L-band distributed Raman amplification using a bi-directional C-band Erbium-doped fiber laser pumping scheme

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ABSTRACT

Operation in the L-band may be useful for broadband DWDM transmission but is limited by the higher fiber attenuation in that region, regardless the fiber type. We present the on-off gain characterization of an L-band Raman amplifier, bi-directionally pumped by two C-band tunable fiber ring lasers and measured with different types of transmission fiber. The main focus of our studies has been on standard and dispersion shifted fibers, aiming L-band system upgrade of already installed fiber plants. The results indicate that L-band distributed Raman amplification allows for the desired bandwidth capacity increase.

1. INTRODUCTION

Distributed Raman amplifiers (DRAs), a key technology to solve both capacity and system reach, use the transmission fiber to provide gain and can operate over a wide range of wavelengths, rather than within a fixed wavelength region, as with erbium-doped fiber amplifier (EDFA) technology [1]. In the Raman amplification technique referred to as "distributed", unlike a conventional EDFA, where amplification takes place in a single discrete amplifier module, the gain is spread out, or distributed, over a significant fraction of the transmission fiber.

For operation in the C-band region (1530 to 1570 nm), Raman amplification occurs when the transmission fiber is pumped with a very high optical power ranging around 1450 nm, or even shorter wavelength regions. The advent of commercial pump sources, such as the cascaded Raman laser (typically, a double-clad fiber laser pumped by an array of multi-mode pump modules, followed by a cascade of fixed resonators) [2], with output power greater than 1 W at the necessary wavelengths, has made Raman gain a cost-effective mean for increasing the power budget of a new or already installed dense wavelength division multiplexing, DWDM, system. In particular, it is attractive for remotely pumped applications in repeaterless transmission systems due to its low noise nature.

For upgrading DWDM systems running over already installed fibers, it is important to consider the Raman efficiency characteristics of the most worldwide used fibers, for example, the standard, STD, fiber and the dispersion shifted, DS, fiber. On the other hand, for designing a new DWDM plant, the likely candidates for the transmission medium are the non-zero dispersion shifted fibers, NZD and the large area NZD fibers.

Dispersion shifted fibers present a very challenging aspect for DWDM transmission due to the incompatible nature of its low dispersion, in the C-band region, and some nonlinear effects, in particular the four-wave mixing (FWM) phenomenon. A good approach to solve such a problem is to shift the wavelength operation region to the so-called "L-band" (1570 to 1610 nm), provided that the amplification region is also shifted. Furthermore, even in standard fibers, the L-band operation is a good option to enlarge a system bandwidth capacity.

Although typical commercial Raman lasers are designed for C-band Raman amplification, considering the large plant of STD and DS fibers already installed in some countries, Brazil for instance, it is very important to develop L-band Raman amplifiers for system upgrades. This way, a combination of L-band channel allocation and low-noise amplifiers can strongly reduce the physical impairments and allow a high capacity DWDM transmission. Unfortunately, high power pump lasers operating at wavelengths out of the typical 1450 nm range are commercially available only on request and may be very expensive, which may imply in a non cost effective use of DRA in L-Band applications.

In this paper, we investigate a distributed L-band Raman amplifier in different types of transmission fiber, with a main focus on the two types of fiber mostly installed in Brazil, i.e. the standard and the DS fibers, aiming DWDM system upgrades. We have measured the amplifier on-off gain [3] as a function of the launched signal power, signal wavelength, pump power, pump wavelength and pump type (forward and backward). For achieving Raman amplification in the L-band, we propose a C-band tunable pumping scheme that allows for a flexible and less expensive system upgrade.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1. The Raman amplifier is bi-directionally pumped by C-band erbium-doped fiber ring lasers. The pump wavelength is selected by means of a tunable band pass filter placed in the rings. High power erbium-doped amplifiers boost the power from the fiber lasers. The forward and counter-propagating pump lights are coupled into the transmission fiber using 90:10 splitters. The pump wavelengths are in the range of 1535 to 1555 nm and the signal, generated by a tunable external cavity laser, is tuned from 1580 to 1625 nm. The on off-gain was measured with an OSA, coupled to the transmission fiber output by the 10% splitter port.

