Up to 64QAM (30 Gbit/s) Directly-modulated and Directly-detected OFDM at 2 µm Wavelength

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Abstract *We report a novel OFDM-transmitter operating in the emerging 2-µm waveband. Sub-FEC limit transmission of a 32QAM signal over 500m of both solid and hollow-core fiber was achieved and the generation of 30Gbits 64QAM demonstrated.*

Introduction

The 2-µm spectral band is emerging as an attractive region for optical communications for several reasons. In particular, a radically new form of transmission fiber, the Hollow-Core Photonic Bandgap Fiber (HC-PBGF), which offers substantially lower nonlinearity, lower-latency and potentially ultimately lower minimum loss in this wavelength range than conventional solid fibers operating at 1550 nm. Furthermore, the Tm-doped fiber amplifier (TDFA), which supports around two times larger bandwidth than the combined C+L bands of the erbium doped fiber amplifier operates in this waveband[1]. However, the lasers, modulators and receivers, required for efficient communications in this new spectral region, are only just starting to become available. To date OOK signal generation using an external modulator at up to 8.5 Gbit/s[2-3] and Fast-OFDM BPSK signal generation via direct laser modulation (5 Gbit/s)[3] were demonstrated. These signals were successfully transmitted and received in two separate four-channel WDM experiments (1 OOK channel and 3 Fast OFDM BPSK channels) - first over 50 m of standard optical fiber[3], and more recently over 290 m of HC-PBGF[4].

Concurrently, there has been significant interest in increasing the transmission capacity while reducing the cost of optical transmission by using simple, low-cost optical transmitters in conjunction with powerful digital signal processing (DSP). A recent example takes advantage of direct multi-level laser modulation using a sub-carrier and direct detection at the receiver[5]. At the conventional 1550 nm spectral band, operation with 16QAM signals at 14 Gbaud symbol rate was demonstrated using a special high-bandwidth semiconductor laser[6]. Data transmission over 4 km of standard SMF-28 fiber was demonstrated. Another report concerns use of a specially-designed semiconductor laser directly-modulated under optical injection locking (OIL) that reduces the chirp of the directly-modulated laser (DML) to enable 5 Gbaud 16QAM OFDM transmission over 25 km of SMF-28[7]. This new approach seems particularly well suited for 2 µm optical communications: it is potentially low-cost (direct modulation + direct detection) and moreover the optical components necessary for 'classical' coherent modulation/detection are still to be developed for the 2 µm region.

Here, we demonstrate a transmitter operating at 2 µm comprising two low-cost recently-developed semiconductor lasers (a single-mode master and a directly-modulated Fabry-Perot slave)[8]. We report 5-Gbaud directly-modulated OFDM transmission for 16QAM, 32QAM and 64QAM signals. Whilst there is still substantial scope for further optimization of these devices we have already achieved a more than 3-times higher data rate per channel than in previous 2-µm based transmission experiments[2-3].

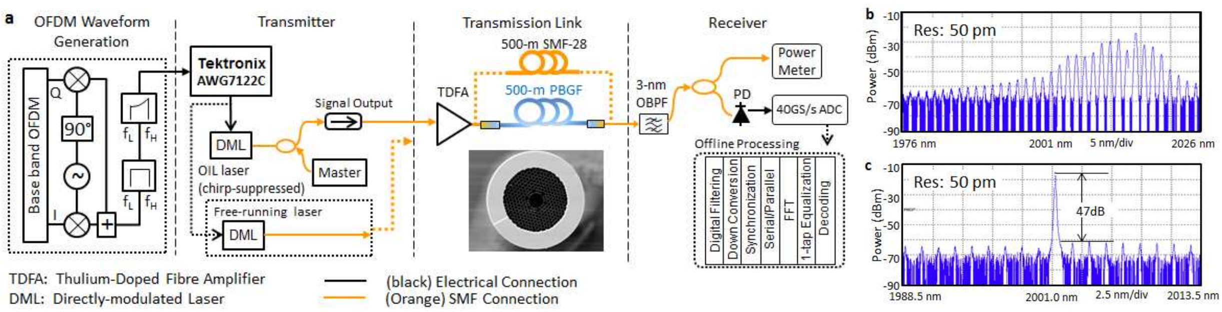

Fig. 1: (a) Experimental setup; (b) Optical spectrum of the free running directly modulated laser (DML); (c) Optical spectrum of the DML after injection locking.

