Reflection and transmission in a heterostructured multilayer narrowband filter containing thin metallic films

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A narrowband filter with two reflection peaks and a single transmission peak is proposed based on a multilayer heterostructure containing two different ultrathin metallic films. The heterostructure filter is formed by cascading two narrowband reflection-and-transmission filters. We use the transfer matrix method to calculate the optical reflectance, transmittance, and absorptance for this filter. Results show that the heterostructure has a pronounced effect on the reflectance, leading to two resonant peaks. The angular dependence of filtering properties is also investigated. This filter is of practical use in the optical signal processing.

(Received April 19, 2010; accepted March 16, 2011)

Keywords: Narrowband filters, Heterostructures, Transfer matrix method

1. Introduction

A Fabry-Perot resonator (FPR) also called a narrowband transmission filter is a typical and useful optical device. It can be achieved by sandwiching a defect layer in a dielectric mirror (DM). A DM, which is commonly referred to as a Bragg reflector (BR), is a periodic quarter-wavelength stack of alternating high- and low-index materials, i.e., Air/$(HL)^N$/Air. Here N is the number of periods, and H and L denote the high- and low-index (n_H and n_L) layers with $n_H d_H = n_L d_L = \lambda_0/4$, where λ_0 is the design wavelength, and d_H, d_L are their physical thicknesses, respectively. A DM has a flat bottom zero-transmission U-shaped transmittance spectrum. Thus a typical FPR is denoted as Air/$(HL)^N L (HL)^N$/Air and its resonant point will be set in the design wavelength λ_0. The peak height in the transmittance can reach unity for the lossless stack. However, the peak height will be substantially depressed as the dielectric loss in incorporated in the filter [1].

With the resonant narrow transmission peak at a certain wavelength, applications of the above FPR include the frequency- or wavelength-selective filter and a wavelength demultiplexer particularly useful in the wavelength division multiplexing (WDM) systems. In addition to this narrowband transmission filter, a narrowband filter operating in both the transmission and reflection peaks at a certain design wavelength is now feasible [2,3]. This filter, depicted in Fig. 1, consisting of an ultrathin metallic film Cr together with a typical FPR is denoted as $Air/Cr(LH)^{m_1} 2L(HL)^{m_2} H/Sub$, where m_1 and m_2 are the numbers of periods of the left and right quarter-wavelength stacks, respectively, and *Sub* means the substrate. To achieve the simultaneous peaks in the transmission and reflection, the metallic film must be selected to have a complex refractive index $n_{Cr} = n_R - jn_I$ with $n_R \approx n_I$. In addition, its thickness has to be much less than the operating wavelength, i.e., $d << \lambda$. Other similar narrowband filter containing thin metallic films are also available [4-7].

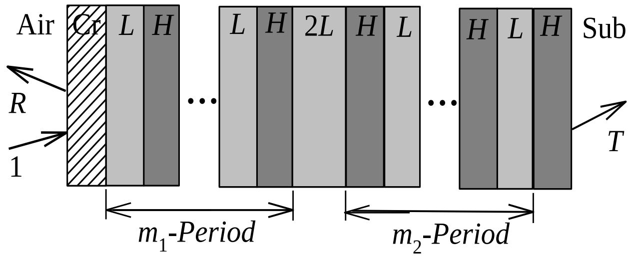

Fig. 1. A narrow band reflection and transmission filter. The ultrathin metallic film, Cr, is deposited on FPR with a low-index defect layer, 2L. The reflectance and transmittance are R and T, respectively.

Treating the filter in Fig. 1 as a building block, in this paper, we consider a heterostructured multilayer that is formed by connecting these two building filters with different thin metallic films Cr and Fe, i.e., $Air/Cr(LH)^{m_1}\,2L(HL)^{m_2}\,H/Fe(LH)^{m_3}\,2L(HL)^{m_4}\,H/Sub$. The design wavelength in the first filter with Cr is set to be 700 nm, whereas the second with Fe is designed as 650 nm. The purpose of this work is to examine how the heterostructured filter affects the simultaneous transmission and reflection peaks in Fig. 1. Can this filter be made to simultaneously obtain the double reflection peaks and double transmission peaks simultaneously? The answer will be given based on the calculated optical properties such as the transmittance, the reflectance, and the absorptance for this filter. These quantities will be calculated by the using the Abeles theory, which is an elegant method in dealing with the multilayer structure [8].

