# SELECTING THE RIGHT NZDF FIBER FOR DISTRIBUTED RAMAN AMPLIFICATION

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Distributed Raman amplification, the technology used to increase the span reach in 10 and 40 Gb/s systems, may reduce overall system cost, in part by reducing the number of amplifiers in the network. This technology has been adapted in commercial systems and is now implemented in the field both in the United States, Europe and Asia.

## Distributed (Raman) Gain Improved Transmission Systems

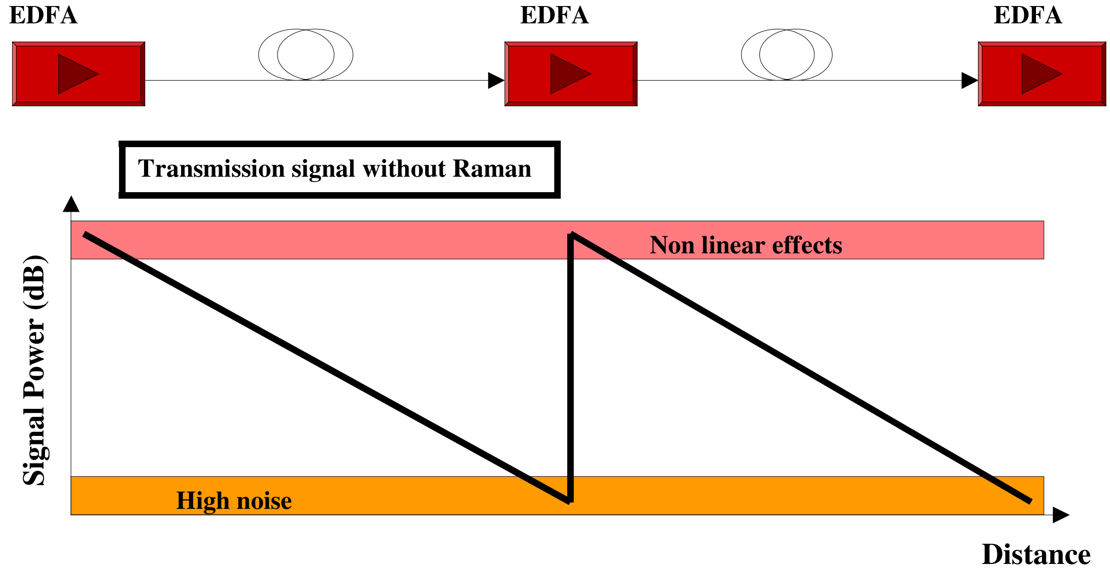

Figure 1. Conventional amplification scheme using lumped EDFAs

Figure 1 shows a conventional transmission system using erbium-doped fiber amplifiers (EDFAs) to amplify the signal. The signal power in the transmission line is shown; at the output of the EDFA the signal power is high. However, nonlinear effects limit the amount of amplification of the signal. The signal is attenuated along the transmission line. In addition, the minimum signal level limits the Optical Signal to Noise Ratio (OSNR) of the transmission. So the transmission distance between each amplifier point is limited by nonlinear effects at the high signal level right after amplification and the minimum allowable OSNR just before amplification.

