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Phase analysis of stimulated Brillouin scattering in long, graded-index optical fiber

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Abstract: A continuous-wave beam was wavefront-split by a prism and propagated through separate paths before being coupled into a long, graded-index fiber. Stimulated Brillouin scattering (SBS) was generated in the fiber and the phase of the reflection was compared to that of the pump using lateral shearing interferometers immediately after reflection and also after propagating back through the separate paths. To analyze the phase conjugating properties of SBS in the fiber, one of the paths included a path-length oscillation. It was found that SBS from the long, graded-index fiber did not conjugate the phase of the pump. SBS formed a phase-locked beam immediately after reflection from the fiber, but did not lock the phases of the two beams after recombination as would be expected from a phase conjugate reflection.

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1. Introduction

SBS can produce a high fidelity phase conjugate reflection under certain conditions. In experiments using pulsed lasers as the SBS pump, step-index fibers with lengths typically 10 m or less have been used for many years to produce high-fidelity phase conjugation.[1-6] The fidelity degrades in longer lengths of step-index fiber due to the frequency shift between pump and SBS (Stokes) beams provided the interaction length is not limited by the coherence length of the source laser.[1, 2, 7] Good fidelity, cw phase conjugation was recently demonstrated in step-index fibers at 15 m and 40 m in length with fidelity shown to have a dependence on the fiber's length and numerical aperture (NA).[8] SBS in short, graded-index fibers has been shown to produce a phase conjugate reflection,[4] but the fidelity was reported to be poor in separate research.[6] In long lengths of fiber on the order of a kilometer or more, SBS has been reported to produce cw phase conjugation in graded-index fiber.[9-12] Conversely, it has also been reported to produce a low-order fiber mode regardless of pump mode structure in a process referred to as beam cleanup.[6, 13-18] While graded-index fibers mitigate the modal dispersion among modes in the fiber, it has been calculated that the graded-index of the core causes preferential Brillouin gain for the low-order modes which inhibits phase conjugation.[6, 15]

To determine the fidelity of phase conjugation, measurements of beam quality are typically used such as irradiance images, pinhole transmission, far-field divergence, or M^2 measurements. In many experiments, an aberration is used to distort the source beam before coupling into the phase conjugate medium. The beam quality is sampled both before and after the aberration. Phase conjugation should restore the beam quality of the source beam after reflecting back through the aberration from a phase conjugate mirror. Beam quality measurements are sufficient when the goal is to increase the beam quality of a laser system, but spatial methods can be ambiguous as the phase conjugation fidelity declines or

beam cleanup occurs.[18] While these measurements are indicative of the spatial coherence of the beam, the goal of coherent beam combining and phase-locking multiple beams through SBS phase conjugation requires a more direct measurement of the phase.

In this work, the phase conjugation properties from SBS in a long, graded-index fiber are explored directly. The source beam was split into two separate and variable paths before being coupled into the long, graded-index fiber. The separate paths impart a phase aberration onto the beam. The resulting phase difference between the two beams was observed using lateral shearing interferometers (LSIs) immediately after the Stokes reflection exited the fiber and after it traveled back through the two beam paths. This method extricates the measurement of phase conjugation from measurements of beam quality. Although the use of LSIs to measure beam phasing is not unique to this experiment, this is the first time it has been used to determine the relative phase characteristics of two beams at locations critical to phase conjugation. While the irradiance images of the beams can be examined before and after the dual-path phase distortion, these indications of beam quality are secondary to the phase relationship of the beams being measured.

The results of this experiment clearly indicate that phase conjugation was not achieved from SBS in a long, graded-index fiber. The phase aberration induced by the first pass through the separate paths was not corrected by the second pass. The beam was phase-locked immediately after reflection by the fiber despite phase variations between the tiled input beams. In addition, the Stokes reflection showed phase variations after the second pass through the dual-path phase distortion in contrast to the locked phase of the input beam at this location. These results are not consistent with phase conjugation since SBS in the long, graded-index fiber did not conjugate the phase of the pump beams.

