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ADVANCED HIGH-POWER NEAR-INFARED FIBER LASERS

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Final Report

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14. ABSTRACT
Experiments were conducted to study stimulated Brillouin scattering (SBS) in optical fibers with a goal of studying its applicability for phase conjugation of radiation from CW lasers, and of using SBS to demonstrate high power fiber lasers by coherent combination of beams from several fiber amplifiers. It was determined that usual plane-wave theory of SBS does not correctly predict the threshold when applied to SBS in single-mode step-index and multimode GRIN fibers. By properly accounting for the mode sizes and modal dispersion in the fibers, good agreement (within 15%) between experiments and theory was obtained. Good compensation of beam distortion was demonstrated via SBS in long multimode fibers (length of the order of 1 km), both with butt-coupling and focusing geometries. We have demonstrated the reduction of the SBS threshold, an increase in the SBS reflectivity and reduction in Stokes power fluctuations for seeded SBS in long multimode fibers. We have demonstrated distortion compensation via (beam "cleanup") in the seeded SBS configuration.

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SUMMARY

- Experiments were conducted to study stimulated Brillouin scattering (SBS) in optical fibers with a goal of studying its applicability for phase conjugation of radiation from CW lasers, and of using SBS to demonstrate high power fiber lasers by coherent combination of beams from several fiber amplifiers.
- It was determined that usual plane-wave theory of SBS does not correctly predict the threshold when applied to SBS in single-mode step-index and multimode GRIN fibers. By properly accounting for the mode sizes and modal dispersion in the fibers, good agreement (within 15%) between experiments and theory was obtained.
- Good compensation of beam distortion was demonstrated via SBS in long multimode fibers (length of the order of 1 km), both with butt-coupling and focusing geometries.
- We have demonstrated the reduction of the SBS threshold, an increase in the SBS reflectivity and reduction in Stokes power fluctuations for seeded SBS in long multimode fibers.
- We have demonstrated distortion compensation via (beam “cleanup”) in the seeded SBS configuration.

INTRODUCTION

The process of phase conjugation via stimulated Brillouin scattering (SBS) has been investigated by many researchers over the last three decades [1-8], more recently because of its utility as a possible method for coherently combining the power from several laser beams into a single beam. Early experimental studies on coherent coupling and beam combination via SBS [1,2] focused on the use of *bulk media and high power pulsed lasers*. The work done in the reporting period focuses on the study of *SBS in optical fibers* with a goal of studying its applicability *for phase conjugation of radiation from CW lasers*, and of using SBS to demonstrate high power fiber lasers by coherent combination of beams from several fiber amplifiers.

Stimulated Brillouin Scattering (SBS) is one of the important nonlinear effects in the interaction of electromagnetic radiation of optical frequencies with matter. It can occur in solid-state media as well as in liquids and gases. SBS was first observed in 1964, and has been studied extensively. It originates from scattering of light by acoustic phonons and manifests itself via the generation of backward-propagating Stokes wave that is downshifted in frequency from the incident pump by an amount determined by the nonlinear medium.

One interesting property of SBS is the reversal of the wavefront of the reflected beam, also referred to as phase conjugation (PC). SBS is commonly used in optical phase conjugation because it has a relatively high gain constant and, consequently a low threshold and also a low frequency shift. In this way high brightness near diffraction limited master oscillator power amplifier (MOPA) systems with high output power (both pulsed and CW operated) have been realized [9,10].

In the early studies, the phase conjugating mirrors based on SBS, used in high power lasers with high beam quality, were realized using cells filled with organic liquids or gases under high pressure. Organic liquids are toxic, and high pressure gases are often difficult to handle. Moreover, the focussing geometry often leads to optical breakdown, which can lead to instability in the SBS reflectivity. In glass *multimode* fibers, SBS has been demonstrated to result in effective beam combining of two low power beams [11]. Fiber phase conjugators have also been developed using multimode glass fibers with core diameters of 25 to 200μm as phase conjugating mirrors. Such fiber phase conjugating mirrors (PCM) have been shown to operate with reflectivities of over *80%* [12], fidelity of over 90% [6] and power thresholds below 1 kW at 1.06μm using 30 ns pulses. The damage threshold is about 1 GW/cm^2. Similar data were achieved in the visible range at a wavelength of 532 nm and at an ultraviolet wevelength of 355 nm [13]. SBS phase conjugation at powers below *100mW* is possible for CW operation using long multimode fibers [7].

The SBS threshold for a fiber phase conjugator depends on the geometry of the fiber [14]. It can be calculated from Eq. (1) :

$$P_{th}=21A_{eff}/L_{eff}g \qquad (1)$$

where A_{eff} is the effective area inside the fiber core, L_{eff} the effective interaction length, which depends on the coherence length of the pumping laser and g is the Brillouin gain. For quartz fibers g is in the range of 2.4cm/GW [15]. It can be seen that the power threshold can be decreased easily with lower core diameters and higher interaction length.

