Frequency-asymmetric gain profile in a seeded Raman amplifier

K. S. Repasky and J. L. Carlsten
Department of Physics, Montana State University, Bozeman, Montana 59717
(Received 8 December 1995; revised manuscript received 6 June 1996)

This paper examines the effect of index guiding on Raman gain. The slowly varying Maxwell wave equation including both the real and imaginary parts of the Raman susceptibility for a seeded Raman amplifier is explored. Using a Gauss-Laguerre mode expansion for the Stokes field, the output Stokes energy is numerically studied as a function of gain and detuning from the Raman resonance. The calculations indicate that the real part of the Raman susceptibility causes the Raman medium to act as a lens when the Stokes seed is detuned from the Raman resonance. This focusing effect leads to higher peak Stokes energy when the Stokes seed is tuned to the blue side of the Raman resonance. Specifically for Raman scattering in H_2 with a pump laser at 532 nm and an input seed near 683 nm, the peak Stokes energy can shift by as much as 300 MHz from the Raman resonance. An experiment which confirms these predictions is also presented. [S1050-2947(96)05611-9]

PACS number(s): 42.60.Da, 42.60.Jf, 42.65.An, 42.65.Dr

I. INTRODUCTION

Raman scattering occurs when a photon is scattered off a molecule leaving the molecule in an excited state and shifting the frequency of the scattered photon. This scattering process can occur either by spontaneous scattering in the presence of pump photons or by stimulated scattering when both a pump photon and a seed photon are present. Recent theoretical work [1–4] in spontaneous and stimulated Raman scattering has shown that Maxwell's wave equations for the Raman system including focusing can be solved by expanding the fields in terms of a Gauss-Laguerre modal basis. The modal solution has been fruitful in understanding the Raman generator and Raman amplifier and has applications to other gain-guided systems such as x-ray lasers [5] and diode laser [6].

Theories based on this modal expansion of the Stokes field have been used to solve the three-dimensional wave equation which describes the Raman amplifier. Generally the gain term in the wave equation includes only the imaginary part of the Raman susceptibility. The real part of the Raman susceptibility is usually not included since this term will be zero when the Stokes input is tuned on resonance. However, recent experiments have successfully shown that a Raman amplifier can be seeded with a tunable laser diode [7,8]. When the seed laser is tuned across the Raman resonance the real part of the Raman susceptibility becomes nonzero and can lead to appreciable effects on the gain.

The real part of the Raman susceptibility, which depends on the pump intensity, manifests itself in the index of refraction [9] and can be thought of as creating a lens which can focus or defocus the Stokes beam depending on which side of the Raman resonance the Stokes seed is tuned. On the blue side of the Raman resonance, the Stokes beam will be focused to a smaller spot which leads to higher peak output Stokes energy. This is because the smaller Stokes beam experiences a higher gain as it spatially overlaps a more intense part of the pump beam. A complete theory which takes into account the real part of the Raman susceptibility is clearly needed to fully understand this effect.

In an earlier paper [10] on waveguide effects in stimulated Raman scattering by Mostowski and Sobolewska, the real part of the Raman susceptibility was included in the theory. The wave equation was solved by reducing the problem to a description of rays which propagate according to geometric optics. However, this method of solution does not readily give the spatial structure of the Stokes beam nor does it easily account for a focused geometry which is often used in Raman generator and Raman amplifier experiments.

In this paper the Raman wave equation including the real part of the Raman susceptibility is solved by expanding the Stokes field in terms of a Gauss-Laguerre basis. This basis was chosen as the basis for expansion of the Stokes field because the input Stokes field that will be used in this paper is a focused Gaussian and can be written simply in terms of the lowest-order Gauss-Laguerre mode. This is in contrast to using a nonorthogonal mode theory which is useful for describing the Stokes output of a Raman amplifier in terms of a single mode [1,2].

The output Stokes energy is studied as a function of detuning from the Raman resonance for a large range of gains. The peak Stokes energy at the output of the Raman amplifier occurs not at the Raman resonance as might be expected but rather is found to be shifted to the blue side of the Raman resonance by as much as 300 MHz for parameters typical of Raman amplifier experiments.

This paper is organized as follows. In Sec. II the wave equation including the real and imaginary susceptibilities is shown and a method of solution will be presented. In Sec. III the output Stokes energy is studied for a Raman amplifier as a function of detuning from the Raman resonance for various gains. In Sec. IV an experiment is described in which the output Stokes energy is measured as a function of gain and detuning. Section V contains the experimental results and Sec. VI contains a brief conclusion.

