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LOW-LOSS 7-CHANNEL VISIBLE WDM SCHEME FOR IMPLEMENTING EFFICIENT DATA TRANSMISSION SYSTEMS OVER SI-POF

P. J. Pinzón[1*], C. Vázquez[1], I. Pérez[1] and J. Zubia[2]

1: Department of Electronics Technology, Carlos III University of Madrid, Avda. de la Universidad 30, 28911, Leganés (Madrid), Spain.
2: Electronics and Telecommunication Dpt., Universidad del País Vasco, Euskal Herriko Unibertsitatea, 48013, Bilbao (País Vasco), Spain.

*Corresponding author: ppinzon@ing.uc3m.es

Abstract: In this work, the design of a visible wavelength division multiplexing (WDM) scheme of 7 channels is presented. The multiplexing is performed using a fiber bundle based multiplexer with insertion losses (*ILs*) lower than 2.2 dB, including the losses by LDs' coupling. The channels separation is performed by using a compact demultiplexer based on a reflective diffraction grating. This demultiplexer is optimized to accommodate up to 8 channels in the range from 430 to 655 nm, with *ILs* lower than 4.5 dB per channel. The analysis done on the proposed WDM scheme shows that the total *ILs* included by multiplexing and demultiplexing are lower than 7 dB. This is enough to obtain a real improvement in the performance of commercial and experimental transmission systems based on visible WDM over SI–POF.

Key words: Demultiplexer, Multiplexer, Polymer Optical Fiber, Visible, Wavelength Division Multiplexing.

1. Introduction

Most important limitation of visible WDM links over the step–index polymer optical fiber (SI–POF) is the power penalty due to the multiplexers (mux) and demultiplexers (demux) high insertion losses (*ILs*), limiting the transmission capacity of each channel in comparison with single channel systems, for the same transmitted power [1]. 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 [2], [3]. Therefore, the development of mux/demux devices with lower *ILs* and higher channel counts than the current proposals is essential in order to implement efficient visible WDM based SI–POF links, working near the eye–safety–limit and using low–power technology [1], especially for In–Home and Office networks [4]. On the other hand, the design of mux/demux devices with a reduced size is another important requirement for the effective implementation of visible WDM based SI–POF networks.

In this work, the design of a complete SI–POF visible WDM scheme of 7 channels is presented. The multiplexing is performed using a low–loss mux of 7 channels based on a fiber bundle and a lenses system for coupling the light from the fiber bundle to the SI–POF. The mux's design and simulation are done using a sequential ray tracing software, considering the main optical power loss factors and the divergence of three commercial laser diodes (LDs) at 405, 520 and 660 nm. The channels separation is performed using a compact demux based on a reflective diffraction grating [5], optimized to accommodate up to 8 channels in the range from 430 to 655 nm with *ILs* lower than 4.5 dB per channel. The power budget analysis of the system is also presented. The low insertion losses of the proposed visible WDM scheme reduce the need of increasing the transmission power, in comparison with single channel systems, which is fundamental for implementing energy efficient technology.

2. 7–Channel Visible WDM Transmission System

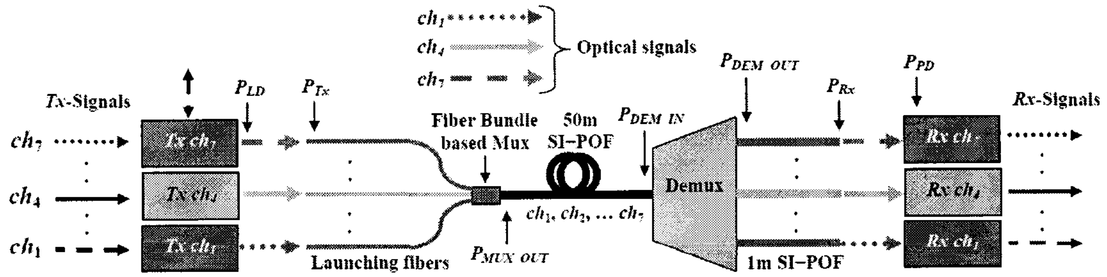

Fig. 1. Transmission scheme of the proposed SI-POF visible WDM system of 7 channels.