2. Transfer matrix method-Abeles theory

According to Abeles theory, the transmission coefficient and reflection coefficient can be determined by the matrix elements of the characteristic matrix of the entire heterostructure given by [8]

$$M=\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}=M_{Cr}\left(M_L M_H\right)^{m_1} M_{2L}\left(M_H M_L\right)^{m_2} M_H M_{Fe}\left(M_L M_H\right)^{m_3} M_{2L}\left(M_H M_L\right)^{m_4} M_H\,. \tag{1}$$

Then the reflection and transmission coefficients are given by

$$r=\frac{p_0 m_{11}+p_0 p_{sub} m_{12}-m_{21}-p_{sub} m_{22}}{p_0 m_{11}+p_0 p_{sub} m_{12}+m_{21}+p_{sub} m_{22}}\,, \tag{2}$$

$$t=\frac{2p_0}{p_0 m_{11}+p_0 p_{sub} m_{12}+m_{21}+p_{sub} m_{22}}\,, \tag{3}$$

where $p_0=\sqrt{\varepsilon_0/\mu_0}$ and $p_{sub}=n_{sub}\sqrt{\varepsilon_0/\mu_0}$ are the parameters for the incident region (air) and substrate, respectively.

If the temporal part, $\exp(j\omega t)$, is taken for all fields, the characteristic matrix for Cr or Fe is given by

$$M_{Cr,Fe}=\begin{pmatrix} \cos\left(k_0 h_{Cr,Fe}\right) & \dfrac{j\sin\left(k_0 h_{Cr,Fe}\right)}{p_{Cr,Fe}} \\ jp_{Cr,Fe}\sin\left(k_0 h_{Cr,Fe}\right) & \cos\left(k_0 h_{Cr,Fe}\right) \end{pmatrix} \tag{4}$$

where

$$p_{Cr,Fe}=p_0 n_{Cr,Fe}\cos\theta_{Cr,Fe}\,, \tag{5}$$

for TE wave, and

$$p_{Cr,Fe}=\frac{p_0 n_{Cr,Fe}}{\cos\theta_{Cr,Fe}} \tag{6}$$

for TM wave, respectively, with $n_{Cr,Fe}$ being the refractive indices of Cr and Fe, and the optical thickness is $h_{Cr,Fe}=n_{Cr,Fe}d_{Cr,Fe}\cos\theta_{Cr,Fe}$, and $k_0=2\pi/\lambda$ is the free-space wave number. In addition, the characteristic matrices of the quarter-wavelength *H* and *L* layers are expressed as

$$M_L=\begin{pmatrix} \cos\left(k_0 n_L d_L\cos\theta_L\right) & \dfrac{j\sin\left(k_0 n_L d_L\cos\theta_L\right)}{p_L} \\ jp_L\sin\left(k_0 n_L d_L\cos\theta_L\right) & \cos\left(k_0 n_L d_L\cos\theta_L\right) \end{pmatrix}, \tag{7}$$

$$M_H=\begin{pmatrix} \cos\left(k_0 n_H d_H\cos\theta_H\right) & \dfrac{j\sin\left(k_0 n_H d_H\cos\theta_H\right)}{p_H} \\ jp_H\sin\left(k_0 n_H d_H\cos\theta_H\right) & \cos\left(k_0 n_H d_H\cos\theta_H\right) \end{pmatrix}, \tag{8}$$

where $n_L d_L=n_H d_H=\lambda_0/4$ with λ_0 being the design wavelength, and p_L, p_H are defined similarly as in Eqs. (5) and (6) for the TE and TM waves, respectively.

