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# Enhanced input coupling into a gain-guided amplifier

J. G. Wessel, K. S. Repasky, and J. L. Carlsten
*Department of Physics, Montana State University, Bozeman, Montana 59717*
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We address the experimentally important issue of coupling a Gaussian beam into an amplifier with a focused Gaussian gain profile. Commonly, in such an amplifier the input beam is adjusted such that it focuses at the same location and with the same Rayleigh range as the gain profile. However, we find that at high gains the input coupling efficiency of a Raman amplifier is increased by using an input beam with a short Rayleigh range that focuses well before the focus of the gain profile. Theoretical modeling and experimental data show that the input coupling efficiency is enhanced by as much as a factor of 2 over that measured with the input beam and gain profile focusing at the same position and with the same Rayleigh range. These effects are attributed to the spatial gain narrowing and wave-front modification that the amplified field undergoes during amplification. [S1050-2947(96)02409-2]

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Efficient use of an optical amplifier requires that the signal to be amplified couple strongly to the gain mechanism [1]. For amplifiers that utilize a pump beam, strong coupling requires that the input signal spatially overlap the pump beam as much as possible. However, if the pump beam focuses or diffracts, has a nonuniform transverse intensity profile, or has a different wavelength than the input signal, it may not be clear how to make the signal optimally overlap the pump beam. For pump and signal beams with Gaussian spatial profiles, many experimental and theoretical papers [2–6] have examined the case in which the pump and signal beams focus at the same location. A common focus may be necessary in some experiments and may simplify the calculations, but we find it does not necessarily maximize the input coupling. The issue of how to best couple a Gaussian beam input signal into a gain-guided optical amplifier is the subject of this paper.

We consider in detail the amplification of an input Stokes beam in a $H_2$ Raman amplifier. However, the equations used to model the amplification process can be readily applied to model other types of gain-guided amplifiers so that the phenomena reported here can be expected to occur in many other systems. In our experiment, the pump beam and the input Stokes beam, considered the signal, are both focused Gaussian beams, yet the output Stokes beam is in general not a Gaussian. Instead the spatial structure of the output Stokes beam, which is the result of a competition between gain guiding and diffraction, varies as a function of the pump laser power [7–9]. At low gains (low pump powers) the output Stokes beam is nearly Gaussian but at high gains transverse gain narrowing, due to the gain being largest on axis, becomes significant and the Stokes beam is no longer Gaussian. Also, since the Stokes beam is narrower at high gains it diffracts more strongly, altering the radius of curvature from that of a Gaussian. It is now argued with the aid of a theoretical model of a gain-guided amplifier that because the output Stokes beam's characteristics change as a function of the gain, the coupling efficiency for a Gaussian beam with fixed Rayleigh range and position of focus is also a function of the gain. We consider only linear amplifiers, so coupling efficiency at a fixed pump laser power can be taken as the ratio of output Stokes power to input Stokes power [10]. It is a relative measure of an input beam's ability to induce stimulated emission (or scattering) in the amplifier.

A nonorthogonal mode theory of a gain-guided amplifier is used to model the experiment [9,11]. For the purposes of this paper the most important feature of the nonorthogonal theory is that at high gains the Stokes output can be described in terms of a single mode, i.e., the growth rate of the dominant mode is much larger than that of the other modes; thus the power contained in these other modes is negligible. Therefore all the interesting characteristics, such as gain narrowing and wave-front distortion, of the total Stokes output are embodied in a single nonorthogonal mode. Describing the amplification process with the nonorthogonal mode theory requires that the Stokes input be written as a linear combination of nonorthogonal modes. To maximize coupling efficiency all the input light should be coupled into the dominant nonorthogonal mode. In general this mode has a complicated transverse radius and radius of curvature [9], making it experimentally difficult to construct an input that couples 100% into the dominant mode. However, by suitable adjustment of its Rayleigh range and position of focus, even a Gaussian beam Stokes input can efficiently couple into the amplifier. The Rayleigh range and position of focus that maximizes the coupling efficiency depends on not only the pump laser but also on the Rayleigh range of the pump beam and the length of the amplifier. We report nearly a factor of 2 increase in input coupling efficiency, over that obtained in the usual experiment in which the pump and input Stokes beams focus at the same location, by focusing the Stokes input at an appropriate position before the pump beam's focus. Theoretical modeling indicates that an even larger increase in the coupling efficiency can be expected in other types of amplifiers. It is now necessary to introduce some of the equations that describe the amplification so that the coupling can be addressed more quantitatively.

