Discrete Multi-Tone Transmission over Step Index PMMA optical fibre for Short-Range Optical Communication

Flávio André N. Sampaio, Vinicius N. H. Silva, Luiz Anet Neto, Tadeu N. Ferreira, Andrés Pablo L. Barbero, Ricardo M. Ribeiro

***Abstract*— In this article we present high spectral efficiency DMT transmissions over 20 m of Step-Index polymethyl methacrylate optical fiber in the visible range. We demonstrated that using illumination light emitting diodes at 450, 520, 560 and 650 nm it is possible to achieve as high as 6.39 bits/s/Hz for a pre-Forward Error Correction target Bit Error Rate of 10^{-3}. The 560 nm optical source was developed in our lab and it can be used as a new channel in WDM system.**

Keywords—Discrete Multi-Tone Transmission, Plastic Optical Fiber, Wavelength Division Multiplexing.

I. INTRODUCTION

The worst disadvantages of step-index polymethyl methacrylate (SI-PMMA) optical fibers are its high attenuation profile and high modal dispersion limiting the distance and capacity of the communication link [1]. However, plastic optical fiber (POF) has several advantages such as low cost, immunity to electromagnetic interference (EMI) and easy handling. These characteristics put the POF as an excellent solution for short range communication. Indeed, this technology is already used in vehicles to provide communication between sensors, radio, GPS and in home networks to provide high communication data rates [2-3]. It is important to highlight that POF is not merely a promising solution; it is already in the market and being used in the development of new device and applications.

Several articles demonstrating data transmission in POF up to Gbps over 20, 50 and 100m [4] have been published in the literature. These articles have shown the possibilities of communication systems and links with different types of modulation and multiplexing techniques, light sources and filters [x]. Furthermore, laser diodes (LD), light emitting diodes (LED) and optical filters at different wavelengths became accessible in the market allowing an improvement on transmission capacity by means of wavelength division multiplexing (WDM), which is a consolidated technology for silica fibers [5]. However, the use of WDM in POF has not yet been widespread for data communication due to the high insertion losses caused by the light multiplexers and demultiplexers [6]. The very high single-wavelength bit-rates already demonstrated over POF prove that WDM for POF is still an open research field.

As a matter of fact, increasing the capacity of a WDM system can be achieved by either improving the single channel transmission, or adding new wavelength channels. Thus, since the attenuation profile in PMMA POF depends on its inherent characteristics, the solution to make higher bit-rates per wavelength is changing the modulation or multiplexing technique to mitigate the modal dispersion. On the one hand, Discrete Multitone (DMT) is a good candidate to increase the spectral efficiency [7]. On the other hand, a new wavelength optical carrier can be added to a WDM system if new optical sources and filters are developed. Many WDM techniques can have been reported in the literature recently [8]. However, none of them explore the yellow/orange transmission window (560-600 nm) because semiconductors compounds such as GaAsP, AlGaInP and GaP:N are not interesting materials allowing to develop fast, efficient and fiber-integrable sources at such window [6].

In this paper, we experimentally demonstrate high spectral efficiency transmissions using DMT in SI PMMA plastic optical fiber at 450, 520, 560 and 650 nm. The 560 nm channel uses a light source developed in our lab [9]. It consists of a commercial fluorescent plastic optical fibre pumped by a green LED at 520 nm. This device is lightweight, eye-safe, compact and we show that can be used as a new optical carrier to increase the capacity of WDM communication system. We have shown data rates up to 127 Mbps for a pre forward error correction(FEC) target bit error rate (BER) of 10^{-3} over 20 m of SI-POF by means of simple direct intensity modulation with direct detection. Transmission spectral efficiencies as high as 6.39 bits/s/Hz and aggregate data bit rates up to 455 Mbps are demonstrated.

II. PRELIMINARY ASSESSMENT OF THE EMITTERS

Figure 1 shows the spectral characteristics of the optical sources used in the transmissions experiments. Their full width at half maximum (FWHM) are 34 nm, 40 nm, 31 nm and 22 nm for blue, green, yellow and red, respectively.

Flávio André N. Sampaio, Vinicius N. H. Silva, Tadeu N. Ferreira, Andrés Pablo L. Barbero and Ricardo M. Ribeiro, Universidade Federal Fluminense (UFF), Niterói-RJ, Brazil, E-mails: vinicius.nhs@gmail.com.
Luiz Anet Neto, Orange Labs, Lannion, France.

