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Incoherent beam combining using stimulated Brillouin scattering in multimode fibers

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Abstract: A beam combining technique for producing a single, spatially coherent beam from two mutually incoherent (temporally and spatially) lasers is demonstrated and the spatial coherence properties of the resulting beam are characterized. The technique is based on simultaneous excitation of stimulated Brillouin scattering by two independent lasers operating at two different wavelengths in a long multimode optical fiber. Though spectrally independent, the resulting Stokes beams produce essentially identical intensity distributions corresponding to the fundamental fiber mode.

OCIS codes: (060.4370) Nonlinear optics, fibers; (140.3300) Laser beam shaping; (190.4370) Nonlinear optics, fibers; (190.5890) Scattering, stimulated; (290.5900) Scattering, stimulated Brillouin

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1. Introduction

In a recent experiment by Rodgers, *et al.*, coherent laser beam combining and cleanup in multimode optical fibers using stimulated Brillouin scattering (SBS) was demonstrated [1]. In this experiment, two beams from a single laser were spatially overlapped and directed into a multimode fiber. The two beams were observed to jointly produce a single Stokes beam in the fundamental fiber mode irrespective of the input (pump) beam profile whenever the sum of the beam power was raised above the SBS threshold of the fiber. It was also demonstrated that this technique could be used to coherently combine beams from two separate lasers, provided the laser beams are within one Brillouin gain line width (typically ~100MHz) of

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each other in frequency. This technique would be appropriate for coherently combining two or more beams from a multi-channel amplifier array in a master-oscillator/power-amplifier (MOPA) configuration, for example. However, fixing the frequencies of separate lasers to within one Brillouin width is not a simple task. Thus, coherent combining of multiple independent lasers might be difficult to implement in practice. The feasibility of employing multiple pumps to increase the gain in parametric amplification processes was theoretically analyzed previously [2].

On the other hand, if the lasers operate at two different frequencies, they can still be combined into one beam using the same technique, although the Stokes beam produced will no longer be temporally coherent. It is a direct extension of the coherent case described above. We will call this incoherent beam combining. In incoherent beam combining individual pump beams excite their own separate Stokes beams, and therefore individual pump beams must exceed the SBS threshold by themselves. Except for the sharing of a common SBS medium in the form of a fiber, there is no mutual interference between the two beams. Nevertheless, each pump beam produces a Stokes beam in the fundamental fiber mode. Since the SBS fiber is common to both beams, the generated Stokes beams become spatially coherent. The exact mechanism by which the SBS process produces a Stokes beam in the fundamental fiber mode in a long multi-mode fiber has not yet been theoretically analyzed. However, it is believed that the superior modal overlap in intensity that the fundamental mode enjoys with multi-mode pump compared with higher-order mode is responsible for the observed effect.

Incoherent beam combining can be used to scale beam power to higher levels than those achievable through coherent beam combining. If one were to coherently combine many lasers into a single beam, the resulting Stokes wave would reach second order SBS threshold rapidly, and the appearance of the second Stokes beam traveling in the forward direction down the fiber would result in decreasing efficiency with increasing input power. This will put severe limits on the total combined power of the input beams. Incoherent combining would relax this limitation significantly. For the incoherent process, pump beams are different in frequency so each pump beam builds its own Stokes beam independently. This means that the second order Stokes threshold is only dependent on the power in each Stokes beam, not the sum of the pump beams. Thus, second order Stokes threshold will be greater than that for a single coherent beam by a factor of the number of lasers being combined [3].

Moreover, this technique is completely general in that lasers of any wavelength can be combined as long as their wavelengths lie in the transmission window of the fiber materials. This kind of beam combining technique would be useful for any applications that require high brute-force laser power in a single beam such as in material processing. It would also be appropriate for applications that require multiple discrete wavelengths in a single beam, such as in multi-spectral electro-optic countermeasures or hyper-spectral imaging. The spatial coherence that this technique provides makes it possible for the combined beam to be directed into a diffraction-limited spot, be it a tight focus or long-distance targeting. In this paper we report on our investigation of incoherent beam combining of diode lasers using SBS in a multimode fiber.

