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K.S. WU
J.W. DONG
H.Z. WANG✉

Phase engineering of one-dimensional defective photonic crystal and applications

State Key Laboratory of Optoelectronic Materials and Technologies, Zhongshan (Sun Yat-Sen) University, Guangzhou 510275, P.R. China

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ABSTRACT It is shown in this paper that many new sensitive phase photonic crystal devices will be developed, if some existing problems can be overcome. The main problems are the rapid change of light intensity around the defect mode and the influence of the substrate. The method for overcoming these problems is to construct the defective photonic crystal in a heterostructure or an asymmetric structure. The phase properties of asymmetric one-dimensional photonic crystals with couple defects are revealed in this paper. As examples, a phase modulator and a phase switch with very high sensitivity are demonstrated.

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1 Introduction

Photonic crystals (PCs) [1, 2] are artificial periodic structures consisting of dielectric or metallic materials. The physical properties of PCs based on their band gap and defect mode have been extensively studied. Recently, many PC devices have been proposed, but most of them are based on the properties of the amplitude of light in the photonic stop band or defect mode [3–10]. Phase devices are scarcely reported.

Phase properties are the representative properties of light. Many important phenomena are related to the phase properties, such as superluminal (faster-than-light) phenomena and slow light in PCs [11–13]. Therefore, from the perspective of the basic properties, the study of the properties of phase is as important as the properties of amplitude.

In the past, signal processing (such as that used in optical communication) was carried out by an electronic system, in which only the amplitude-signal existed. Therefore, in the present optical system, only optical devices using amplitude-signals are used. Even though many PC devices have been developed, optical devices based on phase properties are still rare [14]. In the future, all-optical signal processing will show whether the amplitude- or phase-signal, is more sensitive and more advantageous to use.

✉ Fax: +86-20-84037423, E-mail: stswhz@mail.sysu.edu.cn

In this work, we find two disadvantages (problems) that restrict the development and application of phase devices in one-dimensional (1-D) defective PCs. After overcoming these disadvantages, many new physical phenomena and new application possibilities appear.

2 Phase properties of defective 1-D PC and their disadvantages

2.1 *Phase properties of defective 1-D PC*

In this work, calculations are carried out by using the transfer matrix method [15]. The band structure and the phase property of a 1-D PC with a single defect are shown in Fig. 1a and b respectively. It is well known that the sharp triangular defect mode of a single defect cavity can't satisfy the requirement of application as a filter. Couple defects are often used to form a rectangular defect mode to satisfy the requirements of the application.

The defect mode structure and the phase property of a 1-D PC with three coupled defect layers are shown in Fig. 2. This structure generates a rectangular square peak as shown in Fig. 2a, in which there are three small ripples (we call them sub-peaks). Although the sub-peak is shallow, the phase-shift of every sub-peak is 2π. The phase-shift in the whole rectangular square peak is 6π. We also study the phase properties of PCs with 5 and 10 coupled defect layers, the results are that the phase-shift of every sub-peak is 2π and the phase-shift of the whole defect mode is $2N\pi$. Furthermore, we find that the phase shifts in the sub-peaks at two sides of the defect mode will be more rapid than those in the middle of the defect mode.

However, the two problems of the phase properties of the structures mentioned above, restrict their applications, which will be discussed in the following section.

2.2 *The disadvantages of phase properties in defective 1-D PCs*

2.2.1 Rapid change of the reflected light intensity. It is clearly shown in Figs. 1 and 2 that the intensity of reflected light approaches zero at the middle of the single defect mode or the sub-peak, while away from the center the reflectance rises drastically. The drastic changing of intensity causes the phase

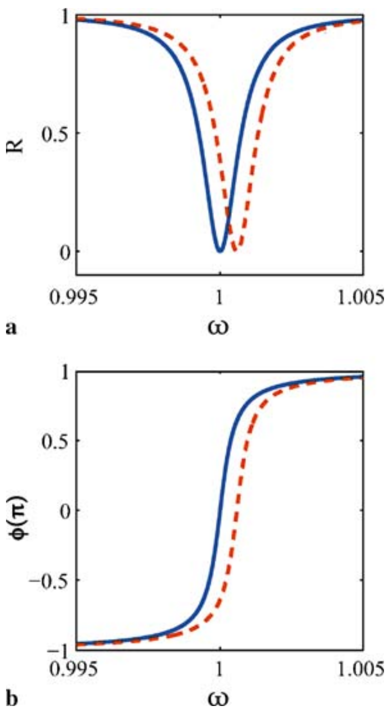

FIGURE 1 The defect mode structure (**a**) and the phase property (**b**) of a 1-D PC with single defect without a substrate, whose structure is $(HL)^4 2H(LH)^4$, $n_H = 3.3$, $n_L = 1.45$, $H = L = n_H d_H = n_L d_L = \lambda_0/4$. The *dashed lines* show the results of the refractive index in the defect layers changing by -0.1%

