Volume 62, number 6 OPTICS COMMUNICATIONS 15 June 1987

CORRECTION OF POLARISATION DISTORTIONS USING PHASE CONJUGATION VIA STIMULATED BRILLOUIN SCATTERING

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Received 17 November 1986

A scheme using phase conjugation via stimulated Brillouin scattering in methane gas has been developed for the accurate conjugation of both the polarisation state and the phase of a non-uniformly depolarised laser beam. It incorporates a two-plate tapered light guide with metallic reflecting surfaces which has the property of preserving the linear polarisation of the input light. This scheme has been successfully applied to a Nd:glass amplifier arrangement. The residual birefringence loss of 3% (after a double pass) was found to be independent of pump power to the amplifier even when this was increased to a level sufficient to give a *single-pass* depolarisation loss of 20%.

1. Introduction

An important application of nonlinear optical phase conjugation is in the correction of optical aberrations produced by laser amplifier stages (see ref. [1] for extensive reviews). Many authors have reported a considerable degree of success in compensating for phase distortions in amplifiers by using a double-pass configuration, but the performance of such systems is often limited by depolarisation of the laser beam whilst traversing a strongly pumped amplifier rod or some other depolarising element [2–5].

One drawback of stimulated Brillouin scattering (SBS) as a means of phase-conjugation is that it does not, in general, conjugate the polarisation state of the incident laser beam [6,7]. For example, a right circularly polarised beam is back scattered as a left circularly polarised beam just as in an ordinary mirror reflection whereas the conjugate polarisation state in the reflected beam would be right circularly polarised. There is one polarisation state, however, which is correctly conjugated, this being the case of a uniformly linearly polarised beam.

In some cases, where the depolarisation is not excessive, the beam remains sufficiently close to uniform linear polarisation that good conjugation still occurs. Under these circumstances, a Faraday rotator, giving 45° of rotation per pass, placed between the depolarising elements and the SBS phase conjugator, as in fig. 1, can provide sufficient cancellation of the depolarisation on the second pass through those elements by effectively interchanging the orthogonal polarisation components for the second pass [8,9]. Belousov and Nizienko [9] have argued that this technique should be effective but in discussing their experimental demonstrations gave no quantitative measurements of depolarisation loss. We have tested the configuration of fig. 1 with a Nd:glass amplifier giving up to 20% depolarisation per single pass and under these conditions we have found that the double pass depolarisation loss of the scheme exceeded 25%.

This result suggests that the configuration of fig. 1 may not be effective for situations involving significant birefringence (or other forms of depolarisation)

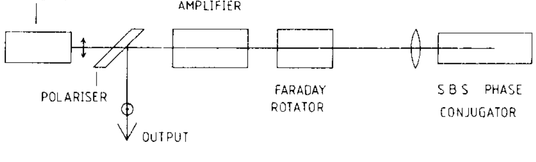

Fig. 1. A scheme for compensation of a moderately depolarised beam using SBS.

and that some more effective scheme is required.

As stated above, there is one polarisation state for a laser beam which is correctly conjugated in the SBS process, that is, a uniform linear polarisation. In principle, therefore, one can accurately conjugate a laser beam of arbitrary polarisation by converting it into a beam of uniform linear polarisation before it enters the SBS phase conjugator. An experiment based on this idea was demonstrated by Basov et al. in 1978 [10]. The beam from a Nd:glass laser, having been depolarised in passing through a ruby laser rod of poor optical quality, was then converted to linear polarisation before being phase-conjugated via SBS in liquid CS_2. Further details of the experimental arrangements involved in this scheme will emerge in the discussion below, but the essential feature is that the depolarised beam is split into two orthogonal linearly polarised beams by a polariser, one of these beams has its polarisation rotated to be parallel to that of the other beam, and the two beams are then combined in the SBS medium. The experimental results of Basov et al. indicate that the demonstration was successful. However, despite the potential importance of this scheme, it appears that there has been no subsequent work reported in the literature in which this technique has been further investigated. Our own attempts to exploit this scheme revealed some problems and were of mixed success. Since it may be that others have encountered similar problems, the purpose of this paper is to describe the precautions that we have found it necessary to introduce in order to obtain a successful implementation of Basov's original scheme. These precautions are outlined in the following section in which the experimental arrangement is explained. In section 3 we describe a polarisation-preserving waveguide configuration that has proved a major factor contributing to the experiment's success, and the experimental results are given in section 4.

