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Comparison of stimulated and spontaneous scattering measurements of the full wavelength dependence of the Raman gain spectrum

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Abstract

We present a direct comparison of the measured spontaneous Raman spectra and the measured stimulated Raman gain from a pump laser. We confirm that the spontaneous Raman spectrum is related to the stimulated Raman gain spectrum through a simple Bose-Einstein temperature factor. Given this simple relation, the full dependence of the Raman gain on both the signal *and pump* wavelength can be extracted directly from spontaneous Raman spectra, which are easily generated with a low-power (few milliwatts) diode laser and calibrated optical spectrum analyzer.

Introduction

Since the early observations of Raman gain in optical fibers [1], Raman amplification has become increasingly important in optical-fiber communication because it can provide gain with a low effective noise figure over a very large bandwidth. Clearly, accurate measurements of the full wavelength dependence of the Raman gain are important in view of the growing use of Raman amplifiers. The gain will depend on both the signal and pump wavelength; however, since the gain depends most strongly on the wavelength difference between the pump and signal beams, the Raman gain is perhaps most usefully described in terms of its dependence on the pump wavelength and on the wavelength difference between the pump and signal beams. Historically, most measurements of Raman gain have used a pump-probe configuration with a fixed-wavelength pump beam to generate the Raman gain versus the pump-signal frequency offset [2]. In a recent letter, one of the authors showed that this same general pump-probe configuration can be used to determine not only the dependence of the Raman gain on the pump-signal frequency offset, but also its dependence on the pump wavelength, provided the probe light spans both the Stokes (gain) and anti-Stokes (loss) region of the Raman effect [3,4]. As a result, a single pump-probe measurement of the Raman gain can provide the full wavelength dependence of the Raman gain over the wavelength range of interest. An alternative method to the pump-probe configuration for measuring the Raman gain is to measure the spontaneous Raman spectrum from a pump laser, from which one can extract the stimulated Raman gain [5]. In this paper, we demonstrate measurements of the full wavelength dependence of the stimulated Raman gain using spontaneous Raman scattering. Using a single low-power pump laser we determine both the stimulated Raman gain curve dependence on the signal-pump wavelength offset and on the absolute pump wavelength.

The Raman gain spectrum and the spontaneous Raman spectrum will depend differently on temperature. Historically, the underlying vibrations responsible for the Raman gain were assumed to be those of a simple harmonic oscillator [6], in which case the temperature correction involves a Bose-Einstein factor. Although it has not been widely acknowledged in the literature, the presence of anharmonicities will, at some level, introduce errors into the simple temperature correction used in this model. Previous work comparing the noise figure from amplified spontaneous emission and the gain of Raman amplifiers indicates that this simple Bose-Einstein factor is at least accurate to a few tenths of a decibel [7,8,9]. One goal of this work is to demonstrate that this factor is accurate to better than 0.1 dB, the experimental limit on the measurement of the absolute spontaneous Raman spectrum.

Direct measurement of the stimulated Raman gain curve typically requires a strong pump of a few hundred milliwatts and a broad probe source. The advantage of measuring the gain from the spontaneous Raman spectrum, as described here, is that only a very low-power pump of a few milliwatts is needed along with a well-calibrated OSA. On the other hand, extracting the gain from the spontaneous Raman spectrum does require calibration of the fiber attenuation and absolute optical spectrum analyzer (OSA) power response at all wavelengths, while a direct measurements of the stimulated Raman gain requires these calibrations only at the pump wavelength. In practice, the choice of technique will be dictated by the available hardware.

Theory

The standard equations governing the Raman effect in single mode fiber of length *L* can be written in terms of the number of pump photons per mode, $n_p(z)$, and the number of counter-propagating signal photons per mode, n_s , at position *z* down the fiber as [10]

$$\frac{dn_s}{dz} = -\alpha(\omega_s) n_s + \gamma(\omega_p, \Delta\omega) n_p(z) \left[n_s + C(T, \Delta\omega) \right] \tag{1}$$