Figure 1 shows the general description of the proposed SI–POF visible WDM scheme. The objective is to obtain a low-loss link between two points for implementing an efficient WDM transmission using 7 channels. In the transmitters (*Txs*), the different transmission signals (*Tx*–signals) modulate the Laser Diode (LD) of the respective channel. A fiber bundle based multiplexer (mux) transmits the 7 channels over the SI–POF link of 50 m, and a diffraction grating based demultiplexer (demux) splits the different channels to their respective receivers (*Rxs*) at the end of the link. The optical signals are converted back to electrical signals (*Tx*–signals) at the receivers by using pin–photodiode based receivers.

2.1. Multiplexer

The proposed multiplexing scheme is shown in Fig. 2. It consists of three main sections. First, the light from each transmitter (laser diode, LD) is injected into different input fibers, through coupling lenses. Then, the 7 input fibers are joined to form a fiber bundle. And finally, they are multiplexed into a single SI–POF using a lens system.

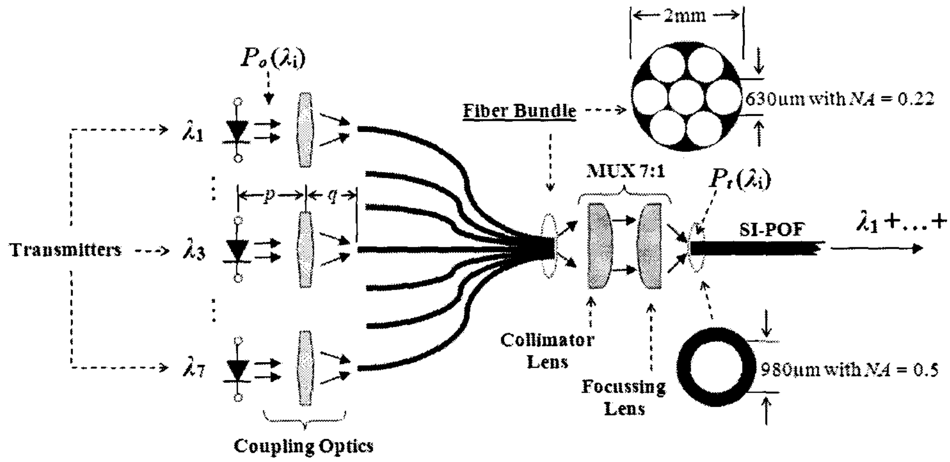

Fig. 2. Proposed 7:1 multiplexing scheme for multi–wavelength transmission over SI–POF networks.

The fiber bundle BF20HSMA from Thorlabs is considered. It is made of seven step–index silica multimode fibers; each one has 550 μm core diameter, 600 μm cladding diameter, 630 μm buffer diameter and 0.22 *NA*. The coupling of the different LD is done using the aspheric lens 352440 from LightPath. The optimal distances p and q (see Fig. 2) of each LD are found by optimizing the coupled power in the input fiber. Table 1 shows the coupling efficiency calculated from the characteristics of three commercial LDs, covering the visible spectrum (405, 520 and 660 nm). It can be shown that the coupling efficiency is over 69% (IL < 1.6 dB) in the three cases.

The multiplexing system is made up of a collimator lens and a focusing lens as shown in Fig. 2. Fig. 3 shows the multiplexing system layout. These lenses are not commercial, but are simple biconvex lenses. The material used for the collimator and the focusing lenses are N-LASF43 and N-LAK12, respectively. The radii of the surfaces 2, 3, 4 and 5 (see Fig. 3) are 7.404, -10.141, 2.337 and -1.441. Finally, the distances between the surfaces 1 and 2, 2 and 3, 3 and 4, 4 and 5, and 5 and the output are 7.091, 13.058, 14.162, 6.552 and 0.028 mm, respectively. A decenter coordinate is used to simulate the position of the input fibers in the bundle. The six outer fibers are at the same distance from the center, so they can be represented by the decenter value (0.630, 0.000) since the system is symmetric. The system has been designed so that the outer fibers have the best possible coupling.

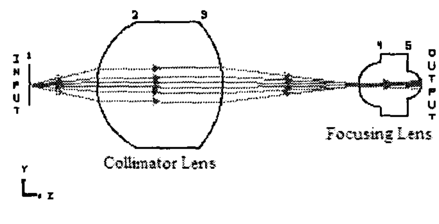

Fig. 3. Layout of the Multiplexing lens system.

