Optics Communications 282 (2009) 242–246

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Narrow band filters in both transmission and reflection with metal/dielectric thin films

Weidong Shen *, Xuezheng Sun, Yueguang Zhang, Zhenyue Luo, Xu Liu, Peifu Gu

State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, 38 Zheda Road, Yuquan Campus, Hangzhou, Zhejiang 310027, China

A R T I C L E   I N F O

Article history:
Received 19 May 2008
Received in revised form 29 August 2008
Accepted 26 September 2008

PACS:
42.79.Wc
42.79.Ci

Keywords:
Optical coatings
Narrow band filters
Metal/dielectric thin films

A B S T R A C T

We present a novel narrow band filter operating in both transmission and reflection for the first time to our knowledge. This proposed structure consists of one unsymmetrical dielectric Fabry–Perot cavity and an ultrathin metal film with $n \approx k$. Theoretical analysis shows that both the reflectance and transmittance at the central wavelength are maximums. Due to the high absorption induced by the metal, a good rejection level can be obtained for a wide spectral range. In addition, the changes of peak value ratio $R_{\max}/T_{\max}$ is also investigated by adjusting the amount of dielectric stacks. We finally demonstrate the experimental results to verify these designs.

1. Introduction

Thin film narrow band filters in transmission have been widely used in a variety of fields, e.g., dense wavelength division multiplexing (DWDM) system [1,2], fluorescence emission/excitation [3] and imaging spectrometry [4,5]. Whereas, reflection filters are fascinating in colorful decoration [6–8], special photography [9] and fiber-optic communication for their relatively easy alignment of the components [10,11]. There are plenty of reports focusing on the design and fabrication of transmission or reflection filters [1–13]. However, these filters operate solely in transmission or in reflection. And in general, the spectral responses in reflection and transmission are complementary, i.e., the reflectance of a transmission filter at the peak wavelength is a minimum, vice versa for a reflection filter. In this paper, a novel narrow band filter in both transmission and reflection, for the first time to our knowledge, is proposed. This filter consists of one unsymmetrical dielectric Fabry–Perot cavity and an ultrathin metal film with optical constants $n \approx k$ (such as Cr, Ni, W). We find that the absorption at resonant wavelength is around zero in this case, and the transmittance and reflectance at resonant wavelength are both maximums with a good rejection level owing to the high absorption properties of the metal film. As a result, the optical properties of this structure are not only a transmission filter but also a reflection filter. Furthermore, the ratio between the peak reflectance and the peak transmittance, i.e., $R_{\max}/T_{\max}$, could be easily tuned by adjusting the dielectric stacks period. A filter operating in both transmission and reflection is promising to construct some compact optical systems, for example, one channel for the reference, the other for the probing. It is also interesting in colorful decoration because the colors in the transmitted and reflected light are similar. We theoretically and experimentally present this new filter in the following contents.

2. Theoretical analysis

The structure of the transmission and reflection filter proposed in this paper is Air/Cr $(LH)^{m1}2L(HL)^{m2}H$/Sub where H and L are respectively, a quarterwave layer of high and low index material, Sub means a glass substrate. $m1$ and $m2$ are integers which represent the stack number and $m2$ should be generally larger than $m1$ ($m2 \geqslant m1$). Notice that the metal film Cr should be ultrathin with a physical thickness of only 3–8 nm, otherwise neither good rejection level in reflection nor the high transmittance could not be realized. We assume the refractive index of Air, H, L and Sub as n_0, n_H, n_L and n_s, respectively. The physical thickness and complex index of Cr are denoted by d and $\eta_c = n_c - jk_c (n_c \approx k_c)$. Then at normal incidence, the characteristic matrix of Cr layer can be defined by [14]:

* Corresponding author. Tel.: +86 571 87951190.
E-mail address: adongszju@hotmail.com (W. Shen).

