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# DESIGN AND ANALYSIS OF A WDM SYSTEM FOR MULTI-GBIT/S TRANSMISSION OVER 50 M OF SI-POF

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**Abstract:** In this work, the design of a data communication system based on a step−index plastic optical fiber link (SI−POF) and a 3 channel wavelength division multiplexing (WDM) scheme is presented. New proposals of multiplexer and demultiplexer devices are also presented. The multiplexer is able to combine 3 channels with insertion loss (IL) of about 1.4 dB. And the demultiplexer is a compact device based on a reflective diffraction grating that is able to separate 3 channels with IL < 4.5 dB and crosstalk < −30dB. The system has been experimentally analyzed using one of the 3 channels available (at 650 nm) and the early results are presented. These results show that the system can establish a real time link at 1 Gbit/s with 50 m of SI−POF and that it has the potential of expanding the transmission data rate up to 3 Gbit/s.

**Key words:** SI−POF, Gbit/s, Multiplexer, Demultiplexer, Diffraction Grating.

## 1. Introduction

There are several proposals of modulation methods [1], spectral grids [2] and multiplexer/demultiplexer devices (Muxes/DeMuxes) [3] that allow to implement transmission systems based on wavelength division multiplexing (WDM) at data rates of Multi−Gbit/s over links of step−index plastic optical fiber (SI−POF), in order to increase the transmission capacity of SI−POF based systems [4]. To date, data rates (R) up to 14.77 Gbit/s, with 4 channels via up to 50 m of a SI−POF link using offline-processed discrete multitone modulation [5], have been reported. A similar system reports 10 Gbit/s over 25 m of SI−POF using offline-processed NRZ modulation [6]. On the other hand, there have also been reported Gbit/s systems over SI−POF links using a single channel, as a commercial system with R of 1 Gbit/s via up to 50 m of SI−POF [7]. Other analysis based on simulations report R of 1.25 Gbit/s, 2.1 Gbit/s [1] and 6.2 Gbit/s [9] via up to 50 m of SI−POF using a single channel with NRZ, CAP−64 and QAM512 modulations, respectively.

The high insertion losses (IL) added by the Muxes and DeMuxes in the SI−POF WDM based systems limit their bit rate−length product (R×L) in comparison to other systems that transmit at a single wavelength (λ), or channel [9]. Current proposals of DeMuxes present IL of less than 6 dB per channel with 3 and 4 channels [3], [6]. These devices are bidirectional and can be used as Muxes. However, some are complicated, large, or expensive, so it is preferred to use N:1 couplers. But 3:1 and 4:1 couplers have IL of up to 8 dB per branch [6], [8]. So in the multiplexing and demultiplexing IL of more than 14 dB per channel can be included, apart from the fiber attenuation.

In this paper, the design of a real−time WDM system over SI−POF that can improve the performance, in terms of R×L, of those systems that transmit a single λ is presented. Three commercial laser diodes are considered. The multiplexing is performed with a 3:1 coupler with very low IL. And the channels separation is performed with a simple DeMux based on a compact reflective grating [3].The experimental results of the coupler and the DeMux, and the analysis done on the system design, as well as some early results of the system, show that the total IL are lower than 17 dB per channel on a 50 m link of SI−POF. This scheme is enough to obtain a real improvement in the performance of commercial [7] and experimental transmission systems [1], [9], reaching speeds up to 3 Gbit/s over 50 m of SI−POF.

## 2. Description of the proposed SI-POF WDM System

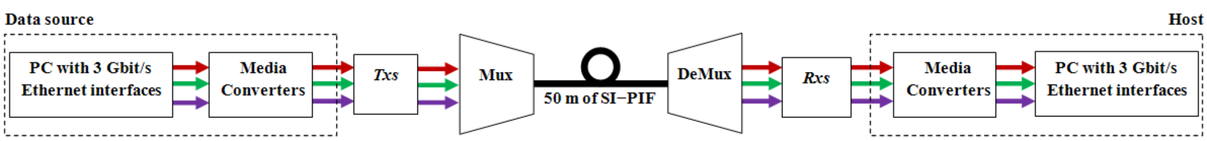


*Fig. 1: General description of the proposed SI−POF WDM system.*

Fig. 1 shows the general description of the proposed SI−POF WDM system. The objective is to obtain a real−time link between two points (data source and host) at data rates of about 3 Gbit/s using 3 channels. The data source and the host are equipped with Gigabit Ethernet interfaces in combination with Media Converters (MCs) to generate and to read the data bits, respectively. The MCs transform the standard Gigabit Ethernet frames into M−PAM signals (called *Tx*−signals), and vice versa. In the transmitters (*Txs*), the 3 different *Tx*−signals modulate the respective laser diode (LDs). These optical signals are multiplexed in a SI−POF link of 50 m. A reflective diffraction grating based DeMux is used at the end of the link to split the different channels to their respective receivers (*Rxs*). At the receivers the optical signals are converted back to electrical signals (*Tx*−signals) by using a commercially available receiver [7], and finally, the Ethernet frames are recovered by the MCs.

