Fabrication of Transmission Color Filters Using Silicon Subwavelength Gratings on Quartz Substrates

Yoshiaki Kanamori, Masaya Shimono, and Kazuhiro Hane

***Abstract*—We investigate theoretically and experimentally transmission color filters using silicon subwavelength gratings on quartz substrates. Each grating area is 120 μm-square, which is suitable pixel size for displays and multichannel detectors. In the fabrication, electron beam lithography and fast atom beam etching are used. The grating periods are 400, 350, and 440 nm for the red, green, and blue filters, respectively. The transmission spectrum obtained from a coupling between an incident light and the submicrometer periodic grating matches with human color perception. The transmittances of 71.1%, 58.1%, and 59.3% are obtained for the red, green, and blue filters, respectively.**

***Index Terms*—Micromachining, optical device fabrication, optical filters, optical gratings, periodic structures.**

I. Introduction

A subwavelength grating (SWG), which has a smaller period than the wavelength of an incident light, does not generate higher diffraction orders. When the grating period is much smaller than the wavelength, the grating behaves as a homogeneous layer with effective refractive index between the material index and the surrounding index. Applications of SWGs today, for example, include antireflection filters [1]–[3] and phase plates [4].

When period of an SWG on a planar waveguide satisfies a guided-mode resonant (GMR) condition caused by coupling between an incident light and a periodic structure, the grating works as a high efficiency band-stop filter at the resonant wavelength [5]–[7]. Band-stop filters based upon GMR condition with both narrow and broad bandwidths have already been investigated with silicon as the SWG material because of its advanced and widespread status. For instance, Brundrett *et al.* theoretically investigated a narrowband filter with approximately 2 nm of bandwidhth using silicon-on-sapphire substrates [5]. Mateus *et al.* experimentally demonstrated a high reflectivity (>98.5%) in a wide spectrum range (500 nm) using a polysilicon grating [6]. Though the material was not silicon, Tibuleac *et al.* [7] and Magnusson *et al.* [8] investigated theoretically the bandpass filters by applying the GMR condition.

As materials for transmission color filters, dye-doped polymers have generally been used. As the filters based on gratings, in 1978, Knop studied diffraction grating filters with the grating periods larger than the incident light both theoretically and experimentally for projection systems [9], [10]. Recently, Lehmann *et al.* fabricated filters functioning as short-pass filters and producing several colors using periodic structures patterned on macro-porous silicon [11]. Biomimetic engineering has got a lot of attention recently, and structural colors of *Morpho* butterflies wings have been investigated and modeled with Lamellar grating theory [12]. However, the structures in this study perform only as reflection filters. To the best of our knowledge, there is no transmission color filter using gratings to produce the three primary colors without generating higher diffraction orders.

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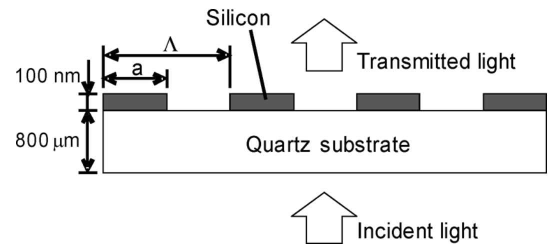

Fig. 1. Schematic of the fabricated color filter design. The grating period and width are defined as Λ and a, respectively.

In this letter, we first fabricate transmission color filters for three primary colors on silicon SWGs. To our knowledge, this letter demonstrates the use of the GMR effect in a bandpass filter mode in the optical region for the first time. The colors are produced by surface structures on the basis of the effects of the guided-mode resonance and effective refractive index. The advantage is that many filters with different colors can be fabricated on the same substrate by a single patterning process. With the use of nanoimprint lithography in the fabrication, moreover, the filters can be produced at a low cost. With the integration of a light-emitting device and a charge-coupled device, respectively, such filters seem to be attractive for displays and colorimeters. In the fabrication, electron beam (EB) lithography and fast atom beam (FAB) etching with SF_6 gas are used [13]. The transmittance is measured for visible spectrum domain, and compared with numerical study using rigorous coupled-wave analysis (RCWA), which yields accurate results using Maxwell's equations in the frequency domain [14].

