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Fresnel lens fabrication for broadband IR optics using hot embossing process

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HIGHLIGHTS

- Hot embossing process for Fresnel lenses fabrication from multi-component glasses.
- Selecting glass considering: transmittance, resistance to crystallization, adhesion.
- We select the lead–bismuth–gallium oxide glass.
- Effective focusing light in the visible and in mid-infrared range.

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ABSTRACT

The aim of the paper was to examine the possibility of fabrication of glass diffractive optical elements that work within near and mid-infrared. The paper focuses on the results of fabrication of Fresnel lenses with the use of hot embossing process from multi-component glasses. In the experiment lead–bismuth–gallium oxide and tellurite glasses were used, which are characterized by high transmittance within the visible light spectrum to mid-infrared (6.5 μm). As the mold a fused silica element was used, which had been fabricated with the standard method of ion etching. The elements presented were fabricated in a static process with the use of low pressure. The quality of the fabricated elements was examined with white light interferometer. The fabricated Fresnel lenses can be used in directing light within the visible spectrum up to c.a. 6 μm into optical fibers and in beam collimation at the output of the optical fiber.

1. Introduction

For the last decade we have witnessed a dynamic development of research and applications of optoelectronics within the infrared (2–14 μm) spectrum. Within this range there are transmission windows in the atmosphere of the Earth and vibration bands of many kinds of bonds in chemical organic compounds [1]. For this reason optical setups working within mid-infrared have found numerous applications from optical telecommunication in free space, through spectroscopy, medicine and dental applications, instrumentation, biotechnology, tomography, thermal imaging up to military defense devices. The main problem of such setups is their high cost resulting from the price of the passive optical elements such as lenses. So far, most of the optical components working in mid-infrared range were based on single crystalline germanium (Ge) or zinc selenide (ZnSe). For their production a costly single-point diamond-tuning process [2] is used. That is why it is important to develop new materials and technologies which will allow for the low-cost fabrication.

One of the solutions for lens fabrication is the use of materials whose formation will involve the hot embossing process [3]. Such materials include standard chalcogenide glass compositions made of germanium arsenic selenium ($Ge_{22}As_{20}Se_{58}$ or GASIR1) and germanium antimony selenium ($Ge_{20}Sb_{15}Se_{65}$ or GASIR2) [4]. However, such glass is poisonous, relatively expensive and, most importantly, not transparent within the visible light range, which excludes some applications. Also, apart from lenses, there are no other passive optical elements available; especially there are no diffractive optical elements (DOEs). An inexpensive material easy to process is polymers used to produce diffractive elements, but they too have their disadvantages. Most importantly, it is their liability, low thermal durability and the change of their optical parameters over time [4].

Diffractive optical elements (DOEs) are thin optical phase objects which operate on light diffraction and interference [5]. An example of DOE are Fresnel lenses, which can be used to form the light beam, similarly to common refractive lenses. What differentiates them from the refractive lenses is their thickness that can be comparable to the length of the light wave. Thanks to that they have found applications in contemporary optics, physics and engineering. For instance, they allow for the production of smaller,

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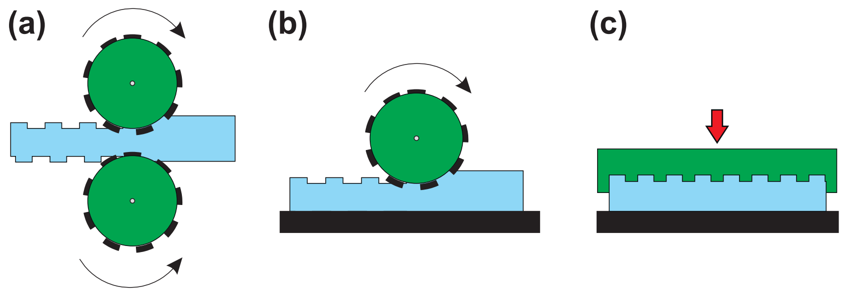

Fig. 1. Basic types of the hot embossing process.

Table 1
Parameters of the glasses considered for the experiment.

