Highly Angle-tolerant Spectral Filter Based on an Etalon Resonator Incorporating a High Index Cavity

Tae-Hui Noh¹, Yeo-Taek Yoon¹, Sang-Shin Lee^{1*}, Duk-Yong Choi², and Seung-Chan Lim³

¹*Department of Electronic Engineering, Kwangjuon University, 447-1 Wolgye-dong,
Nowon-gu, Seoul 139-701, Korea*

²*Laser Physics Centre, Research School of Physics and Engineering,
Australian National University, Canberra ACT 0200, Australia*

³*Korea Elecom Inc., Research Division,
55-20 Mullae-dong 3-ga, Yeungdeungpo-gu, Seoul 150-834, Korea*

(Received May 7, 2012 : revised June 18, 2012 : accepted June 18, 2012)

A high angular tolerance spectral filter was realized incorporating an etalon, which consists of a TiO₂ cavity sandwiched between a pair of Ag/Ge mirrors. The effective angle was substantially extended thanks to the cavity's high refractive index. The device was created by embedding a 313-nm thick TiO₂ film in 16-nm thick Ag/Ge films through sputtering, with the Ge layer alleviating the roughness and adhesion of the Ag layer. For normal incidence, the observed center wavelength and transmission were ~900 nm and ~60%, respectively; throughout the range of 50°, the relative wavelength shift and transmission variation amounted to only ~0.06 and ~4%, respectively.

Keywords : Spectral filters, Etalon, Thin films, Resonators, Metal layers

OCIS codes : (230.7408) Wavelength filtering devices; (310.6845) Thin film devices and applications; (310.3915) Metallic, opaque, and absorbing coatings; (230.5750) Resonators

I. INTRODUCTION

Recently, free space optics technology has been extensively applied to various fields, such as visible light communications, military training systems like multiple integrated lasers engagement systems, and last-mile wireless interconnects. A spectral bandpass filter featuring a wide field-of-view is regarded as one of the essential elements for the implementation of those applications [1, 2], taking into account the fact that it may play the role of mitigating undesirable surrounding noise caused by sunlight or lighting equipment, so as to prevent the malfunction of receivers [3]. So far, spectral filters based on multi-layered films have been actively attempted, because of their simple structure and low cost [4, 5]. However, their performance in terms of center wavelength and transmission efficiency has been critically dependent on the angle of the light beam [6-10],

which is widely regarded as a paramount issue with a spectral filter used for receivers, which are applied to free space optics and image sensors. A device tapping into a complicated photonic crystal structure was also suggested, to alleviate the angular dependence [11-13]. Although the variation in wavelength remained relatively small, transmission degraded excessively with increasing angle. Moreover, the operation was severely polarization sensitive. In this paper, we have proposed and built a near-infrared bandpass filter incorporating an etalon resonator, enabling an extended angular tolerance and small polarization dependence. The resonator was created in such a way that a high index dielectric cavity made of TiO₂ film is sandwiched by a pair of metallic mirrors in Ag/Ge. It was confirmed theoretically and experimentally that the influence of angle upon the resonant wavelength and transmission efficiency was remarkably diminished, as compared to the device using a low index cavity, such as SiO₂.

*Corresponding author: slee@kw.ac.kr

Color versions of one or more of the figures in this paper are available online.

II. PROPOSED ANGLE TOLERANT FILTER AND ITS DESIGN

We aimed to develop an angle tolerant spectral bandpass filter operating at ~ 900 nm wavelength. As illustrated in Fig. 1, the proposed etalon resonator, realized in a glass substrate, is composed of a high index TiO_2 cavity embedded in two identical thin Ag/Ge mirrors. An oxide film is formed on top of the etalon as a protective layer, thereby avoiding the oxidation of the exposed Ag layer. It is noted that a thin Ge film has been combined with the Ag layer for the purpose of not merely reducing the optical loss caused by its surface roughness but also helping strengthen its adhesion to the oxide and TiO_2 layers. An incident beam impinging upon the etalon structure is supposed to undergo a strong resonance that results in periodic transmission peaks [14].