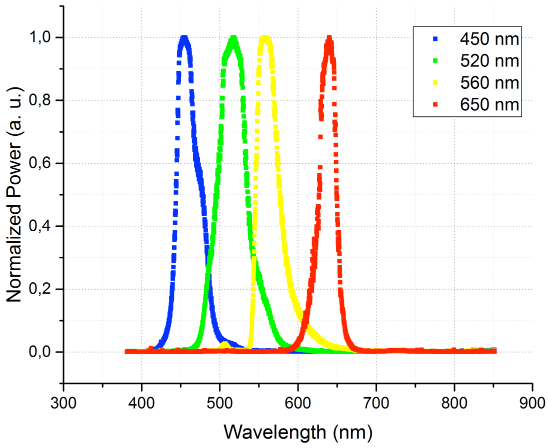

Fig. 1 – Spectrum of the used LEDs.

In Fig. 2 we show back-to-back frequency domain channel measurements obtained with a network analyzer. They allow us to measure the emitters' bandwidths at -3 dB, which will serve as reference values for choosing the DMT signal bandwidths. Respectively 24 MHz, 17 MHz, 10 MHz and 9 MHz are found for blue, green, yellow and red.

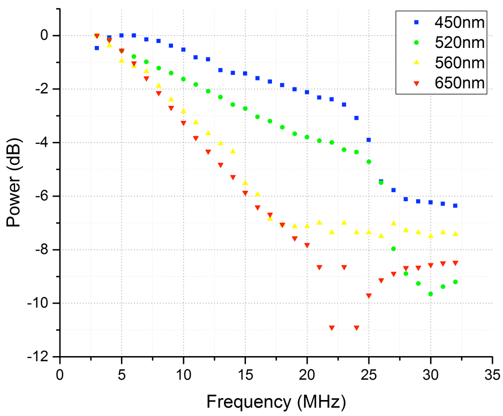

Fig. 2 – Bandwidth characteristics the LEDs.

I. DMT Transmission Block

The offline transmissions for all the optical carriers were done following the diagram in Figure 3. At the transmitter, a Pseudorandom Binary Sequence (PRBS) sequence is parallelized into lower bit-rate sequences. After that, they are mapped into M-ary quadrature amplitude modulation (QAM) symbols (M= 1, 4, 8, …, 64) forming a subcarrier matrix (SM). In order to have a real discrete signal for direct intensity modulation and direct detection, the SM should be rearranged to satisfy the Hermitian symmetry [10]. Then, each subcarrier into SM are multiplexed by applying the inverse fast Fourier transform (IFFT). A cyclic prefix (CP) is added to each time-domain DMT symbol to increased robustness against intersymbol interference (ISI) and to make the channel estimation, equalization and time synchronization as simple as possible. The signal is serialized (P/S) and then converted to analogic by a digital-to-analog converter (DAC). The electrical signal modulates the LEDs optical carriers, which are biased to operate in the linear region, at 450 (blue), 520 (green), 560 (yellow) and 650 (red) nm.

The signal propagates through SI-POF and at the receiver side an analog-to-digital converter (ADC) digitizes the signal.

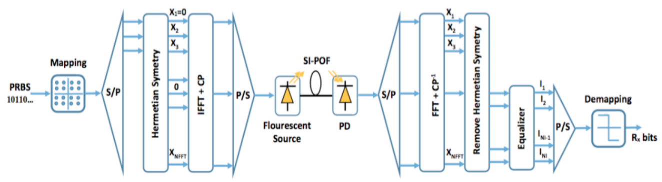

Fig. 3 – DMT transmission block diagram.

The digital signal is then time synchronized and converted from serial to parallel (S/P) before direct Fourier Transformation (FFT). The CP is removed, and the signal is frequency synchronized and equalized. Error vector magnitude (EVM) and signal-to-noise (SNR) are measured on the received symbols and finally the QAM symbols are demapped to provide actual BER measurements.

The bit and power optimization per subcarrier of the DMT signal is implemented in two steps. First, a probe signal is transmitted in which all subcarriers have the same power and are QPSK modulated. The first step allows measuring the signal-to-noise ratio (SNR) of the channel, which will be used by the rate-adaptive version of the Levin-Campello algorithm. The basic idea of this algorithm is to maximize the overall bit-rate of the transmission as a function of a global signal power constraint and a target mean BER over all subcarriers. It is a greedy algorithm whose principle is to fulfill with more information (higher QAM modulation levels) the subcarriers with better SNR so that the overall bit-rate can be maximized. It then compensates the SNR fluctuations on subcarriers with the same modulation levels by changing the relative power coefficient of each subcarrier individually. In the second step of the transmission, a signal with the proper modulation and power coefficient per subcarrier is sent and a mostly constant BER over all subcarriers equal to the target BER is found.

