Asymmetric Mach-Zehnder filter based on self-collimation phenomenon in two-dimensional photonic crystals

Teun-Teun Kim,[1] Sun-Goo Lee,[2] Hae Yong Park,[1] Jae-Eun Kim[1,*] and Chul-Sik Kee,[3,4]

[1]*Department of Physics, KAIST, Daejon ~305-701, Korea*
[2]*Photonics Research Laboratory, Division of Intelligent System Research, Korea Institute of Science and Technology (KIST), Seoul 130-791, Korea*
[3]*Nanophotonics Laboratory, Advanced Photonics Research Institute and School of Photon* Science and Technology, GIST, Gwangju 500-712, Korea
[4]*cskee@gist.ac.kr*
**Jekim@kaist.ac.kr;*

Abstract: A two-dimensional photonic crystal asymmetric Mach-Zehnder filter (AMZF) based on the self-collimation effect is studied by numerical simulations and experimental measurements in microwave region. A self-collimated beam is effectively controlled by employing line-defect beam splitters and mirrors. The measured transmission spectra at the two output ports of the AMZF sinusoidally oscillate with the phase difference of π in the self-collimation frequency range. Position of the transmission peaks and dips can be controlled by varying the size of the defect rod of perfect mirrors, and therefore this AMZF can be used as a tunable power filter.

OCIS codes: (230.5298) Photonic crystals; (260.2030) Dispersion; (310.1210) Antireflection coatings; (070.2615) Frequency filtering.

References and links

1. J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, NJ, 1995).
2. S. G. Johnson, P. Villeneuve, S. Fan, and J. Joannopoulos, "Linear waveguides in photonic-crystal slabs," Phys. Rev. B **62**(12), 8212–8222 (2000).
3. D. Zhao, J. Zhang, P. Yao, X. Jiang, and X. Chen, "Photonic crystal Mach-Zehnder interferometer based on self-collimation," Appl. Phys. Lett. **90**(23), 231114 (2007).
4. Y. Zhang, Y. Zhang, and B. Li, "Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals," Opt. Express **15**(15), 9287–9292 (2007).
5. H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakami, "Superprism phenomena in photonic crystals," Phys. Rev. B **58**(16), R10096–R10099 (1998).
6. J. Witzens, M. Loncar, and A. Scherer, "Self-collimation in planar photonic crystals," IEEE J. Sel. Top. Quantum Electron. **8**(6), 1246–1257 (2002).
7. S. Shi, A. Sharkawy, C. Chen, D. M. Pustai, and D. W. Prather, "Dispersion-based beam splitter in photonic crystals," Opt. Lett. **29**(6), 617–619 (2004).
8. D. W. Prather, S. Shi, D. M. Pustai, C. Chen, S. Venkataraman, A. Sharkawy, G. J. Schneider, and J. Murakowski, "Dispersion-based optical routing in photonic crystals," Opt. Lett. **29**(1), 50–52 (2004).
9. D. M. Pustai, S. Shi, C. Chen, A. Sharkawy, and D. W. Prather, "Analysis of splitters for self-collimated beams in planar photonic crystals," Opt. Express **12**(9), 1823–1831 (2004).
10. S.-G. Lee, S. S. Oh, J.-E. Kim, H. Y. Park, and C.-S. Kee, "Line-defect-induced bending and splitting of self-collimated beams in two-dimensional photonic crystals," Appl. Phys. Lett. **87**(18), 181106 (2005).
11. M.-W. Kim, S.-G. Lee, T.-T. Kim, J.-E. Kim, H. Y. Park, and C.-S. Kee, "Experimental demonstration of bending and splitting of self-collimated beams in two-dimensional photonic crystals," Appl. Phys. Lett. **90**(11), 113121 (2007).
12. S.-G. Lee, J.-S. Choi, J.-E. Kim, H. Y. Park, and C.-S. Kee, "Reflection minimization at two-dimensional photonic crystal interfaces," Opt. Express **16**(6), 4270–4277 (2008).
13. X. Yu, and S. Fan, "Bends and splitters for self-collimated beams in photonic crystals," Appl. Phys. Lett. **83**(16), 3251 (2003).
14. T.-T. Kim, S.-G. Lee, M.-W. Kim, H. Y. Park, and J.-E. Kim, "Experimental demonstration of reflection minimization at two-dimensional photonic crystal interfaces via antireflection structures," Appl. Phys. Lett. **95**(1), 011119 (2009).
15. A. W. Snyder, and J. D. Love, "Goos-Hänchen shift," Appl. Opt. **15**(1), 236–238 (1976).