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doi:10.1016/j.optcom.2008.09.080

$$M_c = \begin{pmatrix} \cos\delta_c & j\sin\delta_c/\eta_c \\ j\eta_c \sin\delta_c & \cos\delta_c \end{pmatrix} \approx \begin{pmatrix} 1 & j2\pi d/\lambda \\ 4\pi d n_c k_c/\lambda & 1 \end{pmatrix} \quad (1)$$

where $\delta_c = \frac{2\pi}{\lambda} d(n_c - jk_c)$ is the phase thickness of Cr layer, and λ is the incident wavelength. The thickness d is much smaller than the wavelength ($\frac{d}{\lambda} \to 0$), therefore δ_c approaches to zero and $\cos\delta_c$, $\sin\delta_c$ can be expanded by Taylor's series. The matrix M_c can be thereby simplified by ignoring high order components as shown in the right part of Eq. (1).

If we assume that the equivalent optical admittance Y of the stack $(LH)^{m1}2L(HL)^{m2}H$/Sub is $Y' + jY''$, the matrix of the whole filter can be expressed as

$$\begin{bmatrix} B \\ C \end{bmatrix} = M_c \begin{bmatrix} 1 \\ Y \end{bmatrix} B' = \begin{bmatrix} 1 + j\frac{2\pi}{\lambda} dY' - \frac{2\pi}{\lambda} dY'' \\ \frac{2\pi}{\lambda} d(2n_c k_c) + Y' + jY'' \end{bmatrix} B' \quad (2)$$

Table 1
Optical constants of Cr film at different wavelengths.

Wavelength(nm)	496	548	617	659	704	756	821
n	2.75	3.18	3.17	3.09	3.05	3.08	3.20
k	3.30	3.33	3.30	3.34	3.39	3.42	3.48

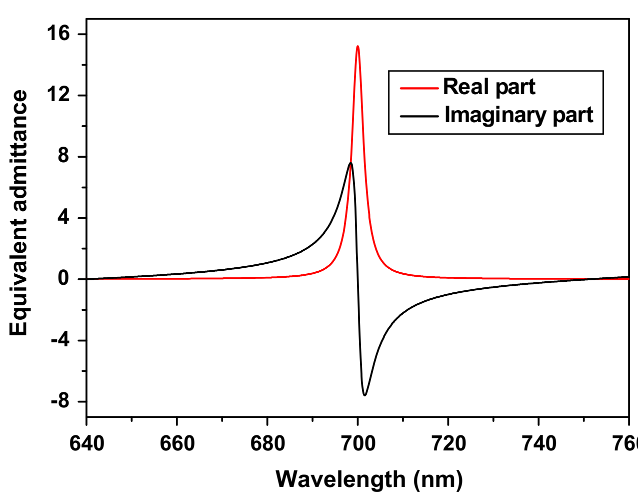

Fig. 1. Equivalent admittance of $(LH)^2 2L(HL)^4$/Sub.

where $Y = C'/B'$ and B', C' are, respectively matrix elements of the stack $(LH)^{m1}2L(HL)^{m2}H$/Sub. Thus, the reflectance at normal incidence of this filter can be calculated based on $R = \left|\frac{B-C}{B+C}\right|^2$ [14] and B' will not affect the reflectance calculation:

$$R = \frac{[n_0 - 2\pi d(n_0 Y'' + 2n_c k_c)/\lambda - Y']^2 + (2\pi n_0 dY'/\lambda - Y'')^2}{[n_0 - 2\pi d(n_0 Y'' - 2n_c k_c)/\lambda + Y']^2 + (2\pi n_0 dY'/\lambda + Y'')^2} \quad (3)$$

From Eq. (3), it can be seen that the value of R approaches to 1 when Y' or Y'' is infinity. However, at the condition of $Y' = 0$ and $Y'' = 0$, the reflectance equals $\left(\frac{n_0 - 4\pi n_c k_c d/\lambda}{n_0 + 4\pi n_c k_c d/\lambda}\right)^2$ and it will tend to be 0 (less than 0.3%) with $n_c k_c \approx 10$, $d = 5$ nm and $\lambda = 700$ nm. The stack $(LH)^{m1}2L(HL)^{m2}H$/Sub can be simplified as $H(LH)^{m2-m1}$/Sub after taking out the absentee layers at central wavelength λ_0. Consequently, the equivalent admittance at this wavelength will be $Y_0 = (n_H/n_L)^{2(m2-m1+1)}/n_s$. If the value of $m2 - m1$ is large enough, Y_0 will be very large due to $n_H > n_L$. According to Eq. (3), it will lead to a high reflectance at λ_0 in this filter.

