Nonlinear Optics and liquid crystal light valve for laser beam control

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Abstract. The recent advances in solid state laser technology now permit to achieve high energy and efficiency sources for a wide range of applications extending from laser physics to material processing, biophotonics, remote sensing and coherent lidar systems. In particular the progress of fibre laser exploiting the double cladding diode pumping structure are impressive: they are compact and emit single mode beams. However optical damage and nonlinear effects limit the output peak power emitted by a single mode fiber laser. Also limitations arise in bulk laser materials due to the thermal loading which induces strong wavefront distortions on the beams. We develop in this paper original concepts adapted to power-energy scaling of bulk or fibre lasers. The final objective is to emit high brightness and high energy beams whose quality is close to the diffraction limit. For this purpose we present new technics to be inspired from from Fourier optics and allowing the wavefront processing either through nonlinear interactions or with adaptive optical components such as electro optic phase modulators or liquid crystal light valves.

1. Introduction.
The fiber lasers suffer from serious limitations when requiring both high energy levels (> millijoules) and narrow linewidth operation. This arises from the core fiber damage and contribution of Stimulated Brillouin Scattering (SBS). A proposed solution to overcome these limitations is to use very large Yb – Er doped core fibers but in such conditions the fiber amplifier is multimode and it exhibits a reduced 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 [1-2]. 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 according to the scheme in fig 1.

2 Beam cleanup with SBS
In this paper, we propose a new fiber SBS beam cleanup scheme operating in a master oscillator power amplifier (MOPA) configuration. A weak narrow-linewidth and single mode probe beam is used to seed the SBS fiber interaction and is amplified by the high energy multimode beam while maintaining its beam quality as well as the narrow spectral bandwidth of the oscillator. This nonlinear interaction also requires that the probe frequency is detuned by a value equal to the Brillouin shift: this is achieved by an integrated lithium niobate phase modulator driven at about 10 GHz. In other words, the two mixing interaction in the SBS fiber does not transfer the phase of the multimode pump beam but only its intensity. It thus results an amplified clean beam due to the transfer of the pump into the contra propagating probe. In this paper, we are building a complete fiber laser experiment in the pulsed regime at the wavelength 1.5 μm. Our results demonstrate a practical system using SBS beam cleanup with master oscillator, fiber preamplifiers, a booster multimode amplifier and a nonlinear fiber as a spatial mode converter [3-4].

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The experimental setup is shown in Fig. 1, including the pulsed MOPA chain and the seeded SBS beam converter. The primary source is a distributed feedback laser diode with a 300 kHz linewidth, 1 μs pulses at 10 kHz repetition rate are produced via an electro-optic LiNbO3 intensity modulator.

The last stage of amplification stage is a multimode double-clad Er-Yb codoped fiber amplifier (EDFA) 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 8 W. 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. In this scheme the SBS fiber is used to generate a diffraction limited Stokes beam due to two wave mixing in fiber. The properties of the Stokes beam as well as its efficiency and spectral characteristics both for the unseeded and seeded configurations have been analyzed.

3. Results and discussion
Experimental investigations on SBS beam cleanup in the GI fiber are 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 a beam quality factor $M^2 \sim 6$ - Fig. 2a. Its horizontal polarization has an energy limited to 300 μJ and is coupled into the SBS GI fiber. When correctly seeding the GI fiber, we observe that the Stokes beam can be reflected as the fundamental mode of the fiber (LP01), as shown in Fig. 2(b). This LP01 mode of the GI fiber has a core diameter of 21 μm and a measured $M^2$ factor of 1.6 (Fig 2b). The measured $M^2$ allow us to quantify the brightness improvement due to beam cleanup. By properly coupling the incident pump beam we were able to obtain a very stable LP01 reflected mode from the GI fiber which confirms the efficiency of the beam cleanup interaction [5].
Figure 2. Beam cleanup demonstration. From left to right: (a) Incident multimode beam. (b) Clean Stokes reflected beam (LP01 mode).

We also experimentally verify that the seeding with the probe beam provides a smooth temporal profile close to the incident one at an energy level of 200µJ. The electrical spectrum measurement has also been done with the self-heterodyne method. We obtained a linewidth close to 1 MHz FWHM. As shown in figures 3 (c-d) this corresponds to the expected spectral width for a single-frequency laser pulse of 1 µs duration. The results shown on the figures 3 clearly confirm that narrow spectrum and clean pulse shape are obtain when the frequency shifted probe beam injects the SBS fiber.

Figure 3. Temporal shapes comparison of the pump and Stokes pulses. With no seed the Stokes pulse exhibits strong intensity modulations due to self-pumped SBS scattering (a), whereas the Stokes pulse is smoother with few mW seed power (c). Measurement of a 20 MHz linewidth for the unseeded Stokes wave (b) and a near Fourier limited linewidth of ~1 MHz after beam cleanup (d).

4 Phasing of an array of fiber lasers

Another promising approach for energy scaling of fiber lasers is to combine a large number of relatively low energy beams into a single one with high energy and a near diffraction limited beam quality. A
solution is to emit with each source at a different wavelength. This technique is known as wavelength beam combining. The other major approach is the coherent beam combining where all the emitters operate at the same wavelength and are phased locked so that their fields add coherently in the far field. The different methods for coherent combining fall under two categories: passive and active phase locking. The concepts under study in our laboratory involve active phase locking with a phase detection and active compensation of phase errors [6-7-8]. This technique brings additional functions such as optical beam steering and shaping, correction of the wavefront aberrations and distortions due to the atmosphere, or to point a receiver in free space communication.