In our recent paper [16] we have demonstrated (theoretically and experimentally) that the SBS threshold in fibers is different from bulk. We have demonstrated the effects of modal dispersion through the numerical aperture *(NA)* and mode size on the SBS threshold of single mode and multimode fibers in an all fiber configuration.

We have measured the SBS threshold in a multimode fiber and found to be approximately a factor of four lower than that predicted by the plane wave theory of SBS generated from noise (Eq.1). We made two changes in the traditional SBS threshold, by replacing, g, the SBS gain coefficient for bulk silica with, $g_i(f_S)$, the gain of the SBS return, at the Stokes frequency, f_S, (the inhomogeneous broadened SBS gain) and the core area of the fiber by the SBS mode area of radius r and got good agreement between theory and experiment.

It is important to note that even though phase conjugation mirrors based on SBS generated in bulk or in short MM fibers (length of the order of meters) have been demonstrated very successfully, there is still a lingering question related to the optimal conditions leading to the observation of phase conjugation [3-8] or beam cleanup [11, 17] in long optical fibers (length of the order of km). This is because of issues such as differential modal gains of the Stokes radiation in long MM fibers and of lack of understanding of the exact nature of mode mixing in multimode (MM) fibers. In particular, phase conjugation with high fidelity appears to be more likely to occur in shorter fibers with lower numerical apertures [3-6], while beam cleanup is more likely to occur in longer fibers [11, 17].

There is a confusion in literature terminology regarding the significance of beam cleanup. Rogers [11] used the term in connection with the experimental observation of the SBS return to have a Gaussian like transversal intensity profile, but no phase conjugation properties. In fact, beam cleanup based on SBS (or seeded SBS) is another promising technique to improve the beam quality of high power laser systems with high efficiency.
In such a setup the beam with high average power but low quality from the laser system is superimposed in a nonlinear medium with a beam with low power but high quality. The resulting interference pattern in the medium generates a refractive index variation which can be adjusted to have a phase shift with respect to the light pattern, allowing an energy transfer from the strong beam to the week beam but with good beam quality. The method can be used also to couple multiple beams in one output with high quality.
This method was applied using photorefractive crystals [18] for coupling beams of diode lasers. This results in high coupling efficiencies but the response time is in the range of several seconds to minutes. Therefore beam clean up based on SBS is appropriate for high power laser systems and can substitute phase conjugating mirrors and offer lower power threshold.

We have experimentally investigated the phase conjugation properties of SBS in long MM fibers (length of the order of km) and beam cleanup in such fibers. We have demonstrated good experimental distortion compensation due to SBS in long MM fibers

(1km length) and obtained the reduction of SBS power threshold, increase of SBS reflection and reduction of Stokes power fluctuations for seeded SBS (also called beam cleanup based on SBS).

SBS THRESHOLD IN SINGLE MODE AND GRIN MULTIMODE FIBERS IN AN ALL FIBER CONFIGURATION

We have demonstrated (theoretically and experimentally) [16] that the SBS threshold in fibers is different from bulk. Previous reports on SBS in fibers have described conflicting results, notably with regard to SBS thresholds. We have measured the SBS threshold in a multimode fiber and found it to be in agreement with the measurement of Ref. [7] , which is approximately a factor of four lower than that predicted by the plane wave theory of SBS generated from noise. V. I. Kovalev [7] has proposed that the lowering of the threshold could be caused by retro-reflection of a portion of the pump radiation by the transversely-cleaved far end of the fiber; however, in our experiments, the far end of the fiber was angle-cleaved, so that reflection of light from the end of the fiber was circumvented.

We have demonstrated the effects of modal dispersion through the numerical aperture *(NA*) and mode size on the SBS threshold of single mode and multimode fibers in an all fiber configuration (see Fig.1).