As an example, we take $m1 = 2$, $m2 = 4$ for simulation by classical transfer matrix method. The refractive indexes of H, L and substrate are respectively, 2.17, 1.45 and 1.52. The optical constants of Cr at different wavelengths [15] are listed in Table 1 and its thickness is 5 nm. The central wavelength is located at 700 nm. Fig. 1 shows the equivalent admittance of $(LH)^2 2L(HL)^4$/Sub. It can be seen that both the real part and imaginary part of the equivalent admittance are extremes near 700 nm while rapidly decreasing to zero at other wavelengths. In consequence, a high reflectance ($R_{max} = 76.5\%$) at 700 nm with a deep cutoff could be obtained as the calculated results shown in Fig. 2a.

For transmittance, this structure Air/Cr $(LH)^{m1}2L(HL)^{m2}H$/Sub can be treated as an unsymmetrical Fabry–Perot cavity with metal-dielectric films. Air/Cr$(LH)^{m1}$ and $(HL)^{m2}H$/Sub represent the two respective mirrors which surround the spacer layer $2L$. So we can use the following equation to calculate the transmittance [14]:

$$T = \frac{T_1 T_2}{[1 - (R_1 R_2)^{1/2}]^2} \times \left[\frac{1}{1 + F\sin^2\phi}\right] \quad (4)$$

where $F = \frac{4(R_1 R_2)^{1/2}}{[1-(R_1 R_2)^{1/2}]^2}$, $\phi = \frac{1}{2}(\varphi_1 + \varphi_2 - 2\alpha)$. T_1, T_2, R_1, R_2, ϕ_1 and are the transmittance, reflectance and phase shift on reflection of the two respective mirrors, while α is the equivalent phase thickness of the spacer layer. In our structure, the two mirrors are not identical, i.e., R_1 is not equal to R_2. Moreover, there is also a little loss in

