



An introduction to Stimulated Raman Scattering and its Applications in Optical Fiber Communications

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Abstract

The nonlinear scattering effects in optical fiber occur due to inelastic-scattering of a photon to a lower energy photon. This review presents the stimulated Raman scattering and some of its applications in fiber optic communications.

I. Introduction

The nonlinear Raman phenomenon was observed by C. V. Raman in 1928. In 1971, the stimulated Raman scattering (SRS) in glass fiber was observed by Stolen et al. [41]. The same group in 1972 measured the Raman gain in single-mode fiber [42]. More recently, the SRS has been used for optical amplification in optical telecommunications in

distributed or discrete signal amplification. Even if discovered many years ago [43] and highly investigated in the past [44], applications of Stimulated Raman Scattering (SRS) presented a renewed interest for compensation of optical losses in fibers transmissions [45], for the development of new tunable laser sources [46] or for low

noise amplification of optically carried radio frequency signals. Research on Raman amplification in optical fibers started early in the 1970s [41]. The advantages from Raman amplification in the transmission fiber were studied since the mid-1980s [47]. But, around 1995, when the maturity of suit-able high power pump lasers was achieved [48] new interest in Raman amplification emerged. Researchers have showed some of the advantages that Raman amplifiers have over EDFAs, particularly when the transmission fiber itself is used as a Raman amplifier [49, 50]. This enabled to increase the advances in Raman amplifier technology [51]. Some of these advances are the novel Raman pumping schemes recently used in transmission experiments.

Recently, there has been much investigation in order to obtain devices to amplify or generate light using stimulated Raman scattering in silicon [52]. The Raman coefficient of silicon is several orders of magnitude larger than silica [53], thus reducing the needed interaction lengths for stimulated Raman scattering and optical gain to practical lengths for planar waveguides [54]. As the first order Raman scattering shift in silicon is 15.6 THz and the 1400-1500 nm wavelength range high power pump lasers are already commercially available, Raman amplification is a possibly

implementable and attractive result for providing narrowband gain or lasing in silicon-on-insulator waveguide devices at the wavelengths for telecommunications [54]. The first experiment of spontaneous Raman emission in silicon waveguides in 2003 [52] was followed by the demonstration of stimulated Raman scattering [53] and parametric Raman wavelength conversion [55].

The Raman Effect in silicon is advantageous since it does not need rare earth dopants and its spectrum is widely tunable through the pump laser wave-length. The use of germanium in the nonlinear Raman processes in silicon presents new possibilities for adjusting the device characteristics. Recently, the first GeSi optical Raman amplifier and laser were demonstrated [56]. The results indicate that the spectrum of Raman scattering can be tailored using the GeSi material system. Therefore, GeSi Raman devices represent a stimulating subject for future research and development.

In this work, the author presents an overview of stimulated Raman scattering and its applications.

Stimulated Raman Scattering

The Raman scattering effect is the inelastic scattering [1] of a photon with an optical

phonon, which originates from a finite response time of the third order nonlinear polarization [20] of the material. When a monochromatic light beam propagates in an optical fiber, spontaneous Raman scattering occurs. It transfers some of the photons to new frequencies. The scattered photons may lose energy (Stokes shift) or gain energy (anti-Stokes shift). If the pump beam is linearly polarized, the polarization of scattered photon may be the same (parallel scattering) or orthogonal (perpendicular scattering). If photons at other frequencies are already present then the probability of scattering to those frequencies is enhanced. This process is known as stimulated Raman scattering.

In stimulated Raman scattering, a coincident photon at the downshifted frequency will receive a gain. This feature of Raman scattering is exploited in Raman amplifiers for signal amplification.

