

Dispersion correction of surface-normal optical interconnection using two compensated holograms

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Performance of optical interconnects using volume holographic gratings and substrate-guided waves is subject to source wavelength detuning which originates from laser chirping and operating temperature changes. In this letter, we characterize and measure the dispersion of commonly used surface-normal volume holographic gratings. Dispersion characteristics of a 20 μm thick photopolymer volume holographic grating are evaluated. A dispersion correction method is demonstrated to provide a dispersion-free surface-normal optical interconnect using two dispersion-compensated volume holographic gratings and substrate-guided waves which automatically compensate the dispersion that results from detuning over a 5.7 nm bandwidth. © 1998 American Institute of Physics. [S0003-6951(98)00725-6]

Optical interconnects have advantages over electrical interconnects in applications where low transmission loss, electromagnetic interference immunity, low power budget, and high bandwidth requirements are critical.¹⁻³ The need for optically-interconnected memories and processors in multichip modules is imperative due to the rapid increase of clock speed and of data throughput. Free-space interconnects must overcome packaging vulnerability in order to be practical. Guided-wave interconnects based on silica or polymeric thin films attract more attention since they can be fabricated in two-dimensional arrays using a standard very large scale integrated (VLSI) microfabrication process. Coupling light into and out of waveguides efficiently becomes more important. Coupling methods using gratings, end-face joints, and prisms have been reported.^{4,5} Surface-normal transmission holographic gratings are widely used to couple light into and out of waveguides due to their high diffraction efficiency and planarized packaging.

In this letter, we investigate the light dispersion of a surface-normal input volume holographic grating. Experimental data of grating dispersion characteristics are obtained using a mode-locked femtosecond laser. A compensation method is developed to eliminate the wavelength-induced dispersion, and we demonstrate surface-normal input and output optical interconnect structures which automatically correct the dispersion resulting from the laser wavelength chirping and therefore greatly enhance the interconnection bandwidth.

The basic structure of a surface-normal input and output optical interconnect using volume holographic gratings and substrate-guided waves is shown in Fig. 1. The grating structure induced by the refractive index modulation is slanted, having a tilt angle ϕ . The grating spacing is Λ . Due to the high diffraction efficiency of the volume hologram and the low propagation loss due to total internal reflection, the surface-normal optical interconnect configuration is useful in photonics applications such as backplane buses, computer clock signal distribution, and waveguide-based wavelength

division multiplexers.⁶⁻⁸ However, laser sources usually contain a spectral width depending on the laser cavity structures and the operating conditions.⁹ Laser wavelength shift is also present when the laser is internally modulated.¹⁰ Light dispersion due to wavelength tuning is thus unavoidable and will affect the output beam characteristics, especially the accuracy of the output beam position.

The dispersion of a volume holographic grating behaves like that of a Bragg grating.¹¹ To achieve maximum diffraction efficiency, the input and the diffracted beams must have the same angle with respect to the phase grating, as indicated in the phase-matching diagram of Fig. 1. The desired diffraction angle θ for surface-normal input is achieved by selecting a grating period Λ , which satisfies the constructive interference condition given by

$$\sin \theta = \frac{\lambda \sin \phi}{n \Lambda}, \quad (1)$$

where n is the refractive index, λ is the center wavelength, and ϕ and θ are defined in Fig. 1. The light dispersion due to wavelength detuning $\Delta\lambda$ is simply derived from Eq. (1) and constructive grating interference, which gives

$$\Delta \theta = \frac{\Delta \lambda}{\lambda} \tan \theta. \quad (2)$$

To evaluate light dispersion, the volume hologram dispersion characteristics are measured using a femtosecond mode-locked laser. In this experiment, we use a CLARK-MXR NTA-5 femtosecond mode-locked laser. Due to the

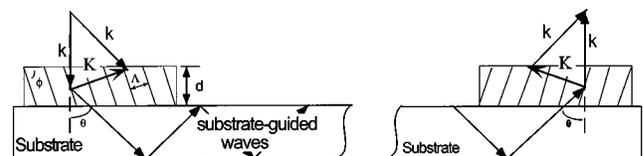


FIG. 1. Schematic of slanted volume transmission hologram and its phase-matching diagram.