The Maxwell wave equation governing the amplification of a linearly polarized Stokes field in a gain-guided amplifier in the steady state, paraxial limit is [7,9,11]

$$[\nabla_T^2 - 2ik\partial_z + ikg(z,\mathbf{r}_T)]E(z,\mathbf{r}_T) = 0, \tag{1}$$

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where $\nabla_T^2 = \partial_x^2 + \partial_y^2$ is the transverse Laplacian, $\mathbf{r}_T = x\hat{\mathbf{x}} + y\hat{\mathbf{y}}$ is a transverse position vector, $k=\omega/c$ is the Stokes wave vector, and $E(z,\mathbf{r}_T)$ is the slowly varying Stokes field. $g(z,\mathbf{r}_T)$ represents the gain profile, due to the pump laser, and is taken to be proportional to a focused Gaussian [7,9,11]. In this paper we assume that the Stokes input is large enough in power to completely dominate amplifier noise due to spontaneous scattering; thus no noise source terms have been included in Eq. (1). Previous experiments [12] have shown that at high gains an input Stokes signal of order 1 nW is large enough to dominate the noise. The present experiment uses a 500-nW Stokes input.

The detailed solution to Eq. (1) has already been presented elsewhere [11] and is not duplicated here. However, a few important equations will be listed for the sake of clarity and continuity. The method of solving Eq. (1) involves writing the Stokes field as the sum over modes

$$E(z,\mathbf{r}_T) = \beta \sum_{l,n} a_n^1(z) \Phi_n^1(z,\mathbf{r}_T), \tag{2}$$

where $\beta$ is a constant and $a_n^1(z)$ is the amplitude of the mode $\Phi_n^1(z,\mathbf{r}_T)$. The modes $\{\Phi_n^1(z,\mathbf{r}_T)\}$ are referred to as the nonorthogonal modes. They are not orthogonal to each other because they are eigenmodes of a non-Hermitian wave equation similar to Eq. (1). The quantity measured in the experiments is the output Stokes energy. This is obtained theoretically by time integration of the Stokes power at position $z, P(z)$, given by

$$P(z) = \frac{c}{2\pi} \int d^2 r_T |E(z,\mathbf{r}_T)|^2$$

$$\approx \frac{c}{2\pi} \beta^2 B_{0,0}^0 |a_0^0(\theta_i)|^2 \exp[2\,\mathrm{Re}(\lambda_0^0)(\theta - \theta_i)], \tag{3}$$

where the second equality holds only in the limit of high gain when the lowest-order mode is dominant. In Eq. (3), $B_{0,0}^0$ is a normalization factor for the lowest-order mode $\Phi_0^0(\theta,\mathbf{r}_T)$, $\theta = \arctan(z/z_0)$ accounts for the focusing of the gain profile [7], $|a_0^0(\theta_i)|^2$ is proportional to the power input into the lowest-order mode, $\theta_i$ locates the amplifier entrance, and $\lambda_0^0$ is the growth rate for the lowest-order mode. $|a_0^0(\theta_i)|^2$ is obtained by projecting the Gaussian input beam onto the lowest-order nonorthogonal mode at the amplifier input. This calculation is straightforward and is detailed in Ref. [9]. Armed with this expression for output Stokes power, we are now in a position to revisit the issue of efficient coupling. Assume for the moment that the amplifier length and the Rayleigh range and power of the pump beam are fixed. With these assumptions $|a_0^0(\theta_i)|^2$ is the only parameter in Eq. (3) that is not uniquely determined. Increasing the coupling efficiency is equivalent to increasing the power coupled into the dominant mode $\Phi_0^0(\theta,\mathbf{r}_T)$ without increasing the total power of the external input into the amplifier. As stated earlier, this mode's wave fronts and transverse radius can be rather complex and in general quite different than those of a Gaussian. Thus to maximize coupling efficiency a rather complicated input beam must be constructed [9]. However, it is experimentally much easier to construct a Gaussian beam input and we find that its coupling efficiency is strongly affected by the Rayleigh range and position of focus of the input Stokes beam. Next, the apparatus used to measure these effects is described.

