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Efficient Multiplexer/Demultiplexer for Visible WDM Transmission over SI-POF Technology

Plinio Jesús Pinzón, Isabel Pérez Garcilópe, and Carmen Vázquez

Abstract: A five channel step index plastic optical fiber proposal for a multiplexer/demultiplexer having insertion losses (ILs) of 2.9-4 dB, pass bandwidths at -3 dB > 30 nm, crosstalk attenuation >30 dB and size of ∼65 mm x 55 mm, is demonstrated. It is based on a reflective diffraction grating with blazed profile and an aspheric lens. The theoretical analysis presented is used to further reduce the system size to ∼37 mm x 30 mm and to increase the number of channels to 8 keeping ILs < 4.5 dB. Experimental results have good agreement with theoretical expectations.

KeyWords: Demultiplexer, diffraction grating, multiplexer, polymer optical fiber, visible, wavelength division multiplexing.

1. Introduction

Today the volume of data transmitted by short-range networks, especially by In-Home networks, both to the Internet Service Provider and between different terminals, is increasing beyond the Gbit/s, exceeding the capabilities of current networking technologies [1]. This is due to the fast growth of new multimedia services like IPTV, multroom/multivision configurations, high-definition TV or remote “face-to-face communication,” among others [2]. On the other hand, polymer optical fiber (POF) has been proposed, and recognized, as one of the most promising transmission media for implementing high speed and low cost short-range communication networks [1]. Specifically, in scenarios, such as local area networks, in-home, and office networks [3], as well as in automotive [4] and avionic multimedia buses, or in data center interconnections [5]. Among the different POF types, the step index POF (SI-POF) with a 980 μm core diameter of polymethyl-methacrylate (PMMA) and numerical aperture (NA) of ∼0.5 offers several advantages, especially in the short-range scenarios listed previously, due to its potential low cost for its easiness of handling, installation, splicing and connecting. However, SI-POF suffers from high modal dispersion due to its large NA, limiting its bandwidth distance product to ∼50 MHz × 100 m [6], and providing acceptable attenuation only in the visible spectrum (VIS) (∼0.17 dB/m at 650 nm) [7].

Gbit/s transmission capacity of SI–POF links has been widely demonstrated in recent years, using single channel (ch) based systems (typically at 650 nm) with different advanced modulation formats and/or adaptive electrical equalization techniques. Reported simulations shows that data rates of 1.25, 2.1 [8] and even 6.2 Gbit/s [9], via up to 50 m, can be reached using a single ch, with NRZ, CAP–64 and QAM512 modulations, respectively, with LED [8] and LD [9] transmitters (Txs). More recent experimental systems demonstrate data rates of Multi-Gbit/s up to 50 m with LD Txs [6] and up to 3 Gbit/s over 25 m using 8-PAM with LED Txs [10]. Fully integrated systems that offer real-time SI-POF links at 1 Gbit/s via up to 50 m using M-PAM modulation with a LED Tx have also been reported [11]. But SI-POF’s data transmission capacity needs a greater exploitation to meet user requirements for higher data rates with a low power consumption and low cost. This generates an interest in the development of new systems for Multi-Gbit/s transmission over SI-POF, including new transmitters and receivers, and in new standards, based on SI-POF [1], [4]. After exploiting the capabilities of a single ch transmission, visible wavelength (λ) division multiplexing (visible WDM) is proposed as a solution to expand the capacity of SI–POF based systems. Current proposals of visible WDM transmission over SI-POF are based on spectral grids with chs between 400 and 700 nm [12], using LEDs. Visible WDM systems using offline-processed DMT modulation, and data rates up to 14.77 [13] and 21 Gbit/s [5] over 50 m, with 4 and 6 chs, respectively, have been recently reported. In both systems, the average data rate per ch is about 3.5 Gbit/s with bit error rate of 1×10⁻³.

In WDM systems two key-elements have to be introduced: a multiplexer (Mux) and a demultiplexer (DeMux). On the other hand, a limitation of visible WDM links over SI-POF is the power penalty due to the current Muxes/DeMuxes high insertion losses (ILs), limiting the transmission capacity of each ch in comparison with single ch systems, for the same transmitted power [9]. This can be overcome by reducing the Muxes/DeMuxes’ ILs, and/or increasing the transmission power. But the latter solution increases the system power consumption and is only suitable for scenarios where working outside the eye-safety-limit is allowed [5], [13]. Mux/DeMux devices with ILs ≈3.5 dB per ch allow to establish SI-POF visible WDM systems with transmission power per ch near to the eye safety limit (<1 mW), that can be used in network topologies [14], where the fiber containing all the WDM chs is kept away from the end user. Therefore, the development of Mux/DeMux devices with low ILs and higher ch counts than the current proposals is essential in order to implement efficient visible WDM SI–POF links, working near the eye-safe-limit and using low-power technology [9], especially for in-home and office networks [14]. On the other hand, the design of Mux/DeMux...
Muxes/DeMuxes for visible WDM over SI-POF networks. Theoretical basic and proposed scheme

