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Performance of a Nd:YAG Oscillator/Amplifier with Phase-Conjugation via Stimulated Brillouin Scattering

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Abstract. Phase conjugation via stimulated Brillouin scattering in CH_4 gas has been used to correct amplifier aberrations in a Nd : YAG oscillator/amplifier system. The single amplifier stage has been used in two-pass and four-pass arrangements. Using the four-pass arrangement incorporating compensation for thermal birefringence, a single-frequency diffraction-limited output of 350 mJ, in a compressed 6 ns pulse is achieved at 15 Hz repetition rate.

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Nonlinear optical phase-conjugation (NOPC) via stimulated Brillouin scattering has received considerable theoretical and experimental attention since the initial work of Zel'dovich et al. [1, 2] (see [3] for extensive reviews). An interesting application of NOPC is in the correction of optical aberrations produced by a laser amplifier stage (or stages). A great deal of the work in this area has been performed with high power glass laser systems (many references in [3]) but there has been little published work based on the Nd : YAG laser, despite its being the most widely used solid-state laser. Exceptions to this are the work of Zubarev et al. [4] and Hon [5]. Zubarev et al. demonstrated a considerable improvement in output beam quality from a Nd : YAG oscillator/amplifier using SBS phase-conjugation. However, the Nd : YAG crystals used in that experiment were of poor optical quality and distorted the beam to a much worse degree than would crystals of typical quality. Furthermore, the final output energy was only at the level ($\sim$100 mJ) that can be achieved from a TEM_{00} oscillator of suitable design [6, 7] with crystals of typical quality. Hon's work [5] demonstrated the successful application of NOPC to a Nd:YAG system consisting of a Q-switched oscillator with two amplifier stages, leading to $\sim$700 mJ of diffraction-limited output. Additional aberration was introduced into the amplifier chain in the form of a Nd : YAG rod subjected to strong continuous pumping. The ability to correct severe pump-induced aberrations was thus demonstrated. In fact, it is also a feature of many NOPC experiments that aberrations are deliberately introduced on the basis that this produces better fidelity in the wavefront reconstruction [8]. However, this can complicate the NOPC set-up since the extra beam distortion raises the SBS threshold and a lightguide arrangement is then needed to reduce the threshold. Meanwhile, the question that needs to be answered for the user of a typical pulsed Nd : YAG laser is whether the additional complexity of a NOPC set-up is worthwhile and how much complexity is necessary (e.g., introduction of aberrator, lightguide, single-mode operation of the oscillator), when the requirement is simply to remove the relatively modest, but still troublesome aberrations associated with the amplifier stage. This paper reports results obtained in an attempt to answer that question. To summarise, we have found that

(i) effective NOPC can be achieved using a simple cell containing high pressure CH_4 gas but not involving the use of a light guide,

(ii) effective NOPC can be achieved even with the oscillator operating on a few longitudinal modes,

(iii) by incorporating birefringence compensation we can successfully use a single amplifier in a four-pass configuration,

(iv) with this four-pass arrangement, a single frequency TEM_{00} output of 350 mJ is obtained in a pulse of 6 ns, compressed temporally from the input pulse duration of 30 ns,
(v) we find that most of this pulse compression occurs in the last two passes of the amplifier rather than (as in the experiments of [9–11]) in the SBS medium.

1. Experimental Details

1.1. Amplifier Configurations

The Nd:YAG laser system consisted of an oscillator (3″ × 1/4″ rod with single flashlamp) and an amplifier (3″ × 3/8″ rod, with twin flashlamps), capable of operating at up to 15 Hz repetition rate, with maximum flashlamp input energies of 50 J to the oscillator and 100 J to the amplifier. The TEM_{00} mode oscillator used a telescopic resonator, similar to that described in [6, 7], with a X3 telescope magnification and a spacing of 0.35 m between the telescope and the resonant reflector output coupler. The oscillator was operated on a single longitudinal mode on every shot, using the technique described in [12], and produced up to 100 mJ output in a 30 ns pulse. When multi-longitudinal mode operation was required, the conventional fast Q-switched arrangement was used, or the mode-selection etalon was removed, or (for the broadest linewidth) both of these measures were adopted. The beam from the oscillator was expanded by a telescope to produce a spot-size (TEM_{00}, radial spot-size w) of 2.8 mm in the amplifier rod, this being close to the maximum size ($3w$ = rod diameter) possible without significant truncation.

We have examined two different experimental arrangements, involving either two passes through the amplifier (Fig. 1a) or four passes through the amplifier (Fig. 1b). We consider the two-pass arrangement first. To assess the effectiveness of phase-conjugation the performance with the SBS "mirror" was compared with that obtained using a conventional plane mirror of 100% reflectivity. With the latter arrangement, various schemes can (in principle) be used to isolate the oscillator from the return beam and at the same time enable the amplifier output to be extracted. The simplest involves a polariser followed by a quarter wave plate (Fig. 1a) which can be located on either side of the amplifier (location 1 or 2 in Fig. 1a). In either