With the reflection coefficient *r* and transmission coefficient *t*, the reflectance *R* and transmittance *T* are expressed as

$$R=\left|r\right|^2, \tag{9}$$

$$T=\frac{n_{sub}\cos\theta_{sub}}{n_{air}\cos\theta_{air}}\left|t\right|^2. \tag{10}$$

Then according to the power balance equation, the absorptance *A* is given by

$$A=1-R-T\,. \tag{11}$$

3. Numerical results and discussion

To calculate the transmittance, the reflectance, and the absorptance for the heterostructured filter, $Air/Cr(LH)^{m_1}\,2L(HL)^{m_2}\,H/Fe(LH)^{m_3}\,2L(HL)^{m_4}\,H/Sub$, the following material parameters are used. The design resonant wavelength at the first stage containing Cr is taken to be λ_{01} = 700 nm, whereas the second one with Fe is at λ_{02} = 650 nm. In Cr, the thickness d_{Cr} = 5 nm and the index of refraction $n_{Cr} = 3.07 - j3.38$ near λ_{01} are taken [2,3]. For Fe, we use d_{Fe} = 5 nm and $n_{Fe} = 2.88 - j3.37$ near λ_{02} [9]. In addition, the refraction indices for quarter-wavelength layers L and H are n_L = 1.45 (SiO_2) and n_H = 2.17 (TiO_2), respectively. The refractive index of the substrate is n_{sub} = 1.52.

