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Optical demultiplexer using a holographic concave grating for POF–WDM systems

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Polymer optical fiber (POF) is one of the best transmission media for short-distance communications. To increase the transmission capacity of the fiber a wavelength-division-multiplexing (WDM) technique is commonly used. Several POF-WDM systems have been realized using interference filters and plane diffraction gratings as wavelength selective elements. In the present paper, for the first time a concave diffraction grating is applied with POF. A holographic concave grating is calculated and optimized for the use in an optical demultiplexer. The optical losses in the designed demultiplexer are estimated theoretically.

Keywords: polymer optical fiber (POF), holographic concave grating, optical demultiplexer.

1. Introduction

Silica single-mode optical fiber is widely used in long-distance communication systems for high-speed data transmission (Gbit/s) because of its high bandwidth and low attenuation coefficient. The use of this fiber for short-distance interconnections is not preferred. This is because of the small core diameter of a single-mode fiber and, consequently, high requirements as regards adjustment. Therefore, in local systems it is favorable to use a multi-mode fiber, which has greater diameter. Nowadays, the polymer optical fiber (POF) is the most promising solution as transmission medium for short-range communications. Its large core diameter (250–1000 μm) gives a possibility to use inexpensive polymer connectors and its flexibility enables bending radii, which are by far more critical for glass fibers [1]. All this makes this fiber extremely suitable for in-home and LAN applications. The best developed at the moment is step-index POF (SI-POF). Because of large diameter and high numerical aperture this fiber has low bandwidth. One approach for increasing the transmission capacity of SI-POF is to use wavelength-division-multiplexing (WDM) techniques.

To date several POF-WDM systems have been developed [2–5]. The devices for combining and separating different wavelengths (multi/demultiplexers) are based on interference filters and plane diffraction gratings. Unfortunately, all these require additional collimating and focusing optics that need alignment and lead to complicated designs. The most appropriate solution in this case can be a concave diffraction grating. A concave grating combines diffraction and focusing properties simultaneously in one element and, therefore, it does not need additional optics. Since such devices have not yet been developed especially for use with POF, in this paper we report on designing a concave grating demultiplexer for POF-WDM systems. At first the diffraction grating will be calculated and optimized for demultiplexing. Finally, a theoretical estimation of optical losses in the demultiplexer will be performed.

2. Design of holographic concave grating for demultiplexer

To build a concave grating demultiplexer, it is necessary to calculate a concave diffraction grating satisfying the specific requirements imposed on the demultiplexer. The main parameters of the demultiplexer are the wavelength band, number of channels, operating wavelengths and insertion losses. Since we intend to work with low NA SI-POF, the operating wavelength band will be from 400 to 700 nm. This fiber has three attenuation minima at 520, 570 and 650 nm, which are normally used for transmission of three different signals. The main problem that arises is the separation of these wavelengths. For this purpose the diffraction grating with a corresponding linear dispersion has to be used. Taking into account a fiber diameter $d_0 = 1$ mm and minimal separation between adjacent channels $\Delta\lambda = 50$ nm, the linear dispersion $\mathrm{d}x/\mathrm{d}\lambda$ has to be

$$\frac{\mathrm{d}x}{\mathrm{d}\lambda} = f\,\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \geq \frac{d_0}{\Delta\lambda} = 20000 \tag{1}$$

where f is the effective focal length and $\mathrm{d}\theta/\mathrm{d}\lambda$ is the angular dispersion. An optical layout of the concave grating demultiplexer with classical grating is shown in Fig. 1. As can be seen from this figure, the parameter f is equal to $R\cos\beta$ and, therefore, Eq. (1) can be written as

$$\frac{\mathrm{d}x}{\mathrm{d}\lambda} = f\,\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} = R\cos\beta\,\frac{m}{\Lambda\cos\beta} = \frac{Rm}{\Lambda} \geq 20000 \tag{2}$$