The investigation of incoherent beam combining was completed in two parts. Section 2 describes a set of experiments designed to investigate the mutual interaction of the two lasers in a single fiber. The goal of the experiments was to demonstrate that since the frequency of the two beams are separated by greater than the Brillouin gain bandwidth, they excite independent Stokes waves in the fiber. Section 3 investigates the spatial coherence properties of the Stokes waves generated by the two laser beams. In this section it is shown that the two beams have nearly perfect spatial coherence.

2. Mutual Independence of Stokes Excitation

2.1 Experiment

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When two laser beams of arbitrary frequencies are simultaneously focused into an SBS cell, the Stokes beams generated by the lasers build up independently [4]. Each pump beam interacts with the Stokes beam it creates but there are no cross interactions since the interactions occur with different groups of phonons with energy $^{2nv}/_{\lambda}$, where n and v are the linear index of refraction and acoustic velocity of the material respectively, and λ is the wavelength of each pump beam. The only exception to this is when the lasers are nearly identical (within a Brillouin line width) in frequency [3-6]. In that case the beams will pump a single Stokes beam common to both, which is the case of coherent beam combining described earlier.

The setup used to demonstrate incoherent beam combining is shown in figure 1. Two SDL single mode (longitudinal) lasers were collimated using 20x microscope objectives. Laser A emitted light at 853 nm while laser B operated at 832 nm. The collimated beams passed through 40-dB Faraday optical isolators and were then spatially superposed with two half-wave plates and a polarizing beam splitter. At the beam splitter, lasers A and B are polarized horizontally and vertically, respectively. After the beam splitter, the light passed through a quarter-wave plate oriented to convert the crossed linear polarizations of the two beams into circular polarizations. Finally, using a 10x microscope objective, the beams were focused into a 4.4 km Corning SMF-28 fiber with an 8.3-micron core (9.5-micron mode field diameter) and a numerical aperture of 0.12.

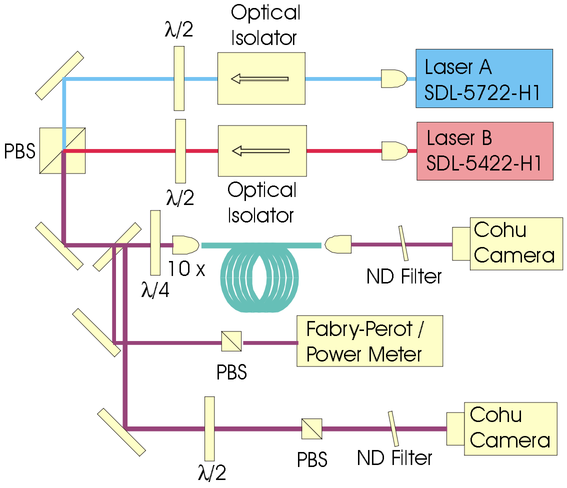
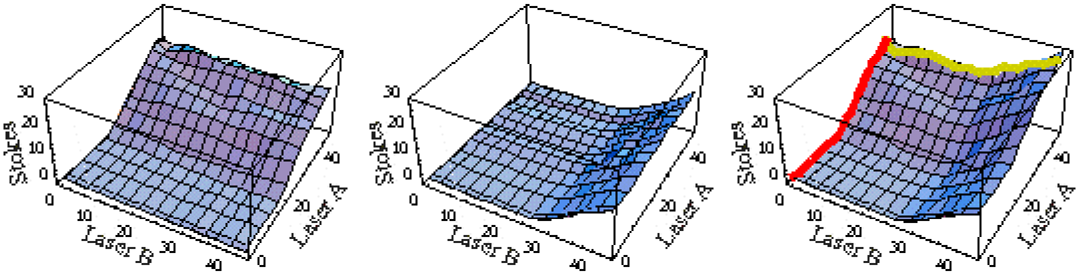


Fig. 1: Two beam incoherent combination experimental setup using a multimode fiber.

The light that was reflected off the surface of the fiber as well as the light generated through SBS was collimated as it passed back through the microscope objective and the quarter wave plate. A portion of this reflected off both the front and back surfaces of an uncoated flat window. The portion of the beam that was reflected off of the rear surface of the flat passed through a half-wave plate, a Glan-Thompson polarizer and neutral density filters before being captured by a Cohu camera and analyzed using a frame grabber (Coherent Beamcode). The portion of the beam that was reflected from the front surface of the flat was picked off using a mirror and directed through a Glan-Thompson polarizer into either a Coherent power meter or a Fabry-Perot interferometer for spectral characterization.