2. Experiment

The apparatus is shown in Fig. 1. The pump laser consisted of an external cavity diode laser operating at 10 mW (1550 nm) followed by a 2-stage fiber amplifier. The first fiber amplifier was 5 m of Nufern's Er-Yb, co-doped 7/130 (core diameter/clad diameter) polarization-maintaining fiber counter-pumped with a 20-W LIMO, fiber-coupled diode at ~935 nm. The output of the first stage was 500 mW with amplified spontaneous emission (ASE) in a ~4 nm bandwidth centered at ~1535 nm suppressed to -36 dB. The output of the first stage was not pump-limited, but further increases in pump power increased the ASE. The second stage was 15 m of the same fiber, co-pumped with another 20-W LIMO, fiber-coupled diode at 935 nm. Free-space coupling was used and all the fiber ends in this work were polished at 8°. The 2-stage amplifier produced a pump-limited output power of 5 W.

After isolation, the beam was expanded to a diameter of 10 mm before being wavefront-split by an uncoated right-angle prism (Prism 1) into two beams with semicircular cross-sections. The beams then propagated through different paths which provided the phase distortion in the form of a variable phase delay between the two beams. One of the paths was equipped with an optical trombone to test the ability of SBS in the long, graded-index fiber to conjugate the phase and correct small path-length variations upon reflection back through the system as expected from a phase conjugate reflection. The optical trombone consisted of a 180° turning prism (Prism 3) on a longitudinal translation stage which could be controlled with a piezo-electric transducer for rapid oscillations. The two beams were tiled side-by-side with a prism (Prism 2) and coupled into a graded-index fiber which had a core diameter of 50 μm and an NA of 0.21.

As shown in Fig. 1, a lateral shearing interferometer (LSI) on each beam pickoff (Wedge 1 and Wedge 2) was used to analyze the SBS reflection from the graded-index fiber immediately after reflecting from the fiber (LSI 2) and after recombination (LSI 1). The LSI was made from two wedged windows separated by ~1 cm, and each window had one side AR-coated. The two uncoated faces created reflections laterally shifted relative to each other. A lens was placed in front of each camera position such that Position 1 (Fig. 1) was imaged

onto Camera 1, and Position 2 was imaged onto Camera 2. In the case of Position 2, the Stokes beam was reflected off Wedge 2 before reaching Position 2, and the Stokes beam was imaged onto Camera 2 as it would be at Position 2.

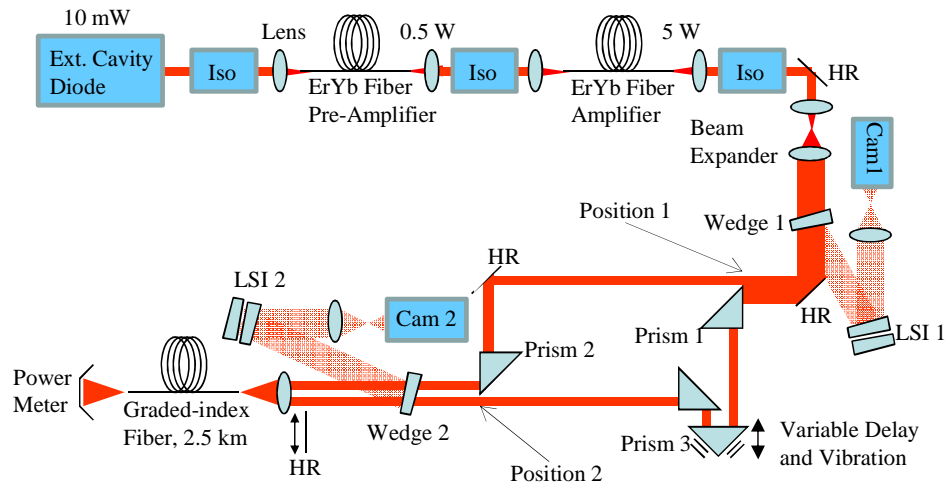


Fig. 1. Apparatus diagram displaying 2-stage, narrow-linewidth fiber amplifier, phase aberration consisting of two optical paths with variable length adjustment on one path, and a 2.5-km, graded-index optical fiber where SBS was generated. LSI: lateral shearing interferometer, HR: high reflecting mirror, Cam: camera.

