Wideband Transmission in the 1-μm Band based on a Hollow-core Fiber and Wideband YDFA

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Abstract: We show the potential of combining a hollow-core NANF with a wideband YDFA for 1-μm transmission through a conceptual demonstration. Penalty-free transmission over a 2.24-km NANF at >100Gb/s is reported across a 16.3-THz bandwidth (1020-1080nm). © 2023 The Author(s)

1. Introduction

Thanks to the maturity of high-power laser and amplification technologies, the 1-μm spectral region has been widely adopted for laser applications in material processing, as well as biomedical spectroscopy, optical power delivery, and LiDAR [1-2]. Thus, there is already a well-developed ecosystem of components designed for these wavelengths, including high-speed modulators, fiber-based passive components and fast photodetectors. In addition, the recent development of 1-μm GaAs-based vertical-cavity surface-emitting lasers [3-4], has stimulated interest in introducing 1-μm single-mode (SM) systems as an upgrade to existing multimode 850-nm short-haul datacom links. However, even though the optical properties of silica fibers at 1 μm are significantly more favorable for data transmission than those at 850 nm, the high loss and chromatic dispersion (CD) of silica is still the major obstacle to achieving longer reaches and/or higher data rates. For instance, 1-μm SM transmission trials were performed using solid-core holey fibers [5-6], yet the fibers' properties were not favorable (e.g., CD = -20.1 ps/nm/km and loss = 1.42 dB/km [5]). More recently, up to 40-Gb/s rates were reported over a 2-km long prototype fiber that was designed to be single-mode at 1060 nm (SMF, CD = -31 ps/nm/km and loss = 0.77 dB/km) [4], but once again severe power penalties induced by the high CD of the SMF were experienced.

In this work, we demonstrate the potential to disrupt the arguments presented above by combining two state-of-the-art technologies. The first technology is the hollow-core nested antiresonant nodeless fiber (NANF) that exhibits a record-low loss of 0.3 dB/km at 1060 nm (≤0.35 dB/km across 1023-1100 nm) [7], which is two times lower than fundamentally achievable in any solid silica fiber in the 1-μm band. The low fiber loss over wide bandwidths, along with the effectively SM guidance and beneficially low CD, latency and temperature sensitivity, make the NANF an attractive transmission medium in the 1-μm band. The second technology is the wideband ytterbium-doped fiber amplifier (YDFA), which as we demonstrate here, can offer broadband gain over a bandwidth in excess of 16 THz, i.e., ~3.6 times broader than that of erbium-doped fiber amplifiers (4.4-THz) in the C-band. This wideband YDFA together with the low-loss NANF may pave the way toward longer-reach and wideband 1-μm transmission, offering the potential for new solutions in future short- to medium-haul systems. Specifically, we present a conceptual system demonstration that integrates these two technologies, and achieves penalty-free 1-μm transmission at >100-Gb/s data rates across 1020-1080 nm (i.e., a bandwidth of 16.3 THz) over 2.24 km of fiber. While clearly still at an early stage, this work represents the highest data rates ever demonstrated for kilometer-scale 1-μm transmission.

2. Experimental Setup

Fig. 1(a) shows the experimental setup of the 1-μm transmission system that adopts the low-loss NANF and wideband YDFA. A tunable laser operating from 1020 to 1080 nm was used as the optical carrier to modulate a 1-μm $LiNbO_3$ Mach-Zehnder modulator (MZM). The MZM exhibited a 3-dB bandwidth of around 17 GHz, which was the main factor limiting the achievable data rates demonstrated in this work. An optical attenuator (ATT) was used to adjust the power to -5 dBm for all investigated wavelengths, after which an in-house built YDFA was adopted as the booster amplifier. The amplifier had two stages comprising a 3- and 4.5-m long YDF, respectively, both lengths of which were optimized for broadband operation. Both stages adopted forward pumping at 980 nm and the corresponding pump powers were 300 and 350 mW, respectively. As shown in Fig. 1(b), under an input power of -5 dBm, the booster YDFA offered a gain higher than 22 dB across the spectral region of interest, apart from the shortest wavelength of 1020 nm, at which the corresponding gain was around 19.5 dB. The amplified signal was then sent through either a 2.24-km long NANF or another ATT with an identical loss to the NANF at each wavelength (referred to as the back-to-back link, B2B, in the following).