II. THEORY

To study the interplay of the focusing effects caused by the real part of the Raman susceptibility and the gain caused by the imaginary part of the Raman susceptibility we start with a wave equation that includes the total Raman susceptibility. The wave equation is then solved using a Gauss-Laguerre modal expansion for the Stokes field. Solving the wave equation with a modal expansion will allow us to study the output Stokes energy of a Raman amplifier.

In this section we consider optical systems in which the growth of the amplified field traveling in the positive z direction can be described by the slowly varying Maxwell equations in the steady-state paraxial limit. A Raman amplifier is one such optical system and will be considered in detail in this paper. In cgs units the amplified field obeys [2–4,10]

$$\nabla_T^2 E_s(z,\mathbf{r}_T) - 2ik_s\partial_z E_s(z,\mathbf{r}_T) = -\frac{4\pi\omega_s^2}{c^2}\chi_R E_s(z,\mathbf{r}_T), \qquad (1)$$

where $\nabla_T^2 = \partial_x^2 + \partial_y^2$ is a transverse Laplacian, $E_s(z,\mathbf{r}_T)$ is the slowly varying Stokes field, k_s is the wave vector of the Stokes field, and χ_R is the total Raman susceptibility. No noise terms are included in the wave equation because it is assumed that the input Stokes seed is large enough to dominate the spontaneous scattering. It has been shown [8] that even a very low power seed beam on the order of 10 nW will dominate the quantum noise.

The Raman susceptibility χ_R can be written as [9]

$$\chi_R = \chi' - i\chi'' = \frac{k_s c^2}{4\pi\omega_s^2} g(z,\mathbf{r}_T)\left(\frac{\Delta\Gamma}{\Delta^2+\Gamma^2} + i\,\frac{\Gamma^2}{\Delta^2+\Gamma^2}\right), \qquad (2)$$

where $g(z,\mathbf{r}_T)$ is the gain profile, $\Delta = \omega_v - (\omega_p - \omega_s)$ is the detuning where ω_v is the resonant frequency of the Raman active medium, ω_p is the pump laser frequency, and ω_s is the Stokes frequency, and Γ is the Raman linewidth. The χ'' term gives the usual gain while the χ' term will affect the index of refraction [9,11] for the Stokes beam and can lead to focusing of the Stokes beam by the Raman medium. The χ' term can either be positive or negative, which means that the lensing effect of the Raman medium can cause focusing or defocusing of the Stokes beam. The strength of the lensing effect is dependent on the amount of detuning as well as on the pump laser intensity which gives rise to $g(z,\mathbf{r}_T)$. In this paper we will assume that the pump laser frequency is fixed but that the frequency of the Stokes beam which is the same as the seed beam will be varied. This is consistent with the experiments in Refs. [7, 8].

Using the Raman susceptibility from Eq. (2), the wave equation can be written

$$\nabla_T^2 E_s(z,\mathbf{r}_T) - 2ik_s\partial_z E_s(z,\mathbf{r}_T) + ik_s g(z,\mathbf{r}_T)\left(\frac{\Gamma^2}{\Delta^2+\Gamma^2} - i\,\frac{\Gamma\Delta}{\Delta^2+\Gamma^2}\right)E_s(z,\mathbf{r}_T) = 0. \qquad (3)$$

The wave equation includes the real and imaginary parts of the susceptibility with Δ, the detuning from the Raman resonance and Γ, the Raman linewidth, included explicitly. For zero detuning this wave equation reduces to the wave equation presented in Refs. [2, 3] (with no spontaneous emission).

The focused nature of the pump beam is taken into account in the gain profile. In this work we will consider a focused Gaussian gain profile

$$g(z,r) = \frac{4G_p}{k_g\omega_g^2(z)}\, e^{-2r^2/\omega_g^2(z)}, \qquad (4)$$

where G_p is related to the pump plane wave gain coefficient [12], k_g is the pump laser wave vector, the Gaussian beam waist is $\omega_g(z) = \omega_g(0)[1+(z/z_0)^2]^{1/2}$, r is the magnitude of the transverse position vector $\mathbf{r}_T$, and z_0 is the Rayleigh range of the focused Gaussian profile. The gain profile has rotational symmetry around the z axis and therefore it will be convenient to work in cylindrical coordinates.