Experimental Setup

Fig. 1 (a) shows our experimental setup. The waveform samples of the base-band OFDM are calculated offline based on a PRBS of 2^{18}-1 for 16QAM mapping and a PRBS of 2^{19}-1 for both 32QAM and 64QAM mapping. An inverse Fourier Transform size of 256 is used. Of the 256 subcarriers, the central 238 subcarriers are selected as data carriers. A four-sample cyclic prefix (CP) is placed both before and after each OFDM symbol. The signals were designed for a symbol rate of 21.2 MHz and the waveforms were digitally up-converted to a 3-GHz RF carrier frequency, which results in an electrical bandwidth of 5.2 GHz (from 0.4 GHz to 5.6 GHz). The nominal data rates for 16QAM, 32QAM, and 64QAM mapping are 20.2 Gb/s, 25.2 Gb/s, and 30.3 Gb/s, respectively. The waveforms are digitally filtered and pre-emphasized to compensate for the high-frequency laser roll-off.

The DML operating as a slave laser[8] is an $In_{0.75}Ga_{0.25}As$ Fabry-Perot laser diode (FP-LD) in a butterfly package with its output directly coupled into a polarization-maintaining (PM) fiber without any in-built isolator (as necessary for the OIL). The master is an $In_{0.75}Ga_{0.25}As$ multiple quantum-well discrete-mode laser diode emitting 3 mW CW light at 2001.1 nm[8] and incorporates a dual-stage isolator within the butterfly package. We characterized its frequency noise[9] and determined a 1 MHz linewidth. A 60:40 split ratio PM fiber coupler is used for the OIL.

More than 30 longitudinal modes are generated by the free-running slave DML (Fig. 1 (b)). Once injection locked with 0.9 mW of master light, single mode operation with a side-mode suppression ratio of 47 dB was achieved (Fig.1 (c)). The slave DML was biased at 43 mA and modulated by electrical signals generated using an arbitrary waveform generator (AWG) operating at 22.4 GS/s with 1.8 Volts peak-to-peak. The wavelength of the injected light was tuned via the bias current control of the master laser.

Due to the relatively low sensitivity of our photo receiver (details below), the transmitter power (1.1 mW) was boosted to 76 mW in a home-built TDFA[1]. The light was launched into either 500 m of SMF-28 (loss ~22 dB/km at 2 µm), or 500 m of HC-PBGF (state-of-the-art loss of 2.5 dB/km and a 3-dB transmission bandwidth of 122 nm (1954-2076nm)). The PBGF was pigtailed with SMF-28 fiber, yielding a total insertion loss of 6.5dB (with an estimated insertion loss of around 2.5 dB at each end arising primarily due to mode-mismatch).

At the receiver side, a 3 nm optical band pass filter was used to remove the out-of-band ASE noise. The filtered light was then split for simultaneous power monitoring and direct detection. A 7-GHz, 2-µm reverse-voltage-biased photo-diode (ET-5010F) in conjunction with a wide-bandwidth (10 GHz) RF amplifier was used for direct detection. The signal was then sampled at 40 GS/s by an Agilent DSO-X 93204A digital signal analyzer. Decoding was implemented using offline digital signal processing, and the bit-error-ratio (BER) was determined based on offline error counting. A 16% training overhead was used for symbol synchronization and channel estimation. After 1-tap equalization the BER was calculated.

Experimental Results

The BER as a function of received optical power for back-to-back operation is shown in Fig. 2 (a). Our transmitter operates error free with 16QAM and below the FEC threshold of 3.8×10^{-3} for 32QAM and 64QAM, at nominal data rates of 20.2 Gb/s, 25.2 Gb/s, and 30.3 Gb/s, respectively. Fig. 2 (b) shows the BER curves after transmission through the 500 m of SMF-28 or HC-PBGF. The power penalty is comparable

