Study and Optimization of Raman Amplifiers in Tellurite-Based Optical Fibers for Wide-Band Telecommunication Systems

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Abstract— **Here we present a numerical analysis and the optimization of a multi-pump discrete Raman amplification system based on the use of a Tellurite optical fiber as the gain media. By using previously reported optimization techniques we were able to exploit the high Raman gain of Tellurite optical fibers and its multi-peak spectrum to achieve amplification over an amplification band from 1520 to 1600 nm. Average gains around 10 dB with ripples in the region of 3 dB were achieved using only 3 pumps with less than 800 mW each. Optimized systems were obtained for different lengths of fiber showing that discrete Raman amplifiers based on tellurite fibers with lengths as short as 100 meters can provide high gains and low ripples in a broad wavelength band. Lower cost systems using only 2 pumps were also analyzed in this study providing 5.8 dB of gain with only 2.4 dB of ripple for an 80 nm signal bandwidth.**

Index Terms— Non-linear optics, Raman amplifiers, Raman Scattering, Tellurite fibers.

I. INTRODUCTION

The development in the last decades of tellurite (TeO_2-based) optical fiber technology has found use in various applications as optical non-linear devices in both near and mid-infrared (IR) region [1]. The fact that its transparency window can extend up to 5-6 µm [2], still presenting high levels of non-linearities makes this type of glasses ideal hosts, for example, for the generation of supercontinuum [3], optical parametric amplification [4] and Raman lasers [5] in regions of the spectrum that cannot be covered by silica fibers. Moreover, tellurite-based glasses present high rare earth ions (RE) solubility, allowing them to be used as active devices emitting light at various wavelengths when doped with elements such as Ytterbium (Yb^{+3}), Thulium (Tm^{+3}) and Holmium (Ho^{+3}) [6].

Another important aspect of tellurite-based fibers is that, apart from the high levels of non-linearities, they present Raman gains that are usually 30 to 50 times that of silica fibers [2],[7], which can be further extended by tailoring such glasses in PCF geometries [4],[8] or by combining them with germanate [9] or fluorite glasses [10]. This feature has already been explored in a number of numerical studies [5] and experimental demonstrations of Raman shifters [11] and lasers [12] at various regions of the spectrum. Nevertheless, the amount of research dedicated to analyze the use of tellurite-based fibers as the Raman gain medium for telecommunication systems has been very modest

[13]-[15].

Broadband amplification in tellurite-based fibers has already been achieved for wavelength ranges up to 160 nm [14],[15]. Even though high average gains higher than 10 dB were obtained in those systems, no special care was taken into significantly reducing the values of ripple, which were of the order of 10 dB in [14] and more than 20 dB in [15]. This issue was addressed in [13] where a ripple as low as 1 dB could be achieved for a wavelength band of 160 nm. However, this low value of ripple was obtained at the expense of using a significantly more complex pumping system with 8 pumps.

Here we present an optimization of multi-pumped 80 nm broad Raman amplifiers based on tellurite fibers, more precisely a TeO_2-Bi_2O_3-ZnO-Na_2O (TBZN) glass-based fiber, that allowed achieving high levels of gains maintaining low levels of ripple (~2dB), using only simple configurations with 2 or 3 low-power pumps in order to reduce complexity and costs. The amplifiers were optimized using very fast and simple analytic and numerical techniques, which allowed also for an optimization of the length of the fiber to be used as the gain medium. In order to evidence the benefits of the use of tellurite-based fibers as discrete Raman amplifiers a comparison with optimized silica-based systems using the same techniques is performed. The results obtained here highlight the potential of using such glasses as host for short-length and high-gain broadband Raman amplification in telecommunication systems.

