10.7-Gb/s Discrete Multitone Transmission Over 50-m SI-POF Based on WDM Technology

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***Abstract*— The capacity of the transmission link based on standard 1-mm core-diameter step-index plastic optical fiber (SI-POF) is strictly limited due to the strong attenuation and inter-modal dispersion. Parallel transmission of the data streams using several optical carriers might overcome the mentioned limits and allows for low-bandwidth transmitters and receivers. In this letter, we demonstrate the implementation of wavelength-division multiplexing technology with three laser diodes operating at 405, 515, and 650 nm with +7.1, +5.4, and +4 dBm fiber-coupled power. The 10.7-Gb/s data transmission based on the offline-processed discrete multitone modulation technique has been realized over 50-m SI-POF at the bit-error ratio of 10^{-3}.**

***Index Terms*— Green laser diode, interconnection, optical communication, polymer optical fiber (POF), wavelength-division multiplexing (WDM).**

I. Introduction

WAVELENGTH-DIVISION multiplexing (WDM) technology is one approach to increase the capacity of actual optical transmission systems. Introduced in 1970s it is widely used in glass-fiber telecommunication. The application of WDM technology in polymer optical fiber (POF) systems seems reasonable [1], but the lack of fast optical sources operating in the visible range impeded the growth of this area.

The current progress in the manufacturing of laser diodes (LD) operating in the visible range [2] brings the opportunity to improve the performance of SI-POF systems implementing WDM technology.

In comparison to conventional red LDs the optical sources operating at shorter wavelengths have advantages for several reasons: Within the red loss window (around 650 nm) the attenuation of PMMA SI-POF is 120–130 dB/km [1]. Within green and yellow loss windows the attenuation goes even down to 70–80 dB/km. Moreover the much broader attenuation minima at shorter wavelengths are less sensitive to transmitters with wider spectrum or to spectral drift with temperature.

Previous publications [3], [4] show that WDM-POF systems based on LED technology cannot provide high-speed data transmission with sufficient margin. Data transmission over 200-m perfluorinated graded-index POF using laser-based WDM technology was published in [5]. Three laser diodes operating at 645 nm, 840 nm and 1310 nm were modulated at 2.5 Gbit/s each. These promising results, however, cannot be directly applied to large-core SI-POF systems operating mainly in the wavelength range of visible light.

This letter focuses on the implementation of WDM technology in SI-POF communication links and shows the experimental results on simultaneous data transmission of three optical channels (at 405 nm, 515 nm, 650 nm) using the spectrally efficient discrete multitone modulation technique (DMT) per wavelength channel. 10.7-Gbit/s data transmission has been realized over 50-m SI-POF link at BER of 10^{-3}.

II. Description of Transmission Setup

The basic setup of the optical link is shown in Fig. 1. It includes 3 butt-coupled edge-emitting laser diodes operating at 405 nm, 515 nm, 650 nm, a 1:3-optical coupler, 50-m Mitsubishi GH4001 SI-POF with 1-mm core diameter (POF class A4a.2, according IEC 60793-240), a filter-based demultiplexer, and optical receivers with Ø 800-μm silicon pin photodiodes (HAMAMATSU S5052), which are connected to trans-impedance amplifiers.

The commercially available laser diodes DL-4146-101S (Sanyo) and U-LD-651041A (Union Optronics) operate at 405 nm and 650 nm correspondingly. Although the wavelength of 405 nm is close to ultraviolet range it does not initiate the photodegradation in PMMA [6]. The InGaN laser diode operating at 515 nm is a research and development (R&D) sample produced by OSRAM Opto Semiconductors in 2009. Additional parameters of laser diodes are shown in Table 1.

The laser diodes were driven in their linear regions with modulation index m $\approx$ 0.9. In order to avoid possible damage of the R&D sample of LD a thermoelectric cooler has been used, which was adjusted to +10 °C.

