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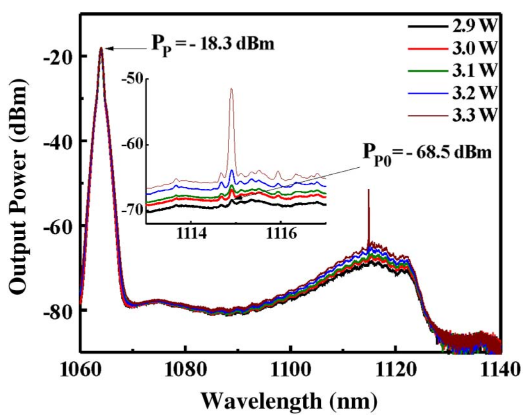

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Novel Technique for Obtaining the Raman Gain Efficiency of Silica Fibers

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Abstract: We present a simple novel technique that determines with precision the Raman gain efficiency for telecom fibers. The method is supported by a mathematical relation, which is the solution for the coupled differential equations that govern the stimulated Raman scattering. This technique is valuable due to its simplicity and consists of measuring the residual pump and the Raman scattering signals at the stimulated Raman scattering threshold. Our technique was proven for different fibers; as a result, we found that the rate of pump power to stimulated Raman scattering at threshold is lower than $\sim$16, which is the historically used value.

Index Terms: Fiber nonlinear optics, stimulated Raman Scattering, Raman laser, Raman amplifiers.

1. Introduction

The design of Raman fiber lasers and Raman fiber amplifiers is an area of study that suffers continuous changes due to new approaches and applications raised in industry, in modern research laboratories, in telecom systems, in the medical field, in applications such as laser guiding stars for astronomical observations and LIDAR [1]–[3]. The coupled differential equations that govern the stimulated Raman scattering that use these models have been widely known and put into practice for decades. The variables involved in these processes such as the Raman gain coefficient and the effective area, have been studied with analytical solutions and experimental techniques. However, the first proposed analytical solution so far, allows interplay between these variables at the specific point called Raman threshold, but this solution comes from several assumptions [4]. And thus, this leads to a mathematical equation that relates the variables approximately. For this reason, to calculate the exact values of the Raman gain coefficient and the effective area other techniques parallel to the Raman threshold technique have been developed. Some techniques for measuring the efficiency of the Raman gain use methods based on optical time domain reflectometry [5]–[8], and others, by analysis of Raman threshold [9]–[12].

In this paper, we take a mathematical equation that relates the Raman gain with experimental variables [13]. This formula comes from an analytical solution to the set of differential equations governing the stimulated Raman scattering. With this simple technique it is possible to accurately estimate the Raman gain efficiency.

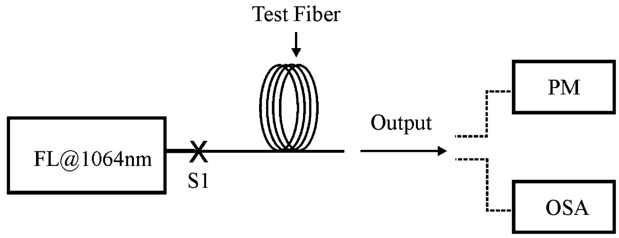

Fig. 1. Experimental setup.

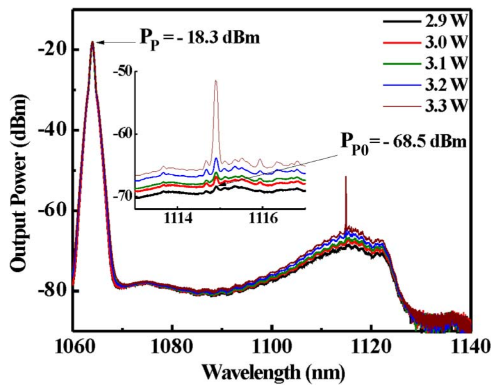

Fig. 2. Intensity spectra of five pump powers for 1 km 1060-XP fiber.

2. Theoretical Analysis

The stimulated Raman scattering (SRS) in silica fibers is governed by a set of nonlinear differential equations that describe the pump power propagation in a single direction and the SRS in both, forward and backward directions [14]. In order to describe the technique that allows us to calculate with high precision the Raman gain efficiency $(g_R = g_r/A_{eff})$, we use one solution to these equations considering only forward propagation [13]:

$$\ln\left(\frac{P_F}{P_{F0}}\frac{P_{P0}}{P_P}\right) = \frac{g_r}{A_{eff}} P_{P0} L_{eff} \tag{1}$$

where P_{P0} and P_P are respectively the coupled input and output pump powers, P_{F0} is the Raman scattered signal (RS) at the pumping end and P_F at the output. RS is the seed for the growth of Stokes signal. $Leff = (1 - \exp(-\alpha L))/\alpha$ stands for the interaction length of pump and Stokes signals. Eq. (1) describes an exponential energy transfer from pump power to Stokes power.

