

This is a postprint version of the following published document:

Pinzon, P. J., Perez, I. & Vazquez, C. (2016). Visible WDM System for Real-Time Multi-Gb/s Bidirectional Transmission Over 50-m SI-POF. *IEEE Photonics Technology Letters*, 28(15), 1696–1699.

DOI: [10.1109/lpt.2016.2529703](https://doi.org/10.1109/lpt.2016.2529703)

© 2016, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Visible WDM System for Real-Time Multi-Gb/s Bidirectional Transmission over 50-m SI-POF

P. J. Pinzón, I. Pérez, and C. Vázquez, *Senior Member, IEEE*

Abstract — We report a 2 Gb/s bidirectional real-time data transmission with BER $< 1 \times 10^{-10}$ in a 50 m SI-POF link. The system is able to transmit 5 Gb/s using 5-channels. The system performance is tested using the most restrictive channels with the shortest and longest wavelengths in a real-time Ethernet link. The implementation takes advantage of the PAM-16 modulation spectral efficiency and low loss multiplexers and demultiplexers which provide an enhanced link power budget. The optical power per transmitted bit taking into account the BER implication for TCP/IP networks throughput is below 5.8 pJ/b. This is due to the low insertion losses < 4 dB, in each 5-channel multiplexer and demultiplexer.

Index Terms — Polymer Optical Fiber, Visible, Wavelength Division Multiplexing, Gigabit Transmission.

I. INTRODUCTION

AFTER exploiting the capabilities of single channel (ch) transmission [1], visible wavelength (λ) division multiplexing (visible WDM) is proposed as a solution to expand the transmission capacity of Step-Index Polymer Optical Fiber (SI-POF) based systems. To date, there are several proposals of modulation methods [1], spectral grids and multiplexer/demultiplexer (mux/demux) devices [2] that allow to implement transmission systems based on visible WDM at data rates (R) of Multi-Gb/s over SI-POF links. Current proposals are based on spectral grids with chs between 400 and 700 nm, using laser diode (LD) transmitters. Visible WDM systems using offline-processed Discrete Multi-Tone (DMT) modulation, and R up to 14.77 [3] and 21.4 Gb/s [4] over 50 m, and 8.26 Gb/s [5] over 75 m, with 4 or 6 chs and bit error rate (BER) of 1×10^{-3} , have been recently reported. Those systems use couplers based muxes to reduce the impact of high insertion losses (ILs) of their mux/demux devices, so that they can only transmit in a single direction. On the other hand, single λ bidirectional (BiDi) SI-POF links [6], [7] use transmission schemes based on beam splitters, with a maximum number of 2 chs and ILs higher than 6 dB (mux plus demux).

In this paper, the design and test of a real-time (RT) BiDi

visible WDM system over SI-POF, for an efficient performance in terms of Ethernet Throughput \times Length ($T \times L$) and power consumption, is presented. A comparative analysis of the power efficiency per transmitted bit is included. Finally, the system performance is compared with the current state-of-the-art of visible WDM systems over SI-POF links.

II. DATA TRANSMISSION EXPERIMENTS

Figure 1 shows the general description of the proposed SI-POF WDM system. The personal computers (PC1 and PC2) are equipped with N Gigabit Ethernet interfaces in combination with N Media Converters (MCs) used to generate and to read the transmitted data bits. The MCs transform the Ethernet frames into 16-level Pulse Amplitude Modulation (16-PAM) signals (called Tx -signals), and vice versa. In the transmitters (Txs), the different Tx -signals modulate the LD or Light Emitting Diode (LED) of the respective ch . Two muxes/demuxes are used, one to transmit the N chs over the SI-POF link of up to 50 m, and other to split the different chs to their respective receivers (Rxs) at the end of the link. The optical signals are converted back to electrical signals (Tx -signals) at the Rxs by using a pin-photodiode based receiver, and finally, the Ethernet frames are recovered by the MCs.

MCs used in the experimental setup are part of a fully integrated system [8] that is able to establish a real-time link (without any post-processing or storage) at 1 Gb/s over up to 50 m of SI-POF, using a LED transmitter at 650 nm with average power of -3.15 dBm (power coupled to the fiber) and total ILs up to 15 dB. A complete monolithically-integrated linear optoelectronic receiver that comprises an integrated pin-photodiode with a diameter of 390 μm and the required amplifiers, logic and lens is used. It features a highly linear trans-impedance amplifier for average optical input power of up to 0 dBm at a wavelength of 670 nm and sensitivity of about -20 dBm at 650 nm for 1 Gb/s operation [8]. In the proposed system, each MC transmitter is replaced by different LD or LED based transmitters. Therefore, the MCs are only used to encode the Ethernet frames into a 16-PAM signal, and vice versa.