With two beams tiled together as shown in Fig. 2(a), the LSI created three zones of interference as shown in Fig. 2(b). Zone 1 of Fig. 2(b) is the left semicircular beam interfering with itself, while zone 3 is the right beam interfering with itself. As long as the two wedges of the LSI are stable and much closer than the coherence length of the individual beams, these self-interference zones produce stable interference fringes regardless of fluctuations in the phase of the incident beams. This contrasts with zone 2, which is the mutual interference between the left and right beams. In this region, the position of the fringes depends on the relative phase between the left and right beams. High contrast fringes indicate spatial coherence between the two semicircular beams, but the fringe position in zone 2 shifts with changes in relative phase between the two beams. If the left and right beams are coherent and have the same phase, the maxima of the high-contrast fringes will line up across all three zones. For example, if only a single beam is incident on the LSI as shown in Fig. 2(c), only a single interference zone is created as in Fig. 2(d). If the two beams of Fig. 2(a) are in phase, the situation is similar to that of only a single beam incident on the LSI: the three zones of interference in Fig. 2(b) become effectively one zone with continuous fringes.

For comparison to the Stokes reflection, a highly reflective (HR) planar mirror was inserted in front of the graded-index fiber to reflect the tiled beams back toward the source. The phase variations imparted by a single pass through the two optical paths were analyzed using LSI 2, and the variations from the double pass were analyzed at LSI 1.

Each image in this work was an average of 10 images taken successively at the camera frame rate of 30 Hz. When activated, the transducer on the path-delay prism (Prism 3 in Fig. 1) varied the relative phase between the two beams. This vibration was chosen in the form of a triangle wave with a 5.5 Hz oscillation frequency to avoid resonance with the camera. The full range of travel was 0.2 mm. These conditions were chosen to contrast still fringes from shifting fringes.

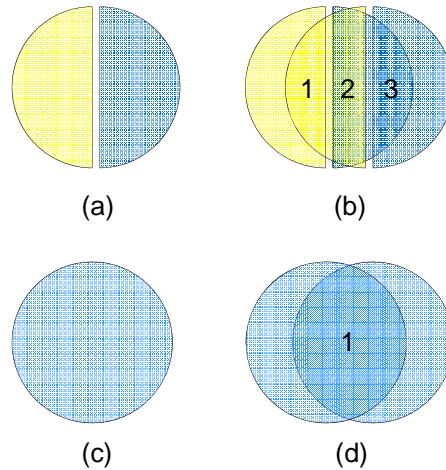


Fig. 2. Diagram of the beam irradiance cross-section and interference zones created by an LSI. With (a) two semicircular beams tiled together, the LSI forms (b) three interference zones consisting of self-interference zones (1 and 3) and mutual interference in zone 2. With (c) a single beam incident on the LSI, (d) a single interference zone exists.

The beam emitted by the single-mode amplifiers is shown in Fig. 3(a) imaged as it would be at Position 1 of Fig. 1. In this case, a second HR was used to reflect the first-pass reflection from Wedge 1 to LSI 1. The contour plot of the same image is also given in Fig. 3(a) for clarity showing a fundamental mode irradiance profile was emitted from the amplifier. Fig. 3(b) shows the irradiance profile of the beam at Position 1 after reflection from the HR mirror in front of the graded-index fiber, and Fig. 3(c) shows the Stokes beam generated in the graded-index fiber after propagation back to Position 1.