2.2 Results

Figure 2a shows a 2-D surface plot displaying the power of the horizontally polarized Stokes beam as it enters the Fabry-Perot over all possible input powers for laser A and laser B. The separation of the Fresnel reflection from the Stokes beam was facilitated by the fact that the polarization of the Fresnel reflection is orthogonal to that of the Stokes, as discussed more fully below. Obviously, as the current on laser A increases (thus laser power), the horizontally polarized Stokes beam (co-polarized with the laser A input) increases as well, once threshold is passed. There is no significant change to the Stokes power due to laser A as the power coupled into the fiber from laser B is increased. Figure 2b demonstrates that the converse is also true. As the current driving laser B is increased, the power in the vertically polarized beam (co-polarized with the laser B input) increases, independent of the laser A power coupled into the fiber. The combined output of both polarizations is shown in figure 2c. If one were to trace out the path along this surface shown by the red and yellow line on figure 2c, distinct threshold powers are seen for each laser. This path is plotted in figure 3. This clearly demonstrates that each laser must exceed its own threshold power in order to excite its own Stokes beam.



(a) (b) (c)

Fig. 2: Polarimetric Stokes Power vs. Pump Power in mW. (a) SBS Power reflected into a horizontally polarized beam. (b) SBS Power reflected into a vertically polarized beam. (c) Total SBS Power.

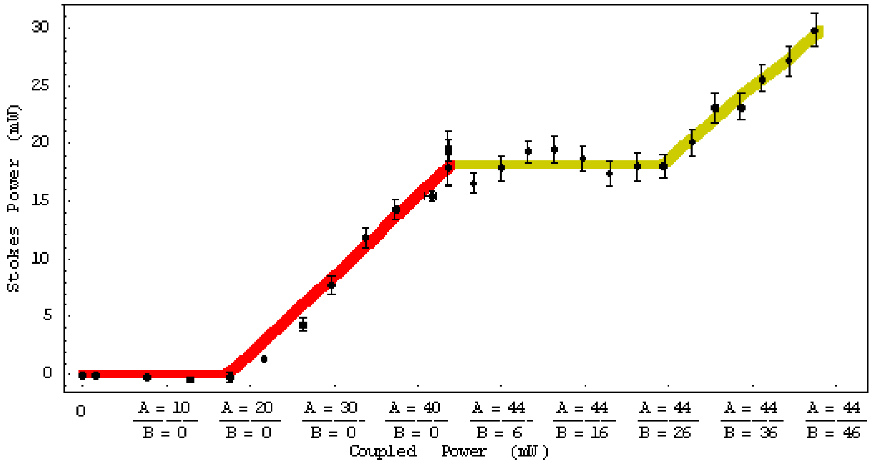


Fig. 3: The indicated path of figure 2c shows that the two input beams have separate thresholds.

In order to determine the possible dependence of the SBS threshold for laser B on the power of laser A, several slices of figure 2b were taken parallel to the laser B power axes. The slices were normalized such that the left hand side of each slice, corresponding to no laser B input, was set to zero. These slices are all plotted using a common axis in figure 4. The average slope efficiency of these curves is 68 ± 8%, the error margin being one standard deviation. The standard deviation associated with the calculation of each slope efficiency is on average 7%. The average threshold is 17 ± 2 mW. The standard deviation associated with the calculation of the threshold is on average 5mW. Thus the data shows that the threshold and slope efficiency are nearly identical within the experimental uncertainty over the full range of laser A input powers, indicating the complete independence between the Stokes beam generated by laser B and the power of laser A. The frequency of all the beams was continuously monitored throughout these measurements with a Fabry-Perot spectrum analyzer. A sample spectrum containing the pumps and their Stokes components is shown in figure 5. It was observed that the Stokes shift remained constant as the power of both lasers was varied.

