Determination of Resonance Frequencies in Silica Fiber using SRS Gain

Mrinal Sen[1] **and Mukul Kumar Das**[2], *Senior Member, IEEE*

[1,2]Dept. of Electronics Engineering, Indian School of Mines, Dhanbad, India
[1]mrinal.sen.ahm@gmail.com, [2]das_mkdas@yahoo.co.in

Abstract--- This paper presents a novel approach for the determination of resonance frequencies in silica fiber using composite susceptibility model and Stimulated Raman Scattering (SRS) gain. The Raman gain coefficient in silica fiber is calculated in terms of composite susceptibility model where resonance frequencies of material are considered. Composite susceptibility is optimized using Genetic Algorithm to match calculated gain with the experimental results and, hence eight resonance frequencies are found.

I. INTRODUCTION

Optical fiber communication link covers a massive part of the existing telecommunication network around the globe. Performance of present day Wavelength Division Multiplexing (WDM) technique in optical network is limited by narrow bandwidth of Erbium Doped Fiber Amplifiers (EDFA) [1-3]. Recently there had been a lot of interest among researchers around the world in Distributed Fiber Raman Amplifier (DFRA) due to its ultra-wide bandwidth, flexibility in operation, low noise and capacity to alleviate fiber nonlinearities which is significant at high power transmission.

This paper presents a comprehensive theoretical study of gain in optical fiber under the influence of SRS. The generation of SRS in optical fiber is accompanied by intense molecular or lattice vibrations which have a high degree of temporal and spatial coherence. These molecular vibrations modulate the incoming light beam and generate sidebands [4]. The signal or stoke waves, that are separated by an amount of the frequency of the lattice vibrations from the pump wave, are get amplified. Nonlinear susceptibility plays a major role in most of the nonlinear optical processes like SRS [5,8]. Thus, quantitative measurement of the stimulated Raman gain spectrum allows determining frequency dependent Raman susceptibility of the material. In this paper, a numerical model for composite Raman susceptibility of bulk silica material is proposed considering classical mechanics. The Raman gain is calculated and compared with the reported experimental results to find the material resonant frequencies and composite susceptibility.

II. MODEL DESCRIPTION

The energy transfer procedure from a pump photon to another photon of shifted frequency is inelastic in nature. The inelastic behavior can be explained by quantum mechanics or by classical mechanics (to a reasonable extent). In a molecular system, due to the light-particle interaction, material absorbs/delivers energy from/to the optical signal (pump signal) and produces photon of lower (Stokes) or higher (Anti-Stokes) frequency.

Intermolecular vibration plays an important on the shifting of frequency of photons. This vibration has already been described as a simple harmonic motion of single resonance frequency [5]. However, for accurate depiction of molecular vibration, instead of single resonance frequency, multiple frequencies need to be considered because molecular vibration is not isotropic in space due to polarization of light signal. Authors proposed the modified equation for jth vibrational mode of molecule as

$$\frac{d^2\tilde{q}_j}{dt^2} + 2\gamma_j\frac{d\tilde{q}_j}{dt} + \omega_{vj}^2\tilde{q}_j = \frac{\tilde{F}_j(t)}{m} \quad (1)$$

where, $\tilde{q}_j$ is the deviation of the intermolecular distance from equilibrium under the influence of applied force, $\tilde{F}_j(t)$, ω_{vj} is resonance frequency of oscillation and γ_j is damping constant. This equation actually presents the motion of the molecular vibration under applied force that acts on the jth vibrational degree of freedom with m as reduced nuclear mass.