### 2.1. *Media Converters and Link Budget Requirements*

The Media Converters used in this work are commercial devices and their performance was presented in [7]. In that publication is shown that using a single channel at 650 nm with transmission power of −3.15 dBm and total IL up to 17.85 dB (at 25ºC) is possible to obtain a real−time 1 Gbit/s link over 50 m of standard SI−POF.

### 2.2. *Transmitters*

Three channels and commercially available LDs are considered for the design, with central wavelengths at 405 nm, 515 nm and 650 nm, which are close to channels number 1, 6 and 13 of the proposed POF WDM grid [2], respectively. The main characteristics of the LDs are shown in Table 1. All LDs include an internal monitor photodiode (MP) in order to stabilize the average optical power by varying their bias current (Ibias). In the transmitter, each LD is modulated in its linear region keeping constant its average power. The *Tx*−signal is amplified and then is mixed with the Ibias through a bias−tee, which is directly connected to the LD, as shown in Fig. 2.

*Table 1. Characteristics of the laser diodes considered in the system design.*

| Laser diode | Central Wavelength [nm] | Current [mA] Threshold | Operation | Optical power | Beam Divergence Perpendicular | Parallel |
|---|---|---|---|---|---|---|
| DL5146-101S | 405 | 35 | 70 | 40 mW (16.0 dBm) | 19º | 8º |
| PLT5 515 | 515 | 50 | 120 | 30 mW (14.8 dBm) | 22º | 7º |
| L650P0007 | 650 | 20 | 28 | 7 mW (8.5 dBm) | 28º | 9º |

## 3. Multiplexer (Mux)

In this work, we have designed and experimentally tested new multiplexers and demultiplexers proposals for the system implementation. Their main characteristics and performance are presented below.

The proposed Mux is very simple and its scheme is shown in Fig. 3. It consists of 3 inputs plastic optical fibers (called launching fibers) joined to form a fiber bundle of less than 1 mm of diameter, which is faced to the SI−POF input section.

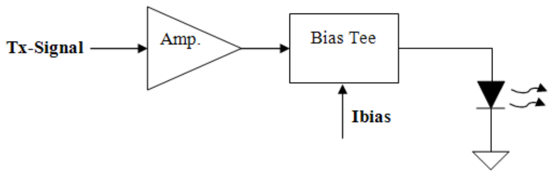


*Fig. 2: Transmitters modulation scheme.*

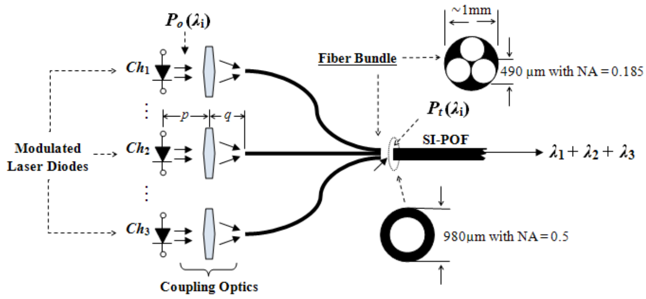


*Fig. 3: Multiplexer scheme.*

The launching fibers are made of 1 m of graded index plastic optical fibers (GI−POFs) with 120 $\mu$m core diameter, 490 $\mu$m cladding diameter and 0.185 numerical aperture (NA). And they are faced to a standard SI−POF section of 980 $\mu$m core diameter, 1 mm cladding diameter and 0.5 NA by using a ST−ST connector (the 3 launching fibers are placed together inside a ST connector). The power of each LD is injected in to the respective launching fiber using an aspheric lens pair with input to output NA relation of 0.55 to 0.15. This NA relation allows light coupling of any of the LD shown in Table 1 in the launching fibers with very good efficiency. The distance between the LD and the coupling optics is represented by $p$ and the distance from the coupling optics to the launching fiber is represented by $q$. Those distances depend on the LDs central wavelengths.

### 3.1. *Experimental Results*

At this point, the multiplexing scheme has been tested using the L650P007 LD ($ch_1$ at 650 nm). The results are summarized in Table 2. It is shown that the multiplexer IL at 650 nm is 1.4 dB (including coupling losses between the LD and the fiber), which represents an excellent performance, especially in comparison with the IL of a 2:1 SI−POF coupler [8], which is about 4.5 dB. The multiplexer IL at the other wavelengths is expected to be similar.