where R is the radius of concave surface of the grating, β is the diffraction angle, m is the diffraction order and Λ is the groove spacing. Looking forward, the last value has to be taken bigger to get a good isolation between channels. Taking it into account, the last relationship will be written for the first diffraction order as:

$$\frac{R}{\Lambda} \geq 40000. \tag{3}$$

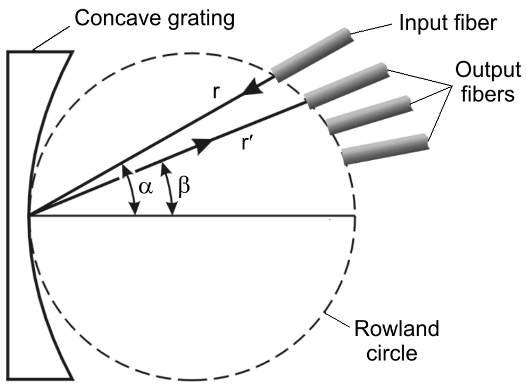

Fig. 1. Optical layout of demultiplexer using a classical concave grating.

Thus, if we know the radius of concave surface of the grating it is possible to find the groove spacing at the grating center. These values have to be selected from practical point of view making the grating applicable for demultiplexer use. Using our approach we have selected optimal values for an incidence angle α, radius of concave surface R and groove frequency $1/\Lambda$. They are 26 degrees, 35 mm and 1200 grooves/mm, respectively.

The size of the grating depends on the location and numerical aperture of input fiber. For our demultiplexer the grating diameter should be approximately 20 mm.

In Figure 1, a general schematic of demultiplexer is shown. Usually, the classical gratings are not used in a demultiplexer because of their large astigmatism. Therefore, a holographic concave grating is normally selected for this demultiplexer. To improve the transmission performances of demultiplexer the grating aberrations have to be minimized and the grating efficiency has to be optimized.

2.1. Minimization of aberrations of holographic concave grating

The focusing properties of concave diffraction gratings are usually studied using an aberration function, which describes a difference between the optical paths of the central (AOB) and non-central (APB) optical rays and defines grating aberrations [6] (see Fig. 2). By expanding this path-difference into a power series of *w* and *l* up to the fourth order the aberration function is simply expressed by

$$\delta F = \sum_{ij} F_{ij} w^i l^j = F_{10} w + F_{20} w^2 + F_{02} l^2 + F_{30} w^3 + F_{12} w l^2 + F_{40} w^4 + F_{22} w^2 l^2 + F_{04} l^4 \quad (4)$$

where F_{ij} are the aberration coefficients. The last ones can be separated into two parts as follows:

$$F_{ij} = M_{ij} + \frac{m\lambda}{\lambda_0} H_{ij} \quad (5)$$

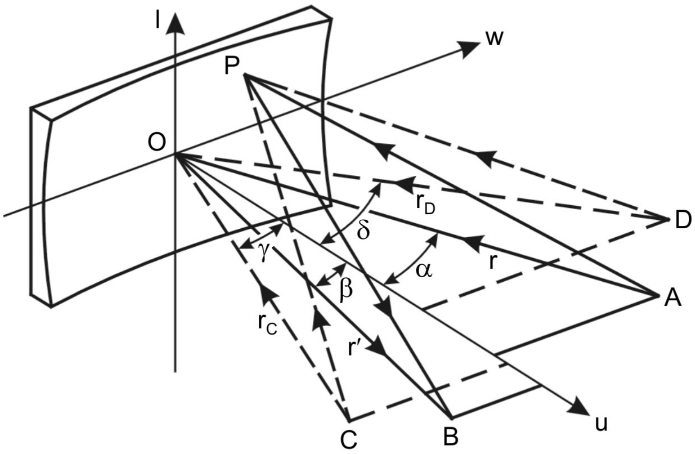

Fig. 2. Schematic diagram of the optical system with holographic concave grating.

where M_{ij} terms depend on the mounting scheme (r, r', α, β), H_{ij} terms depend on the grating recording scheme (r_C, r_D, γ, δ), λ is the wavelength of incident light and λ_0 is the grating recording wavelength. The explicit expressions for M_{ij} and H_{ij}, and also more comprehensive information on aberration function can be found in [7, 8].