where the fiber attenuation as a function of frequency is $\alpha(\omega)$, the frequency offset between the pump and signal beams is $\Delta\omega = \omega_p - \omega_s$, and the Raman gain coefficient $\gamma(\omega_p, \Delta\omega)$ is positive for the Stokes side ($\Delta\omega > 0$) and negative for the anti-Stokes side ($\Delta\omega < 0$). The factor C is responsible for the generation of spontaneous Raman photons and differs depending on whether the signal is on the Stokes side, in which case $C = 1 + \varphi(T, |\Delta\omega|)$, or on the anti-Stokes side of the pump, in which case $C = \varphi(T, |\Delta\omega|)$. The Bose-Einstein temperature-dependent correction factor $\varphi(T, \Delta\omega) = \left(\exp(\hbar\Delta\omega/kT) - 1\right)^{-1}$ can be viewed equivalently as the phonon occupation number at the temperature *T,* or as the thermal average of the squared matrix element between adjoining states of the simple harmonic oscillator. This simple Bose-Einstein temperature correction results from the assumption of simple harmonic vibrations, for which the density of states is exactly the same regardless of the initial state (*i.e.,* the states are evenly spaced) and the matrix elements can be easily calculated. Experimentally, if this simple-harmonic assumption were incorrect, the measured and expected spontaneous Raman curves would deviate at frequency offsets $\hbar\Delta\omega \le kT$, where $\varphi(T) \ge 1$.

In general, there is an equation similar to (1) that describes the pump evolution. For our parameters, the undepleted pump approximation is valid, so the pump decays exponentially in the –*z* direction. At very low pump powers of a few milliwatts, the Raman gain is low and the spontaneously-generated Raman photons undergo negligible Raman gain. Equation (1) can then be solved in closed form as:

$$n_s(\omega_s) = \left[\frac{1 - e^{-\{\alpha(\omega_p) + \alpha(\omega_s)\}L}}{\alpha(\omega_p) + \alpha(\omega_s)} \right] \gamma n_p C = g_{RM}(\omega_p, \Delta\omega) P_p L_{eff,total} C \Delta f \tag{2}$$

where $L_{eff,total}$, the quantity in square brackets, is the total effective length, Δf is the mode spacing so that $n_s/\Delta f$ is the number of photons per Hz bandwidth, P_p is the initial pump power, and $g_{RM}(\omega_p, \Delta\omega)$ is the standard Raman gain. We will assume the pump is unpolarized so that g_{RM} is the unpolarized gain (half the polarized gain) and $n_s/\Delta f$ is the number of photons per hertz *per polarization mode*. Solving Eq. (2) for g_{RM} gives the Stokes Raman gain at a fixed pump wavelength or frequency. As discussed in detail in Ref. [3,4], the pump-wavelength dependence is contained in the asymmetry of the Raman gain spectrum; essentially, the anti-Stokes signal "pumps" the pump laser with a Raman gain corresponding to a pump wavelength equal to the anti-Stokes wavelength. If we assume the Stokes Raman gain varies as $\sim \omega_p^k$, then the exponent *k* can be found from the solution to [3,4]

$$\frac{g_{RM}(\Delta\omega) + g_{RM}(-\Delta\omega)}{g_{RM}(\Delta\omega) - g_{RM}(-\Delta\omega)} = -\frac{k+1}{2\omega_p}\Delta\omega \qquad (3)$$

Experimental Measurements

The experimental setup to measure the backward-generated Raman spontaneous spectrum is shown in Figure 1. As discussed earlier, the OSA calibration is critical to accurate measurements of the Raman spectrum. The OSA was calibrated for three factors: the wavelength scale was calibrated relative to the pump-laser wavelength, the power scale was calibrated relative to a calibrated optical power meter (OPM), and finally the effective resolution bandwidth was measured as a function of signal wavelength. We also separately measured the loss of the circulator and other components between the fiber end and the OSA. Finally, the attenuation over the full wavelength range of interest was measured with a broad source and adjusted by more accurate attenuation measurements taken over a smaller wavelength range with the cutback method. To avoid uncertainties from polarization-dependent loss the pump polarization was scrambled. The measured spectrum *S* in dBm from the OSA was converted to the number of photons per Hz per polarization as $n_s/\Delta f = S\lambda_s^3/(2hc^2\Delta\lambda)$, where $\Delta\lambda$ is the calibrated OSA resolution bandwidth.

