Coherent combining of 49 laser beams from a multiple core optical fiber by a spatial light modulator

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Abstract: We report co-phasing of 49 beams from a multicore fiber based on a spatial light modulator using a simple feedback loop control. A specific fiber of 7x7 Germanium doped cores was fabricated. The power carried by the far field main lobe of the phased array, in the continuous wave regime, amounts to 96% of its theoretical value. Femtoseconde pulses were also phase-locked with the same device configuration.

OCIS codes: (140.3510) fiber Lasers; (140.3298) Laser beam combining; (140.3290) Laser arrays.

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1. Introduction

Laser based on rare earth doped optical fibers deliver ever increasing record powers [1,2]. Continuous laser sources are mainly under concern but the same applies also to the case of Q-switched and ultrafast (picosecond-femtosecond) lasers, although to a less extent. To reach the highest power levels, various schemes have been proposed to combine a plurality of sources. One way consists in the combination of different amplifiers implemented in a same laser cavity [3–7]. Based on self-organization of the composite laser resonant frequencies, they are known as passive coherent combining techniques. Another approach implements a master laser that feeds an ensemble of parallel fiber amplifiers the outputs of which are actively phase-controlled. Usually, in this architecture, individual fiber amplifiers are associated with individual electro-optic phase controllers at their input which result in a complex arrangement of servo-control devices [8–10]. An innovative active technique has been recently demonstrated for which numerical holography acts as an elegant and efficient coherent beam combining process [11].

Doped multicore fiber (MCF) is an alternative to an ensemble of separate amplifying fibers fed by a cascade of couplers. A single MCF fiber including several amplifying cores embedded in a common double clad structure for optical pumping offers an attractive possibility to high power fiber laser emission. In that purpose a microstructured optical fiber with seven single mode cores of large area (50 micrometers diameter) was recently fabricated [12]. Such a fiber design provides very similar mechanical and thermal environment at each guides of the multicore fiber. Consequently, the variations of the phase difference between the various channels are significantly reduced in their magnitude and in their dynamics by comparison with their multiple fibers counterpart. Phase variations to be compensated are weaker and evolve with longer time scale [12]. Therefore slow servo-control can be compatible with the management of the phase relationships between beams delivered by multicore amplifying fibers in the aim of their coherent addition. In the frame of ultra short pulse amplification, a multicore amplifier leads to very similar group delay between the different optical paths which is an extra advantage for their coherent combination.

In view of exploring the potentialities of fibers with multiple cores for parallel amplification and coherent addition, we have fabricated a 7x7 fibre array in a square lattice. We have also achieved coherent combination of the 49 output fields with a spatial light modulator (SLM) driven by a simplified processing loop.

2. Multiple Beam phase-locking using a spatial light modulator

The principle of the investigated architecture is schematically depicted on Fig. 1. The laser beam to be amplified is first expanded and collimated to overlap the SLM. Diffraction on the SLM split the beam in an ordered array of smaller beams the amplitude and phase of which can be independently adjusted. A telescope images the beam array with demagnification onto the fiber face and couples each beam in a separate core. At the other multicore fiber end, a fraction of the power is deflected toward a lens to display the far field of the output beams. In the far field plane a detector filters out and measures the power carried by the central lobe. Straightforward algebra gives the expression of the amplitude E_{cc} of the central component of the diffraction pattern:

$$E_{cc} = \Sigma A_{mn} \exp(if_{mn})$$

where A_{mn} stands for the amplitude of the output laser field in the core identified by its column and raw number in the array respectively denoted here by m and n. Since we expect that the different amplifying channels exhibit a similar saturation power, their corresponding output field should have similar value $A_{mn} \sim A$. A maximum intensity will be reached in the central lobe of the far field provided the various exiting beams have an identical phase ϕ_{mn} = constant. Because it is impossible to make a multicore fiber with strictly identical propagation constant

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for its different cores, a uniform phase for the multiple inputs is unlikely to produce a uniform phase at the output. Therefore an individual control of the beams input phase is required. The simplified process chosen to obtain the co-phased situation consists in an identification of the input phases which maximize the far field axial intensity $I_{cc} = |E_{cc}|^2$. So considering one core at a time, the input phase is scanned from 0 to 2π and the optimal value is stored. Then the full pattern of the optimised phase values is set on the SLM and yields a uniform phase distribution at the fiber array exit. This algorithm has proved to be efficient with a large number of pixels. The method is derived from the one used for beam focusing through a strongly scattering media [13].

