Single-substrate birefringent computer-generated holograms

Fan Xu, Rong-Chung Tyan, and Yeshayahu Fainman

Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, California 92093-0407

Joseph E. Ford

AT&T Laboratories, Holmdel, New Jersey 07733

Received October 2, 1995

A polarization-selective computer-generated hologram fabricated upon a single substrate of birefringent YVO_4 crystal is demonstrated. Rigorous couple-wave analysis was used to model the element. The experimentally measured first diffraction order showed a close-to-theoretically predicted diffraction efficiency of 39%. The polarization contrast ratio was measured to be 33:1.

Diffractive optical elements (DOE's) constructed as phase-only computer-generated holograms are attractive for numerous applications in photonics and optoelectronics. In general, planar DOE's are insensitive to the polarization of the illumination. However, polarization-selective computer-generated holograms are attractive for numerous applications because they use polarization as another degree of freedom to implement two independent and arbitrary impulse responses for the two orthogonal linear polarizations. Previously we demonstrated such polarization-selective DOE's, using two birefringent $LiNbO_3$ substrates.[1,2] These birefringent computer-generated holographic elements have been used for such applications as transparent photonic switching and networking, image processing, and packaging of optical and optoelectronic devices and systems.[1–3]

A normal DOE has a maximum phase delay of 2π between pixels. Therefore the required etch depth is, in general, shallow [see Fig. 1(a)]. Previously demonstrated birefringent computer-generated holographic elements consist of two substrates with different diffractive microstructures on the interior, in which the two independent surface-relief depths provide us with the two degrees of freedom to encode the two independent phase functions for the two orthogonal linear polarizations in the same element.[1,2] The required etch depths on both substrates are deeper than those in a normal DOE because the birefringence is relatively small [see Fig. 1(b)]. Another approach to achieve the same functionality is based on multiple periods of phase delays (also called modular $2m\pi$) with a single birefringent substrate, as first proposed in Ref. 1 and later in Ref. 4. Such an approach may reduce the cost and simplify the fabrication process of such polarization-selective diffractive optical elements. The required etch depth is much deeper than that in a normal DOE [see Fig. 1(c)]. In this Letter we report what to our knowledge is the first experimental demonstration of a polarization-selective computer-generated hologram using a single birefringent substrate. We also describe the design principles, the fabrication procedures, and the experimental characterization results of the single-substrate birefringent computer-generated hologram (SSBCGH).

To design a SSBCGH element, we use a multiorder phase microstructure, in which each pixel of the microstructure is deeply etched such that propagating optical waves will exhibit multiple periods of phase delays. Consider a surface-relief microstructure fabricated in a birefringent substrate with the optic axis parallel to the surface of the substrate. Using geometrical optics, we can find the corresponding phase delays caused by the surface relief compared with those of an unetched pixel for the ordinary- and extraordinary-polarized waves:

$$(2\pi/\lambda)\,(n_o - n_t)d = 2l\pi + \Phi_o', \qquad (2\pi/\lambda)\,(n_e - n_t)d = 2m\pi + \Phi_e', \tag{1}$$

where $\Phi_o' + 2l\pi$ and $\Phi_e' + 2m\pi$ are the phase delays exhibited by ordinary and extraordinary waves, λ is the wavelength of the incident wave in vacuum, n_o and n_e are the refractive indices for ordinary- and extraordinary-polarized light, respectively, n_t is the refractive index of the material surrounding the microstructure, and l and m are integers corresponding to the multiple periods of phase delays exhibited by the ordinary- and extraordinary-polarized light. In general, Eqs. (1) do not have unique accurate solutions for d if Φ_o and Φ_e are arbitrarily specified de-