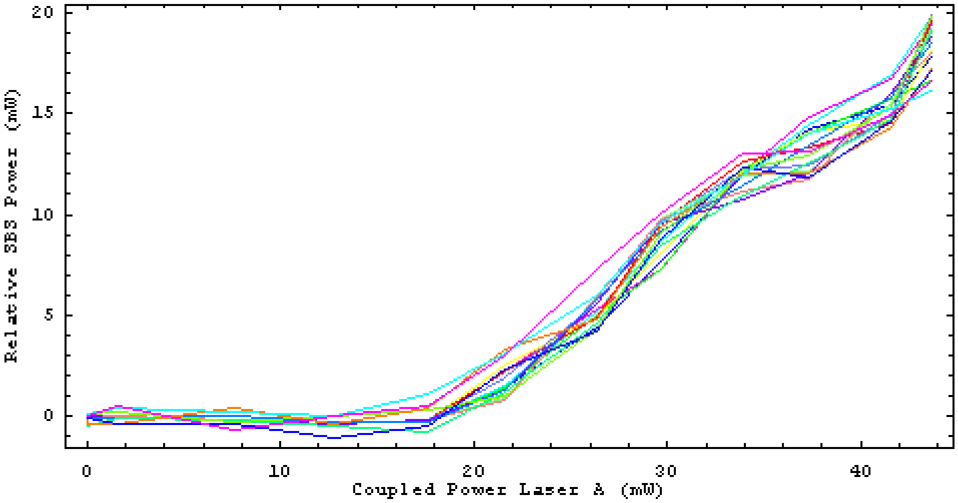


Fig. 4: SBS Power vs. input power at several different input powers of Laser A. The similarity of each curve indicates that the threshold and the slope efficiency of the SBS process is independent of laser A.

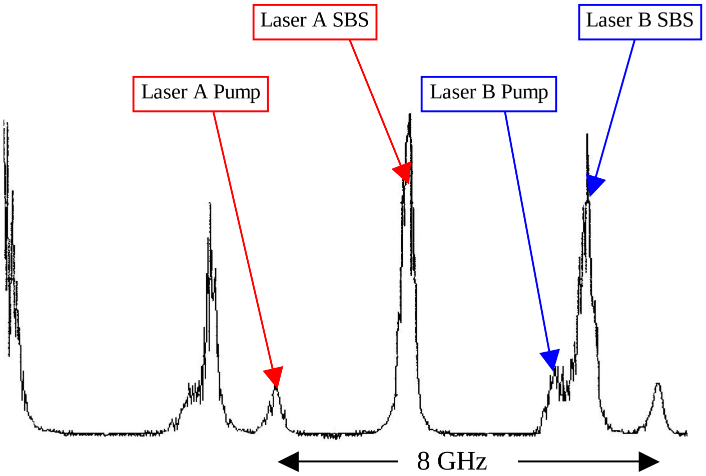


Fig. 5: Dual pump and SBS spectrum generated from a Fabry-Perot interferometer with a free spectral range of 8 GHz.

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The Stokes beam resulting from a linearly polarized pump matches the polarization of the input [1,6]. In the same manner, when the pump beam is circularly polarized, the Stokes beam, unlike the Fresnel reflection, has the same handedness. This was demonstrated using the Fabry-Perot interferometer and a single laser input. Figure 6 shows the co- and cross-polarized output of the Fabry-Perot due to input from laser A. Before passing through the quarter-wave plate as the beam traveled toward the fiber, laser A was horizontally polarized, thus the light that undergoes Fresnel reflection is vertically polarized after passing back through the quarter-wave plate. This resulted in the larger of the two peaks shown in the plot at the bottom of figure 6. The polarization of the Stokes beam on the other hand was not converted to vertically polarized light after reflection and thus has a strong component in the co-polarized plot at the top of figure 6. There is some disparity between the two spectra. The data was taken well above SBS threshold, thus it would be expected that the SBS beam would be much stronger than the reflected pump beam. However, the output of the Fabry-Perot suggests that the Stokes beam is nearly the same intensity as the reflected pump. This is due to the difference in reflectivity of the uncoated flat for horizontally and vertically polarized light. A direct comparison of the powers from the top and bottom plots of figure 6 would require the top plot to be scaled by a factor of about 7.5.

