Transmission type color filter incorporating a silver film based etalon

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Abstract: Transmission type color filters based on a thin film Ag-SiO$_2$-Ag etalon were built on a quartz substrate, enabling the infrared suppressed transmission and large effective area. They were designed by taking into account the influence of the dispersion characteristics and the thickness of the silver metal. Three different color filters were devised: The cavity length for the red, green and blue filter was 160 nm, 130 nm, and 100 nm respectively, while the metal layer was fixed at 25 nm. The observed spectral pass band was centered at 650 nm, 555 nm, and 480 nm for the red, green, and blue device; the corresponding bandwidth was about 120 nm, 100 nm, and 120 nm; and the peak transmission was all ~60%. For the oblique light incidence the angular dependence of the peak relative transmission was measured to be ~1%/degree. The spectral response of the device was also analyzed for two different polarizations as the tilt angle varied up to 12°, and it was found to be hardly polarization dependent. Finally, as for the positional dependence the relative transmission and the center wavelength were found to vary within 10% and 5 nm respectively over an effective area of 4x4 cm$^2$.

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1. Introduction
Color filters have been regarded as an indispensable element for the implementation of complementary metal-oxide-semiconductor (CMOS) image sensors, liquid crystal display devices, light emitting diodes, etc [1,2]. They were already commercialized by using spin-cast dye films of three individual colors, yet several schemes based on a CMOS process compatible technology were proposed rendering the low-cost, simple integration with the
main devices aforementioned. There was a report on the devices incorporating a subwavelength periodic grating in single-crystalline silicon or poly-crystalline silicon which were produced by the e-beam lithography and the laser interference lithography [3,4]. They are useful for simplifying the fabrication but suffer from polarization dependent operation and high cost. Other approaches were also introduced based on a SiO$_2$/TiO$_2$ photonic crystal structure with a SiO$_2$ defect layer inserted in the middle of it [5,6], offering a high transmission but demanding precise film-thickness control. It is undesirable, however, the previous devices allow remarkable amount of light to be transmitted especially in the near infrared (NIR) region.

In this paper we focused on the construction of transmission-type red, green and blue color filters exploiting a Fabry-Perot etalon, consisting of an oxide (SiO$_2$) thin film sandwiched in between two silver (Ag) metal layers. They were rigorously analyzed by taking into account the finite thickness of the metal layer and its dispersion characteristics, making the practical estimation of the device performance possible. And the devices were all created by employing a simple thin-film deposition method instead of the complicated e-beam lithography or laser interference lithography technique. Their performance was assessed in terms of the angular dependence, the polarization sensitivity for oblique incidence, and the positional dependence.

The source of the optical loss associated with the filters was scrutinized in addition.

2. Filter design and its simulation results

Figure 1 depicts the schematic configuration of the proposed color filter utilizing the Fabry-Perot etalon formed on a quartz substrate, where a dielectric oxide film acting as cavity is placed in between the top and bottom reflecting mirror films made of silver. It is supposed to provide a periodic bandpass filtering characteristic [7], with the approximate transmission given by $T = (1 - R)^2 / [(1 - R)^2 + 4R\sin^2(2\pi nd / \lambda)]$ under the assumption the finite thickness of the metal layers and its dispersion are disregarded. Here, $R$ is the reflection coefficient of the metal film, $d$ the cavity length, $n$ the refractive index of the cavity, and $\lambda$ the wavelength. The cavity length was to be adjusted adequately, so that the primary resonance mode of the filters corresponding to the wavelength of the red, green, and blue color is only positioned within the visible band, whereas the rest of the resonance modes are sufficiently separated from it to be located in the NIR band. These undesired secondary modes could be blocked by the high absorption of the metal films, as manifested later through the experimental results.

To predict the practical performance of the filters more efficiently, the influence of the finite thickness of the metal layer and its dispersion characteristics are to be considered. Hence we designed and analyzed the devices by resorting to a commercially available tool OptiFDTD from Optiwave, Canada, based on the finite-difference time-domain method. The dispersion information on the silver was derived from the Lorentz-Drude model and included as an inset in Fig. 2 [8]. The imaginary part of its refractive index, which is responsible for the optical absorption, increases gradually with the wavelength. And the quartz substrate was assumed to give a constant refractive index of 1.5 with a negligibly small optical loss. The metal thickness was adjusted to obtain a high light transmission in the visible region while the light is blocked in the NIR region, and as a result it was determined to be 25 nm thick. The device design was fulfilled in such a way to lead to a spectral response with the maximum transmission efficiency near the center wavelength and an appropriate roll-off characteristic near the cutoff on both sides of the pass band.

Figure 2 shows the simulated transfer characteristics of the filters with and without the quartz substrate. The presence of the substrate was found to help raise the transmission slightly. The cavity length of the etalon was controlled to locate the transmission peaks within the visible band, and it was chosen to be 100 nm, 130 nm, and 160 nm for the blue (Dev B), green (Dev G) and red (Dev R) filters respectively. The calculated center wavelength was 460 nm for the Dev B, 555 nm for the Dev G, and 650 nm for the Dev R; and the peak transmission efficiency reached up to 60% and the 3-dB bandwidth was 130 nm, 115 nm and 110 nm respectively. The filter bandwidth is one of the crucial factors determining the quality
of selected colors, while commercial color filters are known to have the bandwidth of around 100 nm. It is noteworthy the transmission in the NIR band beyond the wavelength of ~700 nm appeared to be suppressed substantially below 10%.

