Hollow-core fiber capacities with receiver noise limitations

Werner Klaus[1] and Peter J. Winzer[2]
1) Photonic Network Laboratory, NICT, 4-2-1 Nukui Kitamachi, Koganei, 184-8795 Tokyo, Japan
2) Nubis Communications, 430 Mountain Avenue, New Providence, NJ, USA
E-mail address: klaus@nict.go.jp

Abstract: Hollow-core fiber promises low loss and low nonlinearity over wide operational bandwidths. However, considering realistic transponder noise floors reveals much lower capacity gains over standard single-mode fiber than generally assumed, even for optimistic fiber designs.

1. Introduction

Exponential network traffic growth has been pushing the limits of networking infrastructure [1]. Consequently, transmission systems using the low-loss window (C+L band) of standard single-mode fiber (SMF) are now operating close to their Shannon limit estimates, leaving little room for further improvement. To deal with the looming capacity bottleneck, both *space division multiplexed* (SDM) and *ultra-wide-band* (UWB) systems are being intensively investigated. The latter seem particularly attractive when using hollow-core fiber (HCF), which promises wide operational bandwidths at substantially reduced propagation loss and nonlinearity. Impressive progress in reducing the loss of Nested Anti-resonant Nodeless Fibers (NANFs) has heightened expectations [2,3]. Previous studies have predicted spectral efficiency (SE) gains of more than 2x compared to SMF, and capacity gains exceeding 6x when operating across a NANF's predicted low-loss transmission window from 1500 to 1700 nm (~24 THz) [4,5]. However, all studies implicitly assume that *(i)* lumped UWB optical amplifiers (OAs) can be built to cover the wide operational bandwidth, and *(ii)* optical transponders are able to achieve arbitrarily high signal-to-noise ratios (SNRs) in the absence of noise originating from transmission. In this paper, we take a more realistic look at potential SE gains and capacity gains of NANFs by lifting these two assumptions, both for systems with and without optical amplification.

2. System Models

We examine two classes of HCF systems, each containing its own practical assumptions: First, long-reach *single-span unamplified* systems may be feasible due to low-loss and low-nonlinearity NANFs *without* having to rely on UWB OAs. Second, should lumped UWB OAs become available, *lumped amplification* systems can closely approach the performance of ideal distributed amplification with OA spacings exceeding 100 km for low-loss NANFs. In fact, an operational bandwidth of 24 THz can readily be achieved for multi-band SMF systems (especially since distributed Raman amplification can be employed). Hence, the capacity advantage of NANFs reduces to its SE advantage.

Practical coherent transponders operate at a maximally recovered electrical SNR, accounting for noise from transmitter and receiver electronics (e.g., quantization noise I/Q crosstalk) as well as from constantly adapting digital signal recovery algorithms. Typical transponders achieve ~20 dB SNR [6], record high-SE research results achieve ~30 dB [7], and sophisticated laboratory results based on single-sideband techniques reach ~38 dB [8]. The impact of a transponder noise floor becomes apparent in the high-SE regime: Fig. 1 shows the Shannon SE estimate per polarization as a function of transmission distance, with and without a maximum transponder SNR of 30 dB for SMF (loss, nonlinearity, and dispersion coefficients are α = 0.2 dB/km, $\gamma = 1.3\ \mathrm{W^{-1}km^{-1}}$, and D = 17 ps/nm/km), assuming ideal distributed amplification and a fully loaded C+L-band (10.8 THz) with Nyquist pulses. Markers represent measured record SEs [1], reflecting a saturating transponder SNR. The maximum SE per polarization of a polarization-multiplexed transmission system is given by

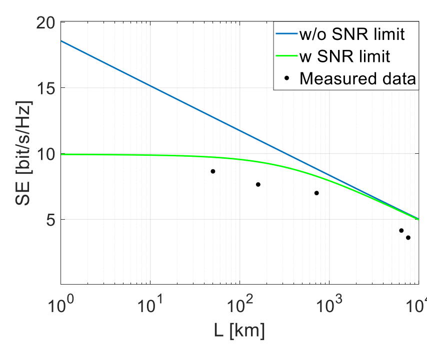

Fig. 1 SE per polarization vs. distance.

$$\mathrm{SE} = \log_2(1+\mathrm{SNR}) \quad , \qquad \mathrm{SNR} = \frac{P}{P_{SH}+P_{ASE}+P_{NLI}+P_{TRX}} \quad ; \tag{1}$$