II. Design

Fig. 1 shows the schematic of the fabricated color filter design. The grating layer, which consists of single crystalline silicon with a period Λ, width a, and thickness 100 nm, is formed on a quartz substrate with a thickness of 800 μm. The groove and surrounding media is air. Since the effective refractive index of the grating layer is high compared to that of the surrounding, the grating layer functions as a planar waveguide

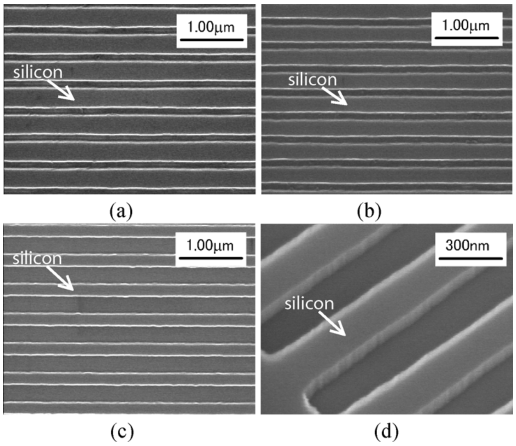

Fig. 2. SEM photographs of the fabricated gratings for (a) red ($\Lambda = 400$ nm, $a = 279$ nm), (b) green ($\Lambda = 350$ nm, $a = 231$ nm), and (c) blue ($\Lambda = 440$ nm, $a = 177$ nm) filters. (d) Oblique view of the fabricated grating for the blue filter at the edge.

and satisfies the GMR condition. Transmitted light generates only zeroth diffraction order because the Λ satisfies the SWG condition. Incident light is irradiated along the direction normal to the substrate surface. The grating design was performed with RCWA. Transmittance for visible spectrum domain was calculated as a function of Λ and a under transverse-magnetic (TM) and transverse-electric (TE) polarized lights. TE and TM polarizations refer to the states in which the electric fields of the plane wave are parallel and perpendicular to the grating grooves, respectively. Then, adequate values of the Λ and a were chosen for each filter in consideration of fabrication difficulty. The material dispersions of silicon and quartz [15] are included in RCWA analysis.

III. Fabrication

In the fabrication, an EB resist (ZEP520 ZEON CO.) was spin-coated on a silicon-on-quartz (SOQ) substrate, which consisted of the 100-nm-thick crystalline silicon layer and the 800-μm-thick quartz substrate. Next, the grating was patterned by EB lithography. Then, using the EB resist as a mask, the silicon layer was etched by the FAB of SF_6 gas. The etching depth was controlled by the etching time. The etching rate of the silicon was 21 nm/min. Finally, the residual EB resist was removed with a $1:1$ solution of H_2SO_4 and H_2O_2.

The scanning electron microscope (SEM) photographs of the fabricated filters are shown in Fig. 2. Fig. 2(a)–(c) shows the top view of the gratings for the red, green, and blue filters, respectively. All of the gratings are fabricated successfully with the periods of 400, 350, and 440 nm and widths of 279, 231, and 177 nm for the red, green, and blue filters, respectively, with the thicknesses of 100 nm. Each grating area is 120 μm-square. Fig. 2(d) shows the oblique view of the fabricated grating for the blue filter at the edge. The gratings have rectangular cross sections. All of the filters are fabricated on a single SOQ substrate. Therefore, unlike the conventional dye-doped polymers, the filters for the three primary colors can be fabricated on the same substrate by a single fabrication process.

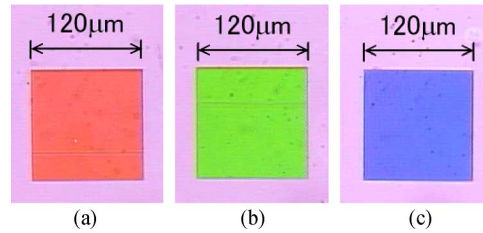

Fig. 3. Transmission colors of (a) red, (b) green, and (c) blue filters under white light irradiation. (Color version available online at http://ieeexplore.ieee.org.)

IV. Results and Discussion

Fig. 3(a)–(c) shows the transmission colors of the fabricated filters for red, green, and blue, respectively, under white-light irradiation. TM polarized light is irradiated for the red and green filters, and TE polarized light is irradiated for the blue filter. Each fabricated filter produces a uniform color in the grating area as shown in Fig. 3. On the other hand, the color outside the filter areas is reddish white, which is a consequence of the optical interference among the interfaces of the air, the crystalline silicon layer, and the quartz substrate. The transmittances for TE and TM polarized lights were measured on each fabricated filter. Color filters yielding the best match with the three primary colors were selected depending upon measurement results. The blue filter irradiated by TE polarized light produced good color property compared to that irradiated by TM polarized light. The other two filters produced good primary colors under TM polarized light irradiation. By patterning the grating line of the blue filter perpendicular to that of the other filters, all of the filters can be used under the same polarized light.