II.   SETUP AND OPTIMIZATION TECHNIQUES

The setup utilized in our simulations is shown in Fig. 1. We use 20 equally spaced signals in the wavelength range from 1520 to 1600 nm with -5 dBm each, which are coupled into a tellurite-based fiber that is counter-pumped by 2 or 3 pumps. The telluride fiber used in our simulations is based in the fiber experimentally demonstrated in [15], which is made of a TeO_2-Bi_2O_3-ZnO-Na_2O (TBZN) glass, from here onward called simply as tellurite fiber. Its Raman gain curve is shown in Fig.2 where a gain peak of 55 $W^{-1}.km^{-1}$ is obtained for a wavelength shift of 22.2 THz. As it is commonly seen in the gain curve of tellurite fibers it presents a second peak at a wavelength shift of around 13 THz with a gain peak of 38.4 $W^{-1}.km^{-1}$, which is still an order of magnitude higher than the gain obtained with standard silica fibers.
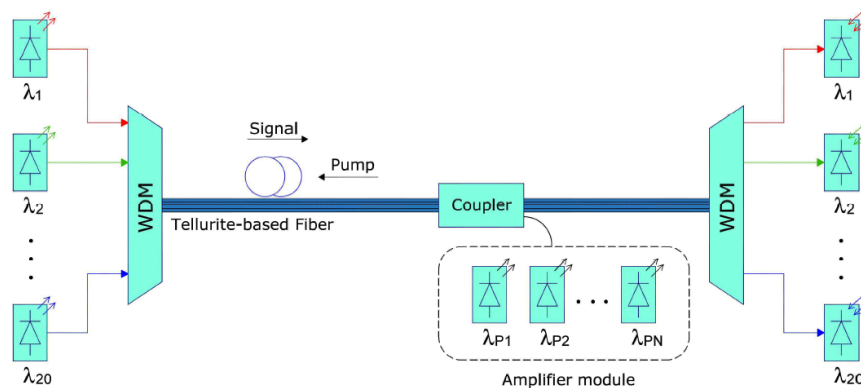

Fig. 1. Schematic of the optimized multi-pump Raman amplification system.

The high-gain two-peak aspect of tellurite fibers make them a very interesting medium to provide broadband Raman amplification since not only different pumps can be combined to flat the gain but also different peaks associated with each pump can be used in the optimization process, which can minimize the number of pumps needed. The attenuation as a function of wavelength can be seen in Fig.3, where a value of 27.6 dB/km is found at 1550 nm. Those high values of attenuation prevent this fiber to be used as a gain and transmission medium at the same time. However, its high Raman peak gain allows the use of very short lengths of fiber (few hundreds of meters) in discrete amplifier configurations, minimizing the effects of the high attenuation.
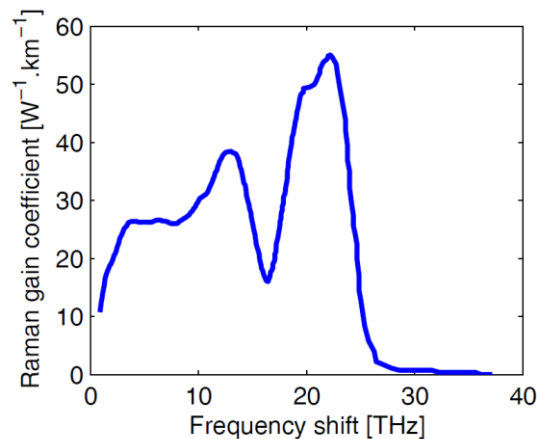

Fig. 2. Raman gain as a function of the pump-signal frequency shift for our tellurite fiber. Obtained from [15].

For the optimization process the pump wavelengths were allowed to vary from 1360 to 1500 nm and their initial powers from 600 to 800 mW each in order to assure that we are proposing a low-cost system. The 2-pump system was optimized using an exhaustive search technique based on the one used in [16], which utilizes a very fast simplified analytic model [17] to simulate multi-pump systems allowing the generation of hundred thousands of different configurations within minutes. This fast technique allowed us to generate all possible combinations varying each pump wavelength by 2 nm and each pump power by 20 mW within the chosen range, which gives a total of 609961 different cases. In order to assure higher precision for the final results, the best chosen configuration were later re-simulated using an very accurate numerical model, similarly of what was done in [16].
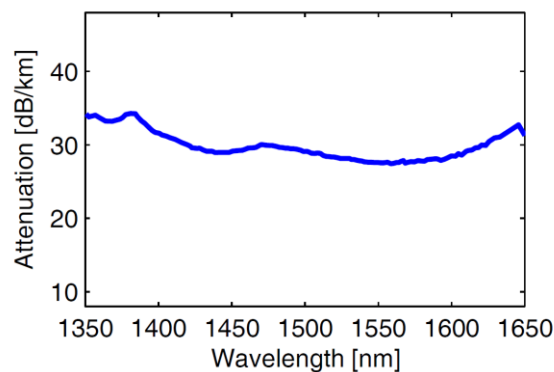

Fig. 3. Attenuation as a function of wavelength for our tellurite fiber. Obtained from [15].

