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Abstract: We propose an original nonlinear beam cleaning fiber laser architecture to obtain high energy pulses with a good beam quality and a narrow linewidth. The output beam of a large core Er:Yb co-doped multimode fiber amplifier ($M^2 \sim 6$, 220 µJ) is converted into a near diffraction limited beam ($M^2 = 1.6$) through a stimulated Brillouin scattering injection seeded beam cleanup process. We report in this experiment a multimode to single mode conversion efficiency of 50% while preserving the master oscillator linewidth.

OCIS codes: (060.2320) Fiber optics, amplifiers and oscillators; (290.5900) Scattering, stimulated Brillouin; (190.4370) Nonlinear optics, fibers.

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1. Introduction

High energy pulsed fiber sources open an attractive wide range of applications, such as range-finding, remote sensing and coherent lidar systems. Their interest relies on their compactness and robustness thanks to the double-clad diode pumping configuration. However, optical damage and nonlinear effects limit the output peak power of standard single mode fibers due to high power density in the fiber core. To overcome these limitations Large Mode Area (LMA) fibers are now widely used providing more than one kilowatt in continuous-wave [1] or the milijoule level in pulsed operation [2, 3]. However these results have been obtained with spectrally broad fiber laser sources and are therefore unsuitable for coherent applications. The major issue using a narrow-linewidth source is the reduced threshold of Stimulated Brillouin scattering (SBS) in the amplifier chain.

A solution to avoid SBS is the use of larger core diameters. Very large core fibers (> 50 µm) have demonstrated their ability to achieve very high energies without any onset of SBS [4, 5], but to the detriment of the beam quality. In order to convert the multimode output beam of a large core fiber amplifier into a single mode beam, nonlinear beam cleaning techniques such as stimulated Raman or Brillouin scattering in multimode fibers are very attractive [6-10]. In our approach based on SBS, the amplifier is designed to achieve high energy and narrow-linewidth pulses without taking into account the beam quality issue, whereas a beam converter subassembly allows the recovery of a single mode beam. However, the spectral linewidth of the Stokes beam generated through the Brillouin effect may be broadened owing to the thermal noise initiation of the process [11-13].

In this paper, we propose a new SBS beam cleanup scheme. A weak narrow-linewidth and single mode beam is used to seed the SBS interaction and is amplified by the intense multimode beam while maintaining its beam quality as well as the narrow spectral bandwidth of the master oscillator. In this paper, we are building a complete fiber laser experiment in the pulsed regime with high pulse energy at 1.5 µm. Our results demonstrate a practical system using SBS beam cleanup with master oscillator, preamplifiers, booster multimode amplifier and a beam conversion device.
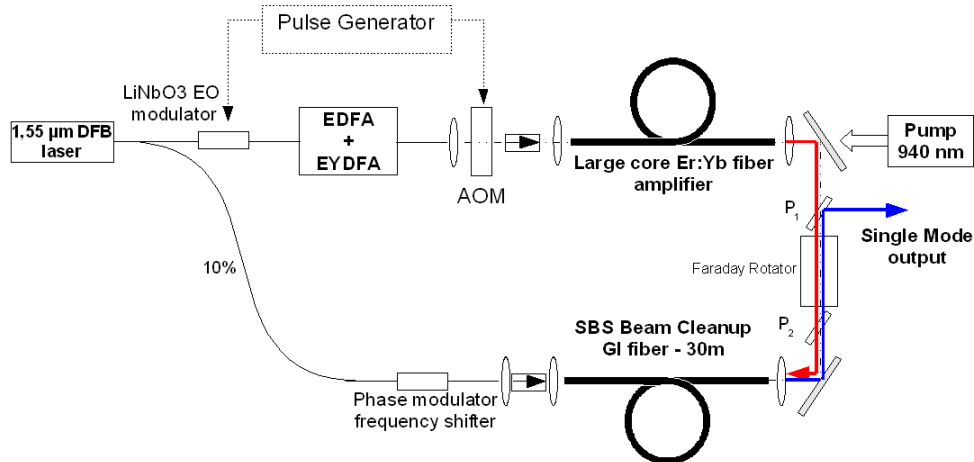
2. Experimental setup

Fig. 1. Experimental setup of high energy MOPA with seeded SBS beam cleanup. DFB : distributed feedback laser diode; EO : electro-optic modulator; E(Y)DFA : Erbium (Ytterbium) doped fiber amplifier; AOM : Acousto-optic modulator; P1,2 : polarizers.

