Chapter

Analysis of Energy Transfer among Stokes Components in Raman Fiber Lasers

Lelio de la Cruz-May, Efraín Mejía Beltrán, Olena Benavides and Rafael Sanchez Lara

Abstract

This work presents a methodology to estimate the pumping power required for the first Stokes to reach its maximum stored energy level, before it generates the next Stokes. These estimates are achieved by experimentally measuring the critical power and the relationship between the pumping power (P_{P0}) and the small signal of the stimulated Raman spread (P_{F0}). For our study we used 1 km of 1060-XP fiber, experimentally obtaining P_{cr} = 6.693 W, P_{F0}/P_{P0} = 6.759x10^{-6}. With these experimental data, the pump power required for the first Stokes to reach its maximum stored energy level was 13.39 W, and the stored energy in the first Stokes was 9.88 W. It is important to note that the Raman threshold $\ln(P_{P0}/P_{F0})$ = 11.9 is smaller than the initially reported ~16.

Keywords: fiber optics, Raman scattering, Raman fiber lasers

1. Introduction

Stimulated Raman Scattering (SRS) in optical fibers has been an intensified subject of studies during the last two decades; at the beginning it was investigated in non-doped optical fibers but during the last decade the hybrid rare-earth-doped combined with the pure Raman effect has been developed and attracted much attention [1]. The SRS is a phenomenon responsible of a new generation of fiber lasers and Raman amplifiers because the high brightness of the confined powers traveling and interacting along optical fibers greatly facilitate the Raman scattering (RS) based amplification. Raman scattering occurs when a monochromatic light beam propagates along an optical fiber, whereas most of the beam power is transmitted without change, a small quantity in the order of 10^{-6} per kilometer of fiber is scattered isotropically with a new frequency [2]. At high coupled pump powers, the stimulated version of this phenomenon, the SRS, occurs and the portion of this frequency-shifted scattered light that travels through the fiber core becomes amplified and demands energy to feed itself from the pump power in order be amplified. This amplification is very efficient such that most of the traveling pump power can be transferred to this Stokes component. Therefore, the SRS is the platform for the development of Raman fiber lasers and amplifiers. As the Stokes component grows very remarkably, the pump power decreases until it is unable to continue transferring energy. In a sufficiently pumped optical fiber such that the pump is practically extinguished during this energy transfer, now this Stokes can be high enough to produce the following Stokes by the same SRS-process; again, a strong enough second Stokes can produce a third one and so on. Using the historically well developed laser operating around 1064 nm as a pump source for this type of Raman-based lasers it is possible to obtain Stokes components that cover the 1.1–1.7 μm region that is of great importance for several applications such as: optical fiber communications (the internet platform), material processing (cutting, soldering, ablating, etc.), laser spectroscopy and medicine [3]. Equations for the behavior of the Raman amplification have been described in [4, 5] and their solutions have been proposed in [4, 6]. Despite these advances with the propagation equations describing the energy transfer among stokes components in Raman amplification, there is a lack of simple methods that allow the exact estimation of some important parameters such as: the Raman threshold power, the maximum pumping power necessary for the power stored in the Stokes signal to be maximized, the Raman gain coefficient and the power required to obtain any N-order of Stokes.

This chapter describes the maximum energy that can be stored in a given Stokes line as after such maximum storage it starts producing the next Stokes. From the existing physical–mathematical theories, a formula has been obtained by us and has been verified with experimental results.

2. Theory

In order to find a mathematical relationship that predicts the maximum power stored in the Stokes signal is necessary to solve the equations that describe the forward propagation of the pumping power and Stokes line in a single mode fiber given by [4, 7, 8];

$$dP_P/dz = -\alpha_P P_P - (\upsilon_P/\nu_S)\left(g_r/A_{eff}\right)P_P P_F \tag{1}$$

$$dP_F/dz = -\alpha_S P_F + \left(g_r/A_{eff}\right)P_P P_F \tag{2}$$

where P_P and P_F, ν_S and ν_P, α_P and α_S are powers, frequencies and loss coefficients of pump power and Stokes signal, respectively. A_{eff} is effective area, and g_r is the Raman gain coefficient of the Stokes signal.

