Optik 126 (2015) 1941–1944

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

# Multiple-photonic band gap of periodically chirped photonic crystal and its dynamic modulation

Ying Chen[a,*], Huiqing Fan[a], Qiguang Zhu[b]

[a] Key Laboratory of Test/Measurement Technology and Instrument of Hebei Province, College of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China

[b] Key Laboratory for Special Fiber and Fiber Sensor of Hebei Province, College of Information Science and Engineering, Yanshan University, Qinhuangdao 066004, China

ARTICLE INFO

*Article history:*
Received 25 March 2014
Accepted 11 May 2015

*Keywords:*
Photonic crystal
Multi-photonic band gap
Periodical chirped
Inverse piezoelectric effect

ABSTRACT

The periodically chirped photonic crystal structure has been proposed, in which the characteristic of multiple-photonic bandgap has been obtained by establishing the mathematical model of the structure using transfer matrix method, and the relationship model between the resonant wavelength and the thickness of each layer has been set up. Using inverse piezoelectric effect, the strain is performed on the photonic crystal and the thickness of each layer will change, which will result in the shift of multiple-photonic bandgap. From the simulation results, it has been shown that the full width at half maximum (FWHM) can be optimized and the quality factor (Q value) can been improved by adjusting the number of layers in the photonic crystal structure. Taking advantage of piezoelectric ceramic stacks, higher strain can be obtained under lower voltage compared with the general piezoelectric ceramic, the shift of wavelength can attain to 120 nm and the sensitivity is about 0.6 nm/V. The multiple-photonic bandgap characteristic and dynamic modulation regularity of the periodically chirped photonic crystal structure can provide some theoretical references for the design of tunable multi-channel filters.



## 1. Introduction

Photonic crystals (PCs) are materials with refractive index which is periodically modulated in space. Because of its photonic band gap (PBG), the propagation of light within the band gap frequency range can be forbidden in the PCs structure. The PBG characteristic has been adopted to develop many optical devices such as add-drop filters, optical switches, optical reflectors, micro-resonator, etc. [1,2].

After the fabrication of PCs, its optical and structural parameters will not change, which can provide stable spectrum characteristics. Therefore, how to achieve the tunability of the optical property for the PCs has become the hotspot in this domain. The recent research works have mainly focused on two aspects: on the one hand, the application of novel materials, for examples, the introduction of the negative index medium and the magnetic photonic crystals [3,4], the plasma defect layers [5] and the liquid crystal materials [6] can achieve the dynamic modulation of optical signal transmission by adjusting the electric field applied. On the other hand, several external factors can influence the PBG [7]. Liu [8] has studied the changing regulation of defect mode in TE and TM wave with the change of mode quantum number and the optical thickness of the impurities, which can achieve the tunable filtering.

Based on the PBG characteristic, some defects have been introduced in the middle or on the surface of PCs, which can obtain the defect peak in the PBG and achieve the filtering of certain characteristic wavelength. In the wavelength division multiplexing (WDM) systems, simultaneous multi-channel filtering is necessary. A flat polarization filter based on the cascaded film glass resonator structure has been proposed by Zhang et al. [9], in which the multi-channel filtering can be achieved by introducing defects in the center of the periodical structure. Chang and Wu [10] have introduced the coupling defect to achieve the multi-channel filtering. On this basis, the filter structure based on the periodically chirped photonic crystal has been proposed [11], in which the periodical chirp is introduced into the thickness of each layer, the periodical distribution will be broken by the structure randomness and the spectrum characteristic of multiple-photonic band gap will be obtained. In addition, the piezoelectric ceramic stacks-PCs compound sensing structure has been established, and according to the inverse piezoelectric effect [12], the dynamic modulation of

* Corresponding author. Tel.: +86 13784508042.
*E-mail address:* chenying@ysu.edu.cn (Y. Chen).

http://dx.doi.org/10.1016/j.ijleo.2015.05.037
0030-4026/

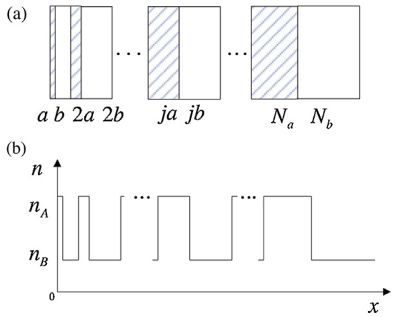


**Fig. 1.** Structure model of the PC structure. (a) Schematic diagram of periodically chirped photonic crystal structure. (b) Refractive index profile.

multiple-photonic band gap can be achieved through the continuous adjustment of the voltage applied.

## 2. Structure model

The structure model mentioned above has been shown in Fig. 1(a), in which the refractive index of medium A and B can be described as $n_A$ and $n_B$, as is shown in Fig. 1(b). One layer of medium A and one layer of medium B can be regarded as one unit, and the thicknesses of medium A and medium B in each unit has constitute an arithmetic sequence which first terms are $a$ and $b$, the amplitudes of variation are $a$ and $b$ respectively, therefore, the thicknesses of medium A and medium B are $ja$ and $jb$ ($1 \le j \le N$), and the optical thicknesses $d_j$ ($1 \le j \le N$) of two media in each unit are equal. The distribution with different interval is similar to the chirped optical grating, therefore, the structure can be called as periodically chirped photonic crystal.