The green LD has a relatively high threshold current of 120 mA, which stems from its optimization for laser projection systems, where a high output power is required. The latest samples of the InGaN laser diodes developed by OSRAM

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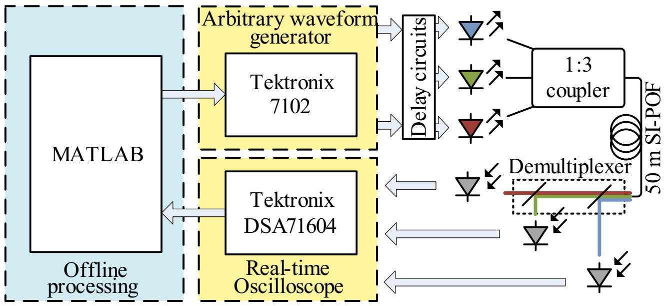

Fig. 1. Schematic transmission setup used for experiments.

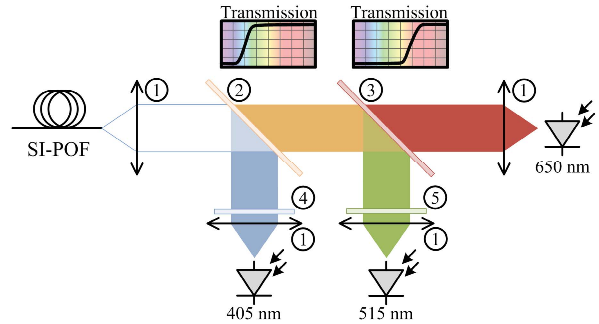

Fig. 2. Schematic of the three-channel demultiplexer. 1: lenses. 2, 3: long wavepass interference filters. 4, 5: additional thin-film filters.

TABLE I
PARAMETERS OF LASER DIODES USED IN THE MEASUREMENTS

Operating wave-length, nm	Max. optical power, mW	Threshold current, mA	Operating bias current, mA
405	10	31	40
515	50	120	170
650	10	16	35

TABLE II
LEVELS OF THE OPTICAL SIGNALS ALONG THE FIBER LINK

Operating wavelength, nm	Fiber coupled power, dBm	Received power, dBm	Photosensitivity, A/W
405	+7.1	−6.9	0.20
515	+5.4	−6.0	0.29
650	+4.0	−10.6	0.38

Opto Semiconductors demonstrate two times lower threshold currents [2].

The 3:1 coupler uses three 340-μm diameter SI-POF input fibers butt-jointed to a 1-mm diameter POF [1]. This gives a maximum 1-dB loss from any input to the output.

The demultiplexer used two long wavepass interference filters produced by CVI Melles Griot, which were mounted at the angle of 45° to the incident beam (see Fig. 2). The cutoff wavelengths of the beamsplitter were 450 nm and 550 nm correspondingly. The BK7 bi-convex lenses with focal lengths of 20 mm were required for the transformation of the fiber output light into the parallel beam and focusing at the photodiodes. To decrease the crosstalk two additional filters were used for 405-nm and 515-nm channels.

In order to provide better flexibility of the simultaneous data transmission at three wavelengths the DMT modulation technique were used [7]. This is a highly spectral efficient modulation scheme, which uses a large number of electrical subcarriers and is a subclass of orthogonal frequency division multiplexing. DMT is used as a basic modulation algorithm for digital subscriber lines.

For the DMT signal generation an arbitrary waveform generator (AWG) with a resolution of 10 bits were used. In order to facilitate digital filtering of high-frequency aliasing products and to improve the frequency response of the constructed signal, the sampling rate of the AWG was adjusted to the value, which is four times higher than the maximal frequency of the transmitted DMT signal. To decorrelate the data streams driving the LDs an additional delay between channels of 5 ns was introduced.

In order to synchronize the AWG and the real-time oscilloscope, the received signal was recorded with an additional oversampling at the sample rate of 12.5 GSa/s. This oversampling would not be required in real systems with e.g. a phase-locked loop. The real-time oscilloscope captured the analog electrical signal with a resolution of 8 bits for subsequent offline processing. The BER was then evaluated by error counting using a computer.

