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Low-cost and High-capacity Short-range Optical Interconnects using Graded-Index Plastic Optical Fiber

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Abstract: We demonstrate a transmission rate of 51.8 Gb/s over 100-meters of perfluorinated multimode graded-index plastic optical fiber using discrete multitone modulation. The results prove suitability of plastic fibers for low-cost high-capacity optical interconnects.

OCIS codes: (060.2330) Fiber optics communications; (160.5470) Polymers

1. Introduction

In recent years, there has been increasing use of commercial perfluorinated graded-index plastic optical fiber (GI-POF) with core diameters of 50-62.5 µm for 10 Gb/s short-reach applications such as low-cost interconnects in datacenters, local area networks (LAN), and supercomputers. For such applications, multimode fibers (MMF) such as the GI-POF are preferred above single-mode fiber due to their large core diameter and numerical aperture. Due to the large alignment tolerances in transceiver components and fiber splices, MMF is attractive for in-building networks as its installation is easy and at low cost. In addition, when compared to silica MMF, GI-POF offers further advantages such as smaller bending radius (~5mm), better tolerance to tensile load and stress, and simpler connectorization.

Recent developments in the standardization of higher-speed networking standards like 40 and 100 Gigabit Ethernet also include MMF as physical medium [1], thereby paving the way for low-cost optical networking at speeds beyond 10 Gb/s. Although current proposals consider parallel transmission of multiple 10 Gb/s MMF links with multiple fibers or multiple wavelengths to achieve higher speeds, serial transmission using only one MMF is attractive because issues such as skew between parallel fibers or multiple wavelengths, inter-channel crosstalk, and reduced reliability due to higher complexity can be avoided. Several research groups have demonstrated 40 Gb/s serial transmission over GI-POF [2]-[4]. However, these results were obtained with expensive large-bandwidth (>25 GHz) single-mode fiber pigtailed components such as external Mach-Zehnder modulators and small-area high-bandwidth detectors [3], [4], as well as optical fiber amplifiers [2], which are neither practical nor suitable for low-cost applications.

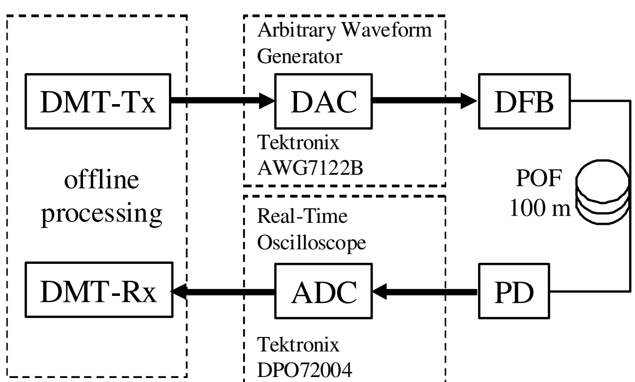

Fig. 1: Measurement setup for DMT over POF transmission.

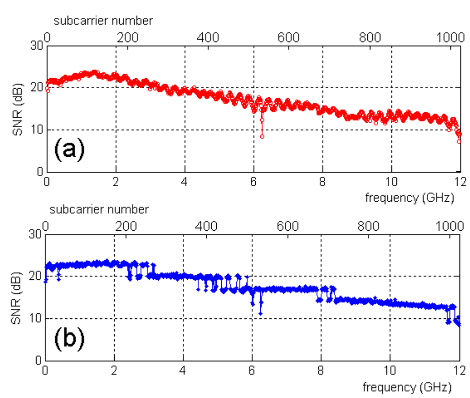

Fig. 2: Measured SNR/subcarrier after 100m POF (a)before and (b) after rate adaptive bit-loading.

In this paper, we demonstrate that by exploiting discrete multitone modulation (DMT) with up to 64-state quadrature amplitude modulation (64-QAM), off-the-shelf and low-cost components such as standard 1300-nm directly-modulated distributed feedback (DFB) laser diode (with 12-GHz bandwidth) and a multimode fiber-coupled 25-µm large diameter photodetector can be used to achieve 51.8 Gb/s serial transmission over 100 m of 50-µm core diameter GI-POF. This demonstrates the potential of DMT for enabling highly spectral efficient transmission at high bit-rates over POF, while overcoming the fiber's modal dispersion and allowing the use of conventional narrow-bandwidth transceivers. It is therefore a promising solution for low-cost, robust, and high capacity POF-based LAN links operating at data rates of 50 Gb/s and beyond. The work in this paper is partly supported by IOP-GenCom Future Home Networks and European Union FP7 research program ICT-224521 POF-PLUS.

