Vol 14 No 12, December 2005
1009-1963/2005/14(12)/2474-04

Chinese Physics

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Ultra-narrow bandwidth optical filters consisting of one-dimensional photonic crystals with anomalous dispersion materials*

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(Received 18 November 2004; revised manuscript received 18 July 2005)

We present a new type of optical filter with an ultra-narrow bandwidth and a wide field-of-view (FOV). This kind of optical filter consists of one-dimensional photonic crystal (PC) incorporating an anomalous-dispersion-material (ADM) with, for instance, an anomalous dispersion of $6P_{3/2} \leftarrow 6S_{1/2}$ hyperfine structure transition of a caesium atom. The transmission spectra of optical filters are calculated by using the transfer-matrix method. The simulation results show that the designed optical filter has a bandwidth narrower than 0.33GHz and a wide FOV of $\pm 30^\circ$ as well. The response of transmission spectrum to an external magnetic field is also investigated.

Keywords: photonic crystals, anomalous dispersion, optical filter
PACC: 3260, 4270Q, 4280C

Ultra-narrow optical filters play a critical role in free-space laser communication, for example, lidar and laser communications between satellites and satellite-ground, in which signal is required to smoothly pass through scattering medium such as seawater or atmosphere.[1−3] A narrow bandwidth and wide field of view (FOV) are important merits for this type of optical filter. One kind of optical filter with a wide FOV and ultra-narrow bandwidth is Faraday anomalous dispersion optical filter (FADOF). Yeh was one of the pioneers in investigating the properties of FADOF theoretically in 1982.[1] Since the 1990's, the rapid progress in the study of the FADOF has been made both theoretically and experimentally.[2−6] Although the FADOF possesses many advantages such as high transmittivity, ultra-narrow bandwidth, and the response time that is limited only by its optical bandwidth,[2−5] its applications are still limited because a few elements, for instance, Cs, Rb, Na, Ca *et al* may also be used as the candidate of the working medium. Many molecules are not available as the working medium because of the weak Zeeman effect. Another kind of optical filter is atomic resonance filter (ARF), which may provide an extremely narrow bandwidth and a very large FOV. However, the ARF exhibits some disadvantages, such as a slow response and a non-imaging filter.[3] Photonic crystals (PCs) as a new kind of artificial optical material have been extensively investigated theoretically and experimentally in the last decade.[7−12] Photonic crystal optical filter (PCOF) consisting of one-dimensional PCs with defect layers have been presented,[13,14] which has much narrower bandwidth than FADOF theoretically. Unfortunately, the transmission frequency spectra strongly depend on the incident angle of the input light wave.[14] Moreover, the transmission frequency spectra of the PCOF are quite sensitive to the thickness of the defect layer.[15] Therefore, it is hard for the PCOF to possess an ultra-narrow bandwidth in practice. Recently, we have proposed a new kind of optical filter by the use of atomic anomalous dispersion behaviour in combination with photonic

*Project supported by the National Basic Research Program of China (Grant No 001CB61040) and the Natural Science Foundation of Beijing, China (Grant No1032003).

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band gap (PBG) structures.[16] Hereafter, for simplicity, we refer them to the photonic crystal anomalous-dispersion optical filter (PCADOF). As a real example, the PCADOF consisting of two-dimensional (2D) PC is calculated by using the plane wave expansion method. The bandwidth of 2D PCADOF reaches 0.9GHz.

Owing to easy fabrication, one-dimensional (1D) PCs have been widely used to design optical filters, as mentioned above. In this paper, we propose a 1D PCADOF that is composed of 1D PC in combination with the behaviour of atomic anomalous dispersion. The transmittance spectra of the 1D PCADOF are calculated by using the transfer-matrix method.[17–18]

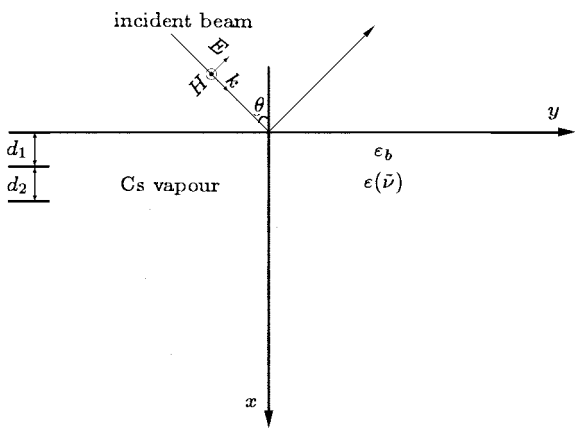


Fig.1. Schematic of PCADOF composed of 11 dielectric layers with a dielectric constant ε_b. Between the two layers sandwiched is one layer of atomic Cs vapour (thus 10 layers of atomic Cs vapour are used altogether). θ denotes the incident angle of light wave.