The wave equation is very similar to the wave equation solved by Perry, Rabinowitz, and Newstein and the details of the solution are presented in Ref. [3]. A brief outline of their solution is presented here with the changes needed to account for including χ'. The Stokes field is expanded over a complete set of orthonormal Gauss-Laguerre modes $U_p^l(z,\mathbf{r}_T)$. The Gauss-Laguerre modes are solutions to Eq. (1) when $\chi_R = 0$, which describes propagation of an electric field in free space. The Stokes field is written as an expansion of the Gauss-Laguerre modes

$$E_s(z,\mathbf{r}_T) = \sum_{p,l} V_p^l(z)U_p^l(z,\mathbf{r}_T), \qquad (5)$$

where $V_p^l(z)$ are the field expansion coefficients. Substituting Eq. (5) into Eq. (3) and using the orthonormality condition of the Gauss-Laguerre modes yields the following set of ordinary linear coupled differential equations in z for the field expansion coefficients:

$$\frac{dV_{p'}^{l'}(z)}{dz} = \sum_{p,l} G_{p'p}^{l'l}(z)V_p^l(z), \qquad (6)$$

where

$$G_{p'p}^{l'l} = \frac{1}{2}\left(\frac{\Gamma^2}{\Delta^2+\Gamma^2} - i\,\frac{\Gamma\Delta}{\Delta^2+\Gamma^2}\right) \times \int_0^{2\pi} d\phi \int_0^\infty r\, dr [U_{p'}^{l'*}(z,\mathbf{r}_T)g(z,\mathbf{r}_T)U_p^l(z,\mathbf{r}_T)]. \qquad (7)$$

Substituting the focused Gaussian gain profile given in Eq. (4) and noting that the integration over ϕ results in nonzero terms only when $l = l'$, the following expression for the coupling element $G_{p'p}^l$ is obtained:

$$G_{p'p}^l = G_p\,\frac{2\mu}{\omega_g^2(z)k_g}\left(\frac{\Gamma^2}{\Delta^2+\Gamma^2} - i\,\frac{\Gamma\Delta}{\Delta^2+\Gamma^2}\right) \times e^{[-2i(p'-p)\tan^{-1}(z/z_0)]}Q_{p'p}^l(\mu), \qquad (8)$$

where the parameter

$$\mu=\frac{\lambda_p}{\lambda_p+\lambda_s} \tag{9}$$

and λ_p (λ_s) is the pump (Stokes) wavelength. $Q^l_{p'p}(\mu)$ is a polynomial in powers of μ and is defined in Ref. [3]. The substitution of the variable

$$\theta=\tan^{-1}\left(\frac{z}{z_0}\right) \tag{10}$$

is made, which has the effect of folding out the focusing nature of the problem. The equation for the field expansion coefficients in terms of θ becomes

$$\frac{dV^l_{p'}}{d\theta}=\sum_p M^l_{p'p}(\theta)V^l_p(\theta), \tag{11}$$

where

$$M^l_{p'p}(\theta)=\mu G_p\left(\frac{\Gamma^2}{\Gamma^2+\Delta^2}-i\,\frac{\Gamma\Delta}{\Gamma^2+\Delta^2}\right)Q^l_{p'p}(\mu)e^{-2i(p'-p)\theta}. \tag{12}$$

The solution for the field expansion coefficients is

$$V^l_{p'}(\theta)=\sum_p A^l_{p'p}(\mu,G_p;\theta,\theta_{\rm in})V^l_p(\theta_{\rm in}), \tag{13}$$

where the matrix elements $A^l_{p'p}(\mu,G_p;\theta,\theta_0)$ are defined in Ref. [3], $\theta_{\rm in}$ defines the input of the Raman amplifier, and θ defines the location in the Raman amplifier. The field expansion coefficients $V^l_p(\theta_{\rm in})$ are used to represent the input Stokes seed beam. When the Raman amplifier is seeded with a Gaussian input, only the $p=l=0$ element of $V^l_p(\theta_{\rm in})$ will be nonzero and the input Stokes power will be proportional to $|V^0_0(\theta_{\rm in})|^2$. In this case the sum in Eq. (13) will drop out. Because only the $p=l=0$ element is needed to describe the input mode, the Gauss-Laguerre modes are a convenient choice for the Stokes field expansion since there will be only one term in the input field expansion. However, the coupling element $G^l_{p'p}$ couples this single input spatial mode to several output modes for each individual l. The fact that many modes can couple together allows the amplified Stokes beam to have a different combination of spatial modes than the input seed hence the Stokes output can have a significantly different spatial structure than the input seed. Note, however, that since the gain does not couple the input field to modes with different angular indices (l values), it is necessary to solve the above matrix equation for $l=0$ only.