A 5- ch visible WDM scheme is considered. The multiplexing and demultiplexing is performed using low ILs mux/demux devices based on reflective diffraction gratings [2]. Each mux/demux has a size of ~ 65 mm \times 55 mm, $ILs < 4$ dB per channel, and 3-dB bandwidths > 30 nm. The central λ of the channels ch_1 , ch_2 , ch_3 , ch_4 and ch_5 are 405, 470, 530,

This work was supported by the Spanish Ministry of Economy and by Madrid region under grants TEC2012-37983-C03-02, TEC2015-63826-C3-2-R and S2013/MIT-2790.

P. J. Pinzón, I. Pérez, and C. Vázquez are with the Electronics Technology Department, Universidad Carlos III de Madrid, Madrid 28911, Spain (e-mail: ppinzon@ing.uc3m.es; isaper@ing.uc3m.es; cvazquez@ing.uc3m.es).

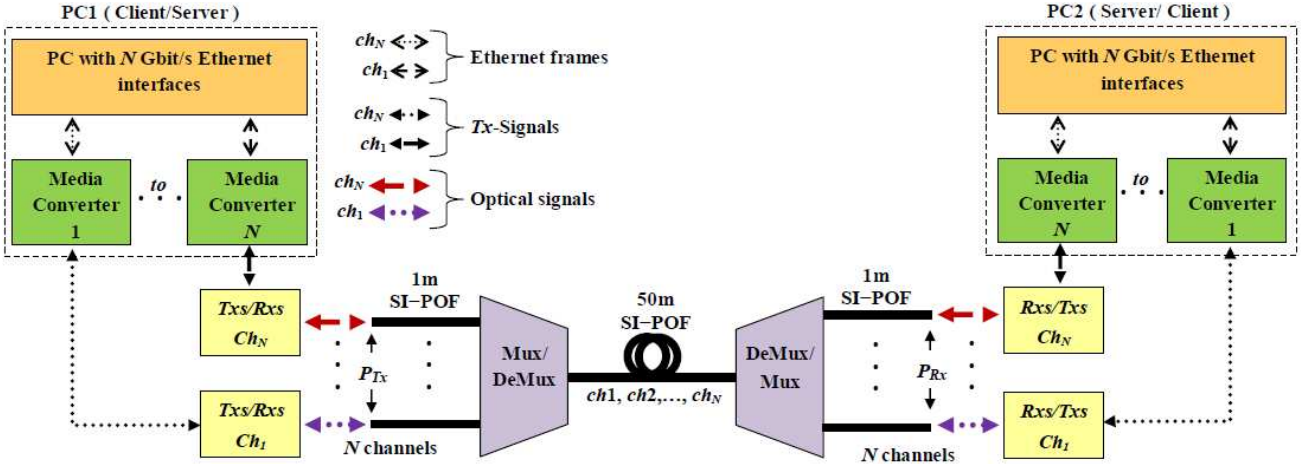


Fig. 1. Transmission scheme of the proposed SI-POF visible WDM system with N channels between 400 and 700 nm.

588 and 650 nm, respectively.

Figure 2 shows the optical transfer function of the 50 m SI-POF link (solid line). The SI-POF attenuation is about 0.212, 0.114, 0.104, 0.124 and 0.170 dB/m at 405, 470, 530, 588 and 650 nm, respectively. Each WDM ch optical transfer function, defined as the average output power over the average power coupled to the input fiber (P_{Rx}/P_{Tx} , see Fig. 1) is also shown. Each ch passes through one mux, 50 m of SI-POF and one demux. These muxes/demuxes based on diffraction gratings exhibit crosstalk (CT) < -30 dB between adjacent chs of the first diffraction order ($ch_1, ch_2, ch_3, ch_4, ch_5$). However, due to their periodic nature the dominant factor in terms of CT is the interference between consecutive diffraction orders in the extreme chs (e.g. crosstalk of the second diffraction order of ch_1 on the ch_5). In addition, the extreme chs have also higher ILs , so they are considered the most limiting ones. So in this first validation of the proposed system, the performance of the extreme chs is tested.