The experimental setup is shown in Fig. 1, including the pulsed master-oscillator power-amplifier chain and the seeded SBS beam converter. The primary source is a distributed feedback laser diode with a 300 kHz linewidth. 1 µs pulses (full width half maximum) at 10 kHz repetition rate are produced via an electro-optic LiNbO$_3$ intensity modulator. It is then

amplified through two single mode preamplifiers, respectively an Erbium doped fiber amplifier (EDFA) and an Erbium - Ytterbium co-doped fiber amplifier (EYDFA). The output of these preamplifiers is time-gated with a synchronized acousto-optic modulator to suppress the amplified stimulated emission noise between pulses which limits the energy extraction in the last amplifier stage. The third amplifier is a multimode double-clad EYDFA with a length of 2.9 m, a 73 µm core and a numerical aperture of 0.2. It is pumped by a high power laser diode emitting at 940 nm. For a launched pump power of 70 W we obtained an average output power of 8W. The multimode output beam is then coupled into a 30 m long passive multimode graded index (GI) fiber (62.5 µm core, 0.27 NA). The Stokes reflected beam generated by SBS in the GI fiber is finally rejected by the first polarizer of an optical isolator.

As shown in Fig. 1, the GI fiber is seeded by a small amount of power issued from the primary DFB laser source, using a 90/10 fiber coupler. An EO phase modulator is used to shift the seed frequency by about 10 GHz into the Brillouin gain bandwidth.

We study the spatial cleanup properties as well as its efficiency and spectral characteristics both for the unseeded and seeded configurations.

3. Results and discussion

Experimental investigations on SBS beam cleanup in the GI fiber have been first carried out with a CCD camera in order to highlight the spatial improvement. The amplified output of the fiber MOPA is depolarized and multimode with an $M^2 \sim 6$ (Fig. 2(a)). Its horizontal polarization has an energy limited to 300 µJ and is coupled into the GI fiber. Without any seed at the output of the GI fiber, we observed that the Stokes beam can be reflected as the fundamental mode of the fiber (LP_{01}), as shown in Fig. 2(b). This LP_{01} mode of the GI fiber has a mode filed diameter of 21 µm and a measured M squared of 1.6 (Fig 2(c)). The measured M^2 allow us to quantify the brightness improvement due to beam cleanup even if it is slightly degraded because of the superposition of the Fresnel reflection of the pump beam on the fiber with the single mode Stokes beam.
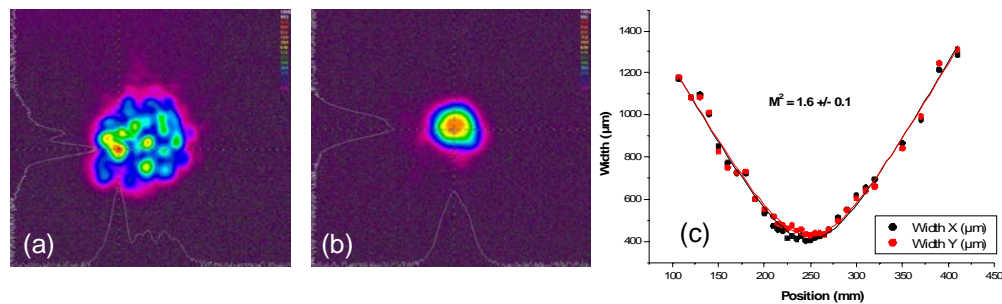

Fig. 2. Beam cleanup demonstration. From left to right : (a) Incident multimode beam. (b) Stokes reflected beam (LP_{01} mode). (c) M^2 measurement of the Stokes beam.

Other Stokes reflected modes have also been observed (LP_{11} and LP_{31}) depending on the coupling conditions of the multimode beam : when we move the GI fiber around the focal point, the reflected Stokes beam changes from one mode to another. However we always observed a single mode return, confirming the mode selection of SBS in a GI fiber [10]: considering an excitation of the pump modes, one Stokes mode experiences a higher Brillouin gain than all other modes. When we move the GI fiber, the excitation of the pump modes is changed and so is the selected Stokes mode. By properly coupling the incident pump beam we were able to obtain a stable LP_{01} reflected mode.

Considering the temporal shape of the reflected pulses we observed strong intensity modulations with several spikes within the 1 µs pulse duration (Fig. 3(a)). This noisy response of the nonlinear medium is due to the initiation of SBS on spontaneous scattering by sound

wave gratings [11-13]. This sound wave starts on thermal density fluctuations of the material distributed all along the fiber length. Spontaneous photons are then amplified trough stimulated scattering while the pump wave is depleted. The behavior of the interaction can be described owing to a three-wave transient model including the noise initiation of the sound wave [13]. The intensity fluctuations of the noise occur on a time scale given by the phonon lifetime τ_B (~8.5 ns). Since the transit time of the optical waves in the fiber (~150 ns) is longer than τ_B, two spontaneous photons scattered at different positions in the fiber may not be in phase. As a result the Stokes wave at the fiber entrance is the complex interference between several amplified photons with phases dependant on the noise initiation. Therefore the reflected pulse exhibits temporal spikes [11-13].