In this paper, we report a five-channels diffraction grating based Mux/DeMux for visible WDM transmission over SI-POF technology, with low IL, large rejection bandwidth, and a compact size, in comparison with the current state-of-the-art, is presented. Thus, we first review the Mux/DeMux devices for visible WDM based SI-POF networks. Then, we analyze the most important requirements imposed by the SI-POF characteristics in the design of diffraction grating based Muxes/DeMuxes. We next describe the five-channels Mux/DeMux design and its experimental characterization.

Finally, we present the discussion and the relevant conclusions.

2. Muxes/DeMuxes for visible WDM over SI-POFs

Muxes/DeMuxes are basic elements in the WDM approach. However, most Muxes/DeMuxes for glass optical fibers (GOFs) [15]–[17], or for graded index POF with low NA [18], are not suitable for SI-POFs. This is due to the spectral range and spectral bandwidths used for visible WDM over SI-POFs [12], and the SI-POF physical characteristics. A summary of different Muxes/DeMuxes for SI-POF is shown in Table I. They are mainly based on thin-film filters [13], [19], prisms [20], and diffraction gratings [5], [21]–[23]. Muxes/DeMuxes based on planar blazed diffractions grading are to date a promising option for implementing compact devices with low ILs and multiple chs. The next lowest IL < 4.5 dB is achieved in a diffraction grating based Mux/DeMux of three chs [24]. The maximum number of chs is reported in [5], but the ILs are up to 10 dB. In this paper, we report a five-channels Mux/DeMux with ILs < 4 dB and an eight-channels Mux/DeMux with ILs < 4.5 dB, both with crosstalk attenuation (CTA) > 30 dB.

3. Theoretical basic and proposed scheme

Fig. 1 shows the layout of the proposed SI-POF Mux/DeMux. It consists of a reflective blazed diffraction grating with blazing angle θB, grating pitch d and tilt angle about the x-axis α; and a collimating/focusing lens with effective focal length f and pupil diameter DL. The light, which emerges from the common port, Pe,C, located at C point, contains the central wavelength λC, and the wavelengths of the extreme chs to be demultiplexed, which are referred as λS, for the shorter λ, (at ~400 nm) and as λL, for the longer λ (at ~700 nm). The system is bidirectional. So the rays that emerge from Pe,S and Pe,L are multiplexed in Pe,C; see Fig. 1(b).

A light beam is directed at the diffraction grating. The grating reflects back a plurality of collimated beams of light, each within a different λ range and at a specific direction defined by

**Table I** Characteristics of Some Multiplexer/Demultiplexer Devices for SI-POF WDM Systems

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar blazed diffraction grating (600 lines/mm)</td>
<td>2</td>
<td>(1)</td>
<td>520, 650</td>
<td>6.2 to 7.5</td>
<td>25</td>
<td>[19], 2002</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Thin film filters</td>
<td>&gt;d(1)</td>
<td>(1)</td>
<td>520, 655</td>
<td>3 to 5</td>
<td>20</td>
<td>[19], 2002</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Holographic concave grating reflector (1200 lines/mm)</td>
<td>1</td>
<td>~20 × 35(1)</td>
<td>520, 570, 655</td>
<td>2</td>
<td>20</td>
<td>[21], 2005</td>
<td>(3), (4), (5)</td>
<td></td>
</tr>
<tr>
<td>Ellipsoidal and Spherical grating mirrors (1200 lines/mm)</td>
<td>1</td>
<td>~30 × 26(1)</td>
<td>480, 520, 630</td>
<td>(1)</td>
<td>30</td>
<td>[23], 2008</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>Prism</td>
<td>2</td>
<td>79 × 94</td>
<td>470, 520, 655</td>
<td>12 to 19</td>
<td>4.6 to 6.8</td>
<td>[20], 2008</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Blazed grating on an aspheric mirror (500 lines/mm)</td>
<td>1</td>
<td>13 × 20</td>
<td>450, 520, 650(7)</td>
<td>(1)</td>
<td>(1)</td>
<td>[22], 2013</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>Thin film filters</td>
<td>12</td>
<td>Large(1)</td>
<td>405, 450, 528, 646</td>
<td>3.3 to 5.7</td>
<td>&gt;30</td>
<td>[13], 2014</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Planar Holographic Diffraction Grating (1800 lines/mm)</td>
<td>2</td>
<td>diam.~75(1)</td>
<td>405, 442, 459, 490, 515, 655</td>
<td>&lt;10</td>
<td>20 to &gt;30</td>
<td>[5], 2014</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Planar blazed diffraction grating (400 lines/mm)</td>
<td>2</td>
<td>65 × 55</td>
<td>504, 515, 650</td>
<td>3.5 to 4.5</td>
<td>&gt;30</td>
<td>[24], 2014</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>Planar blazed diffraction grating (1200 lines/mm)</td>
<td>2</td>
<td>57 × 50</td>
<td>435, 465, 497, 530, 562, 595, 625, 655</td>
<td>3.2 to 4.5</td>
<td>&gt;30</td>
<td>In this work</td>
<td>(2)</td>
<td></td>
</tr>
</tbody>
</table>