The proposed system includes one mux/demux at each end of the link, see Fig. 1, one for multiplexing and one for demultiplexing, each one with $ILs < 4.1$ dB per channel [2]. Due to this configuration, each channel can be used as up or down link (reconfigurable BiDi link). Figure 2 shows that the ch_1, ch_2, ch_3, ch_4 and ch_5 have an increment of 8.1, 6, 6.1, 6.5 and 7.5 dB in their ILs in comparison with the simple 50 m link due to multiplexing plus the demultiplexing ILs . It is important to note that a simple 4:1 SI-POF coupler has ILs of about 8.5 dB.

The blue-violet LD DL-5146-101S and the red LD L650P007 are used for the ch_1 and ch_5 transmission. These

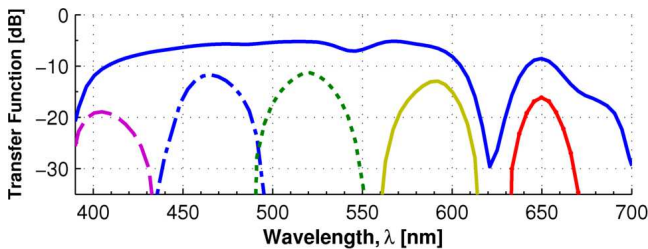


Fig. 2. Measurements of the transfer function of the visible WDM SI-POF system and 50 m SI-POF loss (blue solid line).

LDs have a threshold current (I_{th}) of ~ 20 and 35 mA, respectively. Each LD is directly modulated using a V_{MOD} signal (V_{MOD1} and V_{MOD5}), which is obtained conditioning the Tx -signal; an average optical power of 9.27 and 3.72 dBm is transmitted, using a bias current (I_{bias}) of 42 and 23 mA, and modulation index (m_i) of 0.84 and 0.69, respectively.

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

MCs use PAM-16 modulation and a Multi-level Coset Coding [8] so the Signal-to-Noise-Ratio after the MC's decoding stage (SNR decod) includes the coding gain. We define the receiver sensitivity as the minimum optical power required at the photo-detector to maintain a $BER < 10^{-10}$ at 1 Gb/s. It was determined that the receiver's sensitivity on the experimental setup is -15.79 and -18.85 dBm for channels ch_1 and ch_2 , respectively. Each ch is also evaluated in a single ch configuration (without muxes/demuxes). The SNR decod in the single channel configuration is 28.9 and 34.2 dB, and the SNR decod in the full WDM system is 26.3 and 31.8 dB, for channels ch_1 and ch_5 , respectively. The lower SNR decod of ch_1 in both cases (with and without the WDM system) is due to the low frequencies distortion in the V_{MOD1} conditioning stage.

The experimental setup of the visible WDM transmission system has been tested in a real-time full-duplex Ethernet link. The performance of different channels (ch_1 and ch_5) was tested with and without traffic in the opposite direction. In both cases, the performance of each channel remained the same, with data rates of up to 980 Mb/s and $BER < 10^{-10}$, which proves the bidirectional capacity of the system. There is no difference when ch_1 and ch_5 are transmitted in either directions (same or opposite directions). The crosstalk between channels in both situations is lower than -30 dB [2].

Tab. 1: Comparison Between the extremes channels of recently reported visible WDM SI-POF links of 50 m.