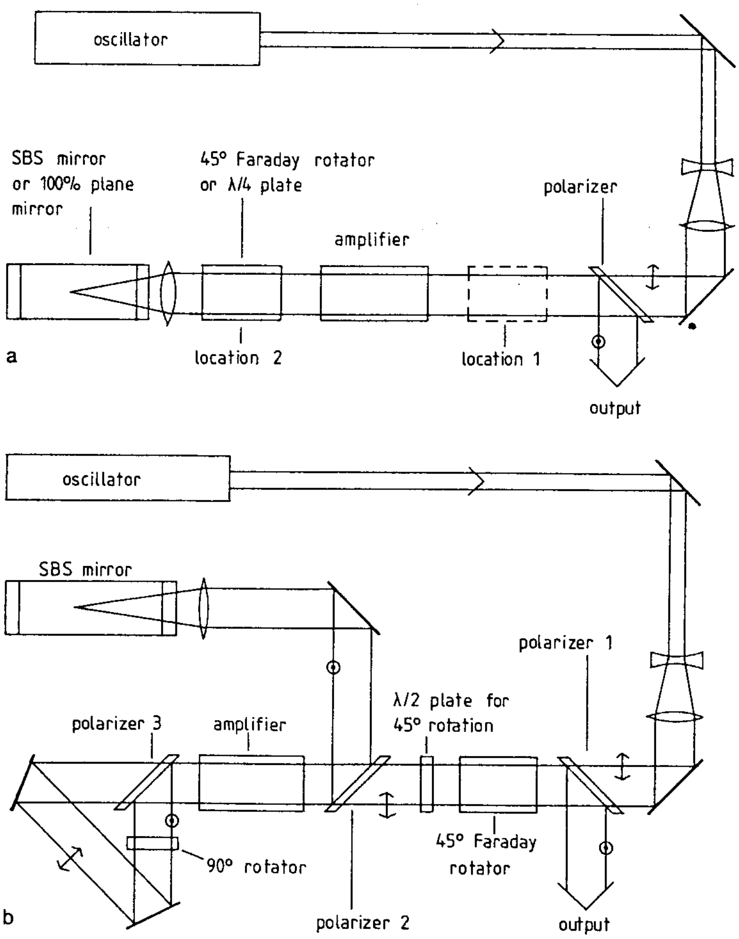

Fig. 1. (a) Two-pass amplifier configuration. For isolation of the oscillator from the amplifier beam a quarter wave plate or 45° Faraday rotator can be placed at location 1 or 2. (b) Four-pass amplifier configuration. The Faraday rotator and $\lambda/2$ plate give zero net rotation for light from right to left but 90° rotation for light from left to right. Details of the polarisation changes after polariser 2 are given in the text

case, one is relying on there being no additional polarising elements following the polariser. In fact, however, the laser rod suffers from thermally induced birefringence [13] which not only introduces an extra polarising element, but one which has a birefringence behaviour distributed non-uniformly over the rod cross section. This has the undesirable effects of i) coupling power back to the oscillator, representing both a source of loss and a damage risk, and ii) producing phase and amplitude variations across the output beam which degrade the beam quality.

One means of compensating the birefringence is to use a Faraday rotator (45° rotation) placed after the first pass of the amplifier (location 2 in Fig. 1a). This arrangement is then equivalent to the unfolded arrangement, as actually used by Scott and DeWitt [14], in which a 90° rotator is placed between two identical amplifier stages. A ray passing through the amplifier has its field component along the fast birefringence axis rotated by 90° so that it lies along the slow axis in the second amplifier, and vice versa. Thus, regardless of the orientation of the fast and slow axes (they are, however, orthogonal to each other) the birefringence in one amplifier is cancelled in the second. (Note that a quarter wave plate at location 2 in Fig. 1a or equivalently a half-wave plate between two identical amplifiers does not achieve this birefringence compensation.) For the compensation to work effectively the following condition must be met: the two amplifiers must be closely matched, a situation that automatically results from double-passing a single amplifier: the beam passing through the amplifier should be collimated if the return mirror is a conventional mirror, so that identical paths are retraced on the second pass: the round-trip distance between the two amplifier passes should be kept short to minimise the effects of diffraction spread. A measure of the birefringence compensation is determined by comparing the power reflected by the polariser (this is the useful output) with that transmitted by the polariser (this is the depolarisation loss), after a double pass of the amplifier.

When the conventional mirror is replaced by the SBS mirror the conditions for birefringence compensation are no longer quite the same since the SBS process does not, in general, produce a Stokes wave with the same polarisation state as the pump wave [15]. However, for a *uniformly* polarised pump beam the SBS mirror has the same effect on polarisation state as a conventional mirror [5, 15] and therefore, in the absence of amplifier depolarisation, a quarter wave plate at location 1 or 2 in Fig. 1a would provide the desired isolation and beam extraction. The situation is more complicated when the amplifier introduces an inhomogeneous birefringence distribution. As discussed above, a 45° Faraday rotator placed at location 2 would correctly compensate the depolarisation if a conventional mirror were in use, but, as Zel'dovich and Shkunov [15] have shown in a theoretical analysis, when a depolarised pump is used the Brillouin Stokes wave can have a quite different polarisation state from that produced by a conventional mirror. One would expect, therefore, the wavefront reconstruction to be degraded as a result of the amplifier birefringence, but the analysis of Zel'dovich and Shkunov does not predict the extent of degradation. We have therefore carried out an experimental examination of the phase-conjugation behaviour with either a $\lambda/4$ plate or a 45° Faraday rotator, in each case placed at location 2 in Fig. 1a. We have found that the depolarisation loss is significantly lower with the Faraday rotator and that furthermore the loss is lower when the rotator is used in conjunction with the SBS mirror rather than the conventional mirror.

