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Abstract: We report new transmission distance records through hollow-core NANF with reduced inter-modal interference. We recirculated 41xPM-QPSK C-band channels @32GBaud up to 2070km with average GMI 3.64 bits/symb. For select channels we reached beyond 5000km.

1. Introduction

Transmitting light in air or vacuum-filled waveguides has attracted the attention of researchers for decades, due to the promise of ultimate low: nonlinearity, latency, dispersion and, potentially, loss. The first flexible hollow-core fiber (HCF), fabricated over 20 years ago, relied on a photonic bandgap in the cladding to confine light, and only transmitted light over meter distances [1]. It took 5 years for the technology to evolve to a point where data could be transmitted through 100m [2], and 10 years more for the first recirculating loop experiment. This achieved ~75km on a single 28GBaud QPSK channel [3]. The cause for the limited reach was identified in the large intermodal interference (IMI) that is somewhat unavoidable in photonic bandgap HCFs. The focus in HCF research therefore shifted towards the search for fiber designs allowing simultaneously a lower fundamental mode loss and a higher loss for all other modes. A breakthrough was provided by the Nested Antiresonant Nodeless Fiber (NANF) technology [4]. Using a first generation of NANFs, transmission through 341km of HCF were achieved by recirculating 71 times through a 4.8km span a PM-QPSK 32GBaud channel, propagating at the center of a C-band WDM comb [5]. Subtle improvements in fiber geometry and use of a longer span of 7.7km, later allowed transmission of all WDM channels at an average GMI 3.44 bits/symbol through 618km, and of the center channel through 772km [6],[7]. This is the longest data transmission so far reported through a hollow core fiber.

Even in these latest NANF-based experiments, it was clear that IMI in the fiber, although orders of magnitude better than in photonic bandgap fibers, still played a crucial role in limiting the maximum reach [7]. To reduce the IMI, in this work we have fabricated NANFs with 5 nested tubes, rather than the 6 used in all previous experiments (Fig.1(b) vs. Fig.1(a)). This has two main advantages: lower intermodal coupling coefficient due to a smaller core, less susceptible to microbending, and higher loss for high order modes due to larger intertube cavities (shown by z in Fig.1(b)). As a result, the IMI in the 5-tube fibers used in this work was measured to be between −45dB/km and −55dB/km, as compared to about −35dB/km in a typical 6-tube version [7].

The improved IMI in the fibers resulted in a remarkably improved transmission performance. In a first loop experiment we demonstrated transmission of a 41-channel 32Gbaud PM-QPSK WDM comb to a record distance of 2070km through NANF, at an average GMI of 3.64 bits/symb. The loop also comprised some PSCF to enable replacing the NANF with an equal-loss variable attenuator (VOA), to allow quantifying signal degradation due to the NANF itself. We found that VOA and NANF results differed much less than in the previous experiment [6],[7]. Because of this, we decided to run a second loop experiment where only NANF was present. We reached 4020km at an average GMI of 3.53bits/symb, with several channels reaching beyond 5000km at GMI greater than 3.55bits/symb.

2. 11.5km NANF span

The 11.5km of 5-tube NANF used in these recirculating loop experiments is obtained by splicing together three bands of 6.2, 2.6 and 2.7km. To improve the longitudinal consistency of the fibers from those used in previous experiments, we used fibers produced by Lumenisity using industrial standards. The cross sections of the six end-faces are almost identical, and similar to the SEM image shown in Fig.1(b). The core size is 31 ± 0.3µm, the average inter-tube gap 4.8µm, and the membrane thickness for both outer and inner tubes is around 500nm, which makes the fibers operating in the fundamental transmission window at 1550nm. Note that 6.2km is the longest single NANF band reported to date. The loss of the three fibers is 0.98, 0.85 and 0.95 dB/km, respectively, and is spectrally flat across the C-band, as shown in Fig.1(e). The total loss of the full 11.5km span (schematic Fig.1(c) and photo Fig.1(d)) is 13dB, of which

10.9dB come from fiber propagation. The remaining 2.1dB come from the two NANF-NANF splices, from the two SMF-NANF end-splices (including mode field adapters - MFAs) and from connector losses.