Parameter	5-ch system [This work]		4-ch system [3]		6-ch system [4]		
	405 nm	650 nm	405 nm	639 nm	405 nm	655 nm	
Budget	LD output Power, P_o (dBm)	9.27	3.72	>22.1 ⁽¹⁾	10 ^{(1) and (2)}	>12 ⁽¹⁾	10 ⁽²⁾
	Launching coupling IL (dB)	0.90	0.80	⁽³⁾	⁽³⁾	⁽⁴⁾	⁽⁴⁾
	Multiplexing IL (dB)	4.00	3.87	5 ⁽⁷⁾	5 ⁽⁷⁾	1.5 ⁽⁷⁾	1.5 ⁽⁷⁾
	50 m SI-POF (dB)	10.59	8.5	~10.59 ⁽⁴⁾	~8.5 ⁽⁴⁾	10.5	7.5
	Demultiplexing IL (dB)	4.05	3.8	5.66	3.19	10	9.5
	Receiver Lens IL (dB)	2.00 ⁽⁵⁾	2.00 ⁽⁵⁾	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾
	Receiver Sensitivity (dBm)	-15.79	-18.85	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾
	Received Power (dBm)	-12.27	-15.25	0.82	-7.04	-10.1	-12.5
	Link Margin (dB)	3.52	3.6	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾	⁽⁴⁾
Throughput	Data Rate, R (Gb/s)	1	1	3.03 ⁽⁸⁾	3.28 ⁽⁸⁾	2.19 ⁽⁸⁾	2.59 ⁽⁸⁾
	BER	<1×10 ⁻¹⁰	<1×10 ⁻¹⁰	1×10 ⁻³	1×10 ⁻³	1×10 ⁻³	1×10 ⁻³
	Data Throughput, T (Gb/s) ⁽⁶⁾	1.00	1.00	1.19	1.29	0.86	1.02
Power	Threshold current I_{th} (mA)	32	20.4	45	30	26	20
	Bias current I_{bias} (mA)	42	23	80	40	38	36
	Modulation index m_i	0.84	0.69	0.9	0.9	0.9	0.9
	Quantum efficiency β (W/A)	0.685	0.667	0.8–1.2 ⁽⁹⁾	0.8–1.0 ⁽⁹⁾	0.7–1.1 ⁽⁹⁾	0.6–0.9 ⁽⁹⁾
	Power per bit P_{Tb} (pJ/b) ⁽⁶⁾	5.8	1.2	21.2–31.8	5.6–7.0	8.8–13.8	8.5–12.7

Notes: (1) From the total ILs and the received power (Link Budget); (2) From the LD datasheet at the I_{bias} ; (3) Included in the Multiplexing IL ; (4) No information is given; (5) Average value taken from manufacturer; (6) From Eq. (1), considering Ethernet frames of 64 Bytes and IPG of 96 bits. (7) Fiber bundle based mux (unidirectional system). (8) 7% overhead required for error correction is not included. (9) Min. to Max. from LD datasheet.

III. DISCUSSION

Most important limitation of visible WDM links over SI-POF is the power penalty due to the muxes/demuxes ILs , limiting the transmission capacity of each ch in comparison with single ch systems. Table 1 shows the experimental link budget of the ch_1 and ch_5 . The link margin in both cases is > 3.5 dB, and the values of LD output power (P_o) and the mux/demux ILs are lower than previous values of other similar proposals.

On the other hand, experimental measurements of Figure 2 show that the total ILs in the other 3 available chs (ch_2 , ch_3 and ch_4) are lower, showing the potential of scaling the transmission capacity up to 5 Gb/s.

A. Power budget estimation of ch_2 , ch_3 and ch_4

The power budget of the complete WDM system is directly affected by the receiver sensitivity. The silicon photo-detector responsivity at 405, 470, 520, 590 and 650 nm is about 0.2, 0.26, 0.29, 0.33 and 0.38 A/W, respectively. Therefore, from the 650 nm experimental sensitivity (-18.85 dBm), the receiver sensitivity at the other wavelengths is calculated. Table 2 shows data for power budget estimation of the central chs (ch_2 , ch_3 and ch_4). It can be seen that the minimum transmission power required on these channels is below -3.5 dBm, which can be easily achieved using LD sources for ch_2

Tab. 2: Data for central channels power budget estimation in our visible WDM system (50 m and 1 Gb/s per channel).

Parameter	ch_2	ch_3	ch_4
P_{Tx} (dBm) ⁽¹⁾	-3.5	-4.4	-3.5
50 m SI-POF att (dB)	5.7	5.2	6.2
Mux plus DeMux att (dB)	6.0	6.1	6.5
Rx Sensitivity (dBm)	-17.2	-17.7	-18.2

Notes: (1) Minimum power required to meet the receiver sensitivity, resulting in a link margin of 0 dB. 2 dB of the receiver lens IL is included.

and ch_3 (e.g. L473P020MLD and PLT5 520_B4_5_6) and a LED source for ch_4 (e.g. LED591E). So it is possible to increase the transmission capacity up to 5 Gb/s.

