Opportunities and Challenges for Long-Distance Transmission in Hollow-Core Fibres

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Pierluigi Poggiolini[1*], **Francesco Poletti**[2]

[1] *DET, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy,* [*]*pierluigi.poggiolini@polito.it*
[2]*Optoelectronics Research Center (ORC), University of Southampton, United Kingdom*

Abstract: Recently NANF fiber prototypes have shown a steady decrease in loss. Theory predicts they could eventually outperform conventional fibers, in both loss and optical bandwidth. We investigate their potential impact on long-haul optical communication systems.

1. Introduction

Capacity demand growth projections indicate that substantial throughput saturation of current systems over the existing cable plants is looming [1]. Several possible technologies are being actively explored to counter this threat, including the use of non-conventional fiber bands (O, E, S, U, etc.) and Space Division Multiplexing (SDM), the latter as either few mode fibers, multi-core fibers, or combinations thereof.

On a parallel research path, Hollow Core Fibers (HCFs) [2] have been studied for over two decades, with substantial success in various applications except for long-haul telecoms, mostly due to their high loss. Recently, however, substantial loss reduction has been achieved in HCFs of the Nested Anti-resonant Nodeless Fiber (NANF) type [3]. Thanks to improvements in the understanding of the loss mechanisms in such structures, loss records have been achieved at a rapid pace, with milestone values of 1.3 dB/km [4], 0.65 dB/km [5] and 0.28 dB/km [6] achieved over the course of the last year three years alone. A path towards reaching and even theoretically getting lower than the loss of SMF, though still to be demonstrated, appears to be in the realm of possibilities.

Besides loss, NANFs also suffer from some residual multi-modality, which may generate enough IMI (Inter-Model-Interference) to be detrimental for long-haul transmission. IMI appears to have been the main limiting factor in recent long-haul transmission experiments with NANFs, such the current distance record [7] (618 km). If the loss gap vs. SMF is finally bridged, and IMI is reigned in, NANFs promise many other advantages vs. SMFs, among which: much broader optical bandwidth (up to several hundreds of nm), 50% faster propagation speed and extremely low non-linearity (with a γ coefficient 3-4 orders of magnitude lower than SMF).

To appreciate the opportunities, challenges and possible potential impact of NANFs, we try to address some key questions related to their use in optical communication systems. Among them: what is the performance parameter space that achieves equivalent performance with respect to SMF? How can such performance be exceeded, and by how much? We look specifically at loss and IMI, the current apparent limiting factors in NANFs performance.

2. Methodology

We employed a similar methodology to [8] and we extended it to include IMI. We focused on certain test system scenarios that could be representative of the current state-of-the-art, to allow a meaningful comparison between SMF and NANF. We assumed: (i) the transmitted channels are all identical and operate at 64 GBaud with roll-off 0.1; (ii) frequency spacing is uniform with value 87.5 GHz; (iii) transmission is performed with Gaussian-shaped constellations; (iv) spans are all identical; (v) fiber loss and dispersion are frequency-independent; (vi) loss is exactly compensated for span by span. To compare systems, we focused on *maximum data throughput* through the link. If noise at the end of the link was additive, white and Gaussian (AWGN), adapting Shannon's formula, similarly to what was done for instance in [9], [10], the link throughput T (Tb/s) would be:

$$T = 2\frac{R_{\rm ch}}{\Delta f} B_{\rm WDM} \log_2(1+\mathrm{SNR}) \qquad , \qquad \mathrm{SNR} = \frac{P_{\rm ch}}{P_{\rm ASE}+P_{\rm NLI}+P_{\rm IMI}} \tag{1}$$

where $B_{\rm WDM}$ is the total optical bandwidth used for transmission (THz), Δf is the channel spacing (THz), $R_{\rm ch}$ is the channel symbol rate (TBaud) and SNR is the signal-to-noise ratio on the received constellation of each channel. The SNR formula holds under the assumption that a *matched Rx filter* is used and that non-linear interference (NLI) due to the fiber Kerr effect can be considered as additive Gaussian noise, approximately white (flat) over each channel. $P_{\rm ch}$ is the transmitted power per WDM channel, $P_{\rm ASE}$ is the filtered amplified spontaneous emission (ASE) noise power due to amplifiers, $P_{\rm NLI}$ is the filtered non-linear interference (NLI) noise due to the Kerr effect, $P_{\rm IMI}$ is the disturbance due to IMI (relevant to NANFs only), all in Watts. The term $P_{\rm NLI}$ is computed using the closed-form incoherent EGN-model approximation Eq. (15) in [11]. Accordingly, we can write:

$$P_{\rm NLI} = \left(\eta \cdot P_{\rm ch}^3\right) \qquad , \qquad \eta = N_{\rm span}\frac{4\gamma^2}{27\pi\,|\beta_2|\,\alpha R_{\rm ch}^2}\,\mathrm{asinh}\left(\frac{\pi^2\,|\beta_2|}{4\alpha}R_{\rm ch}^2 N_{\rm ch}^{2\frac{R_{\rm ch}}{\Delta f}}\right) \tag{2}$$

where $N_{\rm ch}$ is the number of WDM channels in the comb, β_2 and γ are fiber dispersion (ps^2/km) and non-linearity coefficient 1/(W·km), respectively. Eqs. (2) provide $P_{\rm NLI}$ for the center channel in the comb. For simplicity, we