Notes: (1) Unspecified or not analyzed; (2) Experimental results with ports made of SI-POF; (3) Simulations without experimental results; (4) The diameter of the SI-POF is not considered in the simulations; (5) A detection layer is considered at the output; (6) SI-POF input with 0.38 NA and 0.98 mm diameter; (7) An extra channel at 405 nm is included, but only chs with high CTA are considered; (8) There is a thin-film filter in each output to improve the crosstalk attenuation.
A diffraction angle $\beta_s$ given by

$$m\lambda = d\left[\sin(\alpha) + \sin(\beta_s)\right]$$  \hspace{1cm} (1)

where $m$ is the integer of propagating diffraction orders, being $-2d < m\lambda < 2d$ and $d$ is generally represented as groove density $G = 1/d$, in lines/mm or grooves/mm.

Blazed diffraction gratings are optimized to achieve maximum grating efficiency at a specific $m$ and $\lambda$ (blaze $\lambda$), which is defined by the grooves shape, especially by $\theta_B$.

### A. Central Wavelength in Littrow Configuration

The Mux/DeMux is designed for $\lambda_S$ and $\lambda_L$, and their required spatial separation, represented by $S = y_L + y_S$, see Fig. 1(a). This design can be done optimizing the $ILs$ of specific chs, as ports closest to $P_{3\text{c}}$ have a better coupling efficiency. This can be used in order to fulfill the power requirements of a specific WDM system. In our general case, there are two main objectives: 1) minima $ILs$ and 2) chs uniform $ILs$ or all chs $ILs$ near to the minimum value. The system shown in Fig. 1 is bidirectional. Therefore, for simplicity, the design process is done only in the demultiplexing direction; see Fig. 1(a).

The diffraction scheme is done using a Littrow configuration for $\lambda_C$, in order to obtain a fiber-to-fiber coupling efficiency between $P_{3\text{c}}$ and the extremes ports approximately equal. In a Littrow configuration, the diffracted beam $(\lambda_C)$ is back-reflected in the incident beam direction, $\beta_{LC} = \alpha$, and from (1) this is achieved when

$$\sin(\alpha) = m\lambda_c/(2d).$$  \hspace{1cm} (2)

The maximum diffraction efficiency at $\lambda_C$ (for optimum IL), $\alpha = \beta_{LC} = \theta_B$ needs to be met. In a bidirectional system, it is possible to prevent that some of the reflected light returns to the central port including a tilt angle in the diffraction grating about the $y$-axis ($\varphi$).

On the other hand, $\lambda_S$ and $\lambda_L$ have diffraction angles $\beta_{S}$ and $\beta_{L}$, respectively; see Fig. 1(a). These angles are measured from $\beta_{LC}$ as $\beta_S$ and $\beta_L$ (see Fig. 3) and are given by

$$\beta_{(S,L)} = \alpha - \sin^{-1}\left[m\lambda_{(S,L)}/d - \sin(\alpha)\right].$$  \hspace{1cm} (3)

The $chs$ centered at $\lambda_S$ and $\lambda_L$ are spatially separated, in the $y$-axis direction, from the central point $C$, a distance given by

$$y_{(S,L)} = f\tan\left(\beta_{(S,L)}\right).$$  \hspace{1cm} (4)

$\lambda_C$ is a wavelength that, considering a specific diffraction grating (fixed $d$ and $m$), generates the same angular dispersion between $\lambda_S$ and $\lambda_L (\beta_S = \beta_L)$. Therefore, from (2) and (3), $\lambda_C$ must satisfy the following condition:

$$\sin^{-1}\left[\frac{m(2\lambda_S - \lambda_C)}{2d}\right] + \sin^{-1}\left[\frac{m(2\lambda_L - \lambda_C)}{2d}\right]$$

$$= 2\sin^{-1}\left[\frac{m\lambda_C}{2d}\right].$$  \hspace{1cm} (5)

Fig. 2 shows $\lambda_C$ satisfying (5) and $\alpha = \beta_{LC}$ from (2) versus the diffraction grating groove density, considering $\lambda_S = 405$ nm and $\lambda_L = 650$ nm. $\lambda_C$ can be approximated to $\lambda_C = (\lambda_S + \lambda_L)/2 = 527.5$ nm for $G < 1200$ lines/mm (see Fig. 2).