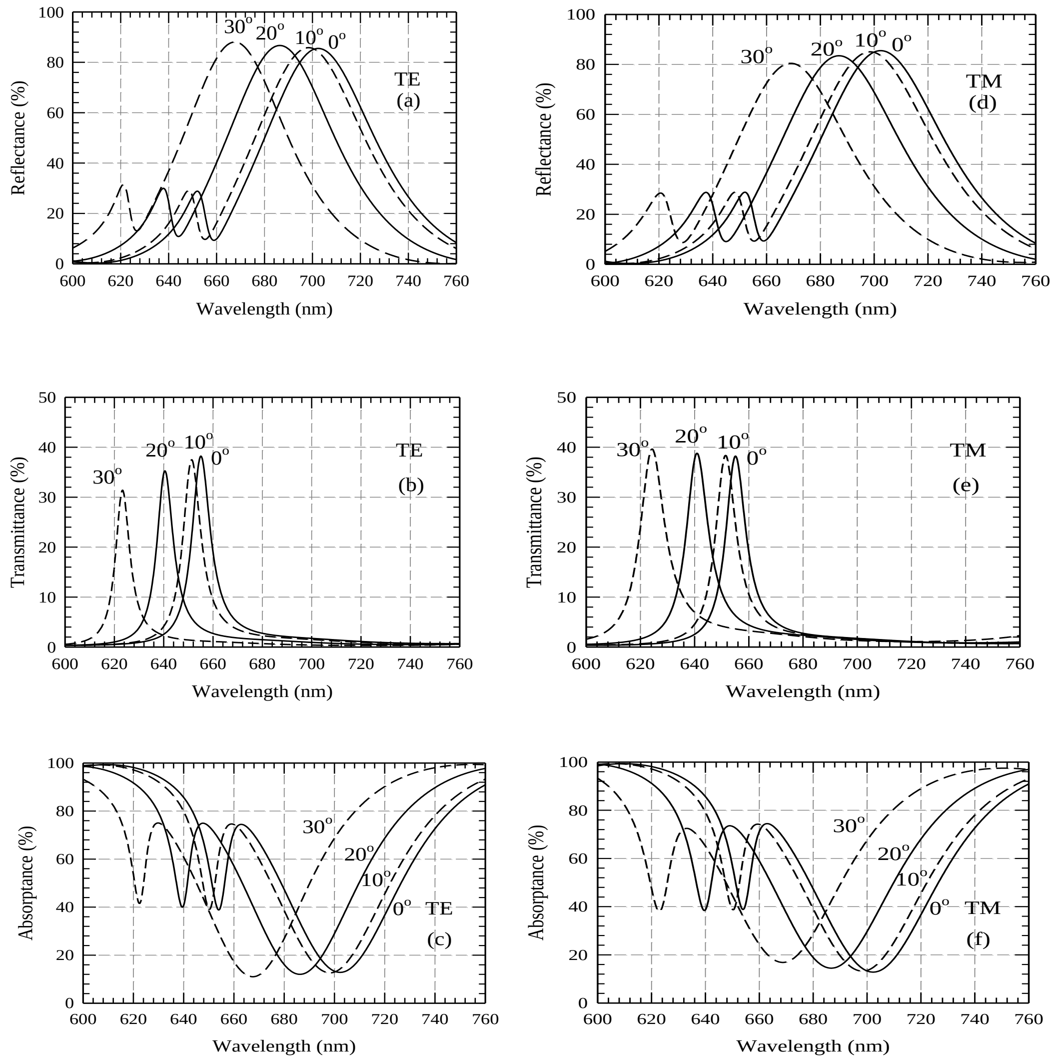

Fig. 2. The calculated reflectance, transmittance, and absorptance for TE wave ((a)-(c)) and TM wave ((d)-(f)) at various angles of incidence. Here the numbers of periods (m_1, m_2, m_3, m_4) = (1, 3, 1, 3) are taken.

Fig. 2 displays the calculated reflectance, transmittance, and absorptance for both TE and TM waves at various angles of incidence θ_{air} = 0°, 10°, 20°, and 30°, respectively. For the normal incidence, θ_{air} = 0, it is seen that there are double peaks in R occurring at the two design wavelengths 700 and 650 nm. However, it is not shown in T, which has only one peak at 650 nm. The double peaks in R are reflected in the presence of double dips in A. The filtering properties for the proposed heterostructured filter are evidently observed. It has, as expected, two peaks in reflection, while only one peak in transmission. In R, the major peak height at 700 nm is substantially larger than the minor one at 650 nm, indicating the first stage plays a dominant role in reflection. In T, a single peak is located at 650 nm, which is obviously determined by the second stage. Such a heterostructured filter thus has some applications. First, at 650 nm, the feature of simultaneous peaks in R and T shown in Fig. 1 is also preserved, which can be used as a color decoration device. As far as only R is concerned, the two peaks at two different wavelengths can be applied to a reflective wavelength multiplexer. It can be used as a two-channel system which has the reference signal and real signal as well.

In Fig. 2, are shown the angle-dependent *R*, *T*, and *A* for both TE and TM waves. In TE wave, the double peak heights in *R* are enhanced appreciably and the positions are shifted to a shorter wavelength. The peak height in *T* is, however, lowered with its position being also shifted to a shorter wavelength. The similar shifting behaviors in *R* and *T* are also seen in TM wave. The peak height in *R* is depressed whereas in *T* is enhanced in TM wave.

Let us now change the numbers of periods at the first and second stages to be $(m_1, m_2, m_3, m_4) = (2, 4, 2, 4)$ and the calculated *R*, *T*, and *A* in TE wave are depicted in Fig. 3. It is of interest to see that the small peak at 650 nm in *R* is severely depressed and becomes nearly disappeared. In addition, the transmittance peak height at 650 nm is also decreased as compared to Fig. 2(b). The results in Fig. 3 reveal that the effect coming from the second stage with Fe becomes weak and the filtering properties are mainly dominated by the first stage with Cr.

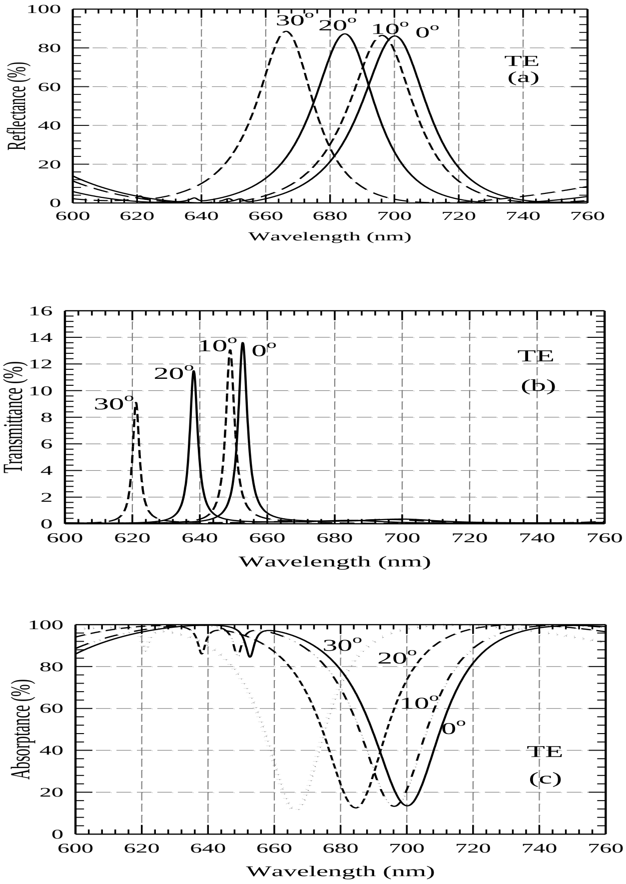

Fig. 3. The calculated R, T, and A for the TE wave ((a)-(c)) at the numbers of periods $(m_1, m_2, m_3, m_4) = (2, 4, 2, 4)$.