A. Basic Theory

Raman scattering is a weak effect in comparison to Rayleigh scattering. It occurs due to slight modulation of the refractive index through molecular vibration of material [2, 15]. A photon with energy $\hbar\omega_p$ travelling through a material can excite a vibrational transition of the material forming optical phonon with energy $\hbar\omega_v$ and a photon with

slightly reduced energy $\hbar\omega_s$ (Figure 1) such that:

$$\hbar\omega_s = \hbar\omega_p - \hbar\omega_v$$

The modulation in refractive index is taken into account through discussion of polarizability of material in case of Raman scattering process. To understand this, the classical model of Raman scattering may be a simple way. In this model, it is assumed that electrons are attached to an atom through a spring, and the strength of the spring is assumed to depend on the position of the atom. If atom is in vibrational motion with angular frequency ω_v , then spring constant is modulated at angular frequency ω_p . If a light wave of angular frequency ω_p propagates through the material, the motion of electron will be amplitude modulated sinusoidal motion. Therefore the radiation generated by the electron will also be amplitude modulated. This radiation has components $\omega_p \pm \omega_v$ corresponding to Stokes and anti-Stokes Raman scattering.

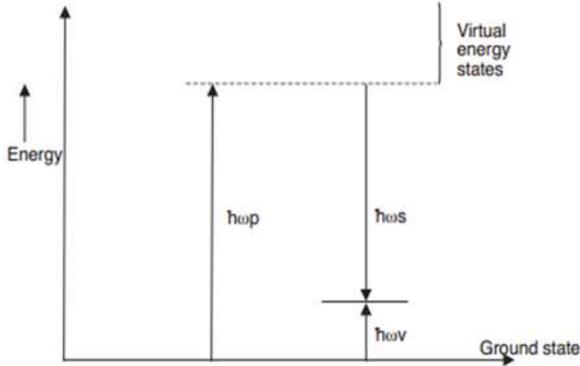
When a light wave with angular frequency ω is incident on the material, the electric field vector will induce a dipole moment p such that:

$$p = \alpha E \quad (1)$$

Where α is molecular polarizability and E is electric field vector. The α measures the

resistance of the particle to the displacement of its electron cloud.

Fig. 1: Schematic Representation of Raman Scattering.



For harmonic electric field $E(t) = E_0 \exp(j\omega_p t)$, the variation of α with time can be written as

$$\alpha(t) = \alpha_0 + \left(\frac{\partial \alpha}{\partial x}\right)_{x_0} dx(t) \quad (2)$$

Here $dx(t)$ is the displacement from the equilibrium molecular length x_0 such that

$$dx(t) = dx_0 \exp[\pm j\omega_V t] \quad (3)$$

Now,

$$p(t) = \alpha(t) E(t) \quad (4)$$

Using Equations (2) and (3), $p(t)$ can be obtained as

$$p(t) = \alpha_0 E_0 \exp[j\omega_p t] + \left(\frac{\partial \alpha}{\partial x}\right)_{x_0} dx_0 E_0 \exp[j(\omega_p \pm \omega_V)t] \quad (4)$$

The polarization vector P is defined as dipole moment per unit volume. If there are N

dipoles per unit volume then,

$$P(t) = N\alpha_0 E_0 \exp[j\omega_p t] + \left(\frac{\partial \alpha}{\partial x}\right)_{x_0} dx_0 N E_0 \exp[j(\omega_p \pm \omega_V)t] \quad (5)$$

This expression consists of two parts. The first part corresponds to linear optical phenomenon, and relative to incident radiation, it remains un-shifted. The second part is nonlinear because the output frequency is different from input one.