The NANF had a core of 29.2-μm diameter, which was surrounded by five nested tubes. The thicknesses of the outer and inner tubes were 755 and 750 nm, respectively. The fabricated NANF exhibited a record-low loss ≤0.35 dB/km across 1023-1100 nm, within which the CD value was calculated to be around 2 ps/nm/km [7]. A cross-sectional scanning electron microscope (SEM) image of the NANF is given in Fig. 1(c). At each end, to inter-connect the NANF with the SMF (*Corning* HI 1060), two micro-lenses [8] with different focal lengths were used to mitigate the mode field diameter mismatch, and the SMF was angle-cleaved to reduce the Fresnel back-reflection. Note that the total insertion loss of the SMF-connectorized NANF was relatively high (~7dB), and further reduction in this loss can be expected by optimizing the mode field diameter mismatch between the two fibers [8]. At the receiver, a tunable filter with a 3-dB bandwidth of 1 nm was adopted, after which a 90:10 coupler was used to monitor the input signal on the photodetector (PD). The PD was specified for use in the C-band and thus exhibited a relatively low responsivity of ~0.3 A/W in the 1-μm band. Fig. 1(d) shows the monitored optical spectra of the signals at the receiver at all investigated wavelengths.

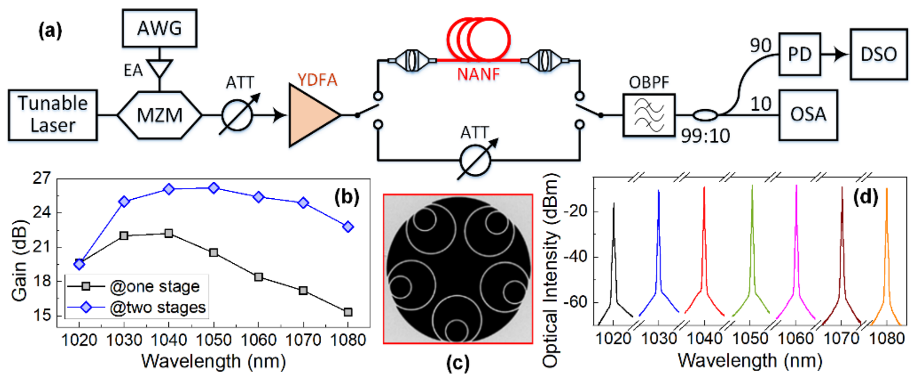

Fig. 1. (a) The experimental setup of the NANF-based 1-μm transmission system, (b) the gain profiles of the YDFA under an input power of -5 dBm, (c) the cross-section SEM image of the NANF, and (d) the received optical spectra at different wavelengths.

In this work, we considered both Nyquist 4-ary pulse amplitude modulation (PAM4) and capacity-maximized discrete multitone (DMT) formats to evaluate the transmission performance of the system. Specifically, the data rate of the Nyquist PAM4 was fixed at 90-Gb/s for all wavelengths, which was mainly limited by the bandwidth of the MZM. For the DMT format, thanks to the use of the adaptive bit-and-power loading, the data rate under a signal bandwidth of ~24.6 GHz was maximized at each wavelength, while keeping the corresponding bit error rate (BER) below the hard-decision forward error correction (HD-FEC) limit of 3.8×10^{-3}. The details of the offline digital signal processing we used can be found in [9].

3. Experimental Results

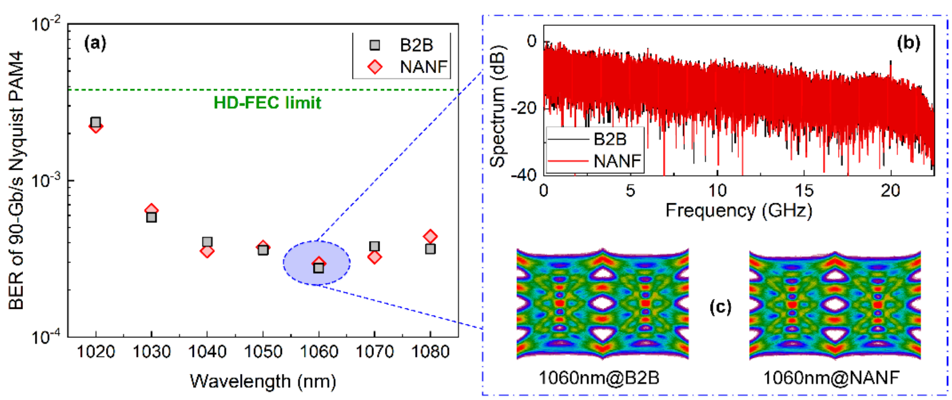

Fig. 2. (a) BER of the 90-Gb/s Nyquist PAM4 transmission over the 1020-1080 nm wavelength range, (b) normalized electrical spectra of the detected signals at 1060 nm for the NANF and B2B cases, and (c) the corresponding recovered eye diagrams.

