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# Holographic Demultiplexer with Low Polarization Dependence Loss using Photopolymer Diffraction Gratings

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A holographic demultiplexer aimed at producing low polarization dependence loss using a long period volumetric diffraction grating inside photopolymer has been reported and experimentally demonstrated. To obtain the long period gratings, two kinds of gratings are recorded by angle of 4° and 6° corresponding to the polarization dependence property of below 0.5 dB. From the experimental results, we demonstrate the 0.8 nm-spaced 21 channel holographic demultiplexer with the polarization dependence loss of less than -0.38 dB, the channel uniformity of 0.495 dB, and the channel crosstalk of -13 dB.

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## I. INTRODUCTION

Dense-wavelength division multiplexing (DWDM) is an important technology for increasing the communication capacity in fiber-optic communication without installing extra fibers. Furthermore, the dramatic increase in the volume of worldwide data traffic has placed an increasing demand for communication networks providing large bandwidth. To satisfy this demand, fiber-optic communication systems using wavelength division multiplexing (WDM) have been developed. In WDM networks, the WDM multiplexer/demultiplexer (MUX/DEMUX) is a key component. There are several technologies to carry out wavelength separation for demultiplexing a composite signal. The representative technologies are thin film filters (TFF) [1], arrayed waveguide gratings (AWG) [1], fiber Bragg gratings (FBG) [1], free space diffraction gratings [2-7], and the integrated holographic Bragg reflector [8]. Among these, free space diffraction gratings show many advantages including simplicity, the low crosstalk and low cost. From the basic scheme, there have been many efforts to improve the DEMUX's performance such as cascading more gratings to expand the channel numbers [2], or using an apodized grating to reduce the crosstalk between the adjacent channels [3]. A chirped VHG and thermal properties in the DEMUX were reported by S. Han *et al.* [6,7]. However, it still suffers from the large polarization dependence loss (PDL), while the PDL is required to be smaller than -0.5 dB.

In this paper, we propose and experimentally demonstrate the holographic DEMUX with low PDL using a long period holographic grating inside the DuPont's photopolymer. A free space diffraction grating has been recorded under small angles such that the DEMUX has low PDL but still satisfies the volumetric grating conditions to eliminate the effect of multi-order diffractions. Experimental demonstrations achieve the low PDL below -0.5 dB successfully.

## II. BACKGROUND AND EXPERIMENT

If a plane wave of wavelength $\lambda_r$ is incident on a volume transmission grating, the reconstruction angle $\theta_r$ satisfies the constructive interference Bragg's conditions given by

$$\theta_r = \sin^{-1}(\lambda_r / \lambda_w \times \sin\theta_s)\,. \tag{1}$$

Where the $\lambda_w$ is the recording wavelength and $\theta_s$ is the incident angle of the signal beam. For a given grating and a fixed incident angle, the angular separations due to the input wavelengths are derived simply from the above condition, which is given by [3]

$$\Delta\theta = \frac{\Delta\lambda}{\Lambda\cos\theta_r} . \tag{2}$$

These properties of the diffraction grating can be applied to wavelength DEMUX when we place a lens normal to the output beam. From this angular dispersion, the spatial distance between the channels is expressed by

$$\Delta d = F\Delta\lambda / \Lambda\cos\theta_r , \tag{3}$$

where the $F$ is the focal length of the lens and the $\Lambda$ is the grating spacing. In this scheme, the diffraction grating has different efficiency according to the incident polarization states and the index modulation amplitude, so that it will induce the PDL in an application of DEMUX. The diffraction efficiency according to the input polarization states could be expressed by the Kogelnik's coupled wave theory [9,10] as follows,

$$\eta_P = \sin^2\left(\frac{\pi\Delta n d}{\lambda_R(\cos\theta_{ri}\cos\theta_{si})^{1/2}}\right) , \tag{4}$$

$$\eta_S = \sin^2\left(\frac{\pi\Delta n d}{\lambda_R(\cos\theta_{ri}\cos\theta_{si})^{1/2}}\right)\cos(\theta_{si}-\theta_{ri}) . \tag{5}$$

