Raman gain: pump-wavelength dependence in single-mode fiber

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The magnitude of the stimulated Raman gain spectrum will depend on the absolute pump wavelength. Measurements of the pump-wavelength scaling of the stimulated Raman gain of several single-mode fibers are presented. The measurements were obtained by use of two techniques: a brute-force comparison of gain versus pump wavelength and a more elegant comparison of the asymmetry in the Stokes and anti-Stokes Raman gain spectrum at a fixed pump wavelength. This second asymmetry technique has the advantage that it is independent of the uncertainties typically associated with relative measurements of optical power.

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In fiber Raman amplifiers, a strong pump laser provides gain to signals at longer wavelengths through stimulated Raman scattering.[1,2] Although stimulated Raman scattering is an inherently weak process, Raman amplifiers have several properties that make them very attractive for current and future communication systems.[3–5] First, a distributed Raman amplifier can have a negative effective noise figure, thereby increasing the system reach or bandwidth. Second, since the Raman gain depends only weakly on the pump wavelength, Raman amplifiers can be used to extend the wavelength range of current wavelength-division multiplexing systems over the entire low-loss window of optical fiber. Because of the growing importance of Raman amplification, there have been a number of papers describing the Raman gain spectrum as a function of the frequency difference between the strong pump laser and the weaker signal beams.[2–6] However, there do not appear to be any available measurements of the dependence of the amplitude of the Raman gain curve on the absolute pump frequency (i.e., the pump-wavelength scaling of the Raman gain), in part because this dependence is weak from 1.4 to 1.6 μm. Instead, the basic Raman gain is often assumed to scale simply with the inverse pump wavelength; however this scaling is only to first order. Moreover, in a single-mode fiber, the experimentally relevant and accessible factor is actually the modal Raman gain factor, which is the Raman gain divided by the effective area. Knowledge of the pump-wavelength scaling of the modal Raman gain is important for simulations of both Raman amplifier performance and other Raman-based effects, such as Raman gain tilt in wavelength-division multiplexing.

In this Letter two different measurements of the scaling of the modal Raman gain with pump wavelength are presented. The first, brute-force measurement, compares the integrated gain strength of carefully calibrated Raman gain curves at different pump wavelengths. This integrated gain approach suffers from systematic uncertainties associated with comparing powers measured at different pump wavelengths. The second, more elegant measurement avoids these systematic uncertainties and determines the pump-wavelength scaling directly from the asymmetry between the Stokes and anti-Stokes sides of the Raman gain spectrum for a fixed pump wavelength. This approach also permits experimental measurements of the wavelength dependence of the wavelength scaling of the Raman gain (i.e., the second-order wavelength scaling of the Raman gain) by measuring the Raman gain curve asymmetry at different pump wavelengths.

To understand the connection between the gain asymmetry and the pump-wavelength scaling, consider three beams: a pump at frequency ω_p, a single beam on the Stokes side at $\omega_p - \delta$, and a signal beam on the anti-Stokes side at $\omega_p + \delta$. The Stokes beam will experience gain from the pump according to the amplitude of the Raman gain curve for that frequency difference δ and pump frequency ω_p. The anti-Stokes beam will experience loss (since it will effectively pump the pump laser) for the same frequency difference δ but an effective pump frequency of $\omega_p + \delta$. The difference between the gain of the Stokes beam and loss of the anti-Stokes beam is therefore directly related to the difference between the amplitude of the Raman gain for a pump at frequency ω_p and a pump at frequency $\omega_p + \delta$.

Below, measurements of the pump-wavelength scaling of the Raman gain for several standard transmission fibers are presented. The measurements are made with both the brute-force integrated gain-strength approach and the gain-asymmetry approach. A comparison of the two approaches is valuable since the uncertainties are, in a very real sense, orthogonal; the uncertainty of the integrated gain-strength measurement is primarily a result of the uncertainty in the relative pump power, whereas the uncertainty of the gain-asymmetry measurement is primarily a result of the uncertainty of the relative wavelengths of the pump and signal.

We can quantify the above-described heuristic argument connecting the asymmetry and pump-wavelength scaling as follows. As a result of stimulated Raman transitions, a strong pump with power P_p at frequency

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ω_p will provide gain to a weaker single beam of power P_s at frequency $\omega_s < \omega_p$ (i.e., on the Stokes side of the pump beam) according to

$$\frac{\mathrm{d}P_s}{\mathrm{d}z} = \int \hbar\omega_s R(\omega_s, \omega_p)\,\mathrm{d}x\,\mathrm{d}y \equiv g_{\mathrm{RM}}(\omega_s, \omega_p) P_s P_p\,, \tag{1}$$

where z is along the direction of propagation down the assumed single-mode fiber, $R(\omega_s, \omega_p)$ is the position- and wavelength-dependent stimulated Raman transition rate, and g_{RM} is the wavelength-dependent modal Raman gain coefficient. On the anti-Stokes side of the pump beam, or for $\omega_p < \omega_s$, the same expression is valid with the substitution

$$\hbar\omega_s R(\omega_s, \omega_p) \rightarrow -\hbar\omega_s R(\omega_p, \omega_s)\,. \tag{2}$$

