Record High Capacity (6.8 Tbit/s) WDM Coherent Transmission in Hollow-Core Antiresonant Fiber

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Abstract: The first multi-terabit/s WDM data transmission through anti-resonant hollow-core fiber is demonstrated. 16×32-GBd dual-polarization Nyquist-shaped 256QAM channels propagated through a 270-m long fiber. No non-linearity penalty was observed for powers up to 1W.

OCIS codes: (060.2310) Fiber optics; (060.1660) Coherent communications

1. Introduction

Hollow-core fibers exhibit low latency, a high damage threshold, and an ultra-low nonlinear response, making them highly desirable for optical communications [1,2]. To date, a significant body of work has been done to demonstrate transmission in hollow-core photonic bandgap fibers, reporting both high capacity (73.7 Tbit/s) [2] and relatively long lengths (up to 74.8 km) [3]. Recently, another class of hollow-core fiber was shown to be capable of data transmission: hollow-core antiresonant fibers (HC-ARFs), which guide light via the antiresonance associated with thin glass membranes surrounding the hollow core (rather than by a bandgap effect) [4-7]. The key advantages of HC-ARF include an ultra-large transmission window (for example, 1100 nm shown in ref. 4) with almost constant mode field diameter and very low chromatic dispersion (CD) over the entire transmission window (<2 ps/(nm·km)) [4]. Although the excellent modal purity of HC-ARF required for high transmission capacities has been already reported [4,5], recent demonstrations have been limited to single-channel 10-Gb/s on-off-keyed signal formats and a fiber length of just 100 m. Yet the key potential advantage of these fibers is in the capability of very high transmission capacities using high-order modulation formats due to high nonlinearity tolerance and low dispersion. Combined with low-complexity digital signal processing, this would have wide applications, such as in sensing and data centers. However, no study of the non-linear transmission impairments in HC-ARFs has been reported.

In this paper, we demonstrate the significant potential of HC-ARF for data transmission. For the first time, we show coherent transmission of a very high-order modulation format (256QAM), over two polarizations, allowing the doubling of capacity. We also show the first WDM transmission and high tolerance to nonlinearities in HC-ARF relative to SMF-28. All these ‘firsts’ are also accompanied by significant improvements compared to the state-of-the art reported to date [4]. Specifically, our experiments are carried over fiber that is 2.7 times longer (270 m), at >3 times higher baud rate (32 GBd), with >14 times greater spectral efficiency (14.5 bit/s/Hz) through the use of dual-polarisation (DP) Nyquist 256QAM) with16 WDM channels.

2. Experimental set-up

Fig. 1 shows the experimental set-up. The WDM transmitter is constructed of 16 tunable external cavity lasers (ECLs， linewidth of 100Hz) spaced between 1544.13 nm – 1550.12 nm on a 50-GHz ITU grid. The odd (and respectively, even) channels were combined through an 8×1 coupler and subsequently modulated with a $LiNbO_3$ IQ modulator driven by two 92-GS/s digital-to-analog convertors (DACs). The modulated channels were amplified and decorrelated before being combined and passed through a polarization multiplexing emulation stage to form a 16-channel 32-GBd DP-256QAM signal. The power of each ECL was adjusted to yield a flat WDM power spectrum (with <1 dB power variation) after the high-power erbium-doped fiber amplifier (EDFA). The high-power EDFA boosted the total signal power to 35 dBm (3.5 W) and the signal was then launched into the HC-ARF transmission link via SMF-28 to HC-ARF spliced connection with a loss of 3.5 dB (due to the significant mode field mismatch) – see Fig. 1b. The HC-ARF fiber consisted of two spans spliced together (Fig. 1c), both drawn from the same cane. It has a non-contacting tubular design with 7 tubes around a hollow core, as shown in Fig.1a. The first span is 130 m long and has a 40 µm core and a 200 µm cladding diameters [4]. Over the C-band it has an average loss of 41 dB/km. The second span is 140 m long and has a 38 µm core and a 180 µm cladding diameter. Its loss over the C-band is 58 dB/km. Improved HC-ARFs are predicted to have much lower loss values (0.15 dB/km and less) [8]. After transmission, the signal was coupled back from the HC-ARF to SMF-28 with 4-dB loss. The total link loss was approximately 21.5 dB, including 14 dB fiber loss and 7.5 dB coupling loss. A lower coupling loss can be achieved by using appropriate, mode field diameter matching buffer fibers, not available for this experiment [4]. The channel of interest was selected by passing the WDM signal through a 50-GHz flat-top optical filter and was subsequently pre-amplified and detected using a 65-GHz dual-polarization coherent receiver. The local oscillator (LO) laser was a 100-kHz-linewidth tunable ECL and the detected signals were captured by four 160 GSa/s analog-to-digital convertors (ADCs) for offline signal demodulation. In order to compare with the back-to-back performance at the same optical signal-to-noise ratio (OSNR), the fiber link was replaced with a variable optical attenuator to emulate the loss.