The optical spectral response is given by the following Equation 1 [15]. Here, R is the reflectance of the mirror, d and n_1 are the thickness and refractive index of the cavity, and λ is the wavelength. ϕ_r is the reflection phase shift from the thin Ag film in conjunction with the substrate or cover, which is both angle and polarization dependent. Although the phase shift may be precisely discovered by considering the dispersion characteristics of the metal, it was approximated to be $\phi_r = \pi$, which is as in the case of a perfect metal, for studying the influence of the cavity index on the angle dependent performance of the proposed filter [15]. The propagation angle θ_p inside the cavity, which is determined by the n_1 and the angle of incidence θ_i , is directly related to the resonant wavelength. In order to enlarge the effective angle, the sensitivity of filter performance to θ_i should certainly be suppressed by decreasing θ_p . The dependence of the fractional change in a resonant center wavelength λ_c upon the incidence angle is derived such that it can be expressed as the following Equation 2, indicating that for a constant angle the relative wavelength shift is decreased by raising the refractive index of the cavity medium [16]. It should be, however, noted that the influence of the reflection phase term ϕ_r has been ignored while deriving the Equation 2, which is approximately valid for relatively small angles of incidence. This will be

evident with reference to the simulation results as discussed later. In order to overcome its limitations, therefore, we have resorted to numerical simulations.

$$T = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2 \left(\frac{2\pi}{\lambda} n_1 d \cos \theta_p + 2\phi_r \right)} \quad (1)$$

$$\frac{(\partial \lambda_c / \partial \theta_i)}{\lambda_c} = \frac{\sin \theta_i \cos \theta_i}{n_1^2 - \sin^2 \theta_i} \quad (2)$$

We theoretically investigated the spectral response of the proposed filter for two different cavity materials of TiO_2 ($n \sim 2.3$) and SiO_2 ($n \sim 1.45$). As for the structural parameters, the thicknesses of the TiO_2 cavity and the Ag mirror film were chosen to be $d = 313$ nm and $t_1 = 14$ nm, respectively. As mentioned above, an ultrathin Ge layer of 2 nm thickness was introduced to improve the surface roughness of the Ag layer and to strengthen its adhesion to the oxide and TiO_2 layers; and a 170 nm thick oxide film served as a protective layer. In order to accurately estimate the actual transfer characteristics of the proposed device, the finite thickness of the metallic mirrors and their dispersion were taken into account with the assistance of a commercially available simulation tool, GSolver, based on a rigorous coupled-wave analysis. Fig. 2 shows the dispersion characteristics of the Ag used for the mirror, which has been derived from the Drude model. For an angle θ_i , ranging from 0 to 50° , the shift in resonant wavelength $\Delta \lambda_c$ was first examined with respect to the case of normal incidence of $\theta_i = 0^\circ$. As shown in Fig. 3(a), the relative wavelength shift, which is defined as $\Delta \lambda_c / \lambda_c$, was found to be much smaller for the high index cavity in TiO_2 , compared to the low index cavity in SiO_2 . In particular, Fig. 3(b) compares the responses corresponding to $\theta_i = 0$ and 50° for TiO_2 and SiO_2 cavities. For filters with the same configuration, the high index cavity provided much smaller variation in the center wavelength than the low index cavity, as predicted.

FIG. 1. Configuration of the proposed spectral filter featuring high angular tolerance.

FIG. 2. Dispersion characteristics of Ag metal.

FIG. 3. Transfer characteristics of an etalon filter depending on the cavity materials of SiO₂ and TiO₂ for unpolarized light: (a) Relative center wavelength shift with incidence angle θ_i (b) Spectral response for $\theta_i = 0^\circ$ and 50° .

