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Lumped Raman fiber amplifiers based on highly non-linear photonic crystal fiber

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ABSTRACT

A lumped Raman amplifier for all-Raman long-haul and ultra-long haul optical communications systems based on highly non-linear Photonic Crystal Fiber (HNL-PCF) is proposed and demonstrated. Applications for such an amplifier are discussed, focusing on discrete loss compensation for L-Band all-Raman reconfigurable systems. The main specifications required for this and similar applications have been analyzed, and include Power Conversion Efficiency above 30%, Net gain of about 15dB, and output power in the range of 20-23 dBm. Additional specifications such as Noise Figure, Multi-Path Interference (MPI), and transient suppression are also considered. In order to achieve the required specifications, the HNL-PCF should exhibit high Raman efficiency and low attenuation at pump wavelengths of 1470-1500nm, resulting in a Figure of Merit (FOM) above $8 \text{ dB}^{-1}\text{W}^{-1}$. The splice loss of the HNL-PCF to conventional Single Mode Fiber is also shown to be critical, and should not exceed 0.5 dB. Initial samples of HNL-PCF have been characterized, and it has been demonstrated that high Raman efficiency and low splice loss are achievable, while further work is being carried out to increase the FOM. Finally, an experimental demonstration of 10Gb/s WDM transmission using a prototype Lumped Raman Fiber Amplifier based on HNL-PCF is presented.

Keywords: Raman Amplification, Lumped Raman Fiber Amplifiers, Highly Non-Linear Fiber, Photonic Crystal Fiber

1. INTRODUCTION

In recent years Raman amplification has become an increasingly important technology for high performance optical networks^[1,2], complementing Erbium Doped Fiber Amplifier (EDFA) technology in many applications, and in others supplanting it altogether. The two main advantages of Raman amplification are the ability to use any type of fiber as an amplification medium, and the ability to amplify signals in any wavelength band using an appropriate pumping scheme.

The ability to use any type of fiber as a gain medium has been successfully utilized for Distributed Raman Amplification (DRA), where amplification takes place inside the transmission fiber itself. When combined with conventional lumped (discrete) amplifiers, such as EDFA's, this provides a significant improvement in the Optical Signal to Noise Ratio (OSNR) ratio of the transmitted optical signals, thus allowing longer reach and/or higher capacity networks. However, Raman technology can also be applied to lumped amplifiers, in which case the ability to amplify signals in any wavelength band can be used to construct Lumped Raman Fiber Amplifiers (LRFA's) which operate in wavelength bands where EDFA technology is either inapplicable or relatively inefficient. For example, Long Haul (LH) and Ultra-Long Haul (ULH), high capacity all-Raman optical links have been deployed combining DRA and LRFA's operating in the L-Band (1570 – 1602 nm)³.

A major factor in the implementation of LRFA's is the Power Conversion Efficiency (PCE), i.e. the ratio of the required pump power to the amplifier output power. Due to the relatively low efficiency of the non-linear Raman process in most fibers, high pump power is required to obtain practical levels of net amplifier gain, leading to relatively low PCE values. This in turn increases the cost of LRFA's, and limits their range of applicability.

Thus, it is clear that for practical implementation of LRFA's it is necessary to utilize Highly Non-Linear Fiber (HNLF) to increase the Raman efficiency and improve the PCE. HNLF is achieved using conventional fiber technology by decreasing the effective area of the fiber (i.e decreasing the core diameter), and/or increasing the Germanium concentration of the core. Using these techniques, a maximum Raman efficiency of about $7 \text{ W}^{-1}\text{km}^{-1}$ has been obtained^[3].

Over the last decade Photonic Crystal Fiber (PCF) technology has rapidly progressed and been shown to hold significant potential for many important fiber based applications^[4]. In particular, PCF technology is well suited to the fabrication of HNLF due to the ability to achieve a high degree of mode confinement by introducing air hold in the fiber cladding^[5]. HNL-PCF has been successfully applied to such non-linear applications as super-continuum generation^[6], as well as the enhancement of the Raman effect^[7]. Recently, within the framework of the European NextGenPCF project, PCF has been fabricated with a record Raman efficiency as high as $11.5 \text{ W}^{-1}\text{km}^{-1}$ ^[8].

