Independent Control of the Gain and Noise Figure Spectra of Raman Amplifiers Using Bi-Directional Pumping

*by Yoshihiro Emori *, Soko Kado * and Shu Namiki **

ABSTRACT Conventional multi-wavelength pumped Raman amplifiers normally use backward pumping, because, in comparison to forward pumping, it has less gain saturation, and less RIN transfer from the pumping light to the signal light. Backward pumping has a problem, however, in that when gain is flattened over a broad bandwidth, the wavelength-dependence of the noise figure becomes pronounced. This paper shows that, in a broadband Raman amplifier having five pumping wavelengths, it is possible by using only the three shortest wavelengths for bi-directional pumping, to design the gain spectrum and the noise figure spectrum independently.

1. INTRODUCTION

It is more than 20 years since fiber-optic communications have been in commercial use and new technological developments are constantly being made. Several years ago wavelength-division multiplex (WDM) transmission using Erbium-doped fiber amplifiers became the mainstream technology for large-capacity long-haul systems, and more recently, to set new records, it has become indispensable to make use of Raman amplifiers, optimizing the dispersion characteristics of the transmission path [1)~4)]. During the 1980s the Raman amplifier was extensively studied as a promising candidate for use in fiber-optic transmission but with the development of commercially viable EDFAs, they were allowed to languish for a period. When bit-rates were rising from 10 Gbps to 40, it was not possible to design systems that used only discrete amplifiers like EDFAs and the advantages of distributed Raman amplification, in which the transmission path as a whole is the amplifying medium, again came to be recognized. We may further say that the concept of multi-wavelength pumping, in which high-reliability laser diodes are used as the pump source to achieve adequate gain over a broad band, was advanced to extend the applicability of Raman amplifiers.

In conventional multi-wavelength Raman amplifiers, backward pumping is the configuration normally used. This is because, in comparison to forward pumping, there is less gain saturation, and less RIN transfer from the pumping light to the signal light [5), 6)]. Backward pumping has a problem, however, in that when gain is flattened over a broad bandwidth, the wavelength-dependence of the noise figure becomes pronounced [7)]. This paper shows, in a broadband Raman amplifier having five pumping wavelengths, by using, as an example, only the three shortest wavelengths for bi-directional pumping, that it is possible to design the gain spectrum and the noise figure spectrum independently.

* Optical Sub-Systems Development Dept., FITEL-Photonics Lab.

2. PRINCIPLE OF RAMAN AMPLIFICATION

Figure 1 shows a schematic diagram of Raman scattering, using a combination of the hypothetical electron state and the actual phonon energy state. When the incident light undergoes Raman scattering, the phonons of the molecules are excited and the energy of the incident light itself decreases. As a result the scattered light is lower in frequency than the incident light corresponding to the energy difference of the phonons. When light of the same frequency impinges simultaneously, Raman scattering is stimulated, and optical amplification is achieved. In Figure 1 the pumping light excites the electrons to the hypotheti-

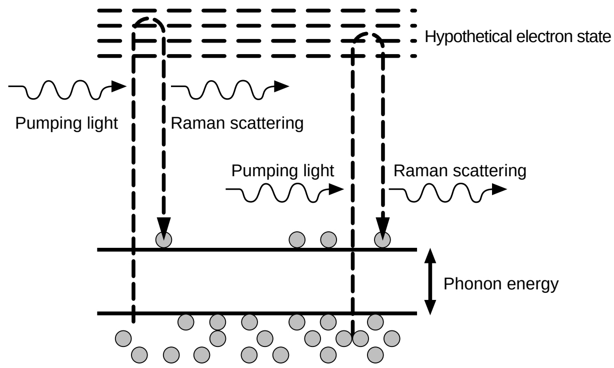

Figure 1 Schematic diagram of Raman scattering.

cal state, but since this state is not stable, the electrons immediately return to the ground state. And since the higher state is hypothetical, there is virtually no absorption with respect to the signal light. For this reason when the pumping light decreases the probability of the occurrence of Raman scattering is reduced and gain is smaller, but at least the pumping light does not act as a medium of absorption. Thus with a Raman amplifier it is possible to achieve a constant low-noise amplification process irrespective of the intensity of the pumping light. This constitutes a major difference from the EDFA, in which, unless the laser system is fully inverted, the signal light is absorbed and the noise characteristic degenerates.

