100-Gbps 100-m Hollow-Core Fiber Optical Interconnection at 2-micron waveband by PS-DMT

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Abstract: 2-micron waveband optical interconnection at record-high-speed of 100 Gbps/lane with 100-m hollow-core photonic bandgap fiber transmission is achieved. Mode-dependent bandwidth restriction is well optimized by probabilistically shaped discrete multi-tone (PS-DMT) modulation.

1. Introduction

Hollow-core fiber (HCF), in virtue of its ultralow latency, near-zero nonlinearity, theoretically low transmission loss and wideband transmission window, has been attracting broad interests for potential applications in short-reach optical interconnection and long-haul transmission. Particularly, hollow-core photonic bandgap fiber (HC-PBGF) has the theoretical lowest-loss window at 2-micron waveband [1], which makes 2-micron HC-PBGF communication very promising for low-latency applications like 5G and so on. Other advantages including low two-photon absorption of silicon photonics, low scattering loss of photonic waveguide, ultra-broadband Thulium-doped fiber amplifier (TDFA) and so on, can also be utilized at 2-micron. Therefore, increasing number of researches have been carried out, focused on 2-micron devices as well as HCFs. At present stage, the attenuation of HCF is at the scale of 1-dB/km, comparable to standard multimode fiber, which means short-reach optical interconnection by HCF is truly practical.

Recently, 0.65-dB/km HCF attenuation is achieved at C-band [2]. A 700-nm-wide-band HCF transmission covering O- to L-band has been presented with 100-Gbps 4-pulse amplitude modulation (PAM4) [3]. And a record hundred-km grade WDM transmission has been reported at C band. However, at 2-micron waveband, the capacity and distance are highly constraint due to the limited bandwidth of active components like modulator and photodetector [4]. In 2015, 8×20-Gbps DWDM HCF transmission was reported by using 8 MQW-InGaAs/InP lasers and external Mach-Zehnder modulator (MZM) [5]. At the same year, 52-Gbps HCF interconnection was obtained by Discrete Multi-Tone (DMT) with injection-locking to enhance the bandwidth [6]. And that was the highest single-lane speed of 2-micron HCF interconnection, excluding some achievements using solid-core fiber at 2 micron [7, 8].

In this work, we achieve 2-micron optical interconnection at the highest single-lane speed of 100 Gbps with 100-m HCF transmission. The HCF is a few-mode fiber with strong restriction of bandwidth due to mode coupling, which is quite difficult to be completely and stably eliminated. By using probabilistically shaped DMT (PS-DMT) to realize frequency-resolved entropy loading, we can well adapt the frequency response of the 2-micron HCF link. The measured normalized Generalized Mutual Information (GMI) of 100-Gbps PS-DMT signal after 100-m HCF is higher than the error-free threshold of 0.86 assuming soft-decision forward error correction (SD-FEC) with 20% overhead.

2. Experimental results and discussions

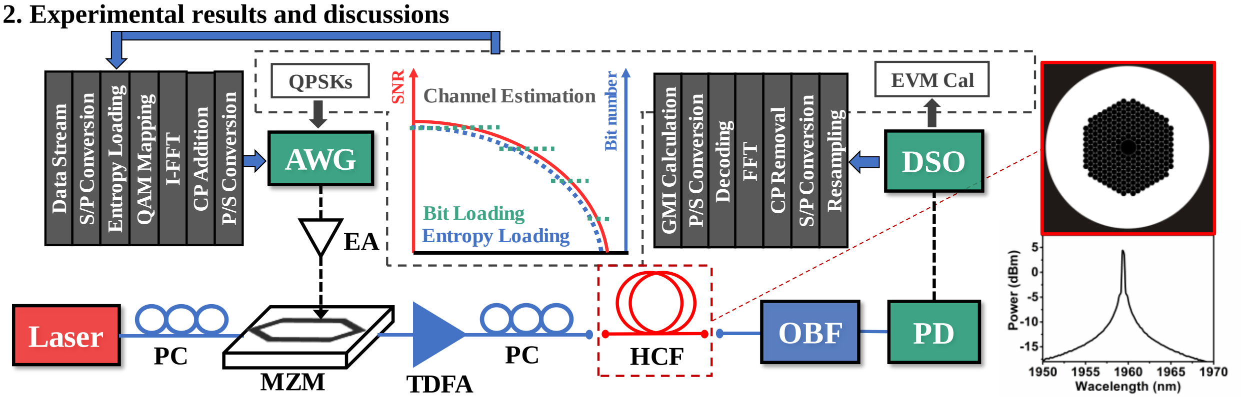

Fig. 1. Experimental setup of the 2-micron HCF optical interconnection.