P denotes the total signal launch power, P_{SH} the local oscillator shot noise, $P_{NLIN} = \chi P^3$ the nonlinear interference noise (NLIN), $P_{TRX} = \kappa P$ a transceiver noise floor (e.g., $\kappa = 10^{-3}$ for 30 dB of maximum transponder SNR) and P_{ASE} the amplified spontaneous emission (ASE) power; χ is derived from the Gaussian Noise (GN) model [9], which we extended to ultra-low fiber losses for the case of lumped amplification using the heuristic formula

$$\chi = \frac{8}{27}\frac{\gamma^2}{\pi\,|\beta_2|B}\,\frac{N_s}{\alpha}\,\frac{\left(1-e^{-\alpha L_s}\right)^3}{1-e^{-\alpha L_s}-\alpha L_s\,e^{-\alpha L_s}}\ \mathrm{asinh}\left(\frac{2\pi^2}{3}\,|\beta_2|\ B^2\,\frac{N_s}{\alpha}\,\frac{1-e^{-\alpha L_s}-\alpha L_s e^{-\alpha L_s}}{1-e^{-\alpha L_s}}\right)\ , \tag{2}$$

and was rigorously derived in [10]. Here, β_2 represents the fiber's dispersion parameter, B the signal bandwidth and N_s the number of spans. When either loss α or span length L_S approach zero, χ of a lumped-amplification system must converge to that of a distributed-amplification system (Eq. (24) in [9]), which Eq. (2) accomplishes. Figure 2 compares Eq. (2) with the hitherto employed Eq. (14) of [9] for N_S = 1, L_S = 100 km and B = 10.8 THz. Finally, by taking the first derivative of Eq. (1) with respect to P, one finds the system's optimum launch power and maximum SNR as

$$P_{opt} = \sqrt[3]{\frac{P_{SH}+P_{ASE}}{2\chi}} \quad \text{and} \quad \mathrm{SNR}_{\max} = \frac{1}{\kappa + \frac{3}{2}\sqrt[3]{2\chi(P_{SH}+P_{ASE})^2}} \,. \quad (3)$$

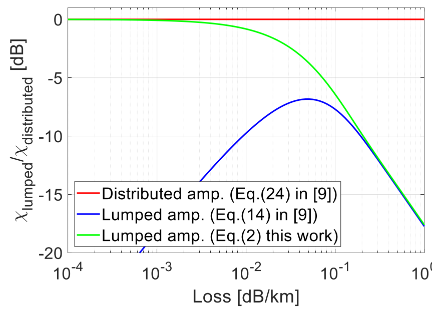

Fig. 2 Normalized noise coefficient.

3. NANF system SE and capacity gains relative to SMF

We next compare the two classes of NANF systems relative to an SMF system with ideal distributed amplification (same parameter set as in Fig.1) for NANFs with loss coefficient α between 0.001 and 0.2 dB/km and nonlinear coefficient γ between 0.0001 and 1.3 $W^{-1}km^{-1}$. The NANF is assumed to be free of intermodal interference and to have uniform loss and nonlinearity across its operational bandwidth. A NANF dispersion of 2 ps/nm/km is assumed [3-5]. Results are shown with and without a transponder noise floor P_{TRX}, with the same values used for both NANF and SMF systems.

Scenario 1: Unamplified single span NANF system, 1000 km reach

In an OA-free NANF system, which does not rely on the availability of lumped UWB-OAs, P_{ASE} = 0. The local oscillator shot noise power in Eq. (1) is $P_{SH} = hfBe^{\alpha L_S}$ where h is Planck's constant and f the signal's optical frequency. The multiplication with the span loss is necessary here because P in Eq. (1) denotes launch power. Figure 3 shows the ratio of SEs for the NANF system relative to an ideal SMF system with distributed amplification (a) without and (b) with a 30-dB maximum transponder SNR. The black markers near the bottom of the figures represent an *"ideal NANF"* with the best numerically predicted loss and nonlinear coefficients (α = 0.02 dB/km, γ = 0.00013 $W^{-1}km^{-1}$). The optimal launch power for this ideal NANF was about 46 dBm for the assumed operational bandwidth of 24 THz. The green area encompasses all {α,γ} combinations that result in an SE gain > 1 relative to SMF. Without a transponder noise floor, the ideal single-span 1000-km NANF system achieves ~2x the SE of an SMF system using distributed amplification. With a 30-dB transponder SNR limit, the achievable SE gain shrinks to ~1.25. In either case, a loss increase from 0.02 to 0.06 dB/km suffices to place the ideal NANF system on the SE gain = 1 contour line, where the single-span NANF system shows no SE gain relative to the amplified SMF system anymore. Such loss increases may occur in practice from splices or cabling. Also, note that in contrast to amplified systems, where lumped optical losses in combination with loss-compensating OAs can be engineered to add only negligible noise at the receiver, *all* optical losses multiply (add linearly in dB) in unamplified systems, including insertion losses of UWB multiplexers/demultiplexers, coherent optical receiver components, and even non-unity quantum efficiencies of receiver photodetectors. If all these losses add up to, e.g., 10 dB, the SE gain = 1 contour line would shift closer to the marker and reduce the maximum loss tolerance for the ideal NANF from 0.06 to 0.05 dB/km. Thus, we conclude that single-span NANF systems provide no practical SE benefit compared to SMF systems with distributed amplification.