In the present paper we consider LRFA's based on PCF technology, focusing on applications, design considerations and initial experimental results. The paper is organized as follows: In section 2 we consider applications of LRFA's, and performance requirements for these applications. Next we consider the design of a LRFA for discrete loss compensation in L-Band long haul and ultra-long haul system, and the resulting specifications for the PCF to be used. Finally, we present characterization results for prototype PCF samples, and initial WDM transmission experiments.

2. LRFA APPLICATIONS AND PERFORMANCE SPECIFICATIONS

As noted above, one of the most attractive applications for LRFA's is within all-Raman LH and ULH systems. In such system the two main advantages of Raman amplification are combined by utilizing DRA on the one hand, and having the freedom to optimize the transmission band for the best system performance on the other. In particular, it has been demonstrated^[9] that systems utilizing Non-Zero Dispersion Shifted transmission Fiber (NZDSF) and operating in the L-Band can provide high capacity transmission over many thousands of km. While EDFA's are by now a mature, cost effect and efficient solution for C-Band amplification, EDFA's operating in the L-Band are much less common and effective. Thus, it is natural to combine DRA with LRFA's to provide all-Raman LH and ULH L-Band systems.

In the first generation of such systems, LRFA's were only implemented as lossless Dispersion Compensating Fiber (DCF) modules. Thus, DRA provided the amplification necessary to compensate for transmission fiber loss, whereas the LRFA was only required to compensate the loss of the DCF module itself. Since DCFs have a very small effective area compared to transmission fibers ($A_{\text{eff}} = 15\text{-}20 \mu\text{m}^2$) and a high Ge concentration, they also have a relatively high Raman efficiency (typically $\sim 3 \text{ W}^{-1}\text{km}^{-1}$). This makes it possible to provide the 5-10 dB of gain required to compensate the DCF module loss by pumping the DCF itself with relatively moderate Raman pump power^[10]

In recent years dynamic reconfigurability has become a key requirement for modern optical networks due to the potential for increased operating ease and flexibility, as well as substantially reduced operating expenses^[11]. Dynamic recondigurabilty is achieved by placing Reconfigurable Optical Add Drop Multiplexer (ROADM) devices at strategic points, thus allowing individual WDM channels to be dynamically added and dropped along the link. In order to support ROADM capabilities, next generation all Raman systems also need to provide amplification to compensate for the discrete loss introduced by the ROADM device. Thus, a discrete LRFA should be placed following the ROADM device, as shown in Fig. 1.

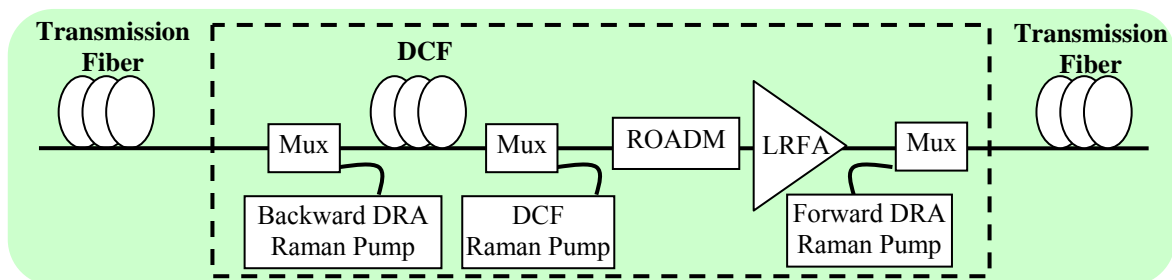


Fig. 1. Possible structure of a Repeater for an All-Raman ROADM transmission system

We now proceed to discuss the requirements of an LRFA for the application as shown in Fig. 1. While the loss of newer ROADM devices (which actually may comprise separate Add and Drop units) is typically below 10 dB, it is also necessary to allocate loss budget for the purpose of channel equalization functions typically performed by these devices. Thus, we believe the LRFA should provide in the region of 15 dB average net gain, with a maximum gain variation of 1 dB across the L-Band. In some cases this may be sufficient to compensate for the DCF loss as well, which would negate the need to pump the DCF, and render the system more cost effective and efficient.