Assuming that $\alpha_p \approx \alpha_s$ it is possible to minimize the errors by establishing $\alpha = (\alpha_p + \alpha_s)/2$ given that the attenuation curve of the silica fiber is approximately constant in the region covering pump and first Stokes signals. An analytical solution of the equations that govern the SRS can be obtained by the following procedure:

A. First dividing the Eq. (1) between Eq. (2),

$$\frac{dzdP_P}{dzdP_F} = \frac{\left(-\alpha - \frac{\upsilon_P}{\upsilon_s}\frac{gr}{A_{eff}}P_F\right)P_P}{\left(-\alpha + \frac{gr}{A_{eff}}P_P\right)P_F} \tag{3}$$

Where the term dz is canceled, and consequently we proceed to the separation of variables, to obtain the following mathematical expression:

$$\left(-\alpha + \frac{gr}{A_{eff}}P_P\right)\frac{dP_P}{P_P} = \left(-\alpha - \frac{\upsilon_p}{\upsilon_s}\frac{gr}{A_{eff}}P_F\right)\frac{dP_F}{P_F} \tag{4}$$

Solving the differential equation by the separable equation method, we obtain the following expression:

$$\ln\left[\left(\frac{P_{FL}}{P_{F0}}\right)\left(\frac{P_{P0}}{P_{PL}}\right)\right] = \left(\frac{g_r}{A_{eff}}\right)\left(\frac{\upsilon_P}{\nu_S}\right)\frac{1}{\alpha}\left[\left(\left(\frac{\upsilon_S}{\nu_P}\right)P_{P0} + P_{F0}\right) - \left(\left(\frac{\upsilon_S}{\nu_P}\right)P_{PL} + P_{FL}\right)\right] \tag{5}$$

Where the parameters represent: P_{PL} output pump power, P_{P0} input pump power, P_{FL} output power Stokes and P_{F0} initial power Stokes, and evaluated in all the fiber from $z = 0$ to $z = L$.

B. Adding the Eqs. (1) and (2).

First, we will multiply the Eq. (2) by (ν_p/ν_s), and consequently, the algebraic operation results:

$$\frac{d}{dz}\left(P_P + \frac{v_p}{v_s}P_F\right) = -\alpha\left(P_P + \frac{v_p}{v_s}P_F\right) \tag{6}$$

Performing algebraic operation and integrating by separable variable, we obtain:

$$\left(\left(\frac{\nu_S}{\nu_P}\right)P_{PL} + P_{FL}\right) = \left(\left(\frac{\nu_S}{\nu_P}\right)P_{P0} + P_{F0}\right)e^{-\alpha L} \tag{7}$$

where P_{P0} and P_{PL} are the input and output powers, P_{F0} and P_{FL} are initial and output Stokes signal. L is the fiber length.

On the other hand, for a 1-Km of any telecom optical fiber, approximately a few millionths of the input pump power (P_{P0}) becomes available at the output as RS (spontaneous, linear) Stokes signal (P_{F0}), this is practically the signal that initiates the amplification process once the stimulated process takes place. Therefore, the term $((\nu_S/\nu_P)P_{P0} + P_{F0}) \approx (\nu_S/\nu_P)P_{P0}$ [2]. Substituting Eq. (7) in Eq. (5), it is obtained a general solution to differential Eqs. (1) and (2), given by [6]:

$$\ln\left(\frac{P_F}{P_p}\frac{P_{P0}}{P_{F0}}\right) = \frac{g_r}{A_{eff}}P_{P0}L_{eff} \tag{8}$$

where $L_{\text{eff}} = [(1\text{-}\exp(-\alpha L))/\alpha]$ represents the interaction length of the pumping and the Stokes signal. Eq. (5) provides information on parameters such as the Raman gain, the powers of the Pump and Stokes signals at the output end of the fiber.

3. Raman threshold

Raman threshold is a very important parameter since above this power the energy transfer from pump to the first Stokes becomes highly efficient (**Table 1**). In optical amplification, it is important to operate above threshold; on the contrary, not reaching threshold becomes crucial in multichannel communications systems as non-linearly produced Stokes-copies of any channel can interfere with neighboring channels. [2].

Figure 1 presents the output powers of: (a) Residual pump (black line with squares) and (b) Stokes signal at 1117 nm (red line with circles) at the output of

Fiber span [km]	L_{eff} [km]	P^{1st}_{Max} [W]	P_1^{Sto} [W]
1	0.846	13.39	9.88
2	1.443	7.48	3.9
5	2.371	4.77	0.88

Table 1.
Three estimates of maximum stokes power for 1060-XP fiber.

