信號處理·시스템 學會 論文集 8 卷 2 號 2007. 4 / 84

Cascaded Volume Holographic Gratings for expanding the Channel Number of a Optical Demultiplexer

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요 약

캐스케이드 홀로그래픽 부피격자를 이용한 130채널 광 역다중화기를 제안하고 실험적으로 입증하였다. 첫 번째 격자와는 서로 다른 격자주기, 경사각, 중심파장 등을 갖는 두 번째 홀로그래픽 격자를 첫 번째 격자에 직렬로 부가함으로써 역다중화기의 동작파장범위를 늘릴 수 있으며, 결국 홀로그래픽 역다중화기의 채널수는 두 배 증가하게 된다. 본 논문에서는 채널 균일도가 3.5dB, 3dB 대역폭이 0.12nm, 채널누화가 -20dB인 0.4nm 채널간격을 갖는 역다중화기를 실험적으로 구현하였다.

Abstract

In this paper, the demonstration of a 130-channel optical demultiplexer based on the cascaded volume holographic gratings is presented. By serially adding the second holographic grating, which has different grating period, slant angle, and center wavelength compared to those of the first grating, the operating wavelength range of the optical demultiplexer could be expanded, and therefore, the number of channels of the holographic demultiplexer is increased by twice. As a result of the experiment, a 0.4-nm-spaced demultiplexer with the channel uniformity of 3.5 dB, the 3dB-bandwidth of 0.12 nm, and the channel crosstalk of -20 dB is experimentally achieved.

Keywords: Volume holographic grating, photopolymer and wavelength-division demultiplexer.

I. Introduction

Dense-wavelength division multiplexing (DWDM) is an important technology for increasing the communication capacity in the fiber optic communication without installing extra fibers [1]. The key components in DWDM system are multiplexers and demultiplexers. The demultiplexer based on volume holographic grating(VHG) has been received much interest of researchers. For example, VHGs superimposed angularly in $LiNbO_3$ can work as multi-filters, whose center wavelengths are corresponding to channels [2-3], or a tunable optical filter can be implemented by rotating a reflection-type VHG recorded in a photosensitive glass [4]. Besides, a transmission-type VHG combined with a focusing lens is used as a completing demultiplexer due to the angularly dispersive property of VHG [5]. In this approach, the demultiplexer permits simultaneous operation on all channels and offers the advantages of a simple structure and low per-channel cost. However, for a large-scale DWDM system, an expansion of the working range of the demultiplexer with high performance is necessary. To achieve that goal, several methods to enhance dispersion power by a path-reversed substrate-guided-wave structure [6], to reduce the crosstalk by using the apodized grating [7], or to increase the number of channels by multiplexed gratings [8] are proposed. An efficient way to increase the channel count in the demultiplexer is by use of a group of VHGs connected serially so that each of them has different grating periods, center wavelengths, and slant angles. By choosing the wavelength selectivity of a grating continuous to that of the adjacent one, the working range of whole system can be expanded, and therefore, the number of channels is increased.

For several years up to now, photopolymers have reached a primary position in the variety of holographic recording materials [9]. They find applications in holographic display, optical data storage, optical interconnection, and holographic optical elements manufacturing[10-12]. The dry-development processing is an important advantage that permits accurate geometries to be saved. Easy handling, relatively low

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***Electronic Engineering at Sunchon National University**

논문 번호 : 2007-1-5　　접수 일자 : 2007. 1. 26
심사 완료 : 2007. 3. 31

※This work was supported by Research Foundation of EngineeringCollege(2003),SunchonNationalUniversity.

cost, long-time stability, and high-index modulation are some of its other practical interests [13-15].

In this paper, we present an optical demultiplexer with a double wavelength selectivity using two cascaded VHGs recorded in the photopolymer films. We choose the DuPont $100\mu m$-thickness photopolymer because it has very high-index modulation. Each grating is designed such that they have different center wavelengths as well as angles of grating vectors. Therefore, each grating works on different wavelength ranges and diffract the incident light to separated directions. As a result, the demultiplexer based on this scheme can handle twice the number of channels as the single grating.