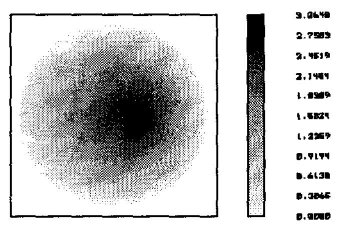

Fig. 4. Profile of a beam from the fiber bundle focused at the end face of the SI–POF, λ = 520nm.

The multiplexing lens system allows that more than 99% of rays fall on the end–face of the SI–POF with a *NA* lower than 0.5. So the multiplexing efficiency is determined by the Fresnel losses, scattering, the material absorption (air, fiber and glasses) and the imperfections of the fibers. These phenomena, except for the fiber imperfections, are considered in the efficiency calculations. It is also considered that the beams at the output of the fiber bundle have a diameter of 0.55 mm and *NA* of 0.22 with Gaussian profile. Fig. 4 shows the profile at the output surface (SI–POF) of a 520 nm beam that comes from an input fiber that is decentered 0.630 mm (one of the six outer fibers). It can be shown that most of the energy is focused at the center of the SI–POF. The coupling efficiency in this case is 89%. The multiplexing efficiency of 3 representative LDs in the visible range is shown on Table 1.

TABLE 1: Transmitters characteristics and efficiency of the proposed multiplexing system. The total efficiency includes the coupling and the multiplexing efficiencies and the attenuation of the input fiber (1 m).

LD	Wavelength	Beam Divergence		Efficiency % (*Eff*)			*IL* = −10log(Total *Eff*)
		Perpendicular	Parallel	Coupling	Multiplexing	Total	
DL–5146–101S	405 nm	19°	8°	0.74	0.82	0.60	2.22 dB
PL 520	520 nm	22°	7°	0.69	0.89	0.61	2.15 dB
HL6544FM	660 nm	17°	10°	0.83	0.89	0.74	1.31 dB

From the results shown on Table 1 we can say that the proposed multiplexer has insertion losses lower than 2.5 dB per channel, in the range of 405 nm to 660 nm.

2.2. Demultiplexer

The demultiplexing is performed using the low–loss 8-channel mux/demux reported in [5], but excluding the channel at 625 nm due to the high attenuation of the fiber. It is based on a collimator/focusing lens and a reflective diffraction grating. The transfer function of each mux/demux channel is shown in Fig. 5. The central wavelengths are λ_1 = 430 nm, λ_2 = 465 nm, λ_3 = 497 nm, λ_4 = 530 nm, λ_5 = 562 nm, λ_6 = 595 nm, λ_7 = 655 nm for channels ch_1 to ch_7, respectively. The *ILs* < 4.5 dB with uniformity of 1.3 dB and the crosstalk attenuation is greater than 30 dB (inside of the 3 dB bandwidth of each channel). The spatial separation between consecutive channels (ports) is greater than 1.23 mm, with total separation of S = 8.84 mm. The size is about 57 mm × 50 mm (height × length). The spectral band–pass bandwidth at –3 dB of all the channels is greater than 20 nm, and their spectral band–pass bandwidths at –25 dB are between 12 and 21 nm. Fig. 5 also shows the experimental attenuation of the SI–POF considered for the link.