Scenario 2: 10 amplification spans of 100-km NANF, 1000 km reach

If lumped UWB-OAs are available, amplifiers may be installed at regular intervals along the NANF perfectly compensate the accumulated loss. For ideal amplifiers (3-dB noise figure), $P_{ASE} = N_s hfB(e^{\alpha L_S} - 1)$ with N_s = 10 and L_S = 100 km. In this scenario $P_{SH} = hfB$ in Eq. (1) because the last OA following the final span lets the received power be equal to the launch power P. For low losses (such as would be the case for the ideal NANF), this system behaves identical to a distributed-amplification system and can therefore be considered ideal. Figure 4 shows the ratio of SEs for this NANF system relative to an ideal SMF system with distributed amplification (a) without and (b) with a 30-dB maximum transponder SNR. An SE gain of ~2.2 is obtained for the case without transponder noise floor, and an ideal NANF. This value is in good agreement with results obtained in previous studies [4,5]. The optimal launch power is about 40 dBm. However, when considering a transponder noise floor, the SE gain of the NANF system is also reduced to ~1.25. Interestingly, this SE gain is practically the same as in the unamplified single-span case, although, as expected, the tolerance to additional losses is greatly improved.

Impact of maximum transponder SNR and transmission distance

Figure 5 shows the SE gain relative to an ideally amplified SMF system for an ideal NANF used (a) in an unamplified single-span NANF system and (b) in a lumped-amplified NANF system with maximum transponder SNRs between10 and 40 dB. In (a) accumulated losses rapidly deteriorate performance beyond 2000 km. In (b), the SE gain steadily increases with transmission distance. Under the reasonable assumption that realistic transponders will not be able to provide SNRs much higher than 30 dB, the SE gain of an amplified NANF system is limited to ~2x for 10000-km transmission. Assuming the availability of 24-THz lumped UWB-OAs, this also results in a maximum achievable capacity gain of ~2x for trans-Pacific systems. Terrestrial NANF systems (~1000 km) operating across 24 THz of bandwidth are limited to capacity gains of ~1.25x relative to multi-band SMF systems.

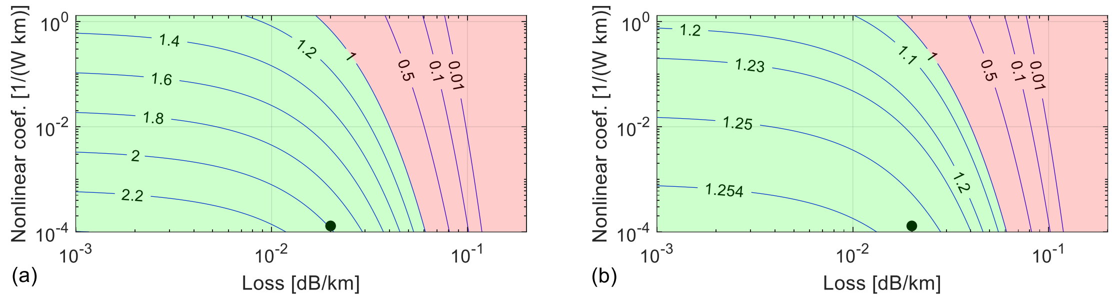

Fig. 3. SE gain over an ideally amplified SMF system for an unamplified single-span NANF system (a) without and (b) with 30-dB noise floor.

