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Modeling and imprint fabrication of an infrared wire-grid polarizer with an antireflection grating structure

Itsunari Yamada [a,*], Naoto Yamashita [b], Toshihiko Einishi [b], Mitsunori Saito [c], Kouhei Fukumi [d], Junji Nishii [e]

[a] Department of Electronic Systems Engineering School of Engineering, The University of Shiga Prefecture, Hassaka-cho, Hikone, Shiga 522-8533, Japan
[b] Isuzu Glass Co., Ltd., Rinkuoraikita, Izumisano, Osaka 598-0048, Japan
[c] Department of Electronics and Informatics, Ryukoku University, Seta, Otsu, Shiga 520-2194, Japan
[d] National Institute of Advanced Industrial Science and Technology, Midorigaoka, Ikeda, Osaka 563-8577, Japan
[e] Research Institute for Electronic Science, Hokkaido University, Sapporo 060-0812, Japan

HIGHLIGHTS

- We fabricated an infrared wire-grid polarizer with an antireflection grating structure using direct imprint lithography on a chalcogenide glass.
- We formed the Al grating (0.7 fill factor, 100 nm thickness, and 500 nm period) by depositing Al obliquely on the grating.
- The transverse magnetic transmittance of the fabricated polarizer was over 70% in the 8.5–10.5 μm wavelength range.
- The TE transmittance of the fabricated element was around 1% in the 2.5 − 12 μm wavelength range.

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ABSTRACT

An infrared wire-grid polarizer with an antireflection (AR) grating structure was fabricated using direct imprint lithography on both sides of a low toxicity chalcogenide glass (Sb–Ge–Sn–S system) simultaneously. The AR grating structure was designed using rigorous coupled-wave analysis theory. Silicon carbide with a grating period of 500 nm and glassy carbon with a grating period of 3 μm were employed as molds. After imprinting, a wire-grid polarizer was made by depositing Al obliquely on the grating. The transverse magnetic (TM) transmittance of the fabricated polarizer was over 70% at 8.5–10.5 μm wavelength, although the transmittance of the glass substrate is 62–66%, and the extinction ratio was over 20 dB at 11 μm wavelength. The polarizer has a high TM transmittance and is cheaper and simpler to fabricate as compared with conventional infrared polarizers.

1. Introduction

Low-cost infrared polarizers have been desired in various applications such as infrared ellipsometry and night vision analysis and others [1–5]. With the significant advance in thermal cameras, demands for infrared devices are increasing. Infrared polarizers are employed to suppress superimposition of reflected images in particular. However, conventional infrared polarizers (wire-grid polarizers) consist of metal wires with hundreds nanometer width that are deposited on an infrared-transmitting material such as Si, Ge, anodic alumina, chalcogenide glass, CaF_2, and BaF_2 [6–10]. Therefore, microfabrication methods such as expensive lithography and dry etching entail various problems in their complex process flow, high costs of processing equipment, and low process rates.

To obtain low-cost polarizers for use in thermal imaging, the following conditions must be satisfied: starting materials has to be inexpensive and the fabrication process has to be efficient. To meet these conditions, imprint lithography is attracting interest in the production technology of nanostructured optical devices, since this method has proved to be efficient for duplicating nanostructures with high throughput, good fidelity, and low cost. Some researchers formed nanostructures on resin or oxide glasses by using ultraviolet-imprinting or thermal-imprinting processes [11–16]. However, these materials are not transmissive in the infrared range. Recently, direct thermal-imprinting processing has been conducted on a chalcogenide glass, that are transmissive in the infrared range. However, thermal imprinting is difficult to

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* Corresponding author. Tel.: +81 749 28 9563.
E-mail address: yamada.i@e.usp.ac.jp (I. Yamada).

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achieve on conventional chalcogenide glasses, since they contain such toxic elements as arsenic (As) and selenium (Se).

Chalcogenide glasses have been studied intensively recently because of their unique optical properties: high transparency in the infrared bands, and markedly low-characteristic temperature, e.g. glass transition temperature $T_g < 300\,°C$. However, chalcogenide glasses present inherent disadvantages that limit the feasibility of their use: conventional chalcogenide glasses contain toxic materials such as arsenic (As) and selenium (Se) [17–19]. One type of chalcogenide glass (IIR-SF®1; Isuzu Glass Co. Ltd.) has good transmission at 0.85–11 μm wavelength, a refractive index of 2.7 at 10 μm wavelength, a low glass transition temperature (230 °C), and low toxicity. This glass consists mainly of sulfur (more than 60 mol%) [20,21].

In a previous study, wire-grid polarizers, those consist of the low toxic chalcogenide glass (Sb–Ge–Sn–S system) substrate and Al grating with subwavelength periods, had been fabricated by using the two beam interference exposure and imprint process, which exhibited high extinction ratio in the infrared range [22–24]. However, the reflection loss of this glass was large (~35%), since this glass had a high refractive index [21]. In this study, to enhance the transverse magnetic (TM) transmittance, we designed an antireflection (AR) grating structure in the infrared range, and fabricated a wire-grid polarizer with an AR grating structure by using direct imprinting process on both sides of the glass.

