Beyond 1 Gbit/s transmission over 1 mm diameter plastic optical fiber employing DMT for in-home communication systems

Beyond 1 Gbit/s Transmission Over 1 mm Diameter Plastic Optical Fiber Employing DMT for In-Home Communication Systems

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***Abstract*—Multi-Gbit/s transmission over 1 mm diameter graded index plastic optical fiber (GI-POF) is reported. Transmission rates between 5.3 and 7.6 Gbit/s are achieved for fiber lengths between 10 and 50 m using discrete multi-tone modulation (DMT) in an intensity modulated direct detection system using directly modulated eye-safe VCSEL and silicon photodiode (PD). The used system bandwidth is only 1.42 GHz resulting in a spectral efficiency of >3.7 bits/s/Hz. All employed components represent a low-cost, off-the-shelf cost-effective solution for high-speed in-home communication systems.**

***Index Terms*—Home communication systems, frequency division multiplexing, optical fiber communication, signal processing.**

I. Introduction

In-home communication systems are becoming of increasing importance for the exchange of information among varieties of consumer electronics in the home, due to emerging services such as video services which require broadband communication. While ongoing standardization activities are specifying regulations for transmission rates of up to 1 Gbit/s for in-home communication over power lines, coaxial and CAT-5 cables [1], [2], the solutions for offering high data rate and converged services over one optical infrastructure for in-home networks are gaining traction. Several optical solutions have been proposed for short-range in-home communication scenarios. The first proposed physical layer approach, based on standard silica 50/62.5 μm core diameter multimode fiber (MMF), is considered especially for transmission rates beyond 10 Gbit/s [3]. However, as the main constraint for in-home networking is the requirement for cheap and user-friendly solutions in brown-field deployment, plastic optical fibers (POFs) are now been considered for short-range links [4]. Among different POF solutions, 1 mm diameter polymethylmetacrylate (PMMA) POFs are an attractive solution for the advantages of 'do-it-yourself' installation [5], due to inexpensive and simple connectorization, easy maintenance, use of visible light transceivers and small bending radius compared with conventional MMFs. Step-index (SI) POF with a numerical aperture (NA) of 0.5 presents a low bandwidth-distance product (80 MHz at 50 m [5]). For this reason the use of graded-index (GI) PMMA POF is a state-of-the-art solution for multi-Gbit/s transmission [6].

Providing between 1 and 2 GHz at 50 m, GI-POF presents a much larger bandwidth when compared to SI-POF. To achieve the maximum bit-rate of the channel spectral efficient modulation formats should be employed. The potential of orthogonal frequency division modulation (OFDM) for achieving high spectral efficient transmission over an optical link, with robustness against impairments such as modal or chromatic dispersion due to its simple and effective equalization in the frequency domain, has been demonstrated [7]–[9]. In particular, the baseband version of OFDM known as discrete multi-tone (DMT) modulation has been studied in recent years within intensity modulation and direct detection (IM-DD) schemes to maintain a cost-effective solution as well as maximizing the channel capacity.

Using this technique, together with adaptive bit and power allocation, more than 40 Gbit/s transmission over 100 m of 50 μm core size perfluorinated GI-POF using high-performance and high-cost infrared transceivers [10], 4.7 Gbit/s transmissions over 50 m 1 mm multi-core POF using avalanche photodetector [11], and 10 Gbit/s over 25 m of SI-POF using high power laser [12] has been demonstrated. However, all this proposed solutions employ neither cost-effective nor eye-safe optical components.

In this paper, we show transmission performance over 50 m using eye-safe transceivers according to the regulations [13] and off-the-shelf optoelectronic components. In particular, we employ the DMT modulation technique with 256 subcarriers and up to 32 level quadrature amplitude modulation (32-QAM) using a rate-adaptive bit-loading algorithm.

The achieved results show that PMMA GI-POF of 1 mm core diameter provides suitable solutions for short-range multi-gigabit in-home networks.

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The paper is organized as follows: the introduction is followed by brief overview on DMT and the bit-loading algorithm employed in Section II. In Section III, the experimental setup and results are discussed. The evaluation of the DMT and optical parameters is outlined. To underline the possible limitations in a real in-home deployment, the implication of lower bending radius is studied. Finally the paper is concluded in Section IV.

II. DMT and Bit-Loading

DMT technique has been widely used in digital subscriber copper lines (xDSL) to efficiently use the bandwidth-limited and noisy copper channel. Based on digital signal processing (DSP) equalization, the possibility to use each subcarrier as a separate narrowband channel provides the possibility to allocate an arbitrary number of bits (constellation size) to each subcarrier. For optimal allocation, bit and power loading algorithms are used to adapt to the channel response.