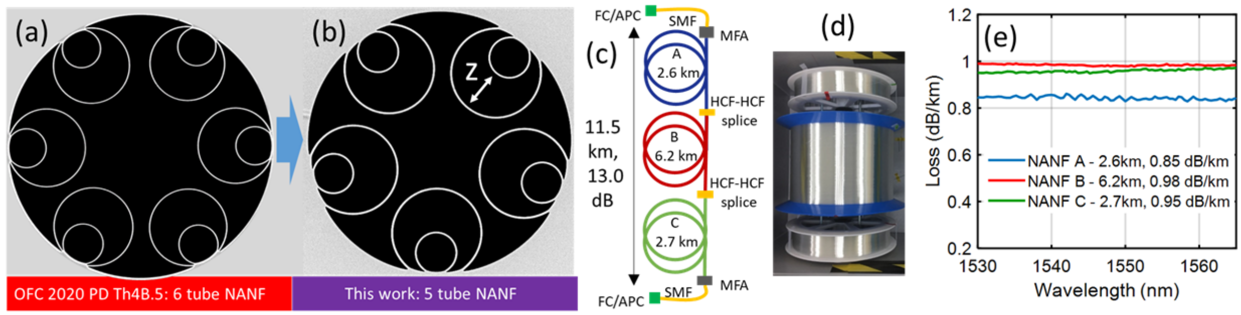

Fig.1: SEM of **(a)** 6 nested tube NANF used in [6],[7]. vs **(b)** 5-tube version used in this work. **(c)** Schematic of the 11.5km span used in the experiment; **(d)** image of the 3 fiber spools spliced together, **(e)** loss of each individual fiber.

3. Recirculating loop experiments

A total of 41 DWDM channels in C-band were emulated by shaping ASE noise with a programmable optical filter (PF, Finisar Waveshaper), as raised-cosine spectra with 32 GHz bandwidth, 0.2 roll-off and 50 GHz spacing. For transmission performance measurements, in turn each one of the 41 ASE-emulated channels was turned off and replaced by an actual modulated Channel Under Test (CUT). The number of WDM channels was limited to 41 because of EDFA-induced bandwidth roll-off at the edges, exacerbated by the extreme number of loop recirculations (hundreds), too large to be compensated for by the other PF positioned inside the loop.

First experiment: The schematic is shown in Fig.2(a). The CUT transmitter used a <100kHz External Cavity Laser (ECL) which was PM-QPSK-modulated at 32GBaud by means of a dual-polarization Mach-Zehnder IQ modulator driven by four 64GS/s DACs. At a pre-FEC BER of 3e-2 (or GMI 3.55 bits/symb) the back-to-back penalty was 0.65dB. The loop consisted of three sections. EDFA1 launched the WDM comb at 20dBm into the 11.5km NANF. It was followed by EDFA2 feeding a loop-synchronous polarization scrambler (PS), used to randomize the state of polarization at each recirculation. Next, a spool of 54.4km of PSCF was present, to allow for signal buffering when the NANF was removed (see later). EDFA3 fed a PF, an acousto-optic modulator switch and a 2x2 splitter/combiner.

