Wavelength-selective planar holograms

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Planar gratings and holograms are normally readout-wavelength insensitive. We show, however, that a binary phase surface-relief hologram can be transparent at one wavelength (λ) yet diffract efficiently at another (λ'), provided that the phase delay is an integer number of waves (e.g., 3) at λ and a half-integer number of waves (e.g., 2.5) at λ'. We fabricated a 7.9-μm-deep binary phase grating in BK7 glass that separates the standard telecommunications wavelengths, 1.3 and 1.55 μm, with 80% efficiency (neglecting Fresnel losses) and greater than 30:1 contrast.

Volume holograms, such as those recorded in photorefractive crystals, are Bragg selective; their diffraction efficiency drops rapidly when the wavelength or direction of the readout beam is changed.[1] Planar holograms, in which the fringe spacing is large compared with the active media thickness, are normally insensitive to the readout wavelength or angle. A ruled metallic spectrometer grating is an example of a planar hologram. When the grating is illuminated with a broad-spectrum beam, the colors are separated because each wavelength is diffracted into a different angle. However, a planar grating fabricated as a *deep surface-relief profile* in a dielectric substrate can be designed to diffract efficiently at one design wavelength while remaining transparent at another specified wavelength.

In a binary phase hologram a two-dimensional fringe pattern is transferred as a surface-relief profile onto an isotropic substrate, for example, by lithography and etching. A grating with a 50% duty cycle and exactly one-half wavelength of delay has a theoretical diffraction efficiency of 40.5% into the 1st and −1st orders and no energy in the transmitted 0th order, while the remaining 19% of the incident intensity is distributed among the higher orders.[2]

Normally, a binary phase hologram is etched to the minimum depth $t_{\min}$ that will produce a half-wave of delay at wavelength λ in a substrate of index n. The optical path difference between unetched and etched regions is $(n-1)t_{\min} = \lambda/2$, so $t_{\min} = \lambda/2(n-1)$. The top of Fig. 1 shows what happens when such a hologram is illuminated at the design wavelength λ and at a slightly longer wavelength λ'. The hologram is not etched sufficiently deeply to provide a half-wave of delay at λ', so the diffraction efficiency is below optimum. For example, suppose that a binary phase grating is designed to diffract 1.3-μm light at a 5° angle. Illuminated with 1.55-μm light, the grating still diffracts, but the deflection angle is increased to 6° and the diffraction efficiency in the 1st order is slightly reduced from 40.5% to ~37%.[3]

The multiple-wavelength phase delay hologram shown at the bottom of Fig. 1 is much more sensitive to a change in wavelength. The etch depth is increased to create a phase delay of $p + 1/2$ waves at the design wavelength λ, where p is any integer $p = 0, \pm1, \pm2$, and so on. At the design wavelength this hologram is essentially identical to the hologram fabricated with a normal half-wave of delay. This approximation is valid, provided that the new, greater etch depth is still small compared with the fringe spacing. However, when the readout wavelength is shifted the small difference in phase delay seen at the top of Fig. 1 is multiplied by a factor of $2(p + 1/2)$. With the correct choice of p, and the correct index dispersion, the phase delay can be exactly zero at a second design wavelength λ'. At λ' the element is transparent.

The computation of the etch depth necessary to create an arbitrary phase delay at each of the two design wavelengths λ and λ' is straightforward. If the

