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***Abstract*—We report a PM-16QAM transmission experiment through hollow-core NANF with reduced inter-modal interference. We recirculated 41 C-band channels at 32GBaud up to 1150km with average GMI 7.14 bits/symb. For selected channels we reached beyond 1500km, the current record for long-haul PM-16QAM transmission over NANF.**

Keywords—NANF, HCF, long-haul, coherent transmission

I. Introduction

Hollow-Core Fibers (HFCs) have attracted keen interest due to their potential for low latency, low nonlinearity, low dispersion, large bandwidth and possibly lower loss than SMF. However, initial HCF prototypes had significant limitations, only achieving 100m transmission distance [1], [2]. About a decade later, substantial progress was made in HFCs and a first recirculating loop experiment was carried out achieving ~75km for a single 28GBaud QPSK channel [3]. The still limited reach was primarily due to the large intermodal interference (IMI) inherent in HFCs. This resulted in an effort towards creating fibers with low loss for the fundamental mode and high loss for all other modes, to essentially make HCFs single-mode.

A very significant reduction of IMI was obtained through the Nested Antiresonant Nodeless Fiber (NANF) structure [4]. Thanks to NANF , transmission through a 341km recirculating loop was possible for a 32GBaud PM-QPSK channel [5]. Further enhancements in NANF geometry enabled transmission of a WDM comb up to 618km [6]. More recently, an experiment has reached a remarkable distance of 4020km [7], the longest PM-QPSK transmission experiment reported on HCF to date. Looking at the broader scope of potential practical applications, higher-order constellations like PM-16QAM become critical, but they requires a much higher SNR. This places NANF transmission under more intense scrutiny, given the tighter tolerance for signal degradation. We achieved PM-16QAM transmission over 201km of NANF, with an average GMI of 7 bits/symb [6]. In this paper, we report on a 1150km WDM PM-16QAM experiment achieving a GMI of 7.14 bits/symb. This experiment demonstrates the feasibility of transmitting more demanding, higher-SNR constellations through more advanced NANF.

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II. The Recirculating Loop Experiment

The NANF in the loop was obtained by splicing three bands of 6.2, 2.6 and 2.7km (total 11.5km). The cross section is shown in the SEM of Fig.1b. 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 500nm. The loss of the three bands was 0.98, 0.85 and 0.95 dB/km, respectively, flat across the C-band (Fig.1(e)). The total loss was 13dB, of which 10.9dB came from NANF propagation and 2.1dB from the two NANF-NANF splices, the two SMF-NANF end-splices (including mode field adapters - MFAs) and connector losses. The 5-tube structure used in this experiment (Fig.1b) has two advantages vs. the 6-tube structure of previous ones (Fig.1a): lower intermodal coupling coefficient due to a smaller core, less susceptible to micro-bending, and higher loss for higher order modes, due to larger inter-tube cavities (shown by “Z” in Fig.1(b)). As a result, the IMI in the 5-tube NANF was measured to be between -45dB/km and -55dB/km, as compared to about -35dB/km in a typical 6-tube version [6].

The experiment schematic is shown in Fig.2. The 41-channel DWDM comb was emulated by shaping ASE noise using a Finisar Waveshaper filter, as raised-cosine spectra with 32GHz bandwidth, 0.2 roll-off and 50 GHz spacing. For transmission measurements, in turn each one of the 41 emulated channels was turned off and replaced by an actual modulated channel-under-test (CUT). The CUT was PM-16QAM-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 the back-to-back penalty was 1.3dB.

The loop consisted of two 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), a programmable optical filter, an acousto-optic modulator switch and a 2x2 splitter/combiner. At the Rx, a tuneable optical filter selected the CUT. The four electrical outputs of the Rx were sampled at 100 GS/s and offline processed. The DSP performed down-sampling to 2 samples/symb, chromatic dispersion compensation, frequency offset removal, then a real 4×4 LMS adaptive equalizer and a blind-phase-search CPE followed. 5% pilot symbols were used for cycle slips mitigation.

The loop was then set to 100 re-circulations, or 1150km in NANF. The blue diamonds in Fig.3(a) show the GMI for each channel, averaged over 5 measurements. Vertical bars range between min and max. The mean GMI across all channels was

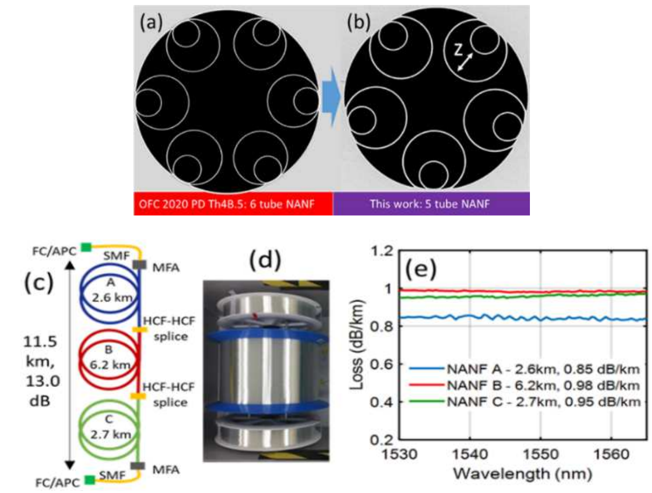

Fig.1: SEM of **(a)** 6 nested tube NANF used in [6],[7]. vs **(b)** 5-tube version used in this work. **(c)** Schematic of the 11.5km span used in the experiment; **(d)** image of the 3 fiber spools spliced together, **(e)** loss of each individual fiber.