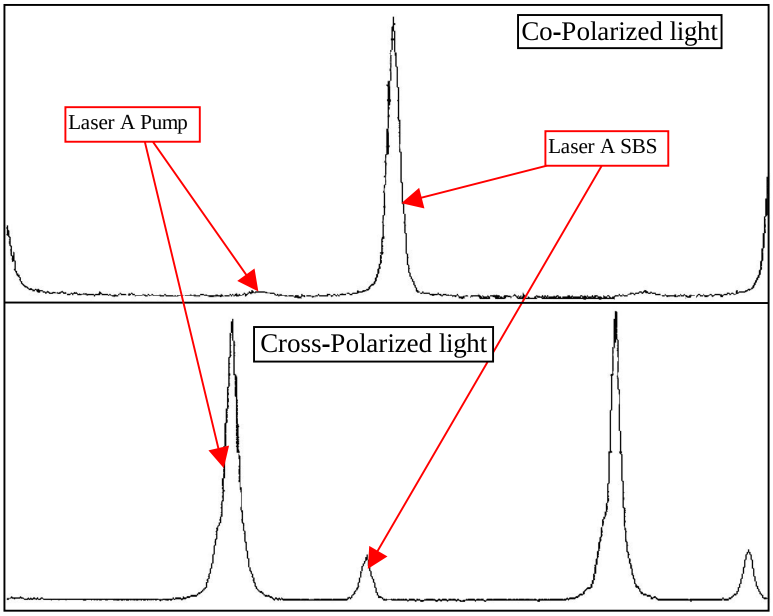

Fig. 6: Polarimetric spectrum of Laser A.

The observations described above collectively lead us to conclude that when two laser beams of arbitrary frequencies simultaneously excite SBS in a common SBS medium (fiber in this case), they individually excite their corresponding Stokes beams without interfering with each other. The simultaneous presence and generation of the Stokes beams by two incoherent pump beams in a single fiber have no effect on the wavelength, threshold, efficiency, or polarization properties of the Stokes beam generated by each pump.

3. Spatial Coherence Properties

3.1 Experiment

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A set of experiments was performed to investigate the spatial coherence properties of the Stokes beam generated through incoherent beam-combining technique. The goal of the experiments was to demonstrate the near-perfect spatial coherence of the Stokes beams generated in SBS process by two arbitrary lasers in a multi-mode fiber.

The experimental setup was identical to figure 1 except the quarter-wave plate was removed. Under such conditions, all light from a single pump (the Stokes beam and the Fresnel reflection) had the same polarization and could be kept separate from the second pump. The Corning SMF-28 fiber used had a fiber parameter of 4.2 at our laser wavelengths, indicating that four modes (LP_{01}, LP_{11}, LP_{02}, and LP_{21}) could be supported by the fiber at our wavelength range [7].

The spatial coherence properties were demonstrated using intensity profiles for each laser in three configurations. First, each laser was turned on well above their respective SBS thresholds. The half-wave plate located in front of the beam profiler was tuned for maximum transmission of laser A and the resulting Stokes beam. At that point, eight intensity profiles were captured and averaged. The averaging was necessary due to the temporal fluctuations that accompanied the Stokes beam. This averaged profile consisted of energy in the Stokes beam created by laser A as well as energy that reflected off the front fiber face. The half-wave plate was then rotated 45° and similar images were collected showing the Stokes beam intensity profile due to laser B and its associated pump beam.

Upon completion of the first set of images, the fiber length was cut to two meters from the entrance face. This was done without altering the position of the front face of the fiber or adjusting the camera location. Two more sets of intensity profiles, identical to the first were then collected, however since the fiber was only two meters long, the SBS threshold was raised well above the operating power of the two lasers. This ensured that the profiles included light due only to Fresnel reflection off the air-fiber interface. These profiles show the relative position of the two input beams and were subtracted from the first set to obtain an intensity profile due purely to the Stokes beam.

The last set of profiles was taken at the exit face of the fiber. Each laser was independently powered when the images were collected. The two profiles clearly show that the input beams were not spatially filtered into the fundamental fiber mode.