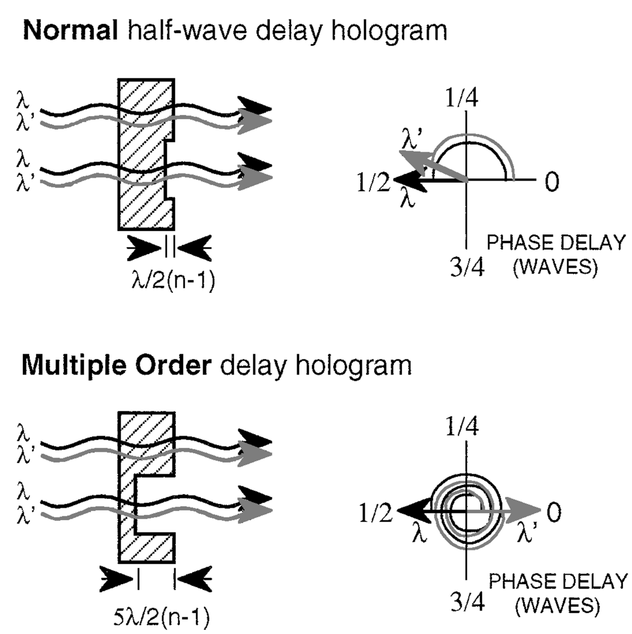

Fig. 1. Effect of wavelength shift on half-wave and multiple-wave phase delay holograms. The path-length difference on wavelength shift is greater when the etch depth is increased. With the correct etch depth and index dispersion the phase delay at the second wavelength is zero, and there is no diffraction.

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index of refraction is n at λ and n' at λ', then an etch of depth t will produce phase delays of

$$\text{wavelength } \lambda: \quad \frac{(n-1)t}{\lambda} = \Phi = p + \phi\,, \tag{1a}$$

$$\text{wavelength } \lambda': \quad \frac{(n'-1)t}{\lambda'} = \Phi' = q + \phi'\,, \tag{1b}$$

where the total delay Φ (Φ') is separated into the integer part p (q) and the remainder ϕ (ϕ') at λ (λ'). Taking as a convention that the longer wavelength will always be called λ', we can define the index difference $\Delta = n - n'$ so that Δ will be positive for materials with normal dispersion.

Once the design wavelengths are set, the object is to determine the substrate material and etch depth that will provide the desired residual phases ϕ and ϕ'. Equations (1) can be combined by solution for t to yield

$$\frac{\lambda(p+\phi)}{(n-1)} = \frac{\lambda'(q+\phi')}{(n-\Delta-1)}\,. \tag{2}$$

For a given substrate material there may or may not be any value of p and q that will solve Eq. (2) to the desired accuracy. For any particular combination of p and q the index difference Δ that will solve Eq. (2) can be calculated as a function of the index n. One can then evaluate a candidate material by plotting the ideal difference for all possible combinations of p and q and then looking to see whether the actual value falls on one of the lines. A multilevel phase hologram can be designed, provided that a material can be found that can generate all the required phase combinations needed, each with appropriate values of p and q.

However, in a color-selective binary phase hologram, the residual phases will always be 1/2 and 0. To diffract λ' and transmit λ, $\phi = 0$ and $\phi' = 1/2$. To diffract λ and transmit λ', $\phi = 1/2$ and $\phi' = 0$. A couple of practical considerations limit the values of p and q. First, the accuracy with which a surface-relief profile can be fabricated tends to be a nearly constant percentage of the etch depth. The absolute phase delay must be maintained to within much less than one wave. A hologram with p or $q \gg 1$ cannot be fabricated because the etch depth error will be too large. Second, solutions in which p and q differ greatly tend to demand materials with unrealistically large index dispersions. Therefore it is reasonably complete to look only at solutions in which $p = -5, -4, \ldots 5$ and $q = p \pm 1$.

Long-haul fiber optics operate at 1.3 and 1.55 μm because these wavelengths have low loss and dispersion in silica single-mode fiber. Setting $\lambda = 1.3$ μm and $\lambda' = 1.55$ μm, we can use Eq. (2) to calculate the index difference Δ as a function of the index for binary phase holograms to diffract only λ' ($\phi = 0$ and $\phi' = 1/2$) or to diffract only λ ($\phi = 1/2$ and $\phi' = 0$). Figure 2 shows the results for all the possible combinations of p and q in which $|p, q| \leq 5$. The resulting phase delay at each wavelength is labeled at the right.

The plots also show the index values and differences for two Schott glass types, BK7 and IRG9. IRG9, an infrared glass with unusually high normal dispersion ($\nu_d = 81$), falls close to the line for the inverse hologram, which diffracts only 1.3-μm light by creating a delay of 2.0 waves at 1.55 μm and 2.5 waves at 1.3 μm. BK7, a glass with moderate normal dispersion

