Comparison of Optical Fiber Types for All-Raman Systems

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Abstract: We experimentally explore several optical fibers for all-Raman systems. We find that while NZ-DSF with small A_{eff} may require slightly smaller pump power, its OSNR disadvantage is approximately 5 dB compared to ultra-low loss fibers.

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1. Introduction

It is understood that moving to higher optical transmission system bit rates generally requires higher optical signal-to-noise ratio (OSNR) values to achieve the desired level of performance. Achieving higher OSNR at the end of a system can be accomplished in several ways, most notably by lowering fiber loss, allowing higher channel launch powers through reduced fiber nonlinearity, and lowering optical amplifier noise figures. Toward that end, future high bit rate systems at 100 Gb/s and greater may employ Raman amplification as a means of reducing the effective noise figure and increasing OSNR.

With regard to Raman amplification, there is often a common perception that non-zero dispersion shifted fibers (NZ-DSF) which have smaller effective area (A_{eff}) than standard single-mode fiber are better suited for Raman amplified systems. This is because the Raman gain coefficient generally scales as the inverse of the fiber effective area and so smaller A_{eff} leads to higher Raman gain for the same pump power. However, total system performance is more complex and it is worthwhile to consider the overall OSNR that can be achieved with different fiber systems including fiber attenuation and nonlinear tolerance in addition to differences in Raman gain coefficient. In this work, we examine 4 different fibers for systems that are all-Raman amplified. The fibers cover a range of characteristics of commercially available products, with A_{eff} from 55 to 112 um^2 in ~30 um^2 increments and attenuation values from 0.163 dB/km to 0.213 dB/km. We calculate analytically and measure experimentally the span OSNR values achieved for each fiber over a 100 km span, and also the Raman pump powers required to fully compensate for the span losses. We find that OSNR is higher for fibers with ultra-low attenuation and larger A_{eff}. The required Raman pump powers are greater for fibers with larger A_{eff}, but this is partially offset with respect to the fiber with smaller A_{eff} because of the reduced Raman gain required by the ultra-low attenuation fibers. Overall, while the Raman gain is highest for the smaller effective area fiber tested, its measured OSNR is on the order of 5 dB lower than for fibers with ultra-low attenuation and larger effective areas.

2. Theoretical approach

The amount of ASE noise F_{ASE} in a Raman-amplified span depends on the signal power evolution along the fiber length z. The signal gain profile for a backward-pumped span can be calculated as [1]

$$G(z) = \exp\left\{ P_p^0 \frac{g_R}{A_{eff}} \frac{1}{\alpha_p} \exp(-\alpha_p z)\left[1 - \exp(-\alpha_p z)\right] - \alpha z \right\}, \tag{1}$$

where P_p^0 is the Raman pump power, α and α_p are the fiber loss coefficients at the signal and pump wavelength, respectively, and g_R is the Raman gain coefficient. The span OSNR is [1]

$$\text{OSNR} = P_{in} T_f / \left(h\nu_s B_o F_{ASE} \right) \tag{2}$$

where P_{in} is the input signal power, T_f is the fiber transmittance (T_f <1), B_o =0.1 nm is the optical bandwidth, and $h\nu_s$ is the signal photon energy. To account for double Rayleigh backscattering (DRBS) crosstalk X, the effective noise figure $F_{eff} = F_{ASE} + \frac{5}{9}\frac{P_{in}T_f}{h\nu_s B_e} X$ is used instead of F_{ASE} in Eq. (2) [1, 2]. B_e is the electrical filter bandwidth.

To properly compare performance of different fiber types, nonlinear penalties should be kept constant for all fiber types. As a measure for nonlinear impairments, the nonlinear phase is frequently used [2,3]. For a comparison of different fiber types we fix the nonlinear phase shift at a certain value (3.74x10^{-5} radians here) and calculate the achievable OSNR and the required Raman pump powers for transparency pumping, for different loss coefficients and effective areas of the fiber. The results are shown in Fig. 1. One can see that under the transparent pumping condition, the achievable OSNR increases with the decrease in the loss and the increase in the effective area. The required Raman pump power increases with both the loss and the effective area of the fiber.

