DIFFRACTION GRATING-BASED DEMULTIPLEXERS FOR SI-POF NETWORKS

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Abstract: In this paper, the possibility of implementing low-loss demultiplexer devices based on diffractive elements for SI-POF networks is studied. Theoretical and experimental analyses of three different diffractive setups are reported. It is also presented a 3-channel demultiplexer proposal, based on a transmission diffraction grating, with experimental insertion loss from 3.6dB to 5.8dB and adjacent channel crosstalk from −16.4dB to −28.6dB. This proposal presents low losses and low crosstalk, and it is very easy to implement in a compact reflective setup.

Key words: SI-POF WDM, demultiplexer, diffraction gratings.

1. Introduction

Polymer optical fibers (POFs) have been reported as one of the most promising transmission media for short distance communication networks, such as automotive and avionic multimedia busses and in-house networks. This is due to their well-known advantages, which include easy handling, low cost, low weight and electromagnetic interference immunity [1], [2]. To date, the most used type of POF is the step index POF (SI-POF), made of polymethylmethacrylate (PMMA). SI-POF has 980µm core diameter, 10µm cladding thickness and 0.5 numerical aperture (*NA*).

SI-POF has large modal dispersion, which reduces the usable bandwidth to 14MHz ×100m [1], [3]. Initially, transmission with standard POFs has been realized with only one wavelength, however, in the last years, wavelength division multiplexing (WDM) has been proposed as one potential solution to expand the usable bandwidth of POF based systems [4], [5]. Nowadays, WDM is well-established in the infrared transmission windows for silica optical fibers, but this technique should be adapted to VIS for POFs, due to its distinct attenuation behavior [6]. For WDM, two key devices, multiplexer (mux) and demultiplexer (demux) are indispensable to combine and to separate the different transmitted wavelengths. But for POF-WDM to become reality, the development of low-loss mux/demux devices is required, so that the power penalty does not impose a limit to the real improvement of the link capacity. Some authors [5], [7], set the insertion loss (*IL*) per channel to 5dB as a reasonable value, for a real increase in the link capacity using POF-WDM. However, the most current proposals have *IL* well above from 5dB or are based on simulations that consider elements that are difficult to manufacture with current technologies [8], [9].

In this paper, the possibility of implementing low-loss demux devices based on diffractive elements for SI-POF networks is studied. Furthermore, a 3-channel demultiplexer proposal, with *IL* from 3.6dB to 5.8dB in the range from 405nm to 655nm, is also presented.

2. State of the art of demultiplexers for SI-POF-WDM

The state of the art is analyzed in terms of the following demux parameters: number of channels, insertion loss, *IL*, and adjacent channel crosstalk, *CT*. *IL* is defined as the ratio of the input power of a channel respect to its power in its respective output port, so *IL* > 0dB. *CT* is defined as the ratio of channel power in its respective output port to the power leaked in that port from an adjacent channel, *CT* < 0dB [10].

Several approaches have been proposed to implement demuxs for SI-POF-WDM networks, mainly based on thin-film filters [8], [11], prisms [12] and diffraction gratings [7], [9], [13]. In the following it is described the advantages and limitations of the most representative proposals.

Thin-film based demux are easy to implement and are a good choice to design demuxs with low *IL* and multiple channels. However, they are large, require many elements (typically the number of elements doubles the number of channels) and their *CT* is limited by the rejection ratio of the thin-film filters. A thin-film filter based 4 channels demux made of 3 filters, an input lens and 4 output lenses (8 elements) is reported in [8]. The reported *IL* is between 4dB and 10dB and the *CT* is between −8dB and −15dB. The *CT* can be improved by using band-pass filters in each output, at the expense of increasing *IL*, the number of elements and the cost. On the other hand, the thin-film filter based 3 channel demux in [11] reports 5dB *IL*. This represents the best measured *IL* for a real

POF demux so far [5]. However, no setup details are provided and the losses are measured after 50m of transmission, which reduces the output beam *NA*, as well as the beam diameter and losses [14].

