Filter characteristics of a chirped volume holographic grating

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Received June 10, 2003

We compare and analyze the filter properties of transmission-type volume holographic gratings, especially the dispersion characteristics for uniform and chirped gratings. It is theoretically and experimentally shown that the dispersion characteristics can be controlled by introducing one-dimensional chirping to the volume grating in a photorefractive crystal. The filter response including output power and dispersion comes from a combined effect of the spatial spectra of the grating structure, input beam, and output-coupling fiber mode.

Filter responses can be designed by controlling these parameters for optical communication applications.

OCIS codes: 050.7330, 060.4510.

Holographic gratings that are realized on photorefractive crystals (PRCs) or photopolymers have been extensively studied for applications such as holographic memory or optical information processing. Recently, the application of holographic gratings for optical communication devices has been attracting a significant amount of attention.1–5 These researchers focused mainly on the implementation of wavelength demultiplexers. The ever-increasing data rate in optical communications also makes the compensation or management of chromatic dispersion and polarization mode dispersion critical issues.6 To deal with these requirements, many optical devices have been proposed such as thin-film reflection stacks, fiber Bragg gratings (FBGs), and arrayed waveguide gratings.6 A holographic grating is also attractive for such purposes because it has the potential for practical application with unique advantages: It can provide new design options, e.g., multiplexing of Bragg gratings in the same volume and polarization-selective anisotropic diffraction.7 Moreover, when the grating is recorded in the polymer media, cost-effective manufacturing processes might be possible.

Although wavelength demultiplexers that use volume holographic gratings have been effectively proposed and implemented in PRCs or photopolymers,7,3,5 the delay properties of a holographic grating have not yet been examined extensively. Actually, previous research took into consideration uniform holographic gratings in general2,3,5 and with some apodization.4 Here we theoretically and experimentally probe chirped transmission-type volume holographic gratings (VHGs). We mention that the transmission-type gratings can have wavelength-dependent spatial dispersion for demultiplexing application although they might have some polarization dependence compared with reflection-type gratings.2,5 But the chirped grating to be discussed in this Letter as a dispersion-control device is quite different from the uniform gratings for wavelength demultiplexers both in design and purpose. The chirped grating is written in a PRC by use of a phase mask. We propose a theoretical model with a 1st-order Born approximation and find that the model agrees with the experimental results. Considering that many FBG applications are based on a nonuniform grating structure and its filter response, our research provides the feasibility of using three-dimensional nonuniform Bragg gratings for various optical communication applications. We note that some research has been performed with one-dimensional chirped volume gratings in relation to femtosecond laser pulse stretching.8,9 Our research is quite different in that we considered dispersion control for optical fiber communications applications. Other research also differs from ours inasmuch as the authors considered a much broader wavelength range (~10 THz) and a smaller dispersion (~0.5 ps/ nm).

Figure 1 is a schematic diagram of our VHG recording and signal filtering. Since most holographic recording materials do not respond to the optical communication wavelength (~1550 nm) when writing holograms, the recording and signal filtering use different wavelengths and geometries. In writing VHGs we used a predesigned optical phase mask in front of the recording medium [Fig. 1(a)]. A visible laser light is collimated and transmitted through aperture $P_m$. The resulting plane optical wave with finite size $P_m$ illuminates the mask, and the –1st-order diffracted wave interferes with the transmitted wave (0th order) in the recording medium to form a VHG. With the aid of the phase mask (by simply introducing chirping on the phase mask period), we could obtain a finely chirped volume grating. The phase mask period was varied slowly in space compared with the writing optical wavelength. The chirping on the phase mask gives the –1st-order diffracted wave minute convergence (or divergence depending on the chirp rate sign),

Fig. 1. VHG schemes for (a) recording with a phase mask and (b) signal filtering.
and it causes the recorded grating to be chirped at the phase mask chirp rate.

The signal filtering comes from a kind of single scattering of the incident wave by the recorded VHG [Fig. 1(b)]. The signal is incident upon the volume grating with some transverse amplitude profile (slowly varying) expanded from the input single-mode fiber (SMF). Then it is diffracted and coupled to the output SMF. The directions of the input and the output-coupling beams vary from the input single-mode fiber [Fig. 1(b)]. The signal is incident upon the volume scattering of the incident wave by the recorded VHG phase mask chirp rate. It causes the recorded grating to be chirped at the wavelength of concern, the tunable laser diode generated a narrow spectrum and the light was sinusoidally intensity modulated at 2.5 GHz. It was then split into two SMFs: One signal goes directly to the sampling oscilloscope, and the other goes through the VHG filter. The oscilloscope measured the relative delay of the two signals and the output power from the sampled data. By scanning the wavelength in the filter spectrum range by computer control, we could obtain the filter response of the volume grating.