III. FREQUENCY DEPENDENCE OF THE STOKES OUTPUT

In this section the output Stokes energy is calculated as a function of the detuning of an input seed for typical experimental parameters appropriate for vibrational Raman scattering in H_2 with a pump laser at 532 nm, and a Stokes seed laser assumed to be near the Raman resonance at 683 nm. We take the length of the gain medium to be 141 cm, and the Rayleigh range, z_0, of the focused Gaussian pump beam in the Raman amplifier to be 30 cm. The input to the Raman amplifier is at $z=70$ cm which corresponds to $\theta_{\rm in}=-1.17$ and the output is at $z=70$ cm which corresponds to $\theta=1.17$. The plane wave gain coefficient [13] $\alpha=2.9\times10^{-9}$ cm/W and the Raman linewidth [14] $\Gamma=3200$ MHz [linear frequency full width at half maximum (FWHM)] are used for the following calculations. A total of 25 radial spatial modes indexed by p' were used in the calculations for $A^0_{p'0}$ which is used in Eq. (13) to calculate the field expansion coefficients $V^1_{p'}(\theta)$. Once the field expansion coefficients are found, the output Stokes field is constructed using Eq. (5). Increasing the number of radial spatial modes in the calculations to 40 increases the output Stokes energy by less than 0.5%.

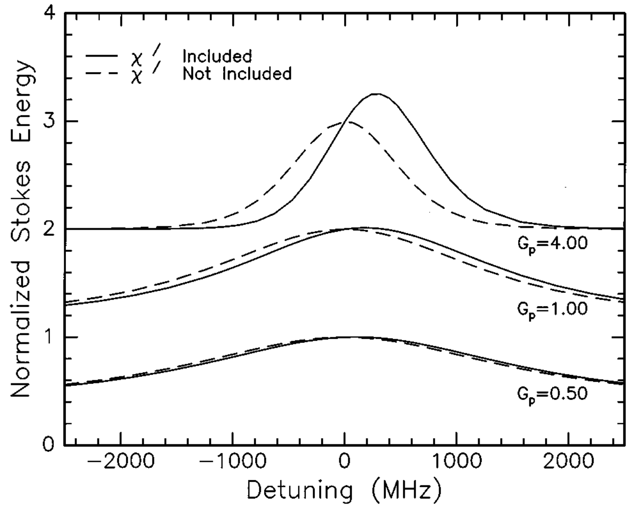

FIG. 1. Normalized Stokes energy as a function of detuning from the Raman resonance for $G_p=0.5$, 1, and 4. The solid line represents calculations done with χ' included in the theory while the dashed line represents calculations done with χ' not included in the theory. The output for each gain has been normalized so that the peak output Stokes energy is unity when χ' is not included in the theory. For $G_p=1$, the output Stokes has been shifted up by 1 and for $G_p=4$, the output Stokes energy has been shifted up by 2. As G_p is increased, the peak of the output Stokes energy shifts in frequency and increases in magnitude.

Figure 1 shows a plot of the output Stokes energy as a function of detuning for $G_p=0.5$, 1, and 4. The dashed line is the predicted Stokes output energy as a function of detuning when χ' is set equal to zero. The solid line represents the predicted output Stokes energy as a function of detuning when χ' is included in the theory. The Stokes energy is normalized to the maximum output Stokes energy when χ' is not included in the theory. For $G_p=0.5$ including χ' makes little difference in the output Stokes energy. However, at $G_p=1$ the peak Stokes intensity is shifted to the blue of the Raman resonance by 186 MHz. At $G_p=4$ this effect is even more pronounced with the Stokes output shifted by 306 MHz and the peak Stokes-output energy increased by 25% compared to when χ' is not included in the calculations. The focusing effect of χ' is responsible for the shifting and enhancement of the peak output Stokes energy. The increased peak Stokes energy on the blue side of the Raman resonance can be explained by realizing that the focusing effect of χ' causes the Stokes beam to spatially overlap a higher gain region in the Raman medium.