## 3. Theoretical modeling

According to the transfer matrix method, the mathematical model between the input and output optical signal has been established. When the incident light entered from the surface of the PCs, for the $j$th layer, the thickness of medium A is $a_j = ja$, the thickness of medium B is $b_j = jb$. According to the calculation method of optical characteristic in the optical film theory, the transfer matrix of the PCs has been deduced. Assume that the transfer matrixes for the medium A and medium B in the $j$th layer are $M_{A,j}$ and $M_{B,j}$, therefore, the transfer matrixes for the $j$th layer is the product of the two matrixes. According to Eq. (1), the matrix for the $j$th layer can be described as

$$M_j = M_{A,j} \cdot M_{B,j} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (1)$$

where $m_{11} = \cos^2 \delta_j - (\eta_{B,j}/\eta_{A,j})\sin^2 \delta_j$, $m_{22} = \cos^2 \delta_j - (\eta_{A,j}/\eta_{B,j}) \sin^2 \delta_j$,. And the second category chebyshev polynomial is

$$x = 1 - \frac{(\eta_{A,j} + \eta_{B,j})^2}{2\eta_{A,j}\eta_{B,j}} \sin^2 \delta_j \quad (2)$$

According to the properties of the chebyshev polynomial, when $x = 1$, Eq. (1) is a unit mode matrix. It has been shown from Eq. (1) that the transitivity is 1, therefore, $\sin \delta_j = 0$, where $\delta_j = k\pi$ ($k = 1,2,\ldots$). When the optical signal incident from the normal direction, $\delta_j = 2\pi d_j/\lambda$, then the characteristic wavelength corresponding to the $j$th layer can be described as

$$\lambda_j = \frac{2d_j}{k} \quad (3)$$

From Eq. (3), it has been shown that the resonant wavelength $\lambda_j$ is proportional to the optical thickness $d_j$. From Eqs. (2) and (3), it can be concluded that the periodically chirped PC can be regarded as $N$ uniform PCs, and for each PC, there will be a PBG in the transmission spectrum, therefore, the periodically chirped PC will have $N$ PBGs. Because of the electromagnetic wave coupling between the neighboring PBG, $N$ independent transmission peaks will be obtained.

## 4. Static spectrum characteristic analysis

### 4.1. The influence on transmission spectrum for the number of layers N

Using matlab, the transmission characteristic of periodically chirped PC has been simulated. As is shown in Fig. 2 that when the number of layers $N$ increased from 15 to 25, the number of resonant peak will increase and the full width at half maximum (FWHM) will decrease. With the increase of layer number, the edge of the PBG will be more steep and the forbidden band effect will be more and more obvious. When $N = 25$, the FWHM will be in the range from 1.6 nm to 2.5 nm, which can improve the $Q$ value of the structure and meet with the requirement of filtering. Therefore, considering the complexity of structure, the number of layers is decided to 25.

### 4.2. The influence on the transmission spectrum for the thickness variations

ZnS and $SiO_2$ have been chosen as the medium A and medium B respectively, the refractive indexes are 2.35 and 1.46. In the first unit, the thicknesses of the medium A and medium B are 19.15 nm and 30.82 nm, and the layer number is 25. When the thickness of ZnS changed with $\Delta a = 0.01 a_j$, the transmission spectrum can be obtained as Fig. 3. According to the Eq. (3), the resonant wavelength will be larger with the increase of the thickness for each layer, therefore, the spectrum will shift in general to the longer wavelength direction.

## 5. Dynamic modulation property analysis

Based on the static characteristic analysis, the dynamic modulation has been performed on the PCs according to the inverse piezoelectric effect. Applying the voltage on the piezoelectric ceramic in the polarization direction, the strain will be obtained on the piezoelectric ceramic. And it can be described as

$$\varepsilon = \frac{\Delta w}{w} = d_{33} \frac{U}{w} \quad (4)$$

where $d_{33}$ is the longitudinal piezoelectric coefficient, and $w$ is the thickness of the piezoelectric ceramic.

The PZT-51 made by Hong-sheng company in Baoding City, Hebei Province of China has been chosen as the piezoelectric ceramic with the piezoelectric coefficient $d_{33} = 700 \times 10^{-12}$ m/V. Because $d_{33}$ is very small, the strain will be very weak even under high voltage applied. The piezoelectric ceramic stack has been adopted to increase the strain, as is shown in Fig. 4, the strain will be the sum of the all piezoelectric ceramic pieces. In the devices, the periodical chirped PC is pasted on the piezoelectric ceramic stack, therefore its strain is equivalent to that of the substrate. However, there are tiny gaps between the piezoelectric ceramic pieces, which will result in the measuring errors. As is shown in Fig. 4(b), in the experiment, two rectangular frames are located at the two ends of the piezoelectric ceramic stack, which can guarantee the PC in the opening of the two rectangular frames with the distance of $l$.

Because of the voltage applied, the strain will generate on the periodically chirped PC, which will achieve the dynamic tunable filtering. The deformation quantity of the periodically chirped PC $\Delta l$ is equivalent to that of the piezoelectric ceramic stacks $\Delta L$, then