In Fig. 3 we have known that the minor peak at 650 nm in *R* can be nearly suppressed by changing the numbers of periods at the first and second stages. Now we try to enhance the magnitude of the major reflection peak at 700 nm. This can be simply achieved by removing the metallic film Fe at the second stage, as illustrated in Fig. 4, where the solid curves are for the structure without Fe and the dash ones are with Fe. Without Fe, the power loss is consequently reduced and the major reflectance peak height can be close to 100%. The increase in the major peak is reflected in the decrease in the minor peak in the reflectance spectrum. The transmittance peak is also enhanced due to the absence of Fe.

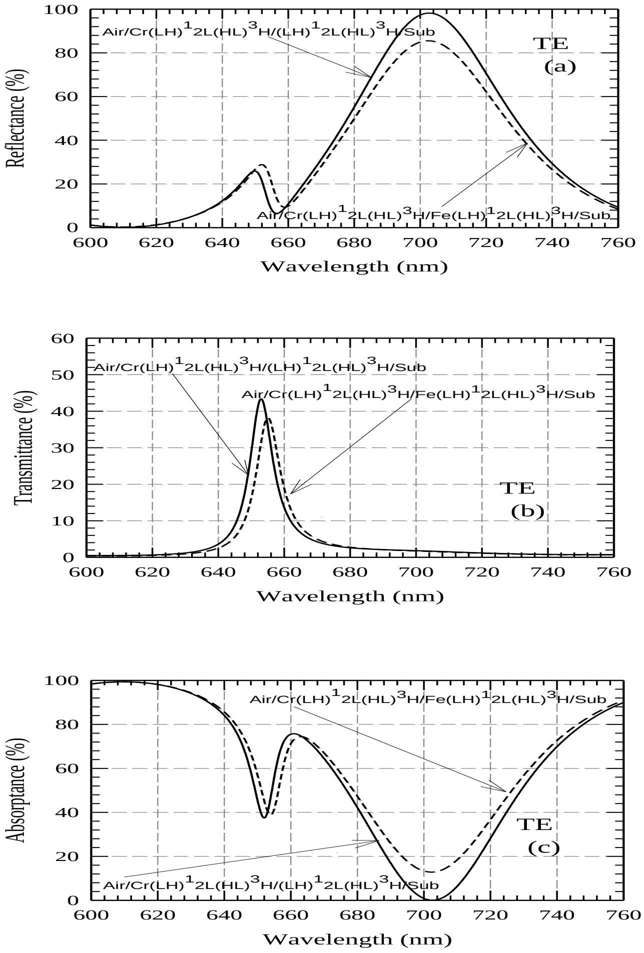

Fig. 4 The calculated R, T, and A for the TE wave ((a)-(c)) at the numbers of periods $(m_1, m_2, m_3, m_4) = (1, 3, 1, 3)$. Here the dash curve is for the heterostructure with Fe in the second stage, while the solid one is for the same structure without Fe. The design wavelengths for the first and second stages are 700 and 650 nm, respectively.

