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Phase Conjugation of High Energy Lasers

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Abstract

In this report we explore claims that phase conjugation of high energy lasers by stimulated Brillouin scattering (SBS) can compensate optical aberrations associated with severely distorted laser amplifier media and aberrations induced by the atmosphere. The SBS media tested was a gas cell pressurized up to 300 psi with SF₆ or Xe or both. The laser was a 10 Hz, 3J, Q-switched Nd:YAG with 25 ns wide pulses. Atmospheric aberrations were created with space heaters, helium jets and phase plates designed with a Kolmogorov turbulence spectrum characterized by a Fried parameter, r_o , ranging from 0.6 – 6.0 mm. Phase conjugate tests in the laboratory were conducted without amplification. For the strongest aberrations, $D/r_o \sim 20$, created by combining the space heaters with the phase plate, the Strehl ratio was degraded by a factor of ~ 50 . Phase conjugation in SF₆ restored the peak focusable intensity to about 30% of the original laser. Phase conjugate tests at the outdoor laser range were conducted with laser amplifiers providing gain in combination with the SBS cell. A large 600,000 BTU kerosene space heater was used to create turbulence along the beam path. An atmospheric structure factor of $C_n^2 = 5 \times 10^{-13} \text{ m}^{2/3}$ caused the illumination beam to expand to a diameter 250mm and overfill the receiver. The phase conjugate amplified return could successfully be targeted back onto glints 5mm in diameter. Use of a lenslet arrays to lower the peak focusable intensity in the SBS cell failed to produce a useful phase conjugate beam; The Strehl ratio was degraded with multiple random lobes instead of a single focus. I will review literature results which show how multiple beams can be coherently combined by SBS when a confocal reflecting geometry is used to focus the laser in the SBS cell.

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NOMENCLATURE

DOE	Department of Energy
ICF	inertial Confinement Fusion
PC	Phase Conjugation
PCM	Phase Conjugate Mirror
SBS	Stimulated Brillouin Scattering
SLM	Single Longitudinal Mode
SNL	Sandia National Laboratories
TFP	Thin Film Polarizer

INTRODUCTION

Most research programs based on high energy lasers would benefit from increased coherent energy delivered to the receiver. Increased energy at the receiver can be achieved through increased output at the laser or improving beam transport to the receiver. Phase conjugation by SBS can help both mechanisms. Apart from building a bigger laser which might not be possible, increased output (energy or power) can be achieved by combining beams from multiple sources. Unfortunately, simple methods such as using passive mirrors or splitters do not ensure mutual coherence of the individual sources resulting in a beam with a non-ideal wavefront and a poor focal spot diameter. Recently, claims have been made but not documented in the open literature that multiple high energy laser beams (>100 kJ) can be efficiently phase conjugated and coherently combined by Stimulated Brillouin Scattering (SBS) with little degradation in Strehl ratio or wavefront integrity. If true, these claims would mark a major breakthrough in extending the energy limit for propagating a coherent laser beam and significantly impact applications relevant to Sandia's mission such as laser production of x-rays for photolithography and Inertial Confinement Fusion (ICF), high resolution laser imaging, material processing and space debris removal. In addition to this work on combining high energy beams, the SBS experimental set up can be used in the future to explore other high energy phase conjugate applications such as compensation of atmospheric turbulence for high power beam propagation or optical phase locking of multiple beams by four wave mixing.

Principles of phase conjugation based on SBS.

Brillouin scattering occurs when light propagates through a transparent medium (solid, liquid or gas) and interacts with density fluctuations in the material. As compared to Rayleigh scattering, which is due to random localized fluctuations in the density, composition or orientation of molecules, Brillouin scattering results from larger scale, correlated fluctuations associated with acoustic waves or phonons in the material. This is known as spontaneous Brillouin scattering. Because the light wave scatters off of a moving acoustic wave, the scattered photon picks up a frequency shift.