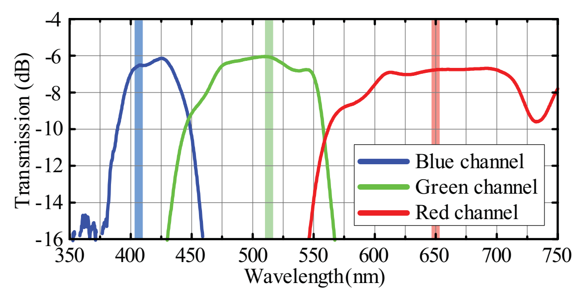

Fig. 3. Transmission of the three-channel demultiplexer.

III. MEASUREMENT RESULTS

The fiber-coupled power measured after the coupler and received power measured at the outputs of demultiplexer are shown in Table II.

The attenuation of the fiber at 515 nm is lower compared to the other channels. It allows achieving a higher power level at the receiver. Unfortunately, the operation in the shorter wavelength range slightly decreases the photosensitivity of the photodiode. However this factor does not play a significant role in the power budget calculation. As a reference the photosensitivity of the pin photodiode is shown in the Table II.

Fig. 3 shows the transmission of the 3-channel demultiplexer used in the experiments. The measured insertion loss of the demultiplexer was <7 dB with a crosstalk below −30 dB.

The LDs were directly driven with a pseudo-random bit sequence (PRBS 2^9-1) mapped to a DMT signal with 256 subcarriers. In order to avoid the influence of inter-symbol interference (ISI) DMT-frames with a cyclic prefix of 3.125% were used.

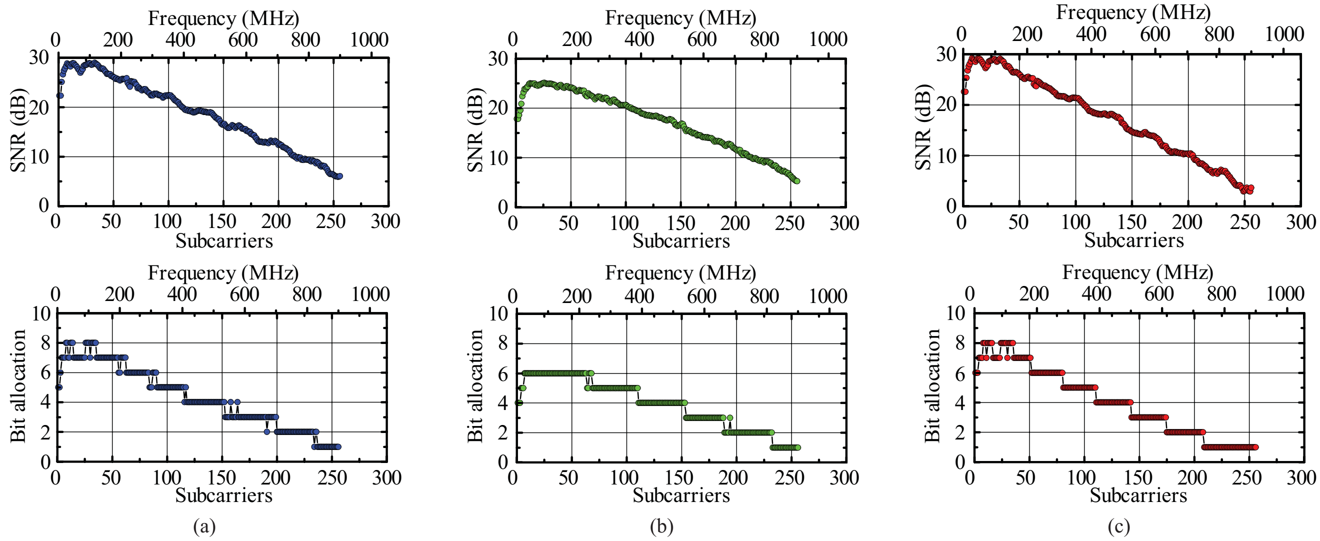

Fig. 4. Measured SNR per subcarrier before bit-loading (above) and bit-loading scheme obtained on the basis of Chow's rate adaptive bit-loading algorithm (below) for (a) 405-nm channel, (b) 515-nm channel, and (c) 650-nm channel.