The 3-pump systems were optimized using a fast-budget heuristic, which was firstly proposed in [18] that in our optimization process is used to find an initial case solution that is later further re-optimized using an nondominated sorting genetic algorithm which was also described in [18]. Both heuristics simulate the Raman amplification systems using a very precise numerical model, and not an approximated analytic solution. This strategy of optimization used for the 3-pump system was made since the analytic model used for the 2-pump system was not robust enough to produce very accurate solutions when the total pump power increased to values over approximately 1.8 watts.

Finally, the optimization process was used for tellurite fiber lengths varying from 30 to 300 meters in order to find not only the best pump scheme but also the fiber length which allows the optimization process to produce the results with the highest gains and low ripple. Optimization using a standard single-mode telecom fiber (SMF) as the Raman gain medium was also performed under the exactly same pump conditions for longer fiber lengths in order to allow a comparison between both amplification systems. However, it is worth mention that the very reduced lengths used in the discrete configurations based on the tellurite fiber possibly means an advantage when costs and practical implementation are taken into consideration.

III. RESULTS

A. Two-pumps system

For systems using two pumps the highest net gains achieved maintaining the levels of ripple around 2.5 dB can be seen as a function of the tellurite fiber length in Fig. 4. The highest average gains are around 5.8 dB and can be achieved for fiber lengths from 90 to 140 m. For longer lengths the high attenuation of the tellurite fiber quickly reduces the achievable gain, preventing its use as an amplifier for lengths over 300 meters. The best optimized system was found to happen when using 100 meters of the gain medium, pump wavelengths of 1398.0 and 1434.0 nm and pump powers of 800.0 and 720.0 mW respectively. Its Net gain as a function of wavelength can be seen in Fig. 5.
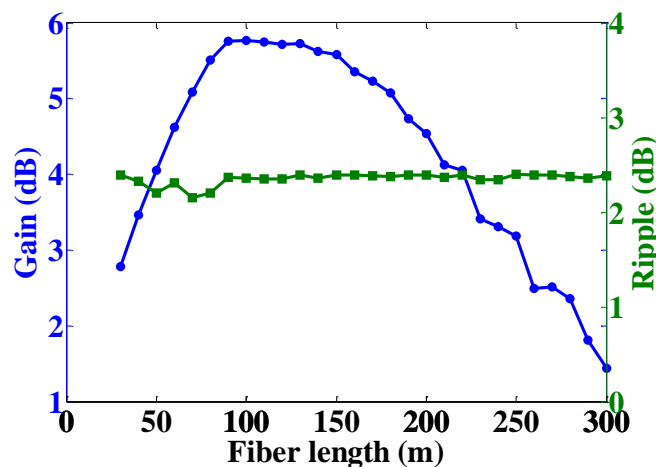

Fig. 4. Average net gain (circle) and ripple (squared dots) as a function of the tellurite fiber length for optimized systems using two pumps.

A similar optimization was performed using a standard SMF instead of the tellurite fiber as the gain medium and the average gain and ripple values for the optimized systems as a function of the fiber length can be seen in Fig. 6. Slightly higher values of average net gain of up to 6.5 dB can be achieved for a range of fiber lengths lower than 25 km. For longer distances, the achievable gain falls to lower than 6 dB and it approaches 4 dB at lengths around 50 km.
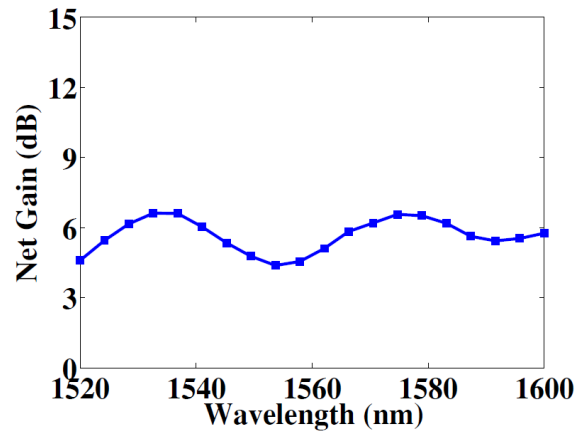

Fig. 5. Net gain as a function of wavelength for the optimized two pump system using 100 m of tellurite fiber as the gain medium.