The aberration function is useful for us because it gives the possibility to get the size of an image formed by the concave grating. The width W_S and height H_S of the image in spectral focus of the concave grating can be evaluated using expressions obtained in [9]:

$$W_S = r'(\Phi/2)^2\left(3|F_{30}| + |F_{12}|\right), \tag{6}$$

$$H_S = r'\left(2\Phi|F_{02}| + \Phi^2|F_{12}|\right) \tag{7}$$

T a b l e. Calculated parameters of holographic concave grating with minimized aberrations.

Parameter	Value	Unit
R	35	mm
r	34	mm
α	26	deg
r_C	34.691	mm
r_D	32.689	mm
γ	–11.583	deg
δ	33.957	deg
λ_0	632.8	nm

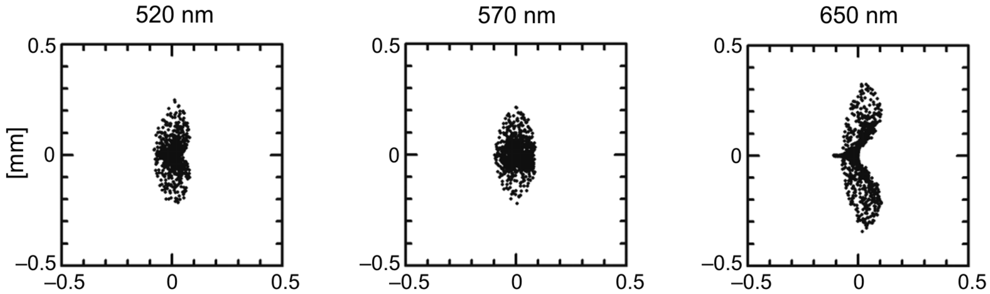

Fig. 3. Focal spot images from an on-axis point source for the three operating wavelengths in spectral focus of the designed holographic concave grating.

where Φ is the grating diameter. From Eqs. (6) and (7) it can be seen that the image size depends on aberrations of the concave grating. Thus, to reduce the image size and, consequently, insertion losses in the demultiplexer, it is necessary to minimize the aberrations. Minimization of aberrations for holographic concave grating is carried out selecting the optimal location of recording sources *C* and *D* (see Fig. 2). For this purpose, we have created a computer program in Delphi with variable parameters r_C, r_D, γ and δ. The obtained parameters of holographic concave grating are presented in the Table. Spot diagrams from a point light source for operating wavelengths have also been obtained using expressions derived in [10] and are shown in Fig. 3.

2.2. Optimization of grating efficiency

Since the concave grating demultiplexer consists of one single concave grating, its performance characteristics strongly depend on the grating efficiency. Usually, after minimization of aberrations of the concave grating the optimization of grating efficiency is carried out to further reduce the insertion losses in the demultiplexer. The maximum efficiency can be obtained with gratings which have triangular groove profile, when the tilting angle of one of the groove facets is such that the directions of light reflected from this facet and light diffracted from the grating for the same incidence angle coincide [11]. Holographic gratings normally have a sinusoidal groove shape and, consequently, lower diffraction efficiency. However, if it is necessary to get a higher efficiency the sinusoidal groove shape can be modified into other groove shapes (quasi-triangular, *etc.*) using different techniques. Unfortunately, this makes the grating cost grow and, therefore, is not suitable for our case.