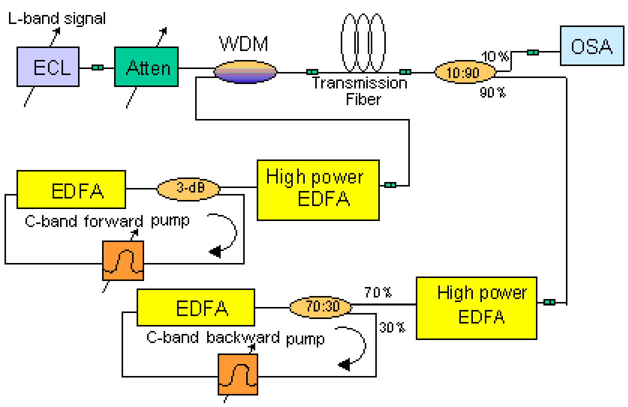


Figure 1. Experimental setup, where the L-band Raman amplifier is bi-directionally pumped by two C-band tunable erbium-doped fiber lasers.

The transmission fiber Raman gain profile was thus evaluated by sweeping the signal wavelength, launched into different types of fibers. The zero dispersion wavelength, the typical effective area and the total length of the six studied transmission fibers are summarized in Table 1.

Tabel 1 – Transmission fibers, used in the L-band distributed Raman amplification on/off gain evaluation

Fiber	l_0 (nm)	Typical A_{eff} (mm^2)	Length (km)
STD	1310.0	80	30
DS	1552.0	55	25
LEAF™	1495.5	72	25
LS™	1570.5	55	25
True Wave™	1591.1	55	25
DCF		25	22

3. RESULTS AND DISCUSSION

3.1 Different transmission fibers

The on-off gain is the ratio between the output signal power with the pumps on and off. The measured on-off Raman gain, in dB, is shown in Figure 2. The results were optimized with both pumps set to the same wavelength (1536 nm) but to different power levels at the fiber under test ends, i.e., 22.3 dBm, for the backward pump, and 20.8 dBm, for the forward pump. As it can be seen, the smaller core fibers show a larger amount of gain and the STD fibers has the least. The variation, however, is not simply a function of the effective area. It is known that the Raman gain coefficient depends on the transmission medium characteristics and will increase with increasing the fiber germanium concentration and reduces as the effective area of the fiber increases [4]. For this reason, the results indicate that the best candidates for the transmission fibers, in terms of L-band Raman efficiency, are the dispersion compensating fiber, DCF, closely followed by the NZD-like and DS fibers - the same trend as found in the C-band [5]-[6]. In fact, dispersion compensating fibers have a small effective area and a high germanium concentration. However, they are packaged as discrete modules that are placed either in the transmission or in the receiver sites (or, in case of non-repeaterless systems, in the in-line amplifier sites). That means they are not part of the external optical cable plant. This leads the DS and NZD fibers to the best medium for the L-band distributed Raman amplification.

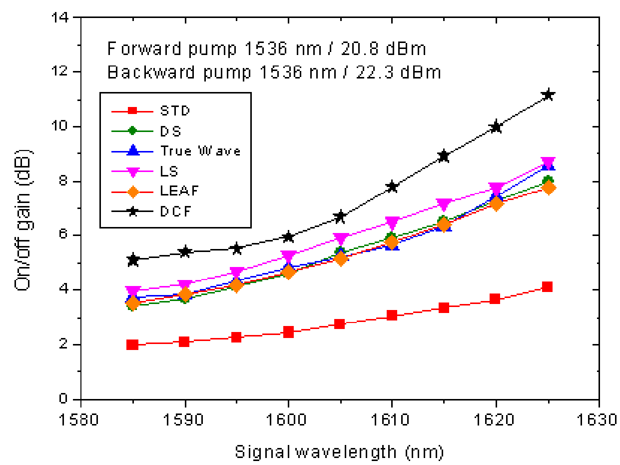
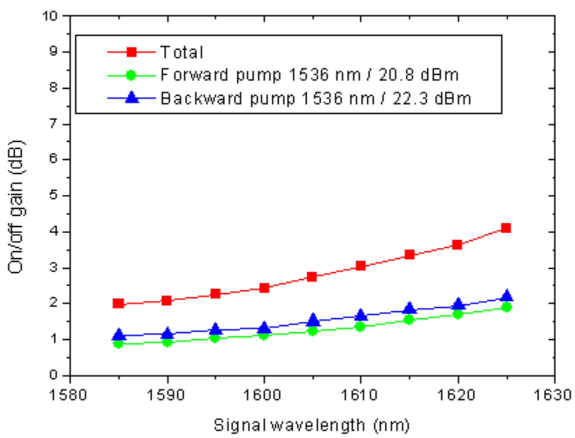


Figure 2. L-band on-off Raman gain for different fibers, same pump wavelengths at different power level.