By going to a four-pass arrangement it is possible to introduce birefringence compensation prior to the phase-conjugation process and thus, in principle, present a uniformly polarised wave to the SBS mirror. Hon [5] used the equivalent unfolded arrangement by having two amplifier stages with a 90° rotator between them, and then followed by the SBS mirror. Our four-pass arrangement is shown in Fig. 1b. Horizontally polarised light (p-polarisation) from the oscillator is passed by polariser 1 and remains p-polarised after being subjected to opposite 45° rotations from the Faraday rotator and $\lambda/2$ plate. On the return path this arrangement produces a vertically polarised (s-polarisation) beam which is then reflected as output by polariser 1. The p-wave passing through polariser 2 enters the amplifier and then, emerging as a depolarised beam, is split into two orthogonally polarised waves at polariser 3. These waves conterpropagate around the ring configuration, each being subjected to a 90° rotation of polarisation on the way round. They recombine as a single beam at polariser 3. The effect of the ring is to interchange the field components for any two orthogonal polarisations (i.e., it acts like a double pass through a 45° Faraday rotator) and thus allows the rod birefringence to be compensated. The beam emerging from the second pass of the amplifier is now s-polarised and therefore reflected off polariser 2 into the phase-conjugator. After conjugation the entire process is repeated for the return beam which is p-polarised as it emerges from the fourth amplifier pass. (We are indebted to Dr. C. L. M. Ireland for pointing out the polarising properties of this ring configuration, and we also note that an equivalent arrangement is embodied in a special Pockels cell Q-switch device reported by Richards [16]).

Besides offering the ability to compensate rod depolarisation before phase-conjugation the four-pass amplifier offers additional potential advantages over the two-pass amplifier such as:

1) a lower input energy requirement from the master oscillator,
2) a better energy extraction from the amplifier, and
3) satisfactory energy extraction with a lower input energy to the phase-conjugator or with lower reflectivity from the conjugator.

1.2. The SBS Medium

We have confined our investigations to the use of high-pressure CH_4 gas as the SBS medium since it had been shown [5] to provide efficient SBS for a 1.06 μm pump. Other media, (see, e.g., [4] and the discussion in [10]) may also prove satisfactory but we have not tested these.

The threshold pump power for SBS is a parameter of practical importance and we now discuss how we have calculated this from the published data. We find good agreement between our calculated and measured values. Under steady state conditions, i.e. with a pump pulse whose bandwidth $\Delta\nu_p$ is such that $(\Delta\nu_p)^{-1} \gg \tau_B$, where τ_B is the acoustic phonon damping time, the gain of the Stokes wave over a length l of medium for a plane wave pump of intensity I_p is $\exp\{g_B I_p l\}$. We define threshold as the condition when the gain reaches exp(30). Hence the threshold pump power $P_{p,th}$ is given by

$$P_{p,th} = \frac{30 A_p}{g_B l} p, \tag{1}$$

where A_p is the area of the pump beam. This simple expression for the pump threshold becomes modified in a number of ways when account is taken of the non-plane-wave nature of the pump (including the possibility of an aberrated pump beam) and the transient nature of the process when $(\Delta\nu_p)^{-1} \leqq \tau_B$. The latter condition can arise either because the overall pump envelope is shorter than τ_B or because the envelope contains fluctuations on a short time scale, e.g. when a multimode pump is used.

To calculate the steady-stade threshold for a Gaussian pump beam we have used the analysis of Cotter et al. [17] which, for a pump beam waist w_p (confocal parameter $b_p = 2\pi w_p^2/\lambda_p$) at the centre of a SBS medium of length L yields a threshold pump power

$$P_{p,th} = \frac{\lambda_p}{4 g_B} \{1 + [1 + 30/\arctan(L/b_p)]^{1/2}\}^2 . \tag{2}$$

The typical parameters relevant to our experiment are $w_p = 150$ μm, hence $b_p = 0.13$ m, and the cell length $L = 1$ m. The dependences of g_B and τ_B on gas pressure p and laser wavelength λ_p are as follows [10], $g_B \alpha p^2$, $\tau_B \alpha p$, $\tau_B \alpha \lambda_p^2$ and g_B is essentially independent of λ_p. For 30 atmospheres pressure (as used in our experiments) $g_B = 8 \times 10^{-5}$ m/Mw and for a 1.06 μm pump, $\tau_B \sim 6$ ns. These values, with (2) yield a calculated steady state threshold pump power $P_{p,th} = 100$ kW. In fact, however, the pump pulse duration τ_p of 30 ns (FWHM) is sufficiently close to the phonon lifetime τ_B for a significant departure from the steady state threshold and with our values $\tau_p/\tau_B = 5$ the threshold power is then predicted [18] to be ~2.5 times greater than the steady state value, i.e. ~250 kW. The actually observed threshold was 400 kW for single-mode pumping. Note that this threshold cannot be significantly reduced by altering the focussing condition since the best that can be achieved is to make $\arctan(L/b_p) = \pi/2$. On the other hand, it can be reduced using an optical waveguide capillary [19, 20], and a threshold reduction of an order of magnitude has been obtained in this way [21]. A threshold reduction can also be achieved by operating at higher pressure p, where the fact that the process becomes more transient ($\tau_B \alpha p$) is offset by the fact that $g_B \alpha p^2$. Thus at 50 atmospheres we observed a threshold of 230 kW for an unguided single frequency, Gaussian pump beam.

To estimate the threshold for a beam which is not diffraction-limited, we note that the product of intensity I_p and the length of medium over which this intensity is maintained (i.e., the Rayleigh range) is smaller by a factor M for a beam whose divergence is M times greater than the diffraction limit. This result would appear to suggest that the threshold is M times greater, however it has to be remembered that the phase-conjugate beam can experience a gain exponent of ~twice that which would result from a single spatial mode of the same spatially averaged intensity [22]. The minimum threshold power for the aberrated beam is therefore ~$M/2$ greater than for the diffraction limited pump beam.