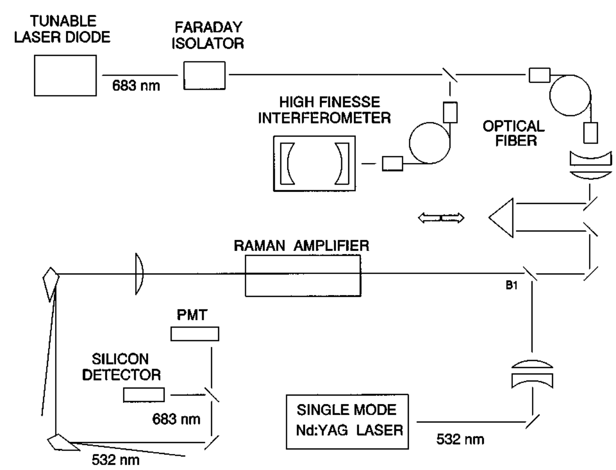


FIG. 1. Experimental apparatus used to measure coupling efficiency. The Nd:YAG laser provides the gain profile while the tunable laser diode provides the Stokes input.

Figure 1 shows the key components of the experimental apparatus. The pump beam at 532 nm is supplied by an injection seeded, frequency-doubled Nd-doped yttrium aluminum garnet (Nd:YAG) laser. Temporally, the beam is near Gaussian with a half width at half maximum of 3.5 ns. Spatially, as the beam exits the laser it is astigmatic and exhibits Fresnel rings. Correction of the astigmatism is accomplished by reflecting the beam off a spherical mirror at an oblique angle [13]. The Fresnel rings were removed by (twice) spatially filtering the beam by focusing it through a tungsten wire die. After these corrections the spatial structure of the pump beam is near Gaussian. The two-lens telescope shown is used to set the Rayleigh range and position of focus of the pump beam. Mirrors after the telescope direct the beam into the Raman cell, which is filled to 95 atm with $H_2$ gas.

The other optical beam used in the experiment is the input Stokes beam supplied by a tunable, continuous-wave laser diode with a wavelength of 683 nm. After exiting the laser, the beam goes through a Faraday isolator to keep unwanted backreflections from entering the laser and degrading its frequency and power stability. The frequency of the laser is accurately monitored with a high finesse interferometer [14] that has a free spectral range of 23 600 MHz and a finesse of approximately 30 000, giving a resolution of greater than 1 MHz. The remainder of the beam is directed into a single-mode optical fiber, which serves as a convenient spatial filter, transforming the beam into a Gaussian at the fiber output. The beam then propagates through a telescope and an optical delay line before entering the amplifier. The delay line allows the position of focus of the diode beam to be varied without affecting its Rayleigh range.

The Nd:YAG pump pulse and the laser diode Stokes input beam are combined at beam combiner B1 near the entrance to the amplifier. They are accurately overlaid at the entrance and exit of the Raman cell using a charge-coupled device CCD camera. Thus the beams travel collinearly throughout the Raman cell. For all experiments discussed in this paper the pump beam focuses in the center of the 141-cm cell with a Rayleigh range of 30 cm. On the other hand, the Rayleigh range and position of focus of the laser diode beam were varied. The beams make one pass through the cell and then are incident on a Pelin Broca prism, which disperses the pump and Stokes beams at different angles. After passing through another Pelin Broca prism, a beam splitter, calibrated neutral density filters, and bandpass filters, part of the Stokes pulse is directed onto a photomultiplier tube (PMT) allowing for detection of low-energy pulses while the remainder is incident on a silicon energy meter. The output of the PMT was correlated to the absolute energy measurements of the silicon meter with the aid of calibrated neutral density filters.