### B. Lens’ f-number and Diameter

SI-POF Muxes/DeMuxes require a higher spatial separation between the different chs than the GOs Muxes/DeMuxes, due to the larger SI-POF cladding diameter. A five ch SI-POF Mux/DeMux requires $S = (\Delta y_S + \Delta y_L) > 5$ mm. This value is 8 times greater than the required GOs $S$ in 125 $\mu$m cladding diameter multimode fibers. As shown in (1) and (4), $S$ can be increased by increasing $G$ or $f$. The design criteria for selecting the optics (collimating/focusing lens), depending on $S$, $G$, and $f$, for the efficient transmission of all the chs is given as follows.

Beams in free space from SI-POFs have a diameter

$$D_F = 2f\tan\left(\sin^{-1}NA\right).$$  \hspace{1cm} (6)

NA range where the lens efficiently transmits the beam is represented as the $f$-number, defined as the ratio of $f$ to the diameter of the lens’ entrance pupil, $D_L$, expressed as

$$f/\# = f/D_L.$$  \hspace{1cm} (7)

Therefore, in order to collimate the beam that emerges from an SI-POF with $NA = 0.48$ and diameter $D_F$, from (6), it is required an $f/\# < 0.91$, considering that $D_L = D_F$ in (7).

The proposed diffraction scheme is symmetrical, if condition (5) is fulfilled. However, in practical cases, it is normal that $y_S + y_S(\neq y_l + y_L)$, especially due to the variation of $f$ with the $\lambda$, or due to choosing a $\lambda_C$ not satisfying the symmetrical condition (5) to overcome the extreme chs ($\lambda_S$ and $\lambda_L$) differences on their
Five channels SI-POF MUX/DEMUX

4 lines/mm. Fig. 5 shows the resulting entrance pupil, with total diameter \( D_L \). From Fig. 3, the diameter must be greater than

\[
D_L \geq \max [y_S + y_{S\psi}, y_L + y_{L\psi}]
\]

where

\[
y_{S\psi} = p_S \times \tan (\psi_a), \quad p_S = (f^2 - y_S^2)^{1/2} \quad \text{and} \quad \psi_a = \sin^{-1} NA; \quad \text{and} \quad y_{L\psi} = p_L \times \tan (\psi_a) \quad \text{with} \quad p_L = (f^2 - y_L^2)^{1/2} .
\]

\( p_S \) and \( p_L \) can be approximated to \( f \), if \( f >> y_S \) and \( f >> y_L \) (e.g., with \( y_S \) and \( y_L < 4 \) mm and \( f > 20 \) mm, the relative error of this approximation is less than 2%). Therefore, the required optics must have

\[
f/# \leq \min \left\{ \frac{\tan (\beta_S) + \tan (\psi_a)}{\tan (\beta_L) + \tan (\psi_a)} \right\}^{-1} .
\]

Then, \( f/# \) is almost independent of \( f \) if \( f >> y_S \) and \( f >> y_L \). Fig. 4 shows \( f/# \) versus \( G \) from (9) with \( \lambda_S = 405 \) nm, \( \lambda_L = 650 \) nm and SI-POFs with \( NA = 0.48 \), for \( m = 1 \). The required \( f/# \) decreases as the grating \( G \) increases. The \( f/# \) required for both \( G = 600 \) lines/mm (\( f/# < 0.8 \)) and \( G = 1200 \) lines/mm (\( f/# < 0.71 \)) is satisfied using aspheric lenses.

C. Spatial Separation Between Channels

Channels’ spatial separation depends on \( G \) and \( f \). Higher \( G \) values require more complex optics and can reduce the grating efficiency, due to the manufacturing tolerances. But, large \( f \) values result in bulky systems. The tradeoff between \( G \) and \( f \) is analyzed in the following example. The objective is to separate more than five SI-POF channels, placed in a spectrum from \( \lambda_S = 405 \) nm to \( \lambda_L = 650 \) nm, therefore, \( S = y_S + y_L > 5 \) mm.