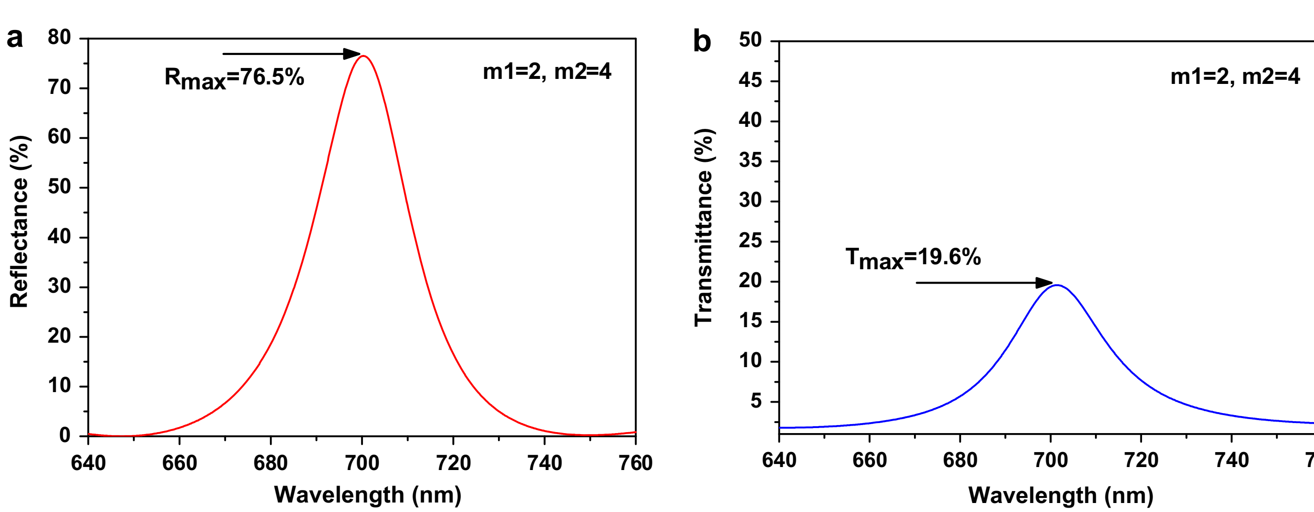

Fig. 2. The simulated results of Air/Cr $(LH)^2 2L(HL)^4$/Sub in the spectral range from 640 nm to 760 nm (a) the reflectance curve (b) the transmittance curve.

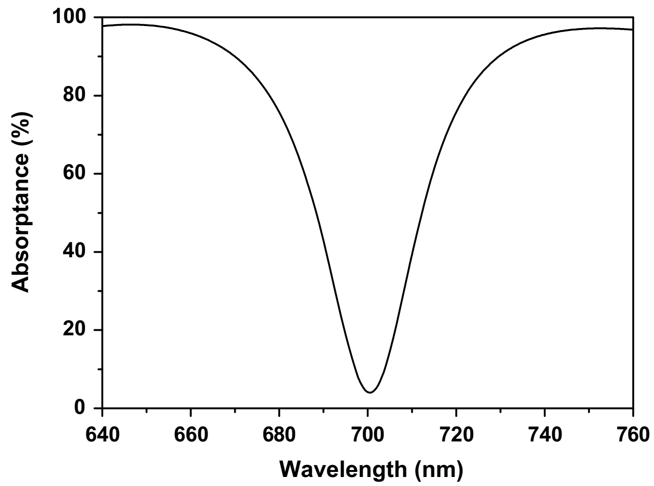

Fig. 3. The absorptance curve of Air/Cr $(LH)^2 2L(HL)^4$/Sub from 640 nm to 760 nm.

one mirror induced by Cr film. These will accordingly lead to a decrease of the peak transmittance at the resonant wavelength compared with an all-dielectric symmetrical Fabry–Perot filter. Fig. 2b shows the calculated transmittance curve of Air/Cr $(LH)^2 2L(HL)^4$/ Sub from 640 nm to 760 nm. Similar with the reflectance curve in Fig. 2a, a peak transmittance at 700 nm with a value of 19.6% can be observed.

The optical properties of this filter can be also analyzed from a viewpoint of the absorption. We simulate and show the absorptance curve from 640 nm to 760 nm in Fig. 3. It can be seen that the absorption at 700 nm is a minimum (less than 4%) while rapidly increase to a high level (near 100%) at other wavelengths. According to the law of energy conservation, the sum of reflectance, transmittance and absorptance is 1, i.e., $R + T + A = 100\%$. Consequently, at the wavelengths away from λ_0, the reflectance and transmittance will be both near zero due to a high absorptance. It is the reason why there is a good rejection level in transmission as well as in reflection. But, at λ_0, the absorptance reaches a minimum and the maximum values of the reflectance and transmittance occur simultaneously. As a result, this structure possesses the properties of both transmission and reflection filter with the same peak wavelength. In contrast, for an all-dielectric filter, there is no absorption ($R + T = 1$) at the whole spectral range, so the spectral responses on reflection and transmission are complementary, for example, a peak in transmission corresponds to a valley in reflection. Thus, it is impossible to realize the transmittance and reflectance filter simultaneously for all-dielectric filters.