When an intense laser beam is spontaneously Brillouin scattered in the opposite direction, the electric fields of the two light waves can interfere. Because the scattered light wave is slightly shifted in frequency from the original, the interference between the two electric fields sets up a travelling wave that matches the wavelength and velocity of scattering acoustic wave. The oscillating field strength of the resulting traveling wave can induce density oscillation via electrostriction. Because the light induced density oscillation matches the scattering acoustic wave, the amplitude of the density oscillation increases in strength until it scatters nearly all the laser light. This process is known as Stimulated Brillouin Scattering or SBS and was experimentally verified in 1964 by Raymond Chiao. In 1972, Yakov Zel'dovich recognized that the reverse phase matching characteristic of SBS could be used to phase conjugate high power laser beams.

EXPERIMENT

SBS Cell Design and Safety Considerations

The SBS Cell was designed to contain pressures up to 1000 psi which is well above the vapor pressure at standard temperature of SF₆ and Xe which are 311 and 845 psi respectively. The main body of the chamber is made of 6061-T6 aluminum alloy. The stresses in the material

Figure 1 Cross section view of SBS Cell. The cell is approximately 1m in length.

were computed using the ASME calculation of pressure rating for a thick-walled cylinder, and checked with a finite element analysis. The resulting design has a safety factor of 10 with respect to the yield strength of the material. A CAD cross sectional view of the SBS cell is shown in Figure 1.

Windows on each end allow the laser to pass through the high pressure gas cell. The laser window was designed using a method based on the allowable probability of failure developed by Schott, the glass manufacturer. Using this method, the probability of window failure is 1 in a million. However, the window is exposed to high energy laser pulses, which means that the quality of the surface may degrade and ultimately fail. To ensure that the failure mode is not catastrophic we designed the window to fracture in two-pieces (Suratwala 1999). The final design met two objectives; 1 in a million probability of failure, and no more than two pieces fracture.

During experiments one of the windows of the chamber was damaged by the laser and fractured. The window is shown in Figure 2. The resulting crack allowed the gas to escape but the window remained intact as designed.

Indoor Laboratory Experiments

The first experiments in the laboratory tested the phase conjugation properties of the SBS cell in simple double pass geometry. The idea was to test how well SBS phase conjugation compensates for aberrations without the additional complication of laser amplification. Figure 3 shows a schematic diagram of the layout. The laser is a seeded Single Longitudinal Mode (SLM) Q-switched Nd:YAG with output energy, $E=1$ J, wavelength $\lambda=1064\text{nm}$, pulse width $t=25$ ns and repetition rate of 10 Hz.

Figure 2 Laser damaged window from high pressure SBS cell failed with a slow leak and not catastrophically.

Figure 3 Experimental layout for phase conjugate SBS experiments in the laboratory without gain. The beam is sent through the aberration source, phase conjugated and returned through the aberration. The diagnostics consist of photodiodes, energy meters, far/near-field cameras and wavefront sensors.

The laser output passes through a Faraday isolator and then the aberration source. Then the aberrated beam is phase conjugated to pass back through the aberration and is rejected by the isolator to the output of the experiment. When conducting phase conjugation experiments, optical isolation is critical to protect the laser. Phase conjugation reverses the beam exactly back into the laser where it could damage sensitive components. A suite of diagnostics to characterize the beam is positioned in three locations; at the laser output, after the aberration source beam and at the phase conjugate corrected beam. The primary diagnostics are an energy meter and near-/far-field cameras. A photodiode and wave-front sensor were used as supplementary diagnostics. The aberrated and corrected beam quality is compared to the original laser beam quality to understand the effectiveness of the phase conjugate compensation.

Reflectivity with no turbulence

The first set of experiments was conducted without any turbulence in order to measure the underlying SBS reflectivity and threshold. The reflectivity curve in Figure 4 shows the typical SBS shape with a threshold (8 mJ) and saturation reflectivity less than one, ~80%.

Figure 5 shows photodiode waveforms for the input, phase conjugate and leakage beams. The top waveforms, Figure 5(a) are for seeded SLM operation of the laser. The PD waveforms show the time dependence of the SBS process. The blue SBS return does not turn on instantaneously. It takes some time and energy from the incident laser light to set up the acoustic waves. Before the acoustic waves has built up, incident light passes through the cell and can be seen by the leakage PD. Note, the timing and amplitudes of the different PD's are not precisely synchronized or calibrated but are sufficiently close to quickly gauge the SBS process in the laboratory.