2. Experimental arrangements and precautions

Following Basov, our initial experiments made use of CS_2 as the SBS medium. However, it was evident that self-focussing effects were occurring which caused severe fluctuating beam distortions and shot-to-shot intensity variations both for a focussed and a guided geometry. Under these conditions, no consistent correction of depolarisation was observed. CS_2 has the further disadvantages of gradually photodissociating and of reacting with many compounds or impurities used in the construction of cells used to contain the liquid, leading to significant absorption at the wavelength of 1.06 μm. Our previous experience with CH_4 gas as a SBS medium for use at 1.06 μm [8] has indicated that it is free from the above problems and we have, therefore, based our experimental evaluation of the Basov scheme on CH_4 as the phase-conjugator. The experimental arrangement is shown in fig. 2. The laser system consisted of a Q-switched, TEM_{00}, single longitudinal mode oscillator incorporating a telescopic resonator and giving up to 100 mJ in a 30 ns pulse, as described in ref. [8]. The horizontal linearly polarised output from this oscillator was expanded to give a

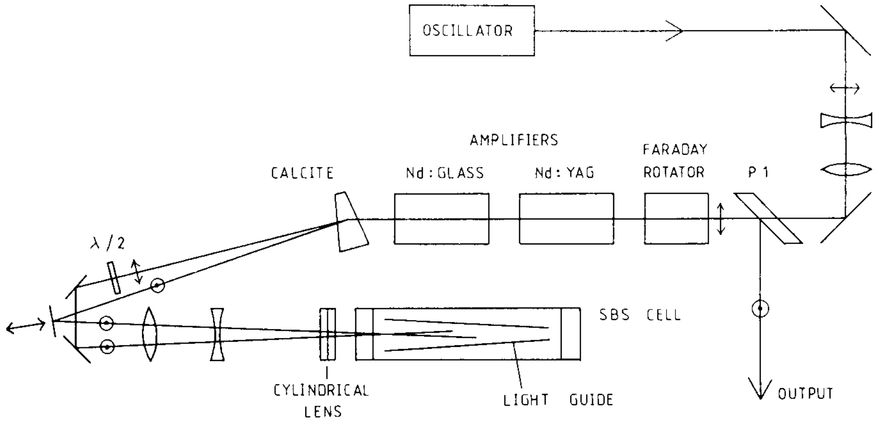

Fig. 2. The experimental arrangement for compensating of a severely depolarised beam.

collimated beam with radial spot size (w) of ~2 mm and passed through polariser P1 (see fig. 2), a Faraday rotator giving 45° of rotation per pass, a Nd:YAG amplifier and a Nd:glass amplifier. Following these elements a calcite prism having an apex angle of 20° split the beam cleanly into two orthogonal linearly polarised beams, the angle between them being 3.3°. One of these beams had its polarisation rotated by 90° by a half wave plate. The two beams were then directed via steering mirrors into the high pressure methane SBS cell. One of these mirrors was mounted on a translation stage to facilitate equalisation of the path lengths. After the mirrors a telescope reduced the spot size to 1 mm before the beams passed through the 50 cm focal length cylindrical lens into the cell containing the guide.

There are five important points to note in the design of this experiment:

(A) The thermally induced birefringence in the Nd:glass amplifier rod, which had dimensions of 75 × 6 mm, gave a polarisation state which was non-uniform over the beam cross section and the degree of depolarisation was continuously variable up to 20% per pass by controlling the mean pump power to the rod up to 160 W. This did not alter the focal length of the rod since it was of athermal glass (Kigre Q-100). We emphasise that this rod was not incorporated to amplify the beam (the gain wavelength differing slightly from that of Nd:YAG) but to serve as a precisely controllable depolarising element. It does, however, test the scheme with respect to one of its potential applications, that is, to corrections of distortions in a chain of Nd:glass amplifiers where birefringence effects cause serious losses and beam distortions.

(B) The calcite prism gives very clean separation of the polarisation components. In this respect it is superior to thin-film dielectric polarisers, which we used at first, but which we found gave a small amount of the vertical polarisation component with the horizontally polarised beam and vice versa.