#123314 - $15.00 USD Received 26 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 1 Mar 2010

16. A. F. Matthews, and Y. S. Kivshar, “Tunable Goos-Hänchen shift for the self-collimated beams in two-dimensional photonic crystals,” Phys. Lett. A **372**, 3098–3101 (2008).
17. A. F. Matthews, and Y. S. Kivshar, “Experimental studies of the internal Goos-Hänchen shift for self-collimated beams in two-dimensional microwave photonic crystals,” Appl. Phys. Lett. **93**(13), 131901 (2008).
18. A. Taflove, *Computational Electrodynamics*: *The Finite-Difference Time-Domain Method*, (2nd Ed. Artech House INC, Norwood, 2000).
19. D. M. Pozar, *Microwave Engineering*, (John Wiley & Sons, New York, 1998), Chap. 3.2.

1. Introduction

Photonic crystals (PCs) are multidimensional periodic structures with periods of the order of electromagnetic wavelengths that can be designed by the photonic band theory [1]. The most important property of PCs is the existence of photonic bandgaps (PBGs) in which light propagation is completely prohibited in any direction [2]. Since PBGs of a PC provide a powerful way to control wave propagation, PCs have several potential applications to photonic integrated circuits (PICs) [3,4]. In particular, light can be controlled to propagate without diffraction along the incident direction of the source beam, which is called the self-collimation phenomenon of light in PCs [5,6]. It is known that the self-collimated beams can be bent at the crystal-air interface, and split into two beams by introducing defects in the PC [7–12]. Moreover, self-collimated beams can be crossed without cross talk, hence optical devices based on the self-collimating property of light beams in PCs have potential for high density PICs.

Recently, Zhao *et al* proposed a PC Mach-Zehnder interferometer (MZI) by utilizing the self-collimated beams [3]. Despite the promising applications, there have been no studies on the wavelength filters for self-collimated beams. Since the self-collimation phenomenon occurs due to the dispersion properties of propagating modes in PCs, not due to the existence of PBGs, it is very difficult to couple the self-collimated beams with the defect modes, and the reflection at the ends of finite PC structures causes crucial performance problems of devices. For these reasons, it is hard to design the wavelength filters of high performance for self-collimated beams. Very recently, it is demonstrated that the unnecessary reflections at the interfaces between a PC and homogeneous background material are effectively minimized by adding antireflection structures (ARS) which can be optimized by varying the radii of rods (holes) of the ARS and the distance between the ARS and the PC truncation [13,14]. Using this method, it is possible to improve the performance of optical devices which make use of self-collimation of light in a PC.

In this paper, we propose a design of a 2D PC asymmetric Mach-Zehnder filter (PC-AMZF) based on the self-collimation effect in a 2D PC and experimentally demonstrate its transmission characteristics in microwave region. This PC-AMZF utilizes the property of self-collimated beams that can be effectively steered by employing line-defect beam splitters and mirrors. Unwanted reflections at the interfaces between a uniform dielectric and the 2D PC is suppressed by introducing the ARS at the input and output interfaces of the PC. Also it is demonstrated that the geometric modification of the perfect mirrors based on the Goos-Hänchen (GH) shift [15] makes the control of the peak frequencies possible. The GH shift was shown experimentally utilizing the self-collimated beam reflected from the surface of a 2D PC and a method for controlling the beam reflection was proposed by modifying the size of surface rods [16,17]. The measured transmission spectra are compared with the numerical ones obtained by the finite-difference time-domain (FDTD) simulations [18].