Fig. 2(a): Stokes scattering process

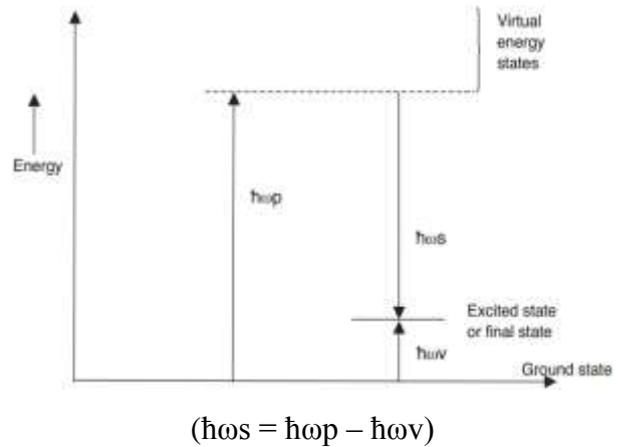
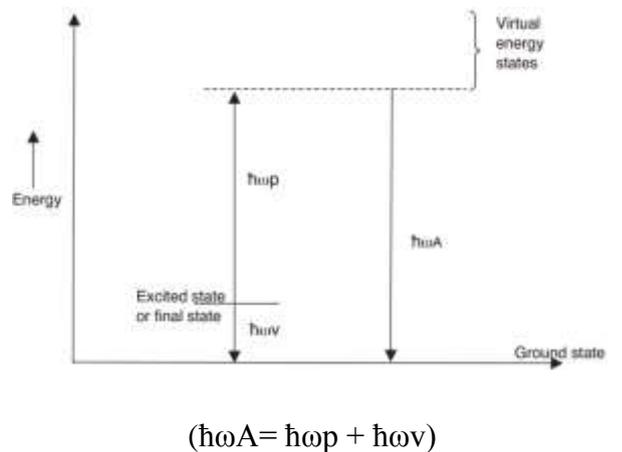


Fig. 2(b): Anti-Stokes scattering process



The scattered light with lower energy

$(\hbar\omega_s < \hbar\omega_p)$ corresponds to Stokes scattering (Figure 2(a)) and with higher energy $(\hbar\omega_A > \hbar\omega_p)$ one has anti-Stokes scattering phenomenon (Figure 2(b)). In thermal equilibrium situation, because of greater population of the ground state in comparison to vibrational state, the Stokes scattering dominates. At low illumination levels, the spontaneous Raman scattering occurs because in this situation molecules contributing to the process are vibrating independently and hence scattered light is non-directional. But when the intensity level becomes high the molecules may be considered as an array of vibrating oscillators and the generated photons aligned in phase or behave coherently. This results in stimulated Raman scattering (SRS).

B. The Raman Process

In quantum mechanical picture, Raman effect is a process, which involves double quantum molecular transition. In most frequent Stokes scattering process, the energy of incident photon $(\hbar\omega_p)$ is reduced to lower level $(\hbar\omega_s)$ and difference energy is transferred to molecule of silica in form of kinetic energy, inducing stretching, bending or rocking of the molecular bonds [21]. The Raman shift $\omega_R (= \omega_p - \omega_s)$ is dictated by the vibrational energy levels of silica.

The Stokes Raman process is also known as

the forward Raman process (Figure 2(a)) and the energy conservation for the process is

$$E_g + \hbar\omega_p = E_f + \hbar\omega_s$$

Where E_g and E_f are ground state and final state energies respectively.

The absorption of incident photon, the emission of scattered photon and transition of the molecule to excited state occurs simultaneously in one step. Therefore, Raman process may be considered as a single step process, which makes stimulated Raman effect possible whenever sufficient numbers of Stokes photons are created. At this juncture it is worth to mention that, in step wise transitions, the absorption and emission of photons occur through two consecutive single quantum transitions via a third molecular energy level. Such transitions are associated with complete disruption of the phase of a molecule after each act of absorption and emission of a single quantum.

C. SRS Spectrum

With classical electromagnetic concepts, the growth of stimulated Raman scattered signal intensity [1] is proportional to the product of the pump (I_p) and signal (I_s) intensities such that

$$\frac{dI_s}{dz} = g_R I_p I_s \quad (6)$$

Here g_R is known as Raman-gain coefficient.