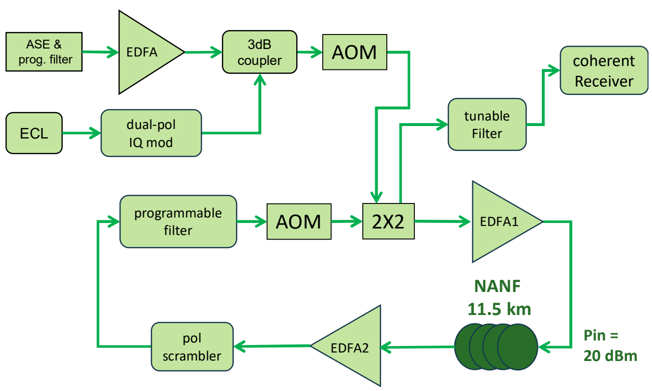

Fig. 2: loop schematic. PS: polarization scrambler. PF: programmable optical filter. AOM: acousto-optic modulator switch.

7.14 bits/symb. We then proceeded to measure the maximum reach for each channel, assuming a threshold GMI of 7.1 bits/symb (approximately BER 3·10-2). Most channels exceeded 1000km and two exceeded 1500km. The worst performing channel still achieved 885km.

We compared the results of the experiment with analytical predictions based on just NANF loss, loop component loss and ASE noise from the amplifiers. We found that the worst performing channels are compatible with a value of NANF IMI no greater than -45dB/km. The best performing channels are compatible with -55dB/km. The reason for the much better reach results of this paper vs. [6] appears mainly to be the substantially lower IMI of this NANF, vs. the NANF used in [6] (-35 dB/km).

III. Conclusion

Nested Antiresonant Nodeless Fibers (NANFs) have been making steady progress over the last few years, to the point where state-of-the-art NANFs can now achieve multi-thousand-km WDM transmission with PM-QPSK modulation [7]. However, in view of possible future practical use of NANFs, it must be shown that these fibers are capable of supporting higher-order constellations. In particular, regarding PM-16QAM, in a previous experiment we achieved 201km [6], at mean GMI 7 bits/symb. In this paper we achieved 1150km

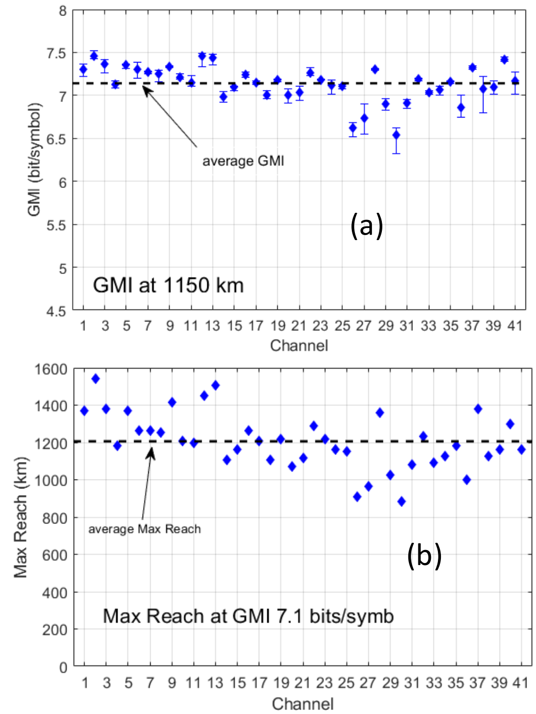

Fig. 3: **(a)** PM-16QAM GMI-vs.-channel number at 1150km of NANF (100 rec.). Vertical bars show the range between min and max over 5 measured values. The diamonds are the means. **(b)** Max Reach in NANF at a GMI of 7.1 bits/symbol. Channel 1 is 191.9THz, channel 41 is 193.9THz.

transmission in NANF, at a mean GMI of 7.14 bits/symb. This is more than five times longer than the previous result. It shows that substantial improvement was obtained in reducing the key aspect of IMI.

It must be mentioned that after this experiment was carried out, a new version of NANF has been developed, with reported loss of less than 0.18 dB/km in the C-band and lower expected values of IMI [8]. Considering its potentially ultra-broad optical bandwidth (hundreds of nm, [4]), these development hints at NANF becoming a promising alternative for future ultra-high-throughput systems and networks [9].

References

[1] R. F. Cregan, et al "Single-mode photonic band gap guidance of light in air," Science, vol. 285, no. 5433, pp. 1537-1539, 19991.

[2] C.Peucheret et al. “10 Gbit/s transmission over air-guiding photonic bandgap fibre at 1550 nm,” Electron. Lett., vol. 41, no. 1, pp. 27–29, 2005.

[3] M. Kuschnerov, et al "Data transmission through up to 74.8 km of hollow-core fiber with coherent and direct-detect transceivers," ECOC 2015, Th1.2.4.

[4] F. Poletti, "Nested antiresonant nodeless hollow core fiber," Opt. Exp., vol. 22, pp. 23807–23828, 2014

[5] A. Nespola et al., “Record PM-16QAM and PM-QPSK transmission distance (125 and 340 km) over hollow-core-fiber,” ECOC 2019.

[6] A. Nespola et al., “Transmission of 61 C-band channels over record distance of hollow-core-fiber with L-band interferers,” J. Lightw. Technol., vol. 39, no. 3, pp. 813–820, Feb. 2021.

[7] A. Nespola, et al. ‘Ultra-long-haul WDM transmission in a reduced inter-modal interference NANF hollow-core fiber,’ OFC 2021, PD F3B.5

[8] G. T. Jasion et al., ‘0.174 dB/km hollow core double nested antiresonant nodeless fiber (DNANF),’ OFC 2022, PDP Th4.C.7, March 2022

[9] P. Poggiolini and F. Poletti, ‘Opportunities and challenges for long-distance transmission in hollow-core fibres,’ JLT, 40 (6), 2022.