The effect on threshold of using a noisy pump (i.e., multi frequency) has been discussed in detail by Akhmanov et al. [23]. The following conclusion can be drawn; the SBS gain with a noisy pump of mean intensity I_p is the same as for a monochromatic pump of the same mean intensity provided the length of medium, $30/(g_B I_p)$, over which an exp(30) fold Stokes growth occurs is much less than the coherence length $(c/\Delta\nu_p)$ of the pump. In practice this means that the confocal parameter of the focussed pump should be less than the pump coherence length; i.e.

$$b_p \ll l_{\mathrm{coh}} . \tag{3}$$

The analysis of Akhmanov et al. also allows an estimate to be made of the threshold increase due to a noisy pump where this condition is not met. With our typical operating conditions, $b_p = 0.13$ m, and with a single mode pump, $l_{coh} \simeq 6$ m, the condition is clearly satisfied. With n longitudinal modes, $l_{coh} = 2L_{laser}/n$, and since for our laser, $L_{laser} \sim 1$ m, the condition $b_p \ll l_{coh}$ is maintained even for 3 or 4 mode operation. This is confirmed by the observation that the threshold and phase-conjugation behaviour are little affected even when a few modes oscillate. However, when the laser oscillated with a bandwidth of ~ 2 GHz ($l_{coh} \sim 0.15$ m, $n \sim 15$ modes) the threshold, at 30 atmospheres, was increased by $\sim 75\%$, a result consistent with the analysis of Akhmanov. Under these conditions phase-conjugation still occurred but it was noticeably less reliable and gave poorer beam reconstruction. We also noted that at a gas pressure of ~ 50 atmospheres, (thus increasing g_B), the threshold for the noisy pump was only slightly greater than for the single mode pump, a result in accord with the requirement $30/(g_b I p) \ll l_{coh}$ and confirmed by Akhmanov's analysis.

2. Experimental Results

The experimental parameters of most interest are the output energy and the beam quality. We have measured beam profiles using a diode array and at the same time a qualitative assessment of the beam has been made by observing the burn patterns on photographic paper. There are some possible pitfalls where beam quality measurements are concerned so we point these out and explain our measurement procedure in some detail.

First we note that an irregular burn pattern in the near field is not necessarily indicative of a poor beam quality since it may be that most of the beam energy is in a diffraction-limited component but mixed with a small component having different beam profile. This sensitivity of the spatial profile to a small admixture is analogous to the sensitive detection of beats when a dominant longitudinal mode is in the presence of a much weaker mode [24]. Lehmberg [25] has confirmed in a numerical calculation that the near-field beam profile in a phase-conjugation set-up may suffer large amplitude modulation when even a small non-phase-conjugate component is present.

Secondly, we note that in comparing the beam quality obtained with and without the phase-conjugator one cannot draw conclusions on beam quality simply from an observation of difference in far-field beam dimensions for these two cases. For example, if the amplifier distortion was in the form of pure spherical lensing or if the input to the amplifier was not collimated, then the two cases would produce quite different output beam focussing, and hence divergence, while both would be diffraction-limited. To remove any uncertainty we have deliberately used a lens to focus the output beam to form a new waist, whose size was then measured using the diode array. The beam divergence from this waist was then determined using the diode array to measure a spot-size in the far field (i.e., many confocal parameters from the waist). The ratio of the measured beam divergence to that calculated from the measured waist yields the factor by which the output beam exceeds the diffraction-limit.

Thirdly, we note that since some of the output beam energy may be in the form of a non-phase-conjugate component of higher divergence, the far-field pattern as indicated either by burn marks or by a diode array may not reveal these low-intensity wings of the spatial profile even if they contain a significant fraction of the total energy. We have therefore measured the energy in the central diffraction-limited part of the profile after first passing the far-field beam through a circular aperture. The aperture size was chosen to have a diameter three times the measured spot-size w of this central diffraction-limited spot.

The results on beam quality can be summarised as follows. With the two-pass amplifier arrangement of Fig. 1a using a plane 100% reflector in place of the SBS cell an output energy of ~ 400 mJ could be obtained in a 30 ns pulse. The output beam quality worsened as the mean power into the amplifier was increased. This is clearly seen in Fig. 2a and b which show burn patterns and profiles monitored by the diode array at various distances from the amplifier. Despite the somewhat ragged appearance of the burn pattern at 5 Hz, the diode array indicated that the beam was essentially diffraction-limited and even the severely distorted patterns at 15 Hz were found to correspond to only a factor of ~ 2 greater divergence than the diffraction limit. Also shown in Fig. 2a and b are the corresponding beam profiles for the two-pass amplifier with the SBS cell. In this case, a total output energy of ~ 330 mJ was obtained in a 16 ns pulse and $\sim 90\%$ of this energy was transmitted by the far-field aperture. Thus ~ 300 mJ of diffraction-limited output was obtained. The output-beam brightness at 15 Hz is therefore improved by a factor of 3 as a result of phase conjugation (or a factor of ~ 6 if one includes the increase of power due to the reduction of pulse length by a factor of ~ 2). At 5 Hz there is only a slight degradation of the beam by the amplifier and so apart from the cleaner appearance of the burn pattern the use of the phase-conjugator does not offer much benefit. At 15 Hz the value of the phase-conjugator is much more apparent and the far-field spots have a clean circular appearance apart from the small degree of square-shaped truncation due to thermal birefringence effects.