The highest average net gain achieved maintaining a ripple lower than 2.5 dB was found to be 6.76 dB for 20 km of SMF, in a system using the pump wavelengths of 1426 and 1476 nm with pump powers of 800 mW and 740 mW, respectively. A summary of the best optimization results found for two pump systems in both Silica and Telluride-based fibers is shown in Table I. This result highlights the fact that, depending on the transmission distance, very short discrete amplifier schemes using tellurite fibers as the gain medium and only two pumps with moderate powers can be a simple and low-cost solution to replace or to be used together with distributed Raman amplification in broadband telecommunication systems.
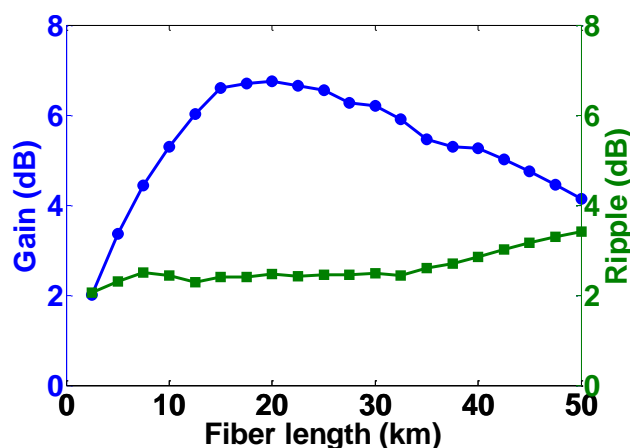

Fig. 6. Average net gain (circle) and ripple (squared dots) as a function of the SMF length for optimized systems using two pumps.

TABLE I. RESULTS FOR TWO-PUMPS CONFIGURATION

Fiber	$\lambda_{1,2}$ (nm)	$P_{1,2}$ (mW)	Gain (dB)	Ripple (dB)	Length (m)
Silica SMF	1426.0 1476.0	800.0 740.0	6.76	2.47	20,000
Tellurite-based fiber	1398.0 1434.0	800.0 720.0	5.79	2.36	100

B. Three-pumps system

The results for average net gain and ripple as a function of the tellurite fiber lengths are shown in Fig. 7. Average gains as high as 10 dB were achieved for a number of different fiber lengths still presenting ripples around 3 dB. The system with the highest gain that presented a ripple below 3 dB was found when using 210 m of tellurite fiber and the pump wavelengths of 1384.7, 1452.6 and 1483.6 nm with powers of 786.4, 782.9 and 777.4 mW, respectively. Table II summarizes the pump features for silica SMF and tellurite fiber, as well as the gain, ripple and fiber length. The gain as a function of wavelength for this configuration can be seen in Fig. 8 showing an average gain of 9.98 dB and a ripple of 2.55 dB.
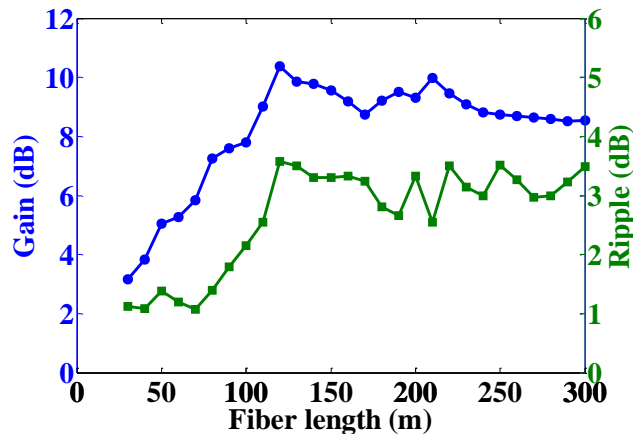

Fig. 7. Average net gain (circle) and ripple (squared dots) as a function of the tellurite fiber length for optimized systems using three pumps.