Now, optical polarizability of molecule depends upon the intermolecular distance as

$$\tilde{\alpha}(t) = \alpha_0 + \left(\frac{\partial\alpha}{\partial q}\right)_0 \tilde{q}(t) \quad (2)$$

and the composite Raman susceptibility can be obtained as

$$\chi_R(\omega_S) = \sum\nolimits_j \frac{(N/6m)(\partial\alpha/\partial q)_{0j}^2}{\omega_{vj}^2 - (\omega_L - \omega_S)^2 + 2i(\omega_L - \omega_S)\gamma_j} \quad (3)$$

The Raman Gain Coefficient g_r is given by [8].

$$g_r = -\frac{12\mu_0^2\omega_L\omega_S^2}{A_{eff}^R K_L K_S} Im(\chi_R) \quad (4)$$

where,

$$A_{eff}^R = \frac{\iint|E_{pump}(r,\varphi)|^2 r\,dr d\varphi . \iint|E_{stoke}(r,\varphi)|^2 r\,dr d\varphi}{\iint|E_{pump}(r,\varphi)|^2 . |E_{stoke}(r,\varphi)|^2 r\,dr d\varphi} \quad (5)$$

N represents the number density of molecules, $(\partial\alpha/\partial q)_{0j}$ represents the rate of change of polarizability with the deviation of intermolecular distance from equilibrium for the jth resonance, ω_L is the pump angular frequency and ω_S is the stoke signal angular frequency. Here the summation is taken over all possible contribution of resonance on Raman susceptibility.

With a typical pump frequency and typical amplitudes for Pump and Stokes power, effective area is calculated using

978-1-4673-1604-0/12/$31.00 ©2012 IEEE

Eq.5 and hence, resonance frequency dependent composite susceptibility is optimized to match the normalized theoretical Raman gain with the experimental data [7]. The Optimization is done using Genetic Algorithm (GA) where we have considered the independent variables as $(\partial\alpha/\partial q)^2_{0j}$, γ_j and ω_{vj} for a range of j from 2 to 10. The fitness function has been considered as the sum of the square of the differences of simulated and measured values. In several different run we found that the fitness with eight different frequency components (i.e., j) is best among the others. In the process optimization we have observed that the variation of $(\partial\alpha/\partial q)^2_{0j}$ and γ_j can affect a little on the peaks of the composite susceptibility whereas ω_{vj} is extremely responsible for determining the peaks. With these observations we have reached to a conclusion that though it is not possible to determine the proper value of $(\partial\alpha/\partial q)^2_{0j}$ and γ_j with the available knowledge, as there may a set of different solutions be available, we can at least predict the resonance frequencies of the molecular vibrational system. The results of this methodology are presented below.

III. RESULTS AND DISCUSSIONS

Pump power of 500mW at 1450 nm and signal (Stokes) power of 1mW in the range of wavelengths are considered. The Pump is co-polarized and co-propagating with the Stokes wave. Step index single mode fiber of core diameter 12µm is taken. The result of 10 different run of GA for eight resonance frequencies with their corresponding fitness values has been presented in table I. Hence the results are produced with the eight resonance frequencies and their respective $\partial\alpha/\partial q$ and γ obtained by the GA with minimum fitness value. The comparison of theoretically calculated gain and the measured gain has been shown in Fig 1. The theoretically calculated Raman Effective Area as a function of frequency shift is shown in Fig 2. Finally, the composite susceptibility with the contribution of individual resonances has been presented in Fig 3. The resonance frequencies are found centered at 7.3594, 13.2039, 14.6445, 18.0898, 24.1391, 32.3625, 10.4297 and 14.2273 THz frequencies.

TABLE I. RESULTS OF GENETIC ALGORITHM FOR TEN DIFFERENT RUN

Fitness Value	***Resonance Frequencies (THz)***							
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***
0.0756	7.75	13.2	14.656	18.25	24.1	32.05	10.566	14.325
0.0746	7.5625	13.2	14.519	18.140	24.037	31.894	10.641	14.254
0.0628	7.4595	13.106	14.614	18.25	24.161	32.05	10.649	14.258
0.0959	7.5469	13.325	14.5	18.25	24.193	32.05	10.687	14.575
0.0699	7.25	13.137	14.671	18.187	24.037	32.3	10.626	14.262
0.0822	7.2969	13.2	14.574	18.043	24.178	31.753	10.402	14.246
0.083	7.7188	13.2	14.578	18.125	24.094	32.057	10.687	14.293
0.0592	**7.3594**	**13.203**	**14.644**	**18.089**	**24.139**	**32.362**	**10.429**	**14.227**
0.0995	8.0044	13.325	14.5	18.125	24.147	32.430	11.187	14.637
0.0729	7.5	13.227	14.554	18.117	24.209	32.55	10.648	14.2