The output beams shown in Fig. 2a and b have not been modified by any focussing elements after leaving the

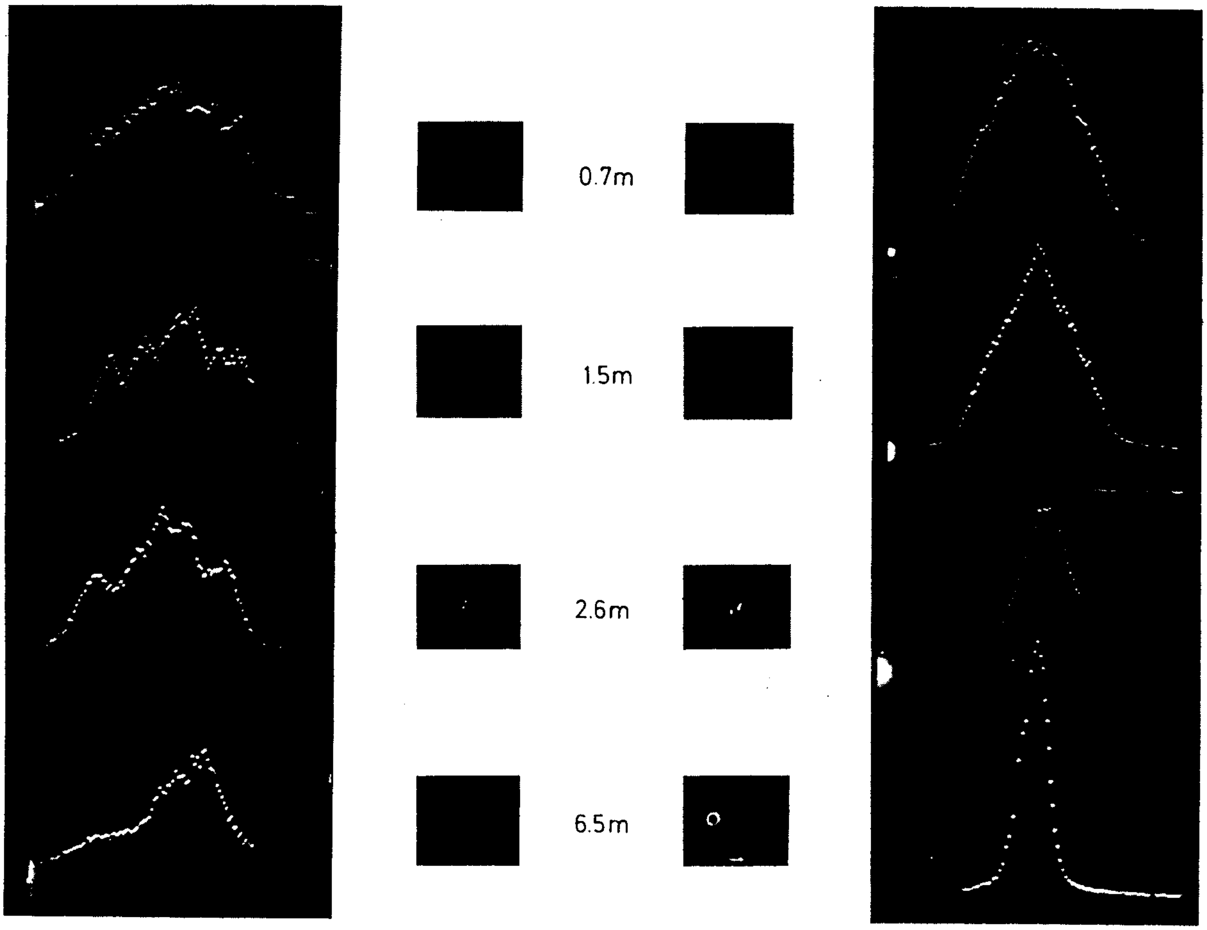

Fig. 2. (a) Beam profiles at various distances from two-pass amplifier, at 5 Hz rep. rate, either with phase-conjugation (right-hand photos) or without phase-conjugation (left-hand photos).

amplifier. The focussing behaviour observed at 15 Hz in the non-phase-conjugated beam, due to amplifier lensing, shows strong astigmatism with the beam coming to foci between 1.5 and 2.5 m from the amplifier. This amplifier lensing effect is removed in the phase-conjugate beam. The focussing behaviour of the phase-conjugate beam is simply due to the fact that the input to the amplifier was slightly divergent and hence the conjugate return beam has an opposite convergence. An enlarged version of the phase-conjugate beam 6 m from the amplifier is also shown, obtained by expanding the beam with a negative lens.

Using the four-pass amplifier arrangement similar results were obtained although at somewhat higher output energies. Measurements were only made with the SBS cell in this case since a conventional mirror in place of the SBS cell led to oscillaton (as a result of depolarisation caused by thermal birefringence in the amplifier). Output energies up to ~440 mJ were obtained, of which ~350 mJ (i.e. 80%) was diffraction-limited. Figure 3 shows the near-field and far-field output beam profiles at 5 and 15 Hz. The pulse duration of the output beam was considerably compressed, from an initial 30 to ~6 ns. Figure 4 shows the pulse shapes at various stages in the amplification process. The reflected SBS pulse shows a sharp leading edge, (rise: ~2 ns) and is truncated to ~20 ns duration. This reflected pulse after the two return passes through the amplifier is further shortened to ~6 ns as a result of saturation in the amplifier. This degree of pulse compression in the amplifier is consistent with calculations following the work of Frantz and Nodvik [26]. We note that Ambartsumyan et al. [27] have used a shutter to deliberately generate a steep leading edge to a Q-switched pulse for subsequent compression in a saturated amplifier. The SBS process achieves this in a simple and automatic fashion.