The output power of the LRFA is dictated by the required launch power per channel into the transmission fiber, which can vary from system to system. A typical value for the launch power per channel is of the order of +5 dBm/channel, which translates into +20 dBm output power for a 40 channel WDM system, and +23dBm for an 80 channel system. As discussed in the introduction, a major performance parameter of the LRFA is the PCE, which should preferably be above 30% in order to cost effectively compete with EDFA based systems.

Since the LRFA in Fig. 1 serves as a booster amplifier, the requirements with respect to Noise Figure (NF) are relatively mild, and it is expected that $NF \sim 7$ dB should be more than sufficient for most applications. Another important noise parameter for LRFA's is Multi Path Interference (MPI), which results from Rayleigh Backscattering within the LRFA^[1,12]. As a general design rule for most LH and ULH system, the MPI of any given device should typically be below -40 dB to avoid MPI accumulation over the length of the link. Finally, as the LRFA is designated to operate within reconfigurable networks, it should provide good transient suppression performance in response to sudden changes in input power^[13,14]. For modern reconfigurable optical networks, the transient suppression time should be less than 100 μ s to avoid high power transients in amplifier cascades.

3. LRFA DESIGN AND PCF SPECIFICATIONS

The basic design architecture of the LRFA is shown in Fig. 2. The output from two semiconductor pump lasers at wavelength λ_1 and λ_2 are combined with a pump combiner, and then multiplexed with the signal path in a counter propagating (backward pumping) configuration. The input and output detectors are used to measure the input and output power of the signal, in order to provide Automatic Gain Control (AGC) for the amplifier.

The wavelengths λ_1 and λ_2 are selected to provide the optimum (most flat) gain profile across the L-Band. For Silica based fibers such as the PCF, it can be shown that wavelengths in the vicinity of 1465nm and 1495nm provide the optimum gain profile, while the exact values of λ_1 and λ_2 depend on the precise details of the PCF (such as the spectral attenuation the precise shape of the Raman gain spectrum). In order to achieve a 1dB gain flatness across the L-Band, a gain flattening filter may also be required (typically placed at the amplifier output)

The backward pumping configuration for the LRFA was selected to achieve optimal PCE, at the expense of NF which is typically worse than for forward pumped LRFA's. However, as discussed above this is not a critical issue since the LRFA is intended to be used as a booster amplifier (Fig. 1).

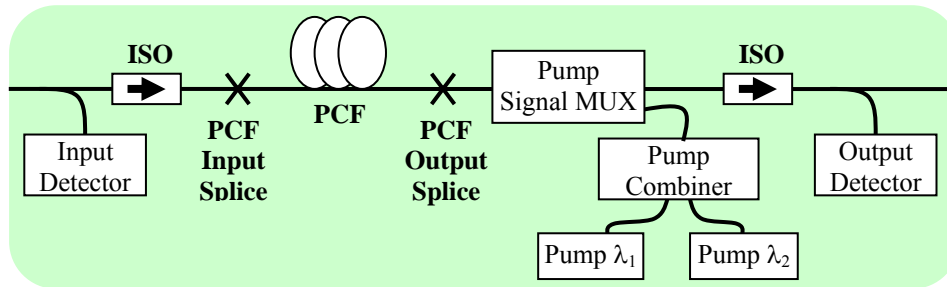


Fig. 2. Basic LRFA design architecture

The equations governing the signal and pump propagation within the LRFA are well known and have been extensively studied in the literature^[1]. In order to understand the qualitative effect of the various PCF parameters on the amplifier performance, we first consider a simplified model with a single pump and single signal channel, and neglect pump depletion (i.e. small input signal). In this case it is simple to show that

$$G = 4.34 \left[C_R \left(\frac{1 - e^{-\alpha_p L}}{\alpha_p} \right) \frac{P}{10^{\beta/10}} - \alpha_s L \right] - 2\beta, \quad (1)$$

where G is the net signal gain (in dB), C_R the Raman efficiency between pump and signal, L the PCF length, $\alpha_{p/s}$ the PCF attenuation coefficient at pump / signal wavelengths, and β the PCF splice loss in dB (we have assumed the same

splice loss for pump and signal wavelengths). In addition we have neglected the losses of all passive components not related to the PCF.