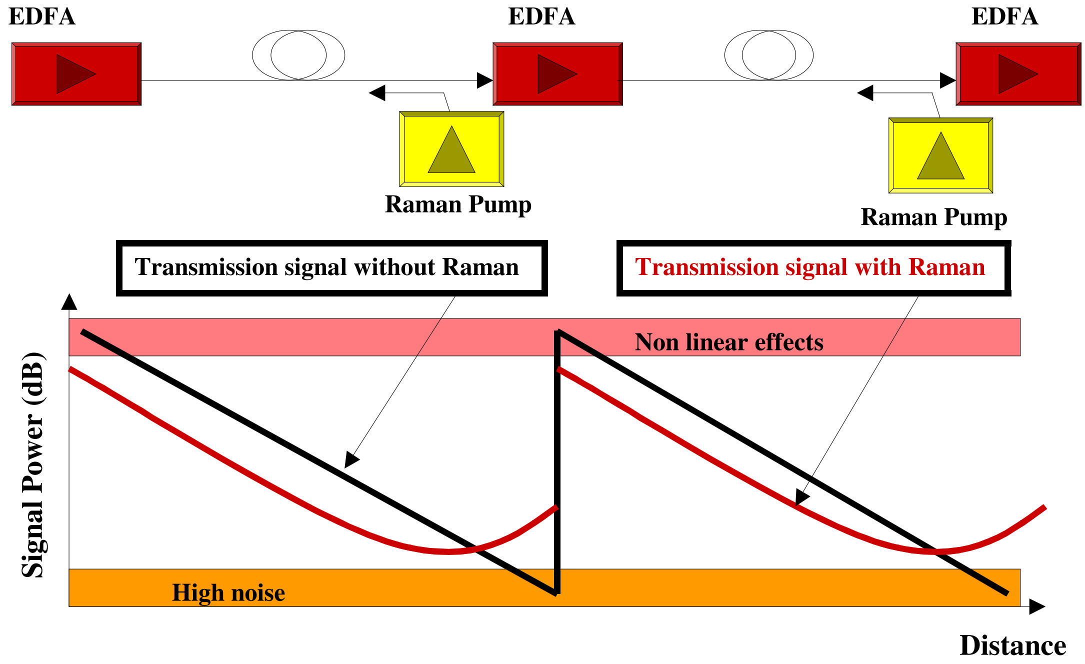

Figure 2. Amplification scheme using distributed Raman amplification together with lumped EDFAs

By comparison, Figure 2 shows a scenario where distributed Raman amplification is used. In this hybrid version with backward propagating pumps and EDFAs, the signal power level evolves as shown by the red curves. At the end of the link, the signal is amplified by the Raman pump, and the OSNR is thereby improved. The input power level can also be lowered, as Raman amplification keeps the signal from the noise limit. The lower input power mitigates the non-linearities in the system. Forward propagating pumps or a combination of both forward and backward propagating pumps may be used.

Installing transmission fibers that have been designed and optimized to take full advantage of the Raman technology allows system designs with higher capacity and lower cost.

## Characteristics of Raman-Optimized Fibers

Fibers optimized for Raman amplification offer the following characteristics:

- high Raman gain efficiency
- low attenuation at signal and pump wavelengths
- low zero dispersion wavelength.

*Raman gain efficiency,* $C_R$

The on-off gain (defined as the ratio between output signal power with and without a pump) in a fiber when a pump power of $P_{pump}$ is used is given by

$$G_{on-off} = \exp\left[C_R P_{pump} L_{eff}\right].$$

This means that the on-off gain in dB is proportional to both the Raman gain efficiency, $C_R$, and to the pump power. Therefore, an increase in $C_R$ allows for a similar reduction in required pump power for the same gain. The Raman gain also depends on the effective length, $L_{eff}$, which will be discussed later.

The Raman gain efficiency $C_R$ is a combination of the cross-section determined by the glass composition and the overlap between the optical mode with the differently doped regions, or

$$C_R = \frac{g_R}{A_{eff,R}},$$

where $g_R$ is the Raman coefficient (composition dependent), and $A_{eff,R}$ is the Raman effective area, which for transmission fiber is given by

$$A_{eff,R} = \frac{1}{2}\left(A_{eff}(\lambda_p) + A_{eff}(\lambda_s)\right) \approx A_{eff}(1550nm)$$

The figure below shows $C_R$ as a function of the effective area for different types of transmission fibers, with different effective areas. TrueWave® fibers from OFS, which are optimized for Raman applications, are compared with a large-area NZDF and standard single-mode fiber (SSMF). It is shown that $A_{eff}$ needs to be smaller to increase gain efficiency.