Such random intensity modulations exclude coherent applications like lidars since the reflected pulse is spectrally broadened compared to the incident one. We pursued linewidth measurements using a self-heterodyne method. Using a fast photodetector with an electrical spectrum analyzer we were able to measure the beat signals between the Stokes wave (shifted by about 10 GHz) mixed with a probe beam coming out from the primary laser. The obtained spectrum is given in Fig. 3(b). A spectral width of about 20 MHz (FWHM) has been measured.
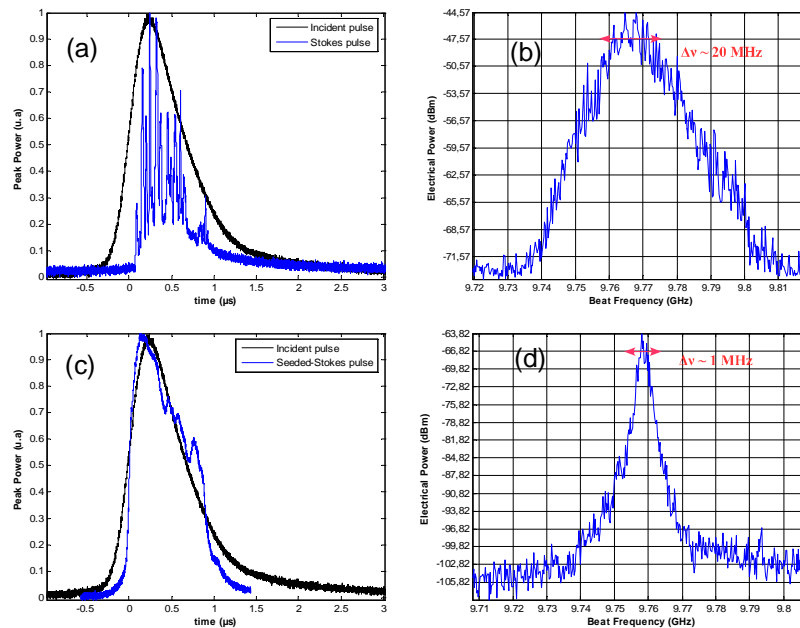

Fig. 3. Temporal shapes comparison of the pump and Stokes pulses. With no seed the reflected Stokes pulse exhibits strong intensity modulations due to self-pumped SBS scattering (a), whereas the Stokes pulse is smoother when obtained with 8 mW seed power (c). A spectral analysis done with a self-heterodyne method allows the measurement of a 20 MHz linewidth for the unseeded Stokes wave (b) and a near Fourier limited linewidth of ~1 MHz for the seeded Stokes wave (d).

In order to obtain a reflected pulse whose linewidth is preserved, we operate the setup in a pump – seed SBS arrangement, already described in the previous section. The seed is taken directly from the primary DFB source and is frequency shifted to match the Brillouin resonance. This is done using a LiNbO$_3$ EO phase modulator driven by an RF adjustable signal. To keep the advantage of the spatial beam cleanup obtained through SBS in the GI fiber, a strict condition is that the probe must be only coupled in the fundamental mode of the fiber and should propagate without mode mixing. This condition can be fulfilled easily with a GI fiber since it is less sensitive to macro bend mode coupling than a step index fiber [14]. We

experimentally injected the seed beam by using a magnifying telescope to match the fundamental mode size of the GI fiber (21 µm). It is then amplified by the pump beam and its spectral width is consequently maintained. We experimentally verified this behavior when seeding the SBS interaction with a cw power of 8 mW at the Brillouin frequency. A smooth Stokes temporal profile close to the incident one is obtained with a pump beam of 200 µJ as it can be seen in Fig. 3(c). The electrical spectrum measurement has also been done with the self-heterodyne method where the reference frequency is given by the zero-order of the phase modulation. We obtained a linewidth close to 1 MHz FWHM (Fig. 3(d)) corresponding to the expected spectral width for a single-frequency laser pulse of 1 µs duration.

