Study of the injection molding of a polarizing beam splitter

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We describe the replication of a relief grating that behaves like a polarizing beam splitter by injection molding. Measurements of the grating master, nickel shim, and replica, performed by atomic force microscopy, allow establishing a limit for the injection molding technique (currently used in CD fabrication) to aspect ratios of approximately 0.15. Although this limit strongly reduces the diffraction efficiency of the elements as well as their polarizing properties, extinction ratios of approximately 10:1 were measured for the replicas in a large range of wavelengths. © 2006 Optical Society of America

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1. Introduction

Holographic optical elements (HOE) can be designed to present high diffraction efficiency and polarizing effects that can be used to build polarizers, wave plates, and polarizing beam splitters (PBSs).[1–6] In particular, surface relief HOEs present the additional advantage that they can be replicated for mass production.[7,8,9]

The replication process consists of three steps:[7,8,9] recording the master, electroforming the nickel shim, and replication. Well-established techniques that replicate HOEs are, for example, hot embossing, injection molding, and casting.[7,8,10,11] The suitability of each replication process depends on the costs and on the resolution requirements of each element. The casting presents the better resolution for the replication of high aspect ratio structures; however, its costs and production time are high.[7,10] On the other hand, injection molding[7,8] is distinguished for mass production and resolution capable of copying pits of an approximately 500 nm width and 125 nm depth in the production of CDs and DVDs.

Subwavelength polarizing elements, such as transmission PBSs[12] and wave plates[4] require the recording of high aspect ratio structures. For other applications, in the resonant domain,[6] the required aspect ratio is not so high, but the polarizing properties are very sensitive to the shape and to the geometric dimensions of the profile.

In this paper we describe the replication of a PBS[6] by injection molding using the facilities of a CD industry. The resolution, as well as the optical properties, of each step of the replication process was analyzed to establish the limits of this process for the replication of such an element.

2. Polarizing Beam Splitter

The PBS that we attempt to replicate is an aluminum-coated photoresist grating with a particular profile.[6] By using the Littrow condition of incidence it is possible to design the grating to split the unpolarized light into the orthogonal directions "TE" (at the minus first diffracted order) and "TM" (at the reflected zeroth order). The working scheme of the element is shown in Fig. 1.

The maximum theoretical extinction ratio that can be achieved with a profile rounded at the top and flat at the bottom is approximately 780:1. The best experimental extinction ratio, obtained for the photoresist element, was approximately 300:1.[6] Although it is lower than that achieved in PBS cubes, such elements can be designed for any particular wavelength range, and the relief profile is appropriate for replication [the bottom is larger than the top of the structure as shown in the Fig. 2 scanning electron microscopy (SEM) profile]. Besides this, the aspect ratio involved depth/period ($\approx$0.34) is a relatively low value in comparison with that required for wave plates.[4]

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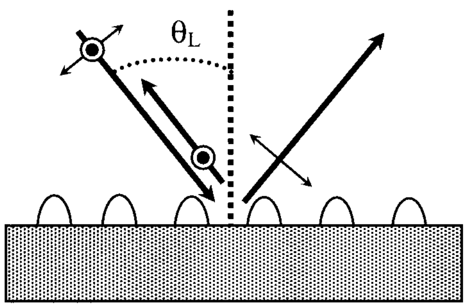

Fig. 1. Working scheme of the holographic PBS. Unpolarized light is incident at the Littrow angle (θL), and the −1 order is reflected in the same direction of the incident light. The −1 diffracted order is linearly polarized in the TE direction, whereas the zeroth order is polarized in the TM direction.

3. Replication

In order to check the fidelity of the replication by injection molding, several surface relief gratings were recorded in AZ1518 photoresist on the same glass substrate [Fig. 3(a)]. The profiles of the gratings were similar to that required for the PBS but with different periods Λ (0.5, 0.8, 1.0, and 1.6 μm) and depths. The gratings were holographically recorded in a fringe locker interferometer,[13] and changing the dose of incident energy during the exposure defined the variation of the grating depth. The substrate used was a 25 cm diameter, 2 cm thick glass plate, the same as is used in the CD industry.

After the development of the glass master, using AZ developer 1:1 diluted in deionized water for 120 s, the shim was obtained by nickel electroforming,[9,14] and the structures were replicated by injection, the same as is done in a CD industry. Figure 3(a) is a photograph of the glass master; Fig. 3(b), the Ni shim; and Fig. 3(c), the aluminized polycarbonate replica. For injection we employed the standard conditions used in the CD production, and the replicas were coated with a 20 nm thick aluminum layer.