2. Discrete Multitone Modulation and Bit-Loading

DMT is a baseband version of orthogonal frequency division multiplexing, which is widely implemented already in ADSL, VDSL, and powerline communication systems, proving that low-cost implementation in combination with existing multimode fiber transceivers is possible [5]. An important feature of DMT is the possibility to allocate the number of bits per subcarrier according to its corresponding signal-to-noise ratio (SNR), typically known as bit-loading. In the following measurements, Chow's rate-adaptive bit-loading algorithm [6] is used, which maximizes the achievable bit rate for a given bit-error ratio (BER). In comparison to the adaptive modulation shown in [5], Chow's algorithm is known to achieve near-optimum channel capacity, resulting in maximization of the transportable bit-rates.

3. Experimental Results and Discussion

In order to realize >50 Gb/s transmission over GI POF, different system parameters have to be investigated and optimized. For this, the experimental setup depicted in Fig. 1 is used. Using a Tektronix AWG7122B arbitrary waveform generator (AWG) with a bandwidth of 10 GHz, a DFB laser is directly modulated at a sampling speed of 24 GSamples/s. To achieve this sampling speed, the two outputs of the AWG, both at 12 GSamples/s, are interleaved. The DFB laser, with a wavelength of 1302 nm, is specified for up to 10 Gb/s on-off keying transmission and has an electrical small-signal modulation bandwidth of approximately 12 GHz. The resulting intensity modulated optical signal is then either transmitted over 100 meters of 50-µm core perfluorinated GI-POF, or directly coupled to the multimode variable optical attenuator in the back-to-back measurement case. After the multimode attenuator, the received optical signal is detected by a multimode-fiber-coupled photo-detector (PD) with a detection diameter of 25-µm and an integrated coupling lens. The resulting received electrical signal is then amplified and captured using a 16 GHz real-time Tektronix DPO72004 digital storage oscilloscope (DSO) running at a sampling rate of 50 GSamples/s for demodulation and evaluation. The sampling rates are chosen high in order to save the processing time. Lower sampling rates do not have significant impact on the results. The clocks of the AWG and DSO are not synchronized, so that clock/phase recovery has to be performed by the DMT demodulator as well.

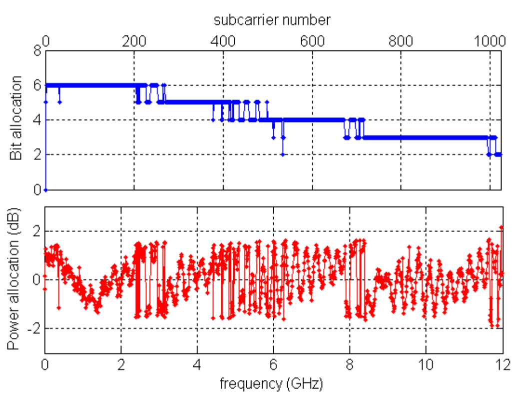

Fig. 3: DMT performance on (*top*) bit allocation and (*bottom*) power allocation per subcarrier.

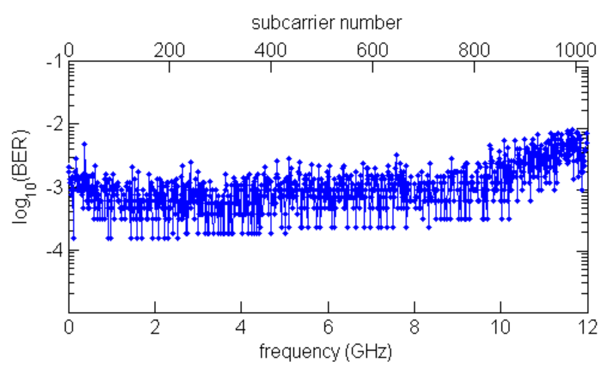

Fig. 4: BER performance for different subcarriers.