In the equations, $\Delta n$ is the refractive index modulation amplitude, $\theta_{ri}$ and $\theta_{si}$ are the reconstruction and signal beam angles inside the material, the d is the thickness of the material, the $\eta_p$ is the diffraction efficiency for the p-polarization and the $\eta_s$ is the efficiency for the s-polarization. From Eq. (4) and Eq. (5), $\theta_{ri}$ must have the values less than 13.5° to achieve PDL less than -0.5 dB. Therefore the maximum recording angle is 4.59° if the recording and readout center-wavelengths are 532 nm and 1550 nm, respectively. Using above polarization dependence properties, we can expect the PDL of the holographic DEMUX using a free space diffraction grating as shown in Fig. 1. From the Fig. 1, it can be seen that we have to use a diffraction grating with over the period of 2.214 μm.

In the recording with a small recording angle, a grating could be a thin-type diffraction grating. In this case, it induces the multi-diffraction order so that it suffers from the large insertion loss and interference between the different orders. For eliminating the effect of multi-order diffraction, we consider the conditions of a volumetric phase grating by Q factor. That is defined by $Q = 2\pi\lambda_R d / n\Lambda^2$, where the $\lambda_R$ is the reconstruction wavelength, and the $n$ is the refractive index of the material. From the above relations, the minimum recording angle outside the material for satisfying volume grating constructions is 1.054 degree if a material thickness is 100 μm. As results, the range of recording angles which satisfy both conditions (volumetric grating and low PDL) is from 1.054° to 6.9° (outside the material).

In order to demonstrate the low PDL holographic DEMUX, two gratings are recorded on the DuPont photopolymer (HRF 150-100) by 532 nm Nd-Yag laser. Gratings are recorded by 4° (Λ=3.813 um) and 6° (Λ =2.544 um) in the air space. Using a shear plate we can make the recording beam into a nearly perfect plane wave. Figure 2 (a) and (b) show the experimental schemes for testing the PDL and the spectral response of the holographic DEMUX, respectively. For measuring the PDL, a tunable light source, a collimating lens, a half waveplate, a photo detector and a powermeter are used as shown in Fig. 2 (a). In here, the PDL is defined as the difference of the diffraction efficiency between different polarization states. Meanwhile, we use the broadband EDFA source, a collimating lens, an iris diaphragm, an output focusing lens with 200 mm focal length, and an optical spectrum analyzer while we measure the spectral response of our DEMUX as shown in Fig. 2 (b). The light from a broadband EDFA source is collimated and spatially filtered to have a diameter of 12 mm. In order to transform the angular dispersion into the spatial separation, the output focusing lens is placed behind the grating. A