The lower waveforms, Figure 5(b) show un-seeded multi-mode operation of the laser. Interference between the modes is clearly visible as spikes in the fast photodiode waveforms. The true amplitude of the spikes could be 2-3x greater due bandwidth limitations of the detector/digitizer system. Note: The photodiodes indicate that the multi-mode beam can be scattered by SBS. However, the quality of the phase conjugation is poor. Some tip/tilt is corrected but higher order aberrations are not corrected resulting in a diverging beam.

Figure 4 Plot of the SBS reflectivity for the laboratory experiments for 300 psi SF6. The SBS threshold is 8 mJ and the reflectivity saturates at around 80%.

Figure 5 Plot of the photodiode traces for the input laser beam (red), the SBS return (blue) and the leakage beam (black). (a) The laser was seeded with a single longitudinal mode. (b) The laser was unseeded. Interference between the multiple modes is clearly seen as spikes in the fast photodiode trace.

Methods for producing atmospheric turbulence

The primary sources of aberration used in laboratory tests were forced air space heaters and specialty phase plates. A helium jet was also tested but the spatial extent of the jet did not cover the full diameter of the laser beam.

The phase plates used in experiments were obtained from Lexitek in Wellesley, MA. Two phase plates were used. Both phase plates were designed with spatial correlation scales to simulate a Kolmogorov spectrum turbulence field. The annular phase plate in Figure 6 had a Fried parameter of $r_0 = 1.33$ mm and could be rotated to create dynamic turbulence. The hexagonal tiled phase plate shown in Figure 7 was used for static testing, each tile having a different level of aberration. The amplitude of the phase disturbance in each hexagon was scaled to create a range of Fried parameters. Table 1 summarizes the various Fried parameters and D/r_0 ratios for $D = 12$ and 24 mm diameter laser beams. D/r_0 is a useful approximation to determine how many speckles will form across the diameter of the beam in the far field.

The main optical aberration produced by space heaters is tip/tilt. The space heaters could produce some higher order aberration but only with $D/r_0 \sim 2-4$. This compliments the annular rotating phase plate which has a limited ability to produce tilt. Utilizing the rotating phase plate and heaters in combination produces a wide range of aberrations in all orders.

Figure 6 Rotating NIM phaseplate to simulate time varying atmospheric turbulence. Gray levels represent phase lag.

Table 1 Summary of the parameters for each of the numbered hexagons in the static phase plate.

Hexagon #	D/r_o , 12 mm dia. beam	D/r_o , 24 mm dia. beam	Fried r_o (mm)
1	2	4	6.00
2	4	8	3.00
3	6	12	2.00
4	9	18	1.33
5	12	24	1.00
6	15	30	0.80
7	18	36	0.67

Figure 7 Static phase plate with varying levels of aberrations. The aberrations are summarized by the Fried parameter in Table 1.

Figure 8 Near- and Far-field images of the 12mm diameter laser beam. The top row shows images of the aberrated beam after a single pass through the static phase plate, hexagon #7, $r_o=0.67$ mm, with $D/r_o = 18$. The bottom row shows the same beam after phase conjugation and double passing the aberrations. The far field focus is dramatically improved.

Laboratory results for phase conjugate compensation of an aberrated laser are shown in Figure 8. Each row in the panel shows a far field and near-field image of the beam. The top row is the uncorrected, aberrated beam, while the bottom row shows the corrected beam which has been phase conjugated and has double passed through the aberration. This figure shows very typical results and represents the highest levels of aberrations explored in the laboratory with $D/r_o=18$. The corrected far-field image shows a dramatically improved focus. The corrected near-field image (lower right) shows a tighter beam profile. There are intensity dropouts across the near-field beam but they do not strongly affect the focus of the far-field beam.