In the absence of high OH absorption, attenuation in highly non-linear PCF is usually governed by surface roughness scattering from the holes in the cladding, which dictates a certain (typically polynomial) wavelength dependence of the attenuation coefficient. Since the wavelengths of pump and signal differ from each other by only $\sim 100\text{nm}$, this means that α_p and α_s are of the same order of magnitude, with α_p typically larger by about 20-30%. For the sake of the current qualitative analysis we may therefore take $\alpha_p = \alpha_s$. As can be seen from Eq. 1, there is an optimum PCF length L_{opt} for which the net gain G is maximum. For $L < L_{opt}$ pump power is not fully utilized, whereas for $L > L_{opt}$ the signal attenuation becomes dominant and decreases the net gain. It is simple to show that $L_{opt} = \eta / \alpha_p$ where η , of the order of unity, is dictated mainly by the target net gain G , and is little influenced by the various details of the PCF. For net gain in the region of 10-20 dB, $\eta \sim 1.5 - 2$. Thus, we may now rewrite Eq. 1 as

$$G = 4.34 \left[\frac{C_R}{\alpha_p} (1 - e^{-\eta}) \frac{P}{10^{\beta/10}} - \eta \right] - 2\beta, \quad (2)$$

If we now define the figure of merit (FOM) of the PCF as $FOM \equiv C_R / \alpha_p$, then we see that the net gain depends only on two PCF parameters, the FOM, and the splice loss β . The latter decreases the net gain by both reducing the available pump power, and directly attenuating the signal. Since the net gain is dictated by the LRFA specifications (in our case about 15 dB), then the pump power required to achieve the net gain, and hence the PCE, is fully dictated by the PCF FOM and splice loss.

The above qualitative analysis can be supplemented using a full numerical analysis of the Raman propagation equations^[1], the results of which are shown in Fig. 3. The analysis uses two pumps of equal power at 1465nm and 1495nm, multiple signals channels covering the L-Band, and takes into account pump-pump interaction and pump depletion. The spectral shape of the PCF gain profile is assumed to be identical to that of SMF fiber, and the pump and signal attenuation coefficients are assumed to satisfy $\alpha_p = 1.3\alpha_s$. As before, the insertion loss of all passive components not related to the PCF is neglected. For each combination of FOM and splice loss, the total pump power required to achieve 15 dB average net gain across the L-Band (using optimum PCF length) is calculated. Figs. 3a and 3b show the resulting PCE for 20 dBm and 23 dBm output power respectively. We see that for 20dBm output power, a relatively high FOM (above $10 \text{ W}^{-1}\text{dB}^{-1}$) and low splice loss ($< 0.4 \text{ dB}$) are required to achieve a PCE $\sim 30\%$. However, for 23dBm output power the situation is much improved, requiring relatively moderate values of FOM and splice loss (for example, $FOM > 7 \text{ W}^{-1}\text{dB}^{-1}$, splice loss $< 0.6 \text{ dB}$) to achieve PCE $\sim 30\%$.

Fig. 4 shows a representative plot of gain and NF as a function of wavelength. Both the shape of the gain spectrum and the NF are quite insensitive to the parameters used in the calculation (i.e. FOM, splice loss and output power), and are instead determined by the target net gain. We see that the gain variation over the L-Band is about $\pm 1\text{dB}$, which can be further reduced by using a gain flattening filter. The NF is in the region of 7 dB or below, which should be sufficient for the booster application for which the LRFA is designed.

The discussion above shows that the main LRFA characteristics, namely Gain, Output power, PCE and NF, are mainly determined by the PCF FOM and splice loss. The question now arises regarding the affect of PCF parameters on other LRFA characteristics, such as MPI and transient performance.