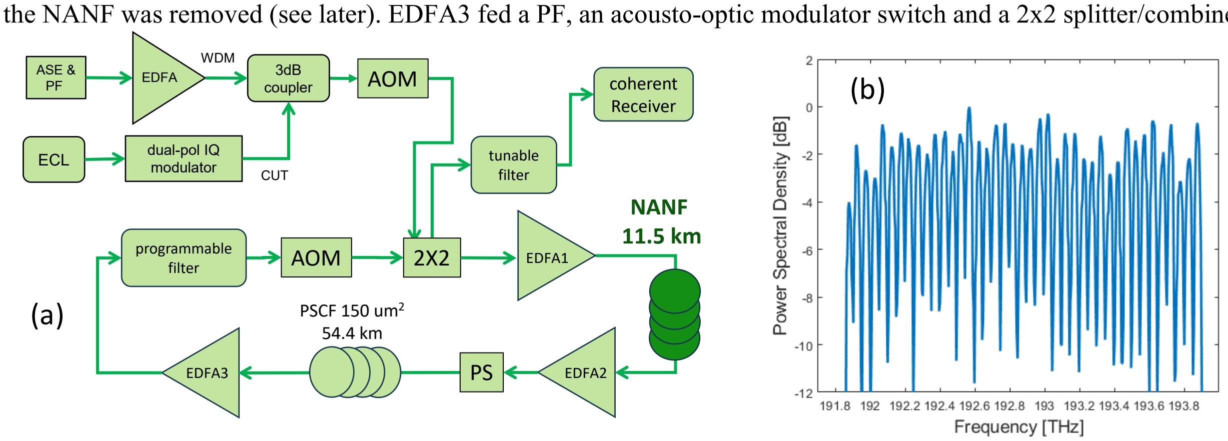

Fig. 2: **(a)** loop schematic. PS: polarization scrambler. PF: programmable optical filter. AOM: acousto-optic modulator switch **(b)** optical spectrum at 100 re-circulations (1150km through NANF).

The launch power into the PSCF was set to 13 dBm, a value which made the non-linearity of the PSCF negligible. At the receiver, a tuneable optical filter selected the CUT, which was combined with a <100kHz ECL local-oscillator in an integrated coherent receiver. The four electrical outputs were sampled at 100 GS/s and offline processed. The DSP performed downsampling to 2 samp/symb, then chromatic dispersion compensation and frequency offset removal. Next, the signal went through a real 4×4 LMS adaptive equalizer, followed by a V&V CPE which used 5% pilot symbols to perform phase unwrapping and improve phase-recovery. The loop was then set to 180 re-circulations, or 2070km in NANF. The blue diamonds in Fig.3(a) show the GMI for each channel, averaged over 6 measurements. Vertical bars range between min and max measured values. The mean GMI across all channels was 3.64 bits/symb. As a control experiment, we replaced the NANF with an attenuator (VOA) set to match the NANF line attenuation (13dB). The results are the red dots in Fig.3(a), whose mean GMI is 3.76 bits/symb.

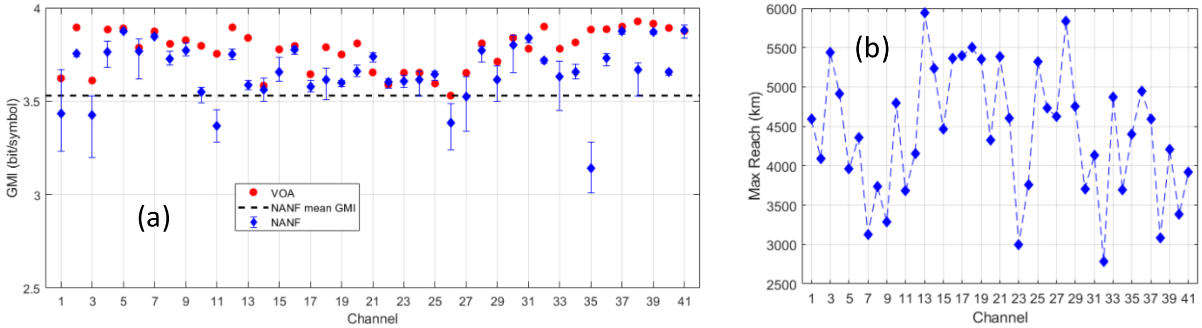

Fig. 3: **(a)** FIRST EXPERIMENT: GMI-vs.-channel number at 2070km (180 rec.) for NANF (blue diamonds) and VOA (red dots). Vertical bars range between min and max measured values for NANF. The dashed line is the average GMI. **(b)** SECOND EXPERIMENT: max reach in NANF at a GMI of 3.55 bits/symbol. Note: channel 1 is 191.9THz, channel 41 is 193.9THz.