The Levin-Campello algorithm itself has two phases. Starting from the initial two bits per QAM symbol (QPSK) on all subcarriers, the algorithm first "efficientizes" the bit-distribution. A bit-distribution is said to be efficient when there is no movement of a bit from one subcarrier to another that reduces the total energy of the DMT symbol. This replaces one bit-distribution with another closer to the efficient through single-information unit changes between subcarriers until no more changes can be done. An additional step is then necessary in order to adapt the total DMT symbol bit-rate with respect to the energy constraint. The second phase of the algorithm is known as "E-tight". E-tightness implies that no additional unit of information can be carried by the DMT signal without violating the total energy constraint.

DieMount, a fluorescent optical source (560 nm) [9], 20 m of SI-POF, a photodetector (Thorlabs PDA10A) and an oscilloscope (Rohde&Schwarz RTO 1002) to digitize the received signals.

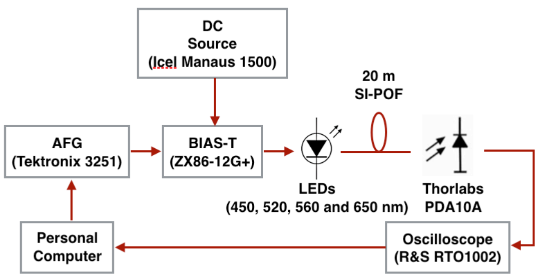

Fig. 4 –Block diagram of the experimental setup.

All the transmissions were adjusted to have the same mean optical power at the photodetector for all operating wavelengths so that a fair comparison can be made between among all emitters. All the baseband signals consisted of a 20 MHz real-valued DMT signal with 491 useful subcarriers (IFFT size = 984 considering DC and Nyquist null subcarriers). 16 samples per symbol are used as CP. The total DMT symbol duration is 25 µs, of each 24.6 µs are the useful data and 0.4 µs represent the guard interval. The DAC and ADC operate at 100 MSa/s and 400 MSa/s respectively. SNR, root-mean square error vector magnitude EVM (EVM_{RMS}) and BER per subcarrier are finally assessed over 1000 DMT symbols.

III. Results and Discussions

As previously mentioned, the first step of the transmission is to send the probe signal to characterize the channel (SI-POF). The resulting received spectra and performance indicators are respectively shown in Figure 5 (bottom) and Figure 6 for all the sources. Figure 5 (top) also shows an example of received signal in the time domain with 80 DMT symbols.

It can be seen from Figure 5 (bottom) that the channel acts as a low pass-filter and that for frequencies below 1.5 MHz some degradation can be seen due to the bias-t response. This confirms the preliminary bandwidth assessment of Fig. 2. The difference between the roll-offs in Figure 5**Fig**. *5* (bottom) for each optical source is due to the frequency response of the LEDs themselves.

IV. Experimental Setup

The experimental setup (Figure 4) consists of personal computer (PC) that performs DMT modulation/demodulation, an arbitrary function generator (Tektronik AFG3251), which works as a DAC, a bias-T (Mini-Circuits ZG85-12G+), a DC source, illumination LEDs (450, 520 and 650 nm) from

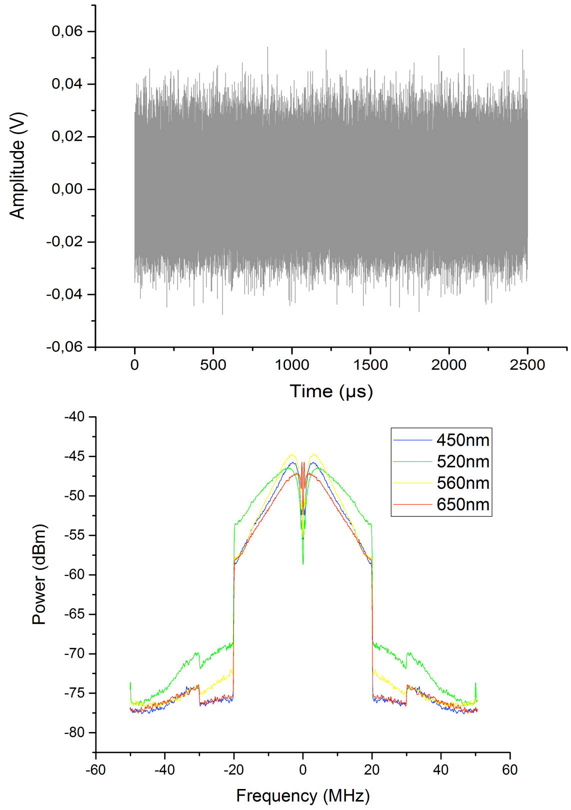

Fig. 5 - Received time domain signal and frequency domain power after 20 m of SI-POF, respectively.