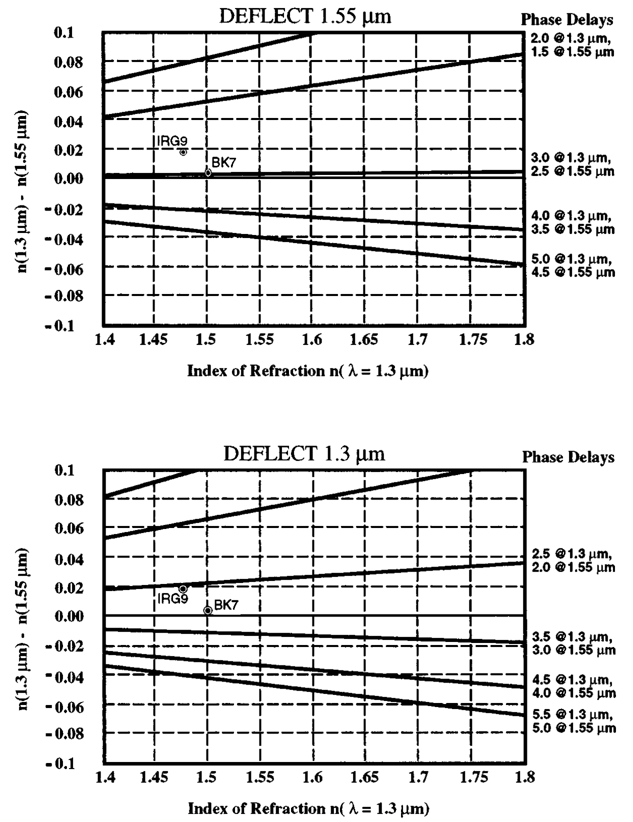

Fig. 2. For each index of refraction at λ, only discrete indices at λ' permit a color-selective hologram. Each line on these graphs show one combination of integer and half-integer phase delays for 1.55- and 1.3-μm light. The top plot shows those values that deflect 1.55 μm and transmit 1.3 μm, and the bottom plot shows the inverse. BK7 lies on the line for a phase delay of 2.5 wavelengths at 1.55 μm and 3 wavelengths at 1.3 μm.

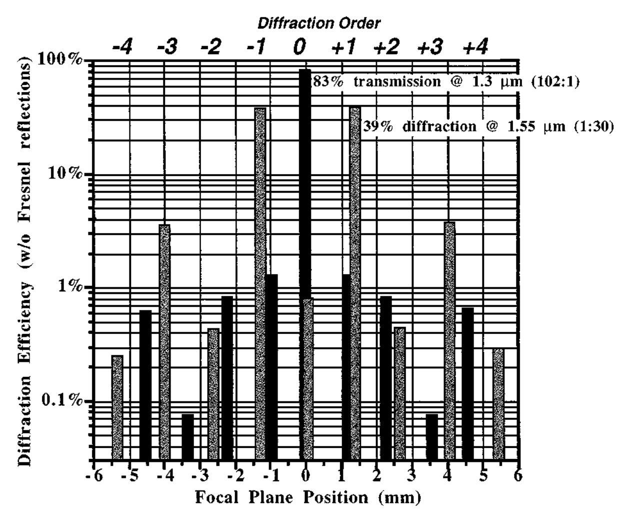

Fig. 3. Intensity at diffraction peaks for 1.3-μm (darker bars) and 1.55-μm (lighter bars) illumination. Bars do not correspond to spot sizes. Intensity between orders dropped to below 0.05%.

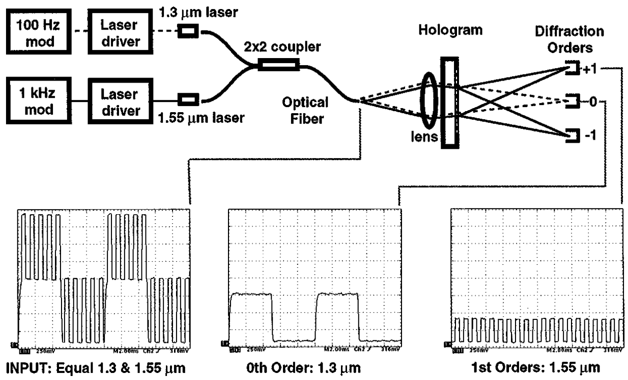

Fig. 4. Demonstration of wavelength demultiplexing of 1.55-μm light, modulated at 1 kHz, and 1.3-μm light, modulated at 100 Hz. An input fiber carrying both signals is imaged to the output plane, where the 1.3-μm signal was transmitted on axis and the 1.55-μm signal was deflected equally into the +1st and −1st orders.

sion ($\nu_d = 64$), falls right on the line to diffract only 1.55 μm by creating a delay of 2.5 waves at 1.55 μm and 3.0 waves at 1.3 μm ($p = q = 2$). This is the element that we fabricated and tested.