A typical PCADOF is displayed in Fig.1, which is a 1D PC composed of 11 layers with a dielectric constant ε_b (shadow area). Between the two layers sandwiched is one anomalous-dispersion-material (ADM) layer. A similar structure has been presented in experiment.[13] We choose atomic Cs vapour as the ADM. d_1 and d_2 denote the dielectric layer thickness and the ADM layer thickness, respectively. The incident plane of the light wave is parallel to the x-y plane. θ denotes the incident angle. The so called S-polarized (P-polarized) electromagnetic wave refers to the magnetic (electric) field of the electromagnetic wave being parallel to the x–y plane.

The dielectric constant $\varepsilon(\nu)$ of the ADM will greatly vary in a anomalous-dispersion frequency range. In contrast, in a normal-dispersion frequency range, the dielectric constant $\varepsilon(\nu)$ approximately remains a constant value, i.e. $\varepsilon(\nu) \doteq \varepsilon_a$. We now consider a particular case that a PBG appears in a frequency range of $[\omega_1, \omega_2]$ with ε_b being a constant and the dielectric constant of the Cs layers being $\varepsilon(\nu) \doteq \varepsilon_a$. When the anomalous-dispersion frequency of the ADM just falls inside this PBG, and a light with just this frequency is incident upon the system, a new impurity band will be generated from the variation of $\varepsilon(\nu)$ resulting from the anomalous dispersion. In other words, the light wave can pass through this particular PC when its frequency is assigned to be in the impurity band. It is evident that this kind of PC may serve as an optical filter, i.e. the so-called PCADOF.

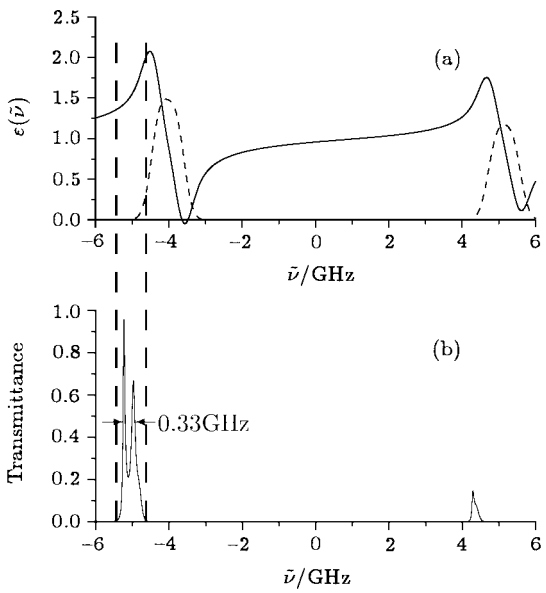


Fig.2. (a) Real part (solid line) and imaginary part (dashed line) of dielectric constant ε of atomic Cs vapour as a function of frequency, which is generated by $6P_{3/2} \leftarrow 6S_{1/2}$ hyperfine structure transition of caesium atoms. Here $\tilde{\nu} = \nu - \nu_0$, ν is the frequency of the incident light wave and ν_0 is the central frequency of $6P_{3/2} \leftarrow 6S_{1/2}$ transition line. (b) The transmittance of the PCADOF as a function of frequency.

The anomalous-dispersion spectrum of the saturated atomic Cs vapour at a temperature of 520K (the saturated vapour pressure $P \doteq 59$Pa) for the $6P_{3/2} \leftarrow 6S_{1/2}$ hyperfine structure transition is calculated by using the standard popular equations;[3,19,20] the obtained result is shown in Fig.2(a). The solid (dashed) line denotes the real (imaginary) part of the dielectric constant $\varepsilon(\tilde{\nu})$. Here $\tilde{\nu} = \nu - \nu_0$, ν is the frequency of the incident light wave and ν_0 is the central frequency of $6P_{3/2} \leftarrow 6S_{1/2}$ transition line, which corresponds to a wavelength of $\lambda_0 = 852.1$nm. It is clearly seen from Fig.2(a) that two absorption lines appear at about $\tilde{\nu} \sim \pm 4.5$GHz. The frequency space between the two absorption lines is determined by the hyperfine Zeeman splitting of $6S_{1/2}$ and $6P_{3/2}$ states