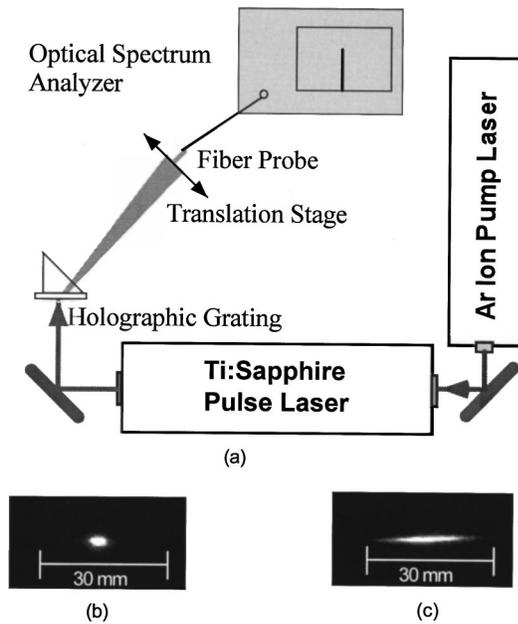


FIG. 2. (a) Setup for measuring hologram light dispersion, (b) diffraction spot of a cw laser input, and (c) diffraction spot of a femtosecond optical pulse after 860 mm propagation distance.

Fourier transform relationship, the ultrafast pulse contains a broad band of optical wavelengths simultaneously. Thus an ultrafast laser is an ideal tool for measuring the grating dispersion. The setup for measuring light dispersion is shown in Fig. 2(a); the optical pulse is coupled into the grating coupler surface normally. The grating is fabricated in a 20 μm thick HRF-600 DuPont photopolymer film using the two-beam interference method. The grating is slanted and is designed for a surface-normal input at the 833 nm center wavelength. The diffraction angle is 45° in the glass substrate, which has a refractive index of 1.51. The light is coupled out by a fused silica prism ($n=1.453$, not shown in the figure) which has a negligible dispersion effect compared with that of the polymer grating. The fanout light wavelength is measured with an optical spectrum analyzer. By letting a femtosecond pulse pass through a grating coupler, the multiple-wavelength composition of the femtosecond pulse causes it to fan out dispersively. Figure 2(b) shows the diffraction spot of a continuous-wave laser beam with a center wavelength of 833 nm. By employing a mode-locked Ti-sapphire laser with a 170 femtosecond FWHM pulse width with a 3 dB spectral width of $\delta\lambda \approx 5.7$ nm, the diffraction pattern is an angularly dispersed continuous fanout which is shown in Fig. 2(c). Experimental data of light dispersion are obtained by measuring the wavelength versus position, using the setup shown in Fig. 2(a). We first measure the light dispersion of the TM (transverse magnetic) wave in the hologram, then we rotate the polarization to the TE (transverse electric) mode and repeat the measurement. The measurement is repeated with different holograms and different distances. With known refractive indices of the materials, we calculate the dispersion angle inside the glass substrate. The measured dispersion angles of both TE and TM waves versus the wavelength are drawn in Fig. 3, together with the dispersion angle predicted using Eq. (2). It is found that TE and TM wave dispersions

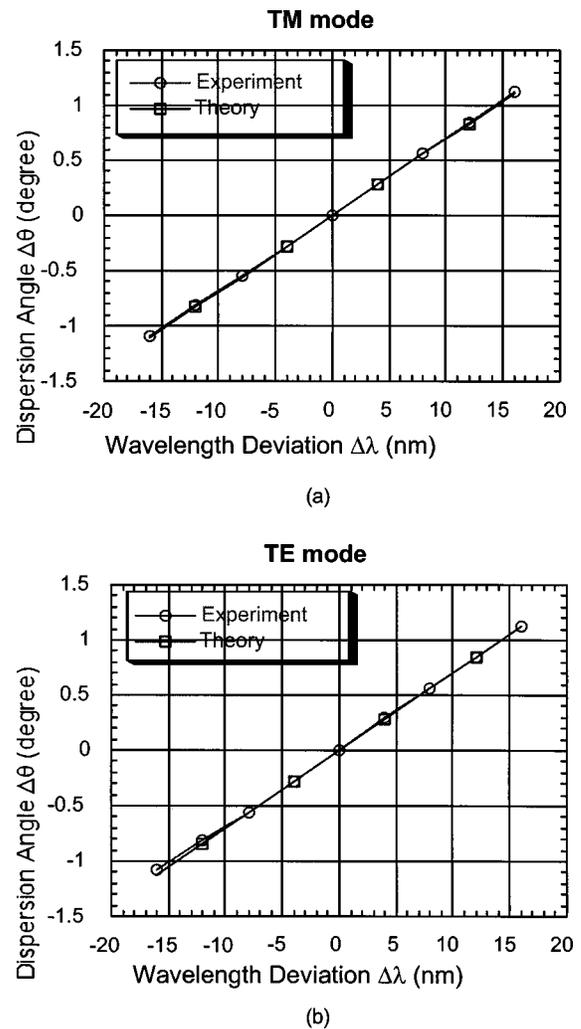


FIG. 3. Theoretical and experimental data of angular dispersion vs wavelength tuning, for (a) TM wave data, and (b) TE wave data.

are the same. The theoretical and experimental angular dispersion data are found to be perfectly matched within $\pm 1\%$.