As opposed to a similar experiment in [6],[7], here the gaps between the VOA and NANF results are small (mean 0.12 bits/symb), with few exceptions, suggesting that the NANF could achieve a longer reach if the loop loss was reduced.

Second experiment: The only element which could be removed to reduce loss was the PSCF (about 10 dB) and thanks to its removal we could also remove one of the EDFAs. The downside was that a comparative test with VOA was no longer possible, since there was not enough fiber left in the loop to store the signal. The results of this minimum-loss loop experiment are shown in Fig.3(b) in terms of max-reach at a GMI of 3.55 bits/symbol. Remarkably, most channels exceeded 4000km and a few exceeded 5000km. The worst performing channel still achieved 2760km. Note that the number of recirculations ranged between 240 and 520, extremely challenging values to sustain in a recirculating loop. Overall (not shown), we reached 4020km at an average GMI of 3.53bits/symb.

Comments: In the loops we managed to keep the WDM spectrum flat within ±2dB at 100 recs (Fig. 2(b)). After 100 recs., the spectrum was left to evolve since the needed correction was beyond the capability of the loop PF. Note, though, that no appreciable non-linearity was excited in the NANF due to its extremely low non-linear coefficient ($\gamma < 10^{-3}$ $W^{-1}km^{-1}$). Therefore, spectral flatness was much less of an impacting factor than in conventional systems.

We compared the results of both experiments with analytical predictions. We found that the worst performing channels are compatible with a value of IMI no greater than -45dB/km. The best performing channels indicate −55dB/km. Direct measurements on the fiber by means of sliding window and Fourier filtering analysis of a transmission spectrum concur with these numbers. The results presented here far outperform the previous record, which was 618km at an average GMI of 3.44 bits/symb [6],[7]. We did use here fewer WDM channels, but the reason was not the presence of NANF, rather, the impossibility to sustain a broader bandwidth through the EDFAs, when imposing such large values of recirculations. The reason for the far better reach results of this paper appears to be the much lower IMI of this NANF, vs. the -35dB/km of the NANF used in the previous record experiment.

4. Conclusion

Nested Antiresonant Nodeless Fibers (NANFs) have been making steady progress over the last few years, to the point that state-of-the-art NANFs can now achieve multi-thousand-km WDM transmission. In this paper we report on two experiments, using a WDM comb of 41 channels at 32GBaud with PM-QPSK modulation. We achieved a record 2070km transmission in NANF, at an overall average GMI of 3.64 bits/symb. This is three times longer than the previous record (618km) [6],[7], where the GMI was actually lower (3.44 bits/symb). Comparison with VOA instead of NANF showed little difference and suggested that a stripped-down loop could push max-reach much farther. A second experiment minimizing loss within the loop achieved indeed between 2760 and 5980km at GMI 3.55 bits/symb. The number of transmitted channels was 41 rather than 61 as in [6],[7] not due to NANF, but to the extreme number of recirculations (from about 200 to 500) which made the EDFA band edges difficult to manage.

Our results show that NANF progress continues and that substantial improvement has been obtained in reducing IMI. If the current loss (~1dB/km) could be reduced to levels comparable to standard fibers, while maintaining the IMI shown here, NANF might become a promising alternative for higher-throughput systems and networks [8].

This research was supported by the PhotoNext initiative of Politecnico di Torino, by the CISCO SRA OPTSYS-2020, by the European Research Council (ERC) (grant agreement n° 682724), by the EPSRC Airguide Photonics (EP/P030181/1), by Lumenisity and by the UK Royal Academy of Engineering. We also thank Lumentum Italy for supplying the dual-polarization MZ modulator.

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