Figure 2 shows the Raman gain efficiency measured for 1510-nm pumping of standard single-mode fiber (SMF), dispersion-shifted fiber (DSF) and dispersion-compensating fiber (DCF). The horizontal axis represents a frequency shift with respect to the frequency of pumping light, and the vertical axis represents the Raman gain efficiency when using unpolarized pumping light. Qualitatively speaking the horizontal axis corresponds to phonon energy and the vertical axis to scattering probability. In silica-based optical fibers, gain efficiency is maximized at a frequency shift of approximately 13 THz; the larger the amount of germanium dopant and the smaller the effective core area, the higher this efficiency will be. Although the peak value for efficiency will vary with the pumping wavelength, the shape of the curves shown in Figure 2 will be substantially the same despite changes in the pumping wavelength. Thus if measurements of the characteristic shown in Figure 2 are made at a specific pumping wavelength, it is possible to predict the wavelength-dependence of gain for any desired wavelength.

3. MULTI-WAVELENGTH PUMPED RAMAN AMPLIFIER

Figure 3 is a schematic showing the configuration of a typical Raman amplifier. Basically pumping light and signal light are input to a single amplifier fiber and amplification is effected by means of the stimulated scattering that occurs in the fiber. Figure 3 shows a configuration in which pumping light propagates bi-directionally in the amplifier fiber, but in some it propagates in the same direction as the signal light (forward pumping) or the opposite direction (backward pumping). Generally speaking with forward pumping the signal-to-noise ratio (SNR) can be kept high, while with backward pumping the saturation output power can be increased. In the case of a Raman amplifier the process of optical amplification takes place so rapidly that, unless the intensity noise of the forward pumping light is sufficiently small, the pumping light noise will be transferred to the signal light resulting in increased transmission error. Thus in many cases only backward pumping is used.

Figure 4 shows the principle of flattening Raman gain by using multi-wavelength pumping, in an example with five pumping wavelengths. The gains produced by each of the various pumping wavelengths are represented by heavy lines, and the gain produced by the aggregate of the four shortest wavelengths is represented by line A. Line C is an aggregation of the five heavy lines. Line B represents the Raman gain produced by the single longest pumping wavelength, and by adjusting lines A and B it is possible to flatten total gain, as in line C. The Raman gain spectrum for single-wavelength pumping shows no ripples on the shorter-wavelength side of the gain peak, but ripples do occur on the longer-wavelength side of the peak. Thus ripples are readily formed in the gain spectrum produced by the shorter pumping wavelengths (corresponding to line A). There are a number of ways to keep these ripples small: increase the number of pumping wavelengths so the gain per wavelength is smaller; allocate pumping

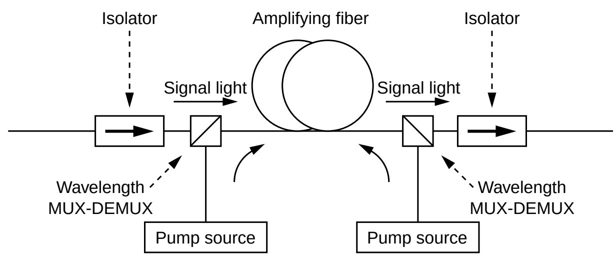

Figure 3 Schematic configuration of typical Raman amplifier.

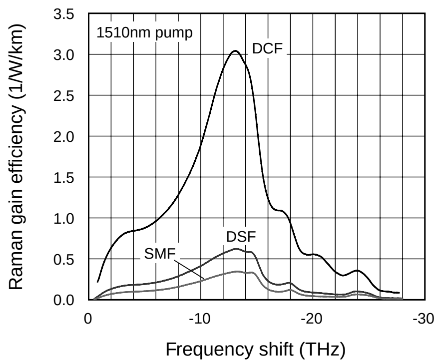

Figure 2 Raman gain efficiency measured for 1510-nm pumping.