The relationship between the wavelength scaling of the modal Raman gain and the asymmetry between the Stokes and anti-Stokes Raman gain spectra follows directly from Eqs. (1) and (2). Let us assume that the modal Raman gain coefficient can be written as the product, $f(\omega_s, \omega_p)\rho(\Delta\omega)$, of a weakly varying function, f, of the signal and pump frequencies and a strongly varying function, ρ, of the difference, $\Delta\omega = \omega_p - \omega_s$ (an assumption implicitly made in discussing the wavelength scaling of the Raman gain). Then, from Eqs. (1) and (2), $g_{\mathrm{RM}} = f(\omega_s, \omega_p)\rho(\Delta\omega)$ for $\Delta\omega > 0$ and $g_{\mathrm{RM}} = -(\omega_s/\omega_p) f(\omega_p, \omega_s)\rho(-\Delta\omega)$ for $\Delta\omega < 0$, giving an asymmetry of

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

to first order in $\Delta\omega/\omega_p$, where for simplicity the pump wavelength scaling has been parameterized by its leading power-law behavior,

$$f(\omega_s, \omega_p) \propto \omega_p^{n_s}\,. \tag{4}$$

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, n_s (which can itself depend weakly on wavelength).

Expressions (3) and (4) are the basis for the gain-asymmetry technique of determining the power-law scaling. They were derived without any explicit assumptions about the form of the stimulated Raman scattering. Nevertheless, it is useful to consider the different factors responsible for the wavelength scaling of the Raman gain. Substituting the known expression for the stimulated Raman transition[1] into Eq. (1), and integrating over the fiber area, gives

$$(g_{\mathrm{RM}})_{\mathrm{Stokes}} = \frac{8\pi^3 N}{c^2}[\omega_s]\left[\frac{M^2(\omega_s, \omega_p)}{n(\omega_s)n(\omega_p)}\right] \times \left[\frac{1}{A_{\mathrm{eff}}(\omega_s, \omega_p)}\right]\rho(\Delta\omega)\,, \tag{5}$$

where N is the density of participating molecules, $\rho(\Delta\omega)$ is the density of vibrational molecular states, M is the Raman matrix element appropriate for unpolarized light, n is the index of refraction, and A_{eff} is the standard effective area or modal overlap integral. The corresponding expression for the anti-Stokes modal Raman gain is obtained by interchange of the arguments of M and reversal of the sign of $\Delta\omega$. In general, Eq. (5) shows that the Raman gain is in fact not separable in $\Delta\omega$ and ω_p; nevertheless, a simple power-law scaling, e.g., expression (4), can often adequately describe the wavelength scaling over the wavelength range of interest.

The three terms in brackets in Eq. (5) contribute to the wavelength scaling of the Raman gain. Ascribing to them the leading power-law exponents of 1, n_M, and n_A, respectively, gives $g_{\mathrm{RM}} \propto \pm\omega_s(\omega_s\omega_p)^{(n_A+n_M)/2}\rho(\pm\Delta\omega)$ for both the Stokes (+) and anti-Stokes (−) gain, plus terms of order $(\Delta\omega/\omega_p)^2 > 10^{-2}$ or smaller. If the lowest-order dependence on the frequency difference is absorbed into the function ρ, the Stokes modal Raman gain indeed scales as expression (4), with an exponent $n_s = 1 + n_A + n_M$. The power-law exponent scaling of the matrix element, n_M, is weak in silica. The power-law exponent scaling of the effective area, n_A, is not weak and is difficult to estimate, but if it has been directly measured, n_s can be estimated.[7]

The basic experimental configuration is shown in Fig. 1. The output of a tunable external cavity laser, filtered to remove amplified spontaneous emission and polarization scrambled, provided 2–5 mW of pump power modulated at 100 Hz. A depolarized 30-μW

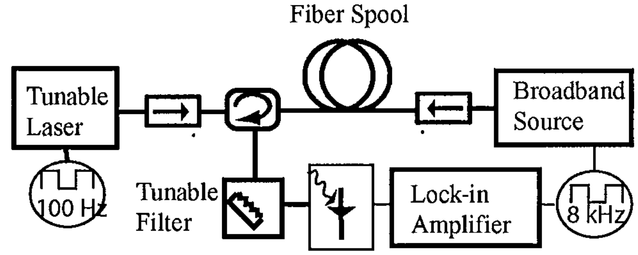

Fig. 1. Simplified schematic of the experimental setup.

