40-Gb/s transmission over 100m graded-index plastic optical fiber based on discrete multitone modulation

40-Gb/s Transmission over 100m Graded-Index Plastic Optical Fiber based on Discrete Multitone Modulation

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Abstract: Spectral-efficient 40-Gb/s discrete multitone transmission over 100m of graded-index plastic optical fiber is experimentally demonstrated by intensity-modulation of a 10-GHz DFB-laser (1302nm) and direct-detection with a 25-µm large diameter photodetector.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (160.5470) Polymers

1. Introduction

In recent years, the commercial graded-index perflourinated plastic optical fiber (GI-POF) with core diameters of 50 to 62.5µm is gaining popularity in 10G short-reach applications such as low-cost interconnects in datacenters, local area networks (LANs), and cloud computing. 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, which allow easy and low-cost installation thanks to the large alignment tolerances in transceiver components and fiber splices. In addition, when compared to silica MMF, GI-POF offer further advantages such as smaller bending radius (5 mm), 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 (by putting fibers and/or wavelengths in parallel) in order to achieve higher speeds, serial transmission using only one MMF can be of interest because issues such as skew between parallel fibers/wavelengths, inter-channel crosstalk, and reduced reliability can be avoided. Several research groups have already shown that 40-Gb/s serial transmission over GI-POF is possible [2-4]. However, these results were obtained with expensive high-bandwidth (>25 GHz) single-mode fiber components such as external modulators and small-area high-bandwidth detectors [3][4], as well as optical fiber amplifiers [2], which is not at all practical and suitable for low-cost applications.

In this paper, we show that by use of discrete multitone modulation (DMT) with up to 64-state quadrature amplitude modulation (64-QAM), a standard O-band directly-modulated distributed feedback (DFB) laser (with 10-GHz bandwidth) and an MMF-coupled 25-µm large diameter photodetector can be used to achieve serial 40-Gb/s transmission over 100 m of 50-µm GI-POF. This demonstrates the potential of DMT for enabling highly spectral-efficient transmission at high bit-rates over MMF, while overcoming the fiber's modal dispersion and allowing the use of conventional low-bandwidth transceivers. It is therefore a promising solution for low-cost, robust, and high

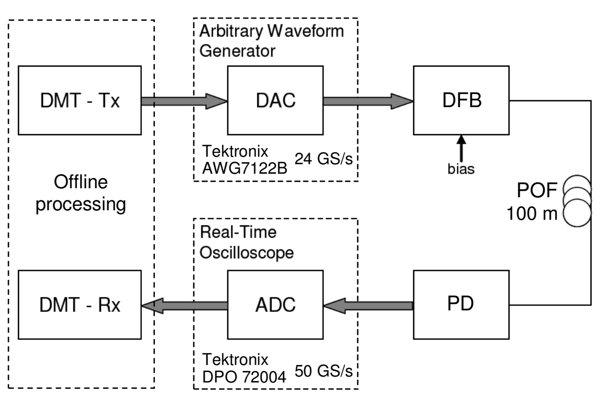

Fig. 1. Measurement setup for DMT over POF transmission

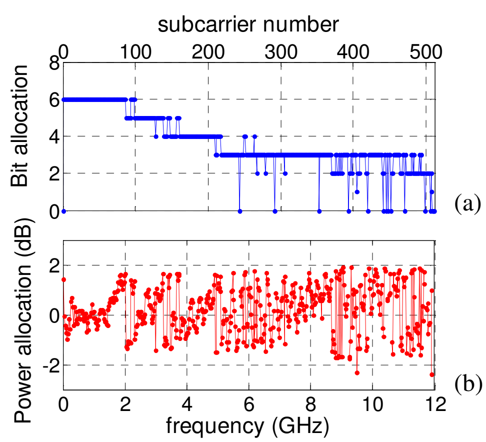

Fig. 2(a) Bit allocation map for 40 Gb/s bit rate; (b) Power allocation for 40Gb/s bit rate

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capacity MMF LAN links operating at data rates of 40 Gb/s and beyond.