Figure 9 reduces the far-field images shown in Figure 8 to radially averaged profiles of the intensity. The radially averaged plots allow comparison of the relative Strehl ratios of the beams. The original laser profile is also included in Figure 9 for comparison. The peak intensity of the original laser beam is normalized to one. The total integrated intensity in the corrected/un-corrected images is set equal to the original laser beam. The intensity on axis is the relative Strehl ratio as compared to the original beam. Note that background counts must be carefully subtracted, particularly for the larger diameter uncorrected beam. The Strehl ratio can be reduced a factor of 30-50 X by the level 7 turbulence in the uncorrected beam. Phase conjugate correction restores the Strehl ratio to 30% of the original.

Figure 9 Plot of the average radial far field intensity for the original laser beam (blue), distorted beam (red) and phase conjugated beam (black). The distorted and phase conjugated beams are normalized to the total energy of the original undisturbed laser beam and azimuthally averaged. Note that the original laser beam is the reference for these experiments but does not have a Strehl ratio of 1.

Lenslet array

When focused into the gas cell, a high energy laser can overdrive the SBS process resulting in poor phase conjugation and breakdown of the gas. A proposed means of reducing the focusable intensity is to use a lenslet array to break up the focus into multiple lower intensity foci. Figure 10 shows a ray trace diagram of the optical layout used to test this concept. The array of foci from the lenslet array is relay imaged into the SBS cell by a pair of lenses. The array of foci from the lenslet array is relay imaged into the SBS cell by a pair of lenses.

Figure 10 Ray trace diagram of the lenslet array focused into the SBS cell.

(a) Far-field image of send beam. No turbulence.

(b) Sequence of far-field image of the return beam. No turbulence.

Figure 11 Far field images of the laboratory experiment using the lenslet array to create multiple focal spots in the SBS cell. No turbulence was introduced in the beam as indicated by the tight focus of the send far-field shown in (a). A sequence of far field images for the SBS return beam is shown in (b). Even without turbulence multiple spots with random positions and intensities are introduced.

Figure 11 shows the results of testing the lenslet array with no turbulence present. The top far-field image in Figure 11(a) is the send beam. Notice how tight the focus is in comparison to the phase conjugate far field images in Figure 11(b) which is a panel of six images taken in sequence. Even without turbulence the far field images have multiple spots with random positions and intensities. The source of all the variation is the random phasing of the SBS light from each focus. SBS builds up from random density fluctuations in the media. When the phase conjugate beams from each focus are recombined the random phases create the complicated interference patterns. Use of a lenslet array for phase conjugate compensation is not recommended.

Korean researchers have demonstrated coherent combination of four Joule class lasers by using a mirror to focus into the SBS cell instead of a lens. Interference between the incoming beam and the reflected focus set the phase of the SBS density wave a priori eliminating random phase fluctuations. PZT control of the mirror position with a feedback loop synchronizes the phase of the two beams and also adjusts for thermal drift. [Kong 2005]

Outdoor range testing

To test the effectiveness of SBS phase conjugation at distance the laser and experiment were moved to the outdoor laser range shown in Figure 12. Range distances were limited to 80 m. Longer ranges could be achieved in the future by using a mirror to fold the beam to the trailer to the north of the building. The laser system was operated in the building while the receiver and

Figure 12 Outdoor laser range with 80m distance shown. Laser system is in the building. The receiver trailer and diagnostics is at the bottom.

Figure 14 Schematic layout of the diagnostics in the receiver trailer at the outdoor range. Large steering mirrors align light onto the glint simulator which is a mirror with an iris in front. The wedge picks off ~4% of light for the diagnostics. The $\frac{1}{4}$ wave plate and thin film polarizer separate the illuminator (send) light from the amplified phase conjugate (re-send) laser light. Note that send and re-send light are circularly polarized with opposite handedness.