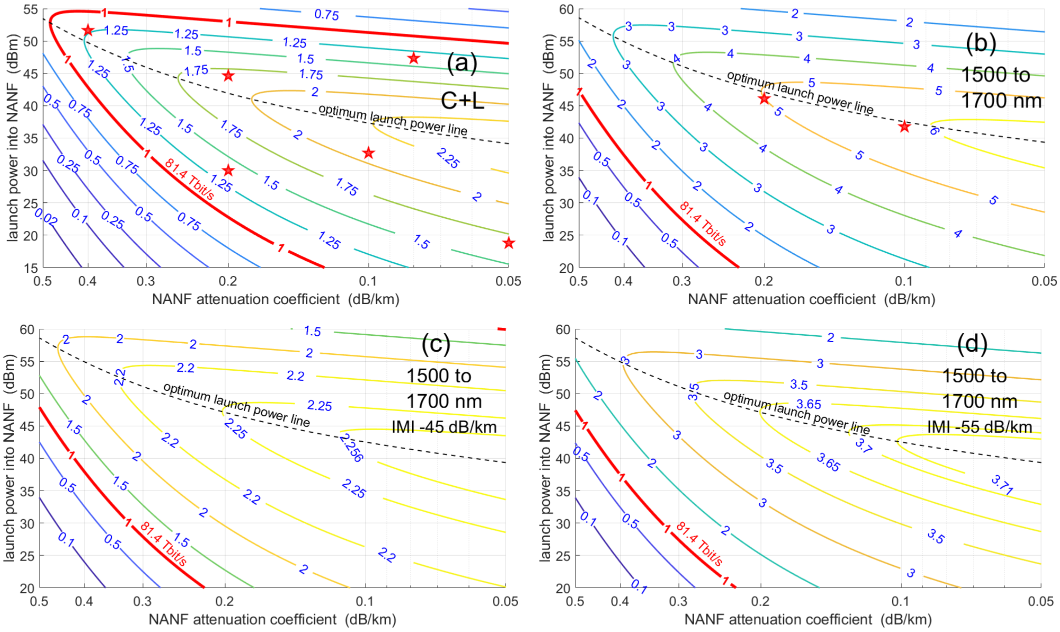

Fig. 1. Isolines of the ratio of NANF systems throughput vs. the benchmark SMF system *maximum* throughput, over 10 spans of 100 km. The benchmark SMF system is C+L bands (9 THz) and its max throughput is 81.4 Tb/s. The NANF systems operate over **(a)** the C+L band or **(b,c,d)** the 1500-1700 nm band (about 25 THz). The red isoline is same throughput as the benchmark SMF maximum. Markers are values verified by full-band split-step simulations. **(b)** assumes no IMI. **(c)** and **(d)** assume -45 and -55 dB/km IMI, respectively.

assume that the same $P_{\rm NLI}$ affects all WDM channels. The term $P_{\rm IMI}$ is modelled similar to what was done for instance in [10] for inter-core crosstalk:

$$P_{\rm IMI} = \kappa P_{\rm ch} L_{\rm tot} \tag{3}$$

where $L_{\rm tot} = N_{\rm span} \cdot L_{\rm span}$ is the total link length (km) and κ is the IMI strength (1/km). From Eqs. (1)-(3), the optimum launch power $P_{\rm ch}^{\rm opt}$ and the corresponding maximum signal-to-noise ratio $\text{SNR}_{\rm MAX}$ can be found in closed-form:

$$P_{\rm ch}^{\rm opt} = \sqrt[3]{P_{\rm ASE}/(2\eta)} \qquad , \qquad \text{SNR}_{\rm MAX} = P_{\rm ch}^{\rm opt} / \left(\tfrac{3}{2} P_{\rm ASE} + \kappa L_{\rm tot}\right) \tag{4}$$

Interestingly, as also noted in [10], $P_{\rm ch}^{\rm opt}$ does not depend on κ. Substituting $\text{SNR}_{\rm MAX}$ into Eq. (1) yields the maximum link throughput $T_{\rm MAX}$. In their simplicity, Eqs. (1)-(4) represent a powerful tool for assessing quite diverse link scenarios. The assumptions and approximations underlying these formulas have been discussed in prior literature, but we will also show results of some split-step simulative checks.

3. Scenarios and impact of IMI

In all scenarios, for the NANF we assume a somewhat larger non-linearity (NL) coefficient $\gamma = 5 \cdot 10^{-4}$ (W km)$^{-1}$ and a lower dispersion value $D = 2$ ps/(nm km) than predicted by design simulations. Both these assumptions cause $P_{\rm NLI}$ to be somewhat overestimated, leading to conservative throughput estimates for NANF. We then sweep the NANF attenuation over the interval 0.5 dB/km to 0.05 dB/km, which ranges between today's records to ideally possible values with future NANFs [3]. As benchmark, we use SMF, with loss 0.2 dB/km, dispersion $D = 16.7$ ps/(nm km) and NL coefficient $\gamma = 1.3$ (W km)$^{-1}$.