In a free-running configuration pumped such that RS just appears at the output, $P_F = P_{F0}$ as the fiber is completely transparent; i.e., the gain equals the fiber loss. At any pump power, in the fiber output (see Fig. 2) the relation between the output coupled pump power P_P and the coupled Raman scattering signal (P_{F0}) may be quantified by:

$$\frac{P_P}{P_{F0}} = 10^{\frac{\Delta Power\,(dBm)}{10}} \tag{2}$$

where $\Delta Power = P_P - P_{F0}$. When RS just appears at the output, the net gain of the Raman amplifier is zero $(g_n = 0)$; i.e., the Raman gain coefficient equals the fiber loss coefficient:

$$g_r^{th} = \alpha_s. \tag{3}$$

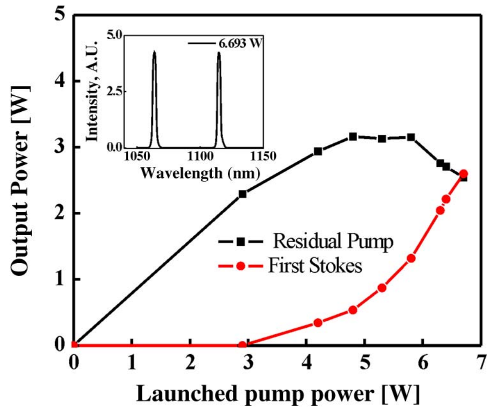

Fig. 3. Pump and Stokes powers in 1 km of 1060-XP fiber span.

Practically, under these conditions the pump signal only suffers linear attenuation and thus the relationship between the residual pump power $P_P(L)$ and the coupled pump power P_{P0} is:

$$P_P = P_{P0} e^{-\alpha L}. \tag{4}$$

Now, substituting (4) in (2), it is possible to numerically establish a relationship for P_{P0}/P_{F0} given by:

$$\frac{P_{P0}}{P_{F0}} = 10^{\frac{\Delta \text{Power (dBm)}}{10}} e^{\alpha L}. \tag{5}$$

And finally, in the Raman threshold when the residual pump power is equal to the first Stokes power at the output $(P_P = P_F)$ the Raman gain efficiency can be written as:

$$g_R = \frac{g_r}{A_{eff}} = \ln\left(\frac{P_{P0}}{P_{F0}}\right) \frac{1}{P_{CR} L_{eff}} \tag{6}$$

where P_{P0} was changed by P_{CR} (the critical power).

3. Experimental Setup

Fig. 1 shows the free-running experimental setup used to obtain the value of the Raman gain coefficient of the optical fibers under test. A 1064 nm CW fiber laser (FL) pumps a fiber and at its end an optical spectrum analyzer (OSA) is recording changes in the emission lines when the pump power is varied. A power meter (PM) measures the average power of the output signal. S1 stands for a splice between the fiber laser and the fiber under test.

With this experimental configuration the pump level was gradually increased to find the P_{F0}, and critical power. When the pumping power is released, instantaneously spontaneous Raman scattering occurs. The pump increases and the energy transfer to the signal Stokes starts, we stop pumping until finding the Raman threshold.

4. Results

With the experimental setup of Fig. 1, three commercial fibers were tested: 1060-XP, SMF-28, and True Wave fiber. Fig. 2 shows the spectral composition of the signal delivered by a 1-km 1060-XP optical fiber. The -18.3 dBm level corresponds to the residual pump $P_P(L)$. At the lowest pump power P_{P0}, only spontaneous RS occurs with signal from 1090 to 1130 nm, its maximum level is around -68.5 ± 1 dBm. We take this level as P_{F0}, the difference is $\Delta\text{Power} = 50.2 \pm 1$ dBm. Moreover, the fiber loss is 1.5 dB/km at 1064 nm given by the manufacturer, substituting these data on equation (5) yields $P_{F0} = 6.76 \times 10^{-6} \pm 1.74 \times 10^{-6}$ P_{P0} $(\sim 27 \pm 5.7\ \mu\text{W})$, such that $\ln(P_{P0}/P_{F0}) = 11.9 \pm 0.3$. The output powers P_P and P_F dependent on P_{P0} are plotted in Fig. 3.