In Fig. *6*, from top to bottom, are the relative power coefficient (ρ) in dB, the number of bits per QAM symbol (log2(M)=2 for QPSK), the measured EVM_{RMS}, the SNR estimated from the EVM and the estimated BER for all subcarriers found with the probing signal. For concision matters, only the result for 450 nm is shown in Fig. *6*. The others optical sources have the same behavior and follow the frequency profiles of Fig. *5* (bottom).

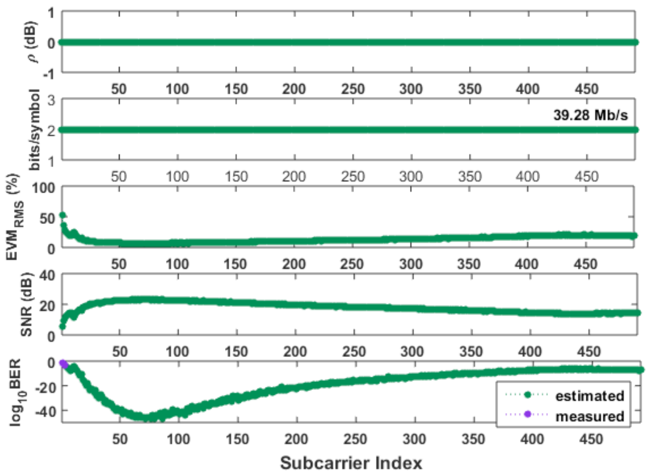

Fig. 6 – DMT probe signal results with the LED at 450 nm showing the relative power coefficient, the number of bit per QAM symbol, the EVM, the SNR and BER per subcarrier.

After sending the probe signal to evaluate the channel for each optical source (450, 520, 560 and 650 nm), several transmissions were done for different pre-FEC targets BER (10^{-3}, 10^{-6}, 10^{-9} and 10^{-12}) using the bit and power-loading algorithm. It can be seen in Fig. *7* that the highest spectral efficiency achieved was 6.39 bits/s/Hz for a pre-FEC target of 10^{-3} at 450 nm leading to a bit rate of 127 Mbps. After the demapping of the symbols, it is observed that the estimated BER from the SNR (green points) is in very good agreement with the measured BER (purple points) and that the target BER has been achieved. Indeed, a mean BER of $8.4 \cdot 10^{-4}$ is achieved. Besides, modulation levels as high as 128QAM (7 bit/symbol) were reached in 320 of 491 subcarriers (65%).

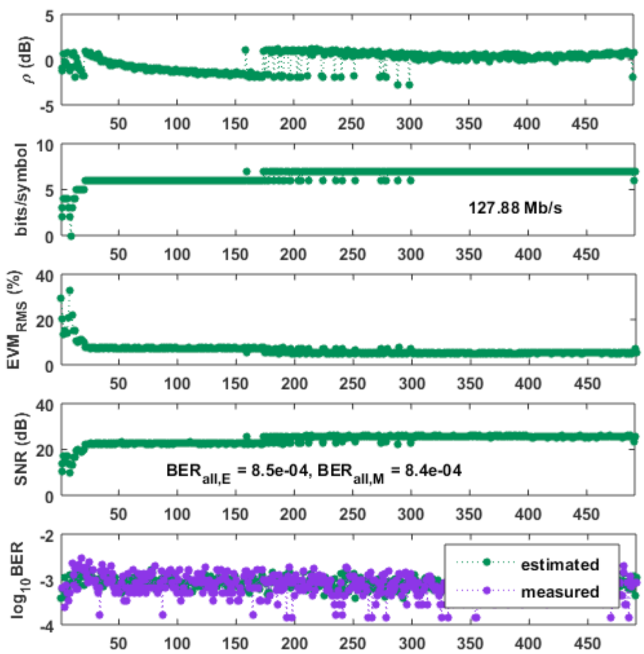

Fig. 7 – Performance indicators per subcarrier after bit and power loading with the optical source at 450 nm after 20 m of SI-POF.