We first experimented with 90-Gb/s Nyquist PAM4 across the wavelength range 1020 to 1080 nm. Fig. 2(a) shows that almost identical BER performance to the B2B was achieved when transmitting over the 2.24-km length of NANF. Furthermore, the BER performance at different wavelengths was broadly comparable, apart from the shortest wavelength of 1020 nm, where the YDFA's gain was lower (see Fig. 1(b)). Nevertheless, the BERs of the 90-Gb/s

Nyquist PAM4 transmission were well below the HD-FEC limit across the entire wavelength range from 1020-1080 nm. Without loss of generality, we take the 1060-nm case as an example and show the corresponding normalized electrical spectra of the detected signals and recovered eye diagrams in Figs. 2(b) and 2(c), respectively. As expected, both the spectra and eye diagrams exhibited negligible differences between the NANF and B2B cases, owing to the low CD of the hollow-core NANF.

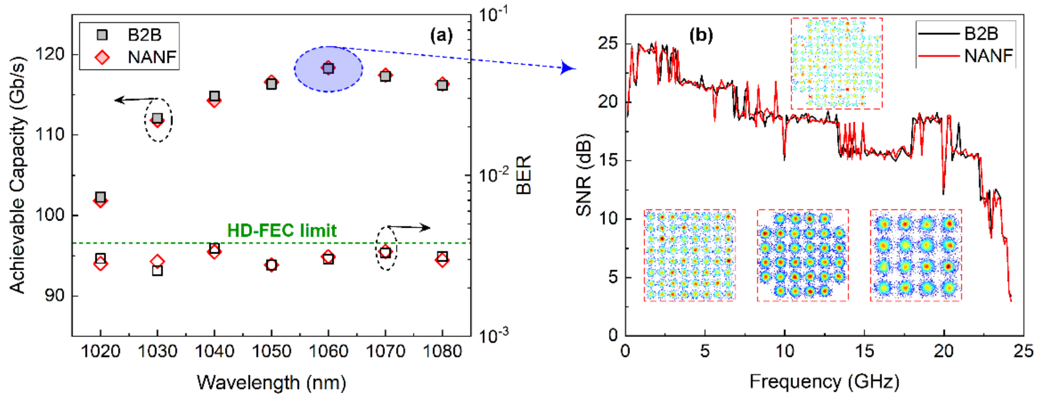

Fig. 3. (a) Achievable capacity and the corresponding BER versus wavelength in the NANF and B2B cases, and (b) the SNR profiles of the adaptively-loaded DMT transmission at 1060 nm. Insets of (b): constellation diagrams in the NANF case.

To combat the limited bandwidth of the MZM in our NANF-based 1-µm system, and thus maximize the transmission capacity, we further investigated the performance of the adaptively-loaded DMT format. Fig. 3(a) shows the achievable capacities and the corresponding BERs at different wavelengths in the NANF and B2B cases. It is seen that comparable capacities were achieved at all wavelengths in the two cases, validating the penalty-free transmission in the NANF. While maintaining the BERs below the HD-FEC limit, the capacities across the spectral range 1020-1080 nm were all above 100 Gb/s (>110 Gb/s over 1030-1080 nm). Fig. 3(b) shows the profiles of the signal-to-noise ratio (SNR) at 1060 nm in the NANF and B2B cases. As expected, the two profiles are comparable to each other and both exhibited a staircase behavior to combat the high-frequency roll-off induced by the MZM. For reference, the constellation diagrams of 16QAM to 128QAM in the NANF case are presented as insets to Fig. 3(b). It is also worth noting that the data rates demonstrated here were mainly restricted by the bandwidth of the MZM, rather than imposed by the NANF. We anticipate that penalty-free 1-µm transmission over the NANF can be realized at higher rates and over longer distances, as has previously been demonstrated in the S+C+L-bands [9].

4. Conclusion

In this paper, penalty-free 90-Gb/s Nyquist PAM4 and >100-Gb/s adaptively-loaded DMT transmission were demonstrated across a bandwidth of 16.3 THz (1020-1080 nm) over 2.24 km of fiber. These record-high capacities for kilometer-scale 1-µm transmission were achieved by using a low-loss hollow-core NANF and an in-house built wideband YDFA. While further improvements in the performance can be anticipated, e.g., by further reducing the fiber and interconnection losses, and using more suitable transmitter and photodetector technologies, our results clearly demonstrate the promising potential for data transmission in the 1-µm spectral region which may offer new opportunities in future optical communication systems.

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