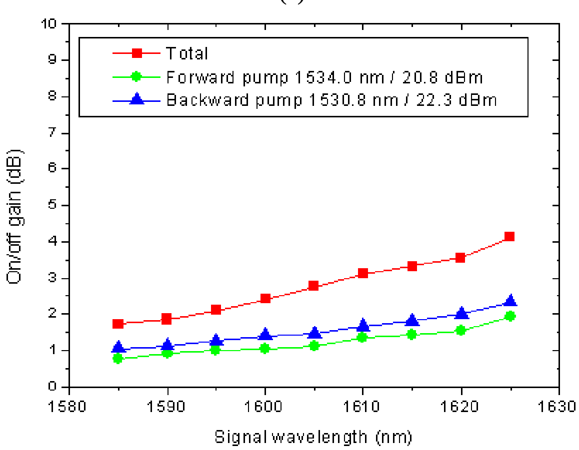
Furthermore, regardless the fiber type and its attenuation in the L-band region (higher and increasing with wavelength, for all of them), the Raman gain keeps increasing with the wavelength signal. Our results indicate that the distributed Raman amplifier can be an important tool in turning the so-called L+ band (1610 to 1650 nm) [7] into a more operational region for broadband optical communication systems [8].

3.2 Singlemode standard fiber

Considering the fact that the majority of the Brazilian installed fiber plant are of the standard type, even knowing that the Raman gain coefficient is less expressive in such a fiber, we choose it as the transmission medium where the influence of the forward and backward pumps, turned on separately, would be first investigated. The pump wavelengths were optimized for achieving maximum Raman gain, and the pump power levels were set to the maximum output power of their boosters. The co- and counter-propagating pump power levels are always measured at the transmission fiber launching side (input and output, respectively). The results are summarized in Figure 3. In all cases, the signal input power was set to -10 dBm.



(a)



(b)

Figure 3. STD fiber on-off Raman gain when the forward and backward pumps are turned on separately: (a) same pump wavelengths and (b) different pump wavelengths, optimized for maximum gain.

As it can be noticed, the contribution of the forward and backward pump was nearly the same, regardless the pump wavelength. The slight improvement when using the backward pump may be attributed to its 1.5 dB higher power level. This result contradicts the Raman amplification behavior observed in the C-band, where the backward pump is more efficient than the forward [1].

It is known that in the L-band region, erbium-doped fiber amplifiers present a different behavior, when compared to their C-band operation. It has been suggested that, in L-band EDFAs, in comparison to C-band EDFAs, interesting and salient differences are presented along with possible areas for research, such as ASE power, pump-mediated inhomogeneity, temperature sensibility and transient gain [9]. Our results indicate that maybe a similar analysis should be made for the L-band distributed Raman amplification, in order to explain/discuss the equal influence on the gain for both, the forward and backward pumps. In fact, recent studies have reported a strong temperature dependence of silica-germanium broadband distributed Raman amplifiers including the L-band operation [10]

Figure 4 shows the gain variation as a function of the signal input power, for three signal wavelengths. As before, the pump wavelengths, set to 1533.9 nm (forward) and 1531.4 nm (backward), were optimized for the maximum gain.