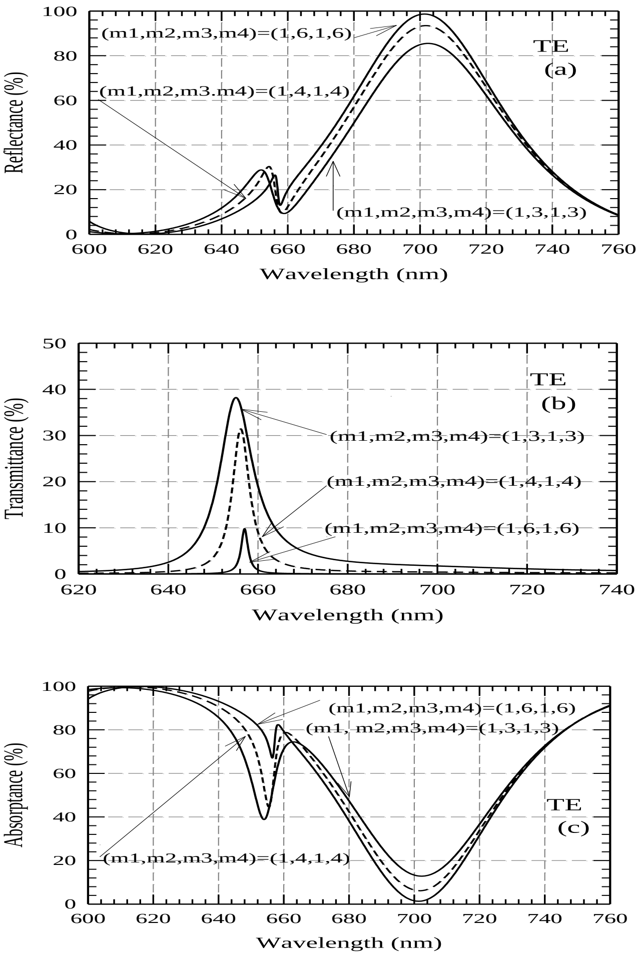

Fig. 5. The calculated R, T, and A for the TE wave ((a)-(c)) at different combinations of (m_1, m_2, m_3, m_4). Here the heterostructure is again with Fe in the second stage.

Now if we keep the numbers of periods m_1 = m_3 = 1 and vary m_2 = m_4 = 3, 4, and 6, we find the major reflection peak can be enhanced as m_2 increases, as illustrated in Fig. 5. Such a tendency is also seen in a single stage filter [2]. In the meantime, the peak height in the transmittance will be decreased as m_2 increases. It means that the numbers of periods are important parameters to change the peak heights in both *R* and *T*.

4. Conclusions

The optical properties for a heterostructured narrowband filter containing two metallic films designed at different wavelengths have been investigated. Based on the numerical results, some conclusions can be drawn. In this two-stage heterostructured filter, the narrowband filtering properties including the double reflection peaks and single transmission peak are obtained. The first stage dominates the major reflection peak, while the minor peak is determined by the second stage. Due to the losses in the two metallic films, the energy into the second stage is considerably small compared to the first stage, which in turn causes the minor peak height to be relatively smaller than the major peak height. The heterostructure has totally changed the filtering properties in the single stage filter where both the reflection and transmission peaks are located at the same design wavelength. The effects of the stack numbers are also numerically demonstrated. Finally, it is worth mentioning that positions of double peaks in *R* can be simply exchanged by interchanging the two metallic films.

Acknowledgement

C.-J. Wu acknowledge the financial support from the National Science Council of the Republic of China under Contract No. NSC-97-2112-M-003-013-MY3.

References

[1] P. Yeh, Optical Waves in Layered Media, John Wiley & Sons, Singapore (1991).
[2] W. Shen, X. Sun, Y. Zhang, Z. Luo, X. Liu, P. Gu, Optics Comm. **282**, 242 (2009).
[3] Y.-H. Chang, C.-C. Liu, T.-J. Yang, C.-J. Wu, J. Opt. Soc. Am. B: Optical Physics, **26**, 1141 (2009).
[4] X. Z. Sun, P. F. Gu, W. D. Shen, X. Liu, Y. Wang, Y. G. Zhang, Appl. Opt. **46**, 2899 (2007).
[5] M. Q. Tan, Y. C. Lin, D. Z. Zhao, Appl. Opt. **36**, 827 (1997).
[6] R. Gamble, P. H. Lissberger, Appl. Opt. **28**, 2838 (1989).
[7] J.-S. Sheng, J.-T. Lue, Appl. Opt.**31**, 6117 (1992).
[8] M. Born, E. Wolf, Principles of Optics, Cambridge, London (1999).
[9] P. B. Johnson, R. W. Christy, Phys. Rev. B **9**, 5056 (1974).

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