The peak value ratio R_{max}/T_{max} of the filter can be tuned by changing the value of $m1$ and $m2$. If we increase $m1$with a fixed $m2$, the equivalent admittance $Y_0 = (n_H/n_L)^{2(m2-m1+1)}/n_s$ of $(LH)^{m1} 2L(HL)^{m2} H$/Sub at the central wavelength will be reduced. According to Eq. (3), this will lead to a drop of the peak reflectance R_{max}. On the other hand, the difference between R_1 and R_2, i.e., the reflectance of the two mirrors surrounding the spacer, will decrease with an increase of $m1$. Consequently, from Eq. (4), the

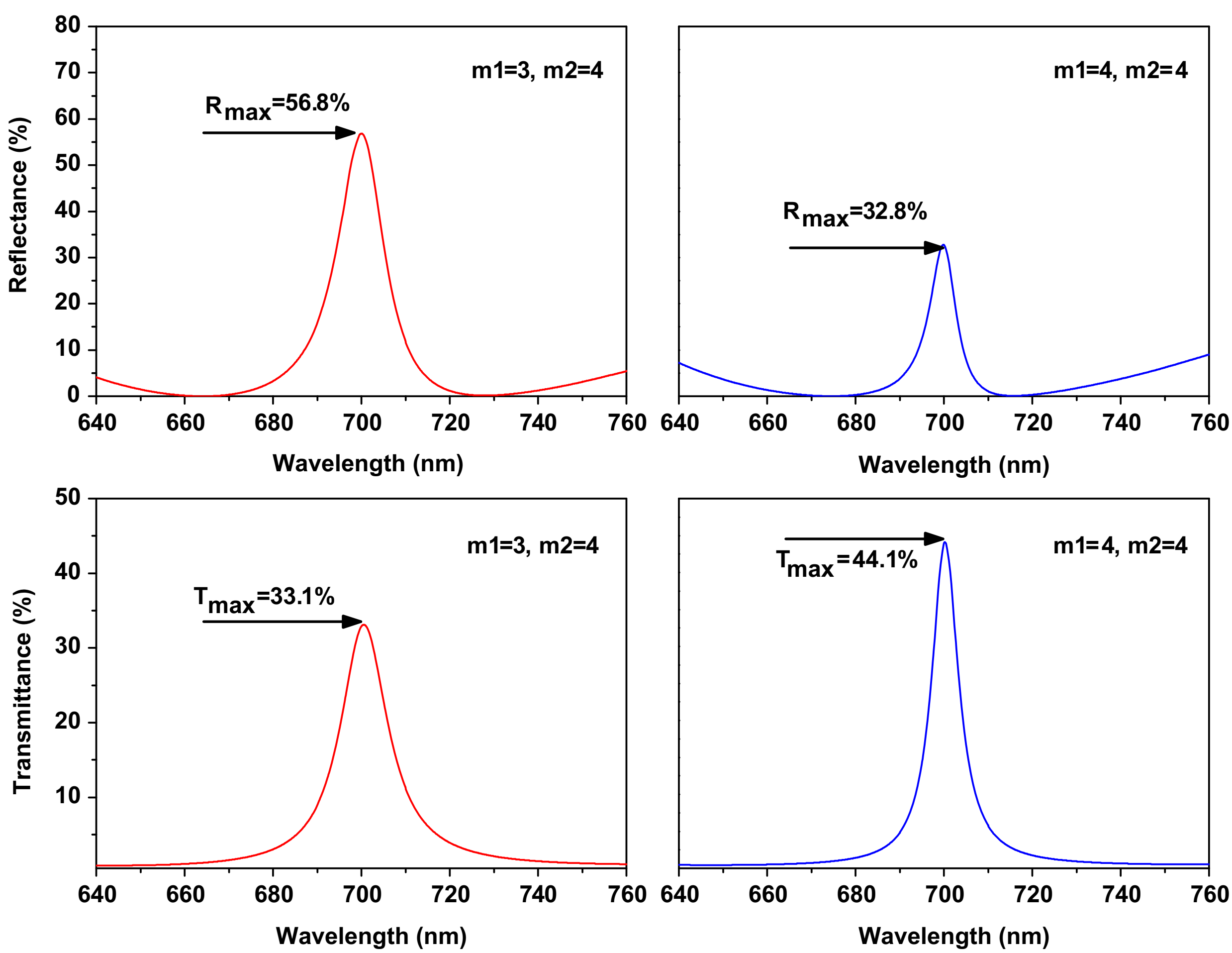

Fig. 4. The calculated transmittance and reflectance curves from 640 nm to 760 nm when $m1 = 3$, $m2 = 4$ and $m1 = 4$, $m2 = 4$.