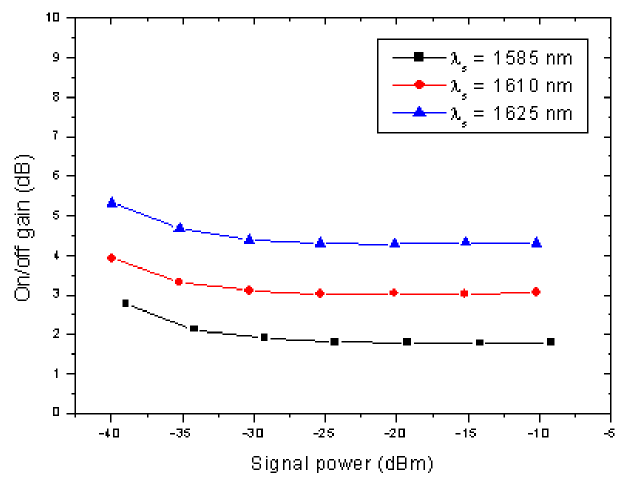
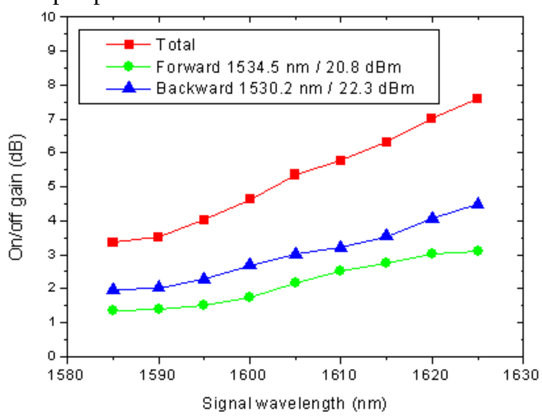


Figure 4. STD fiber L-band on-off Raman gain as a function of the signal input power for three signal wavelengths.

We thus confirm that the gain increases with the signal wavelength, i.e. the further it goes into the L-band, regardless the higher fiber loss, the higher the gain. It can also be noticed that the gain does not vary significantly with the signal input power, as it increases.

3.3 Dispersion shifted fiber

Despite other aspects, already stated, dispersion shifted fibers are naturally interesting for studies of the L-band distributed Raman gain characteristics, since they are an efficient transmission medium for the stimulated Raman scattering, SRS, process. This way, we repeated the same measurements made with the standard fiber, in order to check the full-forward and full-backward pumps were consistent. The results are presented in Figure 5 for the signal input power set to -10 dBm.



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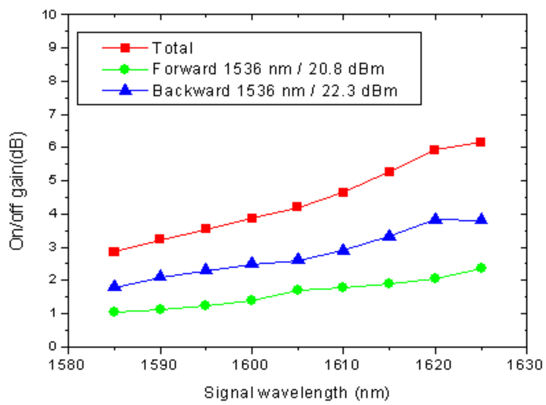
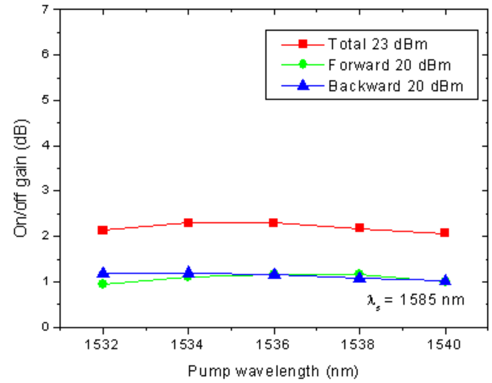


(b)

Figure 5. DS fiber on-off Raman gain when the forward and backward pumps are turned on separately: (a) same pump wavelengths and (b) different pump wavelengths, optimized for maximum gain.

As before, the contribution of the forward and backward pump was nearly the same, regardless the pump wavelength. We must keep in mind that the DS fiber is a high SRS efficient medium and that the backward pump power was 1.5 dB higher than the forward pump power. For this reason, we can notice an improvement of nearly 1 dB in favor of the backward pump. Therefore, this results consistently contradict the Raman amplification behavior observed in the C-band, where the backward pump is significantly more efficient than the forward [1].

To confirm such unexpected behavior, we measured the gain as a function of the pump wavelengths, in a range between 1532 e 1540 nm, when both are set to the same launched power. We repeated the measurements for three signal wavelengths, 1585, 1610 and 1625 nm. Figure 6 shows the results, confirming that the counter-propagating pump presents similar contribution to the gain, in comparison to the co-propagating pump.