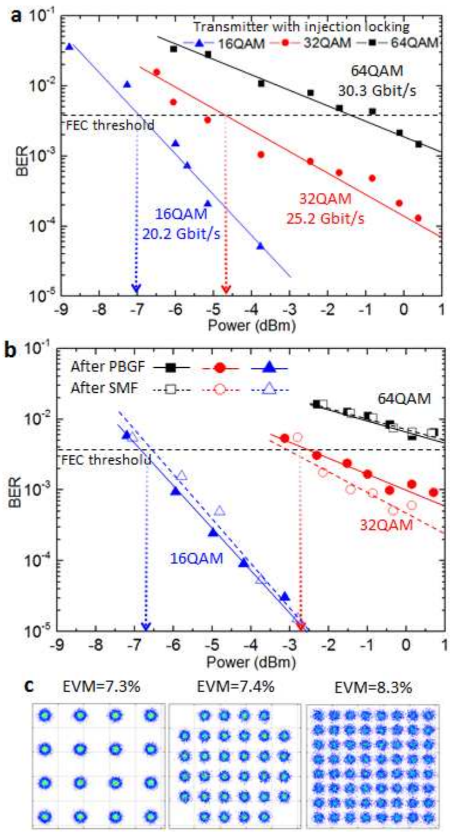

Fig. 2: (a) BER measurements of back-to-back OFDM signal at different optical powers (triangle: 16QAM, circle: 32QAM, square: 64QAM). (b) BER measurements after transmission through PBGF and SMF-28 (c) Constellation diagrams of the demodulated signal for different subcarrier modulation.

for both fibers: 0.3 dB at the FEC threshold for 16QAM, and 1.9 dB for 32QAM, with both operating well below the FEC limit. Whilst the 64QAM transmission is slightly above the FEC threshold we believe use of a narrower-band filter would have allowed sub-threshold operation (we were using a 3 nm filter for a <12-GHz bandwidth signal). Fig. 2 (c) shows clear demodulated constellation diagrams (at an optical power of 1.1mW) with average error vector magnitudes (EVMs) of 7.3%, 7.4%, and 8.3% for subcarrier modulation of 16QAM, 32QAM, and 64QAM, respectively.

Fig.3 (a) compares the electrical spectra of the detected optical OFDM both with and without OIL. Without OIL the DML shows a roll off in frequency response beyond 3.9 GHz. By contrast the flat spectrum obtained under properly pre-emphasized OIL provides clear evidence of a desired bandwidth enhancement under OIL, as anticipated from earlier research at 1550 nm. Fig. 3 (b) shows the optical spectrum after the optical band-pass filtering. Fig. 3 (c) shows the electrical spectra of a 2001 nm CW signal after transmission over 500 m of SMF-28 and PBGF (without using a TDFA). In the case of HC-PBGF low frequency noise up to 80 MHz is observed after transmission. This likely results from low-level intermodal interference since the HC-PBGF is not strictly single-mode[2]. As our signal occupies the frequency range 0.4 GHz-5.6 GHz, the observed intermodal interference noise does not adversely affect the data signal, underlining an advantage of using such modulation formats in conjunction with HC-PBGFs.

Conclusions

A low-cost, high spectral efficiency transmitter for the new 2 µm spectral region was demonstrated using up to 64QAM OFDM and direct detection. Transmission over 500 m of HC-PBGF with a state-of-the art 2.5 dB/km loss was demonstrated showing negligible penalty as compared to use of SMF-28. 16QAM and 32QAM signals were received well below the FEC limit. 64QAM transmission is currently impacted by the lack of a sufficiently narrow-band filter for suppression of ASE from our Tm-doped fiber amplifier but should ultimately be possible.

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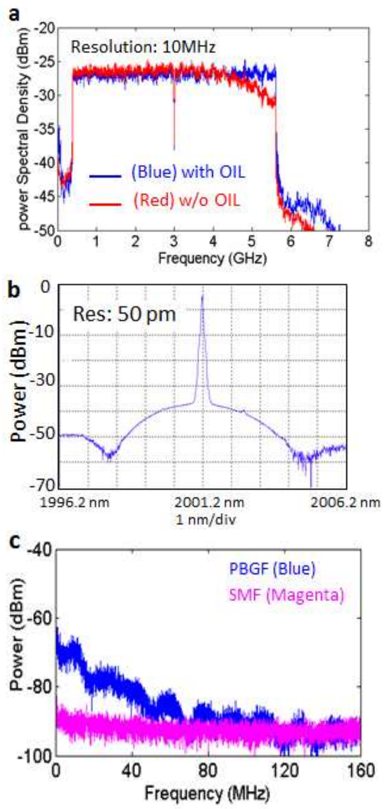

Fig. 3: (a) Modulation bandwidth enhancement using OIL. (b) Optical spectrum after OBPF. (c) Electrical spectra for CW light for the two fibers.

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