A rate-adaptive bit loading algorithm to achieve the maximum number of bits b within a DMT frame period with a power constraint is employed [14]. This is an optimization problem that can be expressed as follows [15]:

$$\max_{\mathrm{E}_n}(b) = \max_{\mathrm{E}_n}\left(\sum_{n=1}^{N} b_n\right) = \max_{\mathrm{E}_n}\left(\sum_{n=1}^{N}\frac{1}{2}\log_2\left(1+\frac{E_n\cdot g_n}{\Gamma}\right)\right) \quad (1)$$

subject to

$$\sum_{n=1}^{N-1} E_n = E_{\mathrm{tot}} \quad (2)$$

where N is the number of subcarriers, E_n is the power associated to the nth subcarrier, b_n is the number of bit of the nth subcarrier, g_n is the signal-to-noise ratio (SNR) of the nth subcarrier when unit energy is applied. Moreover, Γ is the SNR gap, i.e., the difference in SNR required to achieve maximum capacity as defined by the Shannon Limit. Finally, E_{tot} is the fixed total available energy for transmission.

The target is to optimize the number of bits per subcarrier b_n, and the corresponding energy distribution per subcarrier E_n, in order to maximize the total number of bit b. An optimal solution can be found using the water-filling approach [16], but the method proposed by Chow in [14] is more computationally efficient, and hence used in this paper.

According to Chow algorithm, we order the subcarriers according to the value of g_n, and discard the subcarriers which are least energy-efficient for transmitting bits. The energy is redistributed equally among the remaining subcarriers to support higher data rates. Due to the logarithmic relationship, the resulting non-integer number of allocated bits per subcarrier is rounded to the nearest integer. The corresponding energy is adjusted to support the newly allocated integer number of bits to give the same performance. This adjustment causes non-uniform energy distribution among the subcarriers.

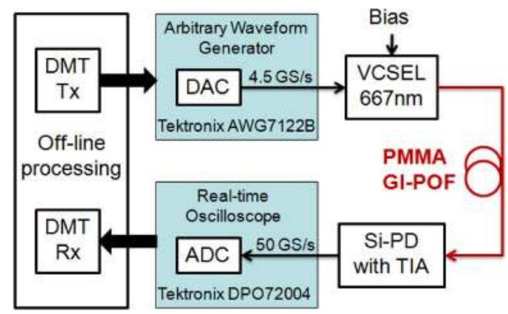

Fig. 1. Experimental setup.

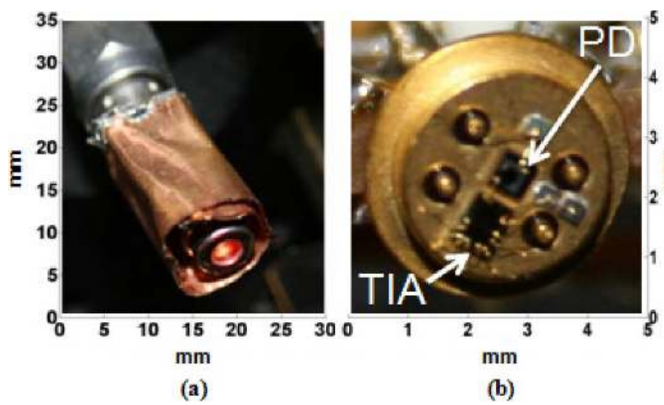

Fig. 2. Photos of the (a) red VCSEL and (b) the PIN-PD used in our setup.

The resulting number of bits per subcarrier b_n determines the modulation level associated to the nth subcarrier. Using quadrature amplitude modulation (QAM) means that the nth subcarrier is allocated 2^{b_n}-QAM. The distance between QAM constellation points is chosen such that the average power of the nth subcarrier is equal to E_n.

III. Results and Discussions

The experimental setup is depicted in Fig. 1. A Firecomms red VCSEL with a wavelength of 667 nm (Fig. 2(a)) is directly modulated by the DMT signal generated from a Tektronix AWG7122B arbitrary waveform generator (AWG) with a bandwidth of 10 GHz. The modulated optical power is launched, without the use of a lens, into a 1 mm diameter Optimedia PMMA GI-POF with the power level of 0 dBm. The optical signal after 50 m link (-15.5 dBm) is coupled, using a lens, to a PIN-based PD (Fig. 2(b)) with a photosensitive diameter of 400 μm and a responsivity of 0.5 A/W at 660 nm. The PD is equipped with a trans-impedance amplifier (TIA), mounted very close to the photodiode chip, with a trans-impedance gain of 10 kΩ. This receiver scheme and the use of a matched PD-TIA guarantees a high sensitivity and large bandwidth of the receiver.