2. Discrete Multitone Modulation using Bit-Loading

Derived from the more general orthogonal frequency division multiplexing (OFDM), DMT is a baseband version that is already applied in large volume in ADSL, VDSL, and powerline communication systems, proving that low-cost implementation in combination with existing MMF 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

To realize 40 Gb/s transmission over POF, the diagram of the experimental setup is shown in Fig. 1. A DFB laser is directly modulated by the output of the arbitrary waveform generator (AWG) at 24 GSamples/s. The DFB laser with 1302-nm wavelength is specified for up to 10 Gb/s on-off keying transmission, and has an electrical small-signal modulation bandwidth of around 12 GHz. The directly modulated signal is then transmitted over 100 meters of 50-µm core perfluorinated GI-POF, and detected by a 25-µm multimode photo-detector (PD). The received signal is electrically amplified and is sent to a real-time oscilloscope running at a sampling rate of 50 GSamples/s for demodulation and evaluation.

For the DMT transmission, a computer is used to emulate the digital DMT modulator and demodulator, as shown in Fig. 1. In the present experiment, 512 subcarriers are available for the DMT transmission, ranging from 0 to 12 GHz. Fig. 2 shows the results from Chow's bit-loading algorithm, after transmission over 100m POF. From the bit-loading parameters, it can be calculated that 40.6 Gb/s is achieved using DMT with bit-loading. Fig. 2a illustrate that almost all the 512 bits are allocated in this calculation, in order to achieve 40.6 Gb/s bit rate. Some of them allocated 6 bits of information at maximum (i.e. 64-QAM). Due to the power allocation shown in Fig. 2b, the measured SNR-s per subcarrier after bit-loading are stair-case-shaped as depicted in Fig. 3b. Fig. 3a presents the BER values as a function of the index of carriers for the received 40.6 Gb/s signal. It is seen from Fig. 3a that the BER value varies from $1\cdot 10^{-4}$ to $5\cdot 10^{-3}$ over 512 carriers. The average BER is $5.7\cdot 10^{-4}$. In the DMT scheme, the signal is not demodulated per carrier, which provides the benefit that even if some carriers have BER larger than $1\cdot 10^{-3}$, the signal quality is still below the forward-error-correction (FEC) limit for error-free operation. The FEC limit for error free is $1\cdot 10^{-3}$ which forms the target BER values in this experiment. We observed excellent performance of the transmitted signals. As an example, we present in Fig. 3c the constellation of the demodulated 100th sub-carrier. This sub-carrier has more than 20 dB (see Fig. 3b) and has 5-bit allocation (see Fig. 2a), which gives a 32-QAM constellation.

In Fig. 4, we present the electrical spectra of the signal as observed before and after 100-m GI-POF transmission. It is shown in Fig. 4 (curve c) that the 3-dB bandwidth of the transmission system is only around 2 GHz and the