The laser wavelength chirping and the dispersion of the volume holograms result in a position shift of the output light beam. The output beam shift will cause the detectors or output fibers to have strong signal aliasing. Such a problem can be solved by employing achromatic input couplers. However, such achromatic input couplers have lower efficiencies than a high-efficiency volume holographic grating.¹² For applications such as wavelength division multiplexing and demultiplexing, dispersive gratings must be used to separate different spectral bands.¹³ To avoid such an output position uncertainty problem, an output holographic grating is made with a grating vector symmetrical to the first, with respect to the surface-normal direction. From the phase-matching diagram in Fig. 1, it is shown that the output beam is also surface normal due to the perfect reversal of the vectors. Surface-normal output is also obtained for slightly phase-mismatched input wavelengths. In order to achieve a fixed, wavelength-independent output spot, we use a quarter-pitch gradient-index (GRIN) lens to couple out the light beams. The paraxial equation describing the ray position at the output GRIN lens surface, for an incident angle $\Delta\theta$, is¹⁴:

$$y(p) = y_0 \cos(2\pi p) + \frac{\tan(\Delta\theta)}{A} \sin(2\pi p), \quad (3)$$

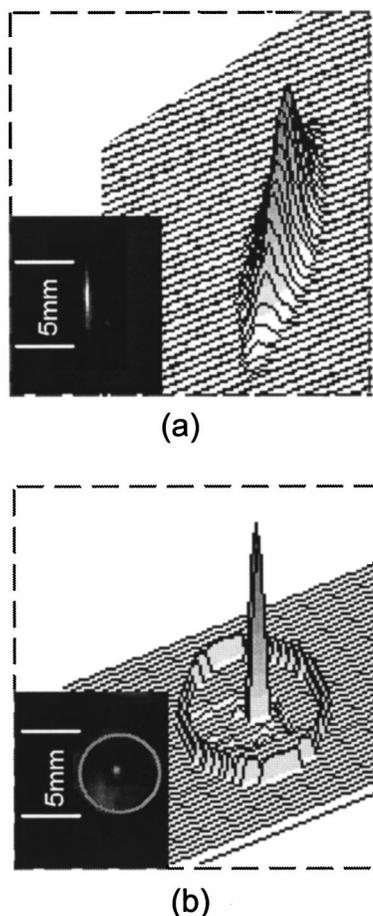


FIG. 4. (a) Output spot shift due to laser chirping. (b) Output spot is fixed after a quarter-pitch GRIN lens.

where A is a radial GRIN lens parameter, p is the pitch size of the lens, and y_0 is the incident position at the lens entrance. Equation (3) shows that when the GRIN lens is a quarter-pitch ($p=0.25$) lens, the output beam spot is focused onto the GRIN lens exit surface only as a function of the incident angle. In our output coupler configuration, the output beam angle is the same. Even though the laser chirping causes the output spot position to shift, by using a GRIN lens with a proper diameter, the output spot at the GRIN lens output surface is fixed. We experimentally demonstrate this dispersion compensation method by using a quarter-pitch GRIN rod lens of 5 mm diameter. An optical interconnect

equivalent to that of Fig. 1 is made using 20 μm thick DuPont HRF-600 photopolymer film with a diffraction angle of 45° . The distance between the input and output holograms is 10 cm. Figure 4(a) shows the output spot shift with laser wavelength chirping without a GRIN lens. With the employment of a quarter-pitch GRIN lens, the output spot is fixed, disregarding the laser wavelength chirping, as shown in Fig. 4(b). Since GRIN lens fiber pigtailling is a simple and reliable process, the laser-chirping-compensated optical interconnect can be made into a rigid and reliable package covering a huge optical spectrum. The device structure presented here can be easily extended to 1-to- N , N -to-1, or other similar optical interconnect scenarios which cover a broad range of photonic applications.

In summary, we investigate the dispersion characteristics of a photopolymer volume holographic grating. Theoretical analysis and experimental data are compared using a femto-second mode-locked laser. We find that TE and TM waves have the same dispersion in a thick volume holographic grating and they conform within $\pm 1\%$ deviation with the theoretical derivation of a thick Bragg grating. Finally, we present a simple and reliable laser-chirping-compensated surface-normal optical interconnect using two symmetrical volume holographic gratings and substrate-guided waves in combination with gradient optics.

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