The Potential for Span Length Increase with NANF

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***Abstract*—We investigate the use of NANF in various system scenarios and specifically we investigate the prospective capability of future NANF to increase span length. NANF appears to have the potential for carving various niches for itself and perhaps achieve widespread adoption in certain contexts.**

Keywords—NANF, long-haul, coherent transmission

I. Introduction

Hollow-Core-Fiber (HFC) has drawn considerable attention due to fast progress in loss reduction. Nested-Antiresonant-Nodeless-Fiber (NANF) HFC was recently reported as having loss of 0.174 dB/km in C-band [1]. It could potentially achieve less than 0.22 dB/km over 300nm of bandwidth (37.5THz) [1], with margins for further improvement [2]. NANF also has various other advantageous features, such as ultra-low non-linearity or faster propagation speed.

Initial investigation has been carried out on the impact of the possible adoption of NANF in practical systems [3-6]. While, in general, NANF appears to potentially provide considerable benefits, it has also been argued that certain limitations, such as on available launch power or transceiver internal SNR [4], may decrease or negate NANF-related advantages. In this paper we first list and comment NANF's pros and cons, in prospect. Following, we discuss the potential of the use of future NANF in conventional Long-Haul (LH) systems, long-span LH systems and long-span submarine systems. We also address the aspect of transceiver and launch power limitations. In general, we find that simply thinking of NANF as replacement for SMF does not realize the full potential of NANF. System design and component specs should be adapted to obtain performance benefits, such as substantially increased span length.

II. Key NANF Features

Loss: NANF reported loss of 0.174dB/km in the C-band [1] is lower than most G.652 SMF and, theoretically, it should be possible to further lower it substantially [2]. In this paper we explore scenarios both with current and lower loss. Ultra-low loss could ensure very high GSNRs at the end of the link [3],[4]. However, the relatively low internal SNR of current high-speed transceivers (about 20dB) has an impact (see next section).

Non-Linearity: the Kerr non-linear coefficient is about 2000 times lower in NANF than SMF. This a substantial NANF plus.

Raman-related effects: like Kerr, they are negligible. This means that Inter-Channel Raman Scattering (ISRS), that strongly affects wideband systems in SMF, is absent in NANF, making the whole low-loss NANF bandwidth truly exploitable. However, Raman amplification is not possible in NANF.

Bandwidth: Current outlook on future NANF bandwidth is 50-60 THz [2], fully usable due to its negligible non-linearity. For comparison, current estimates for SMF of practically exploitable bandwidth over long-haul are around 20 to 25 THz, but with reduced performance outside the C+L bands due a number of unfavorable effects.

Tolerance to high launch power: NANF tolerates very large launch power, even hundreds of Watts [7]. Together with nonlinear effects being negligible this means that, if components can generate high power, performance can potentially be boosted by launching high power.

Dispersion: in NANF is 2.5 to 3 ps/(nm km), about 6 times less than SMF and 8 times less than PSCF. This means that the receiver DSP workload is substantially reduced. EEPN (Equalizer-Enhanced Phase Noise) is decreased accordingly.

GAWBS: Guided-Acoustic-Wave Brillouin Scattering is expected to be negligible in NANF.

Latency: The speed of light in NANF is 50% faster than in SMF. This provides a substantial reduction in latency which is very important for example in data-center geographic coverage.

Inter-Modal-Interference (IMI): NANF has some IMI which may degrade the signal. To be negligible, IMI should be below -60 dB/km. Recent NANF [1] has come close (-54 to -58dB/km) and we will assume that -60 dB/km can be ensured.

III. Analysis of Prospective System Scenarios

In the following analysis, the GSNR and the total throughput are found adapting the analytical approach described in [3].

Terrestrial – We first look at a 1000km long-haul terrestrial system, using a span length L_{span}=100km. We assume that all channels operate at 100GBaud with Gaussian-shaped constellations. The frequency spacing is Δf =106.25GHz. Dispersion is D=2.75 ps/(nm·km) and the NL coefficient is γ=$5\cdot 10^{-4}$ 1/(W·km). Loss and launch power are left as parameters. The NANF bandwidth is assumed to achieve up to its full potential of 60THz (1250 to 1665nm). Multiple amplifiers would be needed to cover all bands and their noise figure (NF) would vary across bands. For simplicity we assume an average value of NF of 7dB. The GSNR at the end of the link is shown in Fig.1(a). Assuming 0.14 dB/km loss, a value that is expected to be reachable in prospect [2], the GSNR is 23dB at a total launch power of 32.5dBm. Note that the fraction of power in any specific band is quite reasonable: for instance, in C-band, the corresponding launch power is 21.7 dBm. This suggests that launching 32.5dBm over 60THz should be amply feasible.

