3(d)] due to the  $\Gamma$ -M directional bandgap of PC<sub>2</sub> in contrast to the strong coupling into the output waveguide in the forward path [Fig. 3(c)].



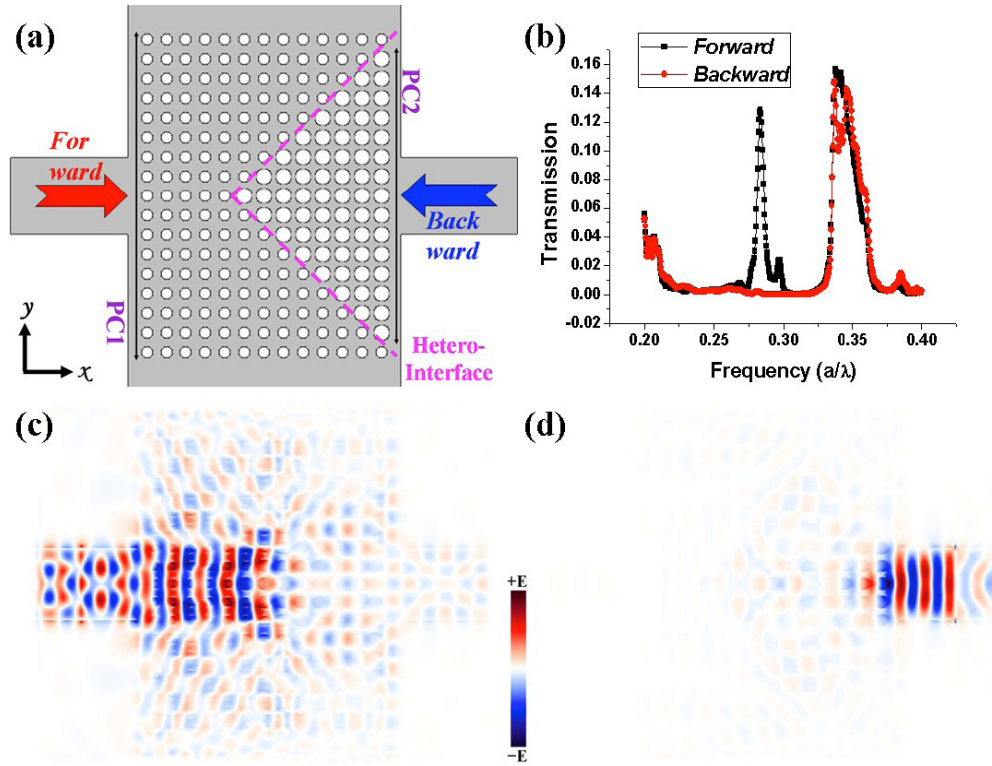


Fig. 3. (a) Schematic geometry of the revised diode structure formed by two heterojunction interfaces (normal to two  $\Gamma$ -M directions) between two PC slabs. (b) Simulated transmission spectra of the revised diode structure in the forward direction (the black line) and the backward direction (the red line). (c),(d) Calculated TE-like mode  $E_y$  field distribution at 0.2834 ( $a/\lambda$ ) in the forward and backward direction, respectively.

### 3. Experiment and discussion

Based on the numerical analysis of the optical diode, the revised diode structures together with the original structures were fabricated in silicon. The patterns were first defined in resist using the electron beam lithography (EBL) on the top layer of a silicon-on-insulator (SOI) chip. The resist patterns were then transferred to silicon layer using the inductive coupled plasma reactive ion etching (ICP) technique. The lattice constant  $a$  was set to 440 nm so that the radii  $r_1$  and  $r_2$  were approximately equal to 110 nm and 160 nm. The slab thickness was 220 nm. The insulator layer ( $\text{SiO}_2$ ) underneath the silicon pattern regions was finally removed by a HF solution to form an air-bridged structure. Figures 4(a) and 4(c) show the scanning electron microscopy (SEM) images of the fabricated diode structures along the light path. Light from a semiconductor laser, which is tunable between 1,500 nm and 1,640 nm, was directly coupled into the photonic crystal heterojunction diode with the aid of tapered ridge waveguides in the input and output ends [27]. The wavelength region is normalized to 0.2683–0.2933 ( $a/\lambda$ ), enough to encompass the isolation region.