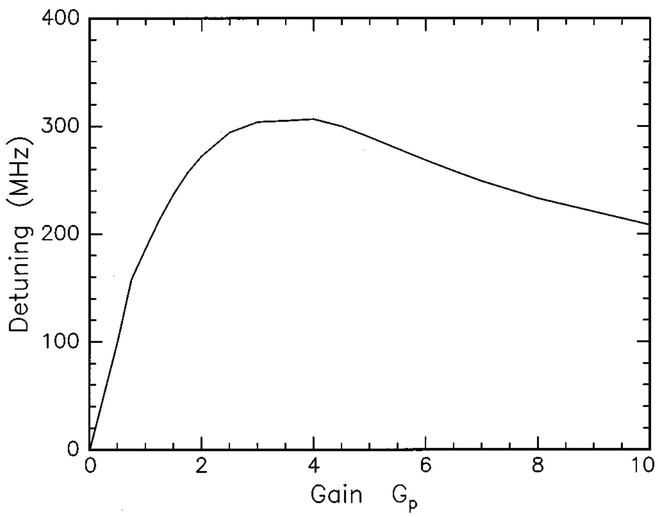

FIG. 2. Normalized Stokes output as a function of detuning from the Raman resonance for G_p=5. The circles represent numerical calculations while the solid line is a Gaussian fit to the calculated results. The output Stokes energy is a Gaussian and the linewidth compares favorably to the gain narrowed linewidths of previous work [15].

The gain narrowing of the Raman linewidth has been discussed in the literature [15] and allows us to compare the linewidths calculated in this paper with previous results. The half-width half maximum (HWHM) linewidth predicted by Ref. [15] is

$$\Delta \nu_{\mathrm{HWHM}} = \frac{\Gamma_{\mathrm{HWHM}}}{\sqrt{4\mu G_p \theta - 1}}, \tag{14}$$

where the results of Refs. [16, 17] have been used to rewrite Eq. (14) in terms of G_p. For G_p=5 and μ=0.438, Eq. (14) predicts a HWHM of 438 MHz. Figure 2 is a plot of the calculated normalized Stokes energy as a function of detuning for G_p=5. The circles denote the calculated values for the Stokes energy at different detunings. The solid line is a least-squares fit to the calculated data points. The HWHM of the least-squares fit is 453 MHz, which compares favorably to the results from Eq. (14).

Figure 3 shows, as a function of gain, the detuning from the Raman resonance which leads to the maximum output Stokes energy. This plot emphasizes the dramatic shift from the Raman resonance that is seen when χ' is included in the theory. The detuning at which the peak Stokes output occurs reaches a maximum at about G_p=4 and then starts to fall as the gain is further increased. This reversal at high gain can be explained as follows. The focusing caused by the real part of the Raman susceptibility on the blue side of the Raman resonance causes the Stokes beam to spatially overlap a higher gain region. However, once the Stokes beam is narrow compared to the pump beam, the entire Stokes beam experiences essentially the on-axis gain. Further increase in G_p has little effect on the Stokes field. On the other hand, the Stokes (frequency) gain profiles, due to the imaginary part of the Raman susceptibility, becomes narrower without bound as G_p is made larger. The net result is that at large G_p the index guiding which leads to larger Stokes output at high detuning

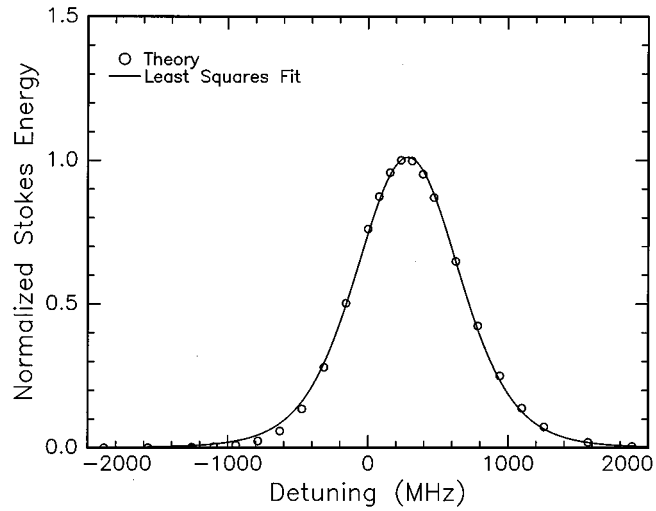

FIG. 3. The detuning from the Raman resonance that gives the peak Stokes output energy as a function of the gain G_p. The maximum detuning of 306 MHz is reached for G_p=4. At higher gains, the pump induced focusing, which leads to larger Stokes output at high detuning, can no longer compensate for the spectral gain narrowing and the peak Stokes energy starts to move back towards the Raman resonance.

can no longer compensate for the spectral gain narrowing and the peak location starts to move back towards the Raman resonance.