MPI in LRFA's^[1,12] is caused by two mechanisms: The first is Single Rayleigh Back-scattering (SRB) in conjunction with back-reflection from a discrete point, such as a splice; and the second is Double Rayleigh Back-scattering (DRB). Clearly, the first mechanism is affected by the PCF splice, so that a high quality splice (i.e. low splice loss) is critical in this respect. For a given Raman net gain, both the DRB and SRB noise powers depend on the product $\kappa_R L$, where κ_R is the Rayleigh back-scattering coefficient, and L the PCF length. Since κ_R scales approximately with C_R (both scale inversely with the fiber effective area, and depend also on the core Ge concentration^[1]), and L scales inversely with

α_p , to a first approximation we may say that the DRB and SRB noise powers depend mainly on the FOM of the PCF. This then means that MPI is also determined mainly by the PCF FOM and splice quality. It should be noted that if necessary, the effect of SRB and DRB may be reduced significantly by using a multi-stage design for the LRFA^[15]

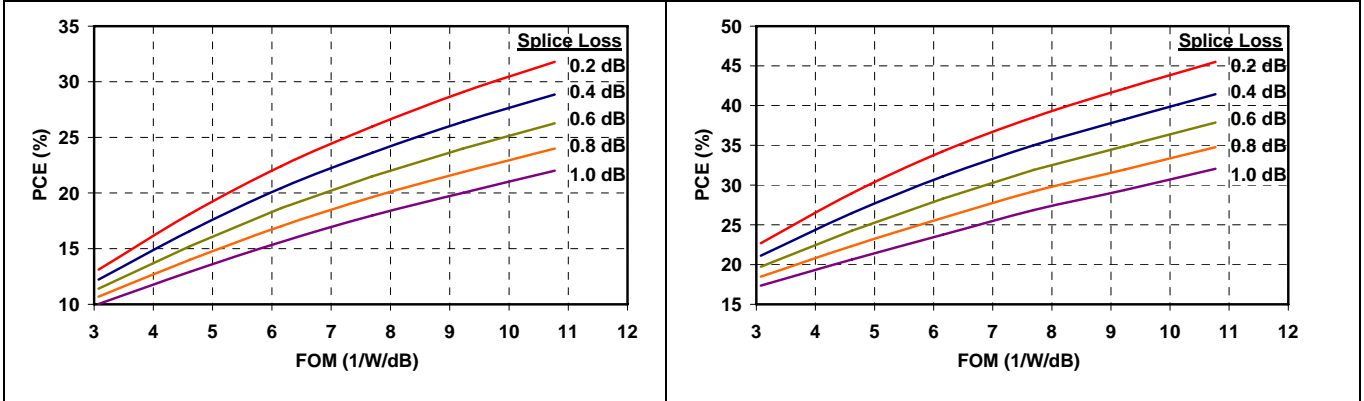


Fig. 2. PCE required to achieve 15dB net average gain across the L-Band, as a function of PCF FOM and splice loss (a) for 20dBm output power; (b) for 23 dBm output power.

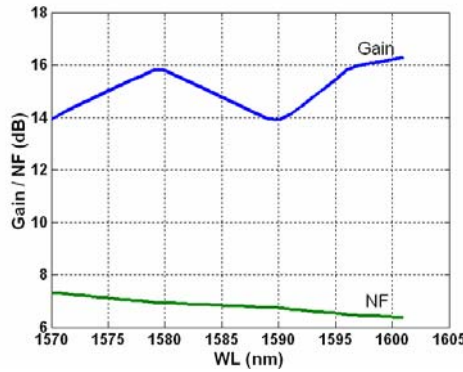


Fig. 3. Representative plot of Gain and NF as a function of wavelength

The transient suppression performance of a LRFA is determined mainly by the length of the PCF, since this determines the optical delay between amplifier input and output, and thus the ability of the amplifier gain control loop to adjust to changes in input power^{13,14}. Thus, the shorter the PCF length, i.e. the larger α_p , the better is the transient suppression of the LRFA. It has been shown that the transient suppression time is approximately three times the length of the PCF^[14], meaning that this length should be <5km in order to ensure a suppression time < 100 μ s.

To sum up this section we see that with the exception of transient suppression, LRFA performance is mainly determined by the PCF FOM and splice quality. On the other hand, transient suppression benefits from a shorter PCF, meaning a higher α_p . Another factor that should be considered is the cost of the PCF used in the amplifier, which obviously also scales with the PCF length. Thus, for a given desired PCF FOM, it may be preferable to have higher Raman efficiency and higher loss, rather than lower Raman efficiency and lower loss.