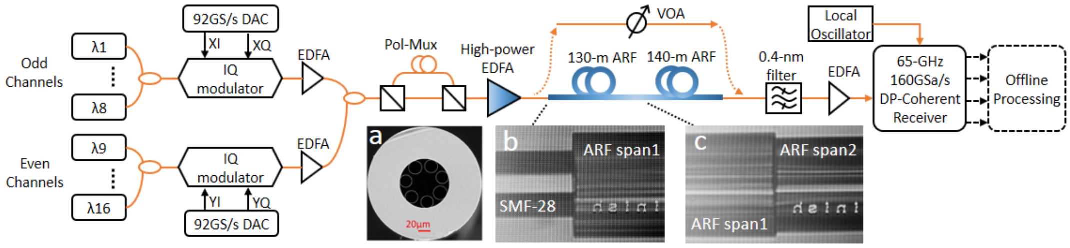

Fig.1 Experimental set-up of the dense WDM transmission experiment through HC-ARFs. Inset: (a) SEM images of the fiber cross section; (b) splice image between SMF-28 and HC-ARF; (c) splice image between HC-ARFs.

The multi-level drive signals required for the QAM format were generated from decorrelated pseudorandom random binary sequences (PRBSs) of length 2^{16}. The transmitter-side digital signal processing (DSP) shaped the generated QAM signal using a root raised-cosine (RRC) filter with a roll-off factor of 1% to generate the 32-GBd Nyquist-shaped 256QAM signals. At the receiver side, the signal was down sampled to 2 Sa/sym before equalizing the digital signals using a 21-tap blind radially directed equalizer (RDE) for polarization demultiplexing. The carrier-frequency offset and phase noise were compensated with conventional DSP algorithms as described in [9]. The demodulated symbols were used to calculate the bit error ratio (BER) and signal-to-noise ratio (SNR). Although the current transmission fiber was too short to require a DSP-based static filter for CD compensation (<2ps(nm·km) across the entire transmission window [4]), the low dispersion of HC-ARFs requires filters with 90% fewer taps than those needed for the DSP for SMF-28 transmission, thereby reducing both the DSP complexity and delay.

In addition to the WDM experiment, transmission over a wide range of powers up to 1W was investigated to explore non-linearity-induced transmission penalties, comparing the HC-ARF with a conventional SMF-28. The experimental setup was the same as for the WDM experiment except that only one ECL at 1550.12 nm was used and the 270-m HC-ARF link was replaced with 100-m HC-ARF (the lowest loss sample available, with attenuation of 40 dB/km) and 100-m SMF-28. Shorter lengths (compared to the WDM experiments) were used due to the relatively high loss of the HC-ARF, as non-linear effects are strongly power-dependent and thus are expected to take place mostly at the input of the fiber.

3. Results

Fig. 2 shows the measured loss profile of the link and the simulated dispersion of the fiber. The inset in Fig.2 shows the spectrum of the optical signal after transmission. The link loss within the C-band increases smoothly from 21.2 dB to 22.2 dB for wavelengths from 1535 nm to 1565 nm. Whilst the difference in loss was less than 1 dB across the entire C-band, the fiber link had insignificant effect on the spectral flatness of the WDM signal, as shown in Fig.2. The fiber has very low and flat dispersion (<1.6 ps/(nm·km)) across the whole C-band, as shown in Fig.2. Fig.3 shows the SNRs and BERs of the transmitted DP-256QAM signals for WDM transmission over the 270-m HC-ARF link. The achieved SNR values range from 22.8 to 23.4 dB and the corresponding BER values ranged from 2.7×10^{-2} to 3.5×10^{-2}, achieving a net rate 6.8 Tb/s by using soft-decision decoding with 17% overhead [9]. The back-to-back results with an optical attenuator with the same loss as the fiber link are shown in Fig. 3. No transmission penalty was observed with respect to the back-to-back performance, confirming the excellent transmission quality of the fiber link.