(C) It is necessary to keep the path lengths equal for the two separated beams. If the path lengths are unequal by an amount Δl then a phase shift $\Delta\phi$ arises as the scattered beams retrace their paths from the Brillouin cell to the calcite prism. This is due to the frequency shift $\Delta\nu_B$ that occurs in the Brillouin scattering process. $\Delta\phi$ is given by

$$\Delta\phi = 2\pi \frac{\Delta l}{c} \Delta\nu_B .$$

For methane, with a Brillouin shift of ~800 MHz, a path length difference of 1 cm leads to a phase difference of 10°. For an initially plane polarised beam this would lead to a loss at the output coupler of approximately 1%. We have therefore, kept path lengths equal to within this tolerance.

(D) The losses in each path were kept equal to within 1%.

Points C and D together ensure that the two beams returning to the calcite prism after conjugation have both the same phase and the same relative amplitude that they had when they were separated on the outward phase. This is necessary for accurate reconstruction of the polarisation state at the prism on the return pass.

(E) Perhaps most importantly: It is essential to have good overlap of the two beams throughout the SBS region. The use of a light guide can achieve this. In addition, the overlapped beams must maintain their linear polarisation. This is a feature which some guides do not offer and we have found it necessary to construct a special guide to ensure this.

We carried out a preliminary experiment [11] in which no guide was used but the two beams were focussed into the SBS cell and overlapped in the focal region. Two drawbacks with this arrangement were apparent:

(a) If both beams were above SBS threshold the SBS interaction could occur in each beam independently in that part of the beam before the focus. In this case the beams were not reflected in phase with each other but their phase difference fluctuated randomly from shot to shot. As a result, the original polarisation state was not reconstructed at the polarising beam splitter when the reflected beams recombined at this element on the return pass.

(b) If one beam was above SBS threshold but the other was not, the weaker beam was still reflected from the focal region but the overlap was insufficient to give complete phase locking between the beams. Again, the correct polarisation state was not reconstructed at the beam splitter on the return.

As stated above, having found methane gas to be a good SBS medium and having found problems with liquids such as CS_2 and CCl_4 where guidance might have been obtained more straightforwardly, we elected to continue using methane and constructed a guide compatible with this medium. We also made use of the fact that to mix (or overlap) the two beams effectively in the SBS cell the guide need only confine the beams in one plane (horizontal) while focussing could still serve to confine them in the vertical plane. The object of focussing is to bring the threshold down to a convenient value.

3. The light guide

It is well known that many metals give high reflectivity for light at grazing incidence. The power reflection coefficient for light polarised perpendicular to the plane of incidence (which is the polarisation having the highest reflectivity) is

$$R_\perp = \frac{(n - \cos\theta)^2 + k^2}{(n + \cos\theta)^2 + k^2} ,$$

where θ is the angle of incidence and n and k are the real and imaginary parts of the refractive index, $\boldsymbol{n} = n - ik$.

To obtain a high reflectivity and low scatter we have used a metal evaporated onto a glass substrate as the guide material. Aluminium was chosen for its resistance to tarnishing despite having a lower reflectivity than silver (for aluminium $n = 1.75, k = 8.5$ while for silver $n = 0.11, k = 6.56$ at a wavelength of 0.95 μm [12]). These figures are not significantly different at a wavelength of 1.06 μm and the calculated reflectivity for aluminium increases from 99.2% at an incident angle of 85° to 100% at an incident angle of 90°. The substrates consisted of strips of glass 2 mm thick with a working surface of 3 mm wide and 500 mm long. These were cut from ordinary sheets of 2 mm thick picture glass.

Metal mirrors are usually considered to be unsuitable for high power lasers because of their poor resistance to optically induced damage, typical power damage thresholds being ~50 MW cm^{-2}. However, at grazing incidence the power handling capability increases for two reasons: (i) the laser beam is distributed over a large area of the metal's surface, reducing the power per unit area of surface and (ii) the reflectivity increases, and hence the absorbed energy decreases, as the angle of incidence increases. Damage occurs by absorption of radiation.

