Temperature-dependent gain and noise in fiber Raman amplifiers

S. A. E. Lewis
Femtosecond Optics Group, Department of Physics, Imperial College, London SW7 2BZ, England

S. V. Chernikov
Femtosecond Optics Group, Department of Physics, Imperial College, London SW7 2BZ, England, and IP Fibre Optics, Ltd./IRE Polus Group, P.O. Box 6169, London SW20 8YD, England

J. R. Taylor
Femtosecond Optics Group, Department of Physics, Imperial College, London SW7 2BZ, England

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An experimental investigation of the temperature dependence of the gain and noise performance of a silica-fiber Raman amplifier is described. A decrease in the Raman scattering cross section in a fiber amplifier cooled from a temperature of 300 K to 77 K was measured and found to be in agreement with theoretical values. No difference between the Raman gain coefficients at these two temperatures was observed.

Raman amplification in silica fiber is a promising means for extending the operational range of optical telecommunication systems to wavelengths beyond those covered by erbium-doped fiber amplifiers. Progress in pump laser sources, in particular, in cascaded Raman fiber lasers, has made reliable and efficient Raman amplifiers a reality. These amplifiers are not confined to any particular wavelength but can operate throughout the low-loss window of optical fiber from 1.2 to 1.7 μm. The use of multiple-wavelength pumping can increase the gain bandwidth available from a single amplifier to the limit imposed by the magnitude of the Raman Stokes shift of ~450 cm⁻¹.¹ In such broad-bandwidth amplifiers the optical noise figure close to the wavelength of the pump laser has been found to be higher than at longer wavelengths.¹,³ It has been pointed out that this is due to the temperature dependence of the Raman scattering cross section.³ From Ref. 4, noise photons are emitted at a rate proportional to

\[ g_R(\nu) \left[ 1 + \frac{1}{\exp(h\nu/kT) - 1} \right] \]  \hspace{1cm} (1)

[where \( g_R(\nu) \) is the Raman gain coefficient at Stokes frequency shift \( \nu \), \( T \) is the temperature of the Raman fiber, \( h \) is Planck’s constant, and \( k \) is Boltzmann’s constant], whereas the Raman gain coefficient shows no temperature dependence. In this Letter we describe a measurement of the gain spectrum and the noise at the output of a silica-fiber Raman amplifier pumped at a wavelength of 1455 nm operating at a room temperature of 300 K and at 77 K after cooling with liquid nitrogen. When the gain fiber was cooled, a decrease in the optical noise figure that corresponded to a decrease in the noise emission rate at wavelengths close to the pump was measured. In addition, the amplifier gain decreased and underwent a change in spectral shape. These changes were accompanied by a significant increase in the distributed fiber loss, particularly at longer wavelengths. By comparing the experimental results with a numerical simulation that took into account the increased fiber loss, we found that the measured noise scattering rate varied according to Eq. (1). We also found that there was no change in either the magnitude or the spectral shape of the Raman gain coefficient when the fiber was cooled.

The Raman amplifier consisted of a single-stage 9-km gain fiber pumped by a cascaded Raman fiber laser at a wavelength of 1455 nm. Optical circulators were used to multiplex and demultiplex the pump and signal, which counterpropagated in the gain fiber. Counterpropagation has the advantage that it averages out the effect on the signal of high-frequency fluctuations in the pump intensity. The optical circulators introduced a loss of less than 1 dB over the range 1450–1600 nm, and the total passive loss of the amplifier at 1550 nm was 4.3 dB. Measurements of the amplifier gain and noise performance were made with a pump power of 870 mW coupled into the gain fiber. In the low-temperature measurement the gain fiber was cooled by submersion in liquid nitrogen. As the gain fiber was cooled, the fiber loss, gain, and noise figure spectra were monitored. These values ceased to change with time after the fiber had been submerged in the nitrogen for ~2.5 h, at which point it was assumed that the fiber had reached a steady temperature. The
optical circulators remained outside the cooling tank and consequently at room temperature. The gain and the noise figure of the amplifier were measured with an optical spectrum analyzer and either a tunable semiconductor laser source (for wavelengths up to 1580 nm) or amplified spontaneous emission from a semiconductor laser amplifier (for wavelengths longer than 1580 nm) as the signal source. The noise figure (NF) calculation included only the signal degradation that was due to beating between the signal and noise according to

$$\text{NF} = \frac{1}{G} \frac{P_{\text{ASE}}}{h\nu_s \Delta f}.$$  \hfill (2)