It is important to note that the layout of outdoor range test is topologically different from the indoor experiment and the difference does not have to do with the four pass amplifier. The fundamental difference is that in the outdoor test, the light passes through the turbulence layer three times, while it only passes through two times in the indoor experiment. For an odd number of passes, not all the aberrations can be reversed. This has implications for the minimum projected spot size for extended glints which are larger than the diffraction limit. For extended glints, the illumination light picks up twice the wavefront aberrations during the out and back trip. However, the amplified light only makes one pass back to the glint. Therefore all the aberrations are not reversed. The implication is that the amplified light cannot be focused to the diffraction limit. It can only be focused to the size of the glint. Still, this is far more efficient than overfilling the glint which is what would happen without phase conjugate correction.

Figure 15 shows near-field and far-field images of outdoor tests conducted with natural turbulence, $C_n^2 = 2 \times 10^{-14} \text{ m}^{-2/3}$. The top four images are with the iris of the glint simulator wide open. The near field image of the illuminator beam shows mild intensity fluctuation due to turbulence. The amplified re-send beam is smaller than the send beam which overfills the glint even when the iris is wide open. The bottom four images are when the glint is closed down to 5mm. The near field image of the amplified re-send beam matches the 5mm glint diameter and shows how the PCM automatically compensates for turbulence and the size of the glint. The far-field image of the amplified beam shows a wider focal spot as expected, illustrating the Fourier transform relationship between near and far field images.

Figure 15 Near- and far-field images of outdoor tests with natural turbulence, $C_n^2 = 2 \times 10^{-14} \text{ m}^{-2/3}$.
(a) The glint simulator was set wide open at 40mm.
(b) The glint is closed down to 5 mm. Note how the near field image of amplified re-send beam matches the 5mm diaphragm.

Figure 16 shows a time series of the beam energy for an outdoor range experiment with relatively strong turbulence, $C_n^2 \sim 10^{-13} \text{ m}^{2/3}$. The turbulence was created by a large forced air space heater blowing across the beam. Strong variation in the intensity of the glint return and amplified re-send are prominent with 1 out of 4 shots having essentially a complete intensity dropout. A greater than 25% chance of failure would not be a favorable way to operate a single shot high energy laser.

Figure 17 plots the amplified re-send energy versus the glint return energy for the same data set shown in Figure 16. The slope of the linear regression through the points indicates a gain of 27 for the four pass amplifier. When the gain in the system was turned up higher, coatings on some of the optical components began to damage. Some of the damage can be seen as diffraction rings in the images in Figure 15.

Figure 16 A sequential time series of laser energies for $C_n^2 \sim 10^{-13} \text{ m}^{2/3}$ at the outdoor laser range. Turbulence created by a large space heater. Note the prominent scintillation and dropouts in the experiment (#5 on 9/19/2012).

Figure 17 Plot of the amplified re-send laser energy versus the return energy from the glint for the data shown in the previous Figure 16 (experiment #5 on 9/19/2012). A linear regression indicates a gain total gain of 27 through the four pass phase conjugating amplifier.

CONCLUSIONS

Phase conjugate experiments in the laboratory compensated strong optical aberration created by a combination of specialty phase plates and space heaters. For the strongest aberrations, $D/r_0 \sim 20$, the Strehl ratio was degraded by a factor of ~ 50 . Phase conjugation in an SF_6 gas cell restored the peak focusable intensity to about 30% of the original laser. Although these corrections are impressive, laboratory experiments like this are not representative of outdoor range tests. In the laboratory all the light that passes through the aberrating media can be collected. Outdoors, at distance, only a small fraction of the light can be collected. Under moderate turbulence, the effect of scintillation creates extreme shot to shot variations in the amount of light returned. It is therefore of critical importance to saturate the gain of the laser amplifiers used with the PCM. For these experiments we could not saturate the gain without damaging the laser optics. Nonetheless, for atmospheric structure factor of $C_n^2 = 5 \times 10^{-13} \text{ m}^{2/3}$ the phase conjugate amplified return could successfully be targeted back onto glints 5mm in diameter. Lenslet arrays were not an effective means to lower the focusable intensity in the SBS cell. SBS is an ideal means to compensate strong time dependent aberrations in laser amplifier media. A hybrid system that uses adaptive optics to correct for atmospheric aberration and an SBS phase conjugate mirror to compensate the laser media could potentially yield the highest focusable intensities at range.

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