Figures 4(b) and 4(d) show the theoretical and experimental results of the transmission spectra of the diodes in the forward and backward directions. In Fig. 4(b) the theoretical forward peak of the original diode structure is at 1,575 nm [0.2793 ( $a/\lambda$ )] and the maximum transmissivity is 6%. The experimental forward peak is at 1,556 nm and the maximum transmissivity is 7%. In Fig. 4(d) the experimental forward peak is at 1,534 nm and the maximum transmissivity is 10% for the revised diode, whereas the theoretical forward peak is at 1,552 nm [0.2834 ( $a/\lambda$ )] with a transmissivity of 13%. The measured signal contrast  $S$  equals 0.718 (the original structure) and 0.831 (the revised structure) at the peak frequency.

Both experimental peaks in Figs. 4(b) and 4(d) have a near 20 nm shift and 50 nm broadening against the theoretical simulations, which is probably due to the imperfections in fabrication. The experiment confirms the existence of the isolation effect in agreement with the theoretical prediction. Due to the arbitrariness of the lattice constant  $a$ , we can freely adjust the isolation frequency to anywhere as desired. This could be more convenient for the design of realistic photonic devices.

The principle for optical diode as analyzed in the above is robust as it is based on a simple directional bandgap mismatch effect of photonic crystal heterojunction. Yet, it should be noticed that in Figs. 4(b) and 4(d) the backward transmissions are fluctuating within 1% to 2% and both are higher than the simulation values, as a result, the signal contrast  $S$  degrades from 0.846 (the original structure, 0.92 in the revised structure) in theory to 0.718 (the original structure, 0.831 in the revised structure) in experiment. The performance improvement of the diode relies on how to maximize the peak of the forward transmissivity and minimize the backward transmissivity in experiment. Several means can help improve the forward transmissivity. First, one can change the air hole size of  $PC_1$  and  $PC_2$  and enlarge the directional bandgap. Calculations show that the forward peak transmissivity of the revised structure with  $r_1 = 0.30a$  and  $r_2 = 0.45a$  grows up dramatically to 29.4% while maintaining the same low level of backward transmissivity. Second, one can change the relative size of the input and output waveguides. Calculations show that by changing the input waveguide width to  $2a$  and keeping the output waveguide width  $4a$ , the forward peak signal increases up to 20.8% in transmissivity.

