A wavelength division multiplexer based on plastic surface-relief grating applied to local area communication network*

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A plastic surface-relief grating as a wavelength division multiplexer is designed and fabricated with the conventional mould pressing technique using the transmission-type fused quartz phase grating as mask pattern and polycarbonate as basal material. The experiment results show that in an optimizing process, the plastic surface-relief grating has the highest first-order diffraction efficiency under adequate groove depth and incident angle, and can be used as the best optical path for wavelength division multiplexing (WDM). We also establish the experiment setup for testing the WDM performance of the plastic surface-relief grating based wavelength division multiplexer. The results show that the proposed wavelength division multiplexer has the high-stability temperature characteristics, the low insertion loss of less than 5 dB, the large isolation of greater than 20 dB, the low polarization-dependent loss (PDL) of less than 0.4 dB and the relatively steep pass-band characteristics. It is a WDM device with good performance, which can be applied in short distance communication.
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With the rapid development of network connection technology, plastic optical fiber (POF) has become an ideal transmission medium to replace copper cables and unshielded twisted-pair cable to realize fiber to the home because of its attractive properties, such as large core diameter, large numerical aperture (NA), cheap price, easy to connect, good flexibility and anti-radiation[1-3]. In recent years, POF networks have been the focus of investigations. But the application of POF networks is confined to a single wavelength with transmission rate lower than 100 Mbit/s, which greatly limits the bandwidth of POF network communications[4-6]. Therefore, wavelength division multiplexing (WDM) is introduced to POF network in order to break through the bandwidth limitation[7]. According to the principle of WDM, wavelength division multiplexer/demultiplexer (MUX/DEMUX) is the key component in the POF WDM systems[8,9]. Many methods for making wavelength division MUX/DEMUX are proposed, such as plastic optical coupler[10], dispersion prism[11] and holographic diffraction grating[12,13]. However, all these methods have higher cost and complexer process. Hence, it is of great significance to find a method to easily make the wavelength division MUX/DEMUX element with low cost. In this paper, we introduce mould pressing technique to make plastic surface-relief grating wavelength division MUX/DEMUX element, and test its WDM performance. The results show that the plastic surface-relief grating can meet the practical application requirements, and greatly reduce the cost.

The main production process of plastic surface-relief grating includes preparing materials, heating, moulding process and separation, which is shown in Fig.1.

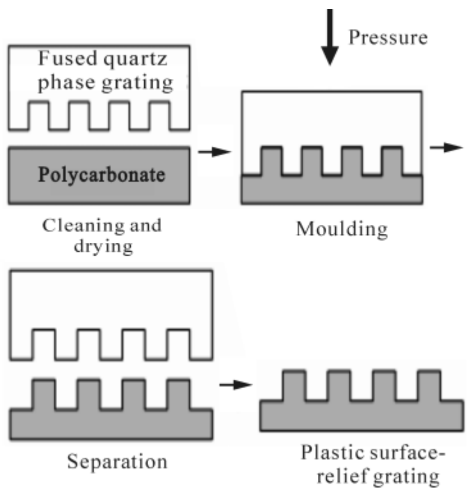

Fig.1 Processing flow of plastic surface-relief grating

On the basis of the above experimental principle, we rep-

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licate the plastic surface-relief grating on the polycarbonate in the different mould temperatures and pressures, and test the diffraction intensity. The parameters of the polycarbonate are the refractive index of 1.58 and the aspect ratio of 0.5. The testing results indicate that when the mould temperature is 144 °C, the concave-convex surface of plastic surface-relief grating has the flat line, no "bubble", "depression" or "bump", and its first-order diffraction has the highest diffraction efficiency under the same pressure. The diffraction efficiencies of plastic surface-relief grating's first order diffraction in different mould temperatures are shown in Fig.2.