The received electrical signal is sampled by a 16 GHz real-time Tektronix DPO72004 digital phosphor oscilloscope (DPO). Both DMT modulation and demodulation are realized offline in MATLAB. Since the AWG and DPO are not synchronized, the clock/phase recovery is performed by the DMT demodulator.

Regarding the digital signal processing (DSP), the DMT digital (de)modulator is implemented offline, hence there

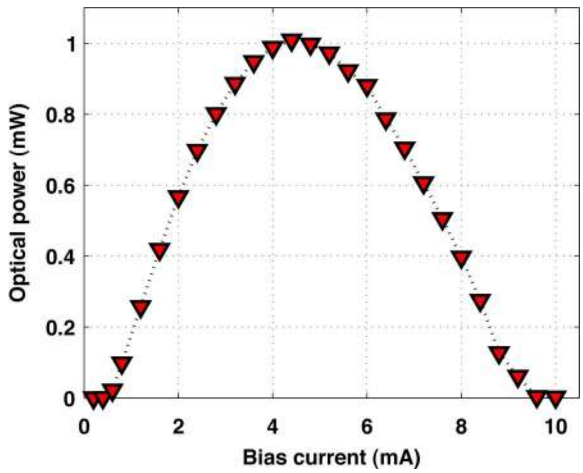

Fig. 3. Optical output power (mW) versus VCSEL bias current (mA).

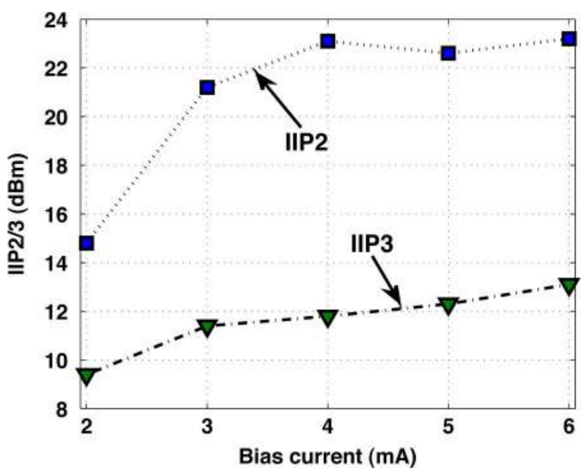

Fig. 4. IIP2 and IIP3 (dBm) of our experimental setup with two tone at 365 and 375 MHz versus VCSEL bias current (mA).

are few limitations in DSP. 8-bit precision is used in the digital-to-analog conversion (DAC) and the analog-to-digital conversion (ADC) in the AWG and the real-time oscilloscope, leading to negligible quantization noise.

The design of the optical link is critical to the performance of the system. Firstly, the VCSEL optimum bias parameter is addressed. Fig. 3 shows the static Light-Current characteristics of the VCSEL at the ambient temperature of 21°C. The optical output power is maintained below 1 mW and reaches this value at the bias current of 4 mA. The VCSEL performance shown in Fig. 3 suggests the bias current of 2 mA, implying operation of the VCSEL in the linear region. However, it was found that the optimal bias current is around 4 mA, as will be further discussed in the following subsections. For the dynamic characterization case, a preliminary explanation is given in Fig. 4, which shows the input intercept points of the second and the third order [17], denoted as IIP2 and IIP3 respectively. These are obtained using a two tone test at 365 and 375 MHz. As shown in Fig. 4, the bias current of 4 mA corresponds to the maximum IIP2 and close to maximum IIP3. On the contrary, the bias current of 2 mA presents the lowest IIP2 and IIP3, hence operation in this biasing region could introduce high non-linearities to the system.

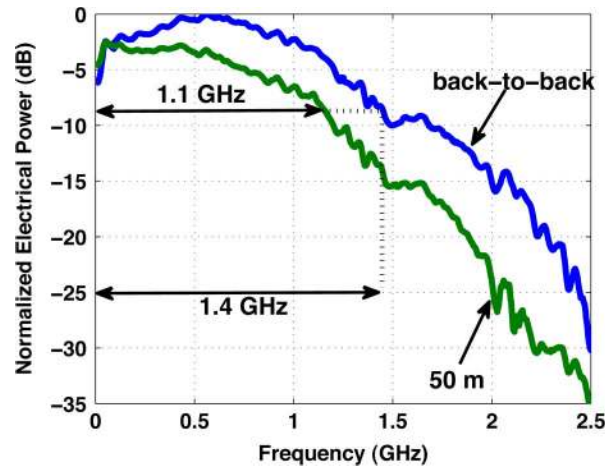

Fig. 5. Frequency response of the system including transceivers, POF link, and receiver in the back-to-back case and after 50 m transmission.