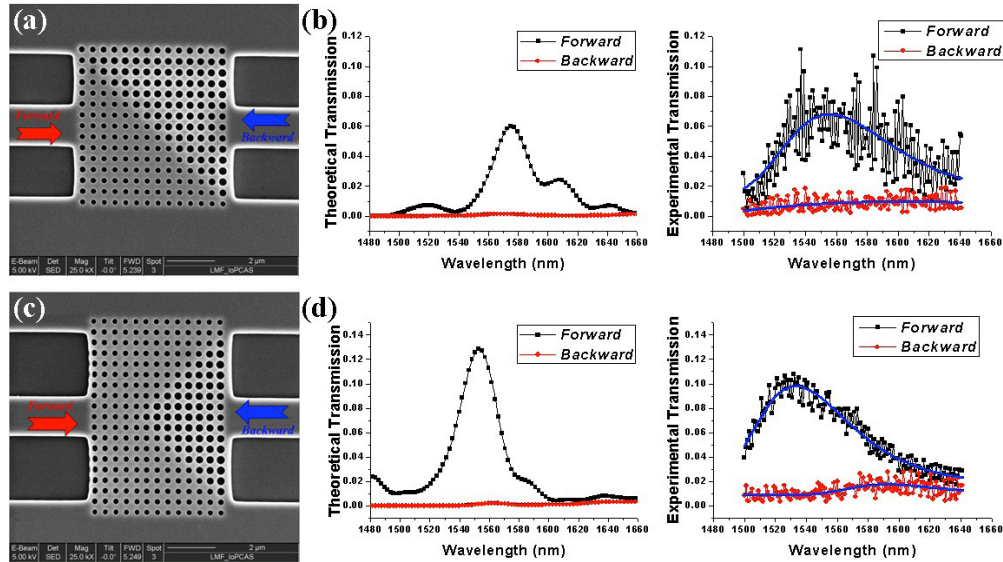


Fig. 4. (a) Scanning electron microscope images of the original optical diode structures. (b) Theoretical [left, part of Fig. 1(b)] and experimental (right) transmission spectra of the original diode structure. (c) Scanning electron microscope images of the revised optical diode structures. (d) Theoretical [left, part of Fig. 3(b)] and experimental (right) transmission spectra of the revised diode structure.

To reduce the backward transmissivity, one can either enlarge the directional bandgap of  $PC_2$  to attenuate the backward signal more strongly, or eliminate the return of leak-out light from the outside of slab or the structure boundary by introducing the absorbing metal dots near the structure, or enlarge the heterojunction structure appropriately so that the leak-out light cannot enter the output waveguide. Following the above general ideas, we further optimize the optical diode structures as illustrated in Fig. 5. The structure has parameters of  $r_1 = 100$  nm and  $r_2 = 160$  nm, and the input and output waveguide width are  $2a$  and  $6a$ , respectively. In experiment, we have got an optical diode with an average of 21.3% of the

forward peak transmissivity and 0.885 of the signal contrast  $S$  at 1,557 nm. Yet, the backward signal intensity is still not reduced to the low level predicted by theory. The performance improvement eventually depends on the nanofabrication precision, as structural disorders or imperfections will induce light scattering to background and reduce the signal contrast. There is also insertion loss due to the impedance mismatch between the photonic crystal heterojunction and the input and output ridge waveguides. This insertion loss problem might be solved by adjusting the geometries of the two connection regions.

Note that the above optical diode based on photonic crystal heterojunctions has a scale about  $14a \times 14a$  (or  $6 \times 6 \mu\text{m}^2$ ), which is much smaller than those constructed based on the scheme of periodic scattering gratings [23–25]. This small size scale can be very beneficial for optical integration in silicon chip.

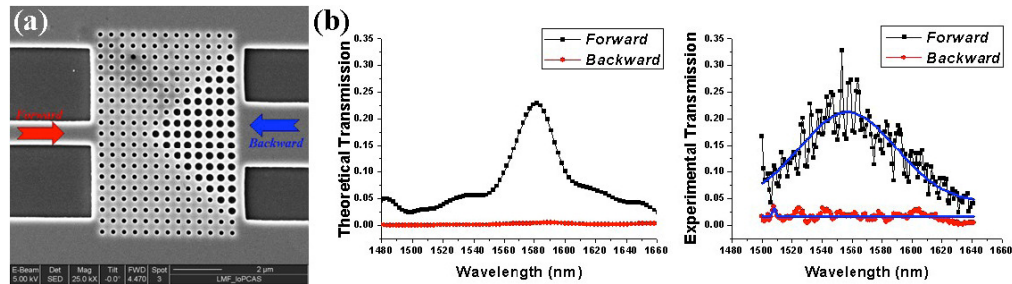


Fig. 5. (a) Scanning electron microscope images of the optimized optical diode system. (b) Theoretical (left) and experimental (right) transmission spectra of the optimized diode structure.

#### 4. Conclusion

Our photonic crystal heterojunction diode has advantages of high signal contrast, wavelength-scale small sizes, and being all-dielectric, linear, and passive. Furthermore, it has a much smaller scale than those based on diffraction gratings and thus greatly facilitates large-scale integration. The high performance on-chip optical diode realized in silicon without nonlinearity or magnetism will stimulate the exploration of other more complex on-chip optical logical devices with ultra-high stability, integration and much less power consumption. Such an optical diode may play the same basic role in photonic circuits as the electrical diodes do in electronic circuits, which have significantly revolutionized fundamental science and advanced technology in various aspects of our routine life due to their capability of rectification of current flux. Furthermore, its large-scale fabrication could be readily achieved by the well-developed CMOS techniques. The realization of high-performance on-chip optical diodes may open up a road toward photonic computers.

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