IV. EXPERIMENT

The experimental setup to probe the effects of pump energy and detuning on the Stokes output is shown in Fig. 4. The pump beam is supplied by a frequency doubled output of an injection seeded Nd:YAG (YAG denotes yttrium aluminum garnet) laser. The temporal output of the laser is near Gaussian with a half-width at half maximum of 3.5 ns. The output of the Nd:YAG laser is reflected off a spherical mirror at an oblique angle to correct a slight astigmatism of the pump beam. The laser then passes through two dielectric

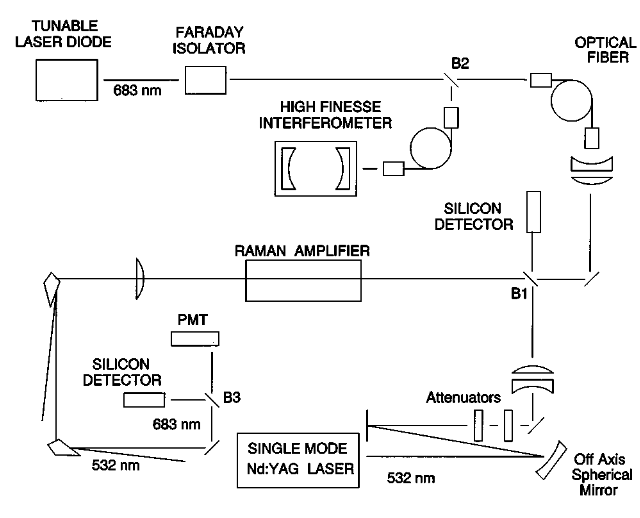

FIG. 4. Experimental apparatus used to study index guiding effects in a gain-guided Raman amplifier.

attenuators to obtain the proper pump energy. The pump energy is changed in the experiment by changing one or both of the dielectric mirrors. The pump beam is then spatially filtered twice (not shown in Fig. 4) to make a near Gaussian spatial beam. The pump beam then passes through a series of two lenses to focus the pump beam in the Raman amplifier with the proper confocal parameter. The pump beam next impinges on beam splitter B1. Part of the pump beam passes through the beam splitter to a Si energy detector. The energy meter allows the monitoring of the pump energy for each pump laser shot. The rest of the beam is combined with the Stokes seed at beam combiner B1.

The Stokes seed is provided by a continuous wave tunable laser diode (TLD) with a center wavelength of 683 nm. The TLD can be tuned over 60 GHz by externally applying −3 to +3 V. The output from the TLD passes through a Faraday isolator which prevents parasitic feedback into the TLD which could cause frequency and power instabilities. After the Faraday isolator, the Stokes seed impinges on beam splitter B2. Part of the beam is sent to a high finesse interferometer (HFI) [18,19]. The HFI has a free spectral range of 23 600 MHz with a measured finesse of greater than 30 000, which implies that the HFI has sub-MHz resolution and the HFI has less than 7 MHz/h drift [19]. The rest of the Stokes seed beam is launched into a single mode optical fiber to spatially filter the Stokes seed. After the optical fiber the Stokes seed passes through a series of two lenses to focus the beam in the center of the Raman amplifier with the proper confocal parameter. The Stokes seed and pump beam are combined at beam combiner B1.

After the beam combiner B1 the Stokes seed and pump beam travel collinearly through the Raman amplifier. The Raman amplifier consists of H_2 at a pressure of 70 atm. The Raman amplifier is 141 cm in length and the pump and Stokes beams make a single pass. The Rayleigh range of both the pump and Stokes beam is 30 cm.

The pump and Stokes beams pass through two Pelin Broca prisms which separate the pump and Stokes beams. The Stokes beam is split at beam splitter B3 with part of the beam traveling to a Si energy detector and part of the beam traveling to a photomultiplier tube (PMT). The PMT is calibrated to the absolute energy of the Si energy detector with the aid of neutral density filters. This detection scheme allows for a large dynamic range of output Stokes energy to be measured.