TABLE I
DMT SIGNAL PARAMETERS

Number of subcarriers:	256
Cyclic prefix length:	8
Schmidl blocks:	4 every 200 DMT frames
Digital clipping:	Clipping factor $\mu = 8$ dB
Transmitter sampling rate:	4.5 Gsamples/s
Receiver sampling rate:	50 Gsamples/s

A. System Frequency Response

At the optimum bias current of the VCSEL (4 mA), the frequency response of the entire optical system was measured. The modulation bandwidth of the VCSEL is 3 GHz [18], while the response bandwidth of the receiver is around 1.4 GHz. For this reason the frequency response in the optical back-to-back case (using a POF length of 1 m) is limited by the receiver response as shown in Fig. 5.

The bandwidth of the graded-index POF is reported to be more than 1.5 GHz after 50 m transmission [19]. In comparison to the back-to-back case, after 50 m, a 3 dB decrease in power at 1.1 GHz is observed (see Fig. 5). Although the optical channel bandwidth is less than 1.5 GHz, we believe that multi-gigabit transmission is feasible provided that the POF attenuation can be minimized. The graded-index POF attenuation is reported to be 0.2 dB/m at 650 nm in [19], while in this case the attenuation was verified to be 0.3 dB/m at 667 nm. After 50 m transmission, the total optical loss became 15 dB. This high value decreases the received SNR and hence the maximum achievable transmission rate, as shown in the following subsections.

B. 5.3 Gbit/s Transmission Over 50 m PMMA GI-POF

The record transmission result was achieved through the optimal application of the DMT modulation. The AWG generated the DMT waveform with a sampling speed of 4.5 Gsamples/s. As shown in Table I, the characteristics of the waveform are: 256 subcarriers with the spacing of 8.8 MHz, within the bandwidth of 2.25 GHz. As shown in Fig. 5, the 3 dB bandwidth of the system is around 1.1 GHz, this means there will be some unused subcarriers after bit loading (while the DC subcarrier

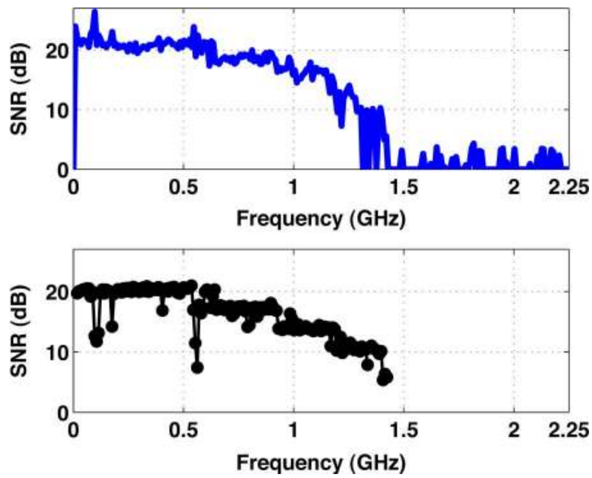

Fig. 6. Signal-to-noise ratio (SNR) measured before (up) and after (down) bit loading for DMT transmission over 50 m PMMA GI-POF.

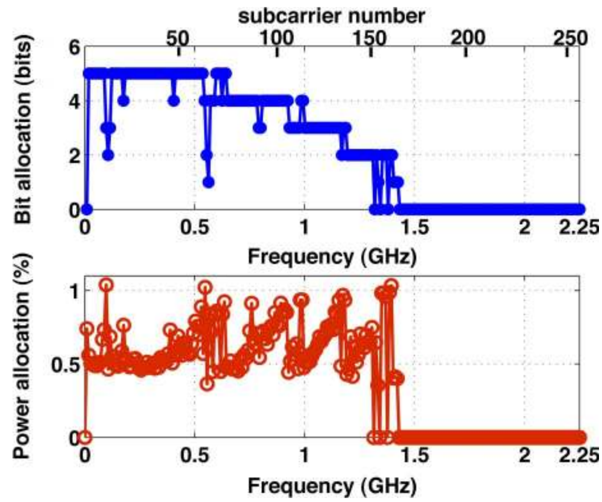

Fig. 7. Bit (up) and Power (down) allocation for DMT transmission over 50 m PMMA GI-POF using 256 subcarriers.

is not used). The DPO sampling speed was fixed to the maximum 50 Gsamples/s. This high sampling speed was chosen to obtain a good clock recovery and digital filter suppression. In fact, since sampling speeds of the transmitter and the receiver are not synchronized and the receiver does not include clock-recovery, oversampling is necessary to minimize inter-carrier interference [20]. For cost-effective real implementation, the use of such high sampling speed can be avoided, using Schmidl & Cox approach [21] and/or training symbols [22].