Two different pump energies, (315±2) $\mu$J and (790±4) $\mu$J, were used in the experiments. These values represent the highest and lowest pump energies appropriate for our experiments, and should show as much and as little gain-guiding effects, respectively, as possible. A significantly lower pump energy than 315 $\mu$J results in a Stokes pulse with an energy too low to be accurately measured. Increasing the pump much beyond 790 $\mu$J causes the amplifier to saturate and the theory presented earlier no longer applies. Specifically, in saturation, the assumption of a focused Gaussian gain profile would no longer be valid. Once the proper pump energy was set, the data were collected in the following manner: The power of the laser diode input was set to 500 nW, large enough to dominate any noise initiated by spontaneous scattering events in the amplifier [12]. The delay line was adjusted so the laser diode beam focused at the desired location. For each position of the delay line, greater than 1200 pump shots were directed into the amplifier while the output Stokes energy was measured. A slow frequency drift made it necessary to sweep the frequency of the laser diode across the Raman linewidth while the experiment was in progress [6].

Figure 2 shows the data for two different pump energies with the Rayleigh range ($z_0$) set to nearly that of the pump beam. This is a rather common scenario, especially for amplifiers placed in a resonator, since beams with the same Rayleigh range, regardless of their wavelengths, will reflect off curved resonator mirrors in nearly the same manner [15]. Each data set is normalized such that unit output Stokes energy is obtained when the input Stokes beam focuses in the center of the amplifier. Also shown (solid lines) are the predictions of the nonorthogonal mode theory obtained by numerically evaluating Eq. (3). The error bars shown in Fig. 2 are characteristic of the error bars on all points. Let us first consider the low pump energy data. At low gain the Stokes beam inside the amplifier is predicted to be nearly Gaussian, focusing at the center of the amplifier. The Gaussian beam Stokes input couples most strongly to the amplifier when it too focuses near the center. At high gains, however, the Stokes pulse differs significantly from a Gaussian beam. A key difference is the radius of curvature of the wave fronts: For a Gaussian beam the wave fronts are flat at focus while $\Phi_0^0(\theta,\mathbf{r}_T)$'s wave fronts, as shown in Ref. [9], are curved at focus and do not show any of the symmetry about focus that the Gaussian beam's wave fronts do. However, by focusing the Gaussian laser diode beam before the center of the amplifier, the wave fronts more closely mimic those of $\Phi_0^0(\theta,\mathbf{r}_T)$. Thus it may not be surprising that the coupling efficiency is increased by focusing the laser diode beam before the center of the amplifier. In fact, Fig. 2 shows a 50% increase in the coupling efficiency, compared to focusing in the center of the amplifier, by focusing 30 cm before the center of the amplifier. Note that this offset in focal position is comparable to the Rayleigh range of the pump beam. Next, we consider the possibility of further increasing the coupling efficiency by varying the Rayleigh range of the laser diode input as well as its position of focus.

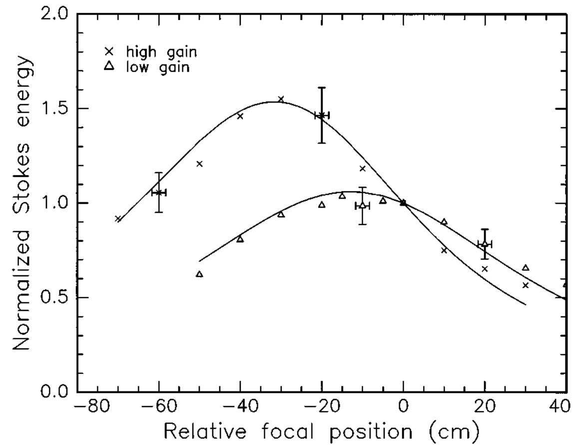


FIG. 2. Normalized Stokes output as a function of the relative focal position of the laser diode input beam for two different gains. The Rayleigh range $z_0$ of the laser diode beam is 30 cm for these data. The pump beam Rayleigh range is also 30 cm. The points (lines) represent experimental (theoretical) data. At low gains the input beam couples most strongly when it focuses near the center of the amplifier. At high gains, diffraction and gain guiding have modified the Stokes beam's wave fronts such that it couples more strongly to the laser diode beam when the laser diode beam focuses well before the center of the amplifier where the pump beam focuses.