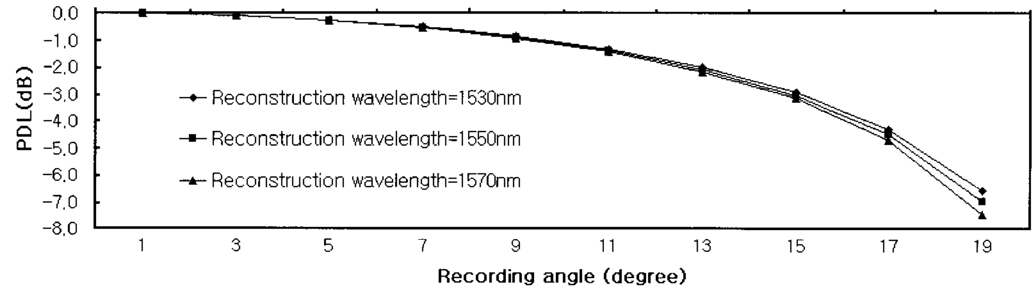
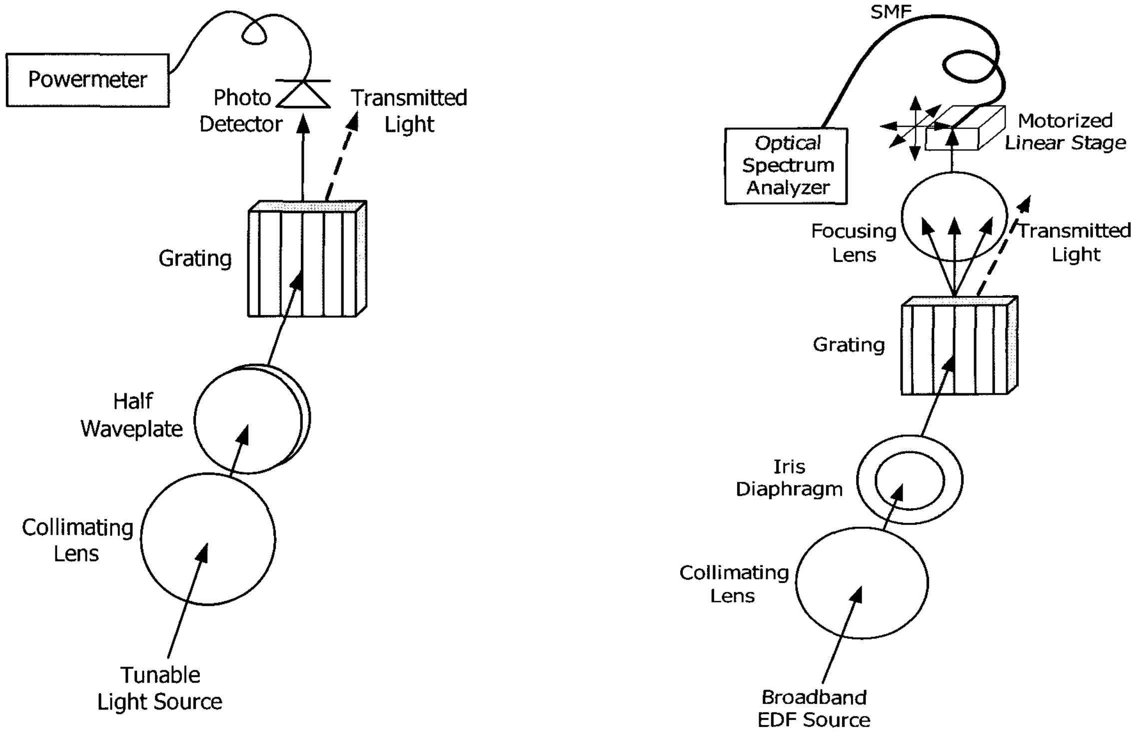


FIG. 1. Calculated PDL according to the recording angles and reconstruction wavelength.



(a) (b)

FIG. 2. Experimental scheme to demonstrate the low PDL DEMUX, (a) optical scheme to measure the PDL, (b) to measure the spectral response.

SMF (single mode fiber) is placed on the back focal plane of the focusing lens and moved along the x-y-z directions by using motorized linear stages from Newport corp. (model MFN25PP). Finally, we can measure the spectral response by the optical spectrum analyzer and the PDL from the optical powermeter.

Figure 3 shows the calculated and measured PDL according to the grating spacing and the center wavelength of holographic DEMUX. The PDL has maximum value of -0.243 dB and -0.369 dB, respectively, for each grating. Also, it shows that the PDL is increased according to the large center wavelength and small grating period as expected in the Fig. 1. These low PDL values mean that the passband difference due to the incident polarization states could be ignored.

Figure 4 shows the spectral response of 0.8 nm channel spacing 21 channels DEMUX. Using the 3.813 μm period grating, we obtain the uniformity of 0.29 dB, the 3- dB passband of 0.55 nm and the crosstalk of -12.5 dB, meanwhile the 2.544 μm period grating has 0.495 dB uniformity, 0.36 nm passband and -14.5 dB crosstalk. Using 3.813 μm period grating, the channel uniformity is better because it has larger wavelength selectivity which is determined by the grating spacing.