A prism based demux is reported in [12], which can separate three channels, at 470nm, 520nm and 655nm, a distance of 1.2mm, with *IL* of 19.3dB, 12.1dB and 14dB, respectively, and with *CT* between −4.6dB and −26.8dB. This proposal has few elements and is cheap but presents a low performance.

Most common proposals are based on concave gratings. These proposals have good expectations as they have a small size and because the light spatial separation and its focusing are performed with a single element. However, they require diffractive elements that to date are not easy to manufacture, so their experimental performance has not yet been tested. Simulations show that these systems [13] can separate three channels with, gap of 2mm, using a concave grating with 1200 lines/mm (or grooves/mm). But, these types of gratings are not to be expected in the next few years, mainly due to the complex manufacturing process [9]. The groove density requirement can be relaxed to 500 lines/mm using the second diffraction order (m = 2), as shown in [9]. However, the losses introduced due to the grating efficiency will be high. For example, the theoretical efficiency expected by [9] is greater than 40% in the range from 450nm to 655nm, which represents 4dB of loss, considering that it is possible to obtain 100% efficiency at the designing wavelength. Actually, the reflective grating (no concaves) have efficiency less than 75% (in the VIS for the first order of the designing wavelength). Therefore, the real efficiency of the grating required in [9] will be well far below 40% (implying much more than 4 dB loss).

Table 1 presents a summary of the current state of art of demultiplexers for POF-WDM applications.

Table 1: Characteristics of some demultiplexer devices for SI-POF WDM reported in the literature

Ref. No. and Type	Output	Diameter × length	POF NA	Channels [nm]	IL [dB]	CT [dB]
[7], [13] Holographic concave grating reflector (1200 l/mm)	Detection Layer	$20{\times}35mm^2$	Low NA	520, 570 and 655	2 Simulated	-20 Simulated
[9] Blazed grating on an aspheric mirror (500 l/mm)	Detection Layer	$16{\times}16mm^2$	0.38	405, 520 and 655(1)	Not analyzed.	Not analyzed.
[8] Thin film filters based	SI-POF	Large (not specif.)	0.5	405, 450, 520, 660	4 to 10	-8 to -15
[12] Prism Based	SI-POF	$79{\times}\ 94mm^2$	0.5	470, 520 and 655	12 to 19	-4.6 to -6.8
[11] Blazed Grating (600 l/mm)	SI-POF	Unspecified	(2)	520 and 655	6.2 to 7.5(2)	-25
[11] Thin film filters based	SI-POF	Unspecified	(2)	520 and 655	3 to 5(2)	-20

(1) An extra channel at 450nm is included, but it cannot be considered as demultiplexed.
(2) The measurements are performed after 50m transmission. Therefore the beam NA is much smaller than 0.5, which reduces losses. This type of measurement is recommended for characterizing optics coupling IL [14].

3. Diffraction Grating Concepts

Fig. 1 shows a basic dispersion scheme. It consists of a transmission diffraction grating and a focusing lens, of effective focal length (EFL) f_L. It is assumed that the incident beam is collimated, therefore, the system has focusing distance q, where $q = f_L$.

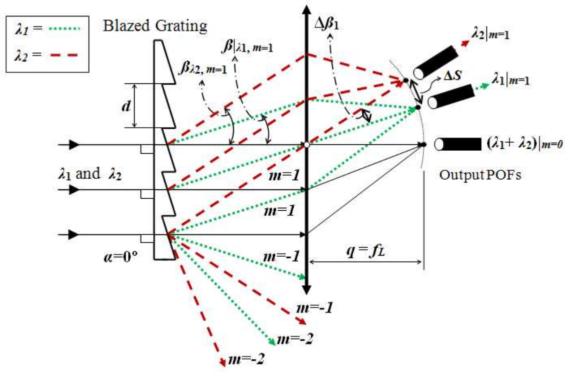

Fig. 1. Simple dispersion scheme is based on a transmissive diffraction grating and a focusing lens. $\lambda_2 > \lambda_1$.