In order to better illustrate the diffraction effect of the plastic surface-relief grating at temperature of 144 °C, we emphatically test the diffraction intensity of plastic surface-relief grating with groove depth of 301 nm, and calculate its ratio of the first-order diffraction intensity to the zero-order diffraction intensity, which is 0.559. According to the Huygens-Fresnel principle, by solving its diffraction integral equation, the theoretical relative diffraction intensity of transmission-type relief grating is expressed as

$$\begin{cases} I_0 = \cos^2(\frac{\varphi}{2}) \\ I_m = 4\sin^2(\frac{\varphi}{2})\frac{\sin^2(m\rho\pi)}{(m\pi)^2}, (m \neq 0, \varphi = 2\pi\frac{(n-1)h}{\lambda}) \end{cases} . \quad (1)$$

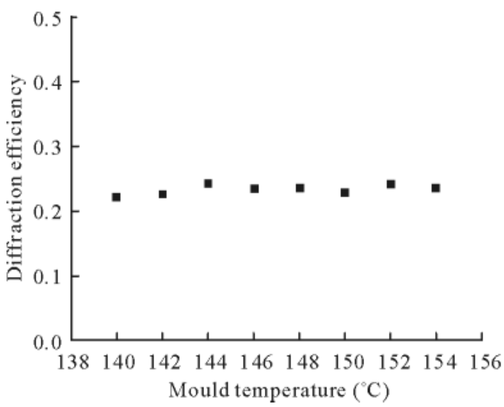

Fig.2 Diffraction efficiencies of plastic surface-relief grating's first-order diffraction in different mould temperatures

Therefore, by substituting the parameters of the plastic surface-relief grating as refractive index n=1.58, aspect ratio ρ=0.5 and groove depth h=301 nm into Eq.(1), the theoretical ratio of the first-order diffraction intensity to the zero-order diffraction intensity is 0.562, which is consistent with the actual value.

Besides, according to Huygens-Fresnel principle, and introducing the transmittance function on Fourier series and complex amplitude of Fourier transform method, the diffraction efficiency of surface-relief grating[14] is obtained as

$$\begin{cases} \eta_0 = 1 - 2\rho(1-\rho)(1-\cos\Delta\phi) \\ \eta_{m>0} = \frac{1}{m^2\pi^2}(1-\cos 2m\pi\rho)(1-\cos\Delta\phi), \end{cases}$$
$$(m = \pm 1, \pm 2, \pm 3, \cdots, \Delta\phi = \frac{2\pi}{\lambda}h\left(\frac{n}{\cos\varepsilon} - \frac{1}{\cos\theta}\right)) \quad . \quad (2)$$

Meanwhile, according to the Rayleigh criterion and vector diffraction theory, we can deduce the distinguishability of relief grating as[7,8]

$$R = \frac{\lambda}{d\lambda} = \frac{Nk\left(\sin\theta\sin\phi + k\frac{\lambda}{d}\right)}{n\sqrt{\sin^2\theta\sin^2\phi + \left(\sin\theta\cos\phi + k\frac{\lambda}{d}\right)^2}} \quad . \quad (3)$$

To perform the numerical simulations, the parameters are chosen as n =1.58, ρ =0.5, λ=650 nm, d=1 μm and m =1. The dependence of diffraction efficiency on incident angle in different groove depths is shown in Fig.3, which shows that the first-order diffraction efficiency of plastic surface-relief grating can attain the highest theoretical value in the adequate groove depth, and the highest first-order diffraction efficiency can be obtained by adjusting the incident angle. For the groove depth of 300 nm, 400 nm, 500 nm, 600 nm, 700 nm and 800 nm, the highest diffraction efficiency of the first-order diffraction can be obtained when the beam incident angle is 0°, 0°, 0°, 25°, 38° and 42°, respectively. Fig.4 presents the dependence of distinguishability on incident angle with different azimuth angles (ϕ), which shows that the distinguishability decreases with the increase of the azimuth angle. Therefore, when its azimuth angle is 0°, the plastic surface-relief grating's first-order diffraction can be used as wavelength division multiplexer/demultiplexer element in the POF WDM network, which has the adequate groove depth and proper incident angle.

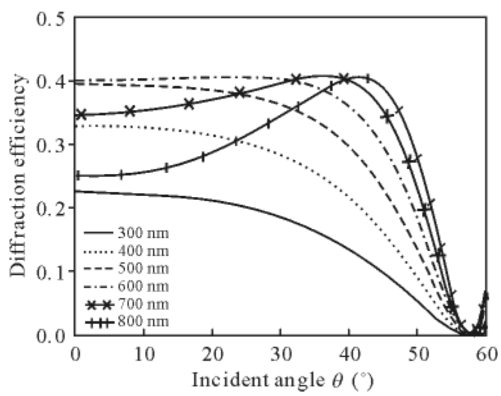

Fig.3 Relationship between diffraction efficiency and incident angle

According to the basic requirements of WDM performance, we emphatically test the main performance parameters of plastic surface-relief grating, including temperature characteristics, insertion loss, isolation, polarization-dependent loss and pass-band characteristics. The measurement system is shown in Fig.5.