Fig. 1 shows the experimental setup of the 2-micron HCF optical interconnection system. The optical source is a narrow linewidth continuous wave fiber laser with output power of 10-dBm and center wavelength near 1960 nm. The PS-DMT signal is generated by an Arbitrary Waveform Generator (AWG) with the sample rate of 54 GSa/s, amplified by the electrical amplifier (EA) to drive the Lithium Niobate MZM. The HCF is a reel of 100-m 7-cell HC-PBGF, with <20 dB/km attenuation and 160-nm-wide low-loss window at 2 micron. The laser wavelength is at the edge of bandgap, resulting in ~2dB loss of the 100-m HC-PBGF. The HCF is butt-coupled with standard single mode fiber with coupling loss of 4 dB/facet. A TDFA is employed to compensate the large insertion loss of HCF, and an optical bandpass filter (OBF) is applied to remove the amplified spontaneous emission (ASE) noise. The modulated optical signal after transmission is received by a photodetector (PD) and then sent into a Real-time Oscilloscope (DSO) with sample rate of 160 GSa/s for the off-line digital signal processing (DSP).

Due to the few-mode performance of HCF, modal dispersion caused power fading of the channel frequency response will seriously restrict the achievable speed of our 2-micron interconnection system [9]. We utilized the Time-of-Flight (ToF) method [10] to measure the excited modes in HCF, using optical pulses with pulse duration of 30 ps and repetition rate of 100 MHz. As shown in Fig. 2(b), the ToF measurement illustrates the few-mode excitation in HCF, and the corresponding SNR responses in Fig. 2(a) emerge sharp valleys, in result of deeply narrowed bandwidth. A polarization controller (PC) is applied to control the input optical polarization state of HCF, in order to ensure an approximately single-mode excitation (like the red line in Fig. 2). However, the frequency response after HCF transmission still has obvious deterioration compared with the optical back-to-back (OBTB) case. Under this circumstance, PS-DMT is the preferable modulation format to fit the worse response and achieve a better transmission performance.

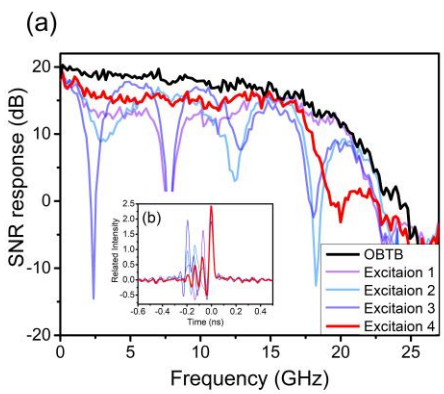

Fig. 2. (a) Channel SNR response under different excitation condition of HCF, compared with SNR response of BTB case. (b) ToF measurement results of the HCF.

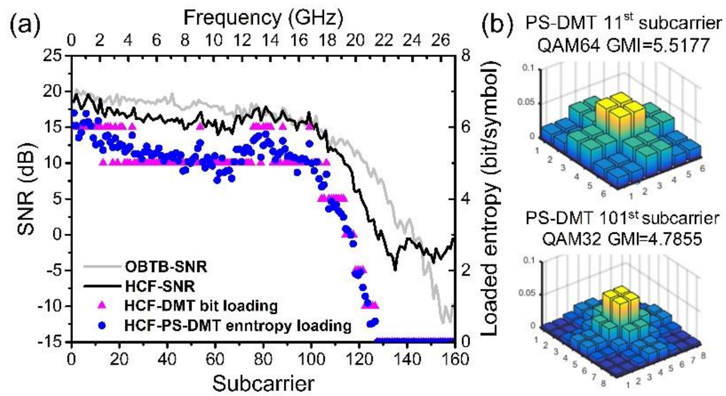

Fig. 3. (a) Measured SNR response and entropy allocation of 100-Gbps DMT/PS-DMT signal after 100-m HCF. (b, c) Shaped probability distributions of two typical subcarriers (11th and 101st subcarriers) for PS-DMT.

Depicted in the gray dashed box in Fig. 1, the channel Signal-to-Noise Ratio (SNR) estimation process, is implemented by sending a multi-tone probe signal (QPSKs) and measuring the error-vector magnitude (EVM) of the received probe signal. Fischer algorithm is employed to calculate the decimal entropies to be loaded on each subcarrier of DMT [11]. For conventional DMT, the loaded bit numbers must be stepped integers with equip probability, shown as green dots in the inset of Fig. 1, and extra power allocation of each subcarrier is required to adapt the measured SNR response. However, PS-DMT applies continuous entropy loading (blue dots) by using Maxwell-Boltzmann distribution, which is more adaptive to the SNR response (red line), and has no need of power allocation. What's more, PS-DMT can achieve higher achievable information rate (AIR) in a bandwidth-restricted system with lower SNR, which is in good according with our 2-micron system in this work. In order to quantitatively evaluate the performance of PS-DMT, we adopt normalized GMI to predict the code rate assuming SD-FEC for achieving error free [12].