The index of refraction of BK7 was specified by the supplier (Newport Optical Materials, Inc.) to be 1.5027 at 1.30 μm and 1.5004 at 1.55 μm. With Eqs. (1) the phase delay for a 7.75-μm deep etch is 2.997 at 1.3 μm and 2.502 at 1.55 μm. A mask pattern with various grating duty cycles and frequencies was lithographically transferred into an 8.8-μm-thick layer of Shipley Microposit STR–1075 photoresist. Three BK7 substrates were etched by chemically assisted ion beam etching for 75.7, 77, and 78 min to yield final etch depths of 7.55, 7.78, and 7.9 μm, respectively. These depths bracket the design value of 7.75 μm to allow for possible inaccuracies in etch depth measurement, index of refraction, and readout wavelength. The mask pattern with a 100-μm period and an initial duty cycle of 1:1 yielded an etched grating with a duty cycle of 1.07:1.

The results with the 7.9-μm-deep etch were nearly optimal. Figure 3 shows the diffraction efficiency and location of each of the first four orders. A perfectly fabricated binary phase hologram (neglecting the Fresnel reflection losses of ~8%) should have no energy in the even orders, 40.5% in the ±1st orders, and 4.5% in the ±3rd orders. At 1.55 μm the diffraction efficiencies of the fabricated element matched these numbers closely, with 39% in each of the 1st orders, 3.6% in each of the ±3rd orders, and a 0th-order transmission of 0.83%. At 1.3 μm the transmission was 83%, whereas the diffraction into any of the orders was less than 1.2%. The background intensity between diffraction orders was below 0.05%,

A multiple-wavelength delay hologram is more sensitive to changes in the illumination angle than a conventional binary phase hologram because of the increased optical path differences. We tested the effect of tilting the element and found that the performance (1st-order diffraction efficiency at 1.55 μm and 0th-order transmission at 1.3 μm) changed by less than 2% for a 5° tilt and less than 10% for a 10° tilt. In fact, the overall performance was slightly improved with a 5° tilt, suggesting that the etch depth should be increased to 7.92 μm to optimize performance. A field angle of 10° indicates that these elements are compatible with $f/3$ and larger optics.

We used this color-selective grating to demonstrate wavelength demultiplexing of 1.3 and 1.55-μm signals with the setup shown in Fig. 4. The output from two fiber-coupled diode lasers was combined into one single-mode fiber by a 2 × 2 fused fiber coupler. The 1.3-μm laser was current modulated at 100 Hz, and the 1.55-μm laser modulated at 1 kHz, for an artificial data signal to distinguish their outputs. The single-mode fiber output was imaged through the hologram onto the detector plane where the 0th, 1st, and −1st orders could be measured. Although the diffraction orders from the two wavelengths could be partially separated, the detector aperture was deliberately made large enough to collect all the 1st-order output. The oscilloscope trace at the left shows the input light, carrying both signals. The traces at center and right show the separated outputs at the same scale. The 1.3-μm signal is transmitted with negligible cross talk into the 0th order, whereas the 1.55-μm signal is deflected with equal efficiency into the 1st and −1st orders. The ratio of 1.3- to 1.55-μm light in the transmitted 0th order is 102:1, and the ratio of 1.55- to 1.3-μm light in the 1st orders is 30:1. The average energy efficiency, including Fresnel reflections, is ~75%. This efficiency could be increased to more than 80% by antireflection coating the hologram.

In conclusion, we have demonstrated that a color-selective planar hologram can be fabricated with a deep surface-relief profile in an isotropic substrate. A binary phase hologram capable of separating 1.3- and 1.55-μm light was fabricated from BK7 substrate and shown to produce close to theoretically limited performance at 1.55 μm, with 78% of the light contained in the combined +1st and −1st orders, while remaining 83% transparent at 1.3 μm. We used this element to demonstrate wavelength demultiplexing in a simple test system. This type of grating might be used to build simple and compact fiber-optic components and also has the added potential to include aspheric terms in the hologram to correct for lens aberrations.

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