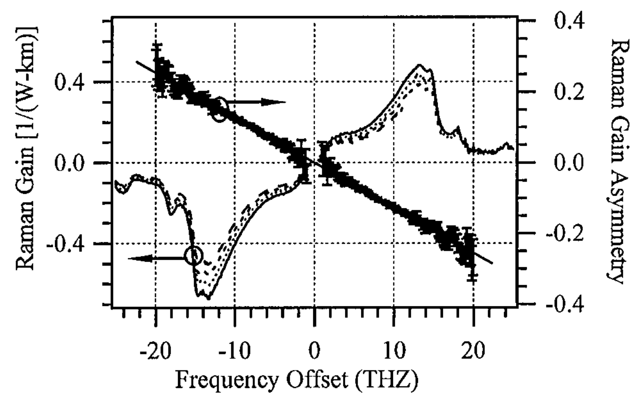

Fig. 2. Raman gain (g_{RM}) spectra versus frequency offset ($\Delta\omega/2\pi$) for LEAF fiber at increasing pump wavelengths of (solid curve) 1460 nm, (dotted curve) 1500 nm, (short-dashed curve) 1540 nm, and (long-dashed curve) 1580 nm. Also plotted is the asymmetry (A) in the Raman gain spectrum for the 1500-nm data. The linear fit is almost obscured by the data points.

Table 1. Pump-Wavelength Power-Law Scaling of the Raman Gain at 1520 nm Obtained With the Integrated Gain-Strength and the Gain-Asymmetry Techniques[a]

	n_s			
Fiber	Gain Strength	Gain Asym.	Avg.	$\mathrm{d}n_s/\mathrm{d}\lambda$ ($\mu\mathrm{m}^{-1}$)
SMF-28	1.91 ± 0.17	2.238 ± 0.096	2.158 ± 0.084	1.5 ± 1.2
SMF-28e	2.32 ± 0.17	2.277 ± 0.086	2.285 ± 0.077	2.4 ± 1.2
LEAF	4.29 ± 0.17	4.102 ± 0.085	4.139 ± 0.076	2.8 ± 1.1
TrueWave	3.40 ± 0.17	3.347 ± 0.080	3.357 ± 0.072	3.7 ± 1.0

[a]All errors are one unit of standard uncertainty (1σ).

broadband source served as a probe to measure the Raman gain from 1275 to 1680 nm. This broadband probe was amplitude modulated at 8 kHz, launched down the fiber in the opposite direction to the pump, optically filtered by a grating monochromator (FWHM of 1.75 nm), and detected by a p-i-n diode followed by a transimpedance amplifier and a lock-in amplifier. The lock-in output was modulated at 100 Hz because of the Raman gain of the probe from the pump and yielded a probe signal S_{on} with the pump on and S_{off} with the pump off. The modal Raman gain spectrum was then calculated from the on–off gain as $g_{\mathrm{RM}} = \ln(S_{\mathrm{on}}/S_{\mathrm{off}})/(P_p L_{\mathrm{eff}})$, where the effective length $L_{\mathrm{eff}} \equiv [1 - \exp(-\alpha L)]/\alpha$, which is set by the attenuation, α, at the pump wavelength, measured with the cutback method, and the fiber length, L. Note, however, that the gain-asymmetry approach is completely independent of both the pump power and the effective length.

Raman gain was measured for four different 25-km spools of standard transmission fiber at each of four pump wavelengths (1460, 1500, 1540, and 1580 nm). The modal Raman gain coefficients as a function of the pump and signal frequency offsets are given in Fig. 2 for one fiber. The basic trends in the data are clear. The Raman gain strength decreases with increasing pump wavelength. There is a corresponding strong asymmetry such that the anti-Stokes loss is larger than the Stokes gain; i.e., the probe light at shorter wavelengths loses more energy pumping the pump laser than the pump laser transfers to the longer-wavelength probe light. The Raman gain is, as expected, higher for fibers with smaller effective areas, e.g., LEAF and TrueWave, than for standard fiber, SMF-28 or SMF-28e (which have very similar Raman gain spectra).[8]

The dependence of the Raman gain on pump wavelength can be extracted from these data in two different, complementary ways: from the integrated gain strength or from the gain asymmetry. The wavelength dependence from the gain strength was calculated by fitting of the areas under identical regions of the Raman gain curves for different pump wavelengths to a power-law scaling of the form of expression (4). Table 1 lists the results for each of the four fibers. The overall standard unit of uncertainty of ±0.17 was a consequence of the 1% standard uncertainty in the measurement of the relative power at each wavelength. The wavelength dependence from the gain asymmetry was calculated by fitting of the asymmetry of each spectrum to a straight line following Eq. (3). The result for one example data set is also plotted in Fig. 2. Note that despite the strong variations of the Raman gain with wavelength the asymmetry is a remarkably straight line, indicating the validity of Eq. (3). The scaling exponents calculated from the asymmetry fit were then fitted to a straight line as a function of pump wavelength for determination of both n_s at 1520 nm and its slope, $\mathrm{d}n_s/\mathrm{d}\lambda$. The results are also presented in Table 1. The dominant uncertainty in the slope of the asymmetry resulted from the ±0.2-nm systematic uncertainty in the relative pump and signal wavelengths (not included in the error bars on the asymmetry plotted in Fig. 2). As can be seen from Table 1, the two approaches gave results that agreed to within their standard uncertainties; the third column gives the average of the two approaches. Based on the results presented here, the gain asymmetry method can provide a simple, straightforward technique for determining the first- and second-order dependence of the modal Raman gain on pump wavelength.

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8. SMF-28 and LEAF fibers manufacted 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 imply endorsement by the National Institute of Standards and Technology.