Fig. 4(a)–(c) depicts the transmittances measured as a function of wavelength for the red, green, and blue filters, respectively. The transmittance of the bare SOQ substrate as a function of incident light wavelength is shown in Fig. 4(d). The results shown in Figs. 3 and 4 are both obtained under the same incident light. RCWA results are shown by the dashed lines in Fig. 4. Numerical models displayed in RCWA analysis were constructed depending upon structures observed under the SEM. Color matching functions [16], which represent the human color perception, are also shown by the solid color lines in Fig. 4. The maximum transmittances of 71.1%, 58.1%, and 59.3% are obtained at the wavelengths of 597.6, 545.4, and 440.9 nm for the red, green, and blue filters, respectively, for wavelengths between 400 and 697 nm. In the RCWA calculations, the maximum transmittances are calculated to be 73.4%, 63.7%, and 59.0% at the wavelengths of 597, 544, and 440 nm for the red, green, and blue filters, respectively. The measured results are in good agreement with the RCWA calculations particularly around the peak transmittances. Though the transmittances are high for the wavelengths above 700 nm, the light is out of perceptibility range by human eye as shown by color matching functions in Fig. 4. All of the transmission spectra overlap well with the color matching functions. Therefore, the optical characteristics of the fabricated filters are similar to that of human eyes. On a color diagram by "Commission Internationale de l'Éclairage 1931," the measured transmitted spectra were pointed on two color coordinates (x, y), which

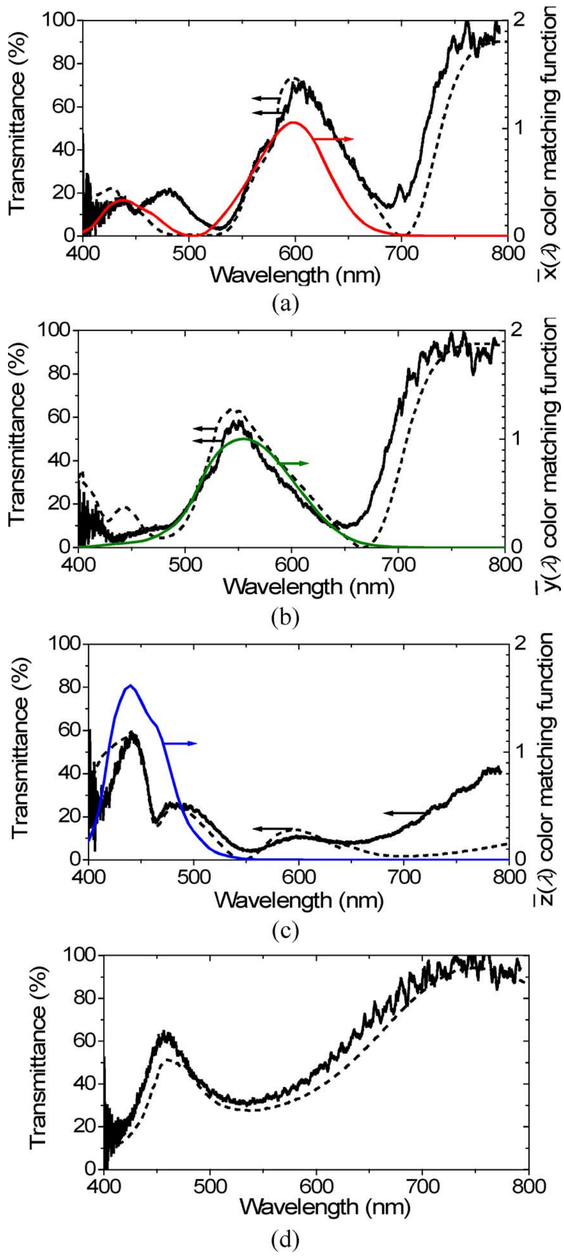

Fig. 4. Transmittances measured as a function of incident light wavelength for (a) red, (b) green, and (c) blue filters. (d) Transmittance of the bare SOQ substrate as a function of incident light wavelength. (Color version available online at http://ieeexplore.ieee.org.)

were (0.485, 0.352), (0.374, 0.515), and (0.231, 0.189) for the red, green, and blue filters, respectively.

V. Conclusion

We have fabricated transmission color filters for the three primary colors using silicon SWGs for the first time. In the fabrication, EB lithography and FAB etching with SF_6 gas were used. All of the gratings were fabricated successfully with the periods of 400, 350, and 440 nm for the red, green, and blue filters, respectively. The transmittances of the fabricated filters were measured for the visible spectrum domain. The maximum transmittances of 71.1%, 58.1%, and 59.3% were obtained for the red, green, and blue filters, respectively. The numerical calculations using the RCWA explained well the measured results. All of the transmission spectra matched well with the color matching functions. Therefore, the fabricated filters have similar optical properties to human eyes, which make them candidates for displays and colorimeters.

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