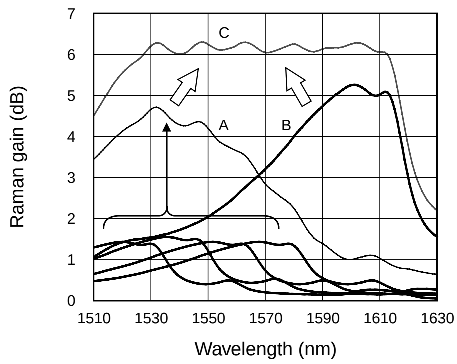

Figure 4 Principle of flattening Raman gain by using multi-wavelength pumping.

wavelengths at the same frequency interval; and arrange that the gain from each of the wavelengths is approximately equal.

4. WAVELENGTH-DEPENDENCE OF NOISE FIGURE

In EDFAs, Raman amplifiers and other optical amplifiers that use the principle of stimulated emission and stimulated scattering, spontaneous emission and spontaneous scattering occur irrespective of the presence of signal light. This light is amplified as it propagates in the amplifier fiber in the same way as the signal light, and is output from the amplifier, and is known as amplified spontaneous emission (ASE). In time slots in which there is no signal, ASE increases the zero level and in slots in which there is a signal, it interferes with the signal light and causes intensity fluctuations. In this way it is the noise figure (NF) of the optical amplifier that qualitatively defines the phenomenon whereby ASE produced inside the optical amplifier constitutes an indeterminate factor (noise) with respect to signal light detection; it is calculated by dividing the SNR before inputting the signal to the amplifier by the SNR at the amplifier output.

Since the SNR at the output is worse (smaller), the noise figure is larger than unity taking a positive value in decibels. Normally the main factor determining the SNR at the amplifier output is the noise produced by ASE, and the noise figure is calculated assuming that noise in the light input to the amplifier is limited to shot noise only.

Figure 5 shows typical spectra of Raman gain and noise figure by backward pumping using five wavelengths. Here we see the results of a simulation assuming a distributed amplifier and 80 km of SMF as the amplifier fiber. By adjusting the pumping power to flatten Raman gain a flatness of 0.5 dB was obtained. The flatness of the noise figure, however, was as large as 2.3 dB, and was dramatically worse on the short-wavelength side than on the long.

To assist in the discussion of the wavelength-dependence of the noise figure shown in Figure 5, the change in signal power along the amplifier fiber under backward pumping is shown in Figure 6. All of the signals were input to the fiber at the same power, and were output at substantially the same value, but the minimum value of signal level, reached at a distance of some 60 km, varies considerably with the wavelength. We may thus say that, in this amplifier, the fiber serves as a loss medium up to the point of minimum power, that the SNR becomes worse in proportion to the loss, and that from there to the fiber output SNR degradation occurs due to ASE. Thus the wavelength-dependence of the noise figure is produced by a combination of the loss up to the point of minimum signal level and, beyond that point, the wavelength-dependence of the noise characteristic of the amplifier. Note, however, that since the value of the wavelength-dependence of the minimum signal level in Figure 6 is approximately 2 dB, this may be considered the dominant factor in the wavelength-dependence of the noise figure in Figure 5.

The following four factors may be identified as contributing to the wavelength-dependence of the noise figure:

1. Wavelength-dependence of fiber loss;
2. Increased absorption due to the inter-signal Raman effect;
3. Difference in distribution of pumping power (gain) due to the inter-pump Raman effect; and
4. Temperature-dependence of efficiency of production of spontaneous scattering.