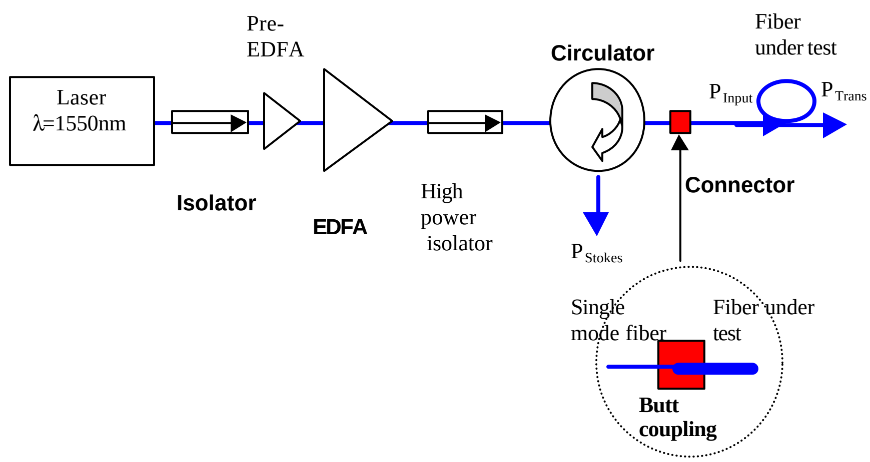

Fig.1 Schematic for measuring SBS performance

The block diagram of the experimental set up is shown in Fig.1. We have used a master oscillator-power amplifier configuration (MOPA) to generate SBS in a multimode fiber. A tunable narrowband (150 kHz) semiconductor laser (Santec TSL 210) was used as a master oscillator for generation of radiation at 1550 nm. Two amplification stages (JDS Uniphase and Keopsys EDFAs, respectively) were used to amplify the small signal from the oscillator (2 mW) up to the watt level (the maximum output power from the Keopsys amplifier was 5 W). We used two isolators in order to avoid feedback into the oscillator and amplifiers. A circulator was used to separate the input and the SBS return from the multimode fiber. The whole pumping configuration is based on single mode fiber (core diameter = 8 µm, cladding diameter = 125 µm). The coupling between the single mode fiber and the fiber under test (single mode and multimode fiber) is made using a FC/APC connector and we call this type of coupling “butt coupling”. The single mode fiber (Corning SMF-28) is of length 1km and the multimode fiber was a GRIN silica fiber (Corning 50/125) with a core diameter of 50 µm, cladding diameter 125 µm, and length 4.4 km.

Prior to the SBS experiments we investigated the excited mode structure in the fiber under test. We have done first the characterization of the Spiricon camera by using a Kepler telescope setup and varied the magnification of the telescope (and thus the spot size incident on the CCD. This was done by butt-coupling a short (2meter) length SM fiber to the pump source and imaging the fiber end onto a CCD array camera (see Fig.2).

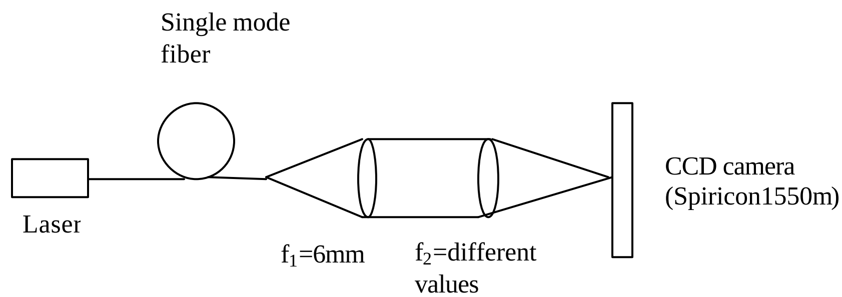

Fig.2 Schematic of the setup to calibrate the Spiricon camera

The deduced spot size at the end of the fiber is observed to decrease with increasing magnification (spot size on the camera), becoming constant only when the spot size on the camera equals 700 μm (see Fig.3). This means that the smallest spot size on the camera that gives an accurate spot size measurement at the end of the fiber (which is expected to be 10 μm) is 700 μm.

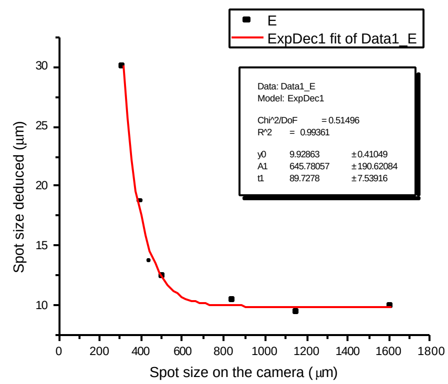

Fig.3 Beam spot size value versus spot size on the camera

Using this technique the mode radius ($1/e^2$ radius) of the single mode fiber was found 4.9 μm and M^2 of 1. For a 2m MM fiber (d=50 μm) the spot had a $1/e^2$ radius of 7.8 μm and M^2 of 1.15. These results agree with the theoretical predictions, see Table1.

SBS thresholds and reflectivities were measured for both fibers. Table 1 shows the measured and calculated thresholds and mode waists;

The SBS reflectivity for the single mode fiber is :

$$R_{SM}=P_c/P_p(0) \tag{2}$$

and was measured as a function of input power $P_p(0)$, see fig.4, where P_c is the Stokes power exciting the circulator.