For the DMT transmission, a computer is used to emulate the digital DMT modulator and demodulator, as shown in Fig. 1. This also includes offline clock/phase recovery, evaluation of BER and SNR per subcarrier, and computation of bit-loading algorithm. In the experiment, 1024 subcarriers are used for the DMT transmission, ranging from a frequency of 0 to 12 GHz. Fig. 2a shows the measured SNR per subcarrier in the initialization stage, prior to applying Chow's rate-adaptive bit-loading algorithm, after transmission over 100 m GI-POF. The channel response is clearly adapted by the large amount of subcarriers in detail. The bit and power allocation per subcarrier, after applying rate-adaptive bit-loading, is depicted in Fig. 3. For subcarriers with the highest SNR, 6 bits are allocated for DMT transmission, which is realized by 64-QAM. The number of allocated bits per subcarrier decreases to 2, for those subcarriers with the lowest SNR. This is equivalent to a modulation format of 4-QAM. By allocating a different amount of power to each individual subcarrier, the SNR per subcarrier can be fine-tuned to a fixed value, which is just enough to achieve a BER of 10^{-3} for the specific modulation format. The resulting SNR per subcarrier after rate-adaptive bit-loading is shown in Fig. 2b. Note that the SNR per subcarrier is stair-case-shaped, as a result of the bit-loading algorithm. A total of 4421 bits are allocated per DMT frame. Fig. 4 presents the measured BER values as a function of the subcarrier index for the received 51.8 Gb/s DMT signal. In the DMT transmission scheme, the signal is not demodulated per subcarrier but as an entire frame. This provides the benefit that even if some subcarriers have BER values larger than 10^{-3}, the signal quality is still good enough to achieve a total average BER of 10^{-3}. In Fig. 5, we present the electrical spectra of the signal as observed before and after 100-m transmission. The available bandwidth for data transmission is seen as less than 5 GHz, taking into account the bandwidth of the AWG and the DFB laser. However, the DMT scheme and the bit-loading algorithm allow us to successfully transmit 51.8 Gb/s data through such narrow bandwidths. The blue curve is the spectrum without data modulation, which indicates the noise floor of the system.

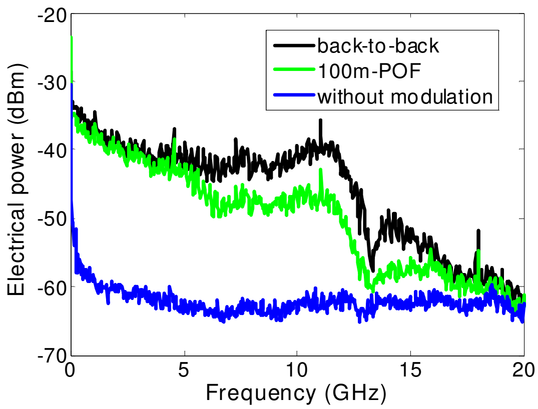

Fig. 5: Signal spectrum of before and after transmission. Also shown is the spectrum of no modulation.

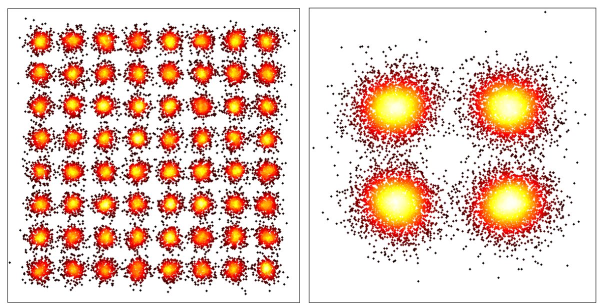

Fig. 6: Constellations of the subcarriers carrying 64-QAM (left) and 4-QAM (right).

In Fig. 6, the superimposed constellation diagrams of the first 20 subcarriers with 64-QAM and the last 10 subcarriers with 4-QAM are shown. These constellations are respectively the largest and smallest of the DMT transmission system over 100 m GI-POF. The clearly distinguishable constellation points indicate that the received signal quality is good and that the one-tap channel equalizers in the DMT demodulator are working as expected.

4. Conclusions

We have experimentally shown that POF is capable of transporting high-capacity optical signals exploiting off-the-shelf low-cost components. A record transmission capacity of 51.8 Gb/s for BER<10^{-3} is achieved through POF in combination with the rate-adaptive bit-loading DMT modulation technique.

Although current 40GbE and 100GbE proposals regard only parallel transmission of multiple 10-Gb/s links in order to achieve higher speeds, the proposed idea of serial transmission at similar bandwidth requirements by use of DMT and POF can result in even lower-cost systems. While one might argue that digital signal processing will increase power consumption, significant power savings resulting from using less transceivers can offer a good trade-off to make a combination of POF and DMT a viable solution for high-speed, low-power, and low-cost serial optical networking operating at bit-rates 50 Gb/s and beyond.

5. References

[1] *IEEE P802.3ba 40Gb/s and 100Gb/s Ethernet Task Force* [Online]. Available: http://www.ieee802.org/3/ba/

[2] J. Yu, et al., "42.8 Gb/s Chirp-Managed Signal Transmission over 100 m Graded-Index Plastic Optical Fiber," OFC 2008, PDP-28.

[3] S. Schöllmann, et al., "First Experimental Transmission over 50 m GI-POF at 40Gb/s for Variable Launching Offsets," ECOC 2007, PDP 3.7.

[4] A. Polley, et al., "40 Gbps Links using Plastic Optical Fiber," OFC 2007, OMR5.

[5] S.C.J. Lee, et al., "24-Gb/s Transmission over 730 m of Multimode Fiber by Direct Modulation of an 850-nm VCSEL using Discrete Multi-tone Modulation," OFC 2007, Paper PDP6.

[6] 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, Feb. 1995.