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Pump-wavelength dependence of Raman gain

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Abstract: The scaling of the Raman gain with pump wavelength is determined by three complementary techniques: gain comparison at different pump wavelengths, gain asymmetry at a fixed pump wavelength, and theory combined with known fiber properties.

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1. Introduction

In fiber Raman amplifiers, a strong pump beam provides gain to one or more weaker signal beams at longer wavelengths through stimulated Raman scattering. In general, the gain depends on both the pump wavelength and signal wavelengths. However, at typical pump wavelengths of 1.4 μm, the Raman scattering in optical fiber occurs far from any electronic resonance, and the gain depends primarily on only the difference between the pump and signal wavelengths [1]. Indeed, available measurements of Raman gain are typically limited to a single pump wavelength. Nevertheless, the Raman gain does depend on the absolute pump wavelength. Knowledge of this pump-wavelength scaling is important for any simulations of the Raman effect in fiber, including Raman amplifiers using multiple pump wavelengths and Raman gain tilt in WDM systems with many channels.

The pump-wavelength dependence of the modal Raman gain, which is the intrinsic Raman gain divided by the effective area, can be quite strong depending on the fiber type. Recently, we measured the wavelength dependence for four different fibers using two complementary techniques and found that the modal Raman gain could vary as strongly as the inverse fourth power of the pump wavelength [2]. Below we compare the results of Ref. [2] to estimates of the pump-wavelength dependence based on the theoretical expression for the modal Raman gain and previously measured fiber parameters.

2. Measurement Techniques

The modal Raman gain $g_{RM}\left(\omega_s,\omega_p\right)$ is a function of the signal frequency and pump frequency ω_p and is defined such that, in the absence of loss, the gain in signal power P_s due to a pump of power P_p is

$$\frac{dP_s}{dz} = g_{RM}\left(\omega_s,\omega_p\right)P_sP_p \ , \tag{1}$$

where z is the direction of propagation down the fiber. In reference [2], it is shown that the wavelength or frequency scaling of the modal Raman gain can be written as

$$g_{RM} \approx \pm\omega_s\left(\omega_s\omega_p\right)^{(n_A+n_M)/2}\rho\left(\pm\Delta\omega\right)C \ , \tag{2}$$

where the + (-) sign corresponds to the Stokes (anti-Stokes) gain, C is a frequency-independent constant evaluated at the reference pump frequency, and $\rho\left(\Delta\omega\right)$ is the density of states for the vibrational modes that provide the Raman gain evaluated at the frequency difference $\Delta\omega \equiv \omega_p - \omega_s$. The pump-frequency scaling is given by the exponents of the first three frequency factors. The first factor of ω_s arises from converting the Raman scattering rate into a rate of power transfer and is responsible for the approximate inverse pump-wavelength scaling of the Raman gain. The second factor in parenthesis has an exponent that is the sum of a weak power-law scaling of the squared Raman matrix element, given by n_M, and the much stronger wavelength scaling of the inverse effective area, given by n_A.

If the lowest-order dependence of the prefactor on the frequency difference is "absorbed" into the function ρ, the *Stokes* modal Raman gain scales as $g_{RM} \propto \omega_p^{n_s}$, with an exponent, $n_s = 1 + n_A + n_M$, equal to the sum of the scaling from the leading ω term, the matrix element, and the effective area. (The scaling of the anti-Stokes modal

Raman gain differs and is given by $\omega_p^{-1}\omega_s^{n_s+1}$). Below, we present three different approaches for estimating the power-law scaling exponent n_s, the first two of which were reported in more detail in Ref. [2].

2.1 Integrated Raman gain strength versus pump-wavelength

Ostensibly, the most direct measure of the pump-wavelength scaling of the Raman gain is to measure the Raman gain curve at different pump wavelengths and compare the peak gain or better yet the integrated gain, over some common range of $\Delta\omega$. The difficulty in such a measurement is that it requires accurate measurements of relative power at the different pump wavelengths; errors in the wavelength scaling of the optical power meter or any unaccounted for wavelength-dependent loss in the system will lead to errors in the pump-wavelength scaling of the gain. Nevertheless, such a measurement can be made and is shown in Figure 1a.

2.2 Gain asymmetry in the Stokes versus Anti-Stokes side of the Raman gain spectrum

An equally direct, and more robust, approach to determining the pump-wavelength scaling is to extract it from the asymmetry in the Stokes and anti-Stokes Raman gain spectrum at a fixed pump wavelength. The asymmetry is given by

$$A = \frac{g_{RM}(\Delta\omega) + g_{RM}(-\Delta\omega)}{g_{RM}(\Delta\omega) - g_{RM}(-\Delta\omega)} = -\frac{n_s + 1}{2\omega_p}\Delta\omega \quad . \tag{3}$$

In other words, the asymmetry in the gain spectrum, plotted as a function of $\Delta\omega$, should be a straight line with a slope that gives the exponent of the power-law scaling. This approach is independent of any optical power measurements and is simpler than the integrated gain strength measurements since it requires a single, two-sided, Raman gain curve. An example is given in Figure 1b.