Fig.4 shows the BERs and the SNRs of the transmitted single-channel DP-256QAM signal as a function of the average power propagated through the 100-m ARF and the 100-m SMF-28, respectively. For a fair comparison, due to different attenuation values, we used the average power (defined as half the difference between input and output powers). The dashed line shows the back-to-back performance (SNR of 24.2 dB) which is limited by the electronic noise of the transceiver. In the SMF-28 transmission, the performance degradation caused by the self-phase modulation (SPM) became significant when the average power through the SMF-28 was increased above 25 dBm. The SNR of the demodulated signal dropped from 24.0 dB to 20.7 dB as the average power was increased from

23.3 dBm to 29.5 dBm. The corresponding BERs increased from 2×10^{-2} to 5.9×10^{-2}. In contrast, no penalty was observed in the HC-ARF transmission, resulting in a 3.2 dB higher SNR at the average power of 29.5 dBm. The constellation diagrams for the HC-ARF and the SMF-28 transmission at an average power of 29.5 dBm, highlight the superior nonlinear tolerance of HC-ARF compared to SMF-28.

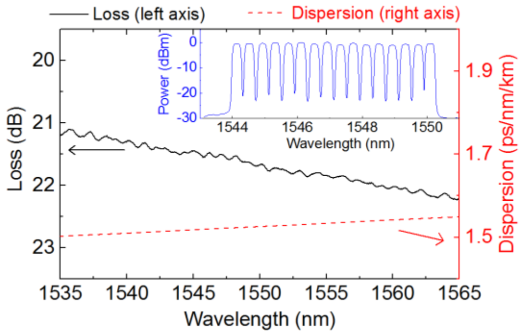

Fig.2 The loss profile of the fiber link (solid line) and the simulated dispersion (dashed line). Inset: Spectrum of the transmitted WDM signals, measured using an OSA with a resolution of 0.1 nm.

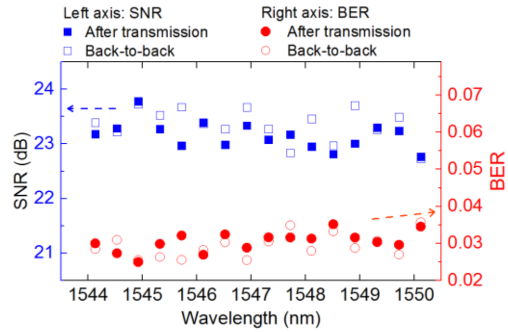

Fig.3 Measured SNR (square marker) and BER (circle marker) both back-to-back and after transmission though the fiber link. Similar performance was observed both back-to-back and after transmission.

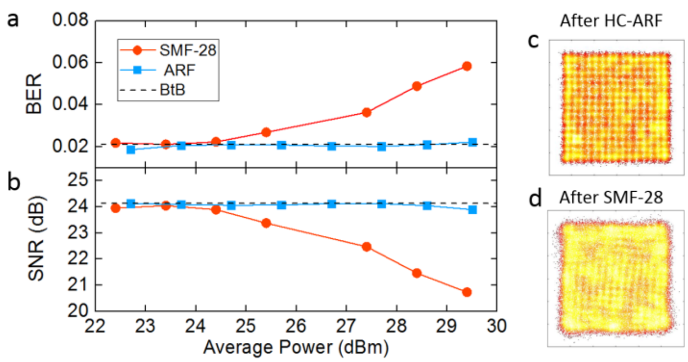

Fig.4 BER (a) and SNR (b) of the single-carrier DP-256QAM transmission over 100-m HC-ARF (blue square marker) and 100-m SMF-28 (red circle marker); Constellation diagrams at an average power of 29.5dBm after (c) HC-ARF and (d) SMF-28.

4. Conclusion

We presented record data transmission over the longest reported, fully spliced span of HC-ARF (270 m). The excellent quasi single mode behaviour of the fiber allowed us to transmit dual-polarization-256QAM signals in a coherent 16-channel WDM system with negligible SNR penalty, and achieve the highest data rate ever transmitted through an HC-ARF (6.8 Tbit/s, a factor of: 680 times higher capacity and 1800-higher length-capacity product than state-of-the-art demonstrations to date). We have also confirmed that the fiber can handle high optical powers, giving it 3 dB SNR advantage over SMF-28 at an average transmitted power of 1W. These results, combined with a low dispersion at any desired wavelength (including 850 nm), inherently lower latency and potential for significant further loss reduction in these types of fibers, make HC-ARFs a very promising transmission medium, e.g., for future low-delay, ultra-high capacity, short haul, intra-data center applications.

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