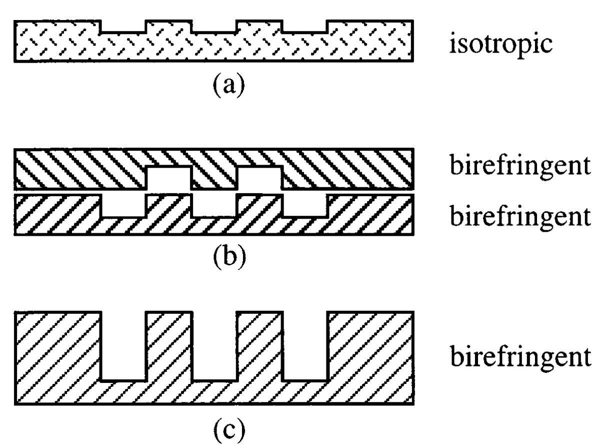

Fig. 1. Schematics of (a) a conventional DOE and (b) two-substrate and (c) a single-substrate birefringent computer-generated hologram.

0146-9592/96/070516-03$6.00/0

sign values, unless the refractive indices n_o and n_e can be controlled in every pixel of the diffractive element, as in form-birefringent artificial dielectric nanostructures.[5] However, for our design with a homogeneous birefringent substrate with constant values of n_o and n_e, there exist approximate solutions for d when the values of integers l and m are arbitrarily large such that

$$(2\pi/\lambda)\,(n_o - 1)d = 2l\pi + \Phi_o + \delta_l\,,$$
$$(2\pi/\lambda)\,(n_e - 1)d = 2m\pi + \Phi_e + \delta_{1m}\,, \qquad (2)$$

where δ_l and δ_m are small numbers introduced to account for the errors and air is used as the material surrounding the microstructure, $n_t = 1$. If δ_l and δ_m are much smaller than the phase quantization step, we consider this to be a valid approximate solution to Eqs. (1). With this approach it is possible to apply an arbitrary phase with some specified accuracy to each pixel at each polarization. Therefore independent multilevel phase holograms can be implemented for the two polarizations. Solving Eqs. (2), we obtain

$$d = \frac{(2l\pi + \Phi_o + \delta_l)\lambda}{2\pi(n_o - 1)} = \frac{(2m\pi + \Phi_e + \delta_m)\lambda}{2\pi(n_e - 1)}\cdot \qquad (3)$$

The ideal substrate material suitable for this application should have large birefringence, to ensure that the required etch depth d can be fabricated with high accuracy. We used a new type of birefringent crystal, yttrium orthovanadate (YVO_4), which has large birefringence and can be relatively easily processed with microfabrication techniques. The birefringent substrates are x-cut YVO_4 grown by Castech-Phoenix, Inc. The refractive indices are $n_o = 2.0241$ and $n_e = 2.2600$ at a wavelength of 0.5145 μm. Using Eqs. (2) and (3) with these values of refractive indices, we find all the possible combinations of Φ_o and Φ_e that are necessary for construction of a binary-phase-level SSBCGH (see Table 1). In Table 1, d_l and d_m are the exact etch depths required for finding the desired phase delays with integers l and m. We observe that the approximation errors are less than 5% for all cases except one, which we can solve by taking the value d as the weighted average of d_1 and d_m instead of one half the summation. Some other optimizations, such as choosing a different set of phase quantization bases, may also reduce the approximation errors. Because the absolute phase in diffractive optics is of no concern, we can remove an etch-depth bias of 1.013 μm without affecting the desired relative phase values between different pixels. The new real values of the etch depths d_r are also listed in Table 1. We can also observe that one needs only two distinct etches to construct a binary-phase-level SSBCGH (s and t in Table 1).

Construction of more efficient multiple-phase-level elements is also possible. Now the minimum etch-depth increments are determined by phase combinations $\Phi_0 = 0$, $\Phi_e = 2\pi/N$ and $\Phi_0 = 2\pi/N$, $\Phi_e = 0$, where N is the number of phase quantization levels. The required etch depths for other values of phase levels are the combination of these basic ones. However, in some cases these values may result in unrealistically deep etch-depth requirements; moreover, the number of required etches is more than that for a conventional multiple-phase-level DOE.

