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Full Wavelength Dependence of Raman Gain in Optical Fibers: Measurements Using a Single Pump Laser

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The dependence of the Raman gain on both the absolute pump wavelength and the signal-pump wavelength difference can be determined using a simple method that relies on a single pump laser, broadband source, and OSA.

Introduction

In fiber Raman amplifiers, a strong pump laser provides gain to signals at longer wavelengths through stimulated Raman scattering [1,2]. At typical pump wavelengths of 1.4 – 1.5 µm, the Raman scattering in optical fiber occurs far from any electronic resonance, and the gain depends primarily on the difference between the pump and signal wavelengths and only weakly on the absolute pump or signal wavelengths. (Indeed, one of the major attractions of Raman amplification is that it can be used over a very wide wavelength range by multiplexing together different pump wavelengths). Initial measurements of the Raman gain focused on the strong dependence of the gain on the pump-signal frequency difference [3-6]. However, with the growing importance of Raman amplifiers, knowledge of the dependence of Raman gain on the absolute pump wavelength is important in predicting the performance of systems employing Raman amplification and of dense WDM systems where Raman gain tilt can play an important role.

In Ref. [7], the author presented and compared two different measurement techniques for determining the pump-wavelength dependence of the Raman gain. The first, brute-force technique relied on a comparison of gain curves measured with different pump lasers. The second, novel, asymmetry technique relied on a comparison of the Stokes and anti-Stokes sides of the Raman gain curve to extract the pump-wavelength dependence. This second method requires only a single pump laser, while the first method requires at least two different pump lasers. Moreover, the second method is freed from any uncertainties associated with absolute power measurements, as compared to the first method. Because Ref. [7] focused on a comparison of the two techniques, a low-power pump was used, necessitating a complicated detection system. Here the author demonstrates that if only the asymmetry technique is used to measure the pump-wavelength dependence, a much simpler experimental apparatus can be used. Indeed, the same setup and data may be used to determine the dependence of Raman gain on both the difference between the signal-pump wavelength, *i.e.,* the standard Raman gain curve, and on the absolute pump wavelength, which sets the amplitude of the standard Raman gain curve. Together, these measurements yield the full wavelength dependence of the Raman gain.

Theory

The relationship between the physical fiber parameters and the pump-wavelength dependence was described in Refs. [7,8]. Below, we follow the general argument of Ref. [7] that links the pump-wavelength dependence to the asymmetry in gain. The Raman gain (or loss) can be written as $\boldsymbol{g(\omega_p,\Delta\omega)}$, where $\boldsymbol{\omega_p}$ is the pump frequency and $\boldsymbol{\Delta\omega=\omega_p-\omega_s}$ is the frequency difference between the pump frequency and signal frequency $\boldsymbol{\omega_s}$. In terms of the stimulated Raman transition rate $\boldsymbol{R}$, we can write the Raman gain on the Stokes and anti-Stokes sides of the pump, respectively as

$$g^+\left(\omega_p,\Delta\omega\right)=\hbar\omega_s \boldsymbol{R}\left(\omega_p,\omega_s\right) \quad \text{for } \Delta\omega>0, \text{ and}$$

$$g^-\left(\omega_p,\Delta\omega\right)=-\hbar\omega_s \boldsymbol{R}\left(\omega_s,\omega_p\right) \quad \text{for } \Delta\omega<0\,.$$

If, out of convenience, the gain on the Stokes side (which is responsible for Raman amplification) is written as

$$\boldsymbol{g}^+\left(\boldsymbol{\omega}_p,\boldsymbol{\Delta\omega}\right)=\left(\boldsymbol{\omega}_p/\boldsymbol{\omega}_{p0}\right)^k \boldsymbol{g}^+\left(\boldsymbol{\omega}_{p0},\boldsymbol{\Delta\omega}\right) \quad \text{for } \boldsymbol{\Delta\omega}>0\,,$$

where *k* is the exponent describing the power-law scaling of the Raman gain with pump wavelength, and $\boldsymbol{\omega_{p0}}$ is an arbitrarily chosen reference pump frequency, then from Eqs. (1) and (2),

$$\boldsymbol{g}^-\left(\boldsymbol{\omega}_p,\boldsymbol{\Delta\omega}\right)=-\left(\boldsymbol{\omega}_s/\boldsymbol{\omega}_p\right)\left(\boldsymbol{\omega}_s/\boldsymbol{\omega}_{p0}\right)^k \boldsymbol{g}^+\left(\boldsymbol{\omega}_{p0},-\boldsymbol{\Delta\omega}\right) \quad \text{for } \boldsymbol{\Delta\omega}<0$$

Finally, from Eqs. (2) and (3) , to first order the asymmetry between the Stokes and anti-Stokes sides is

$$A=\frac{g\ (\Delta\omega)+g\ (-\Delta\omega)}{g\ (\Delta\omega)-g\ (-\Delta\omega)}=-\frac{k+1}{2\omega_p}\Delta\omega$$

In other words, the asymmetry in the gain spectrum, plotted as a function of, should be a straight line with a slope that gives the exponent of the power-law scaling. Note that the choice of a power-law scaling for the pump-wavelength dependence is an arbitrary one; other scaling laws would work equally well. However, the dependence of the power-law exponent on wavelength is weak [7], indicating that the power-law scaling is adequate over the typical wavelengths of interest.