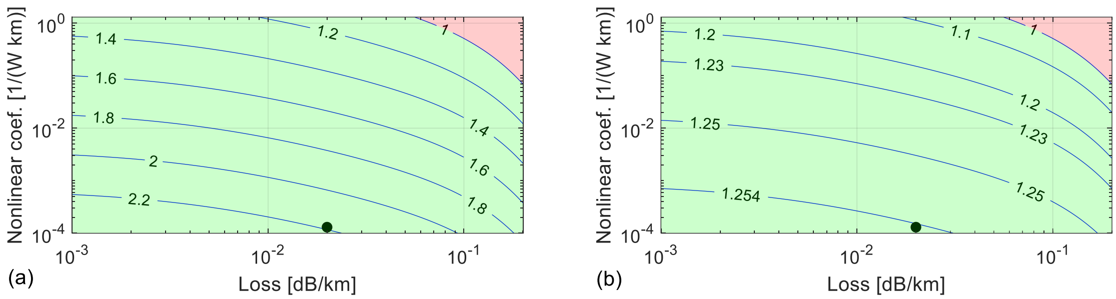

Fig. 4. SE gain over an ideally amplified SMF system for a lumped-amplified NANF system (a) without and (b) with 30-dB noise floor.

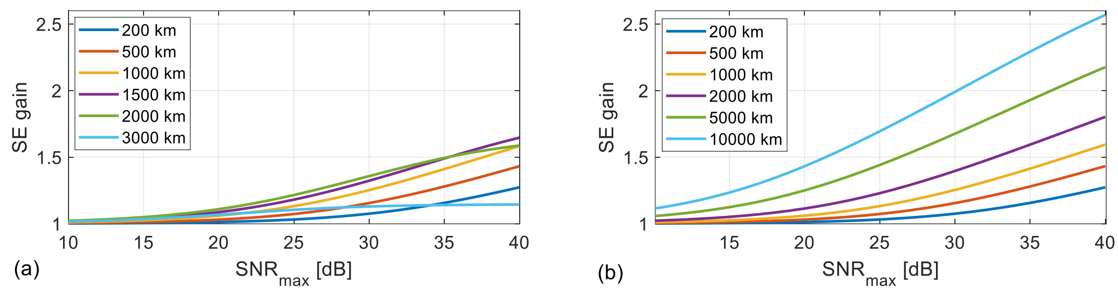

Fig. 5. SE gain over an ideally amplified SMF system for an ideal NANF system using (a) a single unamplified span and (b) 100-km lumped amplification spans as a function of maximum transponder SNR at different transmission distances.

4. Conclusions

Optical transmission systems using even the most optimistic NANFs will be limited to SE gains of ~1.3x compared to SMF systems for terrestrial distances (~1000 km) and up to ~2x for trans-Pacific distances due to transponder noise floors. Since equal operational bandwidths are practically feasible for both NANF and SMF systems, these SE gains also reflect the achievable capacity gains.

References

[1] P. Winzer et al., “Fiber-optic transmission and networking: the previous 20 and the next 20 years,” Opt. Express, 24190, 2018.
[2] F. Poletti, “Nested antiresonant nodeless hollow core fiber,” Opt. Express, 23807, 2014.
[3] H. Sakr et al., “Hollow Core NANFs with Five Nested Tubes and Record Low Loss at 850, 1060, 1300 and 1625nm,” Proc. OFC’21, F3A.4.
[4] F. Poletti, P. Poggiolini, “Potential System Impact of Low-Loss Antiresonant Hollow-Core Fibers,” Proc. ECOC’19, P51.
[5] P. Poggiolini, F. Poletti, “Opportunities and Challenges for Long-Distance Transmission in Hollow-Core Fibres,” Proc. OFC’21, F4C.1.
[6] T. Zami et al. "Simple self-optimization of WDM networks based on probabilistic constellation shaping," J. Opt. Commun. Netw., A82, 2020.
[7] S.L.I. Olsson et al., “Record-High 17.3-bit/s/Hz Spectral Efficiency Transmission over 50 km Using Probabilistically Shaped PDM 4096-QAM," Proc. OFC’18, Th4C.5.
[8] X. Chen et al. “16384-QAM transmission at 10 GBd over 25-km SSMF using polarization-multiplexed probabilistic constellation shaping," Proc. ECOC’19, PD3.3.
[9] P. Poggiolini, “The GN model of non-linear propagation in uncompensated coherent optical systems,” J. Lightw. Technol., 3857, 2012.
[10] M. Ranjbar Zefreh and P. Poggiolini, "A GN-model closed-form formula supporting ultra-low fiber loss and short fiber spans," private communication, to be uploaded onto arXiv.