The amplifier gain and noise figure spectra measured at room temperature are shown in Fig. 1. From this measurement of the amplifier gain we calculated the Raman gain coefficient of this fiber, using the known pump power and the loss in the amplifier. The measured loss of the amplifier is shown in Fig. 2. We used a numerical simulation to calculate a value for the noise figure, using a temperature of 300 K and Eq. (1) for the noise scattering rate. The results of the numerical simulation are shown in Fig. 1 as a solid curve and agree closely with the experimental measurement.

When the gain fiber was cooled there was a significant increase in the fiber loss, as can be seen from Fig. 2. The magnitude of the excess loss increased toward longer wavelengths. This loss spectrum is similar to that which arises from loss caused by fiber bending. The increased stress as a result of compression owing to the reduced temperature is probably the major influence on the increased loss that is due to microbending effects over the complete amplifier length. An optical-time-domain reflectometry measurement confirmed that this loss was distributed over the fiber length without any discontinuity. The loss of the gain fiber was higher close to the fiber input and output. At the ends the fiber loss coefficient was approximately 20% higher than the average, with the loss minimum at the center of the gain fiber being 20% lower than the average. This positional dependence was included in all numerical simulations, and its effect on the amplifier gain and noise figure was found to be small. Figure 3 shows the amplifier gain and noise figure spectrum after cooling. The magnitude of the amplifier gain decreased from the room-temperature value, and there was a change in the shape of the gain spectrum. Close to the pump wavelength there was a decrease in the noise figure when the fiber was cooled. At 1465 nm, for example, there was a 3.4-dB decrease. In contrast, at longer wavelengths, close to the gain peak, either a small increase or a negligible change in the noise figure was observed. To make a comparison between the Raman gain coefficient and the noise emission rate at room temperature and at 77 K it was necessary to separate the effect of increased loss at low temperature. Therefore two situations were analyzed with a numerical simulation and compared with the experimental results. First it was assumed that when the amplifier was cooled the fiber loss increased by the measured amount (see Fig. 2) but that the noise scattering rate remained the same as at room temperature. In the second case the increased loss when the amplifier was cooled and a change in the noise emission rate from its room-temperature value according to Eq. (1) were included in the simulation. The value of the
Raman gain coefficient used in these calculations was the measured room-temperature value. The results of these simulations and the corresponding experimental data are shown in Fig. 3. Considering first the Raman gain coefficient, we observed good agreement between the simulation amplifier gain at 77 K (shown as the thicker solid curve in Fig. 3) and the measured gain. Within the bounds of the experimental error, estimated to be approximately 10%, the changes in the measured amplifier gain are entirely explained by the increased fiber loss, and we conclude that no change in either the spectral shape or the magnitude of the Raman gain coefficient was observed. The noise figure spectrum predicted by the first simulation is shown as a dashed curve in Fig. 3. It significantly exceeds the measured values, particularly at wavelengths close to that of the pump, and is also higher than the room-temperature noise figure. Although the noise figure depends on the fiber loss, this result shows that the measured noise figure reduction is not explain by the increase in the fiber loss. The noise figure predicted by the second simulation, in which a change in the noise emission rate according to Eq. (1) was taken into account, is shown in Fig. 3 as the thinner solid curve. Agreement is found with Eq. (1); the differences between the two lie within the bounds of the estimated experimental error of ±0.6 dB.

In conclusion, it has been shown by an experimental measurement and comparison with simulation that there is no change in the Raman gain coefficient in a silica fiber when it is cooled from 300 to 77 K. It was also found that the noise emission rate is well described by Eq. (1) under these conditions. This temperature dependence of the Raman scattering rate is important for a proper understanding of the performance of broadband Raman amplifiers.

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