Figure 3 shows filter characteristics of transmission-type VHGs. The input signal from the SMF was collimated, and the diffracted signal was coupled to the output SMF by an objective lens with 0.25 numerical aperture. We could adjust the input and the output-coupling beam profiles to the Gaussian beam profile with a beam waist radius of 1.6 mm. The diffraction efficiencies of uniform and chirped gratings were approximately 8%, and, by using an erbium-doped fiber amplifier (in Fig. 2), we could compensate for the filter insertion loss.

Figure 3 shows that the experimental and theoretical filter characteristics are close to each other. The filtered beam power is proportional to |S|², and group delay ρ and dispersion dS are as follows:

\[
ρ = \frac{dθ_s}{dω} = -\frac{λ^2}{2πc} \frac{dθ_s}{dλ},
\]

\[
dS = \frac{dτ_s}{dλ},
\]

where θ_s is the phase of S.

We recorded VHGs in a 1 cm × 1 cm × 2 cm Fe:LiNbO₃ PRC, where the c axis is along the 2-cm side and the input single-mode fiber was collimated and illuminated the phase mask in front of the crystal. The incident angle was 14.4° to satisfy 0th- and −1st-order diffraction interference for the mask pitch period of 1071 nm. Because of finite aperture p of the recording beam, the illuminated area at the crystal surface behind the mask was confined to 1 cm × −1.4 cm. We could obtain uniform and chirped VHGs by using a uniform mask of the above period and a chirped mask with a chirp rate of −0.2 nm/cm (along the x direction). After writing the holograms, to test the filter application, the collimated input optical waves of ~1550-nm wavelength were incident with angle 46.4° for the Bragg condition.

To measure the group delay of the output light we used the measurement setup of a conventional phase shift method as shown in Fig. 2. For each specific wavelength of concern, the tunable laser diode generated a narrow spectrum and the light was sinusoidally intensity modulated at 2.5 GHz. It was then split into two SMFs: One signal goes directly to the sampling oscilloscope, and the other goes through the VHG filter. The oscilloscope measured the relative delay of the two signals and the output power from the sampled data. By scanning the wavelength in the filter spectrum range by computer control, we could obtain the filter response of the volume grating.

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Figure 3 shows that the experimental and theoretical filter characteristics are close to each other. The filtered power in the graphs means normalized
power of the volume-diffracted signal coupled to the SMF. Dispersion of approximately ~10 ps/nm exists in the chirped grating case [Figs. 3(a) and 3(b)]. For the uniform grating case the dispersion is rather small [Figs. 3(c) and 3(d)]. The small peak wavelength mismatch between the experimental and the theoretical data is due to the Bragg condition variation in alignment (~8 nm/deg). The ripples that exist in the overall experimental delay data are similar to those in a FBG.\textsuperscript{6} The amount of ripple, which is the standard deviation from the linear fittings [straight lines in Figs. 3(a) and 3(c)], was approximately 2.8 ps for both gratings. We note that this amount is quite small compared with that of the FBG, although it is comparable with the overall delay variation of the chirped grating. It is considered that the phase errors in masks, dust particles in the recording and filter process, and electrical and optical noise in the measurement are the sources of the ripples. By increasing the chirp rate, dispersion can be increased in proportion to d\(\lambda\)/dx with a spectrum width increase. However, when the chirp rate exceeds some specific value, dispersion decreases since the input beam spatial spectrum and the output SMF mode spatial spectrum cause a phase averaging effect. For large index modulation and grating volume, where strong diffraction occurs, different methods such as coupled-wave analysis and the transfer-matrix method are required to analyze the filter characteristics. In this case we can expect some strong dispersion near the band edges of the filter spectrum.\textsuperscript{13}

In conclusion, we could record and measure, for the first time to our knowledge, VHGs with a fine chirp structure by use of a predesigned phase mask for optical communication applications. We have modeled the filter characteristics using the 1st-order Born approximation and fiber coupling analysis. The filter response depends on the spatial spectra of the volume grating, input beam, and output-coupling fiber mode as convolution and correlation. This differs from the FBG case in which mode coupling occurs among a few modes of the fiber. The experimental results explain these filter properties quite well. Although the filtered power spectrum was not flat and the dispersions were small to be applied to real systems (e.g., chromatic dispersion compensators), practical filtered power and dispersion shaping could be obtained by optimization of the grating spectrum and input and output-coupling beam spatial spectra. This kind of filter system needs an optical amplifier to compensate for the weak diffraction efficiency and have some optical noise from the amplifier. However, considering that, for general holographic media, grating multiplexing is possible under weak diffraction, a novel high-channel-count optical device can be obtained. It can be differentiated from the arrayed waveguide gratings and FBGs in that manufacturing is relatively simple and no additional circulators are required for high channel counts. The chirped VHG filter could provide a new use of holograms for dispersion-control devices in optical communication.

The authors acknowledge the support from the Ministry of Science and Technology of Korea through the National Research Laboratory Program. B. Lee’s e-mail address is byoungho@snu.ac.kr.

References