Samples of these aluminium mirrors were tested for reflectivity and damage resistance at $\lambda = 1.06$ μm using a 30 ns pulse originating from the single-longitudinal mode oscillator, the reflection occurring at a beam waist having a spot size of 160 μm. For angles of incidence of 85°, 86°, 87°, 88° and 89° the measured reflectivities were 93%, 94%, 95%, 97% and 99% (±1%) respectively. Although slightly lower than the theoretical values (99.2%, 99.4%, 99.5%, 99.7% and 99.8% respectively) these reflectivities are perfectly adequate for the incident angles needed in our experiment. The damage threshold power was found to be 75 ± 25 MW per cm^2 of surface with no obvious dependence on the incident angle for the range of angles stated above. Thus the beam intensity itself was a factor $(\pi/2 - \theta)^{-1}$ higher than this surface damage threshold intensity where θ is the (large) incident angle in radians. This damage figure was high enough for the experiment although it could probably be increased with improved coatings.

To form the guide two of these reflective plates were placed facing each other in the SBS cell. The separation between the mirror faces was 3 mm at the entrance to the guide, which was placed close to the entrance window of the cell, reducing to 1 mm at the exit. Plan and side views of the guide are shown schematically in fig. 3.

The two beams entering the cell had a spot size of (radius) ~1 mm and overlapped each other exactly at the entrance to the guide, the angle between the beams being 14 mrad. The walls of the guide confined the beams in the horizontal plane and a cylindrical lens of 50 cm focal length placed immediately in front of the entrance window confined them in the vertical plane by its focussing action. The spot size in the ver-

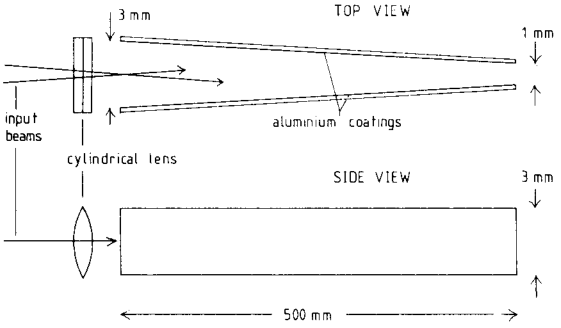

Fig. 3. Schematic diagram of the guide.

tical plane at the focus of this lens was 160 μm. An important point to note here is that this guide has the major advantage over a cylindrical guide of preserving the linear polarisation state of the input beams. By using only two guiding surfaces, the taper and separation can be controlled easily. The absorption losses for the guide can be calculated by considering the number of reflections of the beam and the angle of incidence and hence the absorption at each reflection. Measured transmissions out of the tapered end were slightly lower than values calculated in this way. For example, for a beam incident at an angle of 7 mrad to the guide axis (as in the actual experiment) only one reflection occurs and the transmission was 95% compared to a theoretical value of at least 99%. This measured figure is quite adequate for the system and compares favourably with guides utilizing total internal reflection.

The polarisation of the light transmitted by the guide was checked and found to accurately maintain its vertical linear polarisation as did the light reflected via SBS, thus confirming the polarisation-preserving property of the guide.

A parameter of importance when comparing guided and unguided geometries is the threshold for the onset of SBS. An approximate prediction for the power threshold is found as follows. Under steady state conditions where the pump bandwidth $\Delta\nu_p$ satisfies $(\Delta\nu_p)^{-1} \gg \tau_B$, 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 $\exp(g_B I_p l)$. Defining threshold as the condition when the gain reaches exp(30) gives a threshold pump power of

$$P_{th} = 30 A_p / g_B l ,$$

where A_p is the area of the pump beam. In our experiment the beam area is defined by the focussing action of the cylindrical lens and by the guide walls. Taking the focussed beam width as twice the gaussian spot size, the mean intensity of the beam was calculated numerically to be $1.2P$ Wm^{-2}. At the methane gas pressure of 40 atmospheres used, $g_B = 1.45 \times 10^{-4}$ m/W and the predicted steady state threshold is therefore 350 kW. In fact, since the pump pulse duration is of the order of τ_B, which is 12.5 ns at 40 atmospheres pressure, the effect of transience must be taken into account.

