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Demonstration of a data transmission system with visible wavelength division multiplexing at 3-Gb/s over 50-m of plastic optical fiber

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ABSTRACT:

In this paper, a real–time data communication system based on a step−index polymer optical fiber (SI−POF) link of 50 m and a 3–channel visible wavelength division multiplexing (visible WDM) scheme is demonstrated. Special care on implementing low insertion loss multiplexers/demultiplexers is carried out to allow for greener solutions in terms of power consumption. The system performance has been experimentally tested using the first and last channels of the 3–channel available grid. The results show that the system can establish a real–time link with connection speed of up to 2 Gb/s with bit error rate $<1\times10^{-10}$ over 50 m of SI−POF, and having the potential for expanding its data transmission speed up to 3 Gb/s.

Key words: Data transmission system, visible wavelength division multiplexing, polymer optical fiber, multiplexing, demultiplexing, real-time, Gigabit Ethernet.

1.- Introduction

Primarily due to the 'do–it–yourself' installation, easy maintenance and high bending tolerance, large core step–index (SI) plastic optical fibers (POFs) are considered more suitable than 50 μm core diameter multimode glass optical fibers (GOFs), perflourinated POFs or graded index POFs in many short–range applications [1], specifically, in scenarios such as Local Area Networks (LANs), In–Home and Office networks [2], as well as in Automotive [3] and Avionic multimedia buses, or in Data Center interconnections [4]. 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 Gb/s, exceeding the capabilities of current networking technologies (twisted pair, coax cable, Ethernet Cat–5 cable, powerline and wireless) [5]. On the other hand, SI–POF technology has also an important application niche in providing a solution to the exponential growth of infotainment devices within the car, along with the proliferation of ADAS (Advanced Driver Assistance Systems) that has created a demand for a more efficient way to interconnect devices within the automobile. ADAS global market is substantially growing in recent years and requires increasing the available bandwidth, nowadays up to 1 Gb/s [6] and potentially, in the near future, up to 5 Gb/s [7].

Gigabit/s transmission capacity of SI–POF links has been widely demonstrated in recent years [8], using single channel based systems, typically at 650 nm, with different advanced modulation formats and/or adaptive electrical equalization techniques. Reported simulations show that data rates of 1.25, 2.1 [9] and even 6.2 Gb/s [10], via up to 50 m, can be reached. Some experimental systems demonstrate data rates of Multi–Gb/s up to 50 m [11] and 3 Gb/s over 25 m using 8–PAM [12]. Moreover, fully integrated systems that offer real−time SI−POF links at

1 Gb/s via up to 50 m using 16−PAM modulation have also been reported [13].

After exploiting the capabilities of single channel transmission [11], visible wavelength division multiplexing (visible WDM) is proposed as a solution to expand the transmission capacity of SI–POF based systems. To date, there are several proposals of modulation methods [11], spectral grids [14] and multiplexer/demultiplexer (mux/ demux) devices [15] that allow to implement transmission systems based on visible WDM at data rates (R) of Multi−Gb/s over SI−POF links. Current proposals for visible WDM transmission over SI–POF are based on spectral grids with channels between 400 and 700 nm, using laser diodes (LDs) or light emitting diodes (LEDs) based transmitters. Visible WDM systems using offline–processed DMT modulation, and R up to 21.4 Gb/s [4] over 50 m, and 8.26 Gb/s over 75 m, with 6 and 4 unidirectional channels, respectively, with bit error rate (BER) of 1×10^{-3}, have been recently reported.

In this paper, the design of a real−time (RT) visible WDM system over SI−POF for an efficient performance in terms of Ethernet Throughput × Length ($T\times L$) is presented. The system performance is tested using the extremes channels of the 3–channel available grid.

2.- Data Transmission Setup

Fig. 1 shows the general description of the proposed visible WDM SI−POF transmission system. The objective is to obtain a real−time link between two points (client and server) at data rates of 3−Gb/s using 3 channels. The PCs are equipped with 3 Gigabit Ethernet interfaces in combination with 3 Media Converters (MCs) used to generate and to read the transmitted data bits, respectively. The MCs transform the standard Gigabit Ethernet frames into 16−PAM signals (called *Tx*−signals), and vice versa. In the transmitters (*Txs*), the different *Tx*−signals modulate the Laser Diode (LD) of the respective channel. A fiber bundle based multiplexer (mux) transmits the 3 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 a pin–photodiode based receiver, and finally, the Ethernet frames are recovered by the MCs.