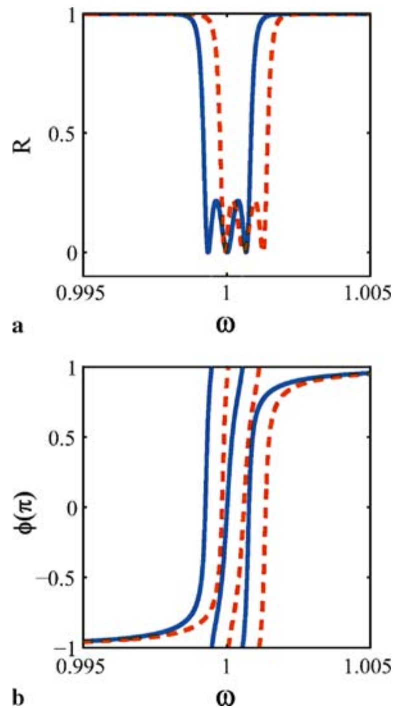

FIGURE 2 (**a**) The defect mode structure of 1-D PC with three coupled defect layers. Its structure is $(HL)^3D(LH)^3L(HL)^3D(LH)^3L(HL)^3D(LH)^3$; $n_{H2} = 3.3$, $n_L = 1.45$, $n_D = 3.6$, $D = \lambda_0/2$, $H = L = n_H d_H = n_L d_L = \lambda_0/4$; (**b**) the phase properties (*solid line*). The *dashed line* shows the result of the refractive index of the defect layer changing by -0.1%

devices to not work. This is one of the main problems to surmount.

2.2.2 Influence of the substrate. The results in Sect. 2.1 are for a defective PC without a substrate, which can't be fabricated. We have calculated for the defective PC with a substrate. The results show that the band structure and the defect mode are scarcely affected by the substrate; but the phase properties are dependent on the substrate. A result (the phase-shift of reflected light around the defect mode depends on the substrate) is shown in Fig. 3.

The two problems mentioned above make the rapidly changing phase of the defect mode useless. In the following sections we will introduce some effective methods and structures to overcome these problems.

3 Phase properties of the PC heterostructure or an asymmetric PC

In our calculations for the heterostructure, we find that the heterostructure not only can be used to broaden the photonic band gap, but also can be used for gap engineering. So we use a heterostructure to overcome the drastic changing of reflectance in the gap. Then, we can study the phase properties of the heterostructure. We have subsequently found that the phase property is dependent on the sub-structure in the front, and the rear sub-structure only plays the role of increasing the reflectance and removing the influence of the substrate. So, we constructed a defective PC with a period structure to form a PC heterostructure, from which satisfying results appeared:

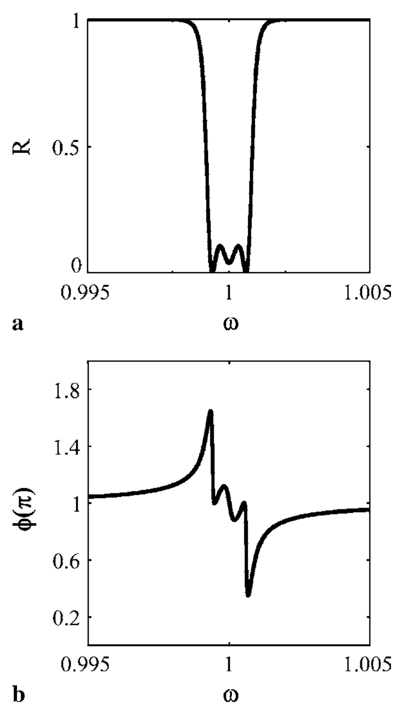

FIGURE 3 (**a**) The defect mode structure of 1-D PC with three coupled defect layers; its structure is the same as that in Fig. 2. The refractive index of the substrate is $n_s = 1.52$; (**b**) the phase-shift of reflected light around the defect mode

1. The defect mode still exists, but it is very shallow; i.e., the reflectance in the whole band gap including the peak of the defect mode approaches 1. This means that the drastic changing of intensity is overcome.