4. Profile Characterization

To analyze the resolution and the fidelity of the whole process, the relief profile of the master, the shim, and

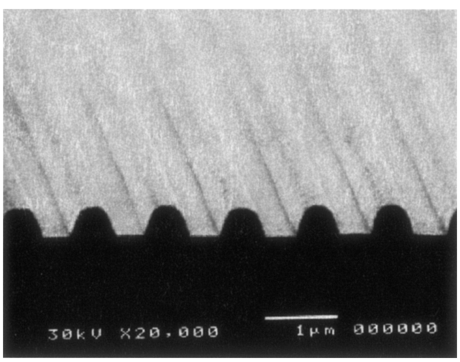

Fig. 2. SEM image of a typical profile of the holographic PBS. The diffraction spectrum of this grating corresponds to the master spectrum shown in Fig. 5.

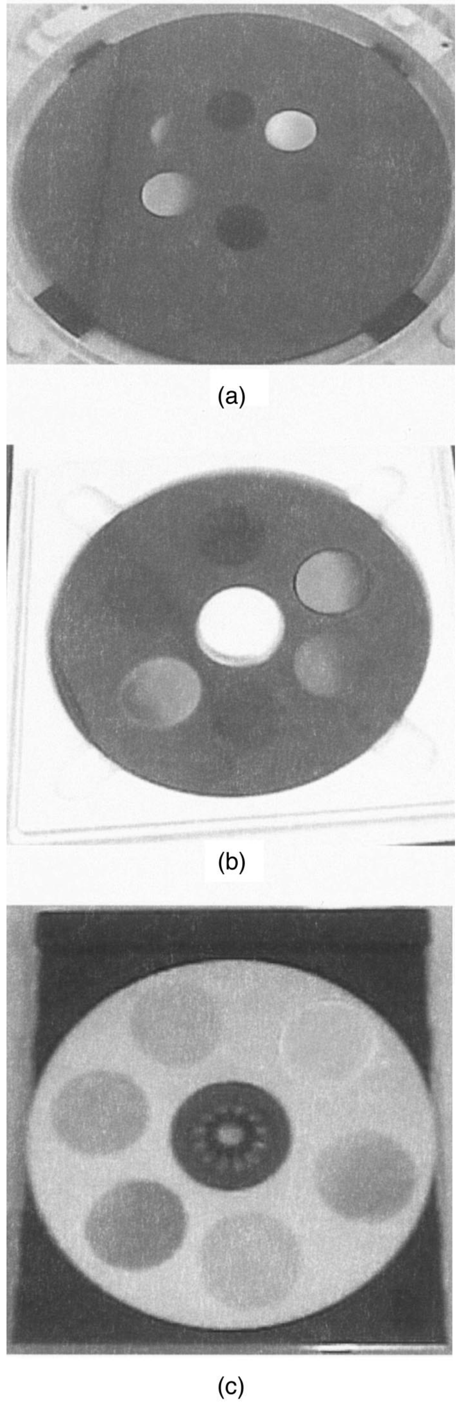

Fig. 3. Photographs of the different steps of the replication process: (a) the glass master, (b) the Ni shim, (c) the polycarbonate replica.

the replica were characterized by atomic force microscopy (AFM). It was not possible to characterize the processes by SEM of the samples because both the Ni shim and the polycarbonate replicas cross section were deformed after cutting. Figure 4 shows the AFM microscopy profiles of the master [4(a)], of the corresponding Ni shim [4(b)], and of the replicated structure in polycarbonate [4(c)]. Note the complementary profile exhibited by the Ni shim in relation to both