Data are collected as follows. At a particular pump energy, the TLD is scanned across the Raman resonance. As the TLD is scanned the input pump energy, relative seed frequency, and output Stokes energy are recorded via a personal computer for each shot of the pump laser. A total of 1200 shots are collected at each pump energy. A scan across the Raman resonance at a reference pump energy is run after each different pump energy. The scan at the reference pump energy allows the monitoring of the HFI to ensure that it is not drifting during the experiment.

V. EXPERIMENTAL RESULTS

Figure 5 shows the result of a scan across the Raman resonance for a pump energy of 545 μJ (G_p=3.44). The +'s correspond to the experimentally measured output Stokes energy as the tunable laser diode was swept across the Raman resonance. The zero detuning point was determined from all the data in Fig. 6. The solid line is the calculated output Stokes energy as a function of the detuning from Eqs. (5) and (13) and the dashed line is a least -squares fit to the data. The linewidth from the least-squares fit to the data is 551 MHz while the linewidth from the calculation is 592 MHz. These linewidths can be compared to the gain narrowed line-

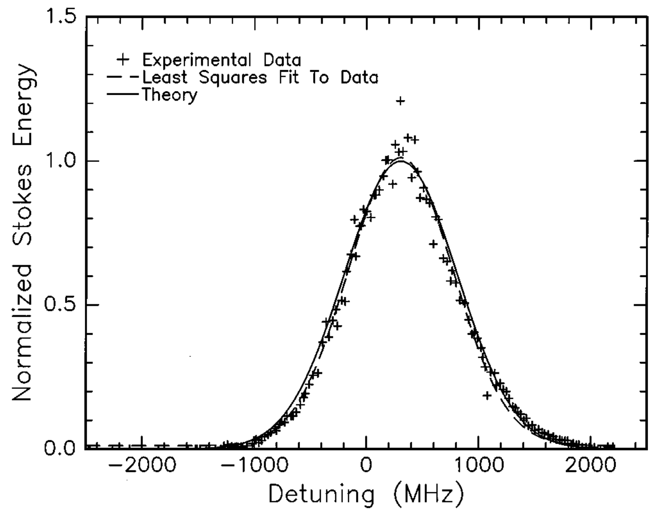

FIG. 5. Normalized output Stokes energy as a function of relative seed frequency. The +'s are experimental points for a gain G_p=3.44. The dashed line is a Gaussian least-squares fit to the data points. The solid line is the prediction from solving the Maxwell wave equation using a Gauss-Laguerre expansion for the Stokes field. The maximum output occurs when the input seed is tuned over 300 MHz to the blue side of the Raman resonance.

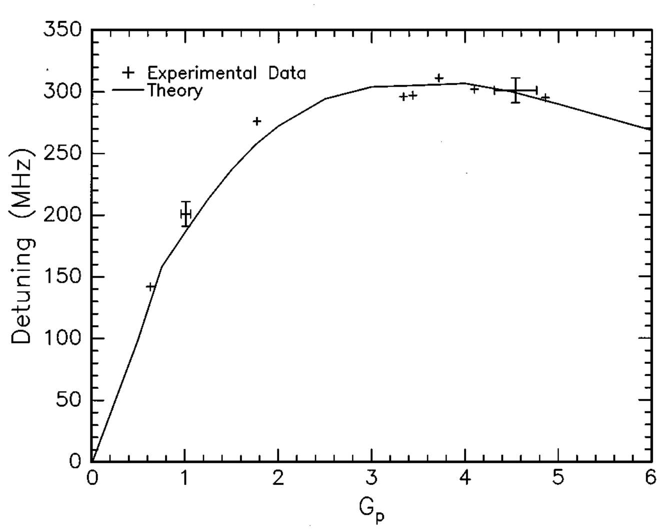

FIG. 6. Detuning which gives the maximum Stokes output as a function of gain. The x's are the measured shift of the peak Stokes output while the solid line is the prediction from solving the Maxwell wave equation by expanding the Stokes field over a Gauss-Laguerre basis. At low gains the effect of index guiding is minimal and the maximum Stokes output occurs at a detuning of zero. At higher gains the index guiding leads to a shift to the blue side of resonance as large as 306 MHz.

width calculated from Eq. (14). The gain narrowed linewidth for $G_p=3.44$ is 542 MHz where the measured Raman linewidth of $\Gamma=3200$ MHz has been used [20]. The measured linewidth and the calculated linewidth compare favorably with the gain narrowed linewidth.