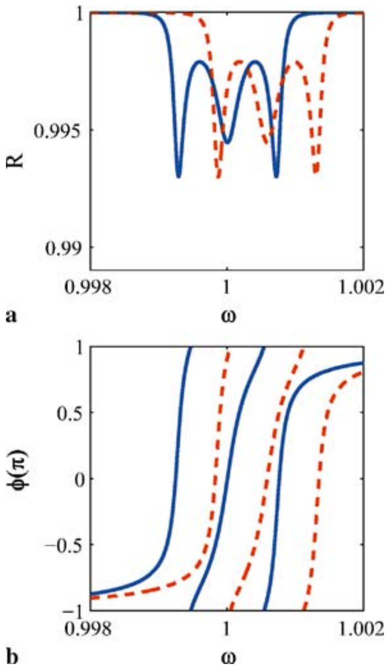

FIGURE 4 (**a**) The defect mode structure of asymmetric PC with couple defective layers. Its structure is $(HL)^3D(LH)^3L(HL)^3D(LH)^3L(HL)^3D(LH)^7$, the parameters are the same as those in Fig. 2; (**b**) the reflected phase-shift around the defect mode of this asymmetric defective PC (*solid line*). The *dashed lines* show the results of the refractive index in the defect layers changing −0.1%

2. A very interesting thing is that although the three sub-peaks in the defect mode are very shallow, the phase-shifts are still only dependent on these shallow sub-peaks, and the phase-shift for every sub-peak is still 2π.
3. No matter if with or without a substrate, the results are the same, which means that the influence of the substrate is overcome.
4. The middle part of the curve of the phase-shift is a straight line, which is suitable for the operation of a phase modulator. All of these properties provide excellent conditions for developing the phase devices. In practice, an asymmetric PC is easier to fabricate than an heterostructure, so we study the properties of the asymmetric PCs.

Our results demonstrate that the properties of asymmetric PCs are exactly the same as those of PC heterostructures. The phase properties of an asymmetric defective PC with three coupled defect layers are shown in Fig. 4. The structure in Fig. 4 is a structure with the least layers and a satisfying result. As the period layers decrease, the reflectance at the pass line peak will be 99.3% for $(LH)^7$, 97.5% for $(LH)^6$ and 82.5% for $(LH)^5$. As the period layers increase, the reflectance will increase little; but it makes the fabrication more difficult. So we choose the structure of an asymmetric PC as shown in Fig. 4.

Furthermore, we also study the properties of the asymmetric PC with 5 or 10 couple defects. The results of asymmetric PC with 10 couple defects is shown in Fig. 5. The reflectance around the defect mode is higher than 99%. The phase shift for every sub-peak is 2π, as shown in Fig. 5b. The phase shifts in the sub-peaks at two sides of the defect mode are changing much more rapidly than those in the middle of the defect mode. If we use these sub-peaks at two sides of the defect mode to design a phase device, 0.003% change of the refractive index in the defect layers is enough to operate the phase device, but to operate an amplitude signal device, as shown in Figs. 1 and 2, the refractive index of the defect layers need to change by 0.3%. This means that the sensitivity of the phase device will 100 times higher than that of the amplitude of the signal device.

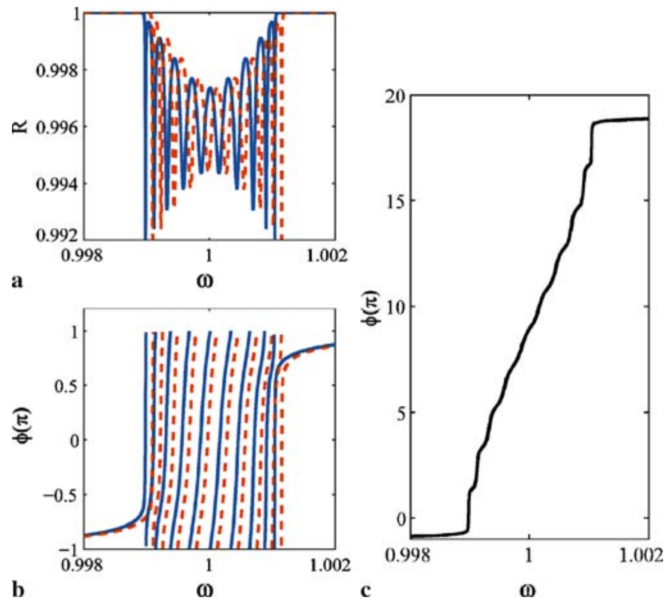

FIGURE 5 (**a**) The defect mode of 1-D PC with ten couple defects. (**b**) and (**c**) the phase-shift of reflected light around the defect mode (*solid line*); the *dashed line* shows the result of the refractive index of the defect layers changing −0.02%. R: reflectance, φ: phase, ω: normalized frequency