*Table 2. Results of the proposed multiplexer at 650 nm. $P_o$ is measured at the output of the LD, $P_L$ is measured at the output of the launching fiber and the $P_t$ is measured at the output of 1 m of SI-POF.*

| Laser diode | Central Wavelength | Emitting Power ($P_o$) | Launching Power ($P_L$) | Transmitted Power (Pt) | Multiplexing Efficiency | Insertion Loss (IL) |
|---|---|---|---|---|---|---|
| L650P0007 | 650 nm | 1.82 mW | 1.63 mW | 1.32 mW | 0.73% | 1.4 dB |

### *3.2. Multiplexer Scalability*

This multiplexing scheme can be easily extend to 4 channels using fibers with a smaller cladding diameter as shown in [6], but the IL can be increased. In order to keep the IL low while increasing the number of multiplexed channels, an extra coupling optics system must be included between the fiber bundle and the SI−POF. Some simulations have been done considering a bundle of 7 fibers and a coupling system (between the bundle and the SI−POF) composed by two lenses with arbitrary dimensions. The IL in this case was better than 2.2 dB for all the wavelengths.

## 4. Demultiplexer (DeMux)

In this section, a new low loss demultiplexer proposal for SI−POF WDM networks is presented. It is based on a collimator/focusing lens and a reflective diffraction grating. The diffraction grating has an area of 50 mm×50 mm, 600 grooves/mm and efficiency between 56% to 68% in the range from 400 nm to 650 nm. The grating area limits the collimation distance, or effective focal length (EFL), to be less than 45 m, in order to get a collimated beam diameter < 50 mm (this is an approximation considering SI−POFs with NA = 0.5). Therefore, the selected collimator/focusing lens has 50 mm diameter and 40 mm of EFL, in order to separate the different channels a distance greater than 2 mm without producing a beam greater than 50 mm in diameter. This guarantees a very low cross-talk between channels. In [3] you can find a detailed description about the design of diffraction grating based demultiplexers for SI−POF WDM networks.

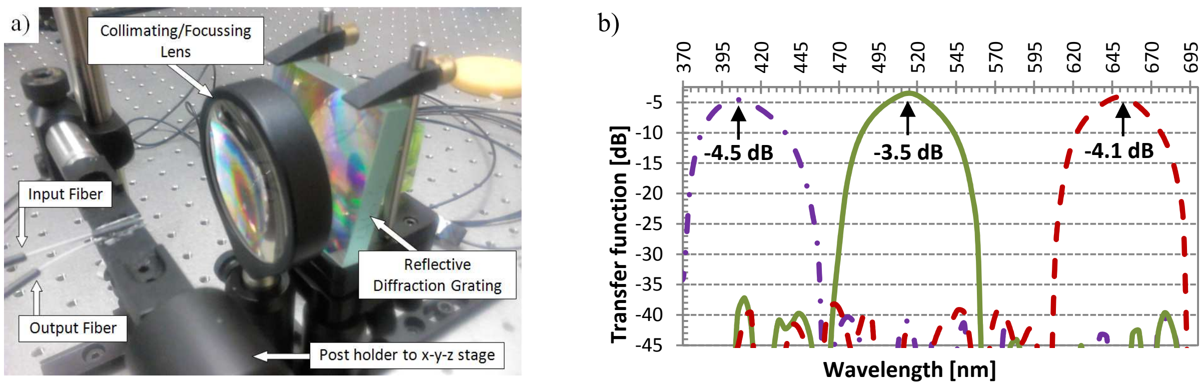


*Fig. 4: a) Proposed low-loss demultiplexer for POF-WDM networks. Ports are made of SI-POF. The lens have $f_C$ = 40mm (EFL) and 50mm CA. The diffraction grating has 600 grooves/mm and 50mm CA. b) Transfer function of the diffraction grating based DeMux: ports at 405nm (dash-dotted line), 515nm (solid line) and 650nm (dashed line).*