Figure 6 is a plot of the detuning which gives the maximum Stokes output as a function of gain G_p. The +'s represent experimentally measured values while the solid line represents the theoretical calculations. Because the frequency measurement is a relative measurement, all the data were shifted to match the experimental points to the theoretical curve in Fig. 6. This is how the zero detuning was determined for the experimental frequency measurements shown in Fig. 5. For G_p in the range of 0–4 the detuning which gives the peak Stokes output is increasing as the gain increases. For $G_p>4$ the detuning which gives the maximum Stokes output begins to fall off as discussed in Sec. II.

VI. CONCLUSION

The theoretical prediction that the peak Stokes output for a seeded gain-guided Raman amplifier will shift to the blue side of the Raman resonance has been presented. The shift of the peak Stokes output from the Raman resonance is attributed to index guiding in which the real part of the Raman susceptibility causes the pump beam to focus and experience a high gain because the Stokes overlaps a more intense part of the pump beam. An experiment was presented in which the shift of the Stokes output as a function of the gain was measured in agreement with theory.

The experiment clearly shows that substantial index guiding is happening in a gain-guided Raman amplifier. Index guiding effects can cause some rather unexpected results such as the shift away from the Raman resonance in a gain-guided Raman amplifier by over 300 MHz. The fact that index guiding is occurring in a gain-guided amplifier implies that the spatial structure of the output beam is caused by a complicated interaction of the pump beam and Stokes beam through the Raman susceptibility and index guiding effects need to be carefully considered in optical systems.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation Grant No. PHY-9424637. We would also like to thank Jim Wessel for many useful discussions.

[1] J. G. Wessel, P. R. Battle, and J. L. Carlsten, Phys. Rev. A **50**, 2587 (1994)

[2] P. R. Battle, J. G. Wessel, and J. L. Carlsten, Phys. Rev. A **48**, 707 (1993).

[3] B. N. Perry, P. Rabinowitz, and M. Newstein, Phys. Rev. A **27**, 1989 (1983).

[4] B. N. Perry, P. Rabinowitz, and D. S. Bomse, Opt. Lett. **10**, 146 (1985).

[5] P. Amendt, R. A. London, and M. Strauss, Phys. Rev. A **44**, 7478 (1991).

[6] W. A. Hamel, and J. P. Woerdman, Phys. Rev. Lett. **13**, 1506 (1990).

[7] M. Uchida, K. Nagasaka, and H. Tashiro, Opt. Lett. **14**, 1350 (1989).

[8] J. G. Wessel, K. S. Repasky, and J. L. Carlsten, Opt. Lett. **19**, 1430 (1994).

[9] A. Yariv, *Quantum Electronics*, 3rd ed. (Wiley, New York, 1989).

[10] J. Mostowski and B. Sobolewska, Phys. Rev. A **34**, 3109 (1986).

[11] R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Lett. **13**, 479 (1964).

[12] The gain coefficient G_p can be related to physical parameters that are typical in Raman amplifier experiments as $G_p=\alpha P_p/\lambda_p$, where α is the plane wave gain coefficient [13], P_p is the peak pump power, and λ_p is the wavelength of the pump laser.

[13] W. Bischel and M. J. Dyer, J. Opt. Soc. Am. B **3**, 677 (1986).

[14] W. Bischel and M. J. Dyer, Phys. Rev. A **33**, 3113 (1986).

[15] M. G. Raymer and J. Mostowski, Phys. Rev. A **24**, 1980 (1981).

[16] Using [17] $gz=4\alpha P_p\theta/(\lambda_p+\lambda_s)$ along with $G_p=\alpha P_p/\lambda_p$ and $\mu=\lambda_p/(\lambda_p+\lambda_s)G_p$ can be related to gz by $gz=4\mu G_p\theta$.

[17] D. C. MacPherson, R. C. Swanson, and J. L. Carlsten, IEEE J. Quantum Electron. **25**, 1741 (1989).

[18] K. S. Repasky, L. E. Watson, and J. L. Carlsten, Appl. Opt. **34**, 2615 (1995).

[19] K. S. Repasky, J. G. Wessel, and J. L. Carlsten, Appl. Opt. **35**, 609 (1996).

[20] The Raman linewidth used in this paper has been measured by scanning a tunable laser diode across the Raman transition while monitoring the Stokes output of the Raman amplifier for several different gains. This information is then used to calculate the Raman linewidth Γ. The measured linewidth compares favorably with the linewidth given in Ref. [14] of 3230 MHz.