In this example, we consider a diffraction grating with \( G = 600 \) lines/mm. Fig. 5 shows the resulting \( S \) and the entrance pupil diameter, \( D_L \), of the lens required as a function of \( f \), from (4), (5), and (8). It can be shown that \( S > 5 \) mm can be obtained using a lens with \( f > 33.5 \) mm and \( D_L > 41.6 \) mm (\( f/# < 0.8 \), see Fig. 4 for \( G = 600 \) lines/mm). If \( G \) increases up to 1200 lines/mm, \( S \) doubles but the optics’ \( f/# \) must be < 0.71.

4. Five channels SI-POF MUX/DEMUX

Equations previously analyzed are based on ideal elements. An optimized design, based on the characteristics of real optical elements, is now reported. It is based on the example analyzed in Section III-C; see Fig. 6. The input/output ports are named \( P_{n}, \) with \( n = 1, 2, \ldots, 5 \), and their \( chs \) cover the spectral range of 405–650 nm: \( \lambda_1 = \lambda_S = 405 \) nm, \( \lambda_2 = 466.25 \) nm, \( \lambda_3 = 527.5 \) nm, \( \lambda_4 = 588.75 \) nm, and \( \lambda_5 = \lambda_L = 650 \) nm; which correspond to \( chs: 1, 4, 7, 10, \) and \( 13 \) of a previous SI-POF visible WDM grid proposal [12]. A distance greater than \( 1 \) mm between consecutive ports is fulfilled using an aspheric lens with \( f = 40 \) mm and \( D_L = 50 \) mm, see Section III-C. In this case, the spatial separation between the extreme \( chs \) is about \( 6 \) mm; see Fig. 5. The considered diffraction grating has an area of \( 50 \) mm \( \times \) \( 50 \) mm, \( G = 600 \) lines/mm, \( \theta_B = 8.62 \) and diffraction efficiency between 56% and 68% (for nonpolarized light) in the range of 400–650 nm [25].

Fig. 6 shows how the common port, \( P_{AC} \), is placed at the system center, \( C \) (point \( y = 0, x = 0 \)). Ports are separated \( 1 \) mm from \( C \) in the \( x \)-axis direction; this separation is controlled by the diffraction grating tilt angle about the \( y \)-axis (\( \psi \)), for a fixed \( f \) value. The distance of each port from \( C \) in the \( y \)-axis direction is defined by \( y_B \). The distance of each port from \( C \) in the \( z \)-axis is defined by \( z_B \). Finally, \( p \) and \( p_G \) are the distances from \( C \) to the Lens surface 1, and from the Lens surface 2 to the grating surface, respectively, in the \( z \)-axis direction (\( x = 0 \) and \( y = 0 \)). The design is done using a ray tracing optical design software. The main target is to optimize the fiber-to-fiber coupling efficiency (\( \eta_{Cn} \)) from the port \( P_{n} \) to the different \( chs \) (\( P_{n} \)) ports. It is also targeted uniform \( ILs \) of the extreme \( chs \) (\( P_{1} \) and \( P_{5} \)), by a proper selection of \( \lambda_{C} \). Table II summarizes the characteristics of the proposed design, based on Fig. 6.

The coupling efficiency is calculated considering a circular object with \( 1 \) mm of diameter (central port, \( P_{AC} \)), with \( NA \) of 0.5 (worst case) and a uniform radiation profile (worst case); see Fig. 7. This means that each point in the SI-POF surface is radiating with the same intensity and with a \( NA \) of 0.5. \( \eta_{Cn} \) is calculated from the rays that reach an image of \( 1 \) mm of diameter with \( NA < 0.5 \) using a geometric image analysis [26].
### TABLE II
**SPECIFICATIONS OF THE FIVE CHANNEL MUX/DEMUX, G = 600 LINES/MM**

<table>
<thead>
<tr>
<th>General Characteristics</th>
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<tbody>
<tr>
<td>Central wavelength, (\lambda_c = 540) nm (for IT of (P_{11} = IT) of (P_{15}))</td>
</tr>
<tr>
<td>(p = 30.479) mm, (\rho_G = 15) mm, (\alpha = \beta_C = -9.327^\circ, \varphi = -0.727^\circ)</td>
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#### Input/Output Ports Configuration