#123314 - $15.00 USD Received 26 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 1 Mar 2010

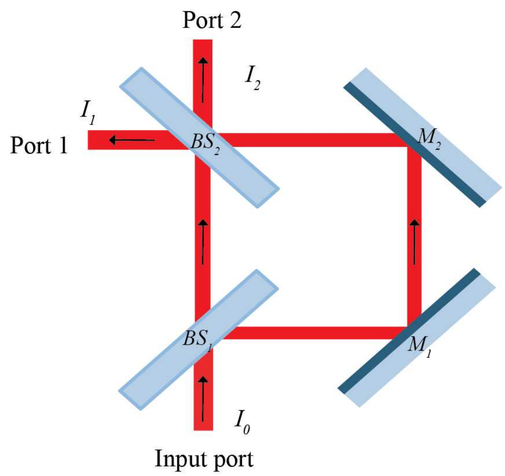

Fig. 1. Asymmetric Mach-Zehnder interferometer composed of two 50:50 beam splitters and two mirrors. Arrows indicate the direction of light propagation.

2. Design and operation principle

The basic AMZF composed of two 50:50 beam splitters and two totally reflecting mirrors is shown in Fig. 1. When a light beam of intensity I_0 is launched into the input port of AMZF, the two beam splitters result in four self-collimated beams, each with intensity $I_0/4$ at the output side beam splitter BS_2. At each of the two output ports, two self-collimated beams with the intensity $I_0/4$ each are added and interfere, and the resulting output intensities are given by

$$I_1 = I_0 \sin^2(\frac{\delta}{2}) \tag{1}$$

at port 1and

$$I_2 = I_0 \cos^2(\frac{\delta}{2}) \tag{2}$$

at port 2, respectively. Here δ is the phase difference between the two beams with the intensity $I_0/4$ each which interfere at each output port, and we use the fact that the phase difference δ between the two split beams at each beam splitter, BS_1 or BS_2 is $\pi/2$ in the PC [3].

3. Experimental setup

The experimental layout, depicted in Fig. 2(a), consists of a network analyzer (Agilent HP8720B) and two microwave horn antennas (ETS Lindgren 3160-08). The source and receiver horn antennas are set to pass TM (the electric field parallel to the axes of alumina rods) polarized microwaves. The resulting frequency-dependent data were normalized with the transmittance measured without the PC sample to remove any loss or other problems caused by cables or connecting parts of the setup. The 2D PC sample composed of alumina is constructed by boring holes through two aluminum plates which are separated by spacers. These two parallel aluminum plates can ensure TM polarized microwaves [19]. The 2D PC-AMZF shown in Fig. 2(b) is composed of $29\sqrt{2}a \times 29\sqrt{2}a$ square array of cylindrical rods in air with two 50:50 beam splitters and two perfect mirrors. A first band gap of this structure ranges from 14.39 to 19.92 GHz. The cylindrical rods of the radius r = 2 mm, length l = 100 mm, and the lattice constant a = 5 mm, are made of alumina with the dielectric constant of $\varepsilon \approx 9.7$. The line-defect beam splitters BS_1 and BS_2 are composed of 17 rods arrayed in the ΓX direction with the radius r_d different from those of host rods. The perfect mirrors M_1 and M_2 are made by removing two rows of 17 rods along the ΓX direction. The components BS_2 and

#123314 - $15.00 USD Received 26 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 1 Mar 2010

M_2 are oriented along the opposite ΓX direction with the components BS_1 and M_1. ARS with the radius of rods R_{ARS} = 1.15 mm is introduced at the input and output interfaces of the PC-AMZF to minimize the coupling loss. The distance d_{ARS} between the ARS and the PC-AMZF truncation is 3.60 mm [13,14]. From our previous work we found that this PC structure has a self-collimation region for electromagnetic waves of frequencies around 12.5 GHz along the ΓM direction [14]. In order to make the 50:50 beam splitter, we obtained the transmitted and bent powers using the FDTD simulations varying the radius of one-row line defect, r_d from 0.5 to 2.5 mm as shown in Fig. 2(c). The result obtained is shown in Fig. 2(d) and one can observe that when r_d = 1.5 mm, the bent and transmitted powers become equal.