II. Demultiplexer Design

A demultiplexer based on a VHG has a simple structure that includes a VHG and an output focusing lens. The VHG disperses the coming polychromatic light, and the lens has a function to turn the angular dispersed light beam into the spatial separation of focused points on its focal plane. Finally, channels carried by different wavelengths are coupled into a fiber array placed on the focal plane. Because the working range of the demultiplexer is limited by the wavelength selectivity, increasing the number of channels accommodated by the VHG requires another method. An obvious method is one that employs two or more VHGs connected serially to increase the working range. Figure 1 shows the structure of a demultiplexer, in which instead of a single VHG, two VHGs are cascaded together. The incident polychromatic light is spectrally divided into two groups, the one containing the first n channels is dispersed by the first grating and the other containing the remaining (m-n) channels is dispersed by the second grating. Two diffracted beams are finally focused by the same lens. In designing the cascaded-grating system, the parameters of the first grating are chosen freely, and those of the second grating will be obtained with concern about the crosstalk and the power loss caused by the addition of a grating.

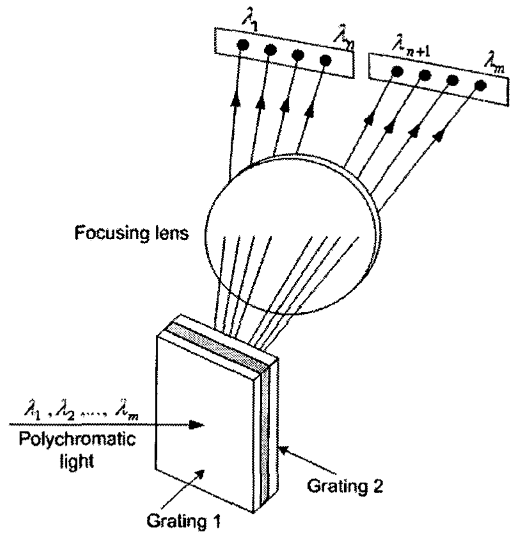
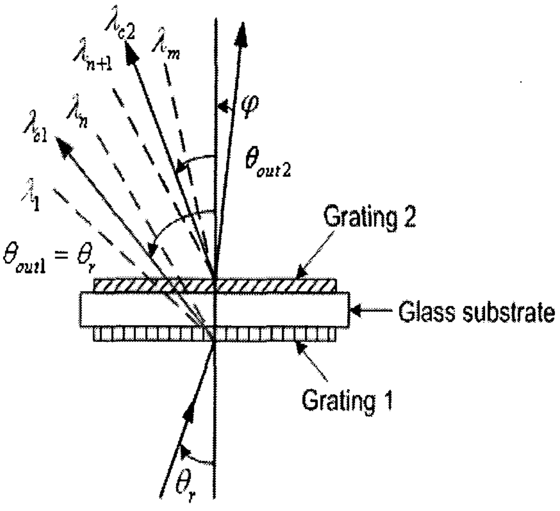
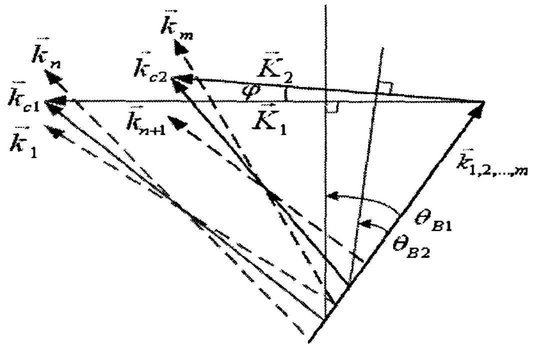


Fig. 1. Scheme of the demultiplexer based on VHGs

Figure 2(a) shows the configuration of the cascaded-grating system working as a demultiplexer. The multi-wavelength light beam $(\lambda_1, \lambda_2, \ldots, \lambda_n, \lambda_{n+1}, \ldots, \lambda_m)$ impinges on the system at the reading angle of θ_r. Here, all the angles are considered in the medium for simplicity. Inside the first grating, only the first n wavelengths, which totally or approximately satisfy the Bragg condition, are diffracted at high diffraction efficiency. The others go on transmitting through, reach the second grating. and are diffracted with the same manner. The directions of two diffracted beams are a little deflected as shown in Fig. 2(a). Here, the output angles are denoted by θ_{out1} and θ_{out2}.



(a)



(b)

Fig. 2. Configuration of two-cascaded VHGs. (a) The input-output beams gratings and (b) their grating-vector diagrams

The deliberate deflection is to avoid the overlap of two output beams. The grating-vector diagram for the Bragg condition is sketched in Fig. 2(b).