3.2 Analysis

Both a qualitative measure of the beam overlap and a numerical figure of merit were used to analyze the experimental data. The qualitative measure was a series of grayscale plots that show the relative position and intensity of each laser. The brightness of the plots was calculated using the following algorithm. The intensity image from each laser was separately scanned through a 10 pixel x 10 pixel mean filter. The size of the filter was chosen to be large enough to remove the random noise from the intensity data but small enough to retain real intensity variations present in the images. The power of the beam in each intensity image was then separately normalized to one. Finally, the difference in intensity profile was obtained by subtracting pixel by pixel the intensity due to laser B from that due to laser A. Pixels having the same intensity for lasers A and B thus were assigned a numerical value of zero. Lastly, the image was plotted and linearly shaded such that a pixel with a value of positive one appeared white and a pixel with a value of negative one appeared black. This scheme clearly shows any significant difference between the positions and profiles of the two Stokes beams due to lasers A and B. The results of this analysis are shown in figures 7-9. In each of these figures, (a) shows the intensity profile of laser A, where a brighter output indicates a higher intensity. Part (b) of figures 7-9 shows the intensity profile of laser B. These images are shaded such that darker regions indicate higher intensities. Finally, part (c) is the addition of both the images from (a) and (b). This image corresponds to a pixel-by-pixel image subtraction of beam B from beam A.

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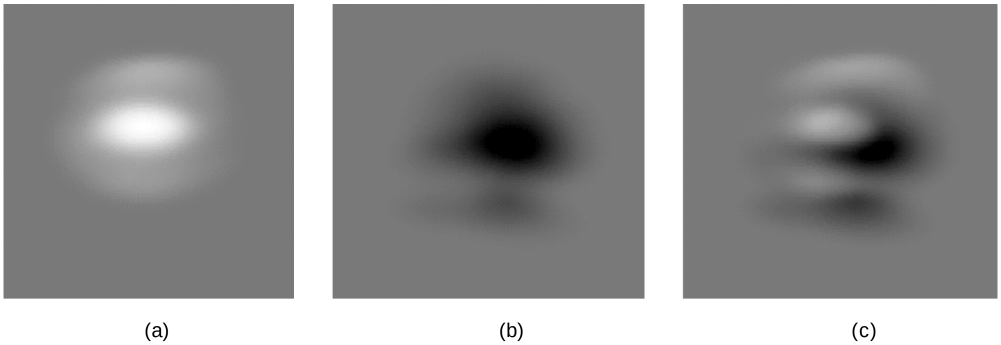

Fig. 7: Reflected beam overlap. (a) Image of Laser A. Lighter shades indicate higher intensity. (b) Image of Laser B. Darker shades indicate higher intensity. (c) Combined laser beams showing significant mismatch between the reflected positions of laser A and laser B.

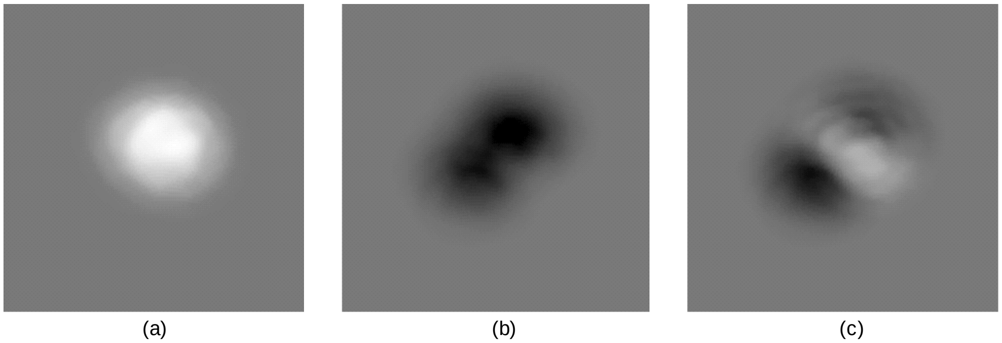

Fig. 8: Transmitted beam overlap. (a) Image of Laser A. Lighter shades indicate higher intensity. (b) Image of Laser B. Darker shades indicate higher intensity. (c) Combined laser beams showing significant mismatch between the transmitted positions of laser A and laser B.