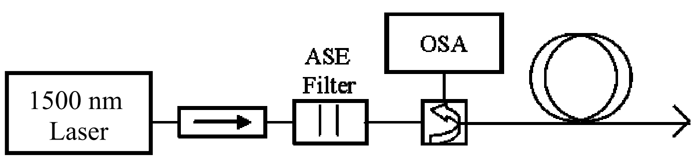

Figure 1: *Setup for measuring the spontaneous Raman spectrum. The laser power was ~4 mW, well below the stimulated Brillouin scattering threshold and low enough to provide negligible Raman gain.*

Figure 2a shows the spontaneous Raman spectrum, in units of $n_s/\Delta f$, measured directly for two different fiber types and calculated directly from Eq. (2) using the calibrated Raman gain curves measured for the same exact fibers, as reported in Ref. [3]. Figure 2b shows the same data set, but in this case in terms of the directly measured stimulated Raman gain and the indirectly measured stimulated Raman gain inferred from the spontaneous spectrum and Eq. (2). No free parameters were used in the comparison. The difference between the measured and predicted Raman spectra, shown in Figure 3, has an average offset of less than 0.1 dB and a standard deviation of ~0.1dB. We attribute these deviations to uncorrected wavelength dependence of the OSA power response or to fiber and component attenuation. No discrepancies attributable to anharmonicities, which would be evident at wavelengths offsets of ~ 45 nm or below, were observed, indicating the Bose-Einstein correction factor is valid to better than 0.1 dB.

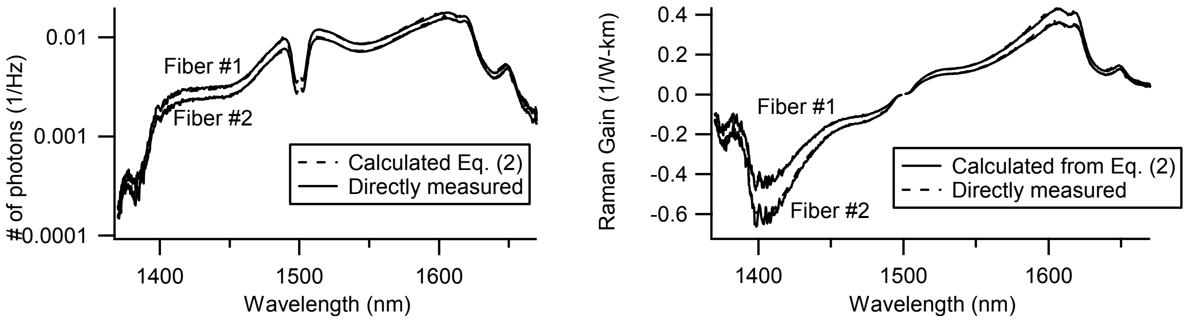

Figure 2: *a) Comparison of measured spontaneous Raman spectra with the calculated spontaneous Raman spectra for two typical communication fibers. b) Comparison of the same data in terms of the stimulated Raman gain spectrum.*

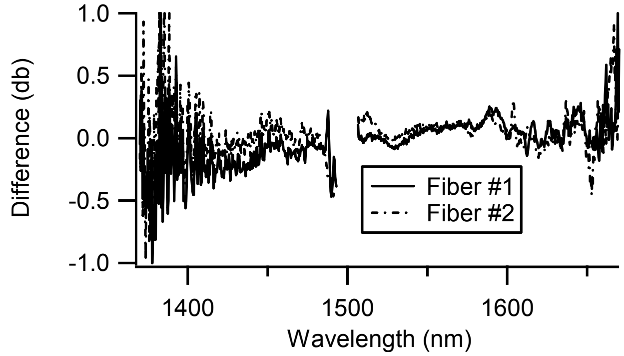

Figure 3: *The difference between the calculated and measured curves of 2(a) or 2(b).*

We have shown that the full wavelength dependence of the Raman gain can be obtained either directly from measurements of the gain or indirectly from measurements of the spontaneous Raman spectrum. In general, the uncertainty for the spontaneous-based measurement will be larger (~0.2 db) since this measurement requires absolute power measurements at each wavelength, whereas the direct measurement requires only relative power measurements at each wavelength. However, if this level of uncertainty is adequate and if only a low-power pump is available, measurement of the Raman gain through the spontaneous spectrum is an attractive choice.

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