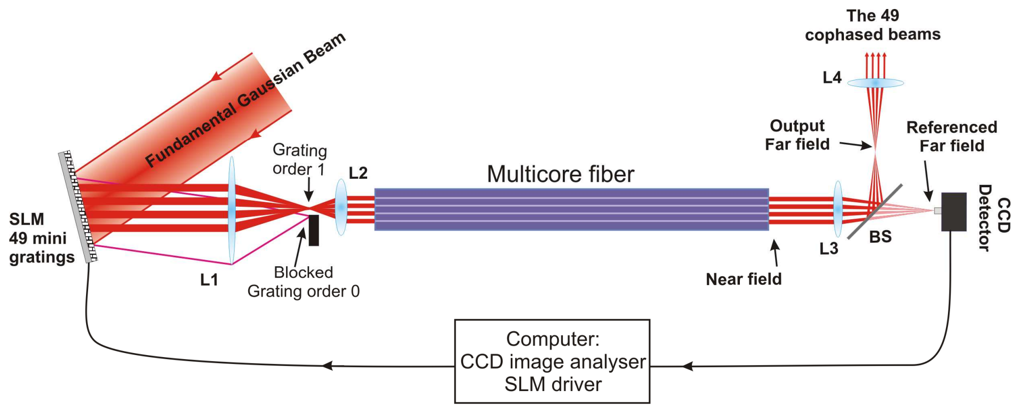

Fig. 1. Experimental setup. A spatial light modulator (SLM) displaying 49 grating shapes the input beam into an array of light spots of identical power to be coupled to the 49 cores of a passive fiber. The SLM also adjusts the input phase distribution in order to get, at the output of the MCF, an array of beams with uniform phase. The command of the SLM comes from a computer controlled servo-loop with feedback from a single detector located on axis in the far field. L1-L2: optical system imaging the SLM 49 mini gratings onto the 7x7 fiber cores. L3: focusing lens displaying the far field of the 49 output beams on the detector. L3-L4 imaging system at the multicore fiber output.

Once the input phase spatial shaping has started the far-field beam combination, the environmental perturbation requires weak and slow corrections only which can be detected by iterated sequential interrogation on a reduced phase range.

3. The 49 cores fiber

In order to experimentally demonstrate the phase-locking of a large number of emitters, a fiber with a two-dimensional array of waveguides in a square lattice has been designed. For the preliminary proof of concept experiments reported here the fabricated fiber was passive (without rare earth doping). Each waveguide was single mode at the laser wavelength.

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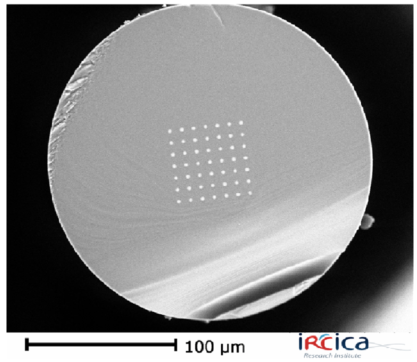

Fig. 2. Scanning electron microscope image of the fiber cross-section showing the 7x7 square array of single mode cores.

The fiber preform was made by stacking rods of Germanium doped silica surrounded by a pure silica layer in a square geometry. The doped area has a parabolic radial refractive index profile with a peak index difference of 3×10^{-2} with respect to pure silica. Figure 2 shows a scanning electron microscope (SEM) image in back-scattered mode of the drawn fiber. A two-dimensional square array of 7x7 Ge doped core is visible in the photograph as light grey spots. In contrast the dark grey background corresponds to the pure silica area. The fiber outer diameter is 210µm and the other parameters are as follow: core diameter 2.5µm, pitch of the square lattice Λ = 7µm. A deep study of various SEM high resolution images indicated that variations in pitch and core diameters were below 1% in a given cross-section. The different guides are not coupled at a wavelength of 800nm. However in the current design the pitch was close to its minimum value so that evanescent couplings are observed by shifting the laser wavelength to 900nm. Characterizations carried in that regime permitted to estimate the deviation in propagation constants to be below 10^{-5}. Following the same technological approach, it is completely realistic to envisage the fabrication of an amplifying fiber array with an air-clad, a microstructured ring with a high air filling ratio for guiding the pump. The fibre array excitation was linearly polarized but the multicore fibre was not polarization maintaining. Adjustment of the input field orientation together with the addition of an output polarizer served to filter out a linearly polarized set of exiting beams with reduced energy loss. Future efforts will be devoted to the fabrication of a polarization maintaining core array which eigenmodes have parallel optical fields.

