High-capacity WDM Coherent Transmission over Hollow-core Fiber

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***Abstract*—In this paper, we experimentally demonstrate a wavelength division multiplexing (WDM) coherent transmission of 20-channel 60 GBaud dual-polarization 16-level quadrature amplitude modulation (DP-16QAM) signals over 342 m homemade nested anti-resonant nodeless fiber (NANF). To our best knowledge, we achieve a record NANF transmission of net bit-rate of 448.6 Gbit/s per wavelength and net capacity of 8.97 Tbit/s, respectively.**

***Keywords*—hollow-core fiber, wavelength division multiplexing, coherent transmission**

I. Introduction

Silicon-based standard single-mode fibers (SSMFs) have been widely applied for fiber optics communication, supporting the ever-increasing demand for data traffic in current society. Unfortunately, further increasing the transmission capacity is prohibited by the inherent nonlinearity of silicon-based SSMF, which is often referred as the capacity crunch [1]. To deal with the SSMF nonliearity, several countermeasures have been explored, whereas face the challenges of power consumption, compact footprint, and digital signal processing (DSP) latency [2]. As a new transmission medium, hollow-core fiber (HCF) has emerged as a possible contender of SSMF [3]. The light propagation speed of HCF is 50% faster than that of traditional SSMF, leading to 33% reduction of transmission latency and making HCF suitable for latency-sensitive applications [4]. Furthermore, the nonlinearity of HCF is 3 orders of magnitude lower than that of SSMF [5]. Besides the ultra-low nonlinearity and propagation latency, HCF has other advantages such as lower dispersion and lower transmission loss over SSMF, which makes HCF an competing option in future optical communication networks with high-capacity and low latency.

According to the light guiding principle, HCFs are mainly categorized into two groups. One is hollow-core photonic bandgap fiber (HC-PBGF), and the other is hollow-core anti-resonant fiber (HC-ARF). HC-PBGF utilizes the photonic bandgap effect to confine the light within the air core. Whereas, HC-PBGF suffers from the issue of surface modes, which substantially reduces the applicable transmission bandwidth, together with the concern of occurrence of higher-order modes. HC-ARF restricts the light within the hollow region by coherent reflection of thin and tubular glass membranes. HC-ARF provides the flexibility of designing a low-loss transmission window with optimization of the film thickness, and numerical simulations indicate that HC-ARF can provide lower attenuation at the designated wavelength band in comparison with SSMF.

Recently, there have been many works reported on the high-capacity and low-latency wavelength division multiplexing (WDM) coherent transmission over HCF, as summarized in Fig.1 [6-11]. A coherent transmission using 96 wavelengths at the extended C-band and 3 modes over 310 m HC-PBGF with 37-cell was reported in [6], with a net bit-rate of 213.3 Gbit/s per wavelength by the use of dual-polarization 16-level quadrature amplitude modulation (DP-16QAM) and a total transmission capacity of 61.4 Tbit/s, respectively. In order to extend the reach of HC-PBGF, 55.8 km fiber loop transmission utilizing HC-PBGF with 19-cell and DP-quadrature phase shift keying (DP-QPSK) signals was reported with a net bit-rate of 100 Gbit/s [7]. However, both the reach and the net bit-rate are found to be limited by the large intermodal interference in HC-PBGF. In contrast, HC-ARF has a very high differential modal loss that effectively supports single-mode transmission. Consequently, the key potential advantage of HC-ARF lies in the use of dense WDM (DWDM) and advanced modulation formats. 16-channel DP-256QAM WDM transmission over 270 m HC-ARF was reported with a net bit-rate of 425 Gbit/s per wavelength and a total transmission capacity of 6.8 Tbit/s, respectively [8]. In order to further reduce the transmission loss of HC-ARF, the nested anti-resonant nodeless fiber (NANF) have been proposed, and now its transmission loss is almost the same as that of traditional SSMF, such as 0.174 dB/km at the C-band [9]. Meanwhile, NANF has other unique advantages, such as wide operating band, low intermodal interference, and easy connection with traditional SSMF. 61-channel C-band WDM transmission with a total capacity of 6.5 Tbit/s was realized over 618 km re-circulating NANF loop, considering the use of DP-QPSK signals with a net bit-rate is 106.7 Gbit/s per wavelength [10]. The NANF reach was further extended to 2070 km at the C-band with a total transmission capacity of 4.4 Tbit/s, when 41-channel DP-QPSK signals with a net bit-rate of 106.7 Gbit/s per wavelength are involved [11]. Above-mentioned transmissions rely on more than 17% forward error correction (FEC) overhead, and increases the DSP latency