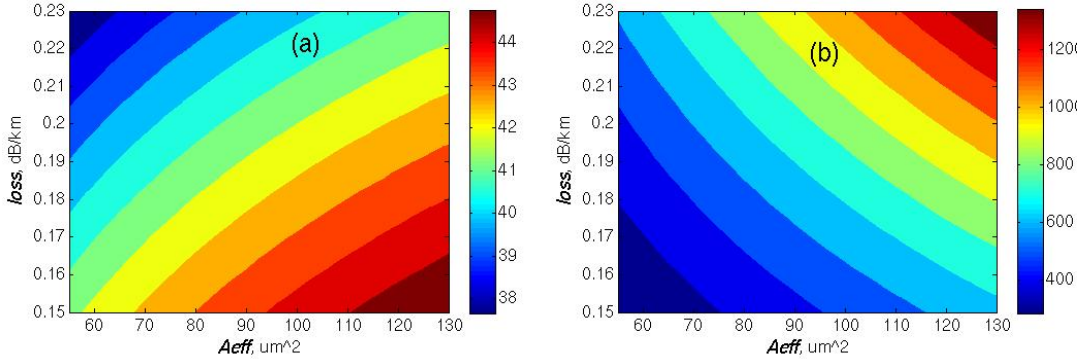

Fig.1. (a) Achievable OSNR (dB), and (b) the required pump power (mW) as a function of loss and effective area of a 100 km fiber span under transparent pumping conditions. The input signal power is scaled to keep the nonlinear phase shift constant for all cases.

3. Experimental set-up and results

Experimentally, we chose 4 different optical fibers to study for all-Raman systems. Each fiber span was 100 km in length. The fiber characteristics are described below in Table 1. Fiber A was a medium dispersion fiber with the smallest A_{eff}. Fiber B was a standard single-mode G.652-compliant fiber, Fiber C was a G.652-compliant fiber with ultra-low attenuation, and Fiber D was a large A_{eff} fiber that also had ultra-low attenuation.

Table 1: Fibers experimentally tested in Raman study

	100 km span loss (dB)	Effective Area (μm^2)	D_{1550} (ps/nm/km)	n_2 (m^2/W)
Fiber A	21.3	55	7	2.3×10^{-20}
Fiber B	18.8	84	17	2.3×10^{-20}
Fiber C	16.6	85	16	2.1×10^{-20}
Fiber D	16.3	112	20.5	2.1×10^{-20}

The experimental objectives were to measure the span OSNR for each 100 km span of fiber with backward-pumped Raman amplification that fully compensated for the fiber span loss, and the Raman pump power required. The experimental set-up is shown in Figure 2. A DFB laser at 1550 nm was modulated at 112 Gb/s with the PM-QPSK modulation format. The signal was amplified with an EDFA and the launch power into one of the 100 km spans was controlled with a variable optical attenuation (VOA). A backward pumped Raman amplifier with 2 pump wavelengths at 1443 nm and 1461 nm and 4 pumps (2 for each wavelength in orthogonal polarizations) was located at the end of the span. The pump powers were set to achieve span transparency. The OSNR was measured with an optical spectrum analyzer at the input to the span, denoted $OSNR_{in}$, and at the output of the span, denoted $OSNR_{end}$. $OSNR_{in}$ was 41.4 dB for all measurements for all launch power levels and for all fiber spans tested.

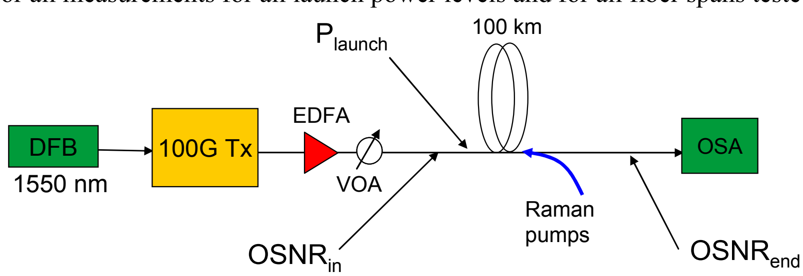

Fig. 2. Experimental set-up for measurement of 100 km span OSNR values with all-Raman amplification.

The span OSNR, ($OSNR_{span}$), was calculated from the measured $OSNR_{in}$ and $OSNR_{end}$. We first note that $OSNR_{end}$ is expressed as

$$\mathrm{OSNR}_{end} = P_{sig} / \left(\mathrm{ASE}_{in} + \mathrm{ASE}_{span}\right). \quad (3)$$

Since the signal power is the same at the input and output of the span with Raman pumping to transparency, we can invert Eq. 1 and solve for $OSNR_{span}$ which yields in linear units the relationship

$$\mathrm{OSNR}_{span} = \frac{\mathrm{OSNR}_{in}\mathrm{OSNR}_{end}}{\mathrm{OSNR}_{in} - \mathrm{OSNR}_{end}}. \quad (4)$$

The measured data for $OSNR_{span}$ for a range of launch powers for the four 100 km fiber spans is shown in Fig. 3a. To fairly compare the fibers, we used the theory to determine relative launch powers for the different fibers that would produce the same nonlinear phase shift. We chose 0 dBm launch power for Fiber C as the reference power and then used launch powers for the other fibers that produce the same nonlinear phase shift of 3.74×10^{-5} radians. The launch power levels determined were -1.0 dBm for Fiber A, +0.2 dBm for Fiber B, 0 dBm for Fiber C, and +1.1 dBm for Fiber D. The span OSNR results measured at these launch powers are given in Fig. 3b, along with the theoretical values. We find good agreement between theory and experiment. Beyond that, we see that the fibers with the best span OSNR are Fibers C and D, the two ultra-low loss fibers. The measured span OSNR values produced by these fibers are higher than achieved with Fiber A by 4.7 dB and 6.3 dB, respectively. The standard single-mode fiber, Fiber B, has span OSNR performance between the two ultra-low loss fibers and the small A_{eff} fiber. The poorer OSNR of Fiber A is due to its higher loss and lower allowable launch power due to smaller A_{eff}.