After estimation of the signal-to-noise ratio (SNR), Chow's rate adaptive bit-loading algorithm [8] has been applied to assign the appropriate modulation format to each subcarrier.

The total average BER was set to 10^{-3}, which is sufficient for applying forward error correction (FEC).

The SNR before bit-loading and the bit-loading schemes for the channels are shown in Fig. 4. Data streams at the rates of 3.8 Gbit/s, 3.39 Gbit/s, 3.53 Gbit/s were transmitted at 405 nm, 515 nm and 650 nm respectively. After considering the 7% FEC bits, an aggregate net bit rate of 10 Gbit/s was achieved.

Our system provides twice the transmission distance of a single-wavelength system operating at 650 nm [9].

IV. Conclusion

In comparison with conventional 650-nm optical sources the LDs operating at the shorter wavelengths provide a higher system margin due to lower attenuation minima of the fiber in this spectral region. Moreover it brings better system tolerance to transmitters with wider spectrum or spectral drift with temperature.

The availability of the blue and green laser diodes makes the realization of the WDM-POF systems possible. For the first time, 10.7-Gbit/s data transmission has been demonstrated over SI-POF link up to a distance of 50 m. Compared to DMT-based POF system operating at 650 nm, the demonstrated WDM-POF link allows doubling the possible link length [9].

The slow progress of the WDM-POF systems is connected not only with the shortage of the cheap and fast optical sources operating in the visible light range. There is no effective solution for the signal demultiplexing available on the POF-market so far. Development of a demultiplexer based on e.g. concave diffraction grating [10], which can provide low insertion loss, will stimulate the further growth of WDM-POF technology.

Further improvement of the system performance can be achieved with the integration of the receiver, which reduces the noise level [11]. It also allows reducing the power of the laser diodes bringing it closer to the eye-safety limit.

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References

[1] O. Ziemann, J. Krauser, P. Zamzow, and W. Daum, *POF-Handbook – Short Range Optical Transmission Systems*, 2nd ed. New York: Springer-Verlag, 2008.

[2] C. Vierheilig, *et al.*, "Beyond blue pico laser: Development of high power blue and low power direct green," *Proc. SPIE*, vol. 8277, pp. 82770K-1–82770K-7, Jan. 2012.

[3] S. Junger, W. Tschekalinskij, and N. Weber, "POF WDM transmission system for multimedia data," in *Proc. 11th Int. Conf. Polymer Opt. Fibers*, 2002, pp. 69–71.

[4] V. Appelt, J. Vinogradov, and O. Ziemann, "Simple FEXT compensation in LED based POF-WDM systems," in *Proc. 11th Int. Conf. Polymer Opt. Fibers*, 2002, pp. 127–129.

[5] H. P. A. Boom, *et al.*, "High-capacity transmission over polymer optical fiber," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 3, pp. 461–470, May 2001.

[6] H. Zweifel, R. D. Maier, and M. Schiller, *Plastics Additives Handbook*, 6th ed. Munich, Germany: Carl Hanser Verlag, 2009.

[7] S. C. J. Lee, *et al.*, "Discrete multitone modulation for maximizing transmission rate in step-index plastic optical fibers," *J. Lightw. Technol.*, vol. 27, no. 11, pp. 1503–1513, Jul. 1, 2009.

[8] 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.

[9] S. Loquai, R. Kruglov, O. Ziemann, J. Vinogradov, and C. A. Bunge, "10 Gb/s over 25 m plastic optical fiber as a way for extremely low cost optical interconnection," in *Proc. Opt. Fiber Commun. Coll. Nat. Fiber Opt. Eng. Conf.*, Mar. 2010, pp. 1–3, paper OWA6.

[10] L. V. Bartkiv and Y. V. Bobitski, "Design and optimization of concave diffraction grating for WDM multi/demultiplexer," in *Proc. 10th Int. Conf. Laser Fiber-Opt. Netw. Model.*, 2010, pp. 128–130.

[11] M. Atef, W. Gaberl, R. Swoboda, and H. Zimmermann, "An integrated optical receiver for multilevel data communication over plastic optical fiber," in *Proc. NORCHIP*, Nov. 2009, pp. 1–4.