We measured the spectral response by a single mode fiber for experimental convenience. In practice, when the fiber array is used, the uniformity and the crosstalk might be higher than those in our results due to the distortion and the non-linear dependence of the spatial separation of the output channels. Furthermore, the crosstalk level could be improved by using the apodization technique, which we already reported previously [3] in which we had reduced the crosstalk level of down to -30 dB. The insertion loss of 2.95 dB is measured by tunable light source and powermeter. The major determining parameters are refractive index modulation amplitude of the diffraction grating and coupling loss on the optical fiber. Using an optimized refractive index modulation and distortion free focusing lens, we can dramatically improve the insertion loss. The spatial distance between two adjacent channels in the focal plane of the lens depends on the grating period and the focal length of the lens, so it has smaller spatial sepa-

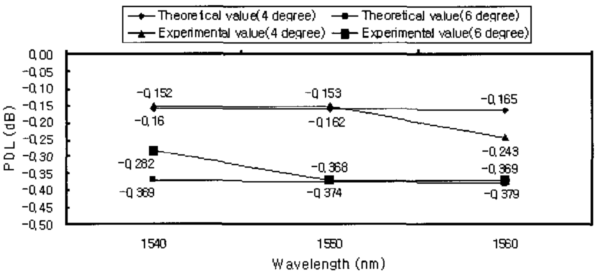
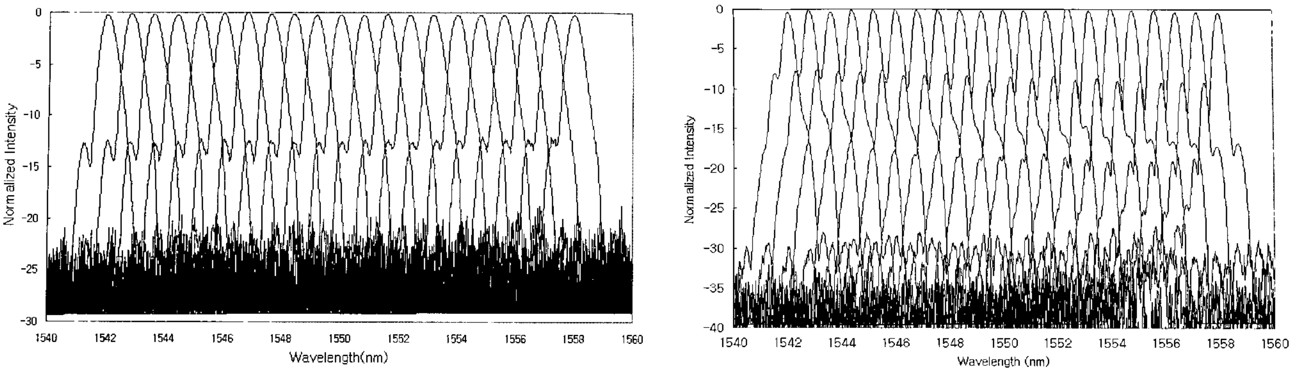


FIG. 3. Comparison of the calculated and measured PDL.



(a) (b)

FIG. 4. Spectral response of the holographic DEMUX with low PDL (a) by 3.813 um grating spacing (b) by 2.544 um grating spacing.

rations compared with previous reported results [3,5] because it has larger grating spacing to obtain the smaller PDL. The spatial channel distances to obtain the 0.8 nm channel spacing are 21.42 μm and 60.029 μm for two different gratings. Using long period grating, the properties of crosstalk, passband, spatial separation between the channels are relatively worse than small period grating. However, it could dramatically enhance the PDL, the channel uniformity and insertion loss as shown in the theoretical and experimental results. Furthermore, our demonstrations should more effective when we use a large diameter of incident beam because the crosstalk level and passband could be enhanced.

## III. CONCLUSIONS

A low PDL DEMUX by using a long period grating has been analyzed and experimentally demonstrated. From the experiment, the holographic DEMUX with PDL of less than -0.38 dB and channel uniformity of 0.495 dB has been successfully demonstrated. Our results show the grating spacing is the most dominant factor when we apply free space holographic grating to WDM DEMUX. However, there are problems including large insertion loss and crosstalk level so that the optimal conditions for satisfying the commercial components have to be determined by trade-off between DEMUX properties.

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