In order to generate stimulated emission, Stokes and pump waves must overlap spatially and temporally. The Raman-gain coefficient g_R is related to cross-section of spontaneous Raman scattering. The probability of a Raman scattering is proportional to the number of photons in pump wave per cross-sectional area and Raman cross-section. The material properties determine almost entirely the frequency spectrum of Raman cross-section because the Raman process is related to vibrational modes of the molecules of material. In crystalline materials, the Raman scattered light has a narrow bandwidth. The silica, which is main constituent of optical fiber, is amorphous in nature. The vibrational energy levels of such materials are not sharp but merge together and form a band [24]. In such a situation the Stokes frequency (ω_S) may differ from pump frequency (ω_P) over a wide range. Two major peaks occur at 13 THz and 15 THz for Raman shift $\omega_R = \omega_P - \omega_S$. For this shift, some minor peaks are also present in spectrum [25]. Therefore, the amorphous nature of silica is responsible for large bandwidth and multippeak nature of spectrum (Figure 3). This extension of Raman-gain over broad range in silica fiber

[26] is exploited in broadband Raman amplifiers.

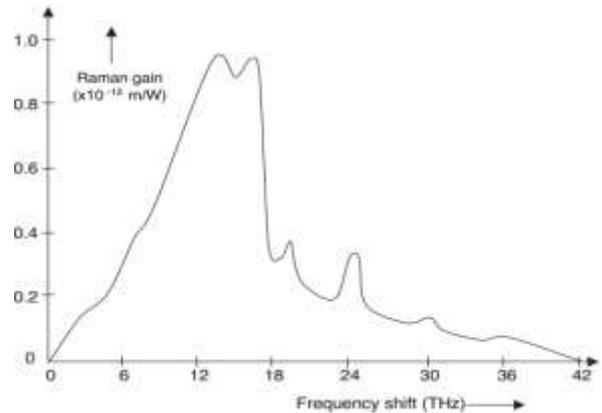
D. Threshold Power

The initial growth in Stokes wave is given by Equation (6). Considering the fiber losses, the net growth in Stokes wave is written as

$$\frac{dI_S}{dz} = g_R I_P I_S - \alpha_S I_S \quad (7)$$

Where α_S is attenuation coefficient.

Fig. 4: Spectrum of Raman gain for silica at pump wavelength 1 μ m



For pump wave the coupled equation can be written as

$$\frac{dI_P}{dz} = -\frac{\omega_P}{\omega_S} g_R I_P I_S - \alpha_P I_P \quad (8)$$

Equations (7) and (8) are known as coupled wave equations for forward Raman scattering process [6]. In case of backward SRS process, Equation (8) remains same but in Equation (7) a minus sign must be added to dI_S/dz . This set of equation is similar to SBS process. The

coupled equations for forward and backward SRS process may be understood phenomenologically by keeping in mind the processes through which photons appear in or disappear from each beam. In absence of losses due to fiber, Equations (7) and (8) can be reduced to

$$\frac{d}{dz} \left(\frac{I_S}{\omega_S} + \frac{I_P}{\omega_P} \right) = 0 \quad (9)$$

This equation dictates the conservation law on total number of photons in pump and Stokes waves during the SRS process.

The stimulation occurs in Raman process when pump power exceeds a certain power level known as threshold power. In order to grow the stimulated scattering, the stimulated gain must exceed linear loss. In fact this is the origin of threshold power.

SRS can occur in both directions i.e., forward and backward direction in optical fibers. The beat frequency $(\omega_P - \omega_S)$ drives the molecular oscillations. These oscillations are responsible for increment in amplitude of scattered wave which in turn enhances the molecular oscillations. In this way a positive feedback loop is setup. It results in SRS process. The feedback process is governed by coupled Equations (7) and (8).