2.1.- Media Converters

MCs are part of a fully integrated system [13] that is able to establish a 1 Gb/s link over up to 50 m of SI−POF using a LED based transmitter at 650 nm with average power of –3.15 dBm (power coupled to the fiber) and a pin–photodiode receiver with sensitivity of about –20 dBm for 1 Gb/s operation at 650 nm [13]. In the proposed system, the LED transmitter of each MC is replaced by different LD based transmitters. Therefore, the MCs are only used to encode the Ethernet frames into 16–PAM signals, and vice versa. The Ethernet frames are encoded into 16−PAM symbols using a technique called Multi−Level Coset Coding (MLCC). Details about the signal encoding can be found in [16]. Fig. 2 shows an example of the 16–PAM signal generated by the MCs (*Tx*–signal). This is a differential signal composed by the single–ended signal Tx^+

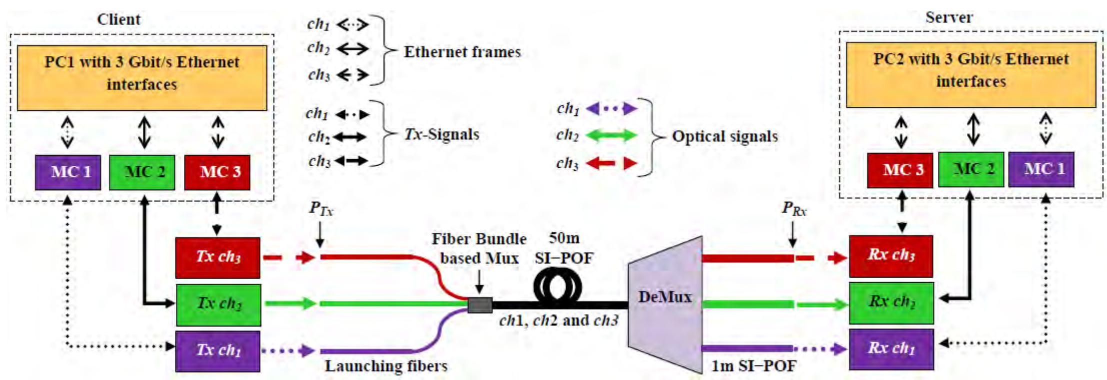

Fig. 1: Transmission scheme of the proposed SI–POF visible WDM system with 3 channels between 400 and 700 nm.

and Tx^{-}. In the visible WDM system, the channels reception is done using the SI–POF receiver available in the MC boards.

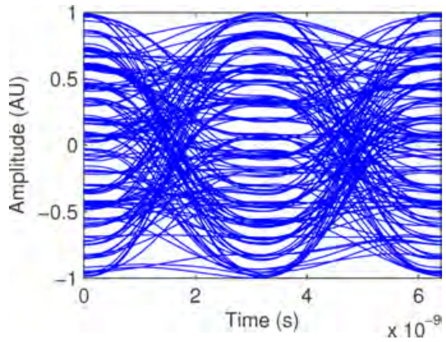

Fig. 2: Example of the Eye diagram of the 16–PAM signal (Tx–signal).

2.2.- Transmitters

A 3−channel spectral grid and the characteristics of commercially available LDs are considered for the transmitters design. The central wavelengths of the channels ch_1, ch_2 and ch_3 are 405, 520 and 650 nm, which are close to channels number 1, 7 and 13 of the visible WDM SI–POF grid proposal of [14], respectively.

2.3.- Multiplexers and Demultiplexers

The multiplexing is performed using a fiber bundle based coupler [17]. 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. The launching fibers are made of 1 m of graded index plastic optical fibers (GI−POFs) with 120 μm core diameter, 490 μm cladding diameter and 0.185 numerical aperture (NA). They are faced to a standard SI−POF section of 980 μm 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 multiplexer *ILs* are between 1.4 and 2 dB, including coupling losses between the LD and the fiber.