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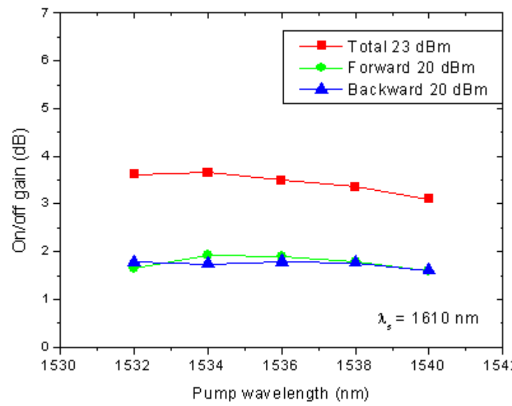

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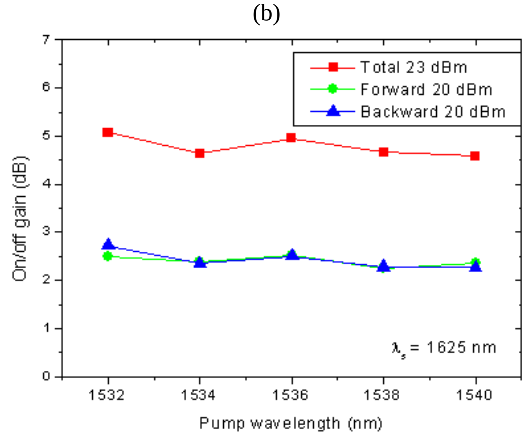

(c)

Figure 6. DS fiber L-band on-off Raman gain as a function of the pump wavelength, for three signal wavelengths: (a) 1585 nm, (b) 1610 nm and (c) 1625 nm.

Finally, Figure 7 shows the gain variation as a function of the signal input power, for three signal wavelengths. As always, the pump wavelengths, set to 1533.9 nm (forward) and 1531.4 nm (backward), were optimized for the maximum gain.

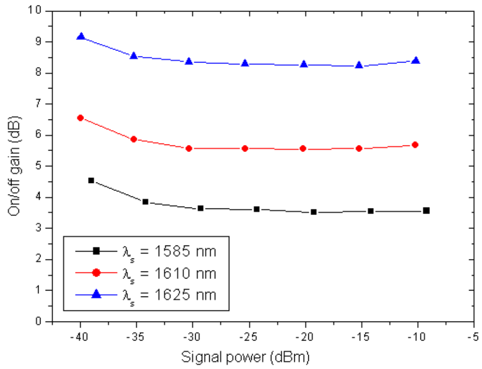

Figure 7. DS fiber L-band on-off Raman gain as a function of the signal input power, for three signal wavelengths.

We notice that, consistently with previous results the for standard fiber, the on-off gain remains constant for input signal powers greater than ~ -30 dBm and increases as a function of the signal wavelength.

4. CONCLUSION

The on-off gain of a bi-directionally pumped distributed L-band Raman amplifier has been evaluated in different types of fiber. The transmission fibers have been grouped in two categories, according to their DWDM application: upgrade in already installed optical plant (standard, STD and dispersion shifted, DS fibers) and new system design (LEAF™, LS™ and TW™). The dispersion compensating fiber, DCF, also tested, has not been included in those categories since it is normally used as a discrete module. To take into account its material and geometrical characteristics that favor the SRS process, a DCF should be part of a discrete, instead of distributed, Raman amplifier [11]. For achieving Raman amplification in the L-band, we used two C-band tunable pump fiber ring lasers, launched into the transmission fiber in the co- and counter-propagating directions, related to the signal propagation.

Although exhibiting a low Raman gain efficiency, the results with the STD fiber show an on-off gain of ~ 4 dB, for a signal wavelength of 1625 nm. For the DS fiber, the on-off gain also increases with the signal wavelength, achieving ~ 7.5 dB for a signal set to 1625 nm, regardless the higher fiber loss in the L-band, and does not vary significantly with the signal input power, as it increases from a threshold of ~ -30 dBm.

The results with the STD and the DS fibers demonstrate the feasibility of using the L-band DRA technique in already installed systems upgrade. In the L-band, the contributions of the forward and backward pumps are nearly the same when both are set to the same power. This result contradicts the Raman amplification behavior observed in the C-band, where the backward pump leads to a significantly higher gain compared to the one due to the forward pump. We suggest that further studies should be carried out in order to better investigate this amplification process.

5. REFERENCES

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