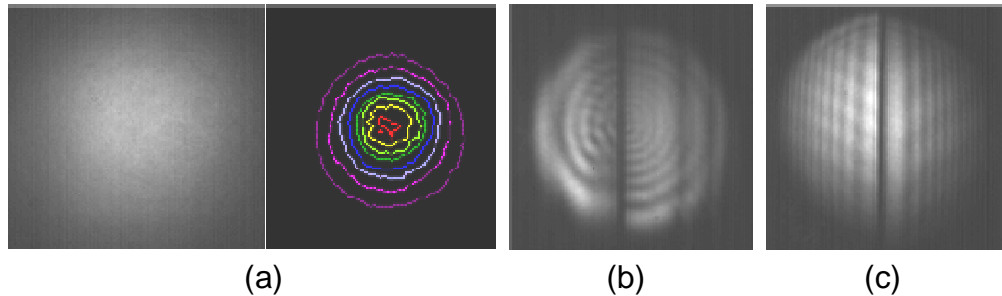


Fig. 3. Shown at Position 1, without interference from the LSI, are (a) the source beam irradiance image and contour plot, (b) the reflection from the HR mirror in front of the fiber, and (c) the SBS reflection.

The coupling efficiency to the fiber was $80 \pm 5\%$. In addition, the power transmitting the fiber from each beam path was $50 \pm 4\%$ of the total transmission measured below SBS threshold. As an indication that many modes were excited in the fiber, sample images of the fiber transmission are shown in Fig. 4. The transmission through the fiber was multimode and slowly varied over time. SBS threshold was reached in the fiber at 0.4 ± 0.1 W of transmitted power, which corresponded to approximately 500 mW coupled to the core of the fiber considering transmission loss and the Fresnel reflection of the back end of the fiber.

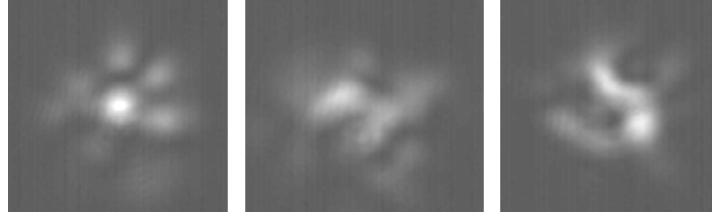


Fig. 4. Sample images of the beam after transmission through the long, graded-index fiber.

The source beam at Position 1 before being split into the two paths is shown in Fig. 5(a) as reflected from LSI 1. With Prism 3 still, the reflection from the HR mirror in front of the fiber and the SBS reflection imaged at Position 1 are shown in Fig. 5(b) and Fig. 5(c), respectively. The source beam was spatially coherent with continuous interference fringes across a single interference zone as shown in the diagram in Fig. 2(d). However, after reflection from the mirror and passing through the separate paths a second time, the beams were not in phase across the three interference zones of Fig. 2(b) as shown by the fringe discontinuities in Fig. 5(b). When the mirror was removed and SBS was generated in the long, graded-index fiber, the fringe discontinuity was also visible as shown in Fig. 5(c). This is in contrast to the smooth phase front of the source beam at this location shown in Fig. 5(a).

While fringe discontinuity does not support phase conjugation, it alone does not negate it. Because of the wavelength shift induced by SBS, even when phase conjugation occurs, the Stokes beam may not have the same continuous fringe pattern as the source beam after propagation back through the individual paths. The dephasing due to the two paths would be $\Delta\phi = 2\pi(\nu_p - \nu_s)\Delta l/c$, [19] where ν_p (ν_s) is the pump (Stokes) frequency, and Δl is the difference between the two beam paths. Given the small Stokes shift in silicate fiber (~ 11 GHz), this function varies slowly relative to a wavelength. The relative phase shifts by 2π when $\Delta l \approx 27$ mm. Given that one path included the optical trombone, the two beam paths varied by more than 27 mm. It is therefore expected that a phase conjugate beam would be only phased coincidentally after propagation back through the two paths. More importantly, however, an additional 0.4 mm change in optical path length caused by vibration of Prism 3 would have a negligible effect on the relative phase ($\Delta\phi_{vib} \approx 0.1 \approx \lambda/60$) if phase conjugation were achieved. Therefore, a phase conjugate reflection would be characterized by visible fringes in zone 2 of the fringe pattern measured at Position 1 even with the vibration stage activated.