Figure 5c shows that the total phase shift equals 20π within a very narrow frequency range of the defect mode. It will be of significance to new research in this area of physics.

4 Examples of PC phase devices

Section 3 shows that the sensitivity of the phase device will be 100 times higher than that of the amplitude signal device after using a PC heterostructure or asymmetric PC to overcome the two problems. In this section, two phase devices are described as examples.

4.1 *Sensitive optical phase modulator*

As shown in Figs. 3–5, the phase curve around the peak frequency of every sub-peak is nearly a straight line, which benefits the use as a phase modulator, if the defect layer is an electrical field sensitive material, for example PLZT [16] and liquid crystal [17]. The phase modulator can be controlled by the electrical field, requiring only the coating of transparent electrodes onto the PC, as the material of the defect is light sensitive, such as GaAs [18]. The frequency of the control light can be both higher or equal to the signal light, which differs from the amplitude signal device.

4.2 *Sensitive phase optical switch*

According to the control sources, the optical switch can be divided into an electrically controlled optical switch and an all-optical switch. According to the signal carriers, the optical switch can be divided into an amplitude signal optical switch and a phase optical switch. As the phase optical switch has not been reported here, we only give a special example to demonstrate the high sensitivity of the phase switch, in which the input and output are amplitude signal, the phase signal only appears in the middle step.

High sensitivity of the phase-control in the defective PC cause a very weak control light (input signal), and a weak steady laser with the same frequency is enough to operate the ultra-high speed phase optical switch. If the intensity of the control beam (B_c) at "1" state is I_0; the intensity of the steady continuous wave (cw) laser is also I_0. The steady cw laser is divided into two identical beams (B_1 and B_2), B_1 inputs to the PC and the reflected light functions as the output phase-signal-beam (B_s). B_s and B_2 are the two arms of a Michelson interferometer. The PC is a total reflection mirror of one arm of the interferometer. The interferential result forms an output amplitude-signal beam; i.e. the phase switch signal will change to the amplitude switch signal automatically. We take Fig. 3 as an example for discussion. We designed the asymmetric defective PC to make the interval of sub-peaks ($\Delta\omega$) equal to twice that of the frequency-shift under an I_0 laser input, and to set the laser frequency at $1 + 0.75\Delta\omega$. As only the B_1 input to the PC, the phase shift of B_s is one π. As both B_c, with an intensity of I_0 (at the 1 state), and B_1 input to the PC, the phase of B_s is 0 (or 2π). Zero phase means a "1" or the "on" state, and a π phase means at "0" or the "off" state; i.e. if the phase-shift is zero, the output from the Michelson interferometer will be I_0; if the phase-shift is π, the output from the Michelson interferometer will be 0.

The description above has implied that sensitive phase control can be used to design optical devices. In some optical devises, some special incident angles are necessary which is not difficult to design.

4.3 *Other advantages of phase devices*

Besides the high sensitivity and small energy loss, phase devices have many other advantages. The first is easy fabrication and low cost. Furthermore, the results above can also be extended to a 2-D PC that is suitable for use in optical integration. In optical integration, all-optical and all-phase-control can be realized and will be a starting point of development.

In integrated circuits, all electrical components and elements are operated by a steady electrical dc voltage. So in optical integration, only one frequency steady cw laser to operate the whole optical integrate circuit is necessary. From the discussion above, it is demonstrated that a steady laser is enough to operate the phase optical devices and the whole optical integration system.

This work implies that phase devices are potential candidates for the practical application of all-optical signal processing.

5 Conclusion

After the two main problems with PC heterostructure or asymmetric PCs are overcome, many new phase properties not only can be used in further research, but also can be used to design very sensitive optical phase devices. The sensitivity of these phase devices will be two orders higher than those of amplitude devices. Moreover, a steady cw laser is enough to operate these phase optical devices.

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