Based on the analysis of Kaiser and Maier [13], the calculated threshold, including the effect of transience, is ~3 times greater, i.e. ~1 MW. For comparison, using a similar method for a beam tightly focussed to a waist of 160 μm in a 1 m long cell at 40 atmospheres pressure by a spherical lens of 50 cm focal length, the predicted SBS treshold is 420 kW.

4. Experimental results

A measurement of SBS threshold using the guide with the cylindrical lens of 50 cm focal length gave an energy of 25 mJ in a 30 ns pulse, corresponding to a power of 0.83 MW, i.e. slightly below the predicted value. Considering the approximations made in the calculation regarding the beam intensity profile and the temporal pulse shape, these two values are in good agreement. For comparison, for a beam tightly focussed by a spherical lens of 50 cm focal length to a 160 μm spot size at the centre of a 1 m methane cell at the same pressure, threshold is measured as 9 mJ in 30 ns, or 300 kW.

As expected for a guide of this configuration, the alignment of the two input beams relative to each other was found to be much more critical in the vertical direction than in the horizontal direction. At the narrow end of the guide the width of each beam was 300 μm in the vertical direction and 1000 μm in the horizontal direction. A movement of one beam of less than one spot size (160 μm) in the vertical direction greatly increased the threshold power as the overlap region decreased in size. However, in the horizontal direction, the alignment of one beam relative to the other was much less sensitive because of the guidance given in this plane.

From past experience with SBS in methane we have found that for high reflectivities of typically 60% it is necessary to exceed threshold by a factor of approximately ten or more. To date, with this configuration, we have used inputs of approximately 75 mJ, i.e. three times threshold, and under these conditions the reflectivity of the gas has been 30%.

In assessing the effectiveness of this plane conjugation scheme we have examined its performance in correcting depolarisation and in correcting wavefront phase distortions. To assess the latter we have compared the beam obtained with a conventional arrangement utilizing a plane mirror to double-pass the amplifier with that obtained for the system of fig. 2. The beam quality was assessed by observing the intensity profile using a linear diode array. The divergence was measured as in ref. [8] by focussing the output to a waist and measuring the spot size w both at this waist (w_0) and at a position further down the beam. Assuming a gaussian beam of waist spot size w_0 one can calculate an expected divergence. The ratio of calculated to measured divergence gives the factor by which the beam exceeds the diffraction limit.

In this way we found that for the version incorporating the plane mirror, the output beam divergence degraded to twice the diffraction limited at the maximum pumping rate to the Nd: glass amplifier (under these conditions the oscillator output was diffraction limited). The beam profile showed modulation of 50% depth with structure of width of ~1/6 beam diameter, and this is shown in fig. 4(a). With the phase conjugate mirror, as in fig. 2, the system output was very close to diffraction limited with a smooth intensity profile, fig. 4(b). Furthermore, as the pump power to the Nd: glass amplifier was varied from zero to the maximum, increasing the birefringence and distortion, the output beam profile, checked at several locations, was found to remain constant.

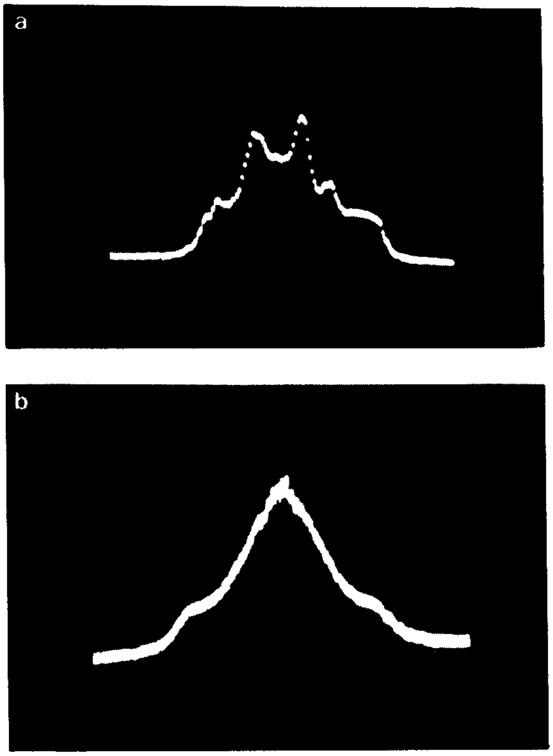

Fig. 4. (a) Beam intensity profile using a plane mirror to double pass the Nd :glass amplifier. (b) Beam intensity profile using phase conjugation.