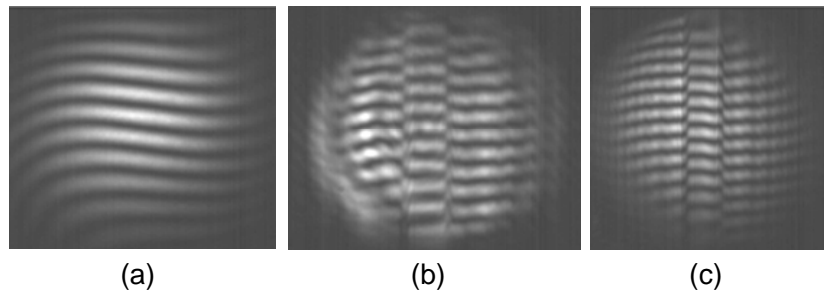


Fig. 5. At Position 1, interference images are shown from LSI 1 of (a) the source beam, (b) the beam reflected by the mirror in front of the fiber, and (c) the SBS reflection.

Prism 3 vibration was activated, and images were retaken at Position 1. The source beam is shown again in Fig. 6(a) for comparison. Fig. 6(b) was taken at Position 1 with the mirror

placed in front of the fiber. The self-interference fringes in zones 1 and 3 were clearly visible, but the fringes due to mutual interference in zone 2 were rapidly oscillating. The motion of the fringes resulted in a drop in fringe visibility in zone 2 as compared to Fig. 5(b). In fact, the remaining fringes can be attributed to the diffraction effects visible in Fig. 3(b) without the interference induced by the LSI.

Fig. 6(c) is an image of the Stokes beam at Position 1 taken with Prism 3 vibration activated. This image shows that phase conjugation did not occur in the long, graded-index fiber. Similar to the reflection from the planar mirror shown in Fig. 6(b), the fringes in zone 2 of Fig. 6(c) rapidly oscillated despite the stable fringe pattern of the source beam at this location shown in Fig. 6(a). A phase conjugate reflection would have conjugated the phase of the beams coupled into the fiber, and the aberration induced by the 2-path phase delay would have been corrected to result in stable fringes in the mutual interference region (zone 2) of Fig. 6(c). The fringe visibility in zone 2 of Fig. 6(c) was measured at $9.6 \pm 3.1\%$, with the remaining fringes in zone 2 most-likely caused by diffraction from Prism 2. In detail, the residual fringes do not span zone 2 continuously and are at a different angle than the fringes in zone 2 of Fig. 5(c). However, this is a minor point compared to the overall lack of fringe visibility in zone 2 as compared to Fig. 5(c) and Fig. 6(a).

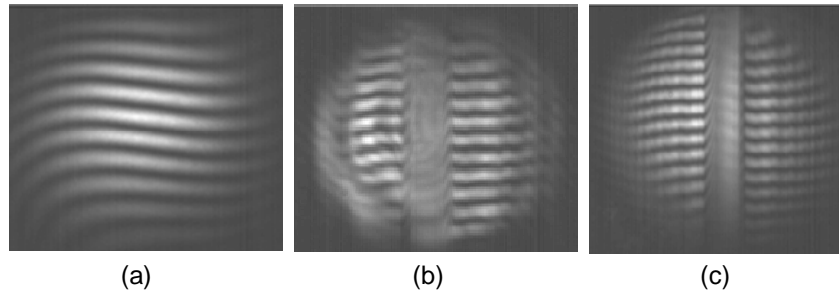


Fig. 6. At Position 1 with the vibration of Prism 3 activated, interference images are shown of (a) the source beam, (b) the beam as reflected from the mirror in front of the fiber, and (c) the SBS reflection.

The beams were also analyzed at Position 2 in Fig. 1. The source beam is shown in Fig. 7(a) as reflected from the planar mirror in front of the fiber. With the mirror removed, the typical Stokes beam observed is shown in Fig. 7(b). The Stokes beam periodically appeared in the double-lobed mode shown in Fig. 7(c), but this mode was very sensitive to minute changes in fiber alignment and the position of Prism 3. The single-lobed pattern of Fig. 7(b) was much more common and stable.