When a monochromatic beam, with wavelength λ, is incident on a grating surface with angle α, respect to the surface normal, it is diffracted into a discrete direction with diffraction angle β, which is given by:

$$m\lambda = d\left[\sin(\alpha) + \sin(\beta)\right] \quad (1)$$

where d is the grating pitch and m is an integer that corresponds to propagating diffraction orders, being $-2d<m\lambda<2d$ (see Fig. 1). d is generally represented as groove density $G = 1/d$, expressed as groove/mm or lines/mm.

The difference between diffraction angles of order m of two given wavelengths, λ_1 and $\lambda_2 = \lambda_1 + \Delta\lambda$, is defined as angular dispersion, $\Delta\beta_m$, Differentiating Eq. (1) and considering a perpendicular incident beam, $\alpha = 0^{o}$, the angular dispersion is given by:

$$\Delta\beta = \frac{m}{d\sqrt{1-(m\lambda/d)^2}}\Delta\lambda \quad (2)$$

The power distribution, of a given diffracted wavelength, into the different propagating orders is defined as the diffraction efficiency, or grating efficiency. It is highly dependent on the groove profile and the design wavelength [15]. This parameter defines mainly insertion losses of the diffraction grating based demultiplexers.

The scheme of Fig. 1 produces a linear dispersion, ΔS, between different focused spots (e.g. λ_1 and λ_2), which, using the cosine theorem, is given by:

$$\Delta S = 2q\sin\left(\frac{\Delta\beta}{2}\right) \quad (3)$$

In demultiplexing applications, ΔS defines the spatial separation between consecutive channels.

4. Simple Schemes for SI-POF Demultiplexing

In this section we present three simple demultiplexing schemes for SI-POF networks (systems 1, 2 and 3). They are designed with commercially available devices and low cost lenses. System 1 and 2 are based on Fig. 2.a and 2.b schemes, respectively, using a transmission grating with blazed profile placed at points DG, as the one shown in Fig. 1. This type of grating is very easy to align and allows us to test the effectiveness of both systems in a simple way. In system 3, a solution for implementing compact reflective systems [16] is analyzed. It is based on the Fig. 2.a scheme but using a grating-prism (grism) as the dispersive element at point GP. The parallel beam has a diameter B_D, the beam divergence is θ_{DIV}, O_D and S_D are the spot diameter at the input and output collimator respectively.

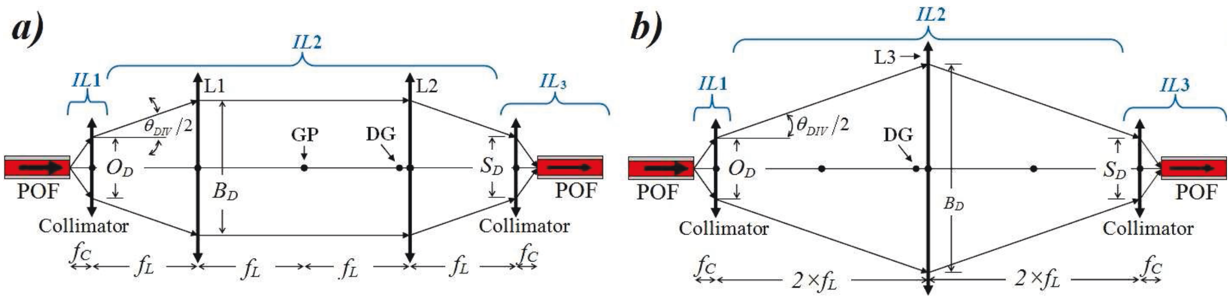

Fig. 2: Coupling optics schemes, where f_C = 4.6mm, O_D is limited to 4.7mm by the collimator clear aperture, $\theta_{DIV/2}$=106.5 mrad and $S_D \approx 5$. In a) theoretical B_D = 33.14mm, experimental B_D = 32mm and f_L = 155mm, while in b) theoretical B_D = 40.62mm, experimental B_D = 40mm and f_L = 100mm. IL1, IL2 and IL3 are the insertion losses of each section.