2. Optimization of AR grating structure in the infrared range

The chalcogenide glass exhibits high reflectance (21%) on the surface because of the high refractive index (2.7). The transmittance of the chalcogenide glass substrate is 65% at the 10 μm wavelength. The reflectance on the surface of chalcogenide glass has to be reduced to attain a high transmittance. A subwavelength grating structure is effective to reduce the reflectance [25]. Considering application for infrared cameras, we examined suitable AR structure in the 9–11 μm wavelength range. The transmittance of a chalcogenide glass with the AR grating structure was calculated by using the rigorous coupled-wave analysis theory (RCWA) [26,27]. Consider the model of grating structure on a chalcogenide glass as shown in Fig. 1. We simulated the both of TM (transverse magnetic: electric-field vector perpendicular to the grid) and TE (transverse electric: electric-field vector parallel to the grid) transmittances using the RCWA.

First, we examined the dependence of the grating depth *d*. Each grating cross section is assumed to be rectangular, and the grating period Λ, the fill factor *f*, and the refractive index of grating are assumed, respectively, as 3 μm, 0.6, and 2.7 [21]. The fill factor is defined here as the ratio of the single grating width *w* to the period [$f = w/\Lambda$]. Fig. 2(a) shows transmission spectra as a function of wavelength for the depth of grating from 1 to 2 μm. All of TM spectra were over TE spectra in the 8–12 μm wavelength range, and the peak of TM transmittance was around 79% at 10 μm wavelength. For forming the AR grating structure on one side of this glass substrate, the maximum transmittance of this glass becomes less than 79% due to the index of 2.7, according to the Fresnel reflection theory [28]. As the depth increases, the peak of the transmission spectrum shifted to the long wavelength range. In addition, all of transmission spectra decrease rapidly in short wavelength range. This phenomenon seems to be caused by diffraction, since the condition of $\Lambda \ll \lambda$ does not hold in short wavelength range.

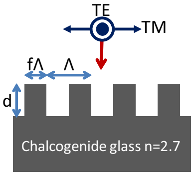

Fig. 1. Model of an AR grating structure of a chalcogenide glass.

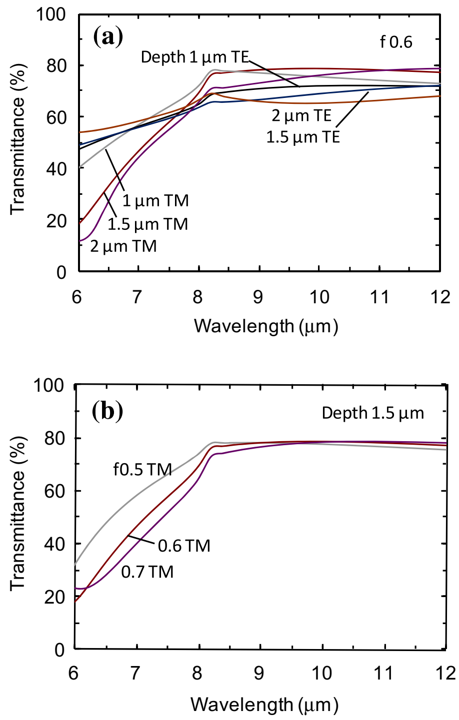

Fig. 2. RCWA simulation results for the TE and TM transmittances of the model shown in Fig. 1 when (a) the grating thickness ($f = 0.6$, $\Lambda = 3$ μm) or (b) the fill factor ($d = 1.5$ μm, $\Lambda = 3$ μm) is changed. The numerals next to the curves denote the polarization, (a) the grating depth, and (b) the fill factor.

Next, we examined the dependence of the fill factor *f*. Fig. 2(b) shows the calculated TM transmission spectra as a function of wavelength for the fill factor from 0.5 to 0.7. The depth and the period of grating were assumed, respectively, as 1.5 μm and 3 μm. As the fill factor increases, the peak of TM spectrum slightly shifted to longer wavelength with increasing the fill factor, since the effective index increases.

As a result, we found that the peak of TM spectrum shifted to longer wavelength with increasing the fill factor and the grating depth, and TM transmittances for the grating on a chalcogenide glass substrate exceeded 70% in the 8–12 μm wavelength range in case of $\Lambda = 3$ μm, $f = 0.6$–0.7, and $d = 1.5$ μm as shown in Fig. 2(b). To achieve higher polarization transmittance in the 9–11 μm wavelength range, our target design requires the fill factor of 0.6–0.7 and the grating depth of around 1.5 μm on the chalcogenide glass surface.

3. Fabrication

Silicon carbide (SiC; Admap Inc.) and glassy carbon (GC; Tokai Carbon Co. Ltd.) plates of 25 × 25 × 2 mm with optically flat surfaces were used as molds for the imprinting process because previous reports described that SiC and GC have heat-resistance, high mechanical strength, and micro-workability [15,16,22,23]. A GC mold was used to fabricate the AR grating structure, which requires deep grooves because GC reacts effectively to O_2 gas. Fig. 3 shows fabrication process. A WSi film was deposited on SiC or GC plate by using the sputtering method. A photoresist on the SiC plate was exposed to an interference fringe of He–Cd laser beams (325 nm wavelength) to generate the short-period grating