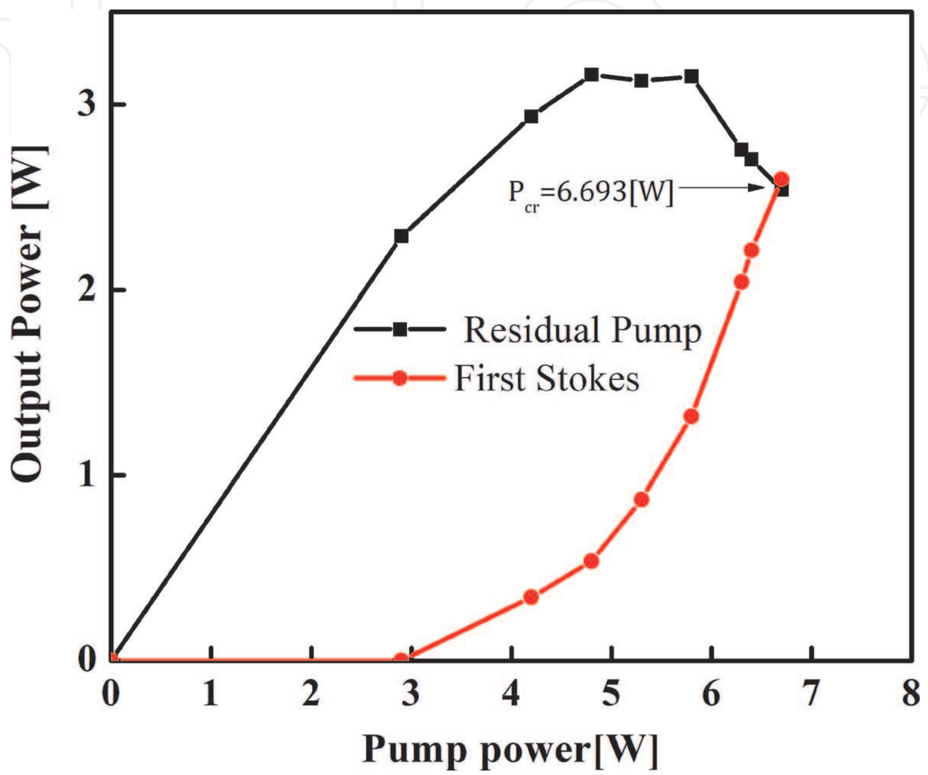

Figure 1.
Residual-pump and stokes powers delivered at the output of an optical fiber as functions of the pump power coupled at the input.

1-km 1060-XP optical fiber as a functions of 1064-nm pump power. Observe that the aforementioned threshold pump was around 2.9 W. There is another important parameter in which the residual and Stokes powers are equal, this is called the critical (pump) power that occurs at 6.693 W. These curves were obtained by splicing the 1060-XP optical fiber to an Ytterbium-based 1064-nm fiber laser without forming a laser cavity; i.e., in a free-running configuration.

At critical power ($P_P = P_F$) from Eq. (8) we have:

$$\ln\left(\frac{P_{P0}}{P_{F0}}\right) = \frac{g_r}{A_{eff}} P_{Pcr} L_{eff} \tag{9}$$

Taking into account that for standard fibers of 1-km length P_{F0} is in the order of $P_{P0}x10^{-6}$; under this assumption, Eq. (9) usually approximates:

$$16 \approx \frac{g_r}{A_{eff}} P_{cr} L_{eff} \tag{10}$$

where P_{P0} is equal to the critical power P_{cr}. This relationship has been previously reported [4] and used in several research works presenting an acceptable accuracy.

Modern specialty optical fibers are designed for purposes other than optical communications and are usually doped with materials such as P_2O_5, GeO_2 and B_2O_4

to improve some of their properties for different applications; for such special fibers the Eq. (10) is not a good approximation, in this sense, the relationship P_{P0}/P_{F0} must be determined experimentally, as it is the case in this work. This ratio is unique for each optical fiber, that is, each optical fiber has its own response to the stimulated Raman scattering [9].

4. Raman gain

The Raman gain coefficient g_r describes how the Stokes power grows as the pump power is transferred through the stimulated Raman scattering; in our case, given that the optical fiber under test has common characteristics, Eq. (9) is useful to calculate the Raman gain. Note that the effective fiber length is a constant that depends on the loss coefficient and the fiber length.

An analysis of the behavior below threshold, at threshold and above threshold is presented by the corresponding spectra on **Figure 2**. These spectra exactly correspond to the same experiment corresponding to **Figure 1**.

Observe that at 2.9-W pump power, the Stokes power has −68.5 dBm, this is the maximum RS level P_{F0} (the figure presents an error, instead of P_{P0} it should be P_{F0}). The evolution of this signal is presented until the SRS signal is evident at 3.3-W pump [9].