The shortened pulse duration must lead to some degree of spectral broadening. Direct confirmation of this was made for the two-pass amplifier configuration where the linewidths of the input and output to the amplifier were measured. The measurement was made

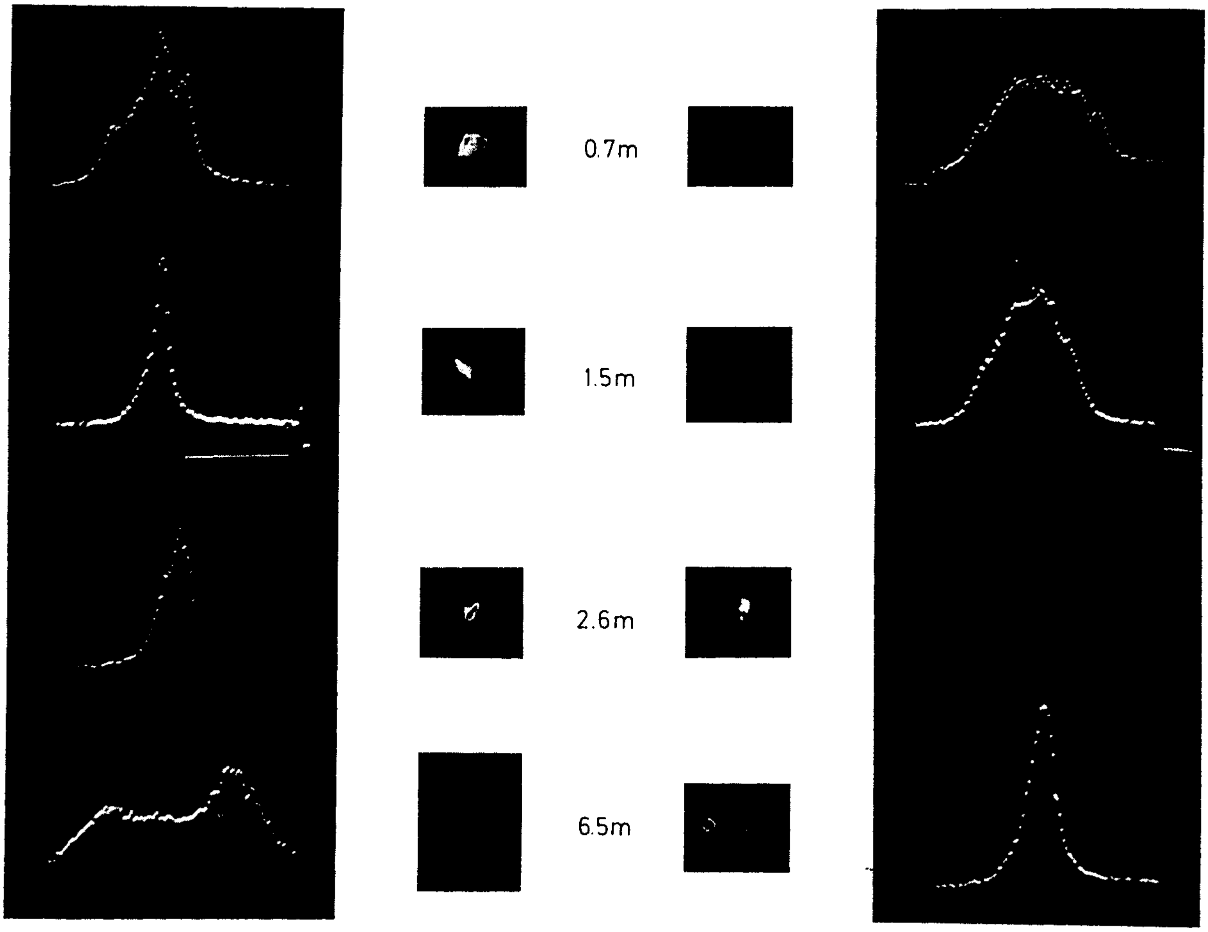

Fig. 2. (b) Beam profiles at various distances from two-pass amplifier, at 15 Hz rep. rate, either with phase-conjugation (right-hand photos) or without phase-conjugation (left-hand photos)

by converting the 1.06 μm radiation to its second harmonic and examining the linewidth of the green light using a scanning confocal Fabry-Perot interferometer. Figure 5 shows scans obtained for the input and output linewidths. After allowing for the spectral modification arising from the harmonic generation we deduce that the linewidth of the SLM input was 33 MHz (i.e., somewhat broader than the bandwidth limit for a 30 ns pulse) and the Brillouin shifted output linewidth was 50 MHz.

In the four-pass amplifier configuration it is, in principle, possible for an unshifted component (i.e., not phase-conjugated) and the Brillouin-shifted component to be both present in the output. The unshifted component is the result of uncorrected depolarisation of the beam after the first two amplifier passes, thus producing some output without undergoing phase-conjugation. However, an examination of the temporal behaviour of the output beam failed to reveal any beats (at ~800 MHz) between the Brillouin-shifted and unshifted components, suggesting that the unshifted component is much weaker and that the output can be regarded as essentially single-frequency. We have also examined the output to see if there is any evidence of oscillation from the SBS mirror once this is established. This could result if uncompensated amplifier depolarisation coupled enough radiation back to the SBS mirror after the fourth amplifier pass, rather than passing through polariser 2. No sign of such an oscillation was found, its absence being an indicator that our birefringence compensation was sufficient.