of Cs atoms. The effect of the absorption lines on the transmittance of the 1D PC in the case of the normal incidence of the light wave is depicted in Fig.2(b). The transmittance curve is calculated by employing the transfer-matrix method (TMM) with the following parameters: d_1=110nm, d_2=220nm, and $\varepsilon_b = 5.76$ (ZnS as the dielectric layer material). Two distinctive transmittance peaks appear at the frequencies near the resonant absorption lines: one is at a lower frequency, exhibiting the dual-peak structure, and the other is at a higher frequency, manifesting a single peak, as seen in Fig.2(b). In the two plots the two vertical dashed lines indicate the frequency range occupied by lower frequency transmissive dual-peaks. It is observed that the full-width at half maximum (FWHM) of the lower frequency dual peak is 0.33GHz. Although the transmissive peaks are believed to be associated with resonant absorption lines of Cs atoms, the peak frequency positions do never coincide with the resonant absorption frequencies of Cs atoms. It is clearly seen from Fig.2 that the lower frequency transmissive dual-peaks are located at the wing of the first resonant absorption peak, shifting substantially from the first absorption line, so does the higher frequency transmissive peak. It is also worth emphasizing that the peaks appearing at Im $\varepsilon(\nu)$ curve (the dashed line) do never create any peak in the transmittance spectrum. It is also seen that the peak level of the lower frequency transmissive peak is much higher than that of the higher frequency transmissive peak: for instance, they are 0.956 and 0.145, respectively. Thus, we can construct a new type of optical filter, i.e. the PACDOF, which possesses an ultra-narrow transmission bandwidth of $\Delta\nu = 0.33$GHz. It is notable that the transmissive peak frequency is basically determined by the anomalous-dispersion frequency that is not sensitive to the surface roughness of individual layer caused by the machine-tooled tolerance, which has influence only on the PBG range of $[\omega_1, \omega_2]$.

We now turn to the investigation of the FOV of the PCADOF. The variations of the transmittance spectrum with incident angle for the P-polarization and S-polarization are displayed in Figs.3(a) and (b), respectively. Here θ denotes the incident angle. It is evident from the two plots that the curve of $\theta = 0°$ (solid line) spreads mainly from about $\tilde{\nu} = -5.3$GHz to -4.2GHz, which corresponds to the widest frequency range because the other curves of $\theta = 15°$ (dotted line) and $\theta = 30°$ (dashed line) occupy only a part of the above-mentioned frequency range, as seen in Fig.3, and the change of incident angle is slow in most cases considered, and it can be transformed into the temperature drift in laser communications. Therefore, we can safely say that the FOV of PCADOF at least reaches $\theta = \pm 30°$ for the P-polarization and $\theta = \pm 20°$ for the S-polarization, the FOV for the latter is limited at a smaller angle than that for the P-polarization case. This merit is much better than that of the defect PC filter (PCOF).[14]

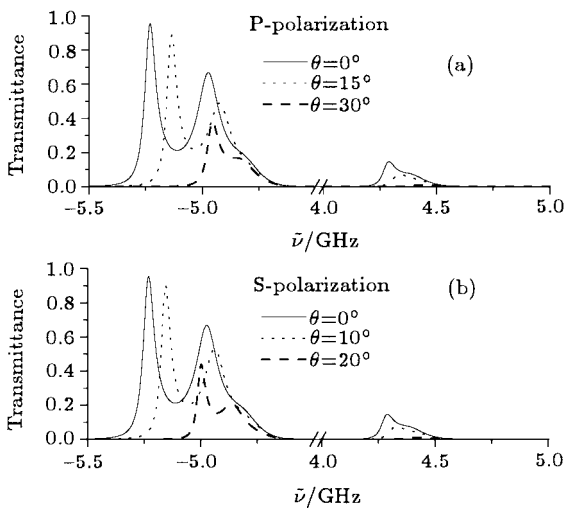


Fig.3. Transmittance spectrum of PACDOF for different incident angles. (a) for the P-polarization and (b) for the S-polarization.

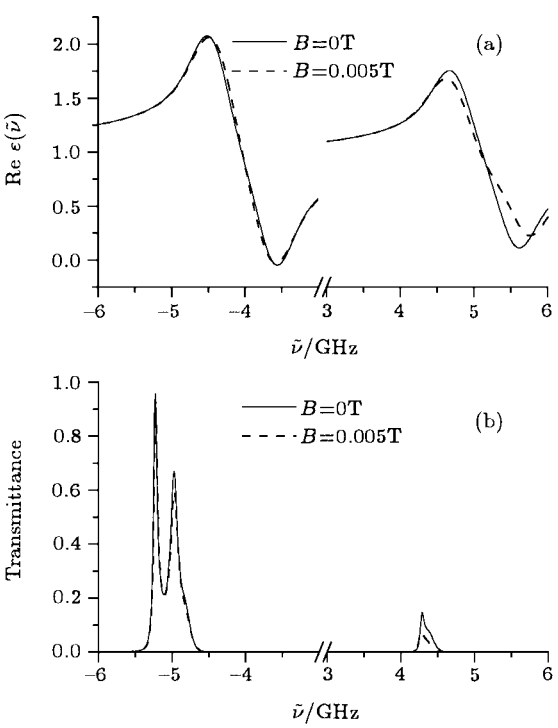


Fig.4. Transmittance spectrum of the PCADOF under different external magnetic fields in the normal incident case of the light wave and the S-polarization.