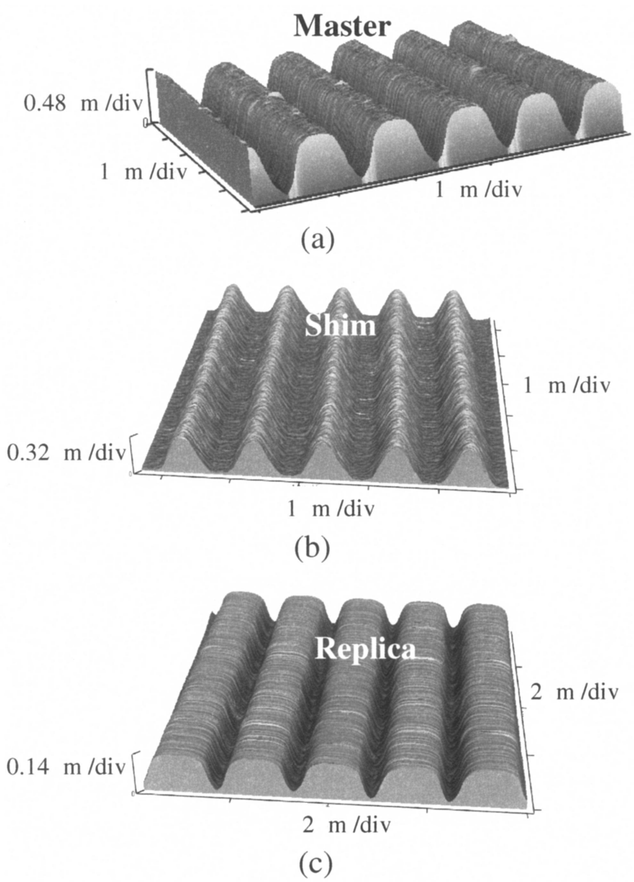

Fig. 4. AFM of the profiles: (a) master, (b) Ni shim, and (c) polycarbonate replica.

Table 1. AFM Measurements (Grating Period Λ and Depth *h*) for the Masters and Their Corresponding Ni Shims[a]

Master		Ni Shim	
Λ (μm)	*h* (μm)	Λ (μm)	*h* (μm)
0.990 ± 0.002	0.392 ± 0.005	1.010 ± 0.005	0.39 ± 0.01
0.998 ± 0.002	0.698 ± 0.005	1.015 ± 0.005	0.67 ± 0.01

[a]Errors were evaluated from the measurements at different regions of each grating.

master and replica. The measured dimensions of the master and the electroformed Ni shim are presented in Table 1. The good accordance between the dimensions of the Ni shim and the master, for both the period and the depth, demonstrates the fidelity in the electroforming step.

Table 2 contains the AFM measurements of the Ni shim of ten different gratings and their corresponding polycarbonate replicas. Gratings with three different periods and different depths were performed. From the information in this table a large reduction in the grating depth (h) can be observed. This reduction increases as the grating period decreases. For gratings with period (Λ) = 0.5 μm, we observe a reduction of approximately 70% in the depth of the replicas in relation to the Ni shim. Note also a systematic decreasing in the period of the replicated gratings (of approximately −5%). This reduction occurs as a result of the contraction of the polycarbonate during the cooling after the injection.[8]

From the measurements shown in Table 2 we can conclude that the injection-molding process, for the employed conditions, reaches a maximum aspect ratio of $h/\Lambda = 0.15$. Additional tests performed with different conditions of injection (increasing the time of injection, the pressure, and the temperature gradient of the injection machine) do not succeed in achieving replicas with a higher aspect ratio.

5. Optical Properties

The optical properties of the replicated PBS were analyzed through the measurement of the first-order diffraction spectrum ($\eta 1 \times \lambda$) at the Littrow condition of incidence (θL) for the two orthogonal polarization states. Figure 5 shows an example of the measured diffraction spectra of a master grating and its replica. For this couple the period (measured by AFM) was $\Lambda = 1$ μm, and the depth was (h) ≈ 0.45 μm for the master and $\Lambda = 0.96$ μm and $h \approx 0.14$ μm for the replica. Both master and replica were coated with aluminum. Note that, besides the similar form of the curves, a strong reduction of the maximum value of the diffraction efficiency (for both polarizations) occurs for the replicated grating. The polarization effect

Table 2. AFM Microscopy Measurements of the Period (Λ) and of the Depth (*h*) for Each Couple Ni Shim and Its Polycarbonate Replica[a]

Ni Shim			Replica		
Λ (μm)	h (nm)	h/Λ	Λ (μm)	h (nm)	h/Λ
0.510 ± 0.001	142 ± 4	0.28	0.484 ± 0.003	63 ± 2	0.13
0.515 ± 0.006	255 ± 5	0.44	0.483 ± 0.004	68 ± 3	0.14
0.510 ± 0.003	228 ± 7	0.45	0.480 ± 0.001	70 ± 3	0.15
0.510 ± 0.002	240 ± 7	0.47	0.483 ± 0.003	68 ± 4	0.14
0.817 ± 0.002	300 ± 4	0.37	0.770 ± 0.002	105 ± 3	0.14
1.020 ± 0.004	152 ± 3	0.15	0.962 ± 0.003	99 ± 4	0.1
1.020 ± 0.004	293 ± 4	0.29	0.969 ± 0.003	115 ± 3	0.12
1.010 ± 0.006	415 ± 6	0.41	0.965 ± 0.003	117 ± 3	0.12
1.014 ± 0.003	452 ± 6	0.45	0.964 ± 0.002	140 ± 5	0.15
1.634 ± 0.007	312 ± 5	0.19	1.548 ± 0.005	145 ± 4	0.09

[a]Errors were evaluated from the measurements at different regions of the grating.