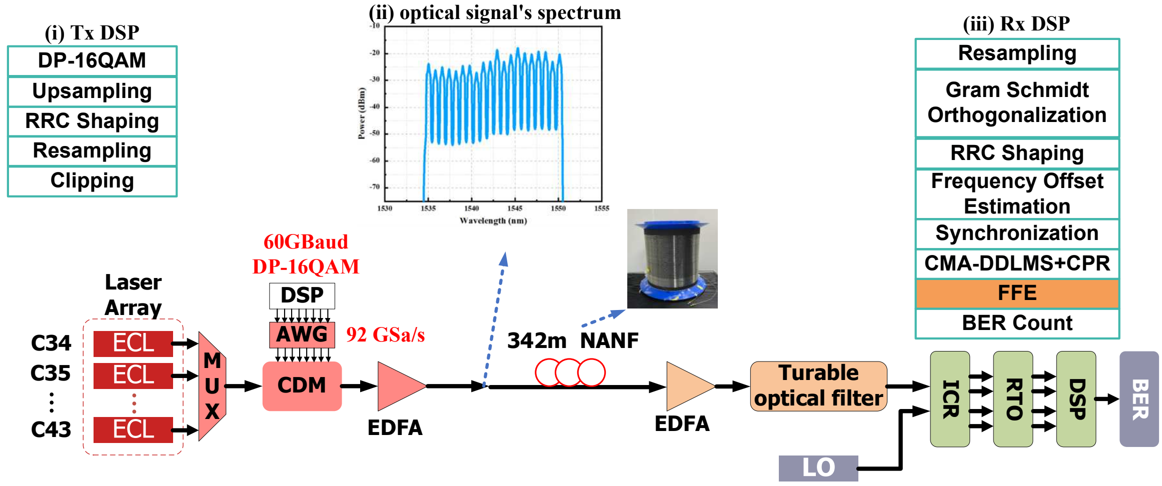

Fig. 2. Experimental setup for WDM coherent transmission and corresponding DSP flow.

significantly, which is undesirable for latency-sensitive applications.

In this paper, we experimentally demonstrated a coherent transmission of 20-channel WDM signals over 342 m homemade NANF with a total capacity of 9.6 Tbit/s. Considering 7% hard-decision FEC, a record of net bit-rate of 448.6 Gbit/s per wavelength using 60 GBaud DP-16QAM signals is achieved.

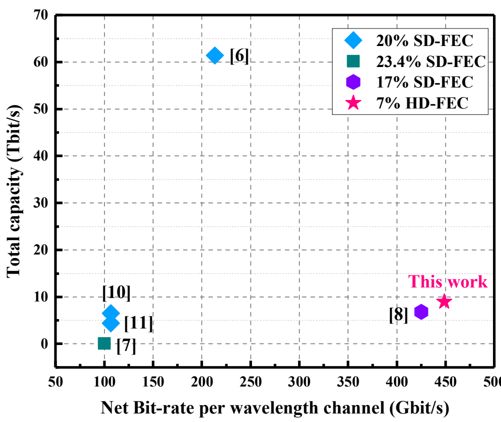

Fig. 1. Progress of coherent WDM transmission over HCF.

II. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup of the WDM coherent transmission over the NANF, with the involvement of offline DSP at both the transmitter-side (Tx) and receiver-side (Rx). As for Tx DSP, a sequence of 2^{17}-1 pseudo-random binary sequence (PRBS) is first generated and then mapped to 16QAM symbols with a symbol rate of 60 GBaud. Next, the 16QAM symbols are up-sampled to 2 sample-per-symbol (sps) with zero insertion. Then, the 16QAM symbols are pulse shaped with root-raised cosine (RRC) filter with a roll-off factor of 0.05 and resampled to 120 GSa/s in order to match the sampling rate of the arbitrary function generator (AWG, Keysight M8196A). Meanwhile, clipping is employed to reduce the signal's peak-to-average power ratio (PAPR). Afterwards, the digital signals are loaded into AWG for digital-to-analog conversion. The generated analog signals are, then fed into a coherent driven modulator (CDM) with a 3 dB bandwidth of 40 GHz for electrical-to-optical conversion. The CDM consists of 4 electrical drivers, two In-phase/Quadrature (I/Q) modulators which are biased at its null point, a polarization beam splitter (PBS), and a polarization beam combiner (PBC). We utilize 20 external cavity lasers (ECLs) with linewidth of less than 100 kHz as the optical carriers. The center wavelength of ECLs is spanned from 1535.04 nm to 1550.12 nm, matching the ITU-T standard. The optical carriers are wavelength division multiplexed using a 20 × 1 arrayed waveguide grating, and fed into the into the CDM. Thereafter, the generated WDM DP-16QAM signals are amplified by an erbium doped fiber amplifier (EDFA) with a total output power of 2.5 dBm, and launched into a homemade NANF. The optical spectrum of the WDM signal is presented in the insertion of Fig. 2. The NANF with a length of 342 m has an average core size of 32 μm and a membrane thickness of 1 μm, as shown in Fig. 2, and has a minimum transmission loss of 4.85 dB/km at 1490 nm. The transmission window with a loss of less than 10 dB/km is from 1450 nm to 1590 nm, covering the traditional C+L band. As a result, the overall loss of NANF with the SSMF pigtails is almost 11 dB, due to the mismatch of mode field diameter. After the NANF transmission and another EDFA for NANF loss compensation, the optical signal in the test channel is filter out by a tunable optical filter and then sent to an integrated coherent receiver (ICR) for optical-to-electrical conversion. Finally, the DP-16QAM signal at the designated wavelength is sampled by a 59 GHz real-time oscilloscope (RTO, LECROY LabMaster 10-59Zi-A) operated at 80 GSa/s. At for Rx DSP, the digital waveform is first resampled to 2 sps and then completed with the Gram-Schmidt orthogonalization to compensate the Rx inphase/quadrature imperfections. Next, the DP-16QAM signals are passed through a matched RRC filter. After the frequency offset estimation (FOE), the DP-16QAM signals are synchronized and equalized by a 51-tap T/2 spaced butterfly FIR filter with the decision-directed least-mean square (DD-LMS) algorithm. Within the DD-LMS loop, a phase lock loop (PLL) is applied for carrier phase recovery (CPR). Training symbols are used at the beginning of the transmission, for the ease of pre-convergence of the butterfly filter and the PLL. To enhance the transmission performance, we use a feed-forward equalizer (FFE) based on the recursive least square (RLS) algorithm as a post-equalizer for each polarization. Finally, the BER of each wavelength channel is counted after symbol-to-bit de-mapping.