To understand better the fabrication accuracy requirements and their effect of the performance of the fabricated SSBCGH elements, we used rigorous coupled-wave analysis[6] to simulate the performances of our first fabricated SSBCGH element. Figure 2 shows the simulation results for diffraction efficiencies and polarization contrast ratios (PCR's) as functions of etch depth for a grating with a 1:1 duty ratio and vertical sidewalls. From the simulation results we can observe that good performance (~41% diffraction efficiency and >100:1 PCR) can be obtained from the geometrical optics design. Also, the results of the rigorous coupled-wave analysis show that the etch depths for the best PCR and the largest diffraction efficiency are very similar but not identical (~1% difference). This important result implies that the desired etch depth can be driven by the application needs and may differ slightly from the values provided by the geometrical optics approximate design listed in Table 1. Additional simulation and experimental evaluations show that the trapezoidal shape and the uneven duty cycle degrade the performance of the SSBCGH significantly.

Figure 3 shows the PCR as a function of the optical wave incidence angle for different grating-period-to-wavelength ratios, calculated with the rigorous coupled-wave analysis. Grating grooves are perpendicular to the incident plane. From this figure we can observe that multiple-order phase-delay elements are sensitive to the incidence angle. These curves also indicate that this design approach is valid only for large grating-period-to-wavelength ratios because, when the grating period is comparable with or smaller than the wavelength of the incident optical field, the form-birefringence effect becomes dominant.[7] Within this region, not only do the PCR's drop considerably but, in addition, most of the incident wave energy propagates into the zeroth diffraction order.

Table 1. Design Results and the Real Etch Depths Required for a Binary-Phase SSBCGH with YVO_4

					Error (%)[a]	
Φ_o, Φ_e	l, m	d_l, d_m (μm)	$d = (d_l + d_m)/2$ (μm)	$d_r = d - 1.013$ (μm)	δ_l/Φ_o	δ_m/Φ_e
0, 0	4, 5	2.010, 2.042	2.0260	1.0130 (=s)	+3.27	−3.9
0, π	2, 2	1.005, 1.021	1.0130	0.0000	+1.63	−3.8
π, 0	2, 3	1.256, 1.225	1.2406	0.2276 (=t)	−6.1	+3.8
π, π	4, 5	2.261, 2.246	2.2535	1.2405 (=$s + t$)	−2.9	+3.8

[a]When Φ_o and Φ_e are zero, they are taken to be 2π for error evaluations.

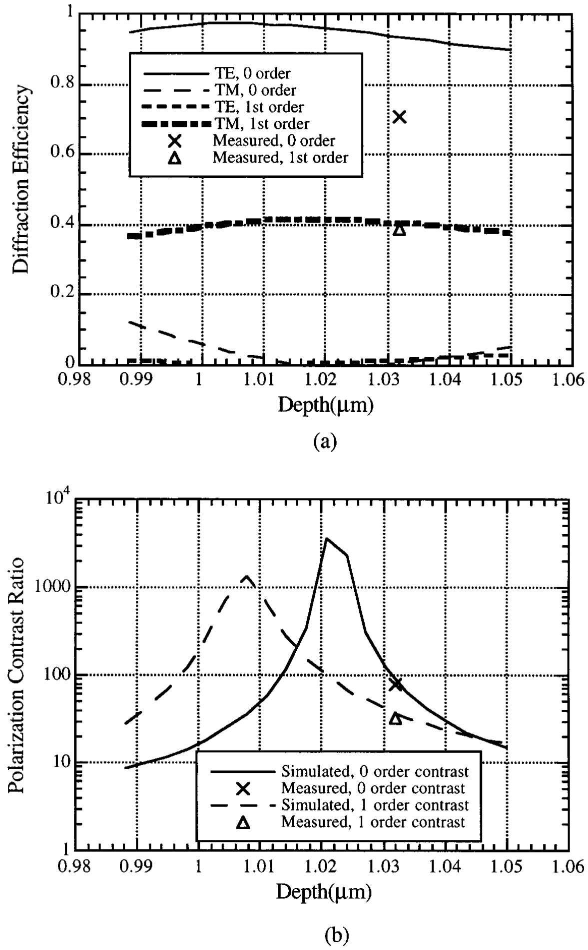

Fig. 2. (a) Diffraction efficiencies and (b) PCR's of the SSBCGH.