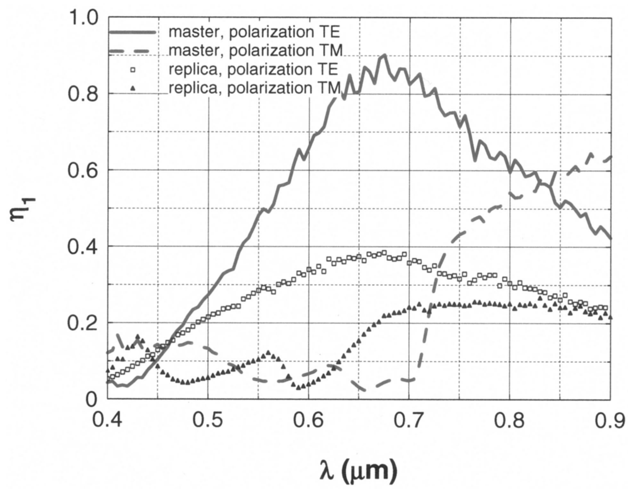

Fig. 5. Diffraction spectrum at the Littrow condition of incidence of the master (solid and dashed curves) and its replica (open box and filled triangle curves) for the orthogonal polarizations (TE and TM).

was also attenuated. Although for the master the extinction ratio [η1(TE)/η1(TM)] for the −1 diffracted order achieves the maximum of 40:1 at $\lambda \approx 660$ nm, for the replica the maximum extinction rate was approximately 10:1 at $\lambda \approx 590$ nm.

In spite of the strong depth variations, the replicated gratings with a period of $\Lambda = 0.5$ μm and a depth of $h = 70$ nm present a significant polarization effect in a larger range of wavelengths. This is observed in the −1 order diffraction spectrum of the replica shown in Fig. 6 for the wavelength range between 600 and 900 nm. In the same figure, the extinction rate for the −1 diffracted order [η1(TM)/η1(TE)] is plotted. Note that the extinction ratio remains between 6:1 and 8:1 for the range between 600 and 900 nm.

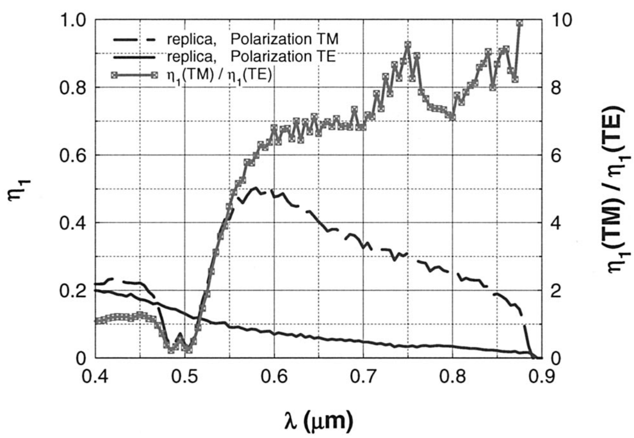

Fig. 6. Diffraction spectrum of a polycarbonate replica at the Littrow condition of incidence for the orthogonal polarizations (TE, solid curve; and TM, dashed curve) and the extinction rate for the −1 diffracted order [η1(TM)/η1(TE)] in the box-barred curve.

6. Conclusions

We have made an analysis of the replication process by injection molding of a PBS. The AFM measurements of the master, the Ni shim, and the replicas demonstrate the Ni shim's fidelity to the mask, whereas great changes in depths were observed in the injected replicas. For the conditions of injection currently used for the CD fabrication, we observed a limited aspect ratio (h/Λ) of 0.15 for the replicas. Additional tests performed under different conditions of injection do not succeed in achieving a higher aspect ratio.

Although the reduction of the depth of the replicas decreases significantly, its total diffraction efficiency, its polarizing properties, and the effect of polarization can be indeed observed. An extinction ratio of approximately 10:1 can be observed in the minus first diffracted order. Because this value is low, it can be enough for some low-cost visual applications.

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