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# Ultra-Long-Haul WDM Transmission Using NANF Hollow-Core Fiber

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***Abstract:*** *Hollow-core fiber NANF prototypes have recently achieved lower loss and wider bandwidth than SMF. Theory predicts further progress may be possible. We investigate the potential impact of future high-performance NANFs on long-haul optical communication systems.*
***Keywords:*** *Hollow-Core Fibers, NANF, Long-Haul Systems, Ultra-Wideband Systems*

## I. INTRODUCTION

Devising how to keep up with the exponential growth of data traffic demand has become a pressing priority for research in optical fiber transmission systems and networks [1]. To this end, the use of more bands of the light spectrum than the C-band has been advocated. While commercial equipment can now operate in the L-band too, no other band is currently in use in long-haul. Theoretically, there are 4 other bands which could be exploited (S, E, O and perhaps U) to implement Ultra-Wide-Band (UWB) systems over standard Single-Mode Fiber (SMF). On the other hand, these bands come with increasingly larger penalties due to both linear and non-linear impairments, which are intrinsic when light propagates in conventional fibers [2], [3]. As an alternative, Hollow-Core Fibers (HCFs) were proposed already in the 1990s [4].

However, for many years HCF loss remained very high and their usable optical bandwidth appeared to be limited. The situation has changed drastically with the advent of a new type of HCF called NANF (Nested Antiresonant Nodeless Fiber), proposed in 2014 [5]. The first fabricated NANFs still had high loss, but decreasing values were obtained in the following years. In 2019 the 1dB/km mark was broken and recently a remarkable 0.174 dB/km was reported in [6], lower than G.652 SMF across the whole C-band and most of the S-band. In fact, [6] shows that if the water peak was eliminated, loss could potentially be less than 0.22 dB/km over 300+ nm (37.5THz) and less than 0.3 dB/km over 400+ nm (50THz), see Fig.1. Further improvement appears to be possible, too [5], [6].

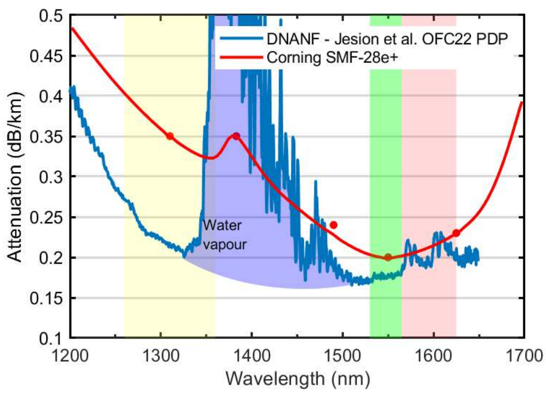


Fig. 1: loss of NANF (of the DNANF type) as reported in [6], compared to SMF-28e+ specifications.

These results highlight the low-loss and large bandwidth potential of NANF, but NANF has other attractive features too. It enjoys a nonlinearity coefficient which is 3 to 4 orders of magnitude lower than SMF [5]. This means that NANF is virtually immune from Kerr non-linearity, as well as from Inter-Channel Stimulated Raman Scattering, which greatly impacts UWB systems in SMF. Another positive aspect of NANF is that Chromatic Dispersion (CD) is much lower than in SMF (about one-seventh, [5]). This can drastically ease the receiver DSP effort for CD compensation and greatly reduce EEPN (Equalizer-Enhanced Phase-Noise), both aspects that may be critical at the ultra-high symbol rates (100+ GBaud) of new-generation commercial transponders.

The NANF potential has started to be tested in actual long-haul transmission by means of re-circulating loop experiments. The longest-reaching so far [7] involved transmission of 41 PM-QPSK channels in C-band and reached 4000km by recirculating the signal over 11.5km of NANF. This experiment was carried out with a previous generation NANF than [6], whose loss was higher (about 0.8 dB/km). Also, its Inter-Modal Interference (IMI), though low, was not negligible (about -50 dB/km). In addition, the limited amount of available NANF made the loop experiment quite challenging, since reaching 4000km required 350 recirculations with unavoidable penalties. Yet, the 4000km reach appears significant in view of these circumstances, suggesting that the improved NANF now available [6] could greatly outperform the loop experiment [7], over much wider transmission bandwidths.