4. RESULTS FROM INITIAL PCF SAMPLES

Within the framework of the NextGenPCF project, a number of initial PCF samples have been designed and fabricated specifically for LRFA applications^[8,16]. These samples have a highly Ge doped core (of the order of 20 wt%) and a very small effective area of the order of 4-5 μ m², resulting in a record Raman efficiency of 11.5 W⁻¹km⁻¹. Fig. 4 shows the Raman gain spectrum of one of these samples, with the inset showing the normalized gain spectrum compared to that of SMF fiber. As expected, the normalized Gain spectrum of the PCF sample is only slightly different to that of SMF fiber.

Fig. 5 shows the attenuation spectrum of the same PCF sample. The signal attenuation in the L-Band is of the order of 6 dB/km, however, the attenuation rises sharply at shorter wavelengths, resulting in pump attenuation at 1465-1495 nm in the range of 9-15 dB/km. The signal attenuation is determined by the intrinsic loss mechanisms of the PCF, mainly surface roughness scattering from the holes. On the other hand, the sharp rise in attenuation at pump wavelength is due to high OH absorption. Recently fabricated PCF samples show that the OH concentration may be reduced significantly, so that the pump attenuation is only about 30% higher than the signal attenuation.

The FOM of the PCF sample shown in Figs 4 and 5 is $\sim 1 \text{ W}^{-1}\text{dB}^{-1}$. However, assuming the OH absorption could be reduced significantly, one can reasonably expect a FOM of $1.5\text{-}2 \text{ W}^{-1}\text{dB}^{-1}$ with similar PCF designs. From Fig. 3 it is clear that further enhancement of the FOM is required to reach practical levels of PCE, which can be achieved by either increasing the Raman efficiency and/or decreasing the intrinsic PCF loss. As noted at the end of the previous section, the former method (increasing Raman efficiency) may be preferable to the latter, assuming the same overall enhancement of the FOM is achieved.

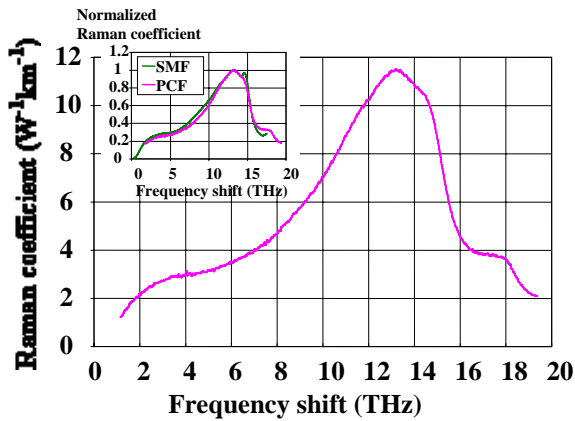


Fig. 4. Raman gain spectrum of an initial PCF sample. Inset – Comparison of normalized gain spectrum for SMF and PCF sample

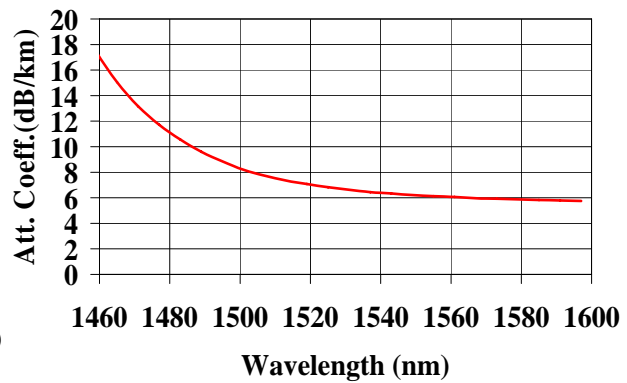


Fig. 5. Attenuation spectrum for the same PCF sample as in Fig. 4.

The splice loss of the PCF sample to SMF fiber was also studied. A loss of 0.3-0.4 dB was achieved for an SMF-PCF splice, while a loss of 0.7-0.8 dB was achieved for a PCF-SMF splice. Thus, the signal experiences a total splice loss of 1-1.2 dB (average 0.5-0.6 dB/splice), while the pump experience a splice loss of 0.3-0.4 dB. Referring to Fig. 3, we see that these values are in the range needed to achieve practical levels of PCE.