The transmittance curve can be changed by an external magnetic field $\boldsymbol{B}$. Apply an external magnetic field along $\hat{z}$-axis, i.e. in the direction perpendicular to the x-y plane, and $\boldsymbol{B} = B\hat{z}$. Both the real part of the dielectric constant $\varepsilon(\tilde{\nu})$ and the transmittance spectra as a function of frequency for different magnetic fields are displayed in Fig.4(a) and 4(b), respectively. The light wave is normally incident upon the surface of the 1D PC and in the S-polarization. In Fig.4, the solid (dashed) lines correspond to the magnetic field of B=0T (B=0.005T). It is evident that the higher frequency transmissive single peak has a much faster decreasing rate than the lower frequency dual-peak, which results from the great variation of the dielectric constant. The decrease in the higher frequency peak of $\varepsilon(\tilde{\nu})$ leads to the decline of the corresponding transmittance. Thus, the higher frequency peak can been ignored. Furthermore, the higher frequency absorption peak may become weaker or disappears when the electron population of the hyperfine structure F=3 is reduced by means of optical pumping. However, we may believe that the higher frequency transmissive peak is unobservable.

In summary, we propose a new type of optical filter with an ultra-narrow bandwidth and a wide FOV. This type of optical filter is composed of a 1D PC incorporating anomalous-dispersion-material (ADM), for instance, Cs atom. We design a special PCADOF and the calculation results show that the designed PCADOF possesses an ultra-narrow bandwidth of $\Delta\nu = 0.33$GHz with a wide FOV of $\theta = \pm 30^\circ$ for the P-polarization and the normally incident light wave. The change of transmittance spectrum with external magnetic field is also investigated. The frequency and bandwidth of the transmittance spectrum peaks are determined only by those of the ADM, but not by the roughness of the individual layer.

References

[1] Yeh P 1982 *Appl. Opt.* **21** 2069

[2] Menders J, Benson K, Bloom S H, Liu C S and Korevaar E 1991 *Opt. Lett.* **16** 846

[3] Dick D J and Shay T M 1991 *Opt. Lett.* **16** 867

[4] Chen H, She C Y, Searcy P and Korevaar E 1993 *Opt. Lett.* **18** 1019

[5] Peng Y F, Tang J X and Wang Q J 1993 *Acta Phys. Sin.* (Overseas Edition) **1** 1

[6] Wang Q, Jia X L, Zhang Y D and Ma Z G 2003 *Acta Phys. Sin.* **52** 1151

[7] Yablonovitch E 1987 *Phys. Rev. Lett.* **58** 2059

[8] John S 1987 *Phys. Rev. Lett.* **58** 2486

[9] Pendry J B 1994 *Journal of Modern Optics* **41** 209

[10] Zhou Y S, Gu B Y and Wang F H 2003 *Journal of Physics: Condens. Matter* **15** 4109

[11] Xu X S, Wang Y Q, Han S Z, Cheng B Y and Zhang D Z 2004 *Chin. Phys.* **13** 1474

[12] Liu X D, Xu X S, Wang Y Q, Zhang D Z and Cheng B Y 2003 *Chin. Phys.* **12** 922

[13] Hillmer H, Daleiden J, Prott C, Römer F, Irmer S, Rangelov V, Tarraf A, Schüler S and Strassner M 2002 *Appl. Phys.* B **73** 3

[14] Jiang H T, Chen H, Li H Q and Zhang Y W 2003 *Appl. Phys. Lett.* **83** 5386

[15] Lin X S, Chong H, Ouyang Y D and Lan S 2004 *Chin. Phys. Lett.* **21** 863

[16] Liu J T, Zhou Y S, Wang F H and Gu B Y 2004 *Acta Phys. Sin.* **53** 3336 (in Chinese)

[17] Zhou P, You H Y, Wang S Y, Yang Y M and Chen L Y 2002 *Acta Phys. Sin.* **51** 2276 (in Chinese)

[18] Li R, Ren K, Ren X B, Zhou J and Liu D H 2004 *Acta Phys. Sin.* **53** 2520 (in Chinese)

[19] Zheng L M and Xu G W 1988 *Atomic Structures and Atomic Spectrum* (Beijing: Peking University Press) p172 (in Chinese)

[20] Zhao J M, Yin W B, Wang L R, Xiao L T and Jia S T 2002 *Chin. Phys.* **11** 241