B. Optical power in the 50-m SI-POF link

The ch_5 power coupled into the 50 m SI-POF link is below 0 dBm ($P_o - \text{Launching } IL - \text{Multiplexing } IL = -0.95$ dBm, see Tab. 1). In a similar way, the power of channels ch_2 , ch_3 and ch_4 coupled into the 50 m SI-POF would be below 0 dBm (see Tab. 2). Therefore, if the lasers and the multiplexer are inaccessible to the end user, channels ch_2 , ch_3 , ch_4 and ch_5 will be working inside the eye safety limit (momentary viewing is not considered hazardous [9]). However, the power of ch_1 coupled into the 50 m SI-POF is about 4.37 dBm (see Tab. 1). It is possible to reduce this power level to values close to 0 dBm by optimizing the optics at the receiver (currently including losses of about 2 dB), or modifying the design of the muxes/demuxes to reduce the ILs at 405 nm (ch_1) [2] meanwhile keeping the ILs at 650 nm (ch_5) low enough for operating inside the eye safety limit.

C. Estimation of the power consumption and transmission efficiency

As a first approach to estimate power consumption, power per transmitted bit (P_{Tb}) at the transmitters' LD is defined taking into account the BER implication for TCP/IP networks throughput [10], in terms of Network Throughput (T). The mean optical power of the instantaneous transmitted signal, $\langle P_{opt}(t) \rangle = \beta I_{peak}$, with quantum efficiency β and driving signal with peak amplitude I_{peak} is used. This peak amplitude can be expressed in terms of the LD modulation index m_i as $I_{peak} = m_i \times (I_{bias} - I_{th})$. Then, the P_{Tb} is given by:

$$P_{Tb} = \frac{\beta \times I_{peak}}{T} \quad \text{with} \quad T = R[1 - BER(Psize + IPG)] \quad (1)$$

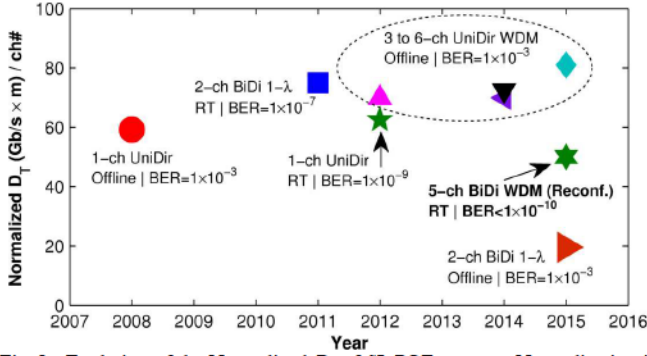


Fig. 3. Evolution of the Normalized D_T of SI-POF systems. Normalization is done considering a TCP/IP network with the minimum P_{size} (64 Bytes) and IFG of 96 bits. Offline is used for offline-processing, UniDir is used for unidirectional and Reconf is used for reconfigurable. References: Circle [11], Square [6], Pentagram [12], Upward-pointing triangle [13], Downward-pointing triangle [3], Left-pointing triangle [4], Right-pointing triangle [7], Diamond [5] and Hexagram [This work].

where P_{size} is the Ethernet packets size and IPG is the inter packets gap. T is calculated in the worst scenario, where each 1 bit-error provokes a packet-error. The minimum 64 bytes Ethernet P_{size} and IPG of 96 bits are considered. However, it is important to note that T is reduced for larger P_{size} [10]. Therefore, a transmission efficiency of 39% is obtained with a BER of 1×10^{-3} . This efficiency is about 100% for BERs $< 1 \times 10^{-10}$. The results shown on Table 1 demonstrate that the proposed system has better P_{Tb} than previous proposals.

The Ethernet T allows performing a better comparison between systems with different BER values. This approach is also used to present current state-of-the-art of SI-POF systems including our proposal and using a parameter called Normalized Data Throughput ($Normalized D_T$). D_T is given by:

$$Normalized D_T = (D_T / ch\#) \times L \quad (2)$$

where D_T is the total Throughput of the system, see (1), and $ch\#$ is the total number of channels.

As shown in Fig. 3, previous bidirectional (BiDi) single λ systems are limited to a maximum number of 2- chs . Although visible WDM systems are easily scalable, current proposals are unidirectional and have too large BER values, which may limit their performance on real-time (RT) Ethernet applications. So the proposed system is the first RT, BiDi and reconfigurable SI-POF WDM link with $BER < 1 \times 10^{-10}$ and normalized D_T comparable with the current state-of-the-art.