The schemes of Fig. 2 are designed to be simple, cheap and with low IL. POF fiber collimators (M011-TU2) are used, since they are easy to adapting to straight tip (ST) connectors. These collimators have EFL $f_C \approx$ 4.6mm, clear aperture (CA) ≈ 4.7mm and diameter of 5.1mm. The diffraction grating implemented in systems 1 and 2 is specifically manufactured by using a prototyping process in Telecom Bretagne University. It has a $d \approx 4.0\mu m$, CA = 45mm and it is optimized to work at 597nm. The diffraction efficiency is 51.05% (2.92dB of IL) and 50.12% (3dB of IL) at 532nm and 655nm, respectively, for the first diffraction order. The grism implemented in system 3 has a $d \approx 3.33\mu m$ and it was designed with a binary grating profile, then, its efficiency is very low [15] (power is distributed across many diffraction orders).

4.1. *Coupling optics Insertion Loss*

As was stated in previous section, *IL* is mainly defined by the diffraction and coupling efficiency, as well as the losses by the mismatch between the beam diameter, B_D, and the *CA* of the optical elements, defined as clear aperture loss, *CAL*, which, considering an uniform beam, since SI-POF is very multimodal, is given by:

$$CAL = -10\log_{10}\left(CD/O_D\right)^2 \tag{4}$$

and the back reflection loss, *BRL*, or Fresnel Loss, which is produced when light passes from a medium with refractive index n_1 to another with refractive index n_2, and it is given by:

$$BRL = -10\log_{10}\left\{1-\left[\left(n_1-n_2\right)/\left(n_1+n_2\right)\right]^2\right\} \tag{5}$$

The considered value for *BRL* is 0.18 dB (per surface), since the refraction index of the POF core and the lenses, is about 1.5. Table 2 summarizes the losses of the two optical schemes of Fig.2. This table compares the experimental values with the theoretical ones and discusses how they can be improved.

Table 2: Results of the characterization of the first and second optical setups.

Loss	Mean measured values: First	Mean measured values: Second	Comments
IL_1	1.47dB		**Collimator (input):** *BRL* of 2 surfaces (0.36dB) + *CAL* (1.06dB) = 1.42dB. It can be reduced using collimators with larger *CA* and antireflection coating.
IL_2	1.50dB	0.96dB	**Lenses System:** Lenses material transmission (25mm of BK7 material have 90% transmission or 0.46dB IL) + BRL of 2 surfaces (0.36dB) + light dispersion.
IL_3	2.24dB	2.34dB	**Collimator (output):** BRL of 2 surfaces (0.36dB) + 1m of POF (~0.22dB). Therefore, the coupling efficiency is about 1.7dB. Using lenses that allow better targeting, this value can be reduced to 1dB.
IL_T	5.21dB	4.77dB	**Total IL**

4.2. *Experimental characteristics for systems 1, 2 and 3*

Fig. 3 shows the spatial separation, *ΔS*, of the focused spots of each system. The system 1 was originally designed to place the diffraction grating element at the point GP (see Fig. 2.a). However, when the diffraction grating is placed at that point, the light path is partially blocked by the L_2 mount, due to the large distance. Therefore, the diffraction grating is placed just in front of L_2, point DG, obtaining Δ*S* = 5.3mm meanwhile the theoretical value from Eq (2) is 4.9mm. This difference is due to adjustments in the focusing distance (from L_2 to the output collimator, see Fig. 2.a), in order to get best coupling efficiency to the output fiber, for both wavelengths. Δ*S* does not change when the grating is moving backwards, since the light beam is collimated.