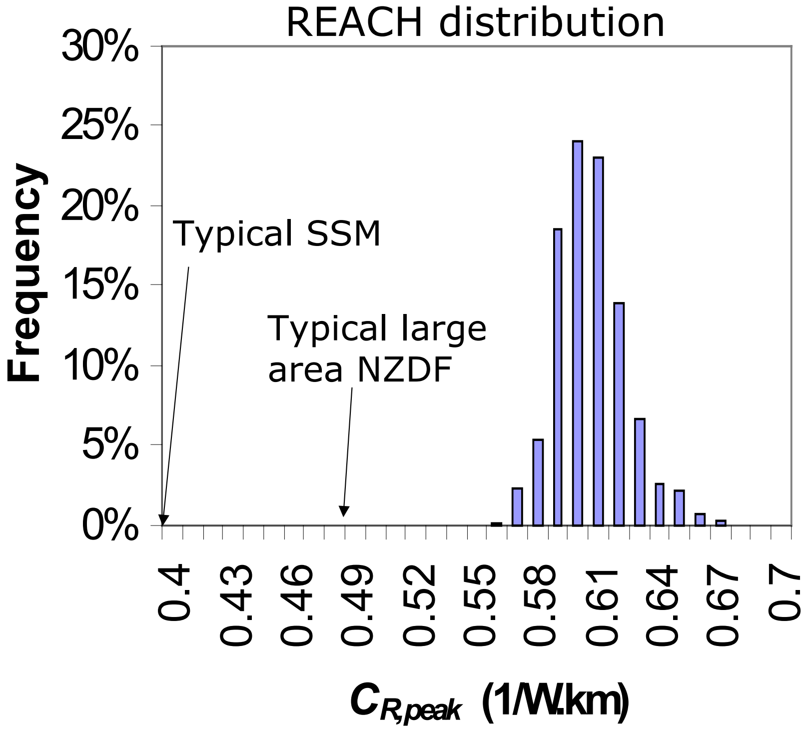

Figure 3. Distribution of $C_{R,peak}$ for TrueWave *REACH*, average 0.60 (Wkm)$^{-1}$ and standard deviation 2.5%. The pump wavelength is 1453 nm.

The Raman gain also depends on the fiber length and the attenuation at the pump wavelength through the effective length, $L_{eff}$ :

$$L_{eff} = \frac{1-\exp(-\alpha L)}{\alpha},$$

where $\alpha$ is the attenuation in units of km$^{-1}$. The lower attenuation the larger $L_{eff}$ and thus gain, the maximum obtainable $L_{eff}$ is $1/\alpha$ . From the on-off gain expression it is also clear that by increasing the effective length of the fiber the Raman gain will also be increased. Typically, the pumps will be located at wavelengths approximately 100 nm below the signal wavelengths to be amplified, i.e. below 1450 nm for amplification in the C-band. The attenuation at these wavelengths is influenced by the water peak attenuation at 1385 nm.

For instance, a pump situated at 1410 nm will experience an attenuation of 0.52 dB/km in a fiber with a 1.0 dB/km water peak, compared to only 0.28 dB/km in a fiber with 0.33 dB/km (LWP NZDF fiber). In other words, by using a LWP fiber the effective length, and thereby the gain, may be increased by more than 85%. In other words, by using a LWP fiber, the effective length may be increased by more than 85%. For the same gain the pump-power can be reduced by a factor of 1.85. This is why a Raman optimized fiber possesses a low water peak.

A Raman figure of merit, $FOM_R$, can also be defined,

$$FOM_R = \frac{C_R}{\alpha_{pump}},$$

which is a measure of how Raman gain efficient a fiber is independent of the pump power.