<table>
<thead>
<tr>
<th>Channel/Port</th>
<th>(\lambda_n) [mm]</th>
<th>(\Delta z_n) [mm]</th>
<th>(\Delta y_n) [mm]</th>
<th>(\eta_{Gn}) [%]</th>
<th>(\eta_{Cn}) [%]</th>
<th>IT [dB] (Expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{11})</td>
<td>405.00</td>
<td>2.325</td>
<td>-3.10</td>
<td>79</td>
<td>62</td>
<td>3.1</td>
</tr>
<tr>
<td>(P_{12})</td>
<td>466.25</td>
<td>0.984</td>
<td>-1.75</td>
<td>88</td>
<td>67</td>
<td>2.3</td>
</tr>
<tr>
<td>(P_{13})</td>
<td>527.50</td>
<td>0.130</td>
<td>-0.30</td>
<td>94</td>
<td>67</td>
<td>2.0</td>
</tr>
<tr>
<td>(P_{14})</td>
<td>588.75</td>
<td>-0.454</td>
<td>1.18</td>
<td>93</td>
<td>63</td>
<td>2.3</td>
</tr>
<tr>
<td>(P_{15})</td>
<td>650.00</td>
<td>-0.813</td>
<td>2.70</td>
<td>88</td>
<td>56</td>
<td>3.1</td>
</tr>
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</table>

#### Spatial Separation

\[|\Delta y_1 - \Delta y_2| = 1.35, |\Delta y_2 - \Delta y_3| = 1.45, |\Delta y_3 - \Delta y_4| = 1.48, |\Delta y_4 - \Delta y_5| = 1.52, \Delta S = |\Delta y_5 - \Delta y_1| = 5.8\]

Fig. 7. Beam profiles of multimode fiber-to-fiber coupling efficiency calculations between \(P_{1C}\) and each input/output port.

Fig. 8. Experimental setup for the characterization of the five \(ch\) Mux/DeMux: \(H_0\): holder of the common fiber, \(H_1\): input/output fiber holder.

Fig. 9. Mux/DeMux transfer function (left vertical axis): \(\lambda_1\) (dash-dot line), \(\lambda_2\) (dashed line), \(\lambda_3\) (dotted line), \(\lambda_4\) (solid line with point markers), \(\lambda_5\) (dashed line with point markers). SI-POF attenuation (solid line, right vertical axis).

Moving the \(H_1\) holder to the different \(ch\) positions with a micrometric \(xyz\) translation stage.

Spectral measurements are done using a Halogen light source and a high speed Spectrometer with spectral resolution of about 4 nm in the spectral range from 360 to 886 nm, using the following procedure: 1) the light source is connected to the spectrometer using 3 m of SI-POF, with mode scramblers next to the source and to the spectrometer, this measurement represents the reference spectra (0 dB reference), 2) the 3 m of SI—POF is cut in half and each end is polished, 3) the section attached to the light source is connected to the common port holder (\(H_0\)) and the section that is attached to the spectrometer is connected to the input/output port holder (\(H_1\)), and 4) the holder \(H_1\) is positioned at the different port locations, from Table II.

The transfer function of each input/output port in the spectral range from 390 to 700 nm is shown in Fig. 9. The \(IT\) per \(ch\) is less than 4 dB. This value includes the \(IT\) produced by the polished surfaces. Fresnel losses per PMMA—air interface is typically \(~4\)% (lens is AR coated: 350—700 nm). The spectral bandwidth at \(-25\) dB is higher than 38 nm. The 3 dB spectral bandwidths are represented by shaded areas on Fig. 9. The 3 dB spectral bandwidth of each \(ch\) is greater than 30 nm. And the crosstalk attenuation (\(CTA\)) is greater than 30 dB. The \(CTA\) is a measure of the part of the optical power at each \(\lambda\) exiting from the port \(P_{1n}\) at wavelengths outside its 3 dB bandwidth. Measurements 40 dB below the reference signal are limited by the spectrometer sensitivity. The SI-POF fiber attenuation at 405, 470, 530, 588, and 650 nm is 0.21, 0.11, 0.11, 0.12, and 0.17 dB/m, respectively. Table III shows the five \(ch\) Mux/DeMux parameters. This table also presents an experimental and expected \(ITs\) comparison. It can be seen that there is a good agreement between them.