The DeMux experimental setup is shown in Fig. 4.a; it is composed by only two optical elements and it has ~60 mm diameter and ~70 mm length. Each output port has its own focusing distance due to the dispersion of the lens in the range from 400 nm to 650 nm. At this point, the output fiber is moved by using a 3-axes stage in order to place it in the position of each output port. Those coordinates will be used to manufacture the final output fibers holder. The IL of each port was measured using a white light source. The IL measurements were done following the next procedure: 1) the light source is connected to the spectrometer using 3 m of SI−POF, this represents the reference spectra (100% of transmission), 2) the 3 m of SI−POF is cut in half and each end is polished, 3) the SI−POF section attached to the light source is connected to the input port and the SI−POF section that is attached to the spectrometer is connected to the output port, 4) the transmitted power of each channel is measured moving the output fiber with the x-y-z stage. The IL of each channel in the range from 370 nm to 700 nm is shown in Fig. 4.b. It is shown that the IL per channel of the proposed demultiplexer is less than 4.5 dB. This value includes the IL produced by two polished surfaces. It is also shown that the adjacent channels crosstalk is less than −30 dB. It is important to note that the measurements under −40dB are limited by the spectrometer sensitivity. This DeMux is compact and presents one of the best performances reported to date with only 2 optical elements. Current works of the authors are aimed to increase the number of channels to 5 keeping the IL and CT below 5 dB and –30 dB, respectively.

## 5. Analysis of the early results of the proposed transmission system

The system has been experimentally tested using the channel at 650 nm. Fig. 5.a shows the transfer function of the 650 nm port, including 60 m of SI−POF and the DeMux. In this case, the IL at 650 nm is 14.14 dB. The experimental attenuation of the SI−POF used is ~0.17 dB/m, so the value of 14.14 dB is very close to the expected value (60 m × 0.17 dB/m + 4.1 dB = 14.3 dB). The overall system (Mux, 50 m of SI−POF and DeMux) test has been done with only the channel at 650 nm, using the LD L650P0007 with average transmitted power of 6 dBm (4 mW), and 50 m of SI−POF. In this case, the received power is of about −8.1 dBm (total IL of ~14 dB) which is enough to full fill the link budget and sensitivity requirements of the receiver [7], see Fig. 1. On the other hand, the system produces an opened eye diagram with NRZ signals up to 333 MHz, as shown in Fig. 5.b. Therefore, the bandwidth requirements for establishing the 1 Gbit/s link are also full filled [7], [10]. At this point, the 1 Gbit/s link at 650 nm was established (the synchronism was reached) but is unstable. This is because the optimum modulation factor and the average power of the LD driver have not yet been determined. Therefore, we can say that once the system stability is improved, the channels at 405 nm and 515 nm can be used to increase the transmission link capacity, up to 3 Gbit/s.

a) b)

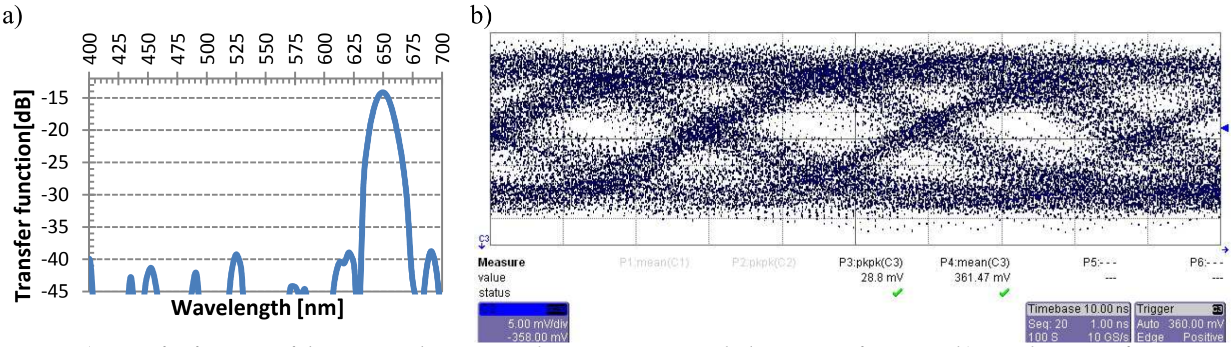


*Fig. 5: a) Transfer function of the proposed Demux at the 650 nm port, including 60 m of SI-POF. b) Eye diagram of the proposed system (Mux, 50 m of SI-POF and DeMux) at 650 nm with a NRZ signals of 333 MHz.*

## 6. Conclusions

In this paper we have presented a new scheme for SI−POF WDM that has the potential of transmitting at data rates up to 3 Gbit/s through a real-time link of 50 m. The Mux has IL of ~1.4 dB including the coupling from the LD to the fiber. The DeMux has IL < 4.5 dB in the 3 channels. Then, the Mux/DeMux scheme adds IL of less than 6 dB. The 1 Gbit/s link has been tested using the channel at 650 nm, with total IL of ~14 dB (Mux, 50 m of SI-POF and DeMux). The other two channels can be used to extend the transmission data rate up to 3 Gbit/s.

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