Item 2 suggests that since a signal of shorter wavelength acts as the pumping light for Raman amplification with respect to a signal of longer wavelength, the shorter the wavelength the greater will be the loss of energy and the faster the attenuation. Item 3 suggests that, in the same way as for the inter-signal Raman effect, the imparting and receiving of energy due to the inter-pump Raman effect causes extreme attenuation in pumping light of shorter wavelength, limiting amplification of signals of shorter wavelength to the region close to the output end of the fiber. Item 4 is based on the fact that the efficiency of production of spontaneous scattering changes with the wavelength, and at normal temperature spontaneous scattering at wavelengths near that of the pumping light is dramatically larger. The wavelength-dependence of the minimum signal level is due to items 1 through 3 above.

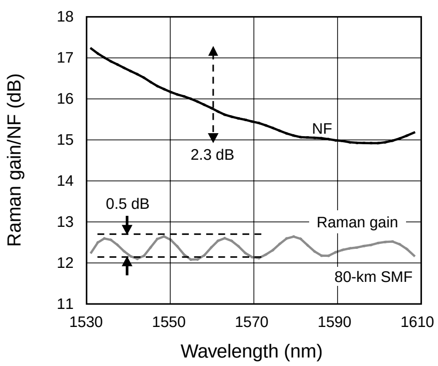

Figure 5 Spectra of Raman gain and noise figure by backward pumping.

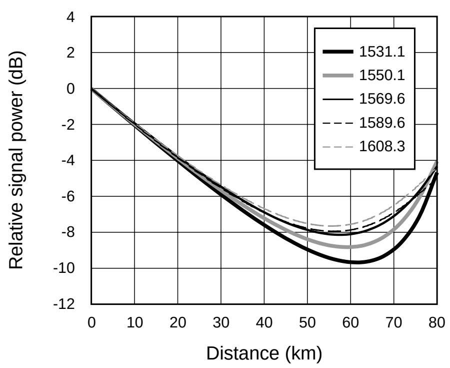

Figure 6 Change in signal power along amplifier fiber under backward pumping.

5. DESIGN OF NOISE FIGURE SPECTRUM USING BI-DIRECTIONAL PUMPING

In an effort to improve the wavelength-dependence characteristic shown in Figure 5, a bi-directional pumping system, shown in Figure 7, was designed. In principle this should, by using forward pumping, suppress the degradation in SNR arising near the input of the amplifier and improve the noise figure of the amplifier as a whole. However in the hope of applying a wavelength-dependence to this improvement, making it greater for the shorter-wavelength signals, bi-directional pumping was used only for the shorter-wavelength pumping light.

Figure 8 shows an example of the wavelength-dependence of the gain and noise figure in a Raman amplifier under bi-directional pumping for shorter wavelengths only, in a simulation carried out using the same pumping wavelengths and amplifier fiber as in Figure 5. By applying a wavelength dependence to the gain due to forward pumping it was possible to obtain the flat noise figure spectrum shown in the figure. Backward pumping power in this case was reduced to keep Raman gain flat, achieving flattening of both gain and noise figure simultaneously.

The change in signal power along the amplifier fiber with the noise figure flattened under bi-directional multi-wavelength pumping is shown in Figure 9. The signal levels at the input and output ends of the fiber are the same as in Figure 6, but the minimum value occurring at a distance of approximately 60 km was substantially the same for all the wavelengths. As a result the wavelength-dependence of the noise figure was reduced, and a substantially flat noise figure spectrum was obtained.

Figure 10 shows the results of simulation using even higher pumping power. In this example, by increasing the gain due to forward pumping while keeping total Raman gain flat, a noise figure spectrum was obtained that is smaller on the shorter-wavelength side than on the longer. In this way the use of a pumping scheme that is both multi-wavelength and bi-directional makes it possible for noise figure and gain spectra to be controlled independently as desired. If, however, the gain due to forward pumping is increased, the high signal level will, as shown in Figure 9, continue over comparatively long distances. This means that the impact of non-linear effects is great, and measures must be taken to assure that the resultant degradation in transmission quality does not present a problem[8].