For the MM fiber we calculated the reflectivity :

$R_{MM} = P_{Stokes} / P_p(0) = [P_p(0) - P_p(L)] / P(0)$ (3)

from $P_p(z)$ which is the pump power measured at both ends of the fiber at z=0 and z=L.

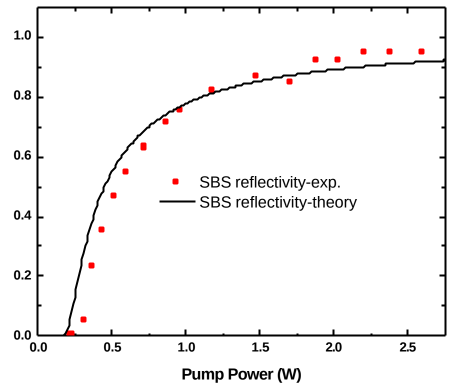

Fig.4 SBS reflectivity versus pump power for SM fiber (Core diameter = 8.3 mm; cladding = 125 mm; NA = 0.14; length = 1km)

Further we determine the fidelity from :

$F_{MM} = Pc / P_p(0) / R_{MM}$ (4)

F_{MM} represents a measurement of phase conjugation. Both these quantities are represented in Fig. 5.

In both figures we show, as solid line, the theoretical calculations for the threshold and the reflectivities, obtained from the well known plane wave model, but taking into account the effects of the mode area and inhomogeneous gain broadening in fibers.

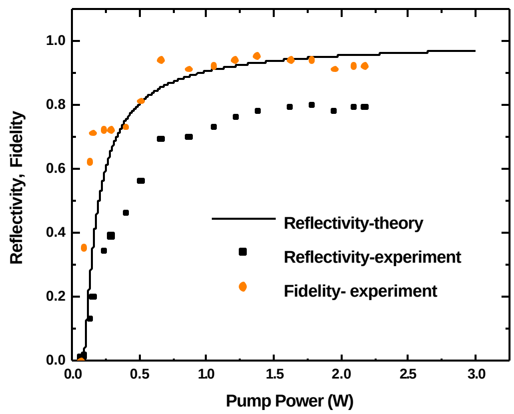

Fig.5 SBS reflectivity versus pump power for GRIN MM fiber
(Core diameter = 50mm; cladding = 125mm; NA = 0.2; length = 4.4km).

We made two changes in the more traditional SBS threshold formula from [14] as follows:

$$P_{th} = \frac{21p\, r^2}{l_{eff}\, g_i(f_S)} \quad (5)$$

by replacing, g_o, the SBS gain coefficient for bulk silica with, $g_i(f_S)$, the gain of the SBS return, at the Stokes frequency, f_S, and the core area of the fiber by the SBS mode area of radius r. We are using the effective length $l_{eff} = (1-\exp(-a\,l))/a$, where $a = 0046$ /km.

The SBS gain coefficient g_i for inhomogeneous broadening due to waveguiding in an optical fiber is derived as [19]:

$$g_i(f) = g_0 \frac{\Gamma_0/2}{F_0 - F_c} \times [\tan^{-1}(\frac{F_0 - f}{\Gamma_0/2}) - \tan^{-1}(\frac{F_c - f}{\Gamma_0/2})] \quad (6)$$

where G_o is the homogenous width of Brillouin spectral line.

The FWHM of the inhomogeneous spontaneous Brillouin spectrum is:

$$\Gamma = \sqrt{\Gamma_0^2 + F_0^2 \frac{(NA)^4}{4n_{co}^4}} \quad (7)$$

In these equations the frequency shift of the SBS field is given by $F_B(f) = 2nv\sin(f/2)/l$, v is the velocity of sound, l is the pump radiation wavelength and f is the backward Stokes angle with respect to the pump. The on-axis frequency shift is $F_0 = F_B(p)$, and the frequency shift at the critical angle is $F_c = F_B(p - 2q_c) = 2nv\sqrt{1-(NA)^2/n^2}/l$ where the complement of the critical angle is $q_c = \sin^{-1}((NA)/n_{co})$. *(NA)* accounts for the numerical aperture of the fiber and n_{co} is the index of refraction of the core.

The optimum Gaussian field radius has been derived by D. Marcuse [20], for both step index and GRIN fibers. For a field dependence of $\exp(-r^2/w^2))$, and a core radius of a the optimum radius for a step index fiber is

$$\frac{w}{a} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \tag{8}$$

and for GRIN fibers this leads to a waist of

$$\frac{w}{a} = \sqrt{\frac{2}{V}} + \frac{0.23}{V^{3/2}} + \frac{18.01}{V^6} \tag{9}$$

the V -number is $V = ka(NA)$ in both of these equations (k is the wave vector). Note that these waists correspond to the e^{-2} value of the measured intensity.