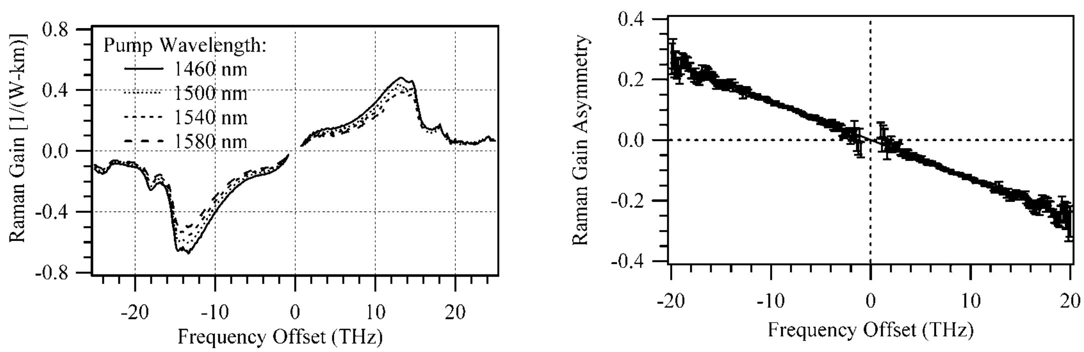

Fig. 1. Example of (a) Raman gain curves versus pump wavelength and (b) Raman gain asymmetry for LEAF fiber calculated from one of the curves of Figure 1a.

2.3 Estimation from known fiber parameters

The final approach to determining the pump-wavelength scaling is to estimate the two power-law scaling exponents appearing in Eq. (2), namely the matrix-element scaling n_M and the inverse effective area scaling n_A, and finally to estimate the overall power-law scaling exponent, $n_s = 1 + n_A + n_M$.

The first exponent represents the power-law scaling of the term M^2/n^2, where *M* is the Raman matrix element [3] and *n* the index of refraction. Since the matrix element $M^2(\omega,\omega) \propto \left(n^2(\omega) - 1\right)^2$, the Sellmeier equations can be used to yield an approximate value of $n_M \sim .07$ over the wavelength range of 1 - 2 µm [2].

In contrast, the scaling of the effective area with wavelength is much stronger and more challenging to estimate. The gaussian-beam approximation is not accurate enough to capture the true wavelength dependence of the effective area for two reasons. First, the constant of proportionality between the effective area and squared gaussian beam width is itself wavelength-dependent [4] and, second, any wavelength-dependent error in the estimation of the gaussian beam width will lead to a large error in the wavelength dependence of the effective area. Even for a nominal step index fiber it is difficult to obtain accurate estimates through calculation since deviations of the actual index profile from a true step function will affect the wavelength dependence. An accurate calculation of the effective-area wavelength-dependence requires accurate knowledge of the index profile of the fiber, which is typically unavailable. Alternatively, measurements of the effective area at several wavelengths can be used to directly estimate the power-law scaling. Fortunately, Humphreys and coworkers have made a set of direct measurements of the effective area of relevant fibers at wavelengths of 1310 nm and 1550 nm using several different methods [5]. The assumption of a power-law wavelength dependence of the effective area yields a scaling exponent n_A for each of the fibers from their data. As an added complication, the Raman matrix element and density of states factors will vary across the transverse fiber dimensions due to the same doping that raises the index to provide guiding of the light. Therefore, the variation in both factors should be included in the overlap integral that defines the effective area. Based on estimates of the variation in the Raman gain from Ge doping [6], inclusion of this variation in the overlap integral will increase the effective value of n_A by ~0.03 for a step index fiber. Including this correction and the matrix element scaling gives a final value for the pump-wavelength dependence of the modal Raman gain as $n_s = 1 + n_A + 0.03 + 0.07$. The results are given in Table 1. The quoted uncertainty assumes uncorrelated errors in Ref. [6] and has an additional included uncertainty of 0.1 to reflect the uncertainty of the matrix element and contributions of Ge doping to the scaling. No additional uncertainties were included to account for the wavelength scaling of the exponent n_s [2] or, perhaps most importantly, the fact that the fibers measured in Ref. [6] were not identical to the fibers used to measure the gain by the first two approaches in Ref [2]. Indeed the wavelength dependence of the effective area is inherently connected with the dispersion characteristics of the fiber, and modifications to the profiles of the dispersion-shifted fibers, such as TrueWave→ or LEAF→[7], will affect the wavelength scaling.

3. Results

The pump-wavelength scaling for four standard telecommunication fibers is given in Table 1 for each of the three methods described above. Overall, the measurements using the gain strength and gain asymmetry agree for all four fibers, with the largest disagreement for SMF-28⎛ just outside of the standard uncertainty. The estimated values are in reasonably good agreement with the measurements, particularly considering that completely different spools of fiber were used. The agreement between the measurements and the estimated values for the SMF-28 fiber type is especially good, which is not surprising since it has the most well-established index profile.

Table 1: Pump-wavelength power law scaling of the Raman gain using three different methods: the integrated gain-strength measurement, the gain-asymmetry measurement, and estimation from measured fiber parameters [7]. All errors are one unit of standard uncertainty (1 sigma).

Fiber	n_s (gain strength)	n_s (gain asym.)	n_s (estimated)
SMF-28⎛	1.91 ± 0.17	2.238 ± 0.096	2.33 ± 0.13
SMF-28e⎛	2.32 ± 0.17	2.277 ± 0.086	2.33 ± 0.13
LEAF→	4.29 ± 0.17	4.102 ± 0.085	4.45 ± 0.18
TrueWave→	3.40 ± 0.17	3.347 ± 0.080	3.09 ± 0.13

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[7] SMF-28⎛ and LEAF→ fibers manufactured by Corning Inc.. TrueWave→ fibers manufactured by Lucent Technology. The use of product names is necessary to specify the experimental results adequately and does not constitute or imply endorsement by the National Institute of Standards and Technology.