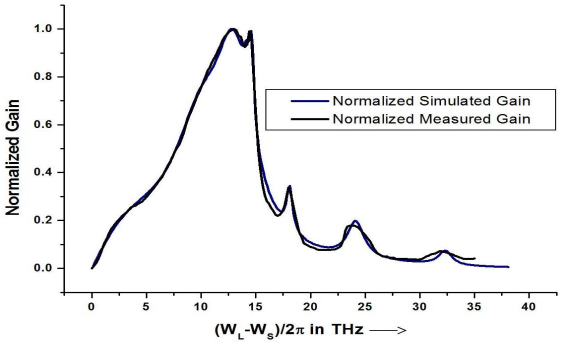

Fig.1. Raman frequency shift verses theoretically calculated and practically measured Raman Gain Plot.

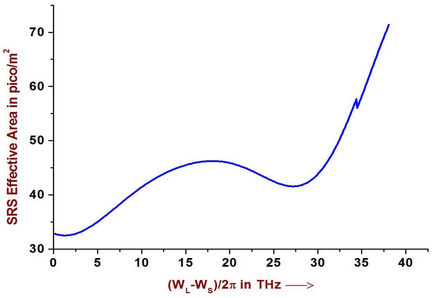

Fig.2. Raman frequency shift verses Raman Effective Area plot.

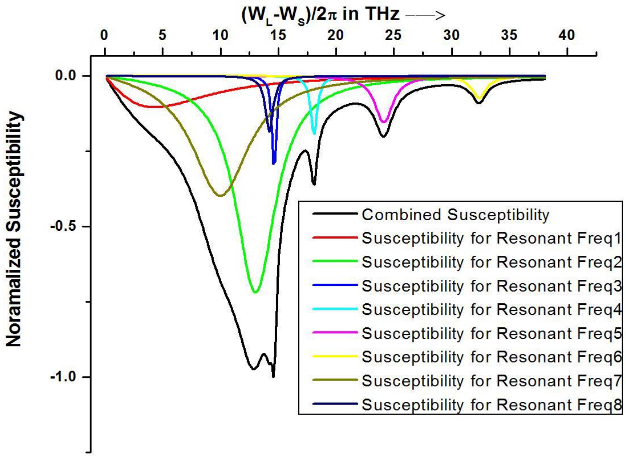

Fig.3. Raman frequency shift verses Composite Susceptibility plot. The thin line represents the individual effect of different resonances 7, 10, 13.2, 14.2, 14.5, 18, 23.6 and 31.8 THz frequencies.

REFERENCES

[1] Mohammed N. Islam (Ed.), *Raman Amplifiers for Telecommunications 1- Physical Principles*, Springer Series in optical sciences, **2004**.

[2] A. Sano et al., in *Proc. of European Conf. on Optical Comm.*, Th 4.1.1, **2006**.

[3] A. Saleh and J. Simmons, in *IEEE J. Lightwave Technol.*, Vol. 24, pp.3303-3321,**2006**

[4] Max Maier, "Applications of Stimulated Raman Scattering," in *Appl. Phys.*, 11, 209—231, **1976**.

[5] Robert W. Boyd, *Nonlinear Optics*, Second Edition, Academic Press, Elsevier Science (USA), **2003**.

[6] R.H. Stolen and E.P. Ippen, "Raman gain in glass optical waveguides," in *Appl. Phys. Lett.*, 22:6, **1973**.

[7] Jake Bromage, "Raman Amplification for Fiber Communications Systems," in *Journal of Lightwave Technology*, vol. 22, no. 1, January **2004**.

[8] A. Yariv and Pochi Yeh, *Photonics – Optical Electronics in Modern Communication*, Sixth Edition, Oxford University Press, **2006**.