### 5. Experimental characterization

The experimental setup is shown in Fig. 8. The distance from the fiber holders (\(H_0\) and \(H_1\)) to the rear surface of the grating is about 65 mm. It has a common port, \(P_{1C}\) (\(H_0\)) and five input/output ports, \(P_{1n}\) (\(H_1\)), with \(n = 1, 2, \ldots, 5\). Each input/output port has its own focusing distance \((p + \Delta z_n)\); see Table II. The transfer function characterization is done by

### 6. Discussion

The proposed diffraction scheme is used for designing an efficient and compact five \(ch\) Mux/DeMux for visible WDM transmission over SI-POF technology. This Mux/DeMux is able to separate adjacent SI-POF \(chs\) a distance greater than 1.35 mm, with a total separation between \(chs\) of 5.8 mm. The spectral bandwidths at \(-3\) and \(-25\) dB are greater than 30 and 38 nm,
To note that a simple 4:1 SI-POF coupler have
ILs < of bidirectional links, made entirely with SI-POFs, including
the same angular emission pattern independently of the chosen
setup.
In the POF surfaces and to the tolerances in the experimental
results. The differences are mainly due to the effects of Fres-
agreement between the theoretical design and the experimental
8d B[7].
The proposed five
ILs bidirectional [5], [13]. This is due to the high
recently proposed SI-POF links based on visible WDM are
visible WDM. ILs of the Mux/DeMux are less than 4 dB and
loss uniformity is 1.1 dB.
Another aspect that must be highlighted is that none of the
recently proposed SI-POF links based on visible WDM are
bidirectional [5], [13]. This is due to the high ILs of the current
Mux/DeMux proposals or due to their complexity and size.
The proposed five chs Mux/DeMux allows the implementation of
bidirectional links, made entirely with SI-POFs, including
ILs < 8 dB (<4 dB in mux and <4 dB in demux). It is impor-
tant to note that a simple 4:1 SI-POF coupler have ILs up to
8 dB [7].
From Tables II and III, it is shown that there is a good
agreement between the theoretical design and the experimental
results. The differences are mainly due to the effects of Fres-
nel losses in each PMMA-air interface, to the imperfections
in the polished surfaces at the input/output ports are not included.

\begin{table}[h]
\centering
\caption{Performance Summary of the Proposed Five Channel Mux/DeMux} 
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Channel/ Port, } & \textbf{Band-pass at:} & \textbf{ILs (dB)} & \textbf{Expected ILs} & \\
\textbf{Port, } & \textbf{–3 dB} & \textbf{–25 dB} & \textbf{Experimental} & \textbf{Expected} \\
\hline
$P_1$ & 405 & 30 nm & 43 nm & 3.9 dB & 0.8 dB \\
$P_2$ & 470 & 35 nm & 43 nm & 2.6 dB & 0.3 dB \\
$P_3$ & 530 & 38 nm & 42 nm & 2.8 dB & 0.8 dB \\
$P_4$ & 588 & 37 nm & 41 nm & 3.1 dB & 0.8 dB \\
$P_5$ & 650 & 37 nm & 42 nm & 3.5 dB & 0.4 dB \\
\hline
\end{tabular}
\end{table}

Expected ILs are given in Table II.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Output beam profile measures: (a) without mode scramblers (FWHM = 4166.67\,\mu\text{m}); (b) with mode scramblers (FWHM = 4234.99\,\mu\text{m}).}
\end{figure}

respectively, in all the chs. The most important characteristics
of the proposed Mux/DeMux are its chs low and uniform ILs.

These characteristics allow the implementation of efficient
transmission links based on visible WDM over SI-POF, since
the power penalty, produced by the low ILs, does not impose a
limit to the real improvement of the link capacity. Some authors
[9], [21] set the ILs per ch to 5 dB as a reasonable value, for
a real increase in the link transmission capacity using SI-POF
visible WDM. ILs of the Mux/DeMux are less than 4 dB and
loss uniformity is 1.1 dB.

A. Tolerances and Ports’ Central Wavelength Tuning

The tolerances of the proposed Mux/DeMux are mainly re-
related to the position tolerance of the output ports, since it is
the most sensitive parameter. The position of the output ports
(holder $H_1$ in Fig. 8) is controlled with a micrometric $xyz$
translation stage. The other distances in the system are adjusted
with much less precision tools. The ILs of the extremes ports
are the most sensitive to the variations in their optimized po-
positions. Fig. 12 shows the experimental characterization of the
ILs variation ($\Delta$ IL) of the ports $P_{1\lambda}$ and $P_{5\lambda}$ against the vari-
ations in the $z$, $y$, and $x$ direction from their optimized positions
($\Delta z_n + \Delta z$, $\Delta y_n + \Delta y$, $\Delta x_n + \Delta x$); see Table II. It can be
seen that the variations in the $z$ direction of up to $\pm 0.25$ mm
increase the ILs in less than 0.3 dB. On the other hand, the vari-
ations in the $y$ and $x$ direction have a higher impact in the $\Delta$ IL.
In order to maintain the $\Delta$ IL of both chs below $–0.5$ dB, the
variations in the $y$ and $x$ directions must be less than $\pm 0.1$ and
0.1 mm, respectively.