We finally carried out measurements of the conversion efficiency from the multimode input beam to the single mode Stokes beam. This has been done for both the seeded and unseeded configurations. The experimental results are depicted in Fig. 4 and compared with the theoretical curve (solid lines) calculated using a transient three-wave model including the noise initiation of the sound wave [13].
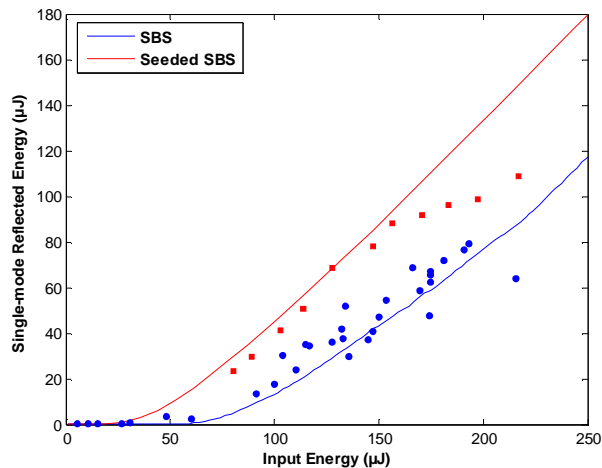

Fig. 4. Reflected Stokes energy as a function of pump energy coupled into the GI fiber. A threshold decrease as well as an efficiency increase is obtained with the seeded SBS configuration. Numerical calculations based on a three-wave model are also plotted for both cases (solid curves).

Without the probe, the minimum detectable SBS signal appears for 60 µJ incident energy, and we obtained maximum of 80 µJ for 200 µJ coupled energy, thus corresponding to a 40% efficiency. These results are in good agreement with the numerical calculations. With a probe power of 8 mW the efficiency is increased to 50% with reflected pulses of 110 µJ for a 220 µJ input beam energy.

4. Polarization recycling

Because the output of the multimode fiber amplifier is depolarized, half of the energy is lost through the isolator before the beam cleanup stage. To treat the depolarization we implemented the optical isolator depicted in Fig. 5(a) where we recycle the energy contained in each linear polarization states [15]. The multimode incident beam is split in two by a Polarization Beam Splitter (PBS) followed by two Faraday rotators and half-wave plates operating on the two independent beams having orthogonal polarizations. They are recombined with a second PBS and focused inside the GI fiber core. It thus result that each beam is independently reflected into two clean Stokes waves. These two waves are then recombined to generate the output beam. However the polarization of the output beam is not controlled since the two beams with orthogonal polarization states are not phased locked after SBS in the GI fiber [16]. The reflectivity measurements are given in Fig. 5(b) for the unseeded

configuration. We obtained a maximum reflected energy of 160 µJ for 320 µJ pump energy coupled in the GI fiber (50% efficiency). The future work will be the characterization in the seeded configuration. It is here expected that seeding the Brillouin interaction in the GI fiber may contribute to restore a fixed polarization state on the output beam.
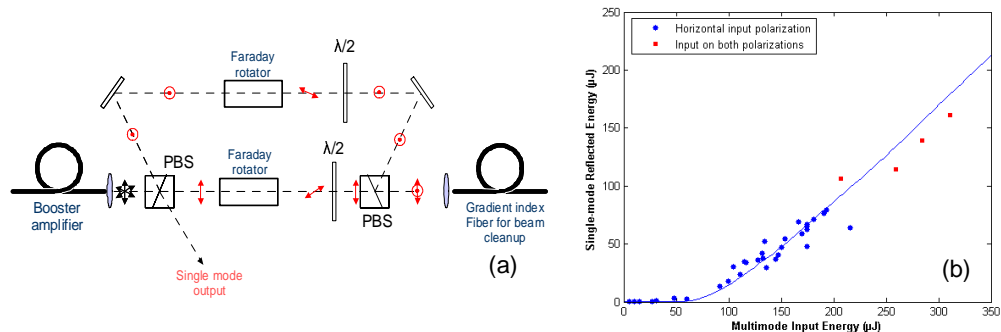

Fig. 5. (a) Polarization recycling setup. Horizontal and vertical polarizations are split through a Glan polarization beam splitter (PBS) and then recombined. In each arm is placed a 45°. Faraday rotator and a half-wave plate to ensure optical isolation. Both polarizations are coupled in the GI fiber. (b) The polarization recycling allows to increase the multimode energy incident on the GI fiber and to increase the reflected single mode output energy.

5. Conclusion

We proposed and demonstrated a new SBS beam cleanup laser scheme to restore the beam quality after a highly multimode pulsed fiber MOPA at 1.55 µm. A single mode return has been obtained with a measured M^2 of 1.6 and a conversion efficiency up to 50%. Additionally the spectral quality of the master oscillator is maintained after the process. We can emphasize that the setup is scalable to larger doped fiber core sizes in order to obtain higher energies. This architecture is thus promising for coherent Lidar applications in which pulse energy, beam quality, and narrow linewidth are required.

Acknowledgments