D. System scalability

The number of chs can be increased up to 8 by using the 8- ch mux/demux design presented in [2], with an impact on the power budget of each ch lower than 1 dB. The number of chs , and the transmission capacity can be doubled, by using a single λ BiDi transmission scheme in each ch as in [6], [7]. In this new scenario the total capacity will be 16 Gb/s.

IV. CONCLUSIONS

In this work, we have proposed a 5- ch visible WDM system

based on low loss muxes/demuxes and a PAM-modulation scheme in order to establish a real-time bidirectional link at 5 Gb/s with $BER < 1 \times 10^{-10}$ over 50 m of SI-POF.

Experiments are presented on most restrictive channels at shortest and longest wavelengths at data rates of 2 Gb/s (1 Gb/s per ch). The receiver sensitivity is below -15.8 dBm. An optical power per transmitted bit taking into account the BER implication for TCP/IP networks throughput below 5.75 pJ/b is estimated, meaning an improvement greater than 30% in comparison with other recent proposals. Each channel can be configured either as uplink or downlink. The system has the potential of expanding the transmission data rate by increasing the number of channels and using recent bidirectional 8- chs mux/demux. The aggregated capacity can also be doubled by using single wavelength bidirectional transmission schemes based on beam splitters.

The reported results constitute, to the best of our knowledge, the first scalable bi-directional multi-gigabit-rate SI-POF multichannel system with $BER < 1 \times 10^{-10}$.

References

- [1] C. M. Okonkwo *et al.* "Recent results from the EU POF-PLUS project: multi-Gigabit transmission over 1 mm core diameter plastic optical fibers," *J. Lightwave Technol.*, vol. 29, pp. 186–193, 2011.
- [2] P. J. Pinzón *et al.* "Efficient Multiplexer/Demultiplexer for Visible WDM Transmission over SI-POF Technology," *J. Lightwave Technol.*, vol. 33, no. 17, pp. 371–3718, 2015.
- [3] M. Jončić *et al.* "Four-Channel WDM Transmission Over 50-m SI-POF at 14.77 Gb/s Using DMT Modulation," *IEEE Phot. Tech. Lett.*, vol. 26, pp. 1328–1331, July 2014.
- [4] R. Kruglov *et al.* "21.4 Gb/s Discrete Multitone Transmission over 50-m SI-POF employing 6-channel WDM," in *Proc. OFC (OSA)*, 2014) pp.1–3, March 2014.
- [5] U. H. P. Fischer, S. Höll, M. Haupt, and M. Joncic, "Polymeric demultiplexer component for wavelength division multiplex communication systems using polymer fibers", *Proc. SPIE* 9368, 93680Q (2015).
- [6] A. Antonino *et al.* "Real-time Gigabit Ethernet bidirectional transmission over a single SI-POF up to 75 meters," *Proc. OFC/NFOEC* (2011).
- [7] X. Li *et al.* "µLED-Based Single-Wavelength Bi-directional POF Link With 10 Gb/s Aggregate Data Rate," *J. Lightwave Technol.*, no. 33, pp. 3571–3576, 2015.
- [8] Knowledge Development for POF, "Simple Introduction to Gigabit Communications over POF," Online: <http://www.kdpof.com/wp-content/uploads/2012/07/Easy-Introduction-v1.1.pdf>
- [9] U.S. Department of Labor - Occupational Safety & Health Administration (OSHA). (2015, April 28). OSHA Technical Manual (OTM) - Section III: Chapter 6 Laser Hazards [Online]. Available: https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_6.html
- [10] E. Rodriguez-Colina *et al.* "BER implication for TCP/IP network throughput over a 10 x 10 Gbps wavelength-stripping cascaded SOA-switch" *Proc. London Communications Symposium*, London (2006).
- [11] J. Lee *et al.* "Gigabit Ethernet over standard step-index polymer optical fiber," in *ICPOF*, Santa Clara, CA, 2008.
- [12] M. Atef *et al.* "Real-Time 1.25-Gb/s Transmission Over 50-m SI-POF Using a Green Laser Diode," *IEEE Phot. Tech. Lett.*, vol. 24, no. 15, pp. 1331–1333, 2012.
- [13] R. Kruglov *et al.* "10.7-Gb/s Discrete Multitone Transmission Over 50-m SI-POF Based on WDM Technology," *IEEE Phot. Tech. Lett.*, vol. 24, no. 18, pp. 1632 - 1634, 2012.