The wave vectors of the incident beam are denoted by $\vec{k_1}, \vec{k_2}, \ldots, \vec{k_m}$. The gratings have different grating vectors $\vec{K_1}$ and $\vec{K_2}$. The Bragg condition for retrieving highest diffraction efficiency is as follows [16]:

$$\lambda_{ci} = 2\Lambda_i \sin\theta_{Bi} \tag{1}$$

where, $i = 1, 2$ is denoted for the parameters of each grating, Λ is the grating period defined by $\Lambda = 2\pi/|\vec{K}|$, and θ_B is the Bragg angle. Beside the Bragg-matching center wavelength λ_c, its adjacent wavelengths are also diffracted at high efficiency. The 3-dB wavelength selectivity of a volume grating, which is given by [5]

$$\Delta\lambda_{sel} = \frac{\Lambda\lambda_c \cot\theta_B}{L}, \tag{2}$$

where L is the grating thickness. In our scheme, it is desirable to have a wide wavelength selectivity to increase the number of channels because the working range is limited by the wavelength selectivity of the diffraction grating. However, when the grating becomes thin, the diffraction efficiency will be reduced [5], i.e. the insertion loss of the demultiplexer will increase. Therefore, in our proposed scheme, by use of the second grating whose wavelength selectivity is successively connected to that of the first grating, the total wavelength range is increased without efficiency loss.

The second grating is designed such that it has the different center wavelength and is oriented obliquely compared to the first one. At the output, the channels are diffracted into two groups corresponding to each grating. It is noted that the first grating will diffract a small portion power of the channels that should be managed by the second grating. With the same manner, the channels from 1 to n can be diffracted by the second grating. This will induce the reduction of the crosstalk between channels of two groups. However, when the slant angle φ is large enough, the direction of two beams diffracted by two gratings are largely different, and the crosstalk between two gratings can be avoided completely.

In our work, the center wavelength λ_{c1} is chosen equal to 1530nm and the incident angle θ_r, which is also the Bragg angle of the first grating, is fixed at 29.7°. Therefore, the grating period calculated by Eq. (1) is 1.028μm. Using Eq. (2), the wavelength selectivity of this grating is evaluated to be 27.5nm. To ensure the consecutiveness of the wavelength selectivity of two gratings, the second center wavelength is fixed at 1.56μm. The second grating vector is rotated by an angleφ of 1.5° resulting in the second Bragg angle of, $\theta_{B2} = \theta_{B1} - \varphi = 28.2^{\circ}$, whereas the first Bragg angle $\theta_{B1} = \theta_r = 29.7^{\circ}$. Therefore, the grating period and the wavelength selectivity of the second grating are calculated to be 1.1μm, and 32nm, respectively. By the above design, the first diffraction beam is going out of the gratings at the angle similar to that of the input beam. However, since the second grating is slanted, the second diffraction beam has the angle of $\theta_{out2} = \theta_r - 2\varphi = 26.7^{o}$ with respect to the normal direction of the film surface. The difference in the output angles of two diffraction beams guarantees that the crosstalk between two gratings is avoided completely. The design parameters of two gratings are summarized in Table 1. The outside reading angles can be obtained from the insides ones by using Snell's law with the refractive index of 1.5 for photopolymer material.

Table 1. Design parameters of two gratings

Parameters	Grating 1	Grating 2
Grating period (μm)	1.028	1.1
Slant angle (degree)	0	1.5
Input beam angle (degree)	29.7	29.7
Output beam angle (degree)	29.7	26.7
Center wavelength (μm)	1.53	1.56
Wavelength selectivity (nm)	27.5	32

III. Experiments and Results

Based on the above design parameters, the gratings are recorded in DuPont photopolymer films with a thickness of $100\mu m$. The laser wavelength for recording is 532nm. The laser beam is filtered by a spatial filter, collimated by a lens, and passed centrally by an aperture to ensure that its intensity has the uniform distribution. The recording beams polarized normal to the plane of incidence are symmetrically interfering. The recording angles, which are the Bragg angles corresponding to wavelength of 532nm, are calculated by Eq. (1). The intensity of each beam is 3.0mW/cm^2. Firstly, a grating was recorded in a photopolymer film attached to one side of a glass plate. After the monomers are fully polymerized, the recording is completed. The second photopolymer film is attached to the other side of the plate and the last grating is recorded. The photo of the recorded cascaded grating is shown in Fig. 3.