Numerical modeling indicates that decreasing the Rayleigh range of the laser diode beam as well as focusing it before the center of the amplifier lead to coupling efficiencies larger than those obtained with the Rayleigh range set equal to that of the pump beam ($z_0$=30 cm). Figure 3 shows the data with the laser diode beam Rayleigh range set to 17 cm. All other experimental parameters were the same as they were for the high gain coupling experiment discussed earlier. Also shown are the numerical calculations (solid lines) and the $z_0$=30 cm data for reference. The striking features of the $z_0$=17 cm data is that the maximum coupling efficiency is nearly a factor of 2 larger than that measured with the beam focused at the center of the amplifier and approximately 20% higher than the maximum coupling efficiency measured with $z_0$=30 cm. The increased coupling efficiency obtained with the shorter Rayleigh range can be explained as follows: At high gains the Stokes beam inside the amplifier is narrower and has a complicated radius of curvature compared to a Gaussian beam with a Rayleigh range of 30 cm. Therefore efficient coupling can be realized by using a spatially narrow input beam with wave fronts similar to those of $\Phi_0^0(\theta,\mathbf{r}_T)$. These characteristics can be approximated by a Gaussian beam that focuses before the center of the amplifier and has a shorter Rayleigh range than the pump beam. Our calculations indicate that it is not possible, without changing the

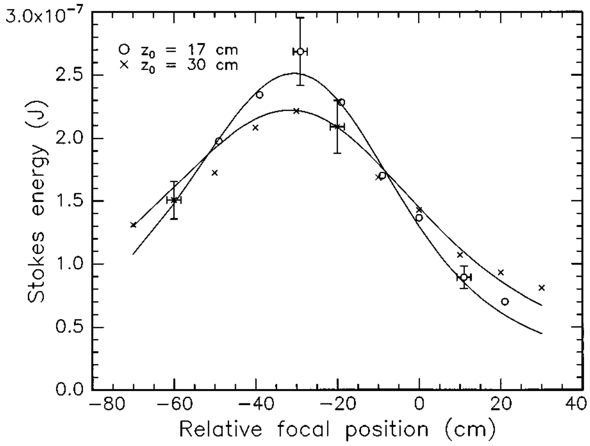


FIG. 3. Theoretical (lines) and experimental (points) Stokes output as a function of the relative focal position and Rayleigh range of the laser diode input. Both data are collected at high gain with the pump Rayleigh range at 30 cm. Gain guiding narrows the Stokes mode as well as modifying its wave fronts; thus a tightly focused (short Rayleigh range) input that focuses before the center of the amplifier couples most efficiently.

pump beam or amplifier characteristics, to further enhance the input coupling efficiency of a Gaussian beam beyond that obtained by focusing a $z_0$=17-cm beam 30 cm before the center of the amplifier. Further enhancements of the input coupling efficiency requires modification of the input beam into a non-Gaussian profile.

In conclusion we have shown that very efficient coupling of a Gaussian beam input into an amplifier with focused Gaussian gain profile requires, in general, that the beams, pump and input, do *not* focus at the same location. Experiments utilizing a Raman amplifier operated at high gains demonstrated that the most efficient input coupling occurs when the Stokes input has a shorter Rayleigh range than the pump and focuses well before center of the amplifier where the pump beam focuses. At low pump laser power, on the other hand, maximum coupling occurs when the pump beam and Stokes input beam focus at the same location. These results are all in accord with a three-dimensional theoretical model of a gain-guided amplifier. The theory, which utilizes a nonorthogonal mode expansion, predicts that at low gains the Stokes beam inside the amplifier is a Gaussian but at higher gains competition between gain narrowing and diffraction causes narrowing of the beam and distortion of its wave fronts. Since the amount of distortion depends on the pump laser power, the Rayleigh range and position of focus of the input beam that maximizes the coupling efficiency also depends on pump laser power.

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