At any pump power, at the fiber output the relation between the output coupled pump power P_P and the produced Raman signal (P_{F0}) may be quantified by:

$$\frac{P_P}{P_{FO}} = 10^{\frac{\Delta Power(dBm)}{10}} \tag{11}$$

where $\Delta Power = P_P\text{-}P_{F0}$. When the spontaneous Raman just appears at the output, practically, 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:

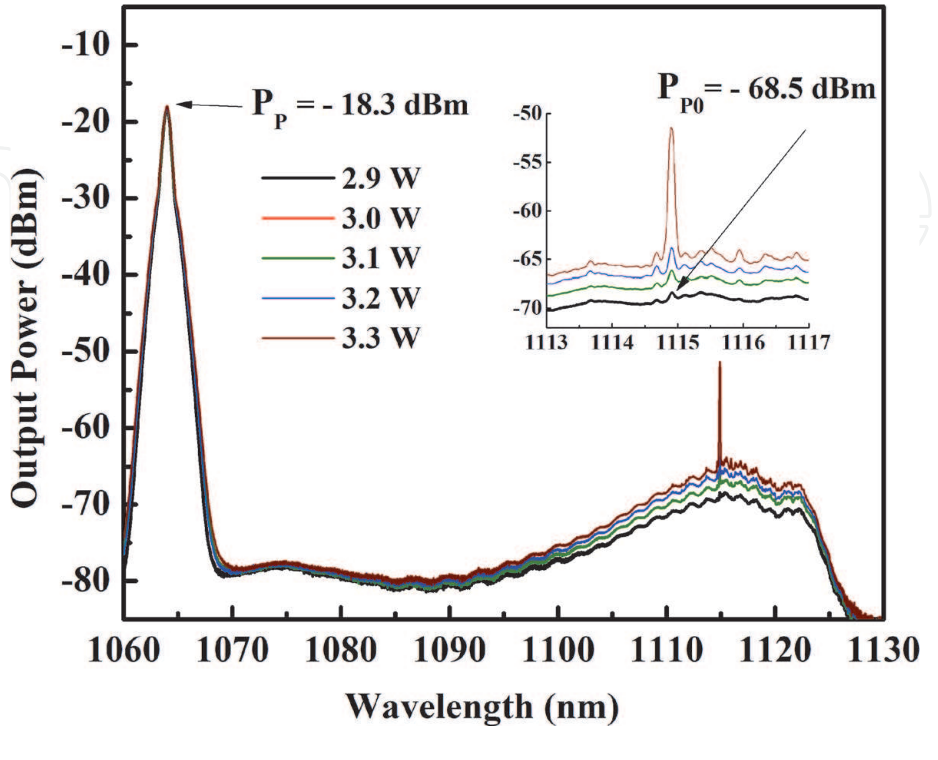

Figure 2.
Output signals of the 1-km 1060-XP optical fiber.

$$P_P = P_{P_0} e^{-\alpha L} \tag{12}$$

Now, substituting Eq. (7) in (6), it is possible to numerically establish a relationship for P_{P0}/P_{F0} given by:

$$\frac{P_{PO}}{P_{FO}} = 10^{\frac{\Delta Power(dBm)}{10}} e^{\alpha L} \tag{13}$$

Note that the term on the left side of Eq. (13) is constant, and it depends on the physical characteristics of the optical fiber and its response to spontaneous RS [8]. And it can be evaluated just when the spontaneous Raman Scattering becomes stimulated Raman scattering, then this relationship can be obtained experimentally from **Figure 2**.

Then using this numerical result, one obtains the Raman gain efficiency by rewriting Eq. (9) as:

$$g_R = \frac{g_r}{A_{eff}} = ln\left(\frac{P_{P0}}{P_{F0}}\right) \frac{1}{P_{cr} L_{eff}} \tag{14}$$

Figure 2 shows the spectral composition of the signal delivered by te 1-km 1060-XP optical fiber. Note that, −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. Taking this level as P_{F0}, the difference is ΔPower = 50.2 ± 1 dBm. The fiber loss is 1.5 dB/Km at 1064 nm according with the technical specification provided by de manufacturer. Substituting these data on the Eq. (13) yields P_{P0}/P_{F0} = 147,945.506 and $\ln(P_{P0}/P_{F0})$ = 11.9, hence P_{F0} = 6.759x10^{-6}P_{P0}. These numbers are of great importance, instead of obtaining the 16-number of Eq. (10), we have obtained 11.9, meaning that this is not considered a standard telecommunications fiber, this is true since it was designed for operating in the 1060-nm region; also note that the RS signal produced by 1-km of this fiber was 6.76x10^{-6} multiplied by the pump power. Everything is within the values expected.