Parameters such as the cyclic prefix length and Schmidl blocks preambles are critical for clock/phase recovery and equalization of the DMT waveform. These were set to 8 and 4 respectively as summarized in Table I. Finally the clipping level is set to 8 dB, which is shown to be optimum for this case study.

In Fig. 6, the SNR is shown before and after bit-loading. Notice that before bit-loading, the SNR measurement result presents a continuous curve from 25 dB to 0 dB. The SNR noticeably decreases at 1.42 GHz. After bit-loading, the SNR assumes a step-like shape similar to the bit-allocation shown in Fig. 7. In particular, since after 1.42 GHz (162th subcarrier) no bits are allocated, the SNR of the last 94 unused subcarriers cannot be evaluated. A spectral efficiency of 3.7 bits/s/Hz is therefore achieved.

We also highlight that the step-like shape of the SNR after bit loading is due to the non-uniform power allocation to each subcarrier as determined by the bit-loading algorithm discussed in Section II. As shown in Fig. 7, power tends to increase with the subcarrier index inside the same bit allocation block, and decreases when a different bit allocation block starts.

Finally, Fig. 8 shows the QAM constellations for 32-QAM and 4-QAM, where 5 and 2 bits are allocated to the lowest and the highest subcarrier indexes respectively. No distortion effects are shown in these constellations which are received after the equalization step.

Fig. 9 shows the maximum achievable bit-rate of the DMT signal versus fiber length using the parameters presented in Table I. Due to the high losses induced by the fiber, the transmission performance is SNR-limited. Hence, Fig. 9 shows a linear relationship between bit-rate and POF length with

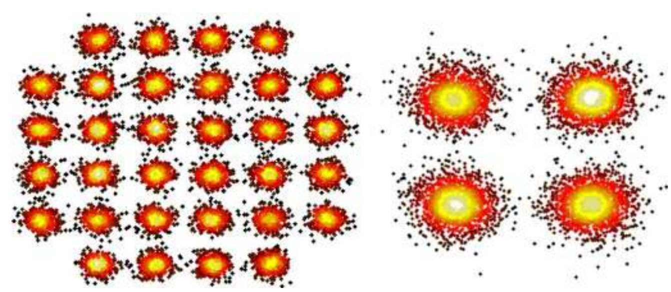

Fig. 8. Highest and lowest constellations (respectively 32-QAM and 4-QAM) used in 50 m PMMA GI-POF experiment.

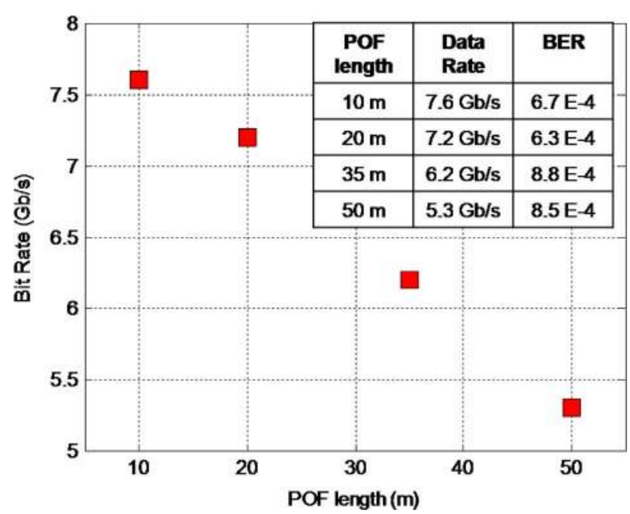

Fig. 9. Maximum achieved bit rate for different POF lengths using bit loading with target BER of 10^{-3}.

negative slope of 60 Mbit/s/m. Since the PMMA GI-POF loss is 0.3 dB/m, this slope is equivalent to 200 Mbit/s/dB.