5. Depolarisation loss

To assess the degree of correction for depolarisation, the losses due to depolarisation were determined by measuring the fraction of the return beam passing back through the polariser P1 (fig. 2) rather than being reflected as output. This loss was recorded as a function of the mean input pump power to the Nd: glass amplifier. The thermally induced birefringence of this amplifier was characterised by measuring the depolarisation of the linearly polarised input beam making a *single* pass through it. To do this a second polariser, placed temporarily after the amplifier, separated the orthogonal polarisation components and the energy ratio of these two was measured. This single pass depolarisation is plotted on fig. 5 together

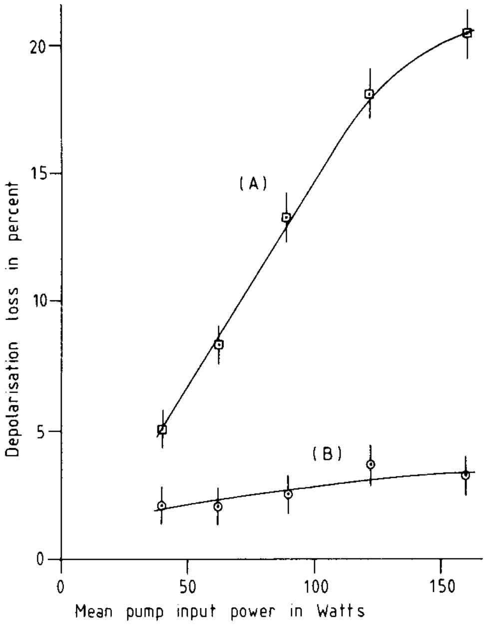

Fig. 5. Single-pass depolarisation in the Nd :glass amplifier rod, curve (A) and double-pass loss of the complete system, curve (B).

with the double pass loss of the complete system of fig. 2.

The dramatic reduction in the depolarisation loss shown in this figure, down to a level of 3% per double pass under conditions where the Nd:glass amplifier contributed a single-pass depolarisation of 20%, confirms the success of this scheme. In particular, it demonstrates that effective mixing of the two beams can be achieved using guidance in one dimension only. The origin of the nearly-constant residual loss of 2–3% is not known but could be due to a number of spurious effects such as depolarisation in lenses or other glass optical elements or slightly non-uniform losses in the guide, for example. The results shown in curves A and B were obtained by varying the pump power to the Nd:glass amplifier only and no beam realignments or other adjustments were necessary. The system was tested for non-equal path lengths of the two beam paths by moving one of the steering mirrors on its translation stage and realigning the beams as necessary. It was found that a path length change of up to ±2 cm from zero length difference produced no observable change in the performance of the system. (We note that this is a significantly greater optical path length difference than the value of ~4.5 mm previously observed by Rockwell and Giuliano [14] in an experiment where separate beams were focussed together in an SBS cell to produce phase locking between them). If the path difference was increased further then the output pulse fluctuated in amplitude from shot to shot and the depolarisation loss increased.

We anticipate that further improvements can be made to this scheme to give even better performance. For example, better quality substrates could be used for the guide walls instead of ordinary picture glass and possibly other coating materials could give higher reflectivity and higher damage threshold than the aluminium coatings we have used. Furthermore, the precise geometry of the guide has not been optimised. For example, a narrower separation at the guide exit would reduce the SBS threshold and increase the reflectivity.

6. Conclusion

The use of a tapered metal guide giving guidance in one dimension with methane gas as the SBS medium has allowed the efficient and accurate conjugation of both the polarisation state and the wavefront phase of a severely aberrated and depolarised laser beam. The guide, which has the particularly desirable feature of maintaining polarisation, can also be used over a wide range of laser wavelengths and with either gas or liquid contained between the guide walls. The technique is potentially important for the phase conjugation of depolarised laser beams and is of particular significance for application to large Nd:glass amplifier chains.

Acknowledgement

We wish to thank the Royal Signals and Radar Establishment at Great Malvern who funded this work.

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