Using the critical power P_{cr} = 6.693 W from **Figure 1**, and calculating the effective length L_{eff} = 0.846 km one may use the Eq. (14) to obtain the Raman gain efficiency g_R = 2.1[W^{-1} km^{-1}]; very important value to be used to model the propagation of pump and stokes in a fiber Raman laser system using Eqs. (1) and (2).

5. Maximum power stored in first stokes

Once the Raman threshold is reached, first Stokes grows quickly until the pump power is unable to continue transferring power, and this energy transfer is described by Eq. (8). When the energy transfer ceases, the first Stokes reaches its maximum value, denoted by P_{Max}^{1st}, and precisely the first Stokes is capable of generating the second Stokes. We have previously known that approximately six millionth of pump power is transferred in spontaneous RS, that is, P_{F0}/P_{P0} = 6.759x10^{-6}. We propose that the pump power ceases to transfer energy to the first Stokes when it reaches a value of six millionth multiplied by the threshold power. In this sense, and to estimate an approximate value to produce the next Stokes, we propose this be similar to $P_{F0}/P_{P0} = P_P/P_F = 1/\varepsilon$, in such a way that Eq. (8) becomes;

$$P_{Max}^{1st} = 2\ln(\varepsilon) \frac{A_{eff}}{g_r} \frac{1}{L_{eff}} \tag{15}$$

Eq. (15) represents the pumping power that must be used for the first Stokes to reach its maximum energy level. Substituting Eq. (15) in Eq. (7), and neglecting the terms P_{F0} and P_{PL}, because their values are very small, consequently, an equation is obtained for the power stored in the first Stokes, given by:

$$P_1^{Sto} = \frac{\upsilon_S}{\nu_P} 2\ln(\varepsilon) \frac{A_{eff}}{g_r} \frac{1}{L_{eff}} e^{-\alpha L} \tag{16}$$

Taking previous data for the 1060-XP fiber, $\ln(\varepsilon) = \ln(P_{P0}/P_{F0}) = 11.9$, $g_R = 2.1$ $[W^{-1}\,km^{-1}]$ and 1.5 dB/Km. On the other hand, using $\lambda s = 1120$ nm and $\lambda p = 1064$ nm, we can estimate the maximum pump power and the maximum power stored in the first Stokes, for different fiber span.

In general, the pumping power for storing the maximum energy in N-order Stokes is given by;

$$P_{Max}^{N} = 2\ln(\varepsilon) \frac{A_{eff}}{g_r} \frac{1}{L_{eff}} \left[1 + \frac{\lambda_P}{\lambda_s} + \frac{\lambda_s}{\lambda_{s2}} + \ldots + \frac{\lambda_{N-1}}{\lambda_N}\right] \tag{17}$$

With this equation, we obtain approximately the maximum power stored in the N-order Stokes before generating the N + 1-order Stokes. This equation is versatile because the parameters involved are simple to calculate. To date, the Eq. (17) at least of our knowledge has not been reported.

And finally, the ratio between the maximum power stored and coupled pump power for the first Stokes is given by;

$$\frac{P_1^{Sto}}{P_{Max}^{1st}} = \frac{\lambda_P}{\lambda_s} e^{-\alpha L} \tag{18}$$

This equation depends on the attenuation and the fiber length, and describes the optical conversion efficiency for a particular fiber length (L) and fiber attenuation (α). If $L = 0$, the Eq. (18) gives the maximum energy conversion efficiency or quantum efficiency.

In this sense, for a longer optical fiber the energy conversion efficiency is lower. For example, for 5 km of 1060-XP fiber this value can be $\sim$17%. This implies that the fibers for the design of Raman lasers and Raman amplifiers must be of a length that allows an acceptable conversion efficiency [10, 11].

6. Conclusions

An analytical equation was developed to predict the pumping power necessary to store the maximum energy in the first Stokes, this is a powerful tool for numerical simulations, which can provide specific data for the design of Raman fiber lasers. Consequently, an analytical equation is deduced that can predict the stored power in the following Stokes orders, that is, progressively, the second, the third, etc.

For a 1 km fiber span, 13.39 W of pumping power is required to get the first Stokes to reach its maximum stored energy level of 9.88 W, while for 5-km of fiber span a pump power of 4.77 W is required to obtain 0.88 W. It is important to mention that the experimental calculation of $\ln(P_{P0}/P_{F0})$ let us conclude that the fiber is not intended for telecommunications as the $\sim$16 number is not satisfied.

Finally, it is important to note that commercial single-mode fiber lasers normally operate at pump powers of around 10 W, therefore, an estimate such as the one made in this work is fundamental.

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