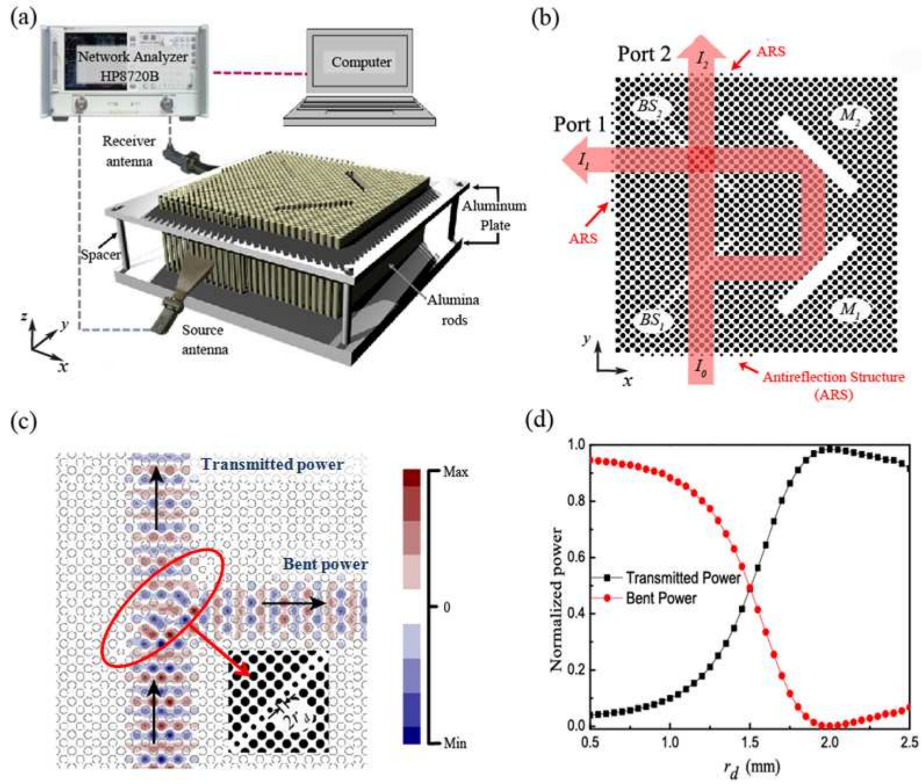

Fig. 2. (a) Schematic diagram of the experimental apparatus of a PC asymmetric Mach-Zehnder filter (AMZF). Two aluminum plates hold alumina rods vertically. (b) Layout of the square lattice 2D PC-AMZF composed of two 50:50 line-defect beam splitters and two perfect mirrors. The ARS are introduced at the input and two output ports. (c) Simulated spatial distribution of the steady-state electric field at the frequency f = 12.5 GHz in the line-defect beam splitter with the radii r_d aligned in the ΓX direction. The inset shows the top view of the beam splitter structure. (d) Power spectra for the split beams by a line-defect beam splitter as a function of the radius of defect rods r_d.

4. Result and discussion

To check the performance of the ARS, we measured the transmission spectra of the PC sample with and without the ARS and the results are displayed in Fig. 3. The measured spectra are compared with the numerically obtained ones and a good agreement exists between the two. When the ARS is not introduced, as depicted in Fig. 3(a), the transmitted light powers at port 1 and port 2 through the PC exhibit the transmission minima at the frequencies 12.44 and 12.67 GHz, respectively. Because of unwanted reflections at the interfaces between the 2D PC and the outside medium it is not possible to use this structure as