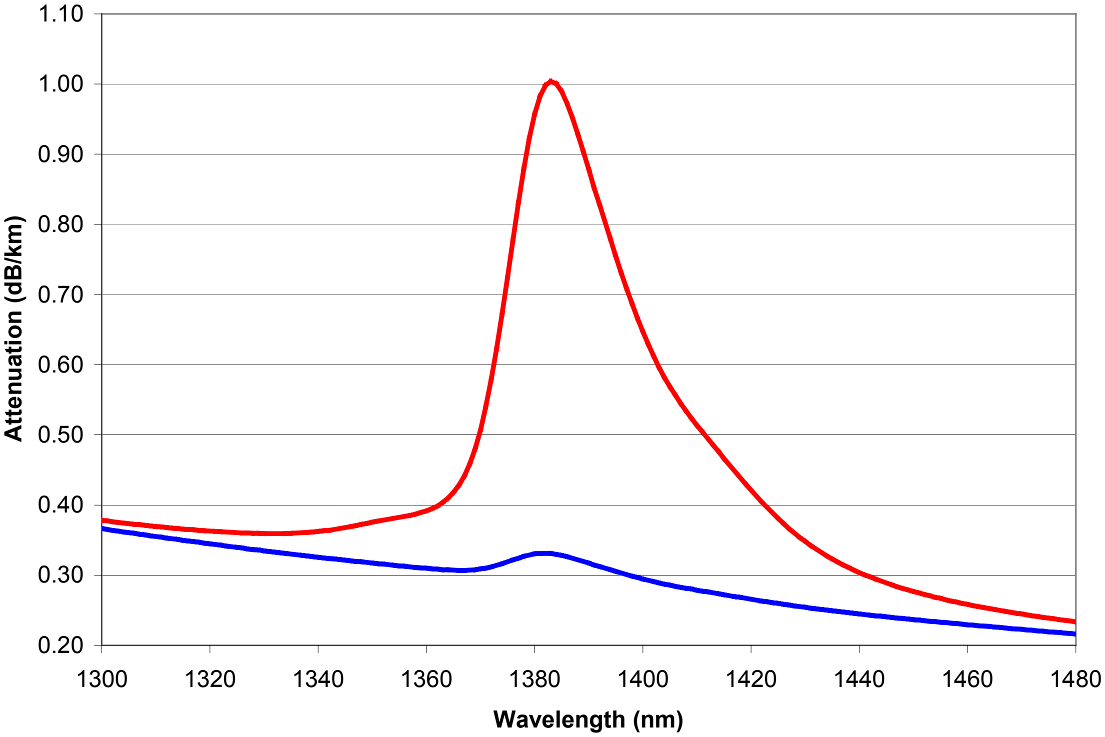

Figure 4. Attenuation at wavelengths in the vicinity of the water peak for 1 dB/km and 0.33 dB/km water peak, respectively.

When Raman amplification is used, the zero dispersion wavelength (ZDW) needs to be below both the signal and pump bands, in order to avoid noise from the nonlinear impairment four wave mixing (FWM) between pumps and signals. For TrueWave *REACH,* the ZDW is therefore kept below 1400 nm. This allows for Raman pumping of signal wavelength down to 1500 nm (i.e. the total C-band and even down into the S-band), as the Raman pumps are typically located 100 nm below the signal wavelengths. The figure below shows the noise due to FWM in NZDF with different ZDW. It is clearly seen that with a ZDW at 1500 nm FWM is causing increased noise the signal in the C-band.

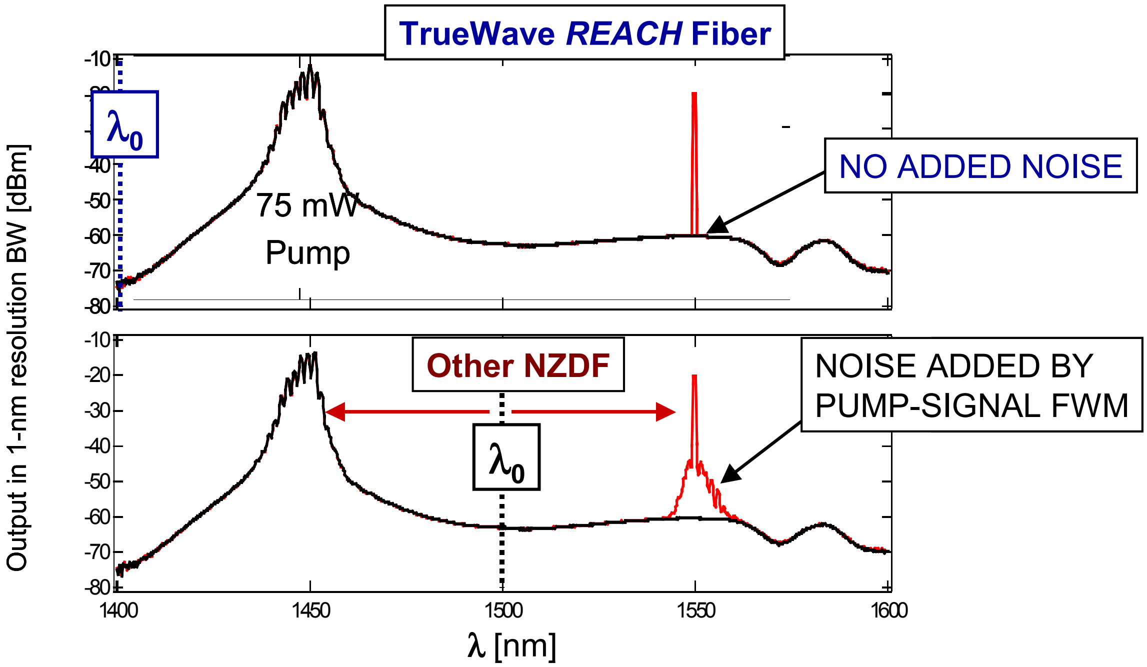

Figure 5. This shows the impact of ZDW on the amount of pump-signal FWM.