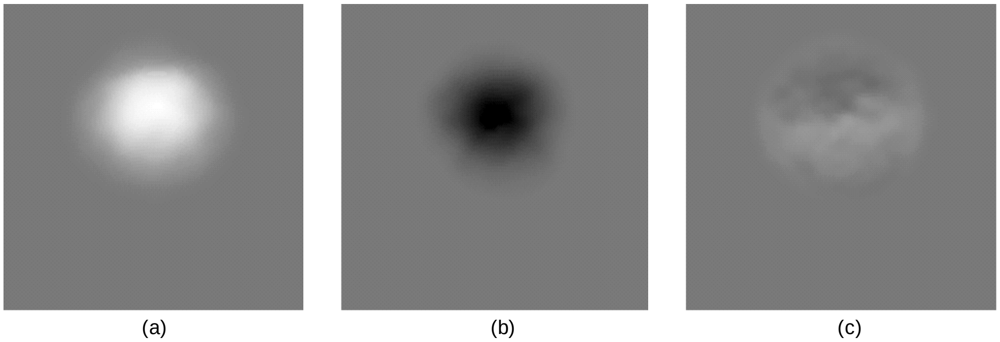

Fig. 9: SBS beam overlap. (a) Image of Laser A. Lighter shades indicate higher intensity. (b) Image of Laser B. Darker shades indicate higher intensity. (c) Combined laser beams showing the two SBS beams are nearly coaxial.

Figure 7 shows the relative positions of the Fresnel reflection off the front fiber facet. This image was collected from the fiber after it was cut to approximately two meters. Since the fiber facet was placed in the focal plane of the microscope objective, the location of the reflected beams on the camera serves as an indicator of the relative direction of the input beams. As can be seen by the obvious structure in figure 7c, there is a significant mismatch between the locations of the output from laser A and laser B. This clearly indicates that the two lasers are not coaxially aligned before entry into the fiber. The transmitted intensity profiles are shown in figure 8. It is apparent by the relative displacement of the two beams that spatial filtering due to the fiber is not aligning the laser beams. Finally, figure 9 shows the Stokes beams generated by the two lasers. Both beams appear to be emitted from a Gaussian-like LP_{01} fiber mode and as can be seen from figure 9c, the two beams have nearly identical spatial intensity distributions.

While visually gratifying, the above analysis does not offer a quantitative measure of the two-beam alignment. In order to define a measurable quantity that would indicate how well the two laser beams were aligned under the different scenarios, the images were again separately normalized but then the mean square deviation between the two images was calculated. This deviation is defined as follows.

$$\varepsilon = \frac{1}{N}\sum_{i}^{N}\left[I_A\left(x_i\right) - I_B\left(x_i\right)\right]^2 \tag{1}$$

where $I_{A,B}\left(x_i\right)$ indicates the intensity of the pixel at x_i associated with laser A,B and N is the total number of pixels in the image. The resulting number is a measure of the quality of the beam alignment.

Table 1 summarizes the degree of misalignment in our experiment. In this calculation N is 57,600 and the pixel intensity differences are those seen in figures 7-9. This table reinforces what was clear based on the images. The mean square deviation described indicates that the Stokes beams overlap nearly 9 times better than the transmitted and input beams. Since the output power of a single laser or amplifier is inherently limited by beam degradation, thermal loading, or pump coupling, this method of incoherent beam combining can be used to scale diffraction-limited powers beyond the limit that a single emitter can produce.

Table 1: Quantitative measure of beam overlap

	$\frac{1}{N}\sum_{i}^{N}\left[I_A\left(x_i\right) - I_B\left(x_i\right)\right]^2$ (10^{-11})	Relative Misalignment
Reflected Beam Misalignment	69.7	1.00
Transmitted Beam Misalignment	69.0	0.99
SBS Beam Misalignment	7.7	0.11

4. Conclusions

This paper described a method for incoherently combining multiple laser beams into a single beam of high spatial coherence through stimulated Brillouin scattering in a long multi-mode fiber. The experiments described herein demonstrate the independence of the Stokes wave excitation for pump beams with different wavelengths. The quality of beam overlap has been quantified using the mean square error between the beam profiles. Using this measure, it was shown that the two multi-mode input pump beams that were not incident coaxially were converted into a beam of single spatial mode, with a slope efficiency greater than 70%. In addition, it was shown that the two Stokes beams resulting from the separate lasers had essentially identical spatial intensity profiles representing the fundamental fiber mode, which indicated that the SBS process in the fiber had in fact aligned the two incoherent beams to give them spatial coherence, in spite of their mutual temporal incoherence and spectral mismatch.

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