6. EXPERIMENTAL RESULTS

Figure 11 shows the results of experiments to verify the independent control of gain and noise figure spectrum using bi-directional pumping. The amplifier fiber used was a 76-km SMF comprising spools of approximately 25 km joined by fusion splicing. Table 1 shows the pumping power used in the experiments. As Figure 11 shows, sev-

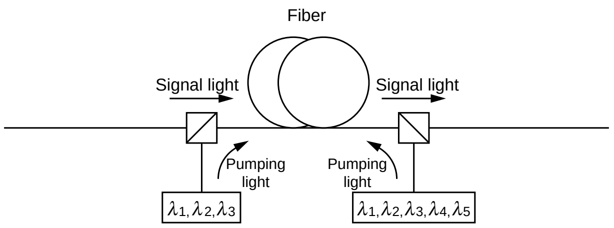

Figure 7 Schematic of a Raman amplifier under bi-directional multi-wavelength pumping.

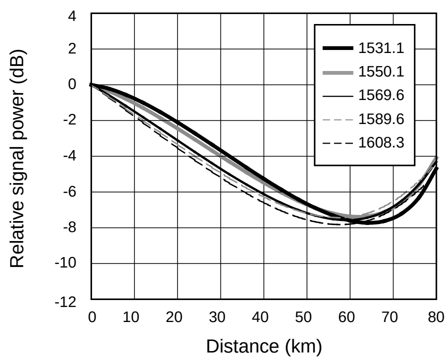

Figure 9 Change in signal power along amplifier fiber under bi-directional multi-wavelength pumping.

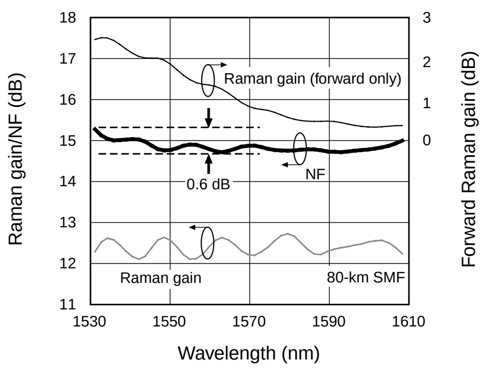

Figure 8 Wavelength-dependence of gain and noise figure in a Raman amplifier under bi-directional pumping for shorter wavelengths only.

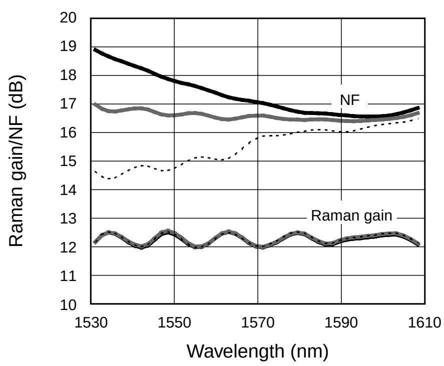

Figure 10 Results of simulation of noise figure spectrum control.

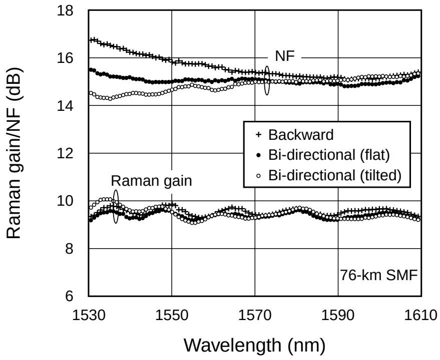

Figure 11 Results of experiments in noise figure spectrum control.

Table 1 Pumping power used in experiments.

	Wavelength	Backward	Flat NF		Tilted NF	
			Forward	Backward	Forward	Backward
λ_1	1426.2 nm	149 mW	31 mW	96 mW	78 mW	32 mW
λ_2	1438.5 nm	161 mW	36 mW	108 mW	54 mW	78 mW
λ_3	1451.8 nm	91 mW	22 mW	65 mW	45 mW	26 mW
λ_4	1466.0 nm	83 mW		105 mW		100 mW
λ_5	1495.2 nm	184 mW		206 mW		210 mW
Total power		668 mW	668 mW		623 mW	

eral noise figure spectra were realized, while maintaining a substantially similar Raman gain spectrum. Because Raman gain was maintained, total pumping power was virtually unchanged. For the three shorter wavelengths, increases in forward pumping power were matched by decreases in backward pumping power. For the longest pumping wavelength, the Raman effect between pumping wavelengths decreased with decreases in the shorter-wavelength pumping power propagating in the same direction, so that it was necessary to increase backward pumping power as forward pumping power was increased.