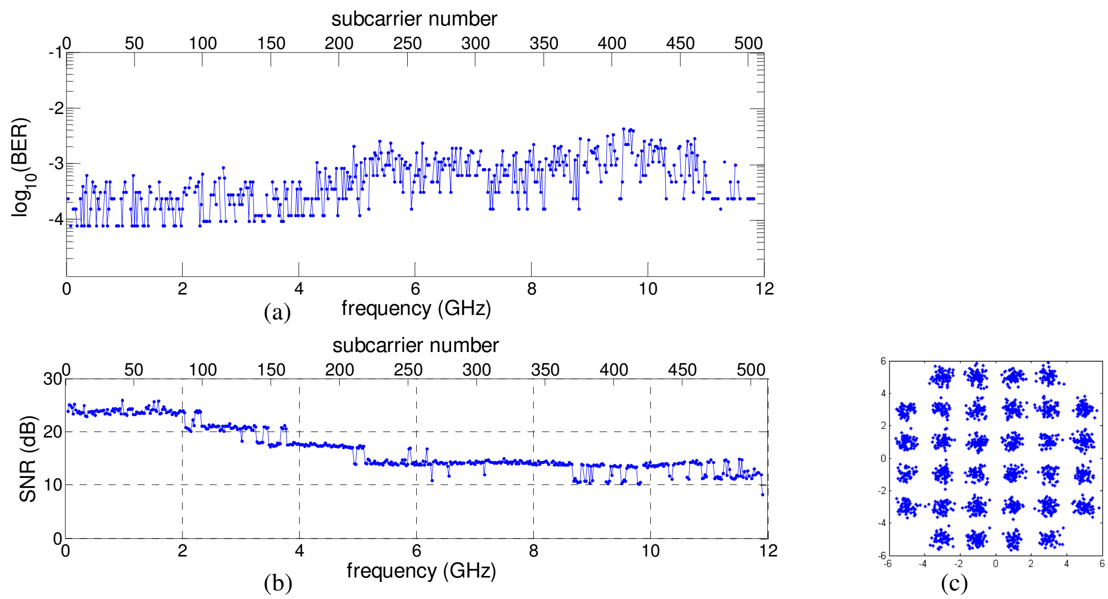

Fig. 3. (a) BER for different carrier index and frequency after transmission employing bit-loading ; (b) SNR for different carrier index and frequency after transmission employing bit-loading; (c) constellation diagram for the 100th carrier (32-QAM)

available bandwidth is not more than 12 GHz (marked “A”). Fig. 4 takes 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 40.6 Gb/s data through such narrow bandwidths. We observe a peak at 24 GHz, which is due to the 24GSample/s sampling rate of the AWG. The (green) dotted curve “a” is the spectrum without data modulation, which indicates the noise floor of the system.

Finally, we show in Fig. 5 the BER values as a function of the received optical power. Back-to-back and transmission using 100-m POF are considered. For BER values under 10^{-3} the received power levels should be larger than 3 dBm for successful transmission of 40 Gb/s signals through 100-m GI-POF. For the back-to-back case, the received power is around -3 dBm to reach the same BER value. This indicates a power penalty of 6 dB, which we consider relatively small, taking into account the narrow transmission bandwidth and the simplicity of the setup, i.e. direct modulation and direct detection. We also show in Fig. 5 that the lowest BER value obtainable from the system is approximately $2\cdot 10^{-4}$. For the back-to-back case and the 100m transmission this BER value is achieved by injecting optical powers of more than 0 and 3 dBm, respectively.

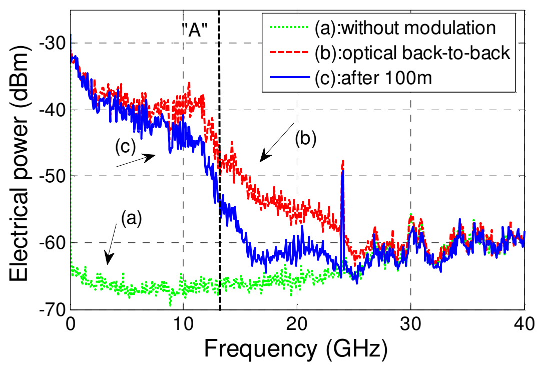

Fig. 4. Electrical spectrum of the signal (a) without modulation, (b) back-to-back and (c) after 100m transmission

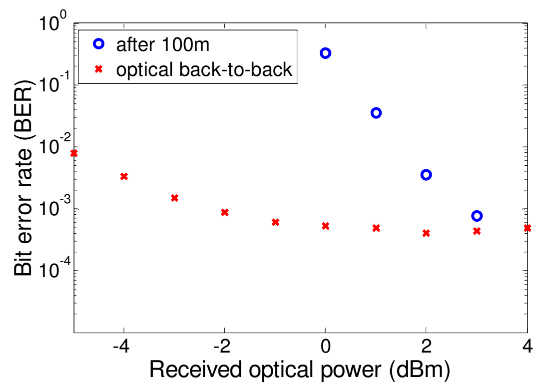

Fig. 5. BER performance measured o: after 100m transmission, x: back-to-back

4. Conclusions

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 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 DMT a viable solution for high-speed, low-power, and low-cost serial optical networking operating at bit-rates 40 Gb/s and beyond. Moreover, DMT has proven to be a robust technique to overcome in an adaptive manner the modal dispersion of multimode GI-POF links, which may be varying due to changing fiber launching and bending conditions.

5. References

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