#123314 - $15.00 USD Received 26 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 1 Mar 2010

a filter in this frequency region. However, in Fig. 3(b), one can observe transmission peaks at the frequencies f_1 = 12.67 GHz for port 1 and at f_2 = 12.44 GHz for port 2, respectively in the frequency range from 12.3 to 12.8 GHz. This figure shows that the transmitted intensities at the two output ports oscillate sinusoidally with a phase difference of π. Besides the sinusoidal oscillations of the two output intensities, the performance of the PC-AMZF is significantly improved by the introduction of the ARS into the PC. With the ARS attached, almost 92% of the incident power is transmitted through the AMZF at the frequencies f_1 and f_2, and this value is more than 30% improved result compared with the case of the ARS not applied to the AMZF. The steady-state electric field distributions of the self-collimated beams which are obtained by the FDTD simulations are shown in Fig. 3(c) for the light of frequency f_1 and in Fig. 3(d) for f_2, respectively. It clearly displays that if the two light beams of frequencies f_1 and f_2 are synchronously inserted into the input port, the proposed PC-AMZF can separate them into two groups such that the light beam of frequency f_1 is emitted through port 1 and that of the frequency f_2 through port 2.

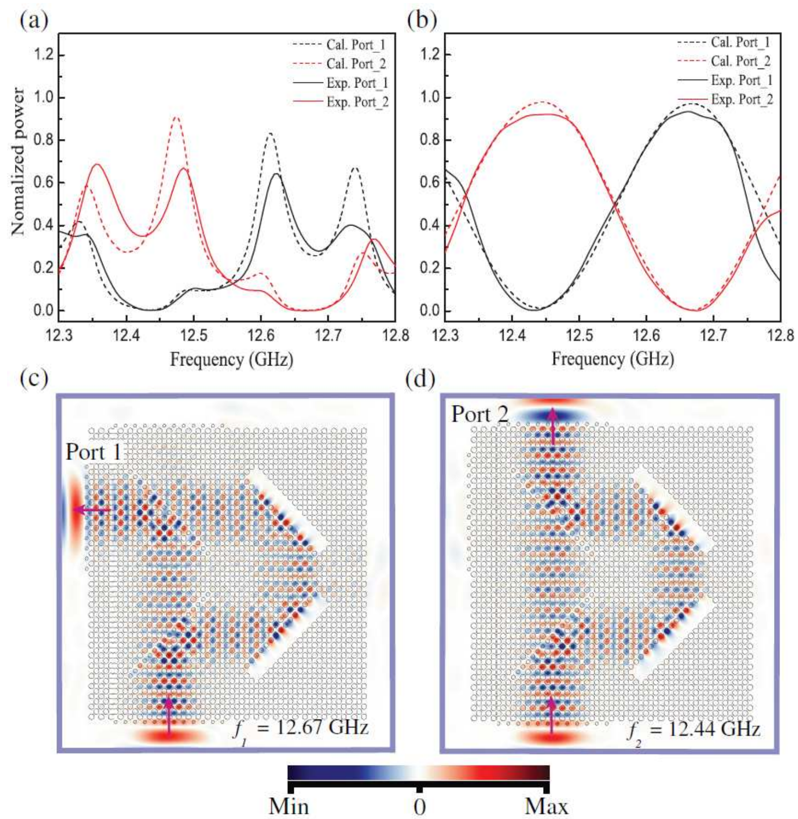

Fig. 3. Transmittance of microwaves (a) without any ARS and (b) with the ARS applied to the proposed 2D AMZF. Two solid lines represent the experimentally measured values at the two output ports, port 1 (black line) and port 2 (red line), respectively, while the dashed lines correspond to the simulation results. Simulated spatial distributions of the steady-state electric fields of the self-collimated beams at frequencies (c) f_1 = 12.67 GHz and (d) f_2 = 12.44 GHz.