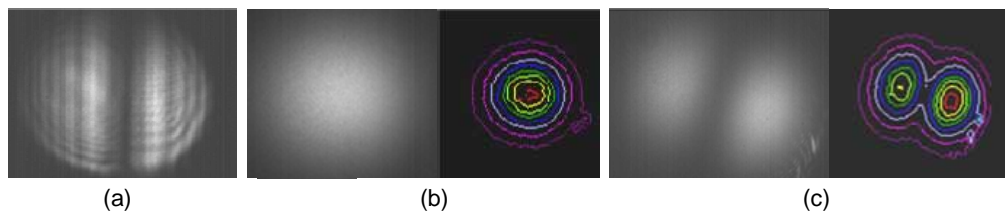


Fig. 7. At Position 2, without interference from the LSI, are shown (a) the source beam after passing through the two channels, (b) the typical SBS reflection from the fiber including a contour plot, and (c) a second SBS reflection from the fiber which was generated periodically, also including a contour plot.

The beams were observed at Position 2 using LSI 2. Despite the phase difference apparent between the two beams coupled into the fiber (Fig. 8(a)), the Stokes reflection

typically had a continuous phase front (Fig. 8(b)). A phase conjugate reflection would conjugate the phase of the input beams including the phase mismatch apparent in Fig. 8(a). The phase difference would only be corrected after propagating back through the phase aberration caused by the two paths. This result is not consistent with phase conjugation.

In contrast, the double-lobed structure of Fig. 7(c) and Fig. 8(c) could certainly be interpreted as a phase conjugate replica of the pump with the high-spatial-frequency components filtered out. However, while small movements of Prism 3 caused the fringes in zone 2 of Fig. 8(a) to shift vertically, the same movement of Prism 3 would cause the two-lobed Stokes beam shown in Fig. 7(c) and Fig. 8(c) to change into the single-lobed beam of Fig. 7(b) and Fig. 8(b). The fringes of zone 2 in Fig. 8(a) would drift in time or shift smoothly with small path-length changes using Prism 3, but the fringes in the double-lobed pattern of Fig. 8(c) would appear only with the fringe pattern shown.

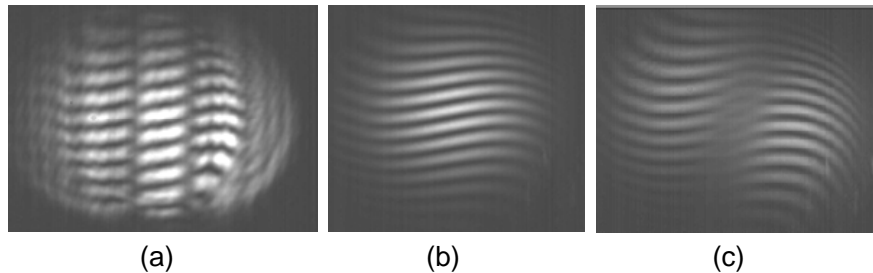


Fig. 8. At Position 2, with interference from LSI 2, are shown (a) the beam reflected from a mirror in front of the fiber, (b) the typical SBS reflection from the fiber, and (c) a periodically-generated SBS reflection from the fiber.

For further analysis of the beams at Position 2, Prism 3 vibration was activated. The source beam viewed with the mirror in front of the fiber is shown in Fig. 9(a). As expected from two passes through the phase aberration, the fringe visibility in zone 2 was greatly reduced as compared to Fig. 8(a). In fact, the remaining fringes are attributable to self-interference fringes in the mutual interference region. The residual interference fringes in zone 2 of Fig. 9(a) are apparent in the self-interference images of Fig. 9(b) and Fig. 9(c), which were taken with one path blocked. In this case, the sharp edge of Prism 1 caused the beams to diffract, which caused self-interference fringes to appear in the mutual interference zone.

With the vibration of Prism 3 activated, the Stokes reflection at Position 2 was stable, as shown in Fig. 9(d), despite the rapid movement of the fringes visible in zone 2 of Fig. 9(a) caused by the varying phase between the two paths of the source beam. Comparison of Fig. 9(d), when Prism 3 was active, to Fig. 8(b), when Prism 3 was still, shows that the Stokes reflection was phased regardless of the phase fluctuations between the two input beams. A phase conjugate reflection would conjugate the varying phase of the input beams. Instead, the Stokes reflection had a stable, continuous phase front.