Next, Fig. 4(a) shows the calculated optical response for unpolarized light when θ_i varies from 0 up to 50° , in 10° steps. For normal incidence, the resonance was centered at ~ 900 nm wavelength with a transmission of $\sim 75\%$. Overall, the relative center wavelength shift and fluctuation in maximum transmission were observed to be approximately 0.06 and 2%, respectively. We have explored the influence of the polarization upon the performance of the proposed filter with the incidence angle. Fig. 4(b) and (c) show the spectral transmission for angles of $\theta_i = 0^\circ$ and 50° for the s(TE)-polarization and p(TM)-polarization. The device exhibited no polarization dependence for the normal incidence as predicted. However, as observed in Fig. 4(b), a slight discrepancy between the two polarizations was actually witnessed for the extreme angle of $\theta_i = 50^\circ$. The difference in the relative center wavelength shift between the TE and TM polarizations was found to increase slightly with the angle. Next, in order to identify the limit in the peak transmission at the center wavelength, we observed the transmission as well as the reflection for the filter as shown in

FIG. 4. (a) Calculated spectral response in terms of various incidence angles for unpolarized light (b) Calculated spectral response with the polarization for incidence angles of 0° and 50° (c) Theoretical relative center wavelength shift with respect to the angle for TE and TM polarizations.

Fig. 5. Since the reflection is negligibly small, the limit in the peak transmission, which is equivalent to the optical loss, is believed to be mostly attributed to the absorption induced by the Ag mirror.

FIG. 5. Calculated optical transmission and reflection for the proposed etalon filter.

FIG. 6. Atomic force microscope (AFM) images of Ag films with and without a Ge film.

III. DEVICE FABRICATION AND EXPERIMENTAL RESULTS

The proposed filter device was manufactured following the procedure described here: Three layers, comprising a

(a)

(b)

FIG. 7. Achieved filter performance with respect to the angle of incidence for unpolarized light: (a) Spectral response (b) Relative center wavelength shift.

film of Ag ($t_1 = 14$ nm)/Ge ($t_2 = 2$ nm) for the bottom mirror, a TiO_2 ($d = 313$ nm) film for the etalon cavity, and a similar top mirror, were successively deposited on a glass substrate, via argon sputtering. A 170 nm thick oxide film was then produced on top of the mirror, to complete the device. For the purpose of verifying the effect of the Ge layer on the surface quality of the Ag layer, atomic force microscope images of Ag films with and without the deposited Ge film were taken, as shown in Fig. 6. The RMS roughness as measured decreased considerably from 8.4 to 0.54 nm, thereby relieving the optical scattering loss stemming from the uneven surface of the film [17].

A collimated light beam, generated by a halogen lamp, Model LS-1, Ocean Optics, was used to illuminate the prepared filter, which was mounted on a precision rotational stage, while the output was captured by use of a spectrophotometer, Model USB-4000-VIS-NIR, Ocean Optics. Fig. 7(a) shows the transfer characteristics for an incidence angle spanning 50° . In the case of normal incidence, the center wavelength was ~ 900 nm as anticipated. The demonstrated peak transmission was nearly 60%, which was elevated by the amount of 30% as compared to the case involving no Ge film. This is due to the enhanced surface roughness of

FIG. 8. (a) Measured spectral transmission with the polarization with respect to incidence angles of 0° and 50° (b) Demonstrated relative center wavelength shift in terms of the angle for TE and TM polarizations.

the Ag/Ge film, leading to lower optical loss. The achieved transmission was still lower than the theoretical level by the amount of $\sim 15\%$, which may be attributed to the unwanted absorption incurred by the fabricated Ag mirror [17]. The center wavelength slightly shifted from 900 nm to ~ 845 nm, as the angle increased from 0 up to 50° . As plotted in Fig. 7(b), the relative wavelength alteration obtained was accordingly observed to be as small as ~ 0.06 , which is in good correlation with the theoretical result. The change in peak transmission was 4% or so while the spectral bandwidth was almost maintained. Finally, the measured transmissions for incidence angles of $\theta_i = 0^\circ$ and 50° are shown in Fig. 8(a) for the TE and TM polarizations, while Fig. 8(b) reveals the corresponding relative wavelength shift as a function of the angle for the two polarizations. As anticipated from the simulation results included in Fig. 4(b) and (c), the polarization dependence was observed to slightly increase with the incidence angle.

IV. CONCLUSION

In summary, a high angular tolerance infrared wavelength filter was constructed relying on a simple etalon resonator, utilizing a high index TiO_2 cavity integrated into a pair of Ag/Ge films. Its angular sensitivity was theoretically and experimentally proven to be sufficiently low in terms of the relative wavelength shift and the variation in transmission efficiency. We anticipate our device will be readily adopted to warrant the viable operation of free space optics based modules/systems regardless of a variety of surrounding noise sources.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2011-0017901 and 2011-0030821), Business for Cooperative R&D between Industry, Academy, and Research Institute funded by Korea Small and Medium Business Administration in 2011 (Grant No. 00043574), and a research grant from Kwangwoon Univ. in 2012.