To appreciate the potential impact of present and possible future NANFs on optical systems and networks, an initial theoretical investigation has been carried out in [8]. The study suggests that NANF could provide a throughput gain vs. a state-of-the-art, Raman-supported C+L band SMF "benchmark" system, of between 1.5x to 5x, depending on various factors. This paper follows up on that investigation, providing a more in-depth analysis of various aspects, among which transceiver performance. The latter is critical because NANF provides a potentially much higher OSNR at the end of the link than the benchmark SMF link: however, if transceivers cannot exploit such higher OSNR, then part of the throughput gain of NANF vs. the benchmark may remain untapped. In the following we will address this aspect in detail.

For context, it is important to mention that UWB is not the only approach for dealing with the increasing throughput demand. Space-Division-Multiplexing (SDM) has been proposed in various incarnations [9], ranging from plain deploying many more fibers, to multicore fibers, to more sophisticated approaches such as few-mode fibers. However, UWB and SDM pursue orthogonal dimensions (frequency and space). As such, they are competitors, but they could be complementary or even synergistic in the future, to some extent. When both technologies mature, it will probably come down to complex techno-economic arguments what the relative mix in the deployment of the two will be.

## II. Methodology and Assumptions

The primary goal of this study is to compare the *throughput* performance of a specific WDM NANF link, with $N_{\text{span}}$ of $L_{\text{span}}$ km, to a *benchmark* WDM system using SMF. To assess throughput, we employed a similar methodology to [8].

We first estimate the *maximum Optical SNR* (or *OSNR*) at the receiver end, defined as:

$$\text{OSNR} = \frac{P_{\text{ch}}}{P_{\text{ASE}}+P_{\text{NLI}}+P_{\text{IMI}}} \tag{1}$$

where $P_{\text{ASE}}$ is the amplified spontaneous emission (ASE) noise due to optical amplifiers, $P_{\text{NLI}}$ is the non-linear interference (NLI) noise due to the Kerr effect and $P_{\text{IMI}}$ is the disturbance due to IMI (relevant to NANFs only), all assessed over a bandwidth equal to the channel symbol rate. The channel power is $P_{\text{ch}}$. All details on how $P_{\text{ASE}}$, $P_{\text{NLI}}$ and $P_{\text{IMI}}$ were estimated can be found in [8]. If noise at the end of the link was additive, white and Gaussian, adapting Shannon's formula similarly to what was done for instance in [10], the maximum ideal link throughput $T_{\text{id}}$ would be:

$$T_{\text{id}} = 2\frac{R_{\text{ch}}}{\Delta f} B_{\text{WDM}}\, log2\,(1+\text{OSNR}) \tag{2}$$

where $B_{\text{WDM}}$ is the total optical bandwidth used for transmission, $\Delta f$ is the channel spacing and $R_{\text{ch}}$ is the channel symbol rate. In practice, actual transceivers cannot achieve ideal performance and the *actual* user throughput is:

$$T_{\text{act}} = 2\frac{R_{\text{ch}}}{\Delta f} B_{\text{WDM}} \cdot \text{IR}(\text{OSNR}) \tag{3}$$

where IR is the net user Information Rate, in bits/symbol, of a transceiver pair at a given OSNR.

We then assume for both NANF and SMF systems the following: the transmitted channels are all identical and operate at 64 GBaud; frequency spacing is uniform with $\Delta f$= 75 GHz; spans are all identical with $L_{\text{span}}$=100km; loss is exactly compensated for by amplification, span by span. Regarding fibers, for SMF we assume standard parameters: loss 0.2 dB/km; dispersion $D$=17 ps/(nm·km); non-linearity $\gamma$=1.2 1/(W·km). For NANF we assume: $D$=2.5 ps/(nm·km) and $\gamma$=5·10$^{-4}$ 1/(W·km). NANF loss is left as a parameter. We assume for simplicity that loss, dispersion and non-linearity coefficients are frequency-independent, for both SMF and NANF.