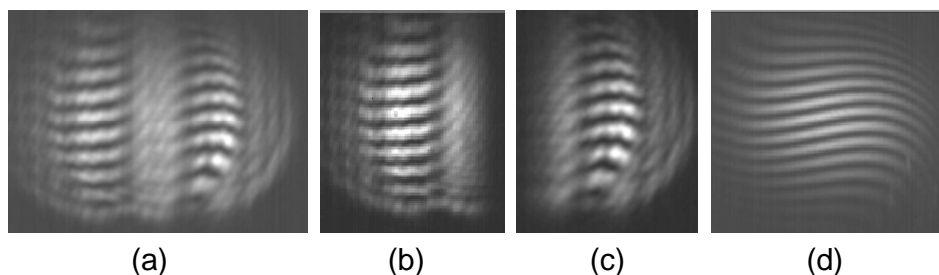


Fig. 9. At position 2, with interference from LSI 2 and Prism 3 vibration activated, are shown (a) the source beam, (b-c) the source beam with one channel blocked to show self-interference fringes only, and (d) the SBS reflection.

3. Discussion

In this experiment, a single-mode source beam was propagated through an aberration in the form of a 2-path phase delay before being coupled into a long, graded-index fiber. The Stokes beam was compared to the source beam both before and after the aberration at Position 1 and Position 2 in Fig. 1. A phase conjugate reflection would conjugate the phase at both positions. Therefore, a stable fringe pattern at Position 1 similar to the source beam would be observed despite variations in phase caused by the oscillation of Prism 3. This was not observed, since zone 2 of Fig. 6(c) is characterized by a rapidly shifting fringe pattern despite the stable fringe pattern of the source beam at this location as shown in Fig. 6(a). At Position 2, a phase conjugate reflection would again conjugate the phase of the input beams. After passing through the two paths, the input beam at Position 2 had a rapidly varying phase difference between the two beams as seen in zone 2 of Fig. 9(a). However, the Stokes beam was phased as shown in Fig. 9(d). These results show that phase conjugation was not achieved.

Beam cleanup would have remarkably different characteristics. Since the beam exits the fiber in a pure fiber mode, it would be spatially coherent across its transverse dimension immediately after exiting the fiber despite variations in phase of the input beams. This was observed as shown in Fig. 9(d). Once the Stokes beam was split into two independent beams at Prism 2 and propagated through the time-varying path lengths, the constant phase would be lost. This was also observed as shown in Fig. 6(c). In addition, the double-lobed structure observed in Fig. 7(c) and Fig. 8(c) is consistent with beam cleanup to the LP_{11} mode. In the null region between the two lobes, the fringes lose contrast as the irradiance drops, and it appears that the two lobes are phase-shifted by π as would be expected from an LP_{11} mode.

This experiment was not designed to study the spatial characteristics of the beams, but some observations can be made. The Stokes beam shown in Fig. 7(b) at Position 2 does not resemble the double-semicircular irradiance pattern of the input beams shown in Fig. 7(a). Additionally, after good coupling efficiency to the fiber had been achieved, precise angle adjustment of the fiber tip was required in order for the Stokes beam to propagate back through the system on-axis. This adjustment would not have been necessary if a phase conjugate beam had been generated. A phase conjugate reflection with high fidelity would propagate in the direction opposite the pump beam despite small perturbations to the coupling characteristics. In contrast, the appearance of Fig. 7(c) could be interpreted as imperfect phase conjugation of the pump or as beam cleanup to the LP_{11} mode of the fiber. Considering the phase analysis of this work removes the possibility that phase conjugation was occurring.

4. Conclusions

Lengths of graded-index fiber on the order of a kilometer are useful for coherent beam combination, but the Stokes beam is not a phase conjugate of the pump. Instead, the Stokes reflection due to multiple beams focused into the graded-index fiber produces a phase-locked beam immediately upon exiting the fiber. Propagation back through a phase distortion such as the independent paths used in this work disrupts the phase relationship.

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