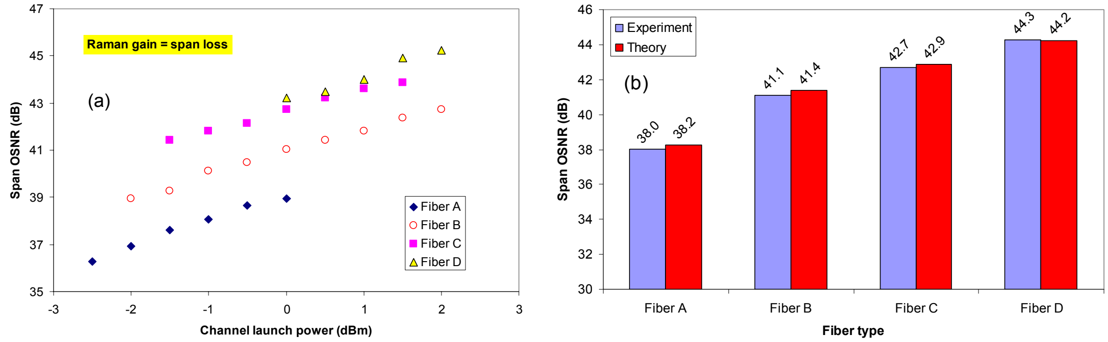

Fig. 3. (a) Span OSNR measured as a function of launch power for the 4 fiber types with Raman gain equal to span loss. (b) Measured and predicted span OSNR at launch power levels that produce equal nonlinear phase shift.

The experimentally required Raman pump powers to achieve span transparency for the 100 km spans are shown in Fig. 4a. As expected, Fiber A required the smallest amount of pump power to achieve transparency, but Fiber C required only about 86 mW additional pump power because of the fact that the Fiber C span needed almost 5 dB lower Raman gain. Finally, while the experimental OSNR measurements do not capture the effects of DRBS, the predicted change in effective electrical SNR when this effect is included theoretically is shown in Fig. 4b. The ultra-low loss and larger A_{eff} fibers have an advantage in this respect too over Fiber A. When included in the analysis, this effect increases the overall performance advantage of Fibers B, C, and D.

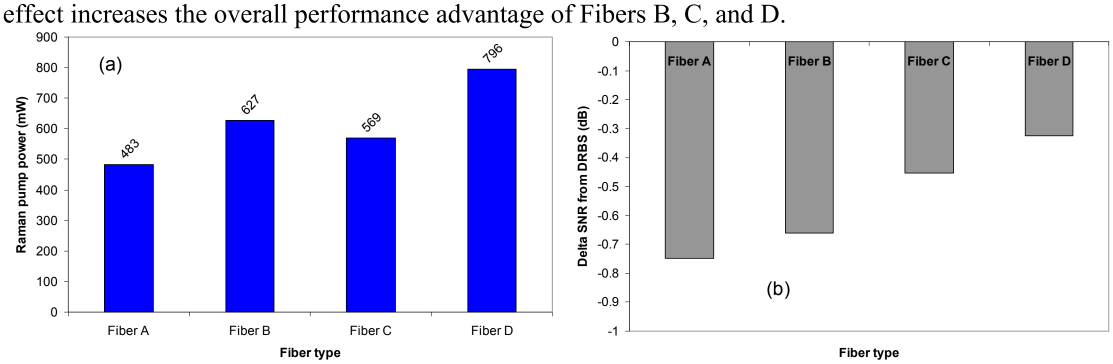

Fig. 4. (a) Measured required Raman pump powers for the 4 fiber spans with Raman gain equal to span loss. (b) Theoretically predicted change in effective SNR including effects of DRBS.

4. Conclusions

We have experimentally and theoretically investigated 4 different fibers for use in all-Raman networks for high data rate systems. While a medium dispersion fiber with small effective area requires the lowest Raman pump power, its higher attenuation and lower allowed launch power lead to an OSNR disadvantage against the 3 other fibers. The best performing fibers were ultra-low loss fibers which had about 5-6 dB OSNR advantages over the small A_{eff} fiber, advantages which become even greater when DRBS effects are taken into account.

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