For the GRIN fiber we modified the radial dependent numerical aperture by introducing an average numerical aperture in the inhomogeneous gain equation. Thus, the acceptance angle is smaller and consequently more of the power is concentrated near the axis which leads to a small threshold for the GRIN fiber.

The summary of the measured and calculated results for the radius of the mode inside the fiber and the SBS threshold is shown in Table 1.

Table 1. Summary of calculated and measured mode radii and SBS threshold for single mode and multimode fibers

Fiber	ω(measured)	ω(calculated)	P_{th}(measured)	P_{th}(calculated)	P_{th}(uncorrected)
SM	4.9 μm	4.5 μm	250 mW	236 mW	65 mW
MM GRIN	7.8 μm	8 μm	100 mW	105 mW	420 mW

EXPERIMENTAL INVESTIGATION OF PHASE CONJUGATION PROPERTIES OF LONG MM FIBERS (D=50 μM AND L=1.1 OR 4.4 KM)

Divergence and M^2 measurement

In order to evaluate the phase conjugation properties of the Stokes beam (SBS return) we had to find a method to measure the spatial width (beam quality) of the laser beam exiting our fibers, in general.

The difficulty in measuring beam quality of laser beams exiting fibers arises from the fact that the beams are highly divergent and power extends far out into the wings of the beam, and is difficult for an instrument to calculate or define what is actual beam width.

Laser theoreticians have proposed, and ISO standards committee [21] has agreed that the true measure of a laser beam width is the Second moment method. The second moment is a method that integrates energy (power) versus distance from the centroid of the laser beam and obtain a properly weighted beam width. The second moment definition of a beam width enables the user to accurately predict what will happen to the beam as it propagates, what is its real divergence, and the size of the spot when the beam is focused.

We have measured the beam width of the beams exiting different fibers by collimating the beam and using a magnifier optical system (see Fig.6), measuring the spot size on a CCD camera (using Spiricon software which calculated the beam width using the Second moment method).

In order to make some estimates to determine if it is necessary to consider the afocal system or if we can use the case when the second lens is in the back focal plane, and the distance between the two lens can be much smaller than the sum of the two focal lengths, we performed the analysis of the two lens optical system, using second order moments theory.

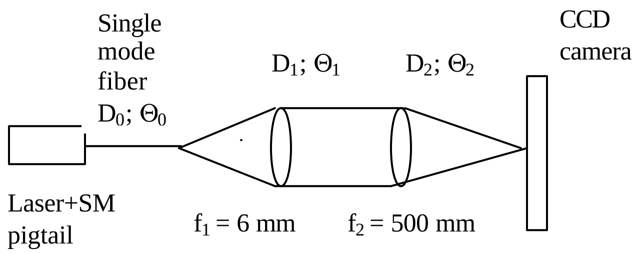

Fig.6 Experimental setup for measuring beam width

The magnification of the optical system in Fig.6 is $M = f_2/f_1 = 83$. We measured $D_2 = 0.87$ mm and then $D_0 = D_2/M=10.48$ µm. The divergence of the SM fiber (Θ_0) is $\Theta_0 = D_1/f_1$. We measured D_1 by replacing the lens with focal length f_2 with a lens with focal length f_3=250 mm. In this way we imaged the waist size D_1 on the camera. The measured value of was 1.1mm and the corresponding value of Θ_0 was 0.183 rad.

We have the relation for the beam propagation factor, M^2 :

$$D_0\Theta_0=(4/\pi)M^2\lambda \tag{10}$$

We can now calculate the M^2 value for the single mode fiber, $M^2_{SM.}$ We obtained values of about M^2_{SM}=0.97. For the a short MM fiber (core diam.=50 µm and L=1.5m) butt coupled to the SM pigtailed fiber after the laser in Fig.6, we obtained the results $D_0 = D_2/M = 16.7$ µm; $D_1 = 0.723$ mm ; $\Theta_0 = 0.121$ rad resulting in M^2_{MM}=1.02.

In order to study aspects of phase conjugation in the multimode fiber, we performed initial experiments using a commercial mode scrambler (Newport FM1) to act as an “intrafiber aberrator” in a 1m long test section of a MM fiber (D=50 µm and L=4.4 km) (which is precisely matched to the SBS generating MM fiber). We studied the ability for aberration correction as a function of the degree of aberration caused by varying the amount of mode scrambling (see Fig.7). For small amount of aberrations, distortion compensation due to SBS was obtained.