TABLE 1

Raman gain specific values

Fiber Span	$\ln(P_{P0}/P_{F0})$	Pcr [W]	α [dB/km]	g_R [$W^{-1}Km^{-1}$]
1 km 1060-XP	11.90 ± 0.30	6.693	1.50	2.10 ± 0.05
1 km SMF-28	12.00 ± 0.38	7.640	0.88	1.75 ± 0.09
1km True Wave	12.11 ± 0.46	5.310	1.00	2.55 ± 0.10
5 km True wave	12.11 ± 0.46	1.600	1.00	2.55 ± 0.10

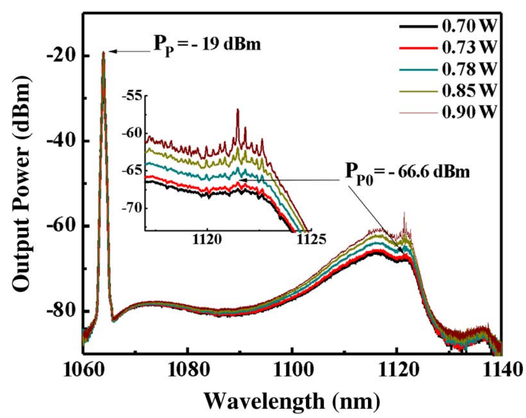

Fig. 4. Intensity spectra of five pump powers for 5 km True Wave fiber. Note that in the inset, the growth of the Stokes signal occurs at 1121.4 nm. At 0.73 W, the pump power exhibits the lowest level of RS, and the signal is evident in 0.90 W.

The inset exhibits (in linear scale) the spectrum that corresponds to $P_{P0} = P_{CR} = 6.693$ W. With these values $g_R = 2.1\ W^{-1}km^{-1}$.

We choose to P_{F0} as the minimum value of the Stokes signal or the maximum value of the spontaneous Raman scattering. Note that in the inset of Fig. 2, the growth of the Stokes signal occurs at 1115 nm. At 2.9 W exhibits the lowest level of RS, and the signal is evident in 3.3 W.

At discrete pump levels the spectrum was recorded and the output power measured. The power of each signal was estimated by comparing the area under the curve of each component with respect to the total area of the spectrum. Curves constructed with these data show the evolution of the power transferred to the first Stokes (see Fig. 3). The inset is the Raman threshold that corresponds to the intersection of the residual pump and Stokes signal. Note that this happens at 6.693 W.

The same experiments were made for various fibers with the results shown in Table 1. Attenuations α, at 1064 nm, were measured with the cutback technique [16].

For example, Fig. 4 exhibits the spectra for 5 km of True Wave fiber. From this, ΔPower $= 47.6 \pm 2$ dBm, $\alpha_P = 1$ dB/km, $P_{CR} = 1.6$ W. Substituting these data on equation (6) yields $g_R = 2.55\ W^{-1}km^{-1}$.

Additionally, using the equation of scaling of the Raman gain efficiency [16] for the True Wave fiber, we obtain $g_R(1116\ nm) = 1.8\ W^{-1}km^{-1}$. Which is approximate to the recently reported value $g_R(1116\ nm) = 1.86\ W^{-1}km^{-1}$ [15], i.e., there is a difference $\sim$4% between the two results. On the other hand, with the traditional relationship of Smith [9] the Raman gain efficiency is 3.36 $W^{-1}km^{-1}$ at 1064 nm pump power, $\sim$25% larger than our result.

On the other hand, using the equation of scaling of the Raman gain efficiency [16] for the SMF-28 fiber, we obtain $g_R(1455\ nm) = 0.37\ W^{-1}km^{-1}$ and $g_R(1480\ nm) = 0.34\ W^{-1}km^{-1}$. Which are very close to $g_R(1455\ nm) = 0.42\ W^{-1}km^{-1}$ and $g_R(1480\ nm) = 0.39\ W^{-1}km^{-1}$ reported by [17].

5. Conclusion

The technique reported in this work is useful to determine one of the most important parameters in the design of Raman lasers and amplifiers; it is versatile, simple and can be applied to any fiber. As we shown it is only required get the beginning of SRS and the critical power. For the True Wave fiber our result is very approximate to previously published data.

References

[1] M. J. F. Digonnet, *Rare-Earth-Doped Fiber Lasers and Amplifiers*. New York, NY, USA: Marcel Dekker, 2001.