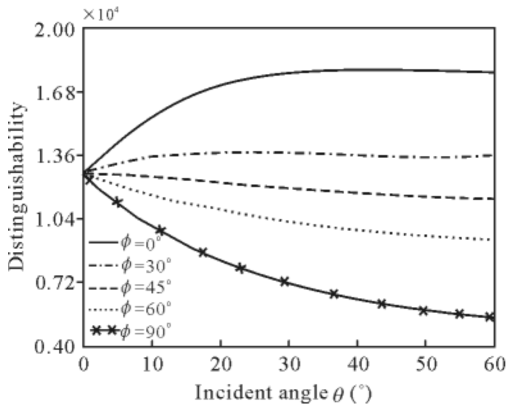

Fig.4 Relationship between distinguishability and incident angle

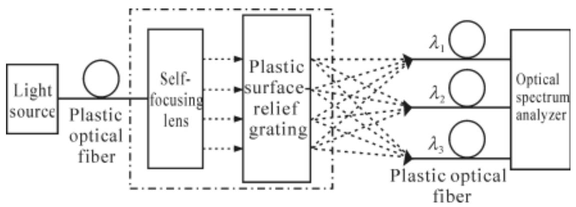

Fig.5 Measurement system for testing the WDM performance of the plastic surface-relief grating

Based on the scalar diffraction theory, we can deduce that the surface-relief grating can realize its demultiplexing function and focusing function simultaneously. So we can make the surface-relief grating equivalent to wedge and lens when the incident waves focus on the focal plane with the angle of optical axis of θ, and the angular dispersion variation with temperature can be obtained after the theoretical derivation as

$$d\theta=-\alpha\theta dT . \quad (4)$$

Fig.6 illustrates the dependence of diffraction angle on temperature in different incident wavelengths with parameters of thermal expansion coefficient $\alpha = 6 \times 10^{-5}$ and grating constant $d = 1$ μm. The variation value of the first-order diffraction angle increases with the increase of incident wavelength. With the temperature rises from -80 ºC to 80 ºC and incident wavelength of 650 nm, the first-order diffraction angle of plastic surface-relief grating can decrease by 0.0672 rad. Clearly, the plastic surface-relief grating has the more stable temperature characteristics when the temperature varies.

According to the definition of insertion loss[15], the input

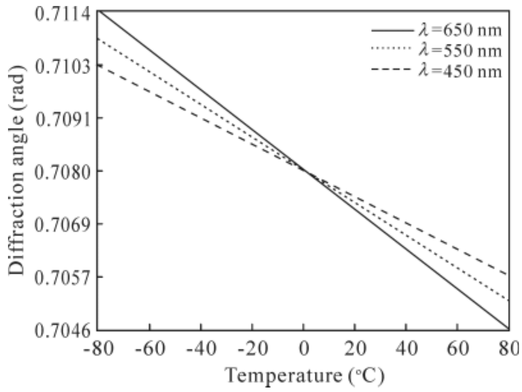

Fig.6 Relationship between the first-order diffraction angle and temperature in different incident wavelengths

and output intensities before and after the plastic surface-relief grating are measured with grating constant of d=1 μm and groove depth of h =350 nm when the center wavelength of incident wave is 467.52 nm, 523.10 nm and 579.69 nm. The results are shown in Fig.7. Substituting input and output intensities into the formula of insertion loss $IL=-10\log\frac{P_{output}}{P_{input}}$, we obtain the insertion losses are 4.7733 dB, 3.977 dB and 2.875 dB, when the wavelengths of incident wave are 467.52 nm, 523.10 nm and 579.69 nm, respectively.