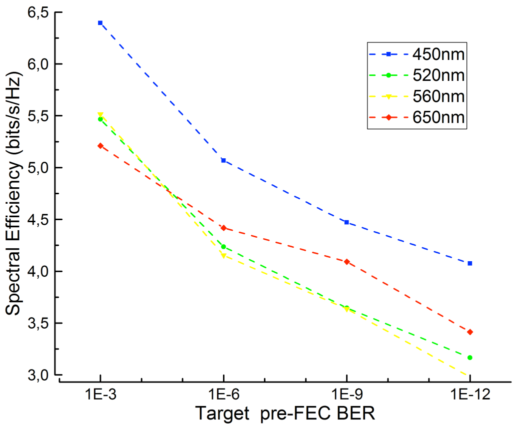

Fig. 8 - Spectral efficiencies of the transmission in the blues, green, yellow and red channels for different pre-FEC target BER.

From Fig. 8 it can be seen that higher than 3 bits/s/Hz is obtained for target BER of $1\cdot10^{-12}$, which could allow avoiding the use of any error correcting scheme. Also, a close estimation of an aggregate bit rate that could be obtained in a WDM system can be performed. For pre-FEC target BER of 10^{-3}, 10^{-6}, 10^{-9} and 10^{-12} the transmission would allow 450, 357, 317 and 263 Mbps, respectively.

V. CONCLUSIONS

We have experimentally demonstrated transmissions over 20 m of SI-POF using different illumination LEDs and a fluorescent optical fiber at 560 nm, which has never been implemented in a WDM system. Furthermore, we also have demonstrated DMT transmissions using a wavelength converted source emitting in the "yellow" wavelength. The results show that the use QAM plus DMT on these LEDs and on the fluorescent source is a good solution to increase the capacity of vehicle or in-home networks and thus that WDM systems with potentially high spectral efficiency could be developed. Up to 450 Mbps of aggregate bit-rate for a pre-FEC target BER of 10^{-3} was demonstrated. Also, 3 bits/s/Hz could still be achieved while reducing the target BER to 10^{-12}. Further research will focus on the transmission of all the signal at the same time by using a POF multiplexer and demultiplexer.

REFERENCES

[1] R. Kruglov, J. Vinogradov, O. Ziemann, S. Loquai and C. A. Bunge, "10.7-Gb/s Discrete Multitone Transmission Over 50-m SI-POF Based on WDM Technology," in IEEE Photonics Technology Letters, vol. 24, no. 18, pp. 1632-1634, Sept.15, 2012.

[2] R. Nazaretian and G. M. Molen, "Reducing Vehicle Weight and Improving Security by Using Plastic Optical Fiber," 2015 IEEE Vehicle Power and Propulsion Conference (VPPC), Montreal, QC, 2015, pp. 1-6.

[3] Y. Shi et al., "Plastic-optical-fiber-based in-home optical networks," in IEEE Communications Magazine, vol. 52, no. 6, pp. 186-193, June 2014.

[4] R. Kruglov, J. Vinogradov, S. Loquai, O. Ziemann and C. A. Bunge, "Eye-safe data transmission of 1.25 Gbit/s over 100-m SI-POF with four laser diodes in the visible range," OFC/NFOEC, Los Angeles, CA, 2012, pp. 1-3.

[5] O. Ziemann, L. Bartkiv, "POF-WDM, The Truth," in 20th International POF Conference 2011, 2011 Bilbao.

[6] P. Pinzón, I. Garcilópez, and C. Vázquez, "Efficient Multiplexer/Demultiplexer for Visible WDM Transmission over SI-POF Technology," J. Lightwave Technol. 33, 3711-3718 (2015).

[7] P. Bienias, G. Budzyń and E. Beres-Pawlik, "WDM for application in passive POF LAN networks," 2016 18th International Conference on Transparent Optical Networks (ICTON), Trento, 2016, pp. 1-3.

[8] M. Jončić, R. Kruglov, M. Haupt, R. Caspary, J. Vinogradov and U. H. P. Fischer, "Four-Channel WDM Transmission Over 50-m SI-POF at 14.77 Gb/s Using DMT Modulation," in IEEE Photonics Technology Letters, vol. 26, no. 13, pp. 1328-1331, July1, 2014.

[9] R. M. Ribeiro, V. N. H. Silva, A. P. L. Barbero, C. M. Alves and C. R. L. Rodrigues, "Fast wavelength conversion to generate 560 nm fluorescence for data transmission in polymer optical fibres," in Electronics Letters, vol. 51, no. 2, pp. 168-170, 1 22 2015.

[10] J. Armstrong, "OFDM for Optical Communications," in Journal of Lightwave Technology, vol. 27, no. 3, pp. 189-204, Feb.1, 2009