7. CONCLUSION

With Raman amplification in the spotlight as a mainstream technology for long-haul large capacity transmission, there is a need for broadband Raman amplifiers with improved characteristics. Past developmental activities have been concentrated on controlling and flattening the gain profile, but in the realization that broadening the bandwidth of noise characteristics was a problem for the future, we have examined bi-directional pumping schemes. This paper reports on a simulation of the possibility of controlling the gain and noise figure spectra independently as desired using a multi-wavelength, bi-directional scheme, and on its experimental verification.

REFERENCES

1) G. Charlet, J.-C. Antona, S. Lanne, P. Tran, W. Idler, M. Gorlier, S. Borne, A. Klekamp, C. Simonneau, L. Pierre, Y. Frignac, M. Molina, F. Beaumont, J.-P. Hamaide, S. Bigo, “6.4 Tb/s (159×42.7Gb/s) capacity over 21×100 km using bandwidth-limited phase-shaped binary transmission,” Proc. European Conference on Optical Communication, (2002), PD Paper 4.1.
2) B. Zhu, L. Leng, A. H. Gnauck, M. O. Pedersen, D. Peckham, L. E. Nelson, S. Stulz, S. Kado, L. Gruner-Nielsen, R. L. Lingle, Jr., S. Knudsen, J. Leuthold, C. Doerr, S. Chandrasekhar, G. Baynham, P. Gaarde, Y. Emori, and S. Namiki, “Transmission of 3.2 Tb/s (80×42.7 Gb/s) over 5200 km of UltraWaveTM fiber with 100-km dispersion-managed spans using RZ-DPSK format,” Proc. European Conference on Optical Communication, (2002), PD Paper 4.2.
3) D. F. Grosz, A. Agarwal, S. Banerjee, A. P. Kung, D. N. Maywar, A. Gurevich, T. H. Wood, C. R. Lima, B. Faer, J. Black, C. Hwu, “5.12Tb/s (128×42.7 Gb/s) transmission with 0.8 bit/s/Hz spectral efficiency over 1280 km of standard single-mode fiber using all-Raman amplification and strong signal filtering,” Proc. European Conference on Optical Communication, (2002), PD Paper 4.3.
4) C. Rasmussen, S. Dey, F. Liu, J. Bennike, B. Mikkelsen, P. Mamyshev, M. Kimmitt, K. Springer, D. Gapontsev, V. Ivshin, “Transmission of 40×42.7 Gbit/s over 5200 km UltraWave® fiber with terrestrial 100 km spans using turn-key ETDM transmitter and receiver,” Proc. European Conference on Optical Communication, (2002), PD Paper 4.4.
5) C. R. S. Fludger, V. Handerek, and R. J. Mears, “Pump to Signal RIN Transfer in Raman Fiber Amplifiers,” J. Lightwave Technology, Vol. 19, No. 8, (2001), pp. 1140-1148.
6) K. Song, and S. D. Dods, “Cross Modulation of Pump-Signals in Distributed Raman Amplifiers, Theory and Experiment,” IEEE Photonics Technology Letters, Vol. 13, No. 11, (2001), pp. 1173-1175.
7) C. R. S. Fludger, V. Handerek, R. J. Mears, “Fundamental noise limits in broadband Raman amplifiers,” in Optical Fiber Communication Conference, (2001), Paper MA5.
8) R.-J. Essiambre, P. Winzer, J. Bromage, and C. H. Kim, “Design of bidirectionally pumped fiber amplifiers generating double Rayleigh backscattering,” IEEE Photonics Technology Letters, Vol. 14, No. 7, (2002) pp. 914-916.