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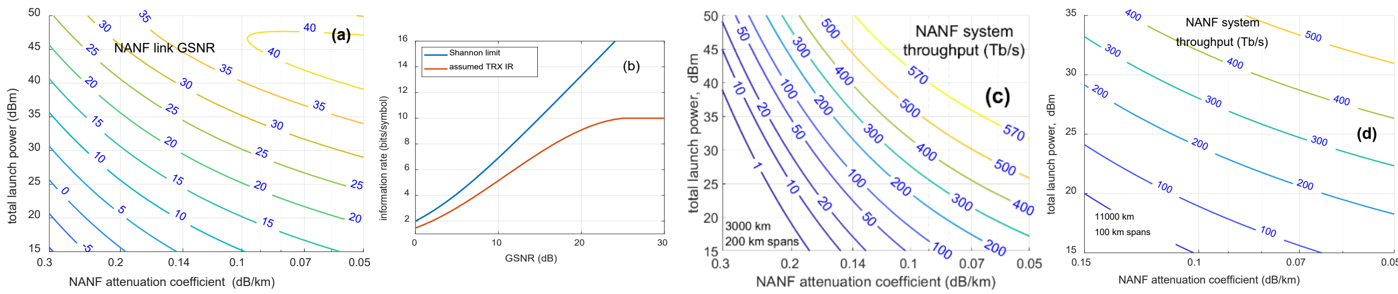

Fig. 1 **(a):** GSNR at 1000km of NANF (10x100km), bandwidth 1250-1665nm, noise figure 7dB, vs. NANF attenuation and total launch power. **(b):** assumed transceiver net information rate (IR) in bits/symbol. **(c):** NANF system throughput at the end of a 3000km link (15x200km), bandwidth 1250-1665nm, noise figure 7dB, vs. NANF attenuation and total launch power. **(d):** same as (c) at the end of a 11000 km link (110x100km), with 2dB extra loss at input of repeaters.

To convert GSNR into throughput, we need to make assumptions regarding the transceiver (TRX). The link 23dB GSNR corresponds to a Shannon-limited IR of 15.3 b/symb (Fig.1(b)). In contrast, current top commercial equipment saturates at 8-9 b/symb at 64 GBaud. The next generation of top TRXs is expected to provide a net IR of up to 10 b/symb at 100GBaud, running roughly as the orange curve in Fig.1(b). Using such curve, despite the inability of the TRX to fully take advantage of the high GSNR, the link still delivers 563 Tb/s on a single NANF for 60THz bandwidth. At 40THz bandwidth and 30.7dBm launch power, NANF would still deliver about 375Tb/s. For comparison, an SMF C+L system with same reach and span length would deliver about 82.1Tb/s with EDFAs at 5dB NF, or 95 Tb/s with Raman amplification at NF 0dB. Hence, a substantial multiple of throughput could be achieved by NANF, despite the limited TRX performance, on the order of the ratio of the assumed fiber bandwidths.

Long spans, terrestrial – Longer spans may take advantage of NANF potentially lower loss. We look at a 3000km link, 15 spans of 200km each. The other system assumptions remain the same as before, including the TRX IR curve of Fig.1(b). The resulting throughput is shown in Fig.1(c). At a launch power of 35.8dBm (25dBm in C-band) the expected throughput for 0.14 dB/km loss is 300Tb/s (GSNR 10dB) and, if 0.1dB/km loss was achieved, close to 500Tb/s (GSNR 18dB), at 60THz NANF bandwidth (about 200 and 330Tb/s at 40 THz bandwidth). Interestingly, here the TRX limitations are much less important: Fig.1(b) shows that at these lower GSNRs the IR curve is still far from saturation. For comparison, a C+L SMF link with 200km spans, with backward Raman amplification at NF 0dB, would deliver a throughput of only 28.6Tb/s. Assuming a further 3dB GSNR gain from forward Raman amplification, 36.8Tb/s would be theoretically achievable but still far from NANF.

Long spans, submarine – In submarine systems the possibility of increasing span length is key. Here there is a double advantage: the needed number of costly submerged repeaters is decreased; power is saved and more of it is at the disposal of the fewer repeaters. We look at a 11000 km trans-pacific cable and assume 100km spans. All other system features are kept the same, including the TRX IR curve of Fig.1(b). We add 2dB extra loss for de-multiplexing the different bands for amplification, since here its impact is substantial. We keep the conservative 7dB amplifier NF used before. Fig.1(d) shows that, if loss in hypothetical NANF submarine cables was 0.1 to 0.05 dB/km, then a total launch power of between 25 to 30dBm (15 to 20dBm in C-band) would be able to deliver between 220 Tb/s to 480 Tb/s, over 100km spans, over the full 60THz bandwidth. As a caveat, whether these throughputs are indeed achievable, it depends on future NANF progress and on specific submarine system constraints, such as available power, that are not explicitly accounted for here [6]. Nonetheless, we believe these figures provide motivation for further research and investigation. For comparison, a 11,000 link with 100km spans of 0.14 dB/km PSCF, using C+L, would achieve about 61Tb/s at 24dBm total launch power, assuming NF=4.5 dB.

IV. Comments and Conclusion

HCFs of the NANF type have very peculiar and distinctive features. Using them as mere replacement of SMF (or other solid-core fibers) in system configurations optimized for SMF may not unfold their full potential. In this paper, we have shown systems scenarios in which NANF becomes more attractive when certain key aspects, such as span length, are designed to take advantage of it. Also, current transceivers favoring increased Baud rate to the detriment of internal SNR may prevent the full exploitation of high-GSNR NANF systems. On the other hand, in long-spans configurations this aspect becomes less important and the NANF advantage becomes more evident.

In addition, the reduced latency (30% lower) is a unique feature of HCFs and of NANF's. In all contexts, and prominently in Data-Center Interconnections (DCI) [8] as well as possibly in ad hoc submarine systems, this issue is likely to provide a key initial motivation for the deployment of NANF.

While the future will most likely see the coexistence of several different fiber types, NANF appears to have the potential for carving various niches for itself and perhaps achieve widespread adoption in certain contexts.

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