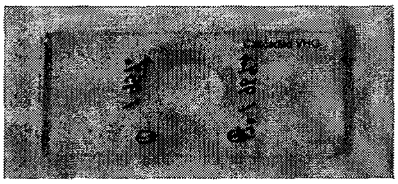


Fig. 3. Photograph of the cascaded VHGs

After the grating system is recorded, its wavelength selectivity is checked experimentally by the setup shown in Fig. 4. The gratings are illuminated by a laser beam emitted from a tunable infrared(IR) laser. The intensity of the two diffracted beams and a transmitted beam are measured by detectors. The diffraction efficiency of a grating is a ratio of the intensity of its diffracted beam to the total intensity of all output beams. The maximum diffraction efficiencies of two gratings are 76% and 71%, respectively, as shown in the Fig. 5. The measured wavelength selectivities of the gratings are 25nm and 29.5nm, respectively. It is clear that the experimental wavelength selectivities of both gratings are a little narrower than the theoretical result. This is understood that, in the case of cascaded gratings, the wavelengths at the spectral intersection are diffracted by both gratings. Therefore the diffraction efficiency in this region is reduced, and the wavelength selectivities are tapered

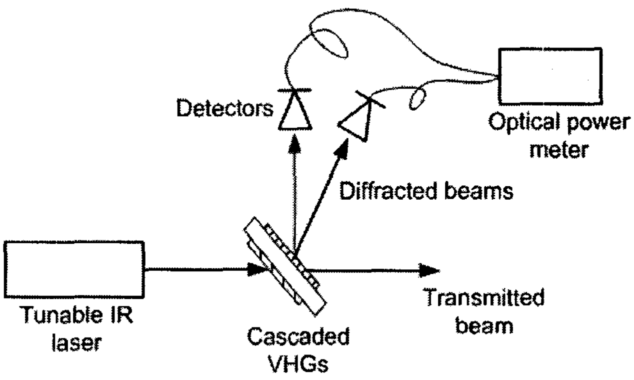


Fig. 4. Experimental setup for measuring the wavelength selectivity of the cascaded VHGs

Figure 6 shows the experimental setup for testing the spectral response of the grating system working as a demultiplexer.

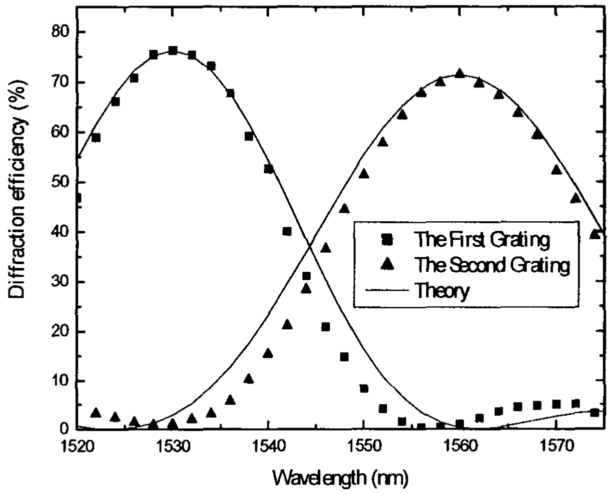


Fig. 5. Wavelength selectivity of the cascaded gratings

It consists of a collimating lens, VHGs, and an output focusing lens. The infrared beam from the broadband erbium-doped fiber amplifier (EDFA) source is expanded and collimated to have diameter of 10.5 mm before impinging on the grating systems. The spectral range of the EDFA source is from 1520 nm to 1572 nm. The output focusing lens has a focal length F of 200 mm. A single-mode fiber is placed on the back focal plane of the lens. This output fiber is held and moved along the horizontal direction by a motorized fiber alignment unit. At each position, the diffracted wave is coupled to the fiber, and its spectrum is examined by an optical spectrum analyzer(OSA).