From the inset in Fig. 9, notice that all the bit error rates (BER) achieved at the various distances remain below 10^{-3}. If a 7% overhead enhanced forward error correction (EFEC) code is inserted, then the BER of $<10^{-3}$ decreases to $<10^{-15}$ [23]. Accounting for EFEC overhead, cyclic prefix and preamble from

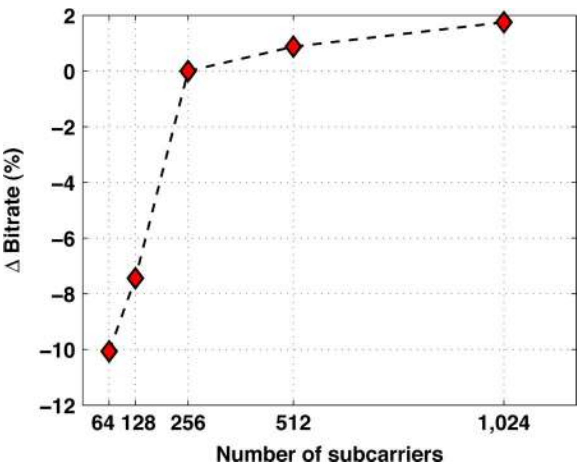

Fig. 10. Percentage Bit-rate variation versus number of subcarrier of the DMT signal.

the gross transmission rate of 5.3 Gbit/s, the net bit-rate becomes 4.85 Gbit/s. To determine the implication of the various electrical and optical parameters on the system performance, the following subsections provide further evaluation.

C. Evaluation of DMT and Optical Link Parameters

The results presented in the previous subsection were obtained with the DMT parameters shown in Table I. Here we evaluate the effect of deviation of these parameters on the link performance. We are very much interested in the dependencies of the total bit-rates on different values of subcarrier counts, clipping levels, laser bias currents, and fiber bending loss. In Figs. 10–12 we present the link performance as a function of these four parameters. For the link performance we take the obtained bit-rate relative to the optimum bit-rate, indicated as Δ Bitrate. We define Δ Bitrate as follows,

$$\Delta\ \mathrm{Bitrate}(\%) = \frac{\mathrm{Bitrate} - \mathrm{Bitrate}_{\mathrm{ref}}}{\mathrm{Bitrate}_{\mathrm{ref}}} \cdot 100$$

where Bitrate is the achieved result for the applied parameter values, while $\mathrm{Bitrate}_{\mathrm{ref}}$ is the reference bit-rate, equal to the achieved gross bit-rate result of 5.3 Gbit/s shown in the previous subsection.

The first parameter under consideration is the number of subcarriers. Increasing the number of subcarriers will better utilize the available bandwidth, hence an increase in the total bit-rate. Up to 256 subcarriers, the link performance increases considerably, thereafter the performance becomes saturated (see Fig. 10). However, increasing the subcarrier counts will increase the system complexity regarding the digital signal processing steps. A compromise between the number of subcarriers and the complexity of the system is then required. For this reason, choosing 256 subcarriers is the optimum compromise between bit-rate and complexity.

Another important parameter of the DMT signal is the clipping level or crest factor. Fig. 11 shows Δ Bitrate against the crest factor of the DMT signal. The optimum crest factor lies somewhere between 6 and 8 dB. For the record transmission, we chose 8 dB crest factor, but it is important to note that the crest factor of 6 dB also gives a reasonably good result. We remark here that the crest factor of the DMT signal without clipping would be around 14–15 dB which results in more than 30% reduction in bit-rates.

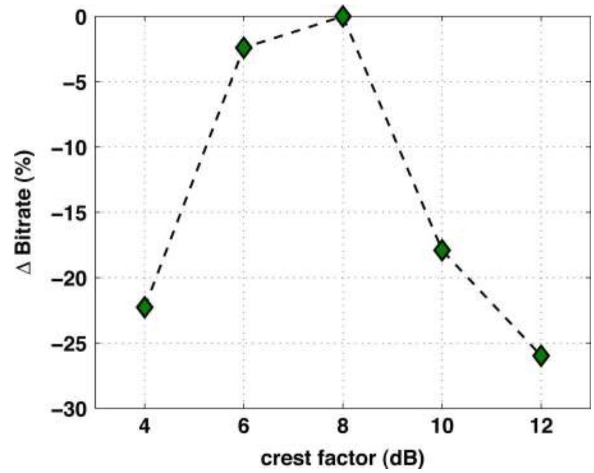

Fig. 11. Percentage Bit-rate variation versus crest factor (clipping level) of the DMT signal.