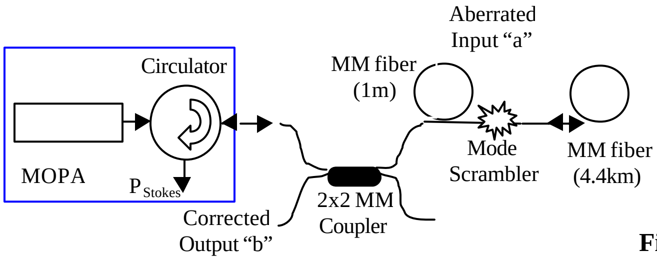

Fig 7a. Experimental setup (the shaded region corresponds to single mode fiber

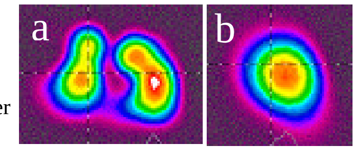

Fig 7b. Distortion compensation due to SBS

To monitor the input beam shape into the SBS MM fiber and the backscattered Stokes beam it is necessary to use two MM couplers (2x2) 90/10 splitting ratio. The only MM couplers, that are readily available commercially, have splitting ratio 50/50 which would drop the input power into the SBS fiber by a factor of 4. Because of the unavailability of non-distorting MM couplers with splitting ratios of 90/10 we have introduced free space optics components (beamsplitters and lens) between the end of the SM fiber and the SBS MM fiber. We have studied phase conjugation properties using this geometry.

The experimental set up used is illustrated in Fig.8. We have used lenses with a focal length of f=11mm to collimate the beam from the SM fiber and to focus into the long SBS MM fiber (d=50μm and L=1.1 km). An aberrator was introduced into the collimated beam. To monitor the beam shape before and after the aberrator we used two single uncoated 5% Fresnel reflectivity polished glass beam splitters, at an incident angle of ~ 45^o.

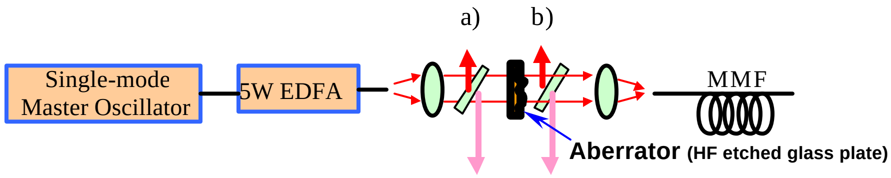

Fig. 8 Experimental setup used to study the phase conjugating properties of MM fibers

We have taken typical recordings of the far-field patterns of a) the incident beam (Fig.9a) b); the incident beam after the aberrator (Fig.9b); c) the SBS return beam before the aberrator (Fig.9c); 4) the SBS return beam after the aberrator (Fig.9d).

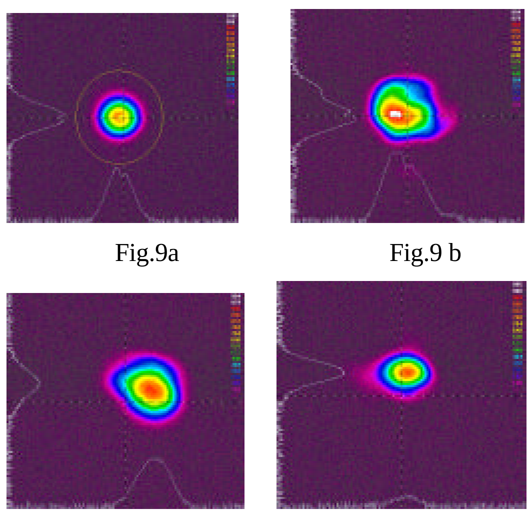

Fig.9a Fig.9 b

Fig.9c Fig.9d

Fig. 9 Recordings of the far-field patterns of the incident beam (Fig.9a); the incident beam after the aberrator (Fig.9b); the SBS return beam before the aberrator (Fig.9c); the SBS return beam after the aberrator (Fig.9d).

In this reporting period we have measured both the divergence and the waist size of these beams and calculated the M^2 parameter for these different situations. The results are summarized in Table 2.

Table 2. Summary of divergence, waist size and M^2 results for characterization of the phase conjugation properties of SBS in long MM fibers

Output from from fiber measured	**Divergence (mrad)**	**Waist size (μm)**	M^2
SM fiber	183	10.5	1
Aberrated beam	3	1700	2.6
SBS before aberrator	120	32	2
SBS after aberrator	2	1500	1.5

The M^2 parameter values of the incident aberrated beam and of the SBS beam before after the aberrator are close; the SBS beam after the aberrator has a M^2 parameter value only of 1.5, indicating "incomplete" phase conjugation.