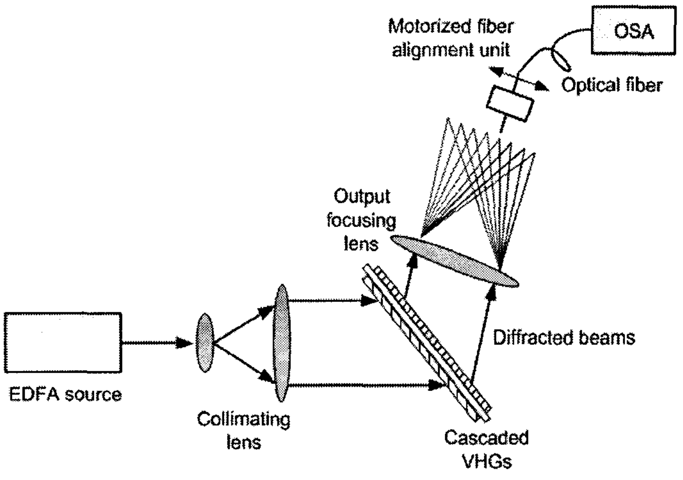


Fig. 6. Experimental setup for testing the spectral characteristics of the cascaded gratings

Figure 7 shows typical spectra of two channels with 0.4 nm channel spacing. The 3-dB bandwidth, the sidelobe, and the crosstalk are 0.12 nm, -15 dB, -20 dB, respectively. In our experiment, the spatial channel distance between two channels of the first channel group at the center wavelength of 1530 nm is 123μm, whereas that of the second channel group at the center wavelength of 1560 nm is 107μm. In practice, the fiber arrays are used to couple the channels at the output. Since two channel groups have separated directions and different spatial channel distances, so two fiber arrays with the corresponding core-to-core distance are suggested to be used for each channel group.

The spectral characteristics of all 130 channels ranging from 1520 nm to 1572 nm of the EDFA source are shown in Fig. 8.

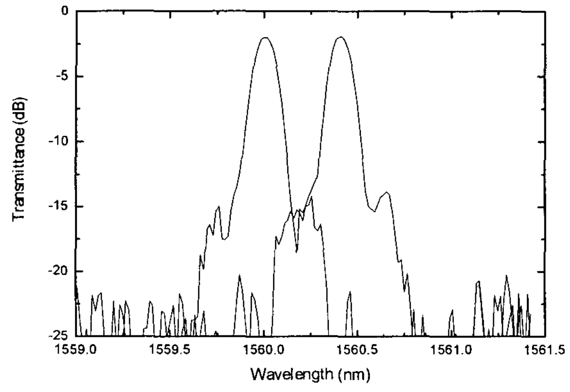


Fig. 7. Spectral response of two channels spaced at 0.4 nm

The transmittance of the demultiplexer at two center wavelengths of the gratings are about -2 dB, whereas that measured at the wavelength of 1543 nm is approximately -5.5 dB. As a result of the experiment, the uniformity of the overall system is 3.5 dB. It is necessary to design more carefully by choosing two closer center wavelengths to improve the uniformity.

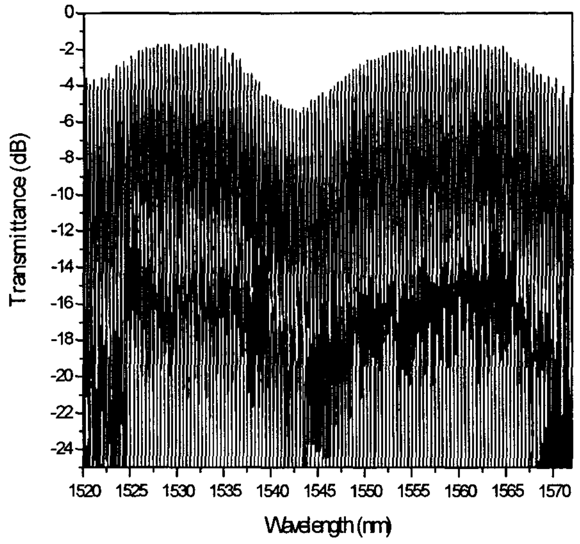


Fig. 8. Spectral characteristics of the demultiplexer based on the cascaded grating system

Ⅳ. Conclusion

In this paper, we have presented the design and the implementation of cascaded gratings working as a optical demultiplexer. The photopolymer with the thickness of 100μm is used to record the grating. The parameters of two gratings are designed such that when those gratings are connected serially, the crosstalk between channel groups is suppressed remarkably. With the cascaded volume holographic grating system, a demultiplexer with 130 channels was optically demonstrated. The channel spacing of 0.4 nm, the uniformity of 3.5 dB, and the crosstalk value of -20 dB were archived successfully. By inserting more gratings in series with a suitable design, it will be able to further expand working range of the demultiplexer based on free-space gratings.

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