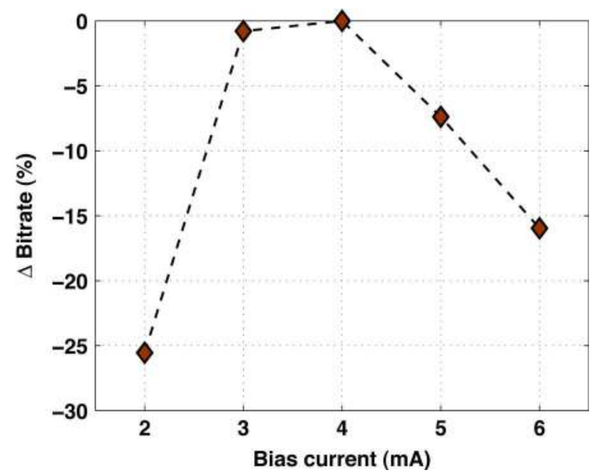

Fig. 12. Percentage Bit-rate variation versus driving bias current.

Besides the number of subcarriers and crest factor, which are the main parameters of the DMT signal and can finely be controlled in the DSP, we we analyze the optical parameters of the link. Driving bias currents of the light source and bending loss are examined. We have shown in Fig. 4 that a bias current of 4 mA is a good operating point when considering the light source linearity performance. For further clarification, Fig. 12 shows Δ Bitrate versus the DC bias currents of the VCSEL, confirming that the optimum value of bias current is 4 mA. For low bias currents, the link performance is dominated by the signal-to-noise ratio as less light is generated by VCSEL. For high bias currents, laser nonlinearity will reduce the achievable bit-rates.

We operated the VCSEL at the optimum bias current. However, note that with a variation of ± 1 mA, the overall bit-rate will degrade by a maximum of 7% still achieving 4.9 Gbit/s. Thus, in a real system implementation, a slightly lower bit-rate can still be achieved without the use of additional hardware such as current controllers.

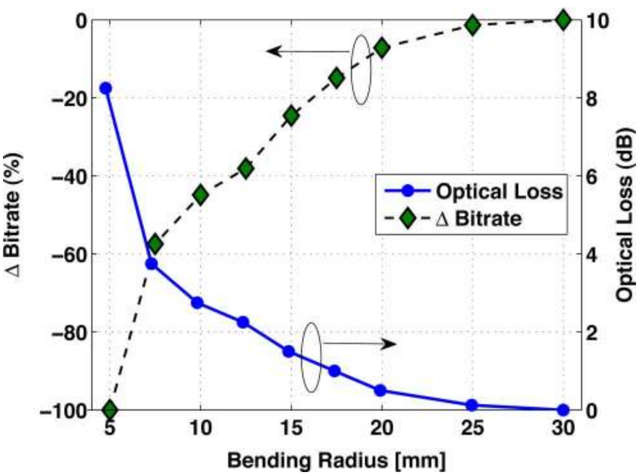

Fig. 13. Percentage Bit-rate variation and optical loss versus the bending radius of a 180° bend.

D. Bending Loss

Graded-index POF is today the plastic optical fiber with the highest available bandwidth. For this reason, this type of fiber is highly considered for realizing multi gigabit transmission in an in-home environment.

In a realistic in-home deployment where fibers need to be pulled throughout the corners of homes, another important feature is the resilience against mechanical stresses, including bending. While for 1 mm diameter step-index POF bending losses below 0.5 dB are reported for a bending radius of 20 mm [5], bending losses for graded-index POF are higher. A bending radius of 25 mm is reported [19]. For this reason, we studied the bit-rate penalty due to decreasing bending radius using a half bend (180° bend). Fig. 13 shows Δ Bitrate and optical bending loss against different values of bending radius. No penalty is observed at the bending radius of 25 mm, while a penalty $>7\%$ is noticeable at bending radius below 20 mm. The bit-rate decreases quite linearly for bending radius under 20 mm, and this decrease becomes asymptotically for 7.5 mm and less.

In conclusion, fiber bending affects the link performance due to less optical power received. Due its elasticity, POF is quite tolerant to bending to some degree. Allowing a tolerance of maximum 7% deviation in the highest bit-rate, a bending radius not less than 20 mm is recommended.

IV. Conclusion

We have shown transmission technology capable of delivering greater than 5 Gbit/s transmission rate over 1 mm diameter plastic optical fiber. By employing DMT techniques in an intensity-modulated direct detection system and optimizing the electrical and optical system parameters, we demonstrate a record transmission rate of 5.3 Gbit/s and 7.6 Gbit/s over 50 m and 10 m respectively. This record corresponds to a spectral efficiency >3.7 bits/s/Hz.

We also presented detailed evaluation on the DMT parameters and optical transmitter employed. These results highlight the implications of the choice of parameters in realizing this state-of-the-art solution.

By combining the advantages of 1 mm diameter PMMA GI-POF with eye-safe off-the-shelf transceivers, a cost-effective end-to-end network solution is presented for realizing multi-gigabit transmission.