A measurement of depolarization losses give a useful guide to the success of any birefringence compensation scheme. We have determined these losses by measuring the fraction of the return beam which passes back through polariser 1 (Fig. 1) rather than being reflected as output. Figure 6 shows the results obtained at 5, 10, 15 Hz for four different arrangements of the two-pass amplifier, viz. plane mirror plus $\lambda/4$ plate, plane mirror plus Faraday rotator (FR), phase-conjugate mirror (PCM) plus $\lambda/4$ plate, and PCM plus FR. In

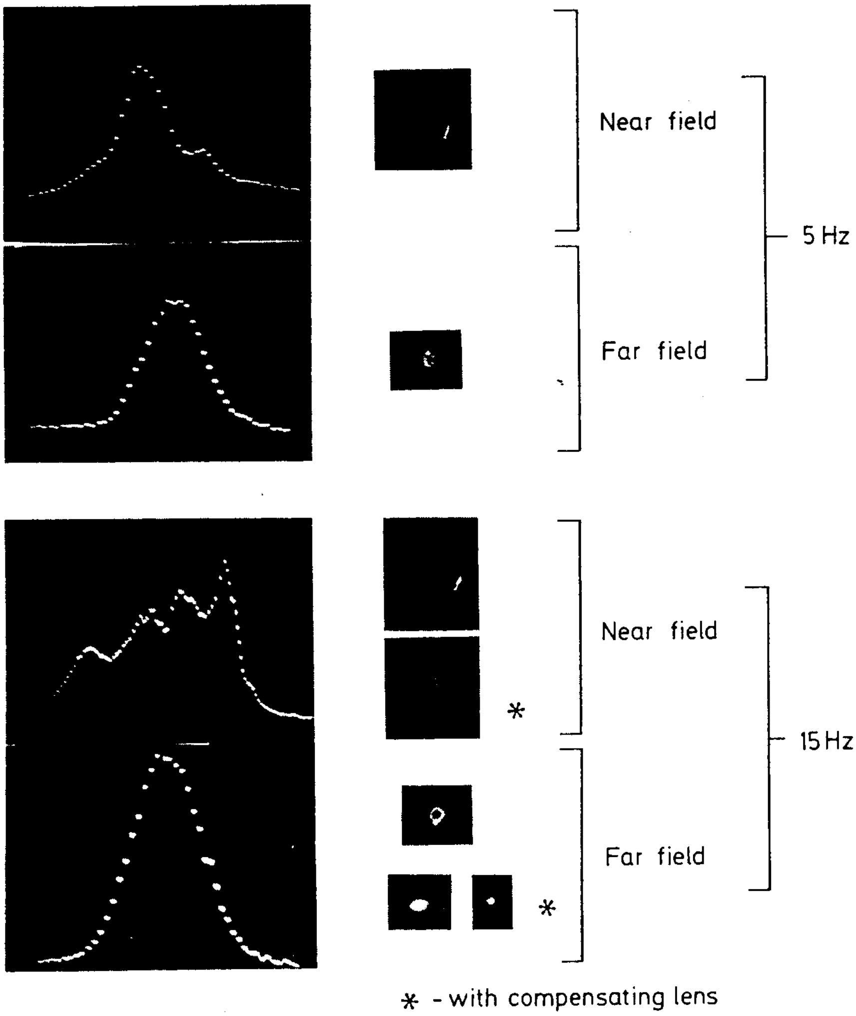

Fig. 3. Near field and far field beam profiles for the four-pass amplifier with phase-conjugation, at 5 and 15 Hz. The effect of adding a compensating lens is shown (see text)

each case, the $\lambda/4$ plate or FR was placed at location 2 in Fig. 1a. The increase of loss with repetition rate is expected since this increases the thermally-induced birefringence. It is interesting to see that the depolarisation losses for the configuration of plane mirror plus $\lambda/4$ plate can be calculated with good accuracy (using an extension of the analysis in[13]). The FR plus plane mirror gave a good performance at 5 Hz but were less effective than anticipated at 15 Hz. However, we conclude that this is because the considerable thermal lensing at 15 Hz upsets the requirement that the return rays should retrace identical paths. Evidence for this was also found in the four-pass amplifier scheme, where the ring configuration plays the role of Faraday rotator. Figure 7 shows the measured depolarisation loss in this arrangement, also increasing rapidly with repetition rate. However, when operating at 15 Hz, placing a negative lens in the ring, whose effect was to recollimate the beam for its return path through the amplifier, the depolarisation loss fell from $\sim$15% to $\sim$5%. This result emphasises the importance of obtaining good birefringence compensation. It also shows that while the arrangement we have used is adequate for the conditions in our laser it is clear that an improved scheme is needed to cope with more severe birefringence such as in a Nd glass laser. The scheme described by Basov et al. [28] looks attractive in this respect. We have conducted preliminary tests of this scheme, which show that a further reduction of depolarization loss can be achieved (down to less than 2% at the maximum pumping rate of the amplifier). Detailed results of this work will be reported in a later publication.

3. Conclusion

We have shown that a simple phase conjugation scheme can produce a significant improvement in the output beam quality from a Nd:YAG oscillator/amplifier system. While the benefits of introducing the phase conjugator are marginal at the 5 Hz repetition rate the technique is certainly worthwhile at 15 Hz,