Parameter	Glass symbol					
	LW-1	PBG08	PBG05	TWNB-1	TWPN/I/6	TCG75921
n_d	1.846	1.938	2.350	2.155	2.149	2.170
α (10^{-6} K^{-1})	8.31	8.30	11.05	15.51	14.40	10.78
DTM (°C)	420.0	500.0	468.5	368.0	385.0	392.2
Temp. (°C)						
T_g $\log\eta = 13.4$	400.0	463.2	443.0	355.9	365.0	368.5
T_z $\log\eta = 9.0$	421.0	542.0	490.0	370.0	395.0	395.0
T_k $\log\eta = 6.0$	450.0	615.0	540.0	395.0	415.0	445.0
T_{pk} $\log\eta = 4.0$	487.5	690.8	575.0	440.0	460.0	485.0
T_r $\log\eta = 2.0$	645.0	800.5	680.0	510.0	535.5	560.0
d (g/cm^3)	5.625	5.798	8.020	5.795	5.881	7.410
Transmission (nm)						
–Lower limit	380	380	460	425	420	460
–Upper limit	3700	5200	8000	6700	6850	7400
A (dB/m)	No data	5–2200	No data	No data	No data	16–2100

n_d – refraction index (d-line), α – linear thermal expansion coefficient (20–300 °C range), DTM – dilatometric softening point, T_g – transition temperature, T_z – ovalization point, T_k – sphere point, T_{pk} – hemisphere point, T_r – spreading point, d – density, A – attenuation.

more compact camera lenses and for increasing the effectiveness of the solar cells.

There are many ways of producing DOE. One of the cheapest is the above mentioned hot embossing, suitable for both small-scale and massive production. The method is especially appropriate for fabricating polymer microoptical elements [3,6,7], and is also used in microlens fabrication in metallic glass [8]. The hot embossing method can also be used with glass, but this involves several problems of technical kind. First, the process requires higher temperatures. Whereas in the case of polymers the process needs the maximum of about 200 °C (e.g. 180 °C for PC and more than 200 °C for polymers for thermal nanoimprint lithography [9]), in the case of glass the temperature required is 400–900 °C, depending on the composition of the glass used [6–8,10]. Secondly, the process requires better temperature stabilization to make the hot glass malleable but not molten and it would not undergo crystallization.

In practice, three basic variants of the hot embossing process are used [3,6–8]: multiplication of the pattern via rolling the material through two master forms (Fig. 1a), rolling the substrate through the master form on a flat surface of the mold (Fig. 1b) and imprinting a flat mold on the surface of the substrate (Fig. 1c). The first two methods are commonly used when the material to be formed is plastic enough and they allow for massive fabrication of the consecutive elements. The third method allows development of elements made of less plastic materials as glass, where thermal processing requires longer time.

In all the methods mentioned it is crucial to choose the mold material according to the type of glass in order to reduce the mutual corrosion of both materials [3]. Additional limitations stem from the mechanical and thermo-chemical properties of glasses. Only glasses characterized by high resistance to crystallization can be processed. Also the right rheology is important and fitting the thermal expansion coefficients to the mold material within the processing temperature range as well as below the temperature of the transformation [3]. It is especially important in the case of DOE element fabrication, where the wrong choice of the thermal expansion coefficients leads to stress, which results in cracking and in the destruction of the delicate pattern on the glass surface.

2. Material choice

For technological tests we chose glasses which were potentially suitable for the visible spectrum and mid-infrared. These were glasses composed of three to six oxides in varying proportions: SiO_2, PbO, Bi_2O_3, Ga_2O_3, CdO, B_2O_3, ZnO, Tl_2O, GeO_2, WO_3, Na_2O,

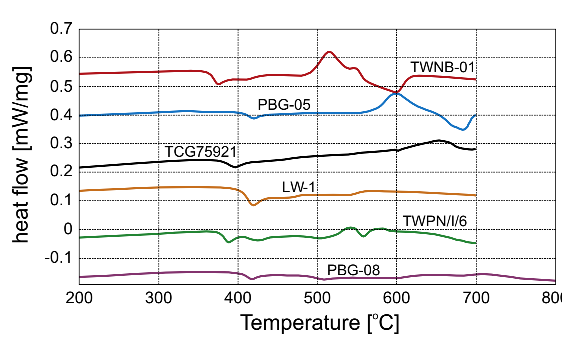

Fig. 2. Curves of differential scanning calorimetry of the considered glasses.