Form-birefringent computer-generated holograms

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Polarization-selective computer-generated holograms made with form-birefringent nanostructures were designed, fabricated, and evaluated experimentally at 1.5 μm. The fabricated element showed a large polarization contrast ratio (>250:1) and a high diffraction efficiency (>40% for a binary phase level element). The experimental evaluation was in good agreement with the design and modeling predictions.

Polarization-selective phase-only birefringent computer-generated holograms (BCGH's) are general-purpose diffractive elements that have independent impulse responses for orthogonal linear polarizations. Such elements are shown to be useful in many applications, including packing optoelectronic devices or systems, free-space optical interconnects, and image processing.[1] BCGH's have been demonstrated with two birefringent substrates[2,3] and with a single birefringent substrate.[4] The birefringence of the substrates in these configurations makes the elements sensitive to the polarization of the light. The two-substrate approach is complicated to fabricate because it includes an assembly process of the two diffractive structures that requires high alignment accuracy. The single-substrate approach, on the other hand, is simpler to fabricate, but it is only an approximate solution. In this Letter we report a new approach for design and fabrication of BCGH elements. Our new approach involves creating a form-birefringent nanostructure and modulation of the refractive index as well as the birefringence at each pixel of the BCGH.

Form birefrigence is a well-known effect of subwavelength periodic microstructures. The electric fields parallel to the grating grooves (TE polarization) and perpendicular to the grating grooves (TM polarization) need to satisfy different boundary conditions, resulting in different effective refractive indices for TE- and TM-polarized waves.[5] Many researchers have demonstrated this effect in the far-IR region.[6,7] Recently, with the help of the advances in nanofabrication, 200-nm period gratings were fabricated in a GaAs substrate that showed strong form birefringence in the near IR.[8] Furthermore, these results were found to be in agreement with the numerical simulation results obtained by a rigorous coupled-wave analysis (RCWA).[9,10] Design optimizations were performed for BCGH by form birefringence.[9] Chen and Craighead demonstrated a polarization-insensitive diffractive optical element that uses two-dimensional subwavelength periodic microstructures.[11] Aoyama and Yamashita demonstrated a grating beam splitting polarizer that uses a subwavelength grating fabricated in a photoresist.[12] The polarization contrast ratios, defined as the ratio of intensities obtained under two orthogonal polarizations at the designed diffraction order, were ~6:1 and ~3:1 for the 0th and 1st diffraction orders, respectively.

In what follows, we report the design, fabrication, and experimental evaluation of a binary phase level BCGH element that uses form-birefrigent nanostructures [or form-birefringent computer-generated holograms (FBCGH's)] fabricated upon GaAs substrates for operation in the near-IR wavelength range. The FBCGH element is designed to transmit the TE polarization straight ahead and deflect the TM polarization at an angle.

Consider a single period in a binary phase diffractive structure as shown in Fig. 1. In this period T, one pixel consists of a high-spatial-frequency grating (HSFG) with period Λ, and the other pixel is the substrate material. Of the two periodic structures, the HSFG does not introduce propagating diffraction orders other than the 0th order because of its subwavelength nature. The diffractive structure, on the other hand, introduces many diffraction orders. The phase differences between rays 1 and 2 for TE and TM polarizations are

$$(2\pi/\lambda)(n_s - n_{\mathrm{TE}})d = \Phi_{\mathrm{TE}}\,,$$
$$(2\pi/\lambda)(n_s - n_{\mathrm{TM}})d = \Phi_{\mathrm{TM}}\,, \qquad (1)$$

where λ is the wavelength in vacuum, d is the thickness of the HSFG layer, n_s is the refractive index of the substrate, and n_{TE} and n_{TM} are the effective refractive indices of the HSFG for TE and TM polarization, respectively. When the wavelength is much larger

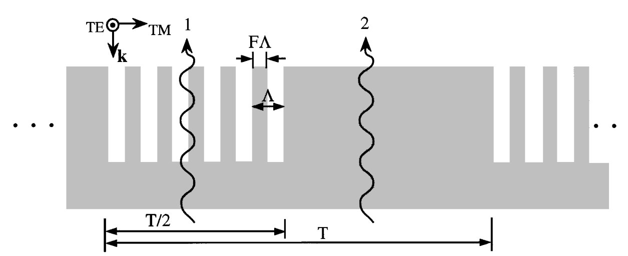

Fig. 1. FBCGH design: one period in a FBCGH.