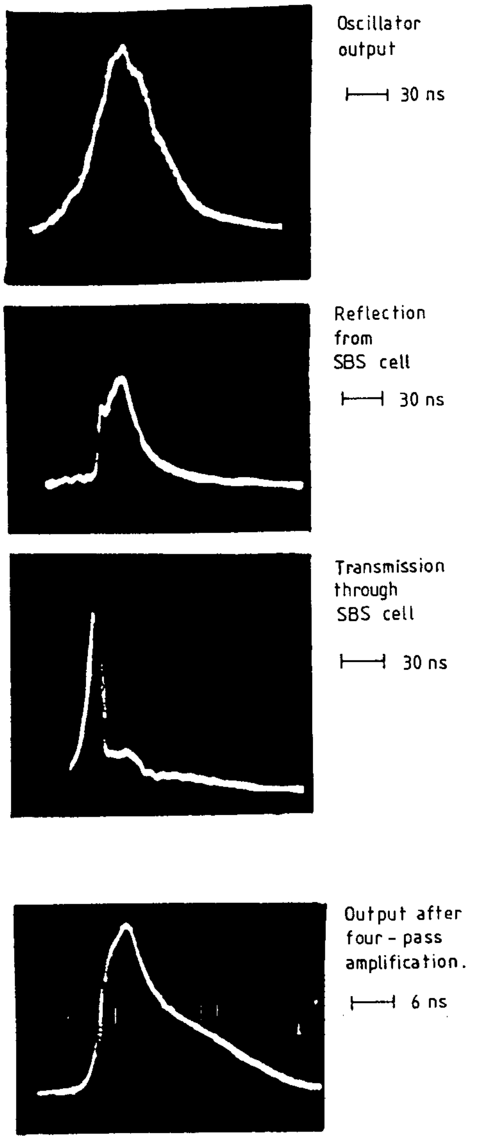

Fig. 4. Pulse shapes at various stages in the amplification process

giving a factor of 3 improvement in beam brightness. This factor does not include any allowance for the increase in power due to pulse compression. If this is included, the four-pass amplifier with phase-conjugator has led to a factor of ~15 improvement in beam brightness.

Besides the improvement in beam brightness the profile of the phase-conjugated beam had a much cleaner appearance, an important feature where accurate measurements are needed. Furthermore, we were able to vary the flashlamp input to the amplifier (as a means of varying the output energy) without causing variations in the output beam as a result of varying thermal conditions in the amplifier. Such output beam variations are a nuisance in conventional oscillator/amplifier systems.

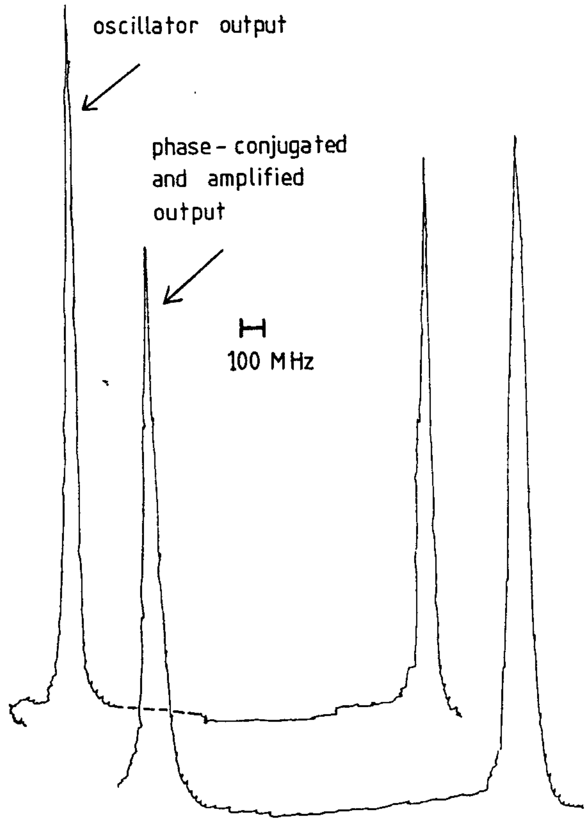

Fig. 5. Transmission Scans from scanning Fabry-Perot interferometer, using second harmonic of the Nd:YAG laser

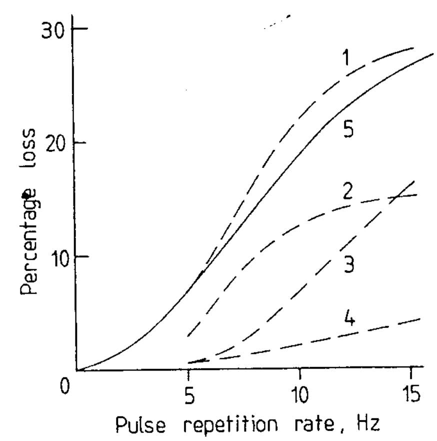

Fig. 6. Birefringence loss versus pump repetition rate for a constant 72 J pump energy per pulse to the amplifier, used in double pass. Curve (1) plane mirror with $\lambda/4$ plate; Curve (2) SBS mirror with $\lambda/4$ plate; Curve (3) plane mirror with Faraday rotator; Curve (4) SBS mirror with Faraday rotator; Curve (5) is calculated for the case of plane mirror with $\lambda/4$ plate

While our results show that a significant improvement in laser performance can be gained without undue complexity we have not made an exhaustive study, either of optimisation or of the degree to which certain conditions can be relaxed without prejudice to the

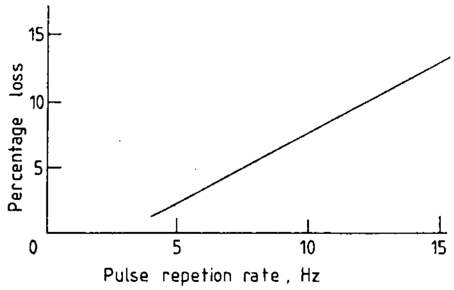

Fig. 7. Birefringence loss versus pump repetition rate for 72 J pump energy per pulse to the amplifier, used in the four-pass configuration

fidelity of the wavefront reconstruction. Certainly however we have seen that single-longitudinal mode operation can be relaxed to some extent and we have seen that a light guide is not essential. Without doubt further improvements in performance should be possible with detailed optimisation. It is also likely that improved schemes for birefringence compensation [28] or possibly a combination of phase-conjugation with a slab laser configuration will lead to similar improvements in the performance of Nd:glass systems.

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