III. Results and Discussion

First, we optimize the FFE filter lengths, under the condition of back-to-back (B2B) transmission. The relationship between BER and FFE filter length is presented in Fig. 3, considering the received optical power (ROP) into the ICR is -10.5 dBm for the 1550.12 nm channel. Generally, better BER performance can be obtained, when longer filter length is employed. However, the performance improvement is saturated, when the filter length is sufficiently large. Finally, the optimal value for FFE filter length is identified to be 201. Note that if a nonlinear post-equalizer is employed to deal with device nonlinearities, the transmission performance can be further enhanced.

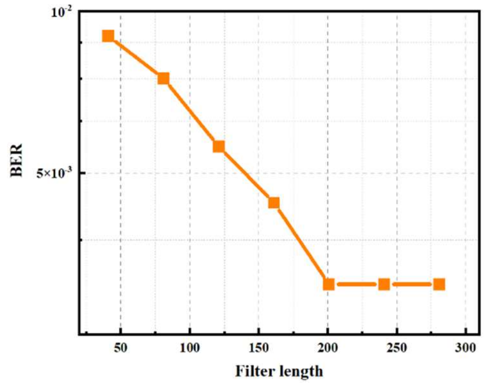

Fig. 3. Optimization of the FFE tap.

With optimized FFE filter length, we then investigate the BER performance of each wavelength channel, under the B2B and after NANF transmissions, as shown in Fig. 4. Considering the 7% HD-FEC threshold of BER = 4.5×10^{-3} [12], the error-free transmission of all 20-channel from 1535.04 nm to 1550.12 nm can be realized under B2B transmission. Specifically, the BER increases from 1.8×10^{-3} to 4.4×10^{-3}, when the central wavelength of each channel varies from 1535.04 nm to 1550.12 nm. The small BER deviation among 20 channels may be attributed to the gain ripple of the used EDFA. After the 342 m NANF transmission, we observe almost negligible performance penalty. Additionally, BERs of all 20-channel can successfully reach the threshold of 7% HD-FEC, indicating we achieve a net bit-rate of 448.6 Gbit/s per channel and a net capacity of 8.97 Tbit/ for NANF transmission, respectively.

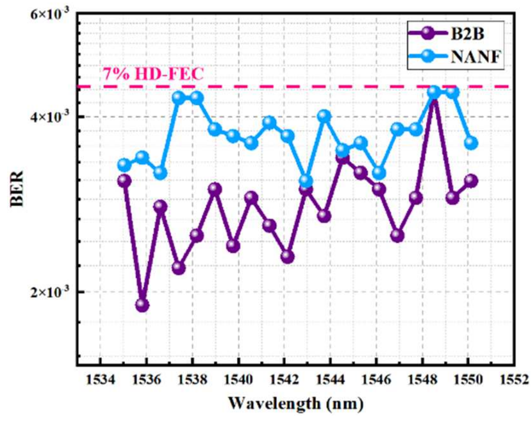

Fig. 4. The BER performance under B2B and after NANF transmissions.

IV. Conclusions

We have experimentally demonstrated a C-band 20-channel WDM coherent transmission over a 342 m homemade NANF with a total capacity of 9.6 Tbit/s. The NANF with low nonlinearity, low transmission latency, and low dispersion allows us to transmit 20-channel 60 GBaud DP-16QAM signals with a negligible performance penalty. Moreover, a record of the net bit-rate of 448.6 Gbit/s per wavelength for NANF transmission has been obtained considering the use of 7% HD FEC.

Acknowledgment

This work was supported by National Key Research and Development Program of China (2021YFB2900702), National Natural Science Foundation of China (U21A20506), and Guangdong Introducing Innovative and Entrepreneurial Teams of "The Pearl River Talent Recruitment Program" (2021ZT09X044).

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