Scenario #1: C+L band long-haul terrestrial link. We consider a C+L band link, consisting of 103 channels (about 9 THz) propagating over 10 spans of 100 km each. Fig. 1(a) shows the ratio of the throughput obtained using the NANF vs. the *maximum* throughput of SMF, both calculated using Eqs. (1)-(4). For SMF we assumed that hybrid Raman/EDFA amplification is used, at an overall noise figure $F = 1$ dB. For the NANF we assumed lumped amplification, since Raman amplification is not possible, with $F = 5$ dB. The resulting SMF maximum throughput is 81.4 Tb/s and is achieved at a total WDM optimum launch power of 20.54 dBm. The thick red line in Fig. 1(a) marks where in the plot the NANF link throughput coincides with the maximum throughput of the SMF link. The thin dashed line marks the points that are optimum from a throughput maximization standpoint for the NANF. The stars represent the points that have been validated by full (C+L)-band split-step simulations based on the Manakov equation. We found the mean MI discrepancy between simulations and calculations to be 1.5%, while the max discrepancy was 2.6%. These numbers, in our opinion, confirm the accuracy of the approach.

Interestingly, a greater throughput than SMF can be obtained even at values of loss greater than the loss of SMF. For instance, for a NANF loss of 0.3 dB/km, a throughput 60% greater than SMF is ideally possible. However, a large total launch power of 46 dBm is required. If we assume same loss for the NANF as SMF (0.2 dB/km), then a 90% max throughput increase vs. SMF can be reached at 40.2 dBm, or a 50% increase at a more comfortable 32.1 dBm. It must be pointed out, though, that achieving higher values of throughput than SMF implies transmission at an increased number of bits/symbol. This is because in this scenario the same C+L optical bandwidth is considered for both SMF and NANF and therefore greater throughput can only be obtained through greater spectral efficiency. As an example, to achieve the mentioned 50% throughput increase, 18.52 (net) bits/symbol transmission (9.26 per polarization) are necessary. While wireless and ADSL commercially use constellations of several thousand symbols, it is an open question whether this is practically achievable in optical communications.

Scenario #2: 1500-1700 nm long-haul terrestrial link. We assume that the NANF usable bandwidth extends from 1500 to 1700 nm, or about 25 THz. This already appears as practically attainable [3]. We also assume that lumped amplification is available with F= 8 dB, a 3-dB degraded noise figure from scenario #1 to account for a possibly inferior performance of non-EDFA amplifiers. As benchmark, we use again SMF (C+L) with hybrid Raman/EDFA (F= 1 dB). The results for this new scenario are shown in Fig. 1b. At 35 dBm launch power, which appears reasonable when considering that such power is spread out over 200 nm of optical bandwidth, a NANF with 0.1 dB/km loss would allow reaching a total of 407 Tbit/s, a 5x throughput increase over SMF. However, the required net bits/symbol per channel would be 22.2, or 11.1 per polarization. Imposing a cap of 8 bits/symbol/pol, a NANF with SMF-like loss of 0.2 dB/km would still allow a 3.5x throughput increase at 35 dBm total launch power, quite a remarkable result, at a realistic operating point.

Impact of IMI. The above results neglect IMI. Introducing IMI through Eq. 3, scenario #2 gets substantially degraded as shown in Fig. 1(c)(IMI -45 dB/km) and Fig. 1(d) (IMI -55 dB/km). IMI stops being a factor above -65 dB/km. These results show that IMI should be brought at least below -55 dB/km, with 5-10 dB lower values being the aspirational target. The recent record-distance experiment (618 km) [7] estimated the average NANF IMI at about -35 dB/km. However, out of the two cascaded NANFs strands used in that experiment, one had an estimated -50 dB/km IMI. This is quite promising as for the quick achievement of low-enough values.

Further scenarios. NANFs could ideally deliver loss as low as 0.05 dB/km over 300-400 nm. If these figures proved achievable in the future, more extreme scenarios would be possible, some of which are discussed in [8].

4. Conclusion

Nested Anti-resonant Nodeless hollow-core Fibers (NANFs) have recently entered the realm of the competing technologies being developed to overcome the throughput limitations of the traditional single-core, single-mode, silica-core fiber. By analytical means, validated through simulations, we have shown that NANFs could potentially provide total throughputs between 2 and 5 times that of C+L band Raman-amplified SMF systems.

These throughput gains require a NANF loss of 0.2 to 0.1 dB/km that, although still not achieved by NANFs today (0.28 dB/km being the record), are theoretically predicted as potentially possible. They also require that Inter Modal Interference (IMI) in NANFs be lower than -55 dB/km (currently -45 to -50 dB/km being the best value). In addition, rather substantial challenges need to be addressed, not just related to NANF performance. Among them, unconventional band amplification technologies, transmission at very high bits/symbol per channel, management of large launched powers, splicing and cabling challenges. Optical technology progress has however attained surprising achievements time and again, over its relatively short history, and we believe that NANFs do have a chance to become a key technology for future ultra-high throughput long-haul systems.

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