An example of the consequences of the different Raman gain efficiency of TrueWave *REACH* and SSMF is shown in Figure 6, below. This example uses 46 channels in the C-band (1529 - 1565 nm) with launched power of 1 dBm/channel and counter-directionally pumped the fiber link with three pump wavelengths (1427, 1442 and 1462 nm). To obtain 10 dB on-off gain, 320 mW pump power is used for TrueWave *REACH*. This is well within the eye safe limit of 500 mW. If a standard SSMF fiber is used, an 80-km link with the same channel loading as analyzed above, a pump power of 455 mW is needed to obtain 10 dB on-off gain, which is an increase of 40% in pump power.

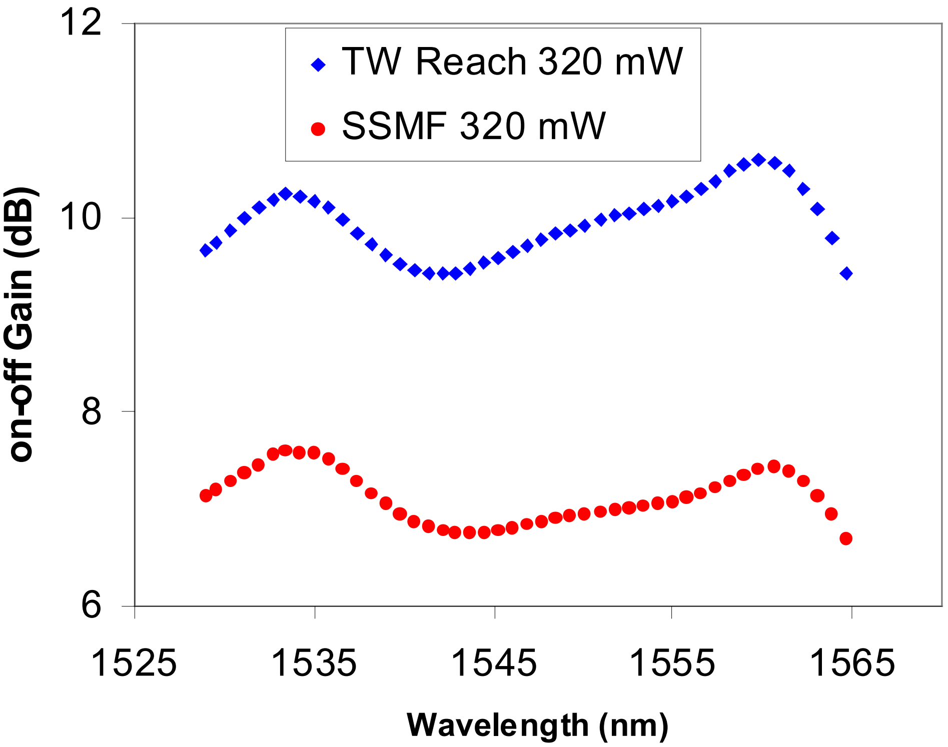

Figure 6. This shows the gain obtained in at TrueWave *REACH* and a SSMF with 320 mW pump power. A difference in gain of approximately 3 dB is the result.

## Conclusion

TrueWave *REACH* fiber from OFS is optimized for distributed Raman amplification. It has an optimized effective area leading to high Raman gain efficiency while minimizing problems due to nonlinearities. The LWP assures low attenuation at signal and pump wavelengths. Finally, pump signal FWM is minimized because of the low zero dispersion wavelength, allowing higher capacity and lower cost.

## About OFS

OFS is a designer, manufacturer, and supplier of leading edge optical fiber, optical fiber cable, optical connectivity and specialty photonics products for a wide variety of applications and industries. OFS, formerly the Optical Fiber Solutions division of Lucent Technologies Inc. [NYSE: LU], has a proven track record of being first in the industry with application specific fibers, optical connectors, ribbon cables, erbium doped fibers, Raman fiber lasers and more. OFS is committed to providing customers increased value by offering products that deliver lowest cost per bit network solutions, protecting investments through future flexible solutions.

OFS distributes its optical fiber, optical fiber cable, optical connectivity and specialty photonics products directly to end users, as well as through valued distributors, external cable customers and equipment vendors.

OFS is owned by Furukawa Electric, Co., Ltd. a multi-billion dollar global leader in optical communications. Headquartered in Norcross, GA, OFS operates facilities in Avon, Connecticut; Carrollton, Georgia; Somerset, New Jersey; and Sturbridge, Massachusetts, as well as facilities in Denmark, Germany and Russia. For more information, please visit www.ofsoptics.com.