Phase conjugation properties of the MM fiber (D=50 mm and L=4.4 km) using feedback

We have investigated SBS with feedback produced using a MM coupler with split ratio 95/5 before the SBS MM fiber and connecting the 5% SBS output to the end of the MM fiber. This feedback acts as a seed for SBS generated in the MM fiber. The experimental set up is shown in Fig.10.

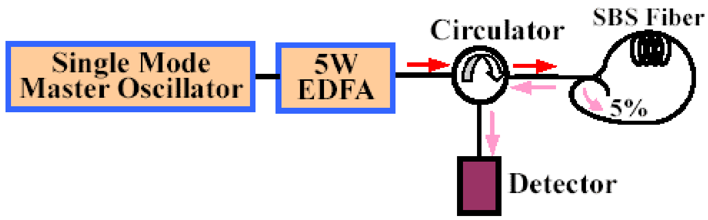

Fig.10 Experimental setup for investigation of SBS with feedback

The SBS with feedback has lower threshold, higher reflectivity (Fig. 11). The SBS behavior in time is illustrated in Fig.12. Less fluctuations of the Stokes beam in time are present when feedback is used (Fig.12b) in comparison with the situation without feedback (Fig. 12a).

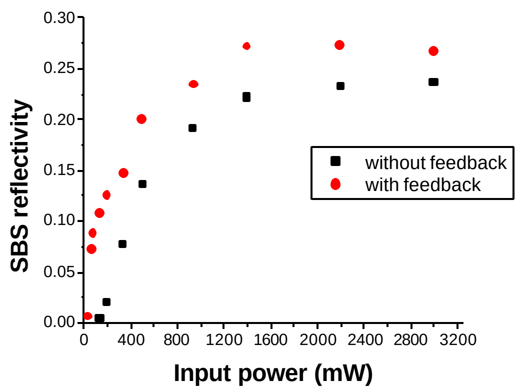

Fig.11 SBS reflectivity versus input power for SBS with feedback

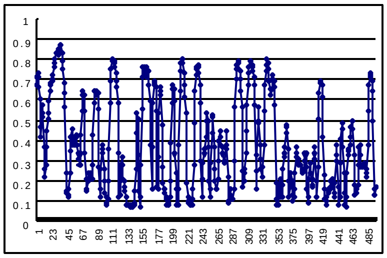

Fig. 12 Temporal behavior of the of Stokes beam fluctuations a) SBS without feedback; b) SBS with feedback

Phase conjugation properties of the MM fiber (D=50 μm and L=4.4 km) using beam cleanup (seeded SBS)

Using beam cleanup (also called seeded SBS), a small amount of a distorted laser beam is improved in beam quality using for example spatial filtering. This so called reference beam is then downshifted in frequency and superimposed in a nonlinear medium with the main part of the laser beam called pump beam in a contra directional way. Due to the frequency shift equal to the Stokes shift for Brillouin scattering in the nonlinear material (fiber) an SBS grating can be induced. This acts as a holographic mirror for the low quality pump beam. Due to this holographic effect the beam quality of the reference beam is transferred to the reflected part of the pump beam. In a phase conjugating mirror such grating starts from noice. In this configuration the Stokes shifted part is yet available and therefore the peak power required to induce the mirror is reduced.

The experimental setup used is shown in Fig. 13. The power from the EDFA was divided in two by a MM coupler with ratio 90/10. The input beam was distorted using an HF etched aberrator, as is shown seen in Fig.13. The seed for the SBS was generated in a separate 1km single mode fiber and was coupled out through the circulator. The output from the circulator was butt coupled to the end of the long MM fiber (4 km) and acted as a seed for the SBS generated in the MM fiber.

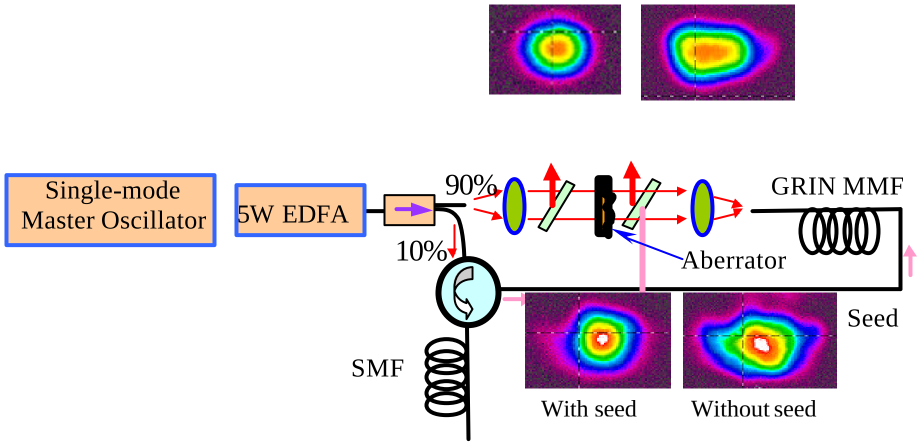

Fig.13 Experimental setup for seeded SBS

We have studied the beam quality of the SBS output with and without seed. The input beam was distorted using an HF etched aberrator, as seen in Fig. 13. When the seed is present the Stokes beam is nearly gaussian while without seed SBS output remains distorted (preserves the beam shape of the aberrated beam).