4. Experimental setup and results

The experiments have been carried out with a titanium sapphire laser set at 800nm. The laser beam was expanded and collimated before illuminating the spatial light modulator (SLM). The device from Holoeye (HEO 1080P) was a phase only modulator working in reflective mode with 1920 × 1080 pixels $8 \times 8\mu m^2$ in size. The SLM was modulated by tiny periodic pattern so as to operate as a blazed diffraction grating (Fig. 3).

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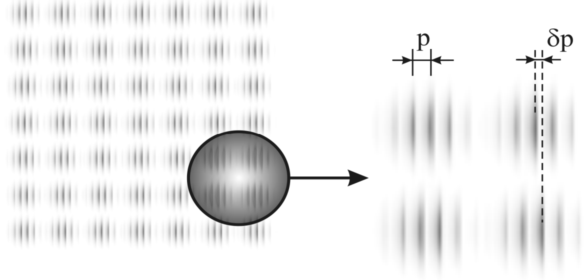

Fig. 3. The phase only liquid crystal SLM is used as a 7x7 square array of blazed diffraction gratings (grating periodicity p = 88μm). The relative transverse positions of the mini grating lines (δp) control the phase-shift difference between the 49 diffracted beams.

Amplitude modulation in the grating's first order was achieved by localized variation in the blaze angle. In this way, the Gaussian beam from laser was split in a square beam array with the opportunity of a separate adjustment of their intensity. This degree of freedom is not really indispensable but it gave an appreciable benefit in practice. The phase difference between the elementary beams was changed by fine shifting of their respective periodic modulations (it can be done also through modification of the absolute phase value). A demagnifying telescope (L1-L2 on Fig. 1) was used to make a reduced image (M = 1/78) of the 7x7 diffracted beams on the input end of the fiber core array. Each of the 49 beams was launch in a corresponding core of the array. Optimisation of the individual coupling efficiency was achieved by means of the SLM mini-gratings. The whole fiber cores were illuminated, even if a completely uniform intensity distribution was not perfectly reached.

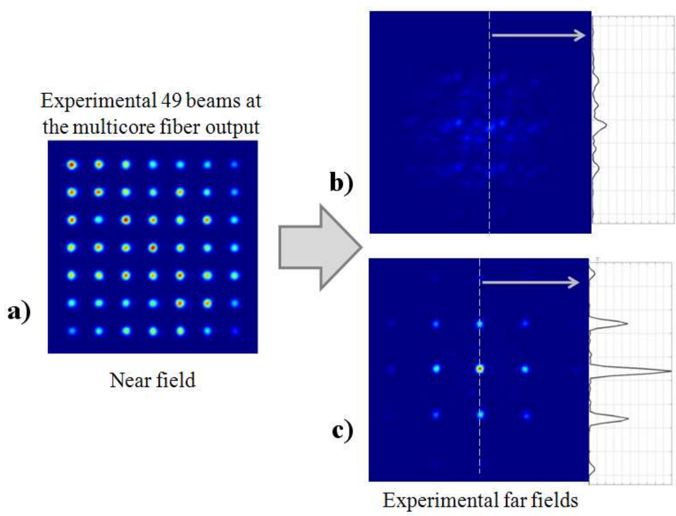

Fig. 4. Experimental recordings of (a) the fiber exit end near field, (b) the fiber output far field with 49 input beams of uniform input phase and (c) the fiber output far field after appropriate shaping of the input phase distributions to get a co-phased array at the exit. Profiles of far field cross-section are shown on the right side of the figure.

Figure 4-a shows a typical intensity distribution (near field) at the multicore fiber output end. This 60cm long fiber was maintained on a straight base. At the fiber output, a small part of the beams was reflected by a beamsplitter trough a focusing lens which displayed the far field pattern onto a CCD camera. This camera was connected to a computer which also controlled the SLM in an active feedback loop.