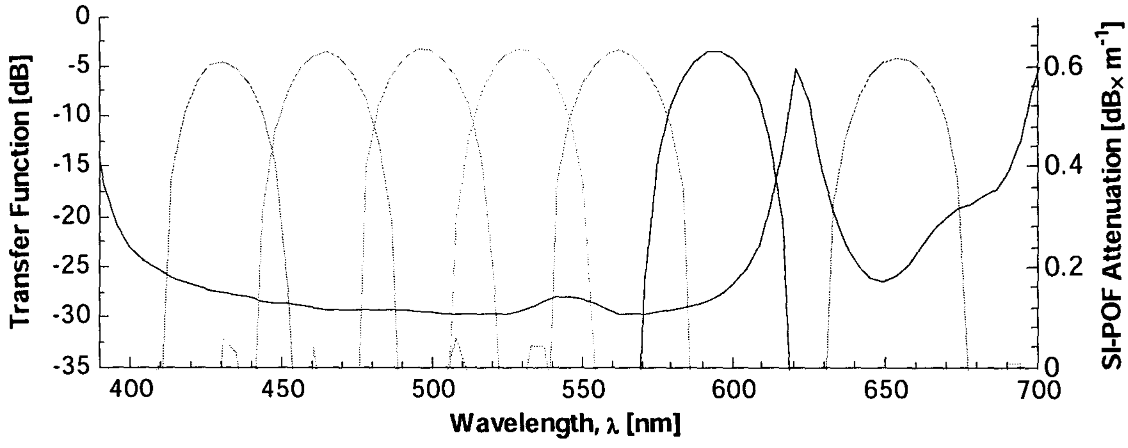

Fig. 5. 7–channels mux/demux transfer function (left axis) and measured SI–POF attenuation (right axis, solid line).

3. Power Budget Analysis

Table 2 shows the Loss budget of the proposed WDM system, considering the SI–POF attenuation, the multiplexing and demultiplexing losses. Where P_{Tx} is the average power coupled to the launching fiber; P_{MUX_OUT} is the average power coupled to the SI–POF; P_{DEM_IN} and P_{DEM_OUT} are the average powers at the input and at the output of the demultiplexer, respectively; P_{Rx} is the average power at the end of the SI–POF link; and P_{PD} is the average power at the receiver's photo–detector (see Fig. 1). It is also shown that the experimental receiver sensitivity at 650 nm is –18.85 dBm. This value is measured as the minimum power required at the receiver to obtain a signal to noise ratio (SNR) lower than −25.4 dB, for 1 Gb/s operation.

The Loss budget presented on Table 2 shows that the insertion losses due to multiplexing and demultiplexing are lower than 7 dB per channel, including the LD coupling losses, that the total losses of the complete visible WDM system are lower than 17.6 dB, and that the required power per channel for a 1 Gbit/s operation is lower than 0 dBm.

Table 2: Loss budget of the proposed visible WDM system.

Parameter	ch_1 (430nm)	ch_2 (465nm)	ch_3 (497nm)	ch_4 (530nm)	ch_5 (562nm)	ch_6 (595nm)	ch_7 (655nm)
Mux IL (dB)				$< 2.5^{(1)(2)}$			
SI-POF attenuation (dB) $^{(3)}$	7.4	5.8	5.4	5.7	5.3	6.8	9
DeMux IL (dB)$^{(3)}$	4.5	3.6	3.4	3.2	3.4	3.5	4.1
R_X lens coupling loss (dB)$^{(4)}$				2			
Total Losses	16.4	13.9	13.3	13.4	13.2	14.8	17.6
PD Sensitivity (dBm)	$-16.5^{(5)}$	$-17.2^{(5)}$	$-17.6^{(5)}$	$-17.8^{(5)}$	$-18^{(5)}$	$-18.3^{(5)}$	$-18.85^{(3)}$
Min. LD Power (dBm) $^{(5)}$	-0.1	-3.3	-4.3	-4.4	-4.8	-3.5	-1.25

Notes: (1) Simulation based on ray tracing; (2) Maximum value for channels in the range from 405 to 660 nm (see Table 1); (3) Experimental values; (4) Mean value taken from SI-POF receiver [6]; (5) Approximation from the receiver responsivity and the receiver sensitivity at 655 nm for the 1 Gbit/s operation of a fully integrated SI-POF media converter [6] (the difference between this approximation and the experimental value at 405 nm is 0.27 dB); (6) Minimum power required considering a link margin of 0 dB.

4. Conclusions

The design of a complete visible wavelength division multiplexing (WDM) scheme of 7 channels, in the spectral range from 430 to 655 nm, has been presented. It is composed by a fiber bundle based multiplexer, with *ILs* lower than 2.5 dB per channel, and a compact diffraction grating based mux/demux, with *ILs* lower than 4.5 dB per channel. The analysis done on the proposed visible WDM scheme shows that the total insertion losses included by multiplexing and demultiplexing are lower than 7 dB. This is enough to obtain a real improvement in the performance of commercial and experimental transmission systems. The low insertion losses of the proposed visible WDM scheme reduce the need of increasing the transmission power, in comparison with single channel systems, which is fundamental for implementing energy efficient technology.

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