The demultiplexing is performed using a low insertion loss (*IL*) 3–channel demux [17]. It is based on a collimator/focusing lens and a reflective diffraction grating. The transfer function (P_{Rx}/P_{Tx}, see Fig. 1) of each channel is shown in Fig. 3. The *ILs* are lower than 4 dB with uniformity of 1.1 dB. The spectral band–pass bandwidth at −3 dB of all the channels is greater than 30 nm. In Fig 3, it is also shown the attenuation of the SI−POF used in the link.

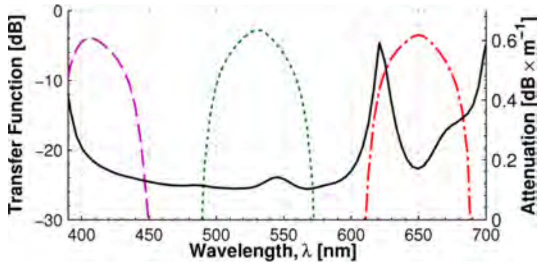

Fig. 3: 3-channels demux transfer function (left axis) and measured SI−POF attenuation (right axis, solid line).

3.- Experimental Results

In this section, the experimental characterization of the visible WDM SI−POF transmission system is presented.

3.1.- Link Power Budget

Main limitation of visible WDM links over SI–POF is the power penalty due to the muxes/demuxes *ILs*, limiting the transmission capacity of each channel in comparison with single channel systems. The optical power budget of the visible WDM system is measured following the schematic shown in Fig. 4. Where P_{LD} is the average power emitted by the LD; 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 aver-

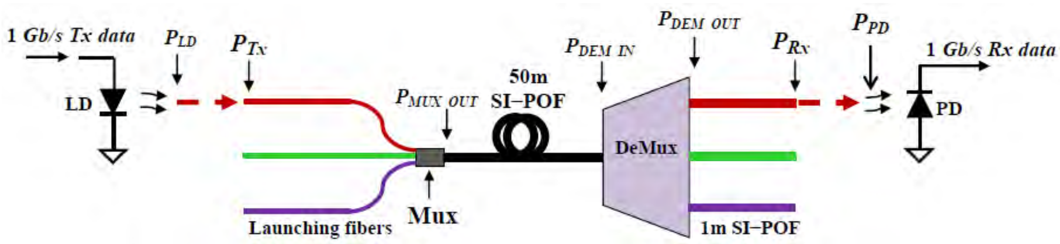

Fig. 4: Transmission schematic used for power budget measurements.

age power at the receiver's photo–detector. All the average optical power measurements are performed with a silica switchable gain detector.

3.1.1.- Receiver Sensitivity

The power budget of the visible WDM system is directly affected by the receiver sensitivity at the different wavelengths ($S_{Rx\lambda}$). There is no accurate information about the photo–detector spectral responsivity ($\mathcal{R}_\lambda$), so the silicon pin photodiode responsivity, shown in Fig. 4, is considered [4].

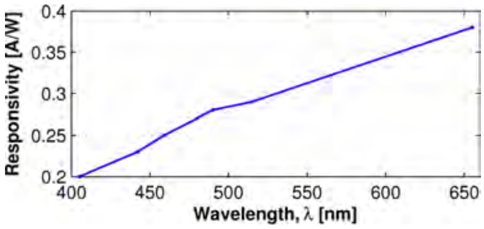

Fig. 4: Typical responsivity curve of a silicon pin–photodiode.

A responsivity decrease can be considered as losses in the power budget of the link or as an increment in the receiver sensitivity at a fixed wavelength. Therefore, the receiver sensitivity at the different wavelengths can be approximated as:

$$S_{Rx\lambda} = S_{Rx|\lambda=650nm} - 10 \times \log_{10}\left[\frac{\Re_\lambda}{\Re_{\lambda=650nm}}\right] \quad (1)$$

From Fig. 4, it can be shown that the silicon photo-detector responsivity $\mathcal{R}_\lambda$ at λ = 405, 520 and 650 nm is about 0.2, 0.29 and 0.38 A/W. The 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. Therefore, the receiver sensitivity at λ = 405 and 520 nm can be approximated to –16.06 and –17.68 dBm, which represents variations of 2.79 and 1.17 dB from the receiver sensitivity at 650 nm, respectively.