![Diagram of a proposed Fabry-Perot etalon based color filter.](image)

**Fig. 1.** Proposed Fabry-Perot etalon based color filter.

![Graph showing transmission vs wavelength for color filters with and without a substrate.](image)

**Fig. 2.** Calculated transfer characteristics of the proposed color filter with and without the substrate.

### 3. Device fabrication and experimental results

The procedure adopted for producing the blue, green and red filters is described here: A bottom silver film of 25 nm thickness was deposited on all of three 4” quartz substrates via the e-beam evaporation. An oxide film of 100 nm, 130 nm, and 160 nm thickness was subsequently made on top of each silver coated substrate via the plasma enhanced chemical vapor deposition (PECVD) method, then a top silver film of the same thickness as the bottom one was similarly formed. The scanning electron micrograph of the prepared blue color filter Dev B is displayed in Fig. 3.
For the purpose of evaluating the fabricated devices, they were mounted on a translation stage. The output beam was captured by an optical spectrophotometer when an input unpolarized beam from a broad band halogen lamp was illuminated upon them. Figure 4(a) displays the observed spectral response of the color filters in conjunction with the corresponding captured color images. It was proven a decent bandpass filtering characteristic was achieved with the center wavelength at 480, 555, and 650 nm for the Dev B, Dev G, and Dev R respectively. They offered the 3-dB bandwidth of about 120, 100, and 120 nm respectively and the peak transmission of ~60%. Overall, the measured transfer curves were shown to be in reasonable agreement with the theoretical curves. The transmission was less than 10% in the NIR region as anticipated.

To identify the source of the optical loss in the pass band incurred by the filters, we analyzed the optical absorption resulting from the metal layer itself as well as the optical reflection by the entire etalon filters as a function of the wavelength as shown in Fig. 4(b). It was discovered the reflection and the metallic absorption accounts for ~10% and ~30% of the resulting optical loss respectively [7]. And the color quality of the output images obtained from the devices may be enhanced by sharpening the roll-off of the transmission curve and diminishing the bandwidth. Toward this end, we have investigated the effect of the silver film thickness on the transfer characteristics. When it varied from 20 nm to 50 nm, the bandwidth was substantially reduced from 132 nm to 48 nm, yet the peak transmission efficiency dropped by one fourth, indicating that there exists a trade-off between the metal thickness and the bandwidth. Next, the angular dependence of the devices for oblique beam incidence was investigated considering their practical alignment with a light source as depicted in Fig. 5, where the filter is tilted with an angle $\theta$ with respect to the incoming wave. The relative peak transmission of the blue color filter was recorded with $\theta$ ranging from 0° to 12°. The transmission was maximized for the normal incidence of $\theta = 0^\circ$ as anticipated, and declined almost linearly with the rate of ~1%/degree. The polarization dependence of the proposed color filter was then examined by calculating its spectral response for different tilt angles as plotted in Fig. 6. Here, for the TM and TE polarization the electric field of the incoming plane
wave was assumed to exist in the x and y axis, respectively. There was naturally no
polarization dependence for normal incidence of $\theta = 0^\circ$. Though the tilt angle increases up to
12°, the spectral responses for the two polarizations remain almost identical except for a slight
difference of less than 2% in the peak transmission at ~480 nm. This little discrepancy may be
attributed to the polarization sensitive reflection from the metal-dielectric interface [9, 10].
The theoretical relative difference in the reflectance and the reflection phase shift between the
two polarizations was only below ~0.3 and ~0.5 percent respectively. For the same
polarization the filter transmission was observed to deteriorate for larger tilt angles. In this
respect the angle between the filter and incident light beam is to be minimized to reduce the
polarization dependence and enhance the color selectivity.

![Diagram showing the input wave and relative transmission efficiency vs. tilt angle.](image)

**Fig. 5.** Measured angular dependence of the blue color filter.

![Simulated transmission graphs for different polarizations with various incidence angles.](image)

**Fig. 6.** Simulated transmission of the blue color filter for different polarizations with various
incidence angles ($0^\circ$, $4^\circ$, $8^\circ$, $12^\circ$).

Lastly, the positional variation in the device performance was studied with respect to the
center wavelength and the transmission efficiency to figure out the effective operation area of
the fabricated filters. Nine different locations on the area of 4x4 cm$^2$ were chosen as described
in Fig. 7. For the case of the red filter Dev R, the variation in the relative transmission and the center wavelength was discovered to be ~10% and 5 nm respectively. This positional dependence may be alleviated by optimizing the fabrication process to ameliorate the uniformity in the thickness and the physical properties of the films involved.

![Graph showing positional dependence of relative transmission and center wavelength.]

Fig. 7. Positional dependence of the relative transmission and the center wavelength.

4. Conclusion

We realized transmission type simple and wide-area color filters taking advantage of a metal-oxide-metal etalon structure. The actual influence of the dispersion characteristics of the metal and its finite thickness was taken into consideration in view of better device design. And their spectral performance was assessed in terms of the polarization dependence, the angular dependence, and the positional variation. In light of their practical applications the three color filters could be integrated on the same chip by selectively depositing an oxide film with different thickness via a shadow mask.

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