The general architecture under study for combining a large number of fiber amplifiers by active control of the phase is shown on figure 4. A master oscillator provides a signal distributed to an array of \( N \) single-mode Polarisation Maintaining (PM) fiber amplifiers. The \( N \) end facets of the fibers are arranged in a 2D matrix and collimated by a lens array. A very small fraction of the resulting beam is sent to a phase sensor which compares the phase of each fiber with a reference beam by heterodyne interferometric detection. The error signal drives the integrated phase modulators via an electronic feedback loop. A kHz rate control is sufficient to compensate the typical phase noise of the fiber amplifiers in its laboratory environment [9-10]. We have developed a complete model for the analysis of the diffraction pattern in the focal plane as a function of the filling factor of the fiber array, residual phase errors and bandwidth of the electronic loop. In particular it is shown that a method to reduce the sidelobes of the diffraction pattern and therefore to increase the Strehl ratio is to maximise the filling factor of the whole pupil with an hexagonal distribution of the fiber emitters in place of a squared array. This leads to improve the Strehl ratio of 30 % with a value of 0.83. Hexagonal distribution also allows to reduce grating lobes by 3dB and diffraction side lobes by 6dB.

![Figure 4. General scheme of the beam combining setup with an active control feedback loop.](image)

The residual standard phase deviation between two fiber amplifiers in closed loop configuration is equal to \( \lambda/100 \), a value which is small enough to ensure a good Strehl ratio of the combined beams as predicted by the modeling. Figure 5 compares the spectral densities of the phase differences between two amplifiers in open and closed loop. It confirms that the active phase control servo-loop is efficient up to a few hundreds of Hz, a result which is in agreement with the electronic cut-off frequency of 2 kHz.
Figure 5. Spectral density of the phase differences between two fiber amplifiers in open loop and in closed loop.

Figure 6 shows the far field intensity patterns obtained in open and closed loop configurations and integrated over 200 ms with an array of 2x2 fibers. In an open loop, the interference fringes are blurred, which leads to a low beam quality due to the incoherent sum of the four Gaussian beam intensities. In the case of a closed loop, the active phase control system allows to perform coherent beam combining by locking the far field interference pattern and thus concentrating most of the energy in a central lobe.

5 Spatial beam shaping with a liquid crystal light valve.

An alternative method for controlling the phase of a laser wavefront is to exploit the large electrooptic properties of a liquid crystal (LC) spatial light modulator. A technology which is used for TV image display or projection and can now be applied both to wavefront correction and programmable focal spot shaping of ns or fs sources. As an active extracavity spatial phase modulator, we use a nonpixelated optically addressed light valve (OALV) composed of a bismuth silicon oxide photoconductor and a liquid crystal layer. Such a device is addressed by the projection of a small LC TV on the photoconductor (fig 7) and it has already been successfully used for intracavity spatial mode control and high-quality wave-front correction (equivalent a spatial resolution of the order of 100µm) [11]. The operating mode is the following: a calculated intensity pattern is displayed on the LCTV and projected with a low power LED in the blue spectral range on the photoconductor. It thus results a spatial phase modulation due to local transfer of the voltage inducing a reorientation of the liquid molecules and consequently a phase change on the transmitted readout beam in the near infrared.
This flexible phase-filtering and programmable element offers a large dynamic range and a high enough spatial resolution together with power threshold values that are convenient for being used for amplified femtosecond laser beam shaping. We demonstrate the generation of various geometrical shapes in a focal plane that are suitable for material processing with ultrashort laser pulses. The beam-shaping principle consists in determining the appropriate spatial phase distribution to be applied to the incident laser beam to produce the desired intensity distribution in a focal plane. The experimental setup shown in figure 7A includes all the components to realize the beam shaping of the femtoseconde Ti Saphire laser for micromachining applications [12-13].

Phase-retrieval problem has already been widely discussed in many papers and efficient solutions based on the Gerchberg–Saxton algorithm have been proposed [14-15]. We have implemented such a numerical iterative procedure where the phase is plotted modulo 6\(\pi\) according to the dynamic range of the OALV. Calculated phase distributions for beam shaping present details as small as \(\lambda/12\) at 800 nm. Before such a precise phase function is attempted, accurate control of the incident laser phase front is required. This is achieved by use of an adaptive-optics loop that enables the wave-front aberrations to be reduced to \(\lambda/15\) peak to valley. Then phase information is added such that beam shaping is achieved in the focal plane of a microscope objective and imaged onto a CCD camera with a magnification factor [16]. Transmissions of the OALV and of the overall setup are 80% and 50% respectively, so 2-mJ pulses at 100 kHz are available in the focal plane. Various focal spot intensity patterns are shown in fig 7B. In other terms the generated pattern is the Fourier transform of the spatial 2D phase distribution which is projected on the OALV.

6 Conclusions.

We have implemented different methods allowing wavefront manipulation for a variety of laser sources such as multimode fiber lasers, arrays of fiber laser, source delivering ultrashort pulses..... The overall objective is to propose and to experiment new advanced concepts for energy scaling while maintaining optimum brightness of the source and also adding new functionalities such beam shaping, steering and wavefront correction. There are several good technological issues to these requirements, respectively: nonlinear optics well suited for beam cleanup or phase conjugation through SBS with nanosecond response time, adaptive optical methods based on electrooptic phase modulators, liquid crystal light valves or micromirror systems...Rapid progress of these technologies now permit to design advanced laser architectures which include new methods of wavefront processing and energy scaling while
maintaining an excellent beam quality and a high brightness as necessary for industrial or scientific applications.

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