Once more to drawn a comparison, an optimization of three pump Raman amplification systems were performed using an SMF as the gain medium, and the result of average gain and ripple as a function of the fiber length can be seen in Fig. 9. Average gains near 15 dB were achieved for all fiber lengths above 50 km still showing ripples lower than 3 dB. However, for a fiber length of 20 km the average gain falls to approximately 11 dB, being even smaller for shorter distances.

This fall in the gain for short SMF distances is expected since the low Raman gain of silica fibers do not allow very high average gain amplifiers to be built when the transmission fiber is not long enough. This result again shows that a simple and very short three-pumped tellurite Raman amplification scheme can be used as a discrete amplification module to provide high gains for telecommunication systems which cannot be obtained from distributed amplification alone under certain conditions. The best three-pump optimized results obtained for both fibers are shown in Table II.
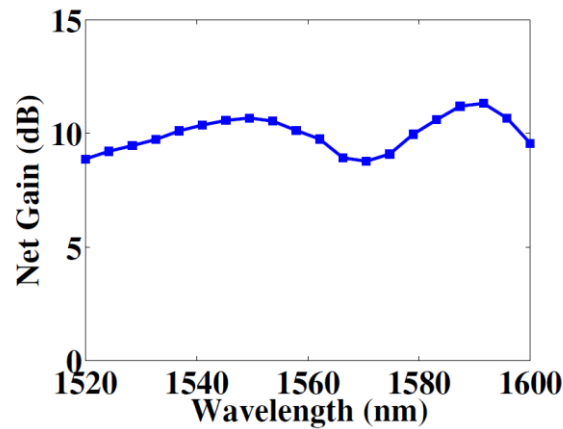
Fig. 8. Net gain as a function of wavelength for the optimized three pump system using 210 m of tellurite fiber as the gain medium.
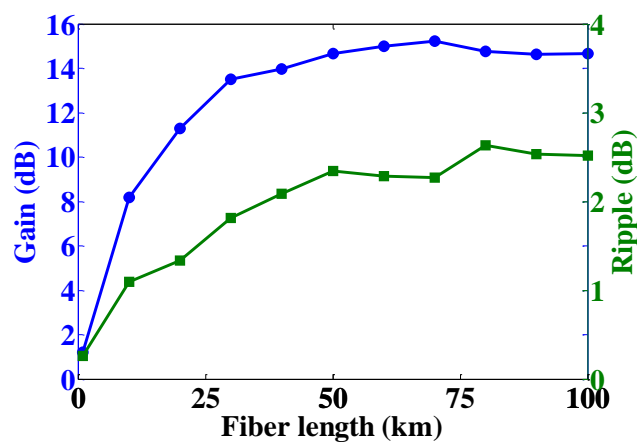

Fig. 9 Average net gain (circle) and ripple (squared dots) as a function of the SMF length for optimized systems using three pumps.

TABLE II. RESULTS FOR THREE-PUMPS CONFIGURATION

Fiber	$\lambda_{1,2,3}$ (nm)	$P_{1,2,3}$ (mW)	Gain (dB)	Ripple (dB)	Length (m)
Silica SMF	1421.9 1435.1 1476.4	887.9 801.6 699.4	15.2	2.27	70,000
Tellurite-based fiber	1384.7 1452.6 1483.6	786.4 782.9 777.4	9.98	2.55	210

IV. CONCLUSION

Here we numerically demonstrate that the high Raman gain present in tellurite-based fibers and its two-peak feature can be exploited to build very short discrete amplification schemes to be used in broadband telecommunication systems. Optimizations were performed not only in terms of pump wavelengths and powers but also analyzing different lengths of the fiber used as the gain medium. Systems with two and three pumps with moderate powers allowed average gains of up to 5.8 and 10 dB, respectively, to be achieved presenting ripples around 2.5 dB over a bandwidth of 80 nm. A comparison with distributed Raman systems using only SMF was performed highlighting that for

certain transmission distances the gain achieved from a discrete tellurite fiber, made of a TeO_2-Bi_2O_3-ZnO-Na_2O (TBZN) glass, with only a few hundreds of meters as the gain medium can be higher.

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