The relative intensity of monochromatic light of wavelength λ diffracted into *m*-th order for sinusoidal reflection grating is expressed by:

$$I_m = J_m^2\left(\frac{\pi\Delta}{\lambda}(\cos\alpha + \cos\beta)\right) \tag{8}$$

where J_m is the m-th order Bessel function, Δ is the groove depth, α and β are the angles of incidence and diffraction, respectively [12]. A portion of the light power diffracted into m-th order can be calculated using the following expression:

$$\eta_m = I_m \times \left[\sum_{k = m_-}^{m_+} I_k \right]^{-1} \tag{9}$$

where m_- and m_+ are the lowest and highest diffraction orders, respectively. As can be seen from Eqs. (8) and (9) the efficiency of a sinusoidal grating depends on the groove depth modulation. Thus, for optimization of diffraction efficiency of a sinusoidal grating it is necessary to optimize the groove depth. For this purpose, another program in Delphi has been composed. It was taken into account that recording beams have a Gaussian light distribution. As a result the groove depth has similar distribution over the grating surface. The incoming light was also considered as Gaussian light beam. The analysis carried out for the efficiencies obtained for different values of Δ has shown that the maximum efficiency is obtained when the groove depth is 202 nm in the grating center.

3. Theoretical evaluation of optical losses in demultiplexer

Optical losses are very critical in communication systems with POFs, which have a relatively high attenuation coefficient. To evaluate the performances of the concave grating demultiplexer designed for use in such systems we applied a ray-tracing method for calculation of insertion losses for each wavelength channel. For this purpose the following approach has been adopted. The incident light beam was separated into N rays with intensities I_P falling on the grating surface. The full intensity of incoming light is the sum of intensities I_P of all N rays. The intensity of each

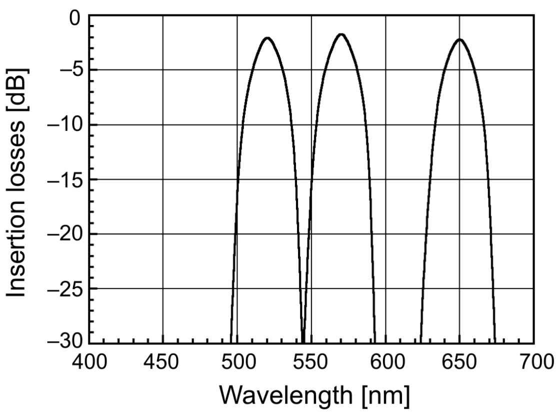

Fig. 4. Spectral transmission of the demultiplexer based on holographic concave grating.

reflected ray is assumed to equal $\eta_P I_P$, where η_P is the diffraction efficiency for each incident ray with intensity I_P. Thus, if M is the number of rays coupled into an output fiber, the optical losses B in demultiplexer can be expressed by

$$B = 10\log\frac{\sum_N I_P}{\sum_M \eta_P I_P}. \tag{10}$$

Since POF has a large core diameter the fiber end face was considered as a number of point light sources. Using the approach described above the optical losses for all channels were obtained. Graphical results are presented in Fig. 4.

As can be seen from Fig. 4, the insertion losses for all the wavelength channels of the designed demultiplexer with holographic concave grating are approximately 2 dB and the channel isolation (crosstalk suppression) is more than 20 dB.

4. Conclusions

In this work, we present a design of the concave grating demultiplexer for use in POF-WDM systems. For this purpose a holographic concave grating was calculated and optimized to have minimal aberrations and maximum diffraction efficiency for multiplexed wavelengths. It has been shown that aberrations of holographic concave grating are usually minimized by optimal allocation of recording sources and diffraction efficiency for sinusoidal grating is optimized by the choice of optimal groove depth. Values of optical losses obtained theoretically for wavelength channels are quite low which allows this demultiplexer to be used in data transmission systems with POFs. The channel isolation is good enough to avoid crosstalk and furthermore to increase the number of channels that can be demultiplexed. The only problem, which can exist, is the demultiplexer cost that is normally defined by the cost of the grating. In any case, a considerable advantage of the concave grating demultiplexer is that no additional optics is needed.

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