Furthermore, we investigated the effect of geometric modification of the perfect mirrors. As illustrated in Fig. 4(a), two rows of 17 rods are removed along the ΓX direction out of the PC matrix and additionally, the radius of one row of rods on the front side surface, r_m is varied from 1.75 mm to 1.95 mm. When a self-collimated beam is reflected by this modified mirror, it is predicted that the phase shift is altered compared with that produced by the unmodified mirror. In the previous work, it is shown that varying the radius of the surface rods changes the effective index of the surface layer of the mirror which is caused by the change in the

#123314 - $15.00 USD Received 26 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 1 Mar 2010

filling fraction of the dielectric material [17]. Manipulation of the surface geometry or the refractive index of perfect mirror can change the duration of the confinement of power on the surface and therefore the GH shift can be modified. The measured and simulated transmission spectra for the modified mirrors are plotted in Figs. 4(b), 4(c) and 4(d) for different values of r_m. It is observed that as the value of r_m decreases, the peak frequencies shift to higher values. These results prove that it is possible to control the peak frequencies of light beams emitting out of the two output ports by adjusting the value of r_m.

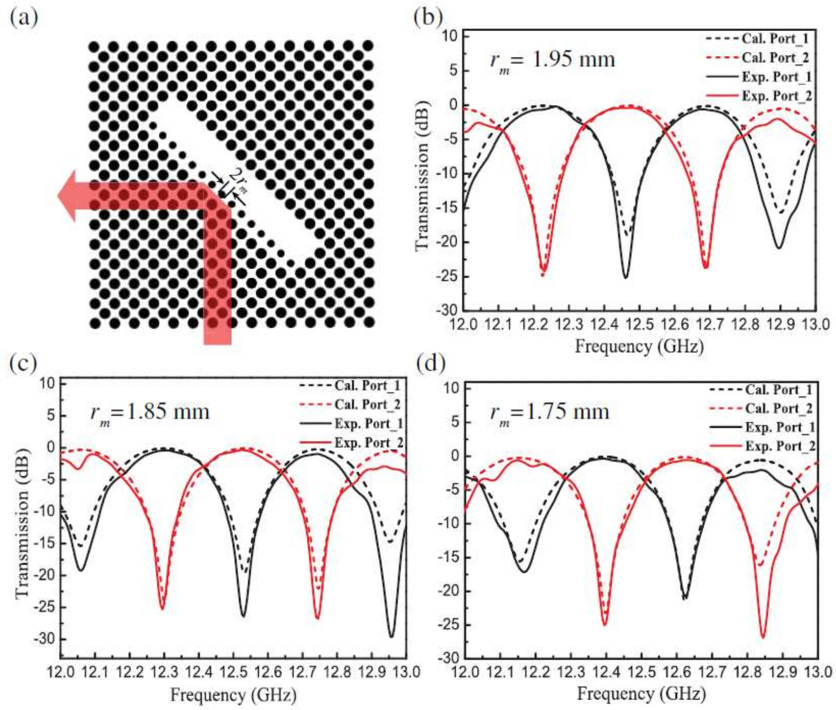

Fig. 4. Transmittance of microwaves (a) without any ARS and (b) with the ARS applied to the proposed 2D AMZF. Two solid lines represent the experimentally measured values at the two output ports, port 1 (black line) and port 2 (red line), respectively, while the dashed lines correspond to the simulation results. Simulated spatial distributions of the steady-state electric fields of the self-collimated beams at frequencies (c) f_1 = 12.67 GHz and (d) f_2 = 12.44 GHz.

5. Conclusion

In conclusion, we propose a design of a 2D PC-AMZF based on the self-collimation effect and experimentally show its transmission properties in microwave region. The ARS with the optimized parameters can effectively eliminate unnecessary reflections at the 2D PC-AMZF and thus the performance of a PC-AMZF can be significantly improved. It is shown that the measured transmission spectra at the two output ports sinusoidally oscillate with the phase difference of π, and therefore the proposed AMZF can effectively separate incoming self-collimated beams into two different output ports. Also demonstrated is that tuning of the peak frequencies can be achieved by modifying the geometry of the perfect mirrors. We expect that the proposed PC-AMZF can also be applied in the optical wavelengths region as well.

Acknowledgements

This work was partially supported by National Research Foundation of Korea Grant funded by the Korean Government (R11-2008-095-01000-0).