Experiment and Results

The experimental setup used to determine the full wavelength dependence of the Raman gain was essentially identical to that commonly used to determine the dependence of the Raman gain on just the pump-signal frequency difference [4,5,9]. The basic difference is simply that the Raman-gain spectrum was measured on both sides of the pump, rather than just on the long-wavelength side. As shown in Fig. 1, 30 mW of pump light, centered at 1480 nm with a root-mean-square (rms) width of 0.3 nm, was directed down the fiber under test counterpropagating to a 30-microwatt broadband signal source. The circulator directed the broadband signal to an optical spectrum analyzer (OSA). In order to remove the effects of spontaneous Raman scattering from the laser, three OSA scans were taken: one with just the broadband source, denoted B(λ), one with both the broadband source and laser, denoted A(λ), and one with just the laser, denoted C(λ). The total gain is ln[(A-C)/B], which was then divided by the pump power and effective length to determine the Raman gain in units of 1/ (W-km). The results are shown in Fig. 2 for three standard telecommunication fibers [10]. From Eq. 4, the asymmetry in the curves of Figure 2 yields the pump-wavelength scaling. Figure 3 shows the asymmetry and Table 1 gives the resulting pump-wavelength scaling.

The uncertainty in the absolute strength of the gain, shown in Fig. 2, is ~ 1.8%, and depends primarily on the uncertainty in the pump power and fiber attenuation. The uncertainty in the pump-wavelength dependence of the Raman gain, since it is related to the asymmetry, is independent of the uncertainty in the pump power and fiber attenuation but is sensitive to factors that would change the shape of the Raman gain spectrum. There are three main contributions to the uncertainty in the pump-wavelength scaling: power drifts of the pump laser, power drifts of the broadband probe source, and relative wavelength uncertainty of the pump and spectrally resolved probe light. To eliminate slow drifts in the pump power, a low-noise current supply was used and the pump polarization was scrambled to avoid polarization-dependent loss of the components that might otherwise lead to slow power changes. The resulting pump power was monitored during a run and was stable to better than 0.002 dB over the measurement period. Drifts in the probe power were mitigated by acquiring several successive Raman-gain measurements with the OSA using different ordering of the scans labeled A, B and C above. The average Raman gain was then computed, which was much less sensitive to drifts. Moreover, the range of measured OSA scans with just the broadband probe source provided an estimate of the error from drift in probe power, and this drift was included in the total error. Finally, the relative wavelength uncertainty between the pump and spectrally resolved probe light was estimated to be ±0.1 nm based on uncertainty in the estimated line center of the pump laser and the relative wavelength uncertainty of the OSA. From Eq. (4), this wavelength uncertainty translates to an uncertainty in the asymmetry. The relative contribution to the total error was dominated by the wavelength uncertainty, followed by the error from probe power drift, and finally by random statistical error.

Fiber	This work	From Ref [7]
SMF-28	2.319 ± 0.051	2.158 ± 0.084
SMF-28e	2.356 ± 0.036	2.285 ± 0.077
LEAF	4.204 ± 0.043	4.139 ± 0.076
TrueWave	3.290 ± 0.078	3.357 ± 0.072

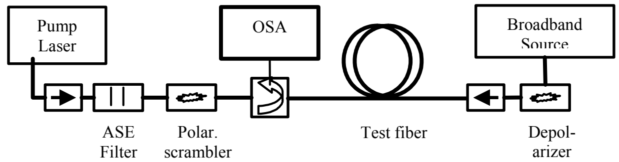

Fig 1: Experimental setup for measuring the full wavelength dependence of Raman gain

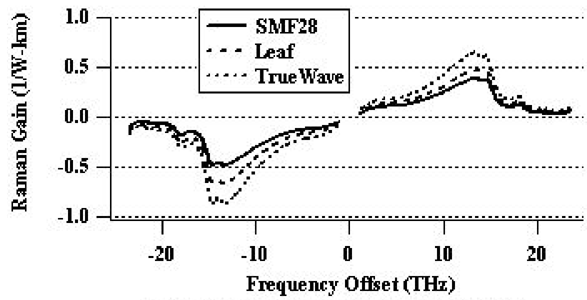

Fig. 2 Raman gain curves for three fibers.

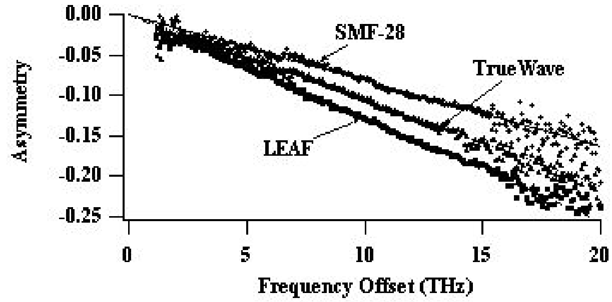

Fig. 3 Asymmetry calculated from the curves of Fig. 2. The slope gives the pump-wavelength dependence from Eq. (4).

Conclusion

The gain-asymmetry method is shown experimentally to provide a simple, straightforward technique for determining the dependence of the modal Raman gain on pump wavelength. Knowledge of this dependence should assist in simulations of Raman amplifiers that use multiple pump lasers and in assessing other Raman-based effects.

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[10]SMF-28 and LEAF fibers manufactured by Corning Inc. TrueWave fiber manufactured by OFS. 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.