The Rayleigh back-scattering coefficient of the PCF sample was measured to be -27.2 dB/km , compared to -42.3 dB/km for regular SMF fiber^[17], and -33.8 dB/km for a DCF fiber^[21]. Comparing this to the Raman efficiency of these three fibers ($11.5 \text{ W}^{-1}\text{km}^{-1}$, $0.42 \text{ W}^{-1}\text{km}^{-1}$ and $3.1 \text{ W}^{-1}\text{km}^{-1}$ respectively), we see that the Rayleigh back-scattering coefficient indeed scales approximately linearly with the Raman efficiency.

Finally, WDM transmission using a PCF based LRFA was successfully demonstrated for the first time^[16]. This experiment used an earlier PCF sample with even higher pump attenuation than shown in Fig. 5, making it necessary to utilize a triple pump scheme (with one of the pumps at 1534 nm where the attenuation is significantly lower). Using a total of 5.2W pump power, 13.2 dB average net gain was achieved over the L-Band with gain variation of 1.4 dB. The WDM transmission setup is shown in Fig. 6 and includes 16 L-Band channels with input power of -7dBm. Half of the channels were modulated with a 10Gb/s NRZ signal. Fig. 7 shows The BER as a function of OSNR both for back to back (without the LRFA) and with the LRFA. As can be seen the LRFA introduces a 1.2 dB transmission penalty which was attributed to MPI due to fiber imperfections in this early sample.

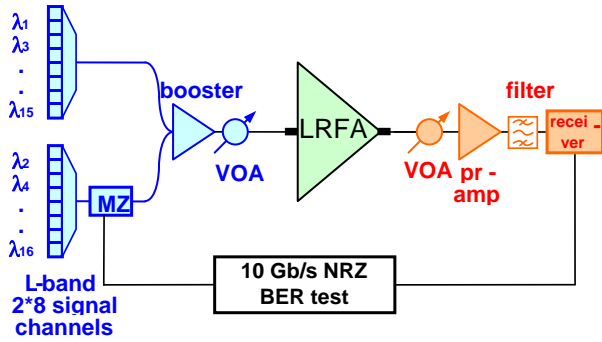


Fig. 6. WDM transmission experimental setup

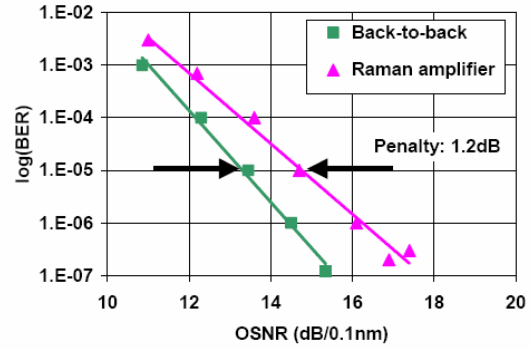


Fig. 7. Measured BER vs. OSNR with and without LRFA.

5. CONCLUSIONS

LRFA's offer the possibility to provide broadband amplification for any transmission band, making them particularly attractive for all-Raman L-Band LH and ULH transmission systems. In such systems LRFA's can provide the amplification needed to compensate for the discrete loss introduced by ROADMs. This requires up to 15dB net gain across the L-Band with 20-23 dBm output power, while maintaining practical levels of PCE > 30%. The design of such an LRFA based on highly non-linear PCF has been discussed, and it has been shown that most LRFA characteristics depend only on the PCF FOM (defined as C_R / α_p) and splice quality to SMF. The exception is transient suppression performance which is directly impacted by PCF length. Results for Initial samples of PCF designed and fabricated for LRFA applications have been reviewed, showing a record Raman efficiency of $11.5 \text{ W}^{-1}\text{km}^{-1}$. In addition, a splice loss to SMF of the order of 0.5 dB has been achieved, which is expected to be sufficient for most applications. However, further work is required to increase the FOM from current levels of $1\text{-}2 \text{ W}^{-1}\text{dB}^{-1}$ to the level of $\sim 8 \text{ W}^{-1}\text{dB}^{-1}$ required for practical implementation. Finally a WDM transmission experiment utilizing a prototype PCF based LRFA has been reviewed.

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