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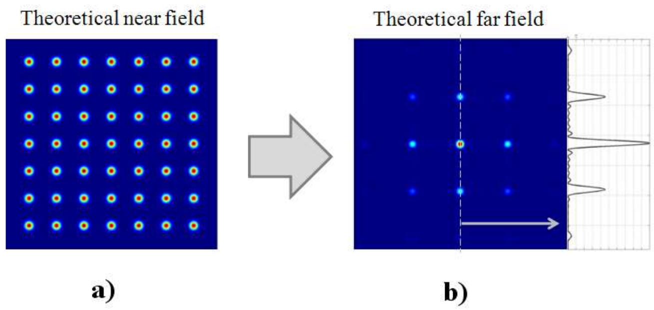

Fig. 5. Theoretical intensity distribution of a 7x7 array of Gaussian beams (a) together with the corresponding far field (b) in the case of a uniform phase.

In the initial status, the whole elementary beams injected in the multicore fiber are in phase. The very small differences between propagation constants in the fiber cores are large enough to induce various phase distribution at the fiber output. This is the reason why the observed far field looks like a speckle figure as shown on Fig. 4-b. Once the SLM adjusts the input beam phases in accordance with the process previously described, the far field evolves toward a distribution with bright and sharp peaks (Fig. 4-c). These peaks, related to the array geometry, prove that the 49 beams at the fiber output are really in phase. It can be compared with the perfect theoretical far field pattern calculated and shown on Fig. 5b. The fraction of energy the main far field peak carries amounts to 96% of its theoretical value indicating the high quality of the phase-locking. A high combining efficiency in a single beam (high Strehl ratio) could be reached despite the sparse array distribution by using an adapted set-up including a diffractive optical splitter in a way similar to the work of E.C. Cheung et al. [14] concerning an array of individual fibre lasers.

Further experiments have shown that the phase-locking scheme can serve for combining ultrashort laser pulses. With respect to the previous situation, the laser source was simply switched from CW to mode-locked operation and the procedure of co-phasing was re-started. Control of the initial phase pattern leads to the new far field intensity distribution reported on Fig. 6. Phase-locking is again attested by the diffraction pattern in good agreement with expectation. The fraction of energy the main far field peak carries has been reduced to 43% of its theoretical value. Difference in the group delay between the different cores of the fiber because of residual inhomogeneity could be at the origin of the lower performance. Using a component which compensate for the group delay difference (structured glass plate, mirror array,…), would make the technique compatible with several meters long amplifying fiber and significant improvement of efficiency with femtoseconde pulses should be expected .

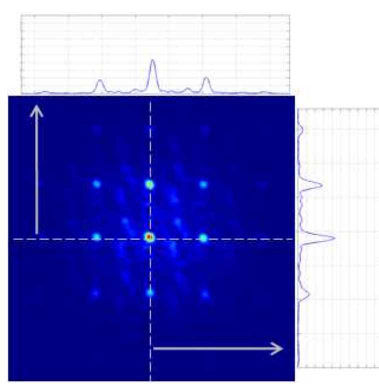

Fig. 6. Experimental recordings of the fiber output far field after appropriate shaping of the 49 input phase relationships to get a co-phased array at the exit. The input beams are pulse (120fs) train of 80 MHz repetition rate.

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5. Conclusion

We report the co-phasing of 49 beams at the output of a multicore fiber which is a record in term of phase locked beam number [9]. The use of a single component (SLM) to phase adjust a large number of beams is adapted to a compact amplifying configuration where a doped multicore fiber is the amplifying medium. SLM is now a mature component of high technology offering a large number of pixels. As a result, the co-phasing architecture we have proposed could be easily used to phase-lock a larger number of beams (higher than one hundred). The co-phasing process does require neither a wavefront sensor nor a reference beam. This simple method was demonstrated with a passive fiber, but it is compatible with the use of amplifying fibers (rare earth doped) which do not add any specific difficulty. The reported results were obtained in the continuous wave regime as well as in the mode-locked regime. This is the first time, to our knowledge, that multiple parallel pulses as short as ~120fs have been phase-locked to be combined in the far field. The speed of the co-phasing process was here very slow (~1mn) and limited by the command and time response of the liquid crystal SLM. In the quiet environment of a laboratory this was sufficient to ensure stable operation, but that point must be improved for more general situation. The performance however was similar to the earlier works of M.A. Vorontsov et al. [15] on phase compensation based on stochastic parallel gradient descent optimization using a LC-SLM. Great speed improvement (60 Hz) was demonstrated later thanks to electronic integration and to the use of fast micro-mirror arrays [16]. We trust that the same technology could solve the current speed issue of our architecture.

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