This solution presents a desired do-it-yourself installation for in-home network environment in comparison to power lines, coaxial and twisted pairs solutions as it can be installed in the same power-line ducts.

In combination with emerging high-capacity, real-time digital signal processing, scalability towards 10 Gbit/s short-range communication over 1 mm diameter POFs is feasible.

References

[1] V. Oksman and S. Galli, "G.hn: The new ITU-T home networking standard," *IEEE Commun. Mag.*, vol. 47, no. 10, pp. 138–145, Oct. 2009.
[2] *Next Generation Home Networking Transceiver*, ITU-T Recommendation G.9960, Oct. 2009.
[3] R. E. Freund, C. A. Bunge, N. N. Ledentsov, D. Molin, and C. Caspar, "High-speed transmission in multimode fibers," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 569–586, Feb. 2010.
[4] I. Mollers *et al.*, "Plastic optical fiber technology for reliable home networking: Overview and results of the EU project pof-all," *IEEE Commun. Mag.*, vol. 47, no. 8, pp. 58–68, Aug. 2009.
[5] O. Ziemann, J. Krauser, P. E. Zamzow, and W. Daum, *POF Handbook: Optical Short Range Transmission Systems*, 2nd ed. Berlin, Germany: Springer-Verlag, 2008.
[6] A. Lopez, P. Heredia, J. Mateo, and M. A. Losada, "Comparative analysis of the transmission capabilities of large core plastic optical fibres," in *Proc. ICTON-MW*, 2009, Paper Th3.4.
[7] J. Armstrong, "OFDM for optical communications," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, Feb. 1, 2009.
[8] A. J. Lowery, "Optical OFDM," in *Proc. CLEO/QELS 2008*, May 2008, Paper CWN1.
[9] N. E. Jolley, H. Kee, P. Pickard, J. Tang, and K. Cordina, "Generation and propagation of a 1550 nm 10 Gbit/s optical orthogonal frequency division multiplexed signal over 1000 m of multimode fibre using a directly modulated DFB," in *Proc. OFC/NFOEC*, 2005, Paper OFP3.
[10] H. Yang, S. C. J. Lee, E. Tangdiongga, C. Okonkwo, H. van den Boom, F. Breyer, S. Randel, and A. M. J. Koonen, "47.4 Gb/s transmission over 100 m graded-index plastic optical fiber based on rate-adaptive discrete multitone modulation," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 352–359, Feb. 15, 2010.
[11] H. Yang *et al.*, "4.7 Gbit/s transmission over 50 m long 1 mm diameter multi-core plastic optical fiber," in *Proc. OFC/NFOEC*, 2010, Paper OWA4.
[12] S. Loquai, R. Kruglov, O. Ziemann, J. Vinogradov, and C. Bunge, "10 Gbit/s over 25 m plastic optical fiber as a way for extremely low-cost optical interconnection," in *Proc. OFC/NFOEC*, 2010, Paper OWA6.
[13] *Safety of Laser Products—Part 1: Equipment Classification and Requirements*, IEC Standard 60825-1, Mar. 2007, 2nd ed..
[14] P. S. Chow, J. M. Cioffi, and J. A. C. Bingham, "A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels," *IEEE Trans. Commun.*, vol. 43, no. 2, pp. 773–775, Feb. 1995.
[15] K. Joonsuk, C. Jiunn-Tsair, and J. M. Cioffi, "Low complexity bit mapping algorithm for multi-carrier communication systems with fading channels," in *Proc. IEEE Conf. ICUPC'98*, 1998, pp. 927–931.
[16] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed. New York: Wiley, 2006.
[17] D. M. Poznar, *Microwave Engineering*, 3rd ed. New York: Wiley, 2005.
[18] Firecomms 665 nm Multimode VCSEL Product Specification [Online]. Available: http://www.firecomms.com
[19] Optimedia OM-GIGA Product Specification [Online]. Available: http://www.optimedia.co.kr
[20] T. Pollet, P. Spruyt, and M. Moeneclaey, "The BER performance of OFDM systems using non-synchronized sampling," in *IEEE GLOCEBOM'94.*, Nov. 1994, pp. 253–257.
[21] T. M. Schmidl and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. Commun.*, vol. 45, no. 12, pp. 1613–1621, Dec. 1997.
[22] Q. Yang, N. Kaneda, L. Xiang, S. Chandrasekhar, W. Shieh, and Y. K. Chen, "Towards real-time implementation of optical OFDM transmission," in *Proc. OFC/NFOEC*, 2010, Paper OMS6.
[23] *Forward Error Correction for High-Bit Rate DWDM Submarine Systems*, ITU-T Recommendation G.975.1, Feb. 2004.

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