## III. Benchmark and Comparison Results

As *benchmark*, we consider a SMF system that uses the full C+L band (1530-1625 nm, 11.5 THz) with Raman NANF (noise figure 0 dB). We neglect ISRS. These assumptions are rather optimistic for the benchmark and hence lead to a conservative estimate of the potential advantage of NANF over the benchmark. We believe that the chosen benchmark uses SMF in a configuration where SMF performance is optimal. It is therefore a meaningful benchmark not only for NANF UWB but also for all types of UWB systems, including those that aim at extending SMF usage beyond C+L.

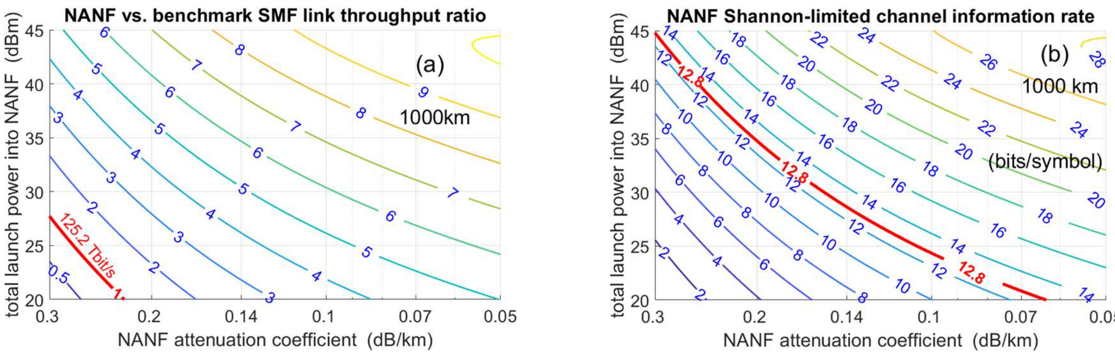


Fig. 2: 1000 km (10x100km) NANF link, bandwidth 1325-1725nm, noise figure 8 dB. **(a)**: throughput ratio between NANF and benchmark SMF C+L+Raman system, vs. NANF attenuation coefficient and total launch power into NANF. Red line: same throughput for NANF as *max* throughput of benchmark (125.2 Tbit/s). **(b)**: Shannon-limited information rate (IR) in bits/symbol. Red line: same IR for NANF as *max* of benchmark link.

Regarding the NANF usable bandwidth, we assume 1325-1725nm (52.5 THz). Such bandwidth is compatible with the results [6] (assuming that the water peak can be removed, see Fig.1) and is consistent with the predictions in [5]. Raman is not possible over NANF, so we assume lumped amplifiers, with a conservative average noise figure of 8 dB.

In Fig.2(a) the ratio between the throughput that can be obtained using NANF and that of the benchmark SMF system is shown. Already at 0.2 dB/km loss, NANF can provide a 3.5x greater throughput, with a launch power of about 30 dBm. Notice that this power appears large but is spread over more than 50 THz. As reference, it corresponds to a power into C-band of less than 20 dBm. Assuming higher but still reasonable launch powers, and/or lower loss in future NANF, multiples on the order of 5x to 7x appear to be possible.

However, such multiples are achieved at very high OSNRs, resulting in very large numbers of bits/symb of IR, as shown in Fig.2(b). For instance, the 6x isoline in Fig.2(a) corresponds to 17 bits/symb in Fig.2(b). For comparison, at large Baud rates (≥64 GBaud) current transceivers operate at most at 8-9 bits/symb, that is, at IR values that are much lower than the ones appearing in Fig.2(b). There is therefore a large IR gap and the key question arises of whether the throughput multiples offered by NANF in Fig.2(a), when Shannon-limited transceiver performance is assumed, can be preserved when a realistic IR curve is factored in.

The next generation of transceivers, coming to market in about a year, may be able to achieve at 100GBaud a performance similar to Fig.3(a), blue curve. The plot shows a substantial and increasing penalty vs. the Shannon limit and a max IR of 10 bits/symbol, reached about 10dB away from the Shannon limit. We use it to assess again the throughput ratio between NANF link and the SMF benchmark. Note that the IR curve of Fig. 3(a) impacts both the NANF system *and* the SMF benchmark, since we assume that the same transceiver technology is used in both. In Fig.3(b) we show the resulting NANF to benchmark SMF throughput ratios. Interestingly, while the highest multiples are no longer achievable, 5x still appears on the map and 4x is reachable at quite reasonable values of both loss and launch power. Above 5.14, the contour surface flattens out completely. As an interpretation of the result, when drastic IR limitations come into play, the maximum throughput ratio saturates at about the ratio of the optical bandwidths of NANF vs. that of the benchmark (C+L), which is indeed approximately 5.