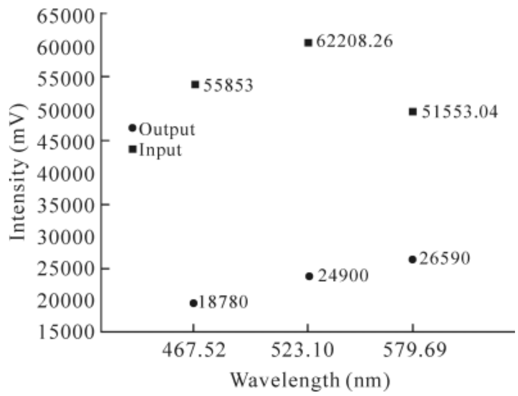

Fig.7 Input and output intensities before and after the plastic surface-relief grating in different incident wavelengths

According to the definition of isolation[16,17], we measure the first-order diffraction spectrum of plastic surface-relief grating with grating constant of d = 1 μm, groove depth of h = 350 nm, and center wavelengths of incident wave of 466.90 nm, 518.25 nm and 596.90 nm, respectively. We find that the center wavelength of incident wave is 518.25 nm, and the corresponding intensity is 4698.60 mV. When the wavelengths are 466.90 nm and 596.90 nm, the diffraction intensities are 37.42 mV and 29.23 mV, respectively. The isolation ratio is calculated as 20.989 dB and 22.061 dB. Clearly, the plastic surface-relief grating has the smaller crosstalk between adjacent channels and larger isolation.

The polarization-dependent loss (PDL), which refers to the maximum transmission difference between TE and TM polarization losses, can be expressed as[14]

$$PDL = 10\log\frac{P_{\max}}{P_{\min}} . \quad (5)$$

Fig.8 shows the first-order diffraction intensities of plastic surface-relief grating in TE polarization and TM polarization. The polarization-dependent losses are 0.241 dB and 0.339 dB, respectively, which indicates that the plastic surface-relief grating has the inherent advantage of polarization insensitivity.

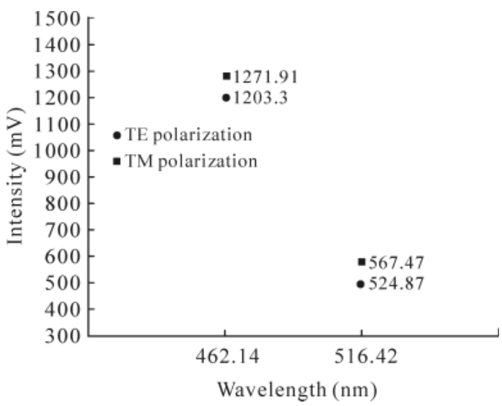

Fig.8 First-order diffraction intensities of TE polarization and TM polarization in different incident wavelengths

The first-order diffraction spectrum of plastic surface-relief grating is measured under the condition of grating constant $d = 1$ μm and groove depth $h = 350$ nm, as shown in Fig.9. The averages of 1 dB bandwidth, 3 dB bandwidth and 20 dB bandwidth are 14.95 nm, 25.53 nm and 105.33 nm, respectively. It can be concluded that the first-order diffraction intensity distribution of the plastic surface-relief grating has better pass-band characteristics.

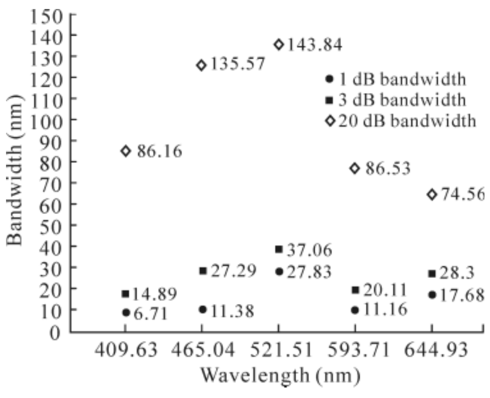

Fig.9 1 dB, 3 dB and 20 dB bandwidths in different incident wavelengths

Based on the experiments and analyses above, we demonstrate that the plastic surface-relief grating, which is replicated under the optimum process, has better optical performance and WDM performance. It can be used as key component for wavelength MUX /DEMUX in the POF WDM network. This study demonstrates the potential application of the plastic surface-relief grating can reduce the cost of wavelength MUX/ DEMUX and increase the network bandwidth.

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