In system 2 the lenses L_1 and L_2 are replaced by L_3, reducing the number of elements and *IL*. Diffraction grating must be placed closest to L_3, at point DG, since the beam is very divergent, so that Δ*S* = 6.5mm; meanwhile the theoretical value is 6.4mm. Δ*S* is reduced when diffraction grating is moved away from L_3, as a tuning capacity (e.g. the central wavelength of the output ports change by moving the grating). In this system, the diffraction grating can be printed on the plane surface of L_3, further reducing the number of optical elements and *IL*, without complicating the manufacturing process.

In system 3, the grisim is placed at the midpoint between L_1 and L_2, point GP in Fig 2.a, since, unlike diffraction gratings, grisims produce on-axis dispersion. For this reason the zero order diffraction (*m*=0) has the large dispersion (*β*), being partially blocked by L_2 mount. Meanwhile, the *β* of first and second diffraction orders (*m*=1 and 2) are small enough not to be blocked, and to produce the necessary *Δβ* to properly separate λ_1 from λ_2 a distance *ΔS* = 6.2mm (for *m* = 1). The tested grism has a binary grating profile; therefore, its efficiency is not comparable to the efficiency of the diffraction grating with blazed profile used in systems 1 and 2. These results show the feasibility of using grisims as a long term solution for implementing systems in reflection configurations in POF-WDM networks, similar to those used in IR for silica optical fibers [16], [17].

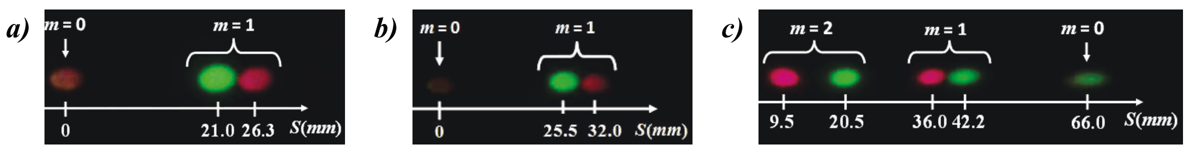

Fig. 3: Spatial separation, ΔS, of the focused spot, at the output collimators, of systems a) 1, b) 2 and c) 3.

Table 3: Experimental insertion losses (ILs) of the systems 1 and 2. IL_1 is collimating IL, IL_2 is the free space IL, including lenses and diffractive elements, and IL_3 is the coupling IL plus 1m of POF attenuation.

Description	Losses	System 1		System 2	
		533nm	660nm	533nm	660nm
Total system losses	$IL_1+IL_2+IL_3$	8.27dB	8.50dB	8.22dB	8.28dB
Focusing at a detection layer	IL_1+IL_2	5.98dB	6.16dB	5.65dB	5.63dB

Table 3 presents a summary of the losses of the 3 systems. These results show that, the first and second proposed diffractive setups are close to fulfilling requirements for being implemented as POF-WDM mux/demux devices [5]. The *CT* in both systems is better than −20dB, since both channels are well separated and the focusing distances for both channels are similar. Design requirements, such as ΔS and system size, can be relaxed by using GRIN lenses as collimators. Similar to the solutions reported by [17], but using one GRIN lens per POF port, due to SI-POF large diameter (a = 1mm). A similar solution can be achieved by using POF tapers.

5. Low loss demultiplexer proposal for POF-WDM networks

In this section, a low loss demultiplexer proposal for SI-POF-WDM is presented. It is based on the system 1 scheme, since the collimators can be eliminated, by using lenses with NA ~ 0.5, and because, as was demonstrated in previous section, the diffraction grating can be placed just in front of the focusing lens, therefore, it can be easily adapted into a compact reflective scheme.