transmittance T_{max} will be raised. The calculated transmittance and reflectance curves with $m1 = 3$ and $m1 = 4$ are respectively shown in Fig. 4 from 640 nm to 760 nm. Compared with the results in Fig. 2, T_{max} increases from 19.6% to 33.1% at $m1 = 3$ while R_{max} decreases from 76.5% to 56.8%. When $m1$ is equal to $m2$, T_{max} reaches to 44.1% while R_{max} decreases to 32.8%.

3. Experimental results and discussion

To verify the above analysis, the filters with different m1 were manufactured by classical electron beam evaporation. The high and low index materials were respectively TiO_2 ($n_H = 2.17$@700 nm) and SiO_2 ($n_L = 1.45$@700 nm) whose optical constants were determined by a photometric method. The background vacuum was 2.0×10^{-3} Pa while the partial pressure of oxygen for TiO_2 was 1.8×10^{-2} Pa. Meanwhile, the deposition temperature on substrate was kept at 300 °C during the process. The deposition rates of TiO_2, SiO_2 and Cr are respectively 0.3 nm/s, 1 nm/s and 0.2 nm/s controlled by a quartz sensor. During the deposition of the filter, the indirect monochromatic optical monitoring in transmission was used to control the thickness of each layer. In our plant, there are altogether six test substrates located in the center of vacuum chamber for optical monitoring. All the dielectric layers were monitored on one test substrate by a turning point method with a reference wavelength of 700 nm. After all the dielectric films were deposited, a new test substrate was used to control the Cr film thickness and the evaporation of Cr film was stopped by a shuttle at a predetermined transmittance value, i.e., a trigger point method.

After fabrication, the metal film surfaces in all the filters are smooth and bright. This brightness remains even after the samples are stored in atmosphere for five months. Therefore, the ultrathin Cr film deposited at 300 °C temperature should be continuous over the surface. The measurements of transmittance and reflectance in the spectral range from 640 nm to 760 nm were performed with a resolution of 0.5 nm on a spectrophotometer (Shimada UV310). Fig. 5 shows the measured results of the filters with $m1 = 2$, $m1 = 3$, $m1 = 4$ at $m2 = 4$. On the whole, the experimental results agree well with the theoretical calculations though there is a little difference of the maximum transmittance/reflectance and the central wavelength owing to the small variation of thickness and optical constants of Cr between the deposition and the design. As m1 increases from $m1 = 2$ to $m1 = 4$, R_{max} drops from 77.3% to 34% while T_{max} increases from 20% to 45.2%. When $m1$ equals $m2$, the reflectance R_1 and R_2 of the two mirrors surrounding the spacer will be close and a maximum T_{max} could be consequently obtained. However, limited to the absorption induced by Cr, the obtainable T_{max} will not be as high as that of a lossless all-dielectric filter. In comparison with T_{max}, R_{max} could reach near 100% if we increase the difference between $m2$ and $m1$. For example, a reflection filter with high reflectivity ($R_{max} = 92\%$) have been reported when $m1 = 3$ and $m2 = 7$ [7]. Meanwhile, as $m1$ changes from 2 to 4, the reflectance R_1 will be increased. According to Eq. (4), FWHM (Full Width at Half Maximum) of the filters equals $\frac{2\lambda_0}{\pi}\sin^{-1}\left[\frac{1-(R_1R_2)^{1/2}}{2(R_1R_2)^{1/4}}\right]$. Thus, an