In case of forward SRS process the pump depletion can be neglected for estimating the

Raman threshold [11]. Therefore first term on right hand side of Equation (8) can be neglected.

$$\frac{dI_P}{dz} = -\alpha_P I_P \quad (10)$$

Solution of this equation can be written as

$$I_P(z) = I_0 \exp[-\alpha_P z] \quad (11)$$

With Equation (7) and (11) we may have,

$$I_S(L) = I_S(0) \exp[g_R I_0 L_{eff} - \alpha_P L] \quad (12)$$

Where, effective length, $L_{eff} = \frac{1 - \exp[-\alpha_P L]}{\alpha_P}$.

Practically, SRS builds up from spontaneous Raman scattering occurring throughout the fiber length. The Stokes power can be calculated by considering amplification of each frequency component of energy $\hbar\omega$ according to Equation (12) and integrating over the whole range of Raman-gain spectrum, i.e.,

$$P_S(L) = \int_{-\infty}^{\infty} \hbar\omega \exp[g_R(\omega_P - \omega)I_0 L_{eff} - \alpha_S L] d\omega \quad (13)$$

The main contribution to the integral comes from narrow region around the gain peak. So using $\omega = \omega_S$, above equation can be written as

$$P_S(L) = \int_{-\infty}^{\infty} \hbar\omega \exp[g_R(\omega_P - \omega)I_0 L_{eff} - \alpha_S L] d\omega_S \quad (14)$$

In terms of power, the Equation (11) may be written as under

$$P_p(L) = P_0 \exp[-\alpha_p L] \quad (15)$$

Where $P_0 = I_0 A_{eff}$ is input pump power and A_{eff} is effective core area. The Raman threshold is also defined as the input pump power at which the Stokes power becomes equal to the pump power at the fibre output. So,

$$P_s(L) = P_p(L) = P_0 \exp[-\alpha_p L] \quad (16)$$

With assumption $\alpha = \alpha_s$, the threshold condition may be approximated [11] by using Equation (14) and (16) we can write,

$$P_{th} \approx \frac{16 A_{eff}}{g_R A_{eff}} \quad (17)$$

Exactly a similar analysis can be carried out for backward SRS, and threshold power can be approximated as

$$P_{th} \approx \frac{20 A_{eff}}{g_R A_{eff}} \quad (18)$$

Clearly the threshold for forward SRS is reached first at a given pump power. The backward SRS is generally not observed in fibers.

The Equation (17) is derived by using many approximations, but it is able to predict the Raman threshold quite accurately. For a typical optical communication system at 1550 nm, $A_{eff} \approx 50 \mu m^2$, $L_{eff} \approx 20 km$ and $g_R \approx 6 \times 10^{-14} m/W$. With these values Equation (17) predicts $P_{th} \approx 570 mW$. As channel powers in optical communication systems are typically below 10 mW, SRS process is not a limiting factor for single-channel light wave systems. However it affects the performance of WDM systems considerably.

E. Threshold Power

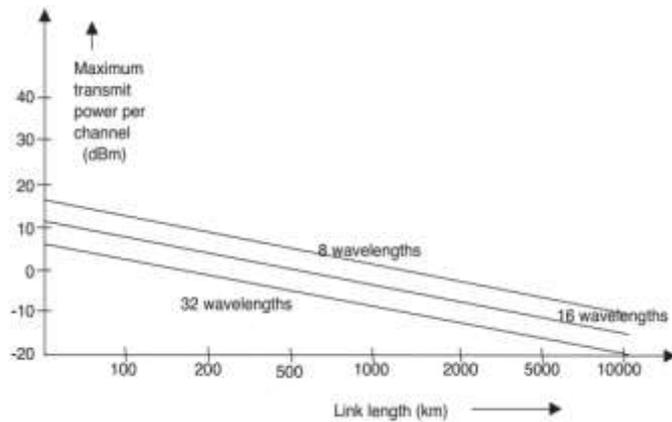
Many schemes can be applied for reduction of power penalty in SRS process [14, 15], such as,

Presence of dispersion reduces the SRS penalty. In presence of dispersion, signals in different channels travel at different velocities and hence reducing chances of overlap between pulses propagating at different wave lengths.