A theoretical model for diffraction-limited high power multimode fibers amplifiers using seeded SBS PC(SBS beam clean up) have been published [22].The model predicts large amplitude fluctuations of the Stokes field growing from noice but suggests that seeding the Stokes field at low power can largely supress these fluctuations and produce phase locking of the Stokes output with the seed. However the model is demonstrated for a very short fiber length(5m) even it is required that the master oscillator of the MOPA configuration would be diffraction-limited and linearly polarized.

CONCLUSIONS

The usual plane-wave theory of SBS does not correctly predict the threshold when applied to SBS in long optical fibers. For example, in the case of a MM fiber with core diameter, D=50 μm and length, L=4.4 km, the experimentally determined threshold is 100 mW, while that predicted by plane-wave theory is 400 mW. The reason for this is that the effective cross section of the fiber illuminated by the input light is not given by the core area, as normally assumed, but "an effective modal area'' given by the beam parameters at the input face of the fiber.

We have demonstrated the effects of modal dispersion through the numerical aperture *(NA*) and mode size on the SBS threshold of single mode and multimode fibers in an all fiber configuration. In this model we made two changes in the traditional SBS threshold, by replacing, *g*, the SBS gain coefficient for bulk silica with, $g_i(f_S)$, the gain of the SBS return, at the Stokes frequency, f_S, (the inhomogeneous broadened SBS gain) and the core area of the fiber by the SBS mode area of radius r and got good agreement between theory and experiment.

In order to understand the modal energy distribution in fibers (single mode and multimode) with the use of different coupling geometries (*near on-axis* connectorized SM-to-MM butt coupling, and free space coupling with lenses of different focal lengths), we have performed M^2 measurements for different configurations (butt coupling geometry and focused geometry) using single mode and multimode fibers (short and long) and checked the spot size values determined by the M^2 measurements with those obtained using a telescope method.

Because we discovered of an incompatibility between the CCD camera (from Spiricon) and the software used for beam width calculations (from Coherent), we performed detailed characterization of the Spiricon camera, including measurement of the minimum spot size (700 μm-this value gives an accurate spot size measurement) and beam width measurements with a Coherent Beam Master (which uses another beam diagnostics technique). M^2 measurements were repeated for beams exiting single mode and multimode fibers (short lengths, L= 1.5m).

We also performed experiments on mode mixing using passive fibers and studied the phase conjugation and "beam cleanup" properties of MM fiber SBS generation, using the butt coupling geometry. Because of the unavailability of non-distorting MM couplers with splitting ratios of 90/10 we have introduced free space optics components (beamsplitters and lens) between the end of the SM fiber and the SBS MM fiber. We have studied phase conjugation properties using this geometry.

We have obtained good distortion compensation due to SBS in long multimode fibers (length of the order of km) using butt-coupling and focused geometries. Also we have performed for the first time (to our knowledge), detailed measurements of the beam quality, M^2 measurements, of the initial laser and Stokes beam using CW laser radiation, at 1550nm for the case of a long MM fiber (L=1km). We determined that the M^2 parameter value of the SBS beam, after passing the aberrator, is only 1.5, indicating "incomplete" phase conjugation. However, contrary to the report by authors of Ref. [11, 17] we found that phase conjugation properties of SBS in long fibers are quite complicated, and issues related to the understanding of the "dividing line" between phase conjugation behavior and beam cleanup behavior need to be investigated more carefully.

We have demonstrated the reduction of the SBS threshold, an increase in the SBS reflectivity and reduction in Stokes power fluctuations for seeded SBS in long multimode fibers. We have demonstrated distortion compensation via (beam "cleanup") in the seeded SBS configuration.

RECOMMENDATIONS

Based on our studies, we still foresee significant potential of the use of SBS in optical fibers for optical phase conjugation and beam combining applications. In this regard, we recommend that the following experiments be conducted in the near future;

- Measure the fidelity of seeded SBS in long MMFs and its dependence on properties of the seed
- Phase locking fiber amplifier arrays by using SBS in MM fibers
- Demonstrate high power fiber laser (>100W) with diffraction-limited output by using SBS in MM fibers and MOPA configuration.

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