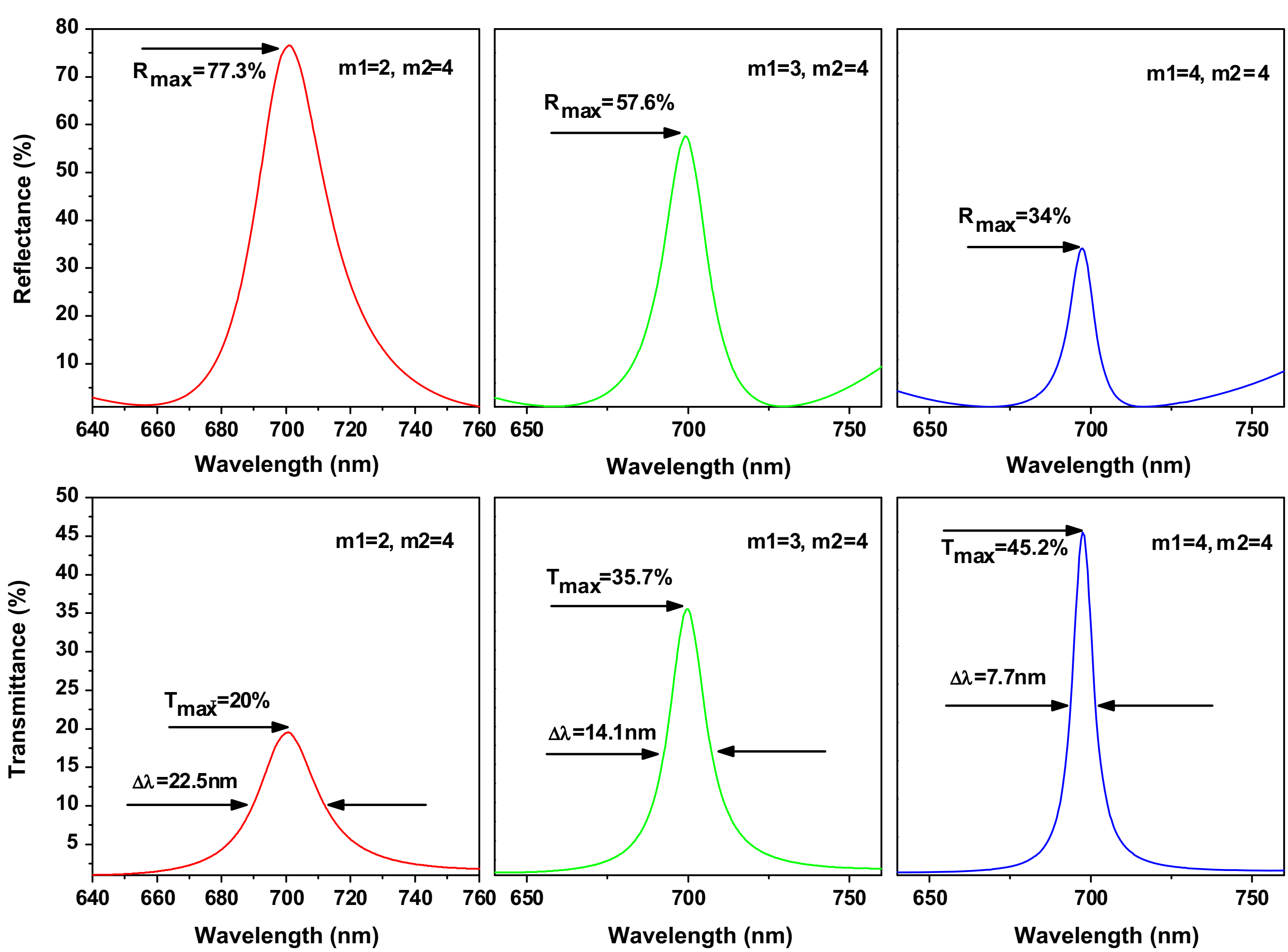

Fig. 5. The measured reflectance and transmittance curves in the spectral range from 640 to 760 nm at different $m1$ values ($m1 = 2$–4).