3.1.2.- Approximated Power Budget

Table 1 shows the approximated power budget of the proposed visible WDM system, considering the SI–POF attenuation, the multiplexing and demultiplexing losses and the receiver sensitivity variation from sensitivity at 650 nm for 1 Gb/s operation, see (1). It can be shown that the P_{LD} of each channel for 1 Gb/s operation must be greater than 2.52, –5.94 and −3.12 dBm.

3.1.3.- Measured Power Budget

The power budget of the first and last channels in the proposed visible WDM SI–POF system has been experimentally measured. The receiver sensitivity at 650 nm and at 405 nm is –18.85 dBm and –15.79 dBm, respectively. The difference between the sensitivity at 650 nm and at 405 nm is 3 dB, which is close to the 2.79 dB approximation obtained from Fig. 4 and (1), see Table 1. The power transmitted by ch_1 is 9.27 dBm with a resulting link margin of 6.52 dB. And the power transmitted by ch_3 is 3.72 dBm with a resulting link margin of 6.87 dB. These values are in agreement with the approximations made in the previous section 3.1.2. An extra loss of 2 dB is included in the power budget calculation due to the receiver coupling lens (R_X lens IL). It is a mean value taken from [13].

Table 1: Approximated optical power budget of the proposed visible WDM system (50 m @ 1 Gb/s).

Parameter	Calculation	ch_1 (405 nm)	ch_2 (520 nm)	ch_3 (650 nm)
P_{LD} (dBm)	----	2.52$^{(1)}$	–5.94$^{(1)}$	–3.12$^{(1)}$
SI–POF attenuation (dB)	$P_{MUX\ OUT} - P_{DEM\ IN}$	10.58	5.24	8.53
Mux IL (dB	$P_{LD} - P_{MUX\ OUT}$	2	1.5	1.4
Demux IL (dB)	$P_{DEM\ IN} - P_{Rx}$	4	3	3.8
R_X lens coupling loss (dB)	-----	2	2	2
PD Sensitivity at 650 nm (dBm)	-----	−18.85	−18.85	−18.85
Losses due to photosensitivity variation (dB)$^{(2)}$	-----	2.79	1.17	0
PD Sensitivity (dBm)$^{(3)}$	-----	–16.06	–17.68	–18.85
Received Power (dBm)	$P_{Rx} - R_X$ lens IL	–16.06	–17.68	–18.85
Link margin (dB)		0	0	0

Notes: (1) A link margin of 0 dB is considered. (2) From the photosensitivity curve shown in Fig. 4, see (1). (3) Calculated from 650 nm PD Sensitivity, see (1).

3.2.- Data Throughput

The visible WDM link is evaluated using the monitoring features of the MC boards. In both channels tested, the transmission speed of the physical layer (PHY rate) is 1035.78 Mb/s (for 1 Gb/s data rate) with BER < 1×10^{-10}, the data transmission rate achieved was 980 Mb/s (using a traffic generator software), which represents the 100% of the transmission rate achieved with a direct Ethernet cable between the PC1 and PC2 (100% throughput).

3.3.- BER and Data Throughput

The BER has a direct impact over the data throughput (percentage of Ethernet frames transmitted with no errors × the physical layer rate, *R*). A BER of 1×10^{-3} can reduces the Ethernet throughput to 39% of the physical layer rate, considering the minimum size of TCP/IP frames (64 Bytes). However, a BER < 1×10^{-10} keeps the 100% of the physical layer rate, even for big Ethernet frames (1518 Bytes × 16) [18].

4.- Conclusion

The performance of the proposed visible WDM link has been evaluated using channels ch_1 and ch_3. In both channels, the transmission speed of the physical layer (PHY rate) is 1035.78 Mb/s, for 1 Gb/s data rate, with BER < 1×10^{-10}, which represents an error free transmission. The Ethernet data transmission rate achieved in each channel is 980 Mb/s (using a traffic generator software), which represent the 100% of the transmission rate achieved with a direct Ethernet cable between the PC1 and PC2 (100% throughput due to the BER < 1×10^{-10}). The system has the potential of expanding the transmission data rate up to 3 Gb/s in longer distances, with better Ethernet Throughput than recent proposals. This represents a real improvement in the performance of commercial and experimental SI−POF transmission systems.

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