[2] Y. Feng, L. Taylor, and D. Bonaccini Calia, "25 W Raman-fiber-amplifier-based 589 nm laser for laser guide star," *Opt. Exp.*, vol. 17, no. 21, pp. 19021–19026, Oct. 2009.

[3] V. R. Supradeepa, J. W. Nichsolson, C. E. Headley, M. F. Yan, B. Palsdottir, and D. Jakobsen, "A high efficiency architecture for cascaded Raman fiber lasers," *Opt. Exp.*, vol. 21, no. 6, pp. 7148–7155, Mar. 2013.

[4] R. G. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering," *Appl. Opt.*, vol. 11, no. 11, pp. 2489–2494, Nov. 1972.

[5] D. Mahgerefteh, D. L. Butler, J. Goldhar, B. Rosenberg, and G. L. Burdge, "Technique for measurement of the Raman gain coefficient in optical fibers," *Opt. Lett.*, vol. 21, no. 24, pp. 2026–2028, Dec. 1996.

[6] G. Ravet, M. Wuilpart, J. C. Froidure, M. Blondel, and P. Mégret, "Measurement of the distributed Raman gain spectrum in single-mode optical fibers," in *Proc. IEEE/LEOS Benelux Chapter*, 2002, pp. 242–245.

[7] Y. Tsutsumi and M. Ohashi, "Simple technique for measuring Raman gain efficiency spectrum distribution in single-mode fiber," in *Proc. Asia Commun. Photon. Conf. Exhib., Opt. Soc. Amer.*, 2009, pp. 1–6.

[8] K. Toge, K. Hogari, and T. Horiguchi, "Measurement of Raman gain distribution in optical fibers," *IEEE Photon. Technol. Lett.*, vol. 14, no. 7, pp. 974–976, Jul. 2002.

[9] G. Agrawal, *Nonlinear Fiber Optics*. New York, NY, USA: Academic, 2007.

[10] K. Rottwitt, A. J. Bromake, and L. Leng, "Scaling of the Raman gain coefficient: Applications to germanosilicate fibers," *J. Lightw. Technol.*, vol. 21, no. 7, pp. 1652–1662, Jul. 2003.

[11] I. A. Bufetov, M. M. Bubnov, V. B. Neustruev, V. M. Mashinsky, A. V. Shubin, M. V. Grekov, A. N. Guryanov, V. F. Khopin, E. M. Dianov, and A. M. Prokorov, "Raman gain properties of optical fibers with a high Ge-doped silica core and standard optical fibers," *Laser Phys.*, vol. 11, no. 1, pp. 130–133, Sep. 2001.

[12] O. Frazão, C. Correia, M. T. M. Rocco Giraldi, M. B. Marques, H. M Salgado, M. A. G. Martinez, J. C. A. Costa, A. P. Barbero, and J. M. Baptista, "Stimulated Raman scattering and its applications in optical communications and optical sensors," *Open Opt. J.*, vol. 3, no. 1, pp. 1–11, Feb. 2009.

[13] L. de la Cruz-May, J. A. Álvarez-Chávez, E. B. Mejía, A. Flores-Gil, F. Méndez, and S. Wabnitz, "Raman threshold for nth-order cascade Raman amplification," *Opt. Fiber Technol.*, vol. 17, no. 3, pp. 214–217, May 2011.

[14] J. AuYeung and A. Yariv, "Theory of CW Raman oscillation in optical fibers," *J. Opt. Soc. Amer.*, vol. 69, no. 6, pp. 803–807, Jun. 1979.

[15] I. D. Vatnik, D. V. Churkin, S. A. Babin, and S. K. Turitsyn, "Cascaded random distributed feedback Raman fiber laser operating at 1.2 μm," *Opt Exp.*, vol. 19, no. 19, pp. 18486–18494, Sep. 2011.

[16] L. de la Cruz-May, E. B. Mejía, O. Benavides, D. V. Talavera, and J. Vasquez Jimenez, "Exact determination of scaling of the Raman gain efficiency in silica fibers," *Laser Phys.*, vol. 23, no. 5, pp. 1–4, May 2013.

[17] E. Pincemin, D. Grot, L. Bathany, S. Gosselin, M. Joindot, S. Bordais, Y. Jaouen, and J. M. Delavaux, "Raman gain efficiencies of modern terrestrial transmission fibers in S-, C-, and L-band," presented at the Nonlinear Guided Waves Applicat. Meeting, Stresa, Italy. [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=NLGW-2002-NLTuC2