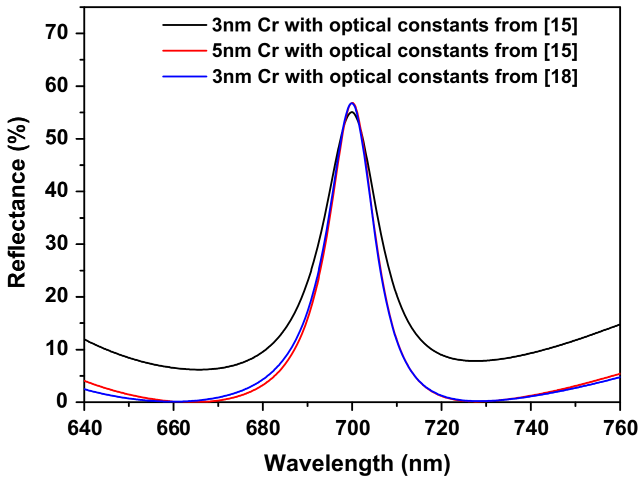

Fig. 6. The reflectance curves of the filter ($m1 = 3$, $m2 = 4$) with different optical constants of Cr film.

increase of the reflectance R_1 will result in a decrease of FWHM which can also be observed in Fig. 5.

It should be noticed that the dielectric layer close to Cr film in this structure must be a low index material. Otherwise, the filters both in transmission and reflection can not be realized. For example, H is added close to Cr film in a filter and this structure becomes Air/Cr $H(LH)^{m1}2L(HL)^{m2}H$/Sub. Then $H(LH)^{m1}2L(HL)^{m2}H$/Sub can be simplified as $(LH)^{m2-m1}$/Sub by removing the absentee layer at the central wavelength and the equivalent admittance will be $Y_0 = n_s(n_L/n_H)^{2(m2-m1)}$. If $m2 - m1$ is large enough, Y_0 will be infinitesimal around zero due to $n_L < n_H$. In this case, according to Eq. (3), the reflectance at the central wavelength will be 0.

It is interesting to analyze the effect of optical constants of Cr film on the optical properties of the filter. In this article, optical parameter of Cr was taken from reference [15] which was widely used in the literature [16,17]. However, we use the optical constants of Cr film from reference [18] in our previous work [9]. For comparison, the reflection properties of the filters with different optical constants are simulated and displayed in Fig. 6. It can be seen that the reflectance curve with 5 nm Cr from reference [15] is very similar with that of 3 nm Cr from reference [18]. The calculation results of the filters with various $m1$ and $m2$ confirm this point. Therefore, the two optical constants of Cr film can be both used to design this filter. As described above, the deposition of Cr film was controlled by optical transmission monitoring with a trigger point method. By this method, a variation of optical constants during the deposition could be compensated by the physical thickness. Consequently, for 5 nm Cr [15] and 3 nm Cr [18], the transmittance values at the trigger point are very close (respectively 51% and 51.7%). So, the optical properties of the manufactured filters agree well with those of the design ones.

4. Conclusion

In conclusion, we theoretically and experimentally present a novel narrow band filter in both transmission and reflection. This filter is composed of dielectric and metal films. The simulation results along with the experimental results show that the maximums in both transmittance and reflectance occur simultaneously at the central wavelength while the absorptance reaches a minimum. The ratio R_{max}/T_{max} can also be tuned by adjusting the dielectric stacks. Such a filter could be used to construct some compact optical systems and is also interesting in color decoration.

Acknowledgements

This work is partially supported by National Natural Science Foundation of China (Grant Nos. 60708013 and 60778025) and China Post-doctoral funding (20070421168). The authors also thank Michel Cathelinaud from Institut Fresnel (Marseille, France) for his helpful discussion.

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