REFERENCES

1. T. Fohl, "Wide angle, narrow band optical filter," U.S. Patent, 5,288,992 (1994).
2. B. E. Johnson, T. A. Lindsay, D. L. Brodeur, R. E. Morton, and M. A. Regnier, "Wide-angle, high-speed, free-space optical communication system," U.S. Patent, 5,359,446 (1994).
3. A. J. C. Moreira, R. T. Valadas, and A. M. Duarte, "Reducing the effects of artificial light interference in wireless infrared transmission systems," in *Proc. IEEE Colloquium on Optical Free Space Communication Links* (Savoy Place, UK, Feb. 1996), pp. 5/1-5/10.
4. G. Minas, J. C. Ribeiro, J. S. Martins, R. F. Wolffenbuttel, and J. H. Correia, "An array of Fabry-Perot optical-channels for biological fluids analysis," *Sens. Actuators A* **115**, 362-367 (2004).
5. M. Bartek, J. H. Correia, and R. F. Wolffenbuttel, "Micro-machined Fabry-Perot optical filters," in *Proc. 2nd Int'l Conf. on Adv. Semiconductor Devices and Microsystems* (Slovakia, Oct. 1998), pp. 283-286.
6. Y. Yoon, J. Shim, D. Jang, J. Kim, Y. Eo, and F. Rhee, "Transmission spectra of Fabry-Perot etalon filter for diverged input beams," *IEEE Photon. Technol. Lett.* **14**, 1315-1317 (2002).
7. M. Jablonski, Y. Tanaka, H. Yaguchi, K. Furuki, K. Sato, N. Higashi, and K. Kikuchi, "Entirely thin-film allpass coupled-cavity filters in a parallel configuration for adjustable dispersion-slope compensation," *IEEE Photon. Technol. Lett.* **13**, 1188-1190 (2001).
8. Q. H. Wang, D. H. Li, B. J. Peng, Y. H. Tao, and W. X. Zhao, "Multilayer dielectric color filters for optically written display using up-conversion of near infrared light," *IEEE J. Display Technol.* **4**, 250-253 (2008).

9. M. L. Baker and V. L. Yen, "Effects of the variation of angle of incidence and temperature on infrared filter characteristics," *Appl. Opt.* **6**, 1343-1351 (1967).
10. Y. T. Yoon and S. S. Lee, "Transmission type color filter incorporating a silver film based etalon," *Opt. Express* **18**, 5344-5349 (2010).
11. W. Nakagawa, P. Sun, C. Chen, and Y. Fainman, "Wide-field-of-view narrow-band spectral filters based on photonic crystal nanocavities," *Opt. Lett.* **27**, 191-193 (2002).
12. B. H. Cheong, O. N. Prudnikov, E. Cho, H. S. Kim, and J. Yu, "High angular tolerant color filter using subwave-length grating," *Appl. Phys. Lett.* **94**, 21304 (2009).
13. S. Koyama, Y. Inaba, M. Kasano, and T. Murata, "A day and night vision MOS imager with robust photonic-crystal-based RGB-and-IR," *IEEE Trans. Elect. Dev.* **55**, 754-759 (2008).
14. R. A. Booth and D. K. Reinhard, "Diamond thin film Fabry-Perot optical resonators," in *Proc. The 6th Applied Diamond Conf./Second Frontier Carbon Technology Joint Conf.* (USA, 2001).
15. M. Born and E. Wolf, *Principles of Optics*, 7th ed. (Cambridge University Press, New York, USA, 1999), Chapters 7 and 14.
16. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, 2nd ed. (Wiley-Interscience, New York, USA, 2007), Chapter 10.
17. W. Chen, M. D. Thoreson, S. Ishii, A. V. Kildishev, and V. M. Shalaev, "Ultra-thin ultra-smooth and low-loss silver films on a germanium wetting layer," *Opt. Express* **18**, 5124-5134 (2010).