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than the period of the HSFG, second-order effective medium theory[13] (EMT) can be used to calculate the effective indices with high accuracy. The effective indices for TE and TM polarizations calculated with a second-order EMT are given by

$$n_{2\mathrm{TE}} = \left\{ n_{0\mathrm{TE}}^2 + \frac{1}{3}\left[\frac{\Lambda \pi F}{\lambda}(1-F)(n^2 - n_0^2) \right]^2 \right\}^{1/2},$$

$$n_{2\mathrm{TM}} = \left\{ n_{0\mathrm{TM}}^2 + \frac{1}{3}\left[\frac{\Lambda \pi F}{\lambda} n_{0\mathrm{TM}}^3 n_{0\mathrm{TE}} \times (1-F)\left(\frac{1}{n^2} - \frac{1}{n_0^2}\right) \right]^2 \right\}^{1/2}, \qquad (2)$$

where

$$n_{0\mathrm{TE}} = [Fn^2 + (1-F)n_0^2]^{1/2},$$

$$n_{0\mathrm{TM}} = \left[\frac{(n_0 n)^2}{Fn_0^2 + (1-F)n^2} \right]^{1/2}$$

are the effective indices calculated with zero-order EMT, Λ is the period of the HSFG, F is the grating fill factor of the HSFG (defined as the ratio between the width of the unetched portion within one period of grating to the grating period Λ; see Fig. 1), and n and n_0 are the refractive indices of the two materials that form the HSFG. We chose GaAs as the substrate; therefore $n = n_s = 3.37$ (index of GaAs at 1.55 μm) and $n_0 = n_{\mathrm{air}} = 1$. In general, $n_{\mathrm{TE}} > n_{\mathrm{TM}}$. To design a diffractive polarization beam splitter, we implement a binary phase grating for TE polarization (i.e., $\Phi_{\mathrm{TE}} = \pi$) and without affecting the TM polarization (i.e., $\Phi_{\mathrm{TM}} = 2\pi$).

Once the reconstruction wavelength λ is chosen, the period of the HSFG, Λ, can be determined. This Λ should be large enough to facilitate the fabrication and small enough not to cause higher than the 0th propagating diffraction orders. From our RCWA simulation we found that

$$\Lambda \le \lambda / n_s \qquad (3)$$

is a useful criterion.[9] Thus we only need to find the grating fill factor F and the etch depth d to design the element. First, we determine F. From Eqs. (1) with our design parameters $\Phi_{\mathrm{TE}} = \pi$ and $\Phi_{\mathrm{TM}} = 2\pi$ we have

$$\frac{n_s - n_{\mathrm{TE}}}{n_s - n_{\mathrm{TM}}} = \frac{\Phi_{\mathrm{TE}}}{\Phi_{\mathrm{TM}}} = 1{:}2. \qquad (4)$$

Substitute n_{TE} and n_{TM} from Eqs. (2) into Eq. (4); choose operating wavelength $\lambda = 1.55$ μm and HSFG period $\Lambda = 0.3$ μm. By solving the resultant Eq. (4) we find the grating fill factor $F = 0.3509$. With this fill factor and other parameters, the corresponding effective refractive indices from Eqs. (2) are found to be

$$n_{2\mathrm{TE}} = 2.309, \qquad n_{2\mathrm{TM}} = 1.2447.$$

Finally, we find from Eqs. (1) the required etch depth of the HSFG, $d = 0.728$ μm.

To ensure the accuracy of this design we also simulate the phase delay introduced by the HSFG, using a RCWA.[9,10] In the RCWA a single period of a surface relief grating is divided into a large number of planar layers. The optical fields are formulated in terms of spatial harmonics by Fourier series expansions of the dielectric constant of each layer. Boundary conditions are matched and energy conservation law is employed to solve the resultant coupled diffraction equations. In our simulation we only try to calculate the phase delay caused by HSFG to confirm the results that we obtained by using the EMT. The actual diffraction efficiency of a FBCGH is estimated later by scalar diffraction theory. The grating parameters are the same as those given above. The simulation indicates that the phase delay introduced by a 0.73-μm-thick HSFG is 2.154π for TE polarization and 1.190π for TM. A GaAs layer of the same thickness without HSFG introduces 3.178π phase delay. Thus the designed grating will have a 1.024π phase difference between the HSFG pixel and an unetched pixel for TE polarization and 1.987π for TM polarization. This simulation shows the validity of our design. It also indicates that the EMT, if used carefully, can be used in designing FBCGH elements.