By decreasing channel spacing SRS penalty can be reduced.

The power level should be kept below threshold level which requires the reduction in distance between amplifiers [27]. The SRS imposed limitations on the maximum transmit power per channel is shown in Figure 5.

Fig. 5: SRS produced limitation on maximum transmit power per channel. Channel spacing = 0.8 nm, and amplifiers are spaced 80 km apart.



III. Applications of SRS Phenomenon

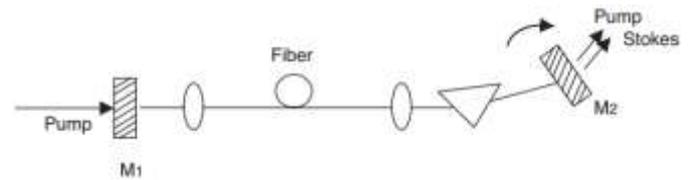
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The SRS process is exploited in many applications, which includes,

Raman Fiber Laser: Fiber based Raman lasers [28, 29] are developed by employing the SRS phenomenon. The Figure 11 shows a schematic of Raman laser. The partially reflecting mirrors M1 and M2 form a Fabry-

Perot cavity. Inside the cavity a piece of single mode fiber is placed in which SRS process occurs due wave length-selective feedback for the Stokes light. This results in intense output. The spatial dispersion of various Stokes wavelengths allows tuning of the laser wavelength through an intra-cavity prism. The Raman amplification during a round trip should be as large as to compensate the cavity losses, and this determines the Raman threshold power.

Fig. 6: Schematic Representation of A Tunable Raman Laser

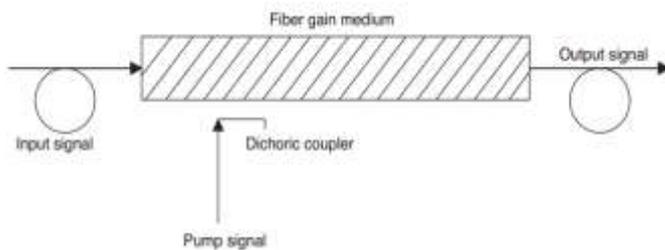


Higher-order Stokes wavelengths are generated inside the fiber at high pump powers. Again these wavelengths are dispersed spatially by the intra-cavity prism in association with separate mirrors for each Stokes beam. Such kind of Raman laser can be operated at several wavelengths simultaneously.

Raman Fiber Amplifier: The SRS phenomenon may be applied to provide optical amplification within optical fibers. The SRS process in fiber causes energy transfer from the pump to the signal. The Raman

amplification may occur at any wavelength as long as appropriate pump laser is available. There are three basic components of Raman amplifier: pump laser, wavelength selective coupler and fiber gain medium. A schematic diagram is shown in Figure 7. Raman amplification exhibits advantages of self-phase matching and broad gain-bandwidth which is advantageous in wavelength division multiplexed systems [30].

Fig. 7: Schematic of Raman fiber Amplifier



Raman amplification may be realized as a continuous amplification along the fiber which let the signal never to become too low. Raman amplifier is bidirectional in nature and more stable.

Eye-Safe Laser: Fundamentally eye-safe laser utilizes stimulated Raman scattering phenomenon. Using a special s-polarized reflective resonator, a beam of an eye-safe laser with 31.8 mJ output energy and 2.0 ns pulse width can be obtained [40]. In such resonator configuration the length of the Raman resonator is shorter than the

fundamental radiation resonator. Such eye-safe laser has the highest output energy and shortest pulse width among the Nd:KGW lasers.

IV. Conclusion

Stimulated Raman Scattering or SRS phenomenon is discussed in this paper. Normally SRS phenomenon put limitation on optical systems. But with suitable system arrangement it can be exploited in many applications. Typical threshold power for SRS is about 570 mW. The typical value of channel power in optical systems is below 10 mW. Therefore, SRS is not a limiting factor for single-channel light wave systems.

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