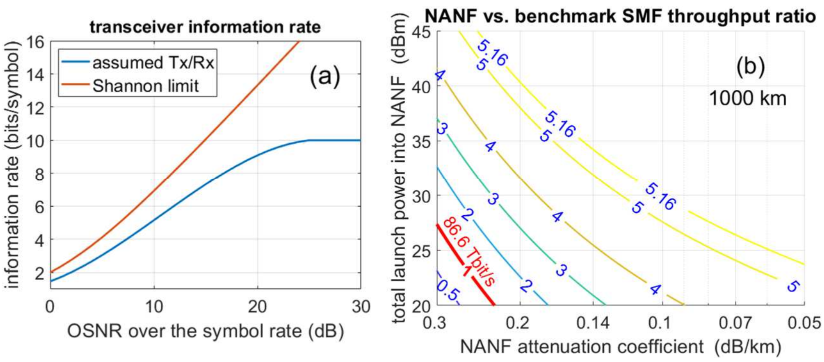


Fig. 3: **(a)** blue solid line: information rate of hypothetical next-generation transceiver at 100 GBaud. For comparison the Shannon limit is shown (red solid line). **(b)** and **(c)**: total throughput ratio between NANF link and benchmark SMF C+L link, vs. NANF attenuation coefficient and total launch power into NANF. **(b)** 1000km link (10x100km), **(c)** 3000km link (30x100km). Red line: same throughput for NANF link as max of benchmark.

The problem of limited transceiver IR gets mitigated when longer reaches are considered. If 3000 km links are assumed, together with the transceiver IR of Fig.3(a), then the plot of Fig.3(c) is obtained, which shows somewhat better performance than Fig.3(b). The highest isoline now reaches 6.45 before the surface flattens out.

Of course, if better IR was available, this would improve results. Substantial research is ongoing on improving transceiver IR and impressive laboratory results have been obtained. At large Baud rate (100 GBaud), 13 bits/symb were demonstrated in [11]. However, even higher IR could be obtained at lower symbol rates. A remarkable result of 17.3 bits/symb at 3 GBaud was reported in [12] and an impressive 22.3 bits/symb at 10 GBaud in [13]. Apart from research results, IRs of 11-12 bits/symb might be possible in the next generation of commercial transceivers when operated at 32-48 GBaud. Operating at lower symbol rates has of course the down-side of requiring more optical carriers to transmit the same throughput, but various techniques have been proposed to arrange multiple optical subcarriers into super-channels.

IMI is a potential NANF impairment. Not shown for lack of space, the impact of IMI was assessed too. The threshold value to ensure that virtually no impact is seen in Figg.3(b)-(c) is -60dB/km. While -50 dB/km were estimated for the NANF used in [7], the new NANF [6], estimated at -54 to -58 dB/km, already comes close to such safe level.

## IV. Conclusions

The recent quick progress in the reported performance of NANF makes such hollow-core fiber an increasingly credible candidate for UWB systems. The results of [6] indicate in prospect a possible usable bandwidth reaching and exceeding 400nm. In this paper we have compared the potential throughput of a NANF link exploiting such bandwidth (1325-1725nm) with a reference benchmark consisting of SMF over C+L with Raman amplification. In the comparison, we have also taken into account the impact of limited transceiver information rate (IR). Our results show that even when factoring in possible substantial limitations in transceiver IR, the NANF solution could achieve throughput multiples on the order of 4x-5x vs. the benchmark, over long-haul distances (1000-3000 km). If NANF caught on, it is also conceivable that specifically-tailored high-IR transceiver could be developed, to further improve NANF systems effectiveness.

Other promising candidates for increased system throughput have been proposed and are being quite actively researched, including UWB over SMF by extending transmission beyond C+L, as well as various SDM solutions (reduced diameter fibers, multicore, few-mode). However, NANF overall features, including its negligible non-linearity, very low chromatic dispersion and reduced latency, make it a credible contender with specific unique features.

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