In Fig. 3(a), the solid lines describe the measured SNR response of OBTB case (gray) and after HCF transmission (black), pink circle symbols denote the bit-loading of DMT, and blue triangle symbols denote the continuously entropy loading of PS-DMT. Apparently, the entropy-loading of PS-DMT is more adaptive to the SNR response after HCF. And Fig. 3(b) displays the shaped probability distributions of two typical subcarriers of PS-DMT at the transmitter side: 11th subcarrier is QAM64 with loaded GMI of 5.5177 after PS; 101st subcarrier is QAM32 with loaded GMI of 4.7855 after PS.

At the receiver side, the measured normalized GMI curves of 100-Gbps DMT signals are shown in Fig. 4(a). Compared with the BTB case, the HCF brings in about 1.45-dB power penalty mainly caused by the modal dispersion.

When the received optical power is higher than 0.15 dBm, the measured normalized GMI of 100-Gbps PS-DMT after 100-m HCF is beyond the threshold of 0.86, which means error-free signaling can be obtained after soft-decision decoding with 20% overhead [13]. Furthermore, we can see the curves of PS-DMT are evidently above that of DMT signal, whether at the BTB case or after transmission, which demonstrates that PS can contribute an increased AIR. In the 2-micron HCF system, we achieve the power sensitivity gain of 0.72 dB by PS at BTB case and 0.64 dB after HCF transmission. Fig. 4 (b) displays the received constellations of the two typical subcarriers, the 11th and 101st, with equip probability (EP) or shaped probability at BTB case and after transmission. The constellations after HCF present more indistinctly than that in the OBTB case. However, the PS constellations show better performance at both cases. That is because the Euclidean distances between symbols are broadened, with more symbols gathering at the center under the fixed average power.

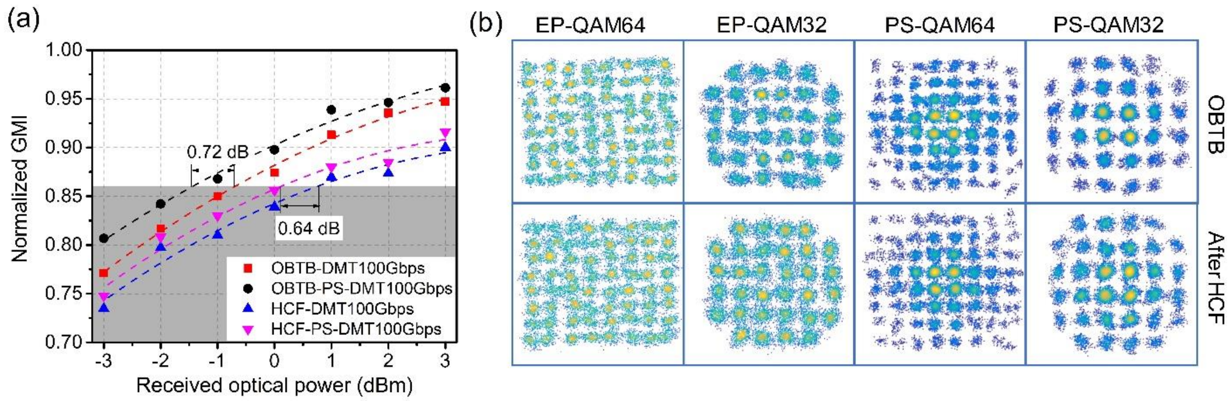

Fig. 4. (a) Measured NGMI of 100-Gbps DMT/PS-DMT signal at the case of OBTB or after HCF transmission. (b) The received constellations.

One needs to note that, the modal dispersion of HCF leads to severe deterioration on the modulation bandwidth. In this work, it is hard to generate high-power and picosecond pulses for the ToF method, resulting in the inaccuracy of modal measurement. And the excitation condition needs to be improved by 3D alignment platform with high stability and precision. Besides, the large transmission loss and coupling loss of HC-PBGF reduce the transmission performance due to the ASE noise brought in by TDFA. In previous researches, single-mode 3-cell HC-PBGF has been reported with 4 dB/km loss [14]. Although there will be sacrifices like higher coupling loss and smaller NA due to the smaller core, higher speed over 100 Gbps is promising since single mode is well and stably maintained. And this work makes a prospect for that. Further exploration will be carried out.

3. Conclusion

We present the state-of-art highest single lane optical interconnection speed of 100 Gbps at 2-micron waveband by external MZM modulation of PS-DMT, with measured normalized GMI above 0.86 assuming 20%-overhead SD-FEC after 100-m HC-PBGF transmission. This work substantially leaps over the 100G milestone of 2-micron HCF optical interconnection.

Acknowledgement

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