Three channels are considered for the design, at 405nm, 532nm and 655nm, that represent channels number 1, 7 and 13 of the proposed POF WDM grid [6], respectively, as well as light sources with 30nm FWHM, and a commercial diffraction grating with d = 3.3µm (600 grooves/mm), with efficiency of 50% to 75% in the channels range, and CA = 50mm. Grating CA limits q to be less than 45.7mm, in order to get B_D <= 50mm. We chose q = 40mm, in order to separate all channels a distance $\Delta S \geq$ 1.45 mm (Eq. 3). With q = 40 mm a source with 30nm FWHM, in the considered range, will be distorted less than 0.37mm (ellipticity induced in the focused spot, Eq. 3). Focused spots will be designed to have S_D = 1mm. Then, minimum required separation is 1.37mm. Therefore $\Delta S \geq$ 1.45mm guarantees the separations of the different channels with low *CT*.

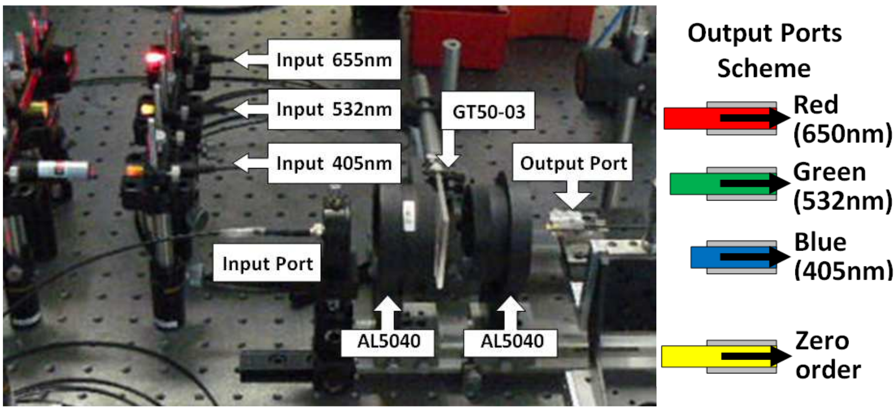

Fig. 4: Proposed low-loss demultiplexer for POF-WDM networks. Ports are made of SI-POF. Ports Blue, Green and Red correspond to channels at 405, 532 and 655nm, respectively. Port zero corresponds to the zero diffraction order. Lenses AL5040 have f_C = 40mm (EFL) and 50mm CA. The diffraction grating GT50-03 has 600 grooves/mm (d = 3.33µm) and 50mm CA.

The experimental setup is shown in Fig. 4, it has 60mm diameter and 120mm length. It was tested using 3 laser sources at 405nm, 532nm and 655nm, and an optical power meter. The output ports have very specific focal lengths due to the large dispersion of the lenses in the considered spectrum (from 405nm to 655nm). This is represented in the output port scheme of Fig. 4. For this reason the output fibers holder has not been manufactured so far. Therefore, in order to perform the power measurements, a single output port is moved across the different positions by using a 3-axes stage.

The experimental setup separate the 3 channels a distance $\Delta S \geq$ 1.5mm. The total *IL* of the channels at 405nm, 532nm and 655nm are 5.8dB, 3.6dB and 4.2dB in the blue, green and red ports, respectively. The isolation of the channel at 655nm is better than 40dB (at the green and blue ports), and for the channel at 532nm is better than 28dB (at the red and blue ports), which represents very good values. At the moment, the isolation of the channel at 405nm is better than 20dB (at the red and green ports). Finally the adjacent *CT* values of the blue, green and red ports are better than −28.6dB, −20.4dB and −16.4dB, respectively.

6. Conclusions

State of the art of different demultiplexer for WDM SI-POF networks is analyzed. Some simple demux designs based on diffraction grating are reported. A novel three channel demultiplexer with insertion losses between 3.6dB and 5.8dB and adjacent channel crosstalk between −16.4dB and −28.6dB is proposed and tested. The crosstalk value can be improved by blocking the second diffraction order of the channel at 405nm. These results show that the proposed simple demultiplexer has a good performance, better than those reported in the current state of art. Therefore, it is a good option to be implemented in SI-POF WDM networks.

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