Following this design, we fabricated a diffractive structure upon a (100)-cut GaAs substrate, using electron beam lithography and dry etching techniques.[8] The total area of the element was 100 μm × 100 μm. The period of the binary phase diffractive grating T was 10 μm. The period of HSFG Λ was 0.3 μm, and the fill factor of the HSFG F was 0.35. The fabricated element has an etch depth of 0.75 μm for the HSFG. Figure 2 shows a scanning electron micrograph of the fabricated element.

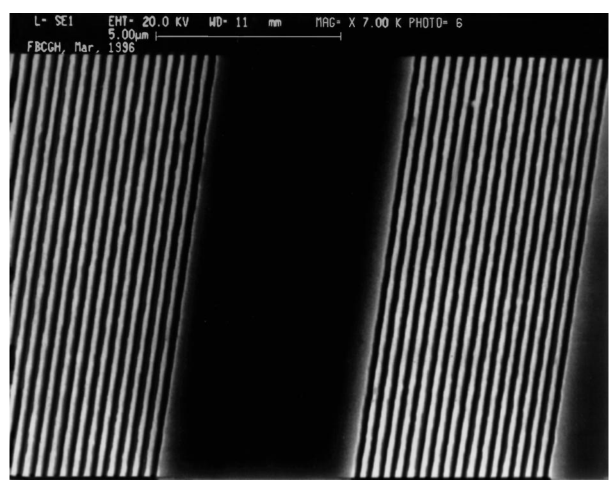

Fig. 2. Scanning electron micrograph of the fabricated FBCGH.

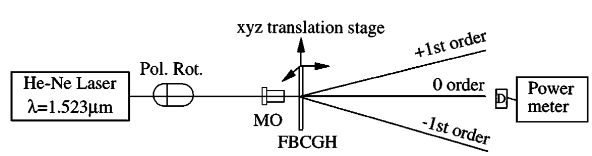

Fig. 3. Schematic of the experimental evaluation of the fabricated FBCGH.

Table 1. **Measured Results of the Fabricated FBCGH**[a]

Performance	0th Order	1st Order	−1st Order
TE efficiency	0.86% (0.0%)	41.4% (40.5%)	44.2% (40.5%)
TM efficiency	75.5% (100%)	0.15% (0%)	0.44% (0%)
Polarization contrast ratio	88.2:1	275:1	99.2:1

[a]The results calculated by scalar diffraction theory for a binary phase level diffractive optical element are given in parentheses for comparison.

We evaluated the fabricated element with a He–Ne laser (Melles Griot) operating at 1.523 μm, using the setup shown schematically in Fig. 3. The beam was focused onto the FBCGH by a low-power (6×) microscope objective (MO). A Ge detector was used to measure the far-field diffraction patterns. The polarization state of the beam incident upon the FBCGH was controlled with a polarization rotator (Pol. Rot.).

In the binary phase FBCGH reconstruction stage we anticipate observing +1 and −1 propagating diffraction orders. In our characterization experiments we observed only two spots on the IR phosphor viewing card under TE polarization and one spot under TM polarization, although higher orders do exist and can be detected with a photodetector. We can optimize the distance between the microscope objective and the FBCGH by minimizing the measured energy diffracted into the 0th diffraction order at TE-polarized illumination. The measured diffraction efficiency, excluding reflection, and the polarization contrast ratios are summarized in Table 1. The diffraction efficiency of Table 1 was calculated as the ratio between the intensity measured at a certain diffraction order and that of the total light transmitted through the GaAs substrate without a FBCGH. These measured results show that the FBCGH has good polarization selectivity (large polarization contrast ratios) and diffraction efficiencies close to the theoretical limit. Note that the form-birefringent structure also serves as an antireflection coating, explaining the slightly higher measured diffraction efficiencies compared with that predicted by scalar diffraction theory for a binary phase element (40.5%). The expected results calculated with scalar diffraction theory are also listed in the table for comparison. The slight asymmetry between the efficiencies of ±1st diffraction orders is due to imperfect normal incidence.

In conclusion, we have designed, fabricated, and evaluated a polarization-selective computer-generated hologram that uses form-birefringent nanostructures upon GaAs substrates. The element was designed by use of effective-medium theory and verified to be valid by the rigorous vector field theory. The design and the experimental evaluations were found to be in good agreement. The fabricated element shows a large polarization contrast ratio (as large as 275:1) and high diffraction efficiencies (>40% for the first diffraction orders). Such an element may be useful in fabrication of compact and efficient free-space transparent photonic switching fabrics as well as packaging optoelectronic devices and systems.

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