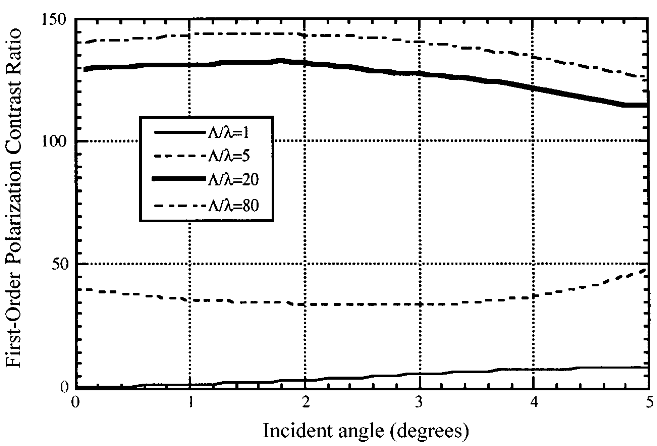

Fig. 3. Simulated PCR's as functions of the incident angle and the grating-period-to-wavelength ratio.

For experimental demonstration and characterization of the SSBCGH, we constructed a diffractive polarization beam splitter that diffracts one polarization while transmitting the other. This is a special case of the dual-function element. First, a 40-μm-period grating pattern defined by electron-beam lithography was photolithographically transferred into a 1.7-μm-thick photoresist. The resist was spun coated onto a 100-nm-thick Cr layer evaporated onto the YVO_4 substrate. Then the surface-relief profile was ion milled into the YVO_4 substrate to 1.032 μm. In this multiple-phase-period approach the etch depth must be controlled with higher accuracy than that used for construction of conventional DOE's. This is because the error introduced by the over/under etch is determined not by the ratio of etch error to the total etch depth but by the ratio of the etch error to a fraction of the total etch depth that is, in effect, responsible for encoding the desired phase values in a given pixel. The duty ratio of the fabricated SSBCGH element was measured to be 1:1. The experimental evaluations of the element show 70.8% diffraction efficiency and 79.7:1 PCR into the zero order, 37.4% diffraction efficiency and 33.0:1 PCR into the $+1$ order, and 38.9% diffraction efficiency and 32.5:1 PCR into the -1 order. The experimental performance of the element is very close to that predicted by the rigorous coupled-wave analysis (see Fig. 2). From the simulation we can also see that the performance of a SSBCGH can be further improved with more-accurate etch depths.

In conclusion, we designed, fabricated, and experimentally evaluated polarization-selective computer-generated holograms, using a single birefringent substrate. The fabricated elements show diffraction efficiencies close to the theoretical limit and large polarization contrast ratios. The duty ratio and the shape of the grating change the performance of the SSBCGH and need to be controlled accurately. Such elements may be useful in many applications such as image processing, transparent photonic switching, and the packaging of optoelectronic devices and systems.

The authors thank K. Urquhart and P. C. Sun for helpful discussions. This research is funded by the National Science Foundation and the U.S. Air Force Rome Laboratory.

References

1. J. Ford, F. Xu, K. Urquhart, and Y. Fainman, Opt. Lett. **18,** 456 (1993).
2. F. Xu, J. Ford, and Y. Fainman, Appl. Opt. **34,** 256 (1995).
3. A. Krishnamoorthy, F. Xu, J. Ford, and Y. Fainman, Proc. SPIE **2297,** 345 (1994).
4. S. Liu and Y. Chen, Opt. Lett. **20,** 1832 (1995).
5. I. Richter, P. Sun, F. Xu, and Y. Fainman, Appl. Opt. **34,** 2921 (1995).
6. M. G. Moharam and T. K. Gaylord, J. Opt. Soc. Am. **72,** 2921 (1995).
7. F. Xu, R. C. Tyan, P. C. Sun, Y. Fainman, C. C. Cheng, and A. Scherer, Opt. Lett. **20,** 2457 (1995).