Ports position shifts in the $y$ direction has an almost linear
effect in their central $\lambda$ shifts, $\Delta \lambda$. The Mux/DeMux has a
$\Delta \lambda$ [nm] in all the chs of about $43.48 \times \Delta y$ [mm].

The separation between adjacent chs is greater than 1.35 mm.
Therefore, in a final application, the central $\lambda$ of each port shown
in Fig. 9 can be tuned up to $\Delta \lambda = 15.22$ nm ($\Delta y = 0.3$ mm), in
order to accommodate specific chs. Obviously, this fact reduces
the band-pass bandwidths. However, even if the pass bandwidths
values reported in Table II are reduced by 15 nm, they still allow
the use of laser sources, with little or no interference [5].
B. Scalability: Eight Channels Mux/DeMux

It is possible to increase the spatial separation between the extreme chs to $S \approx 9$ mm using a diffraction grating with $G = 1200$ lines/mm and a lens with $f = 35$ mm and $D_L \geq 45$ mm ($f/\# < 0.71$; see Fig. 4). This configuration is also experimentally tested. However, due to the low performance of the available diffraction grating at 405 nm, the design is optimized to accommodate eight chs in the range from 430 to 655 nm. The experimental transfer function of each ch is shown in Fig. 13. In this case, $\lambda_1 = 430$ nm, $\lambda_2 = 465$ nm, $\lambda_3 = 497$ nm, $\lambda_4 = 530$ nm, $\lambda_5 = 562$ nm, $\lambda_6 = 595$ nm, $\lambda_7 = 625$ nm, and $\lambda_8 = 655$ nm. The separation between consecutive chs is greater than 1.23 mm, with total separation of $S = 8.84$ mm. The spectral band-pass bandwidth at $-3 \text{dB}$ in all the chs is $\approx 25.6 \times \Delta\lambda_{[\text{mm}]}$ and $ILs < 4.5$ dB with uniformity of 1.3 dB. The size is reduced to about 57 mm of length by about 6 mm using a diffraction grating with 50 mm of height. The spectral band-pass bandwidth at $-3 \text{dB}$ is reduced to less than 37 mm in length and 30 mm in height, which represents a reduction factor of 1.75 in length and 2.2 in height.

Apart from visible WDM SI-POF links, these low insertion losses Mux/DeMux can also be used in intensity based fiber-optic sensing configurations using WDM as the self-referencing principle [27].

C. Size Reduction and Applicability

It is possible to spatially separate five chs a total distance of about 6 mm using a diffraction grating with $G = 1200$ lines/mm, and a lens with $f = 20$ mm and diameter of $D_L = 25$ mm. The lens requirement can be fulfilled using an aspheric lens ($f/\# < 0.71$; see Fig. 4), in this case, the Mux/DeMux size can be reduced to less than 37 mm in length and 30 mm in height, which represents a reduction factor of 1.75 in length and 2.2 in height.

Apart from visible WDM SI-POF links, these low insertion losses Mux/DeMux can also be used in intensity based fiber-optic sensing configurations using WDM as the self-referencing principle [27].

7. Conclusion

A five ch Mux/DeMux for visible WDM transmission over SI-POF has been designed and experimentally tested. It is based on a reflective blazed diffraction grating and an aspherical lens. It has a length of $\sim 65$ mm and height of $\sim 55$ mm. The experimental $IL$ and $CTA$ are found to be less than 4 dB and higher than 30 dB, respectively, and the spectral band-pass bandwidths at $-3$ and $-25$ dB in all the chs are greater than 30 and 38 nm, respectively. Tolerance analysis shows that extremes ports $IL$ increments around 0.3–0.5 dB are expected for ports’ positions shifts of up to $\pm 0.25$, $\pm 0.1$, and $+0.1$ mm in the $z$, $y$, and $x$ directions, respectively. This analysis also shows that the central wavelength of each port can be tuned up to 15 nm, in order to accommodate specific chs. The Mux/DeMux design can be extended to eight chs keeping the $ILs < 4.5$ dB and $CTA > 30$ dB in a device with length of $\sim 57$ mm and height of $\sim 50$ mm. In this case, spectral band-pass bandwidth at $-25$ dB is 12–21 nm. Theoretical expectations are in good agreement with experimental results. This theoretical analysis can be used to design a five ch Mux/DeMux with a size reduction factor of 1.75 in length and 2.2 in height, versus the five ch design reported.

The Muxes/DeMuxes presented in this paper have the best characteristics, in terms of performance, number of chs and size, reported in experimental systems. These devices allow the implementation of visible WDM links over SI-POF with a low power penalty compared to single ch systems.

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References


