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Lenslet array-free efficient coherent combining of broadband pulses at the output of a multicore fiber with a square core grid

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Abstract: An efficient optical scheme for coherent combining of radiation from the output of a multicore fiber (MCF) with a square array of cores in the out-of-phase supermode is proposed. The scheme uses only simple optical elements and is suitable for an arbitrary number of MCF cores. In a proof-of-concept experiment broadband pulses transmitted through a 25-core fiber were combined with 81% efficiency and good beam quality. In numerical modeling a close to unity efficiency is obtained for a large number of cores. The proposed scheme can be used in a reverse direction for efficient beam splitting and launching the out-of-phase supermode into the MCF.

1. Introduction

Multicore fibers and coherent beam combining are two highly promising technologies for scaling average and peak power of fiber laser systems. It appears that a certain multicore fiber design, a proper choice of the propagation regime, and the development of a well-matched scheme for coherent summation of the radiation at the fiber output can make the combination of these technologies very efficient.

Peak power of light that could be transferred through a single-core fiber is limited by non-linear effects. Even when the peak power is relatively low, these effects play a significant role due to a tiny beam size and a long length of optical fibers.

A promising way to build a high-peak-power fiber laser system is to use several amplification channels and subsequent coherent combining of the amplified beams [1]. To date, fiber laser systems with high peak and average power were demonstrated, utilizing coherent combining of a few beams amplified in independent fibers [2,3]. An important part of these systems is a high-bandwidth phasing system that compensates for phase drifts in different amplifiers. The origins of phase fluctuations are usually temperature drifts and mechanical vibrations, that require the phasing system to have a sufficient bandwidth (reaching a kHz range in some works) [4]. It is possible to scale such systems to a larger number of channels [5], but this demands rather complicated phase detection schemes and increases the required bandwidth of the active feedback phasing system [6].

An alternative to an array of independent fiber amplifiers is a multicore fiber (MCF). In the simplest approach, the cores in an MCF are not coupled, and the light propagates independently in each core. In this case it is relatively easy to increase the peak power of a pulse by up to N times, where N is the number of cores. The propagation, amplification and coherent combining of the radiation transferred through such an MCF were recently successfully demonstrated [7,8]. Unfortunately, such systems are very similar in properties to an array of independent fibers; in particular, there is a need for the active phase stabilization, and the optical scheme for coherent

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combining is complicated and not very efficient [9,10]. When the cores in an MCF are located closely, they are coupled, thus the coherence between the cores can be maintained without a phase stabilization system, and the optical scheme for coherent combining can be simplified. Light in such MCFs propagates as a combination of supermodes, so if only one supermode is excited, the relative phase in different cores is fixed [11]. Such MCFs are being actively studied, MCF-based amplifiers utilizing the fundamental in-phase supermode [12], and CW lasers with mode selection in MCF [13,14] are being developed. Also, such MCFs are promising for exploring nonlinear effects, such as nonlinear combining, compression, and contrast enhancement [15,16], supercontinuum generation [17,18], and formation of solitons and light bullets [19,20]. In most studies the fundamental in-phase supermode of an MCF is used to amplify and coherently combine the amplified radiation, which is subject to nonlinear instabilities in a high peak power propagation regime [21,22], and thus does not provide efficient scaling of the maximum possible peak power. Moreover, the far-field combining efficiency of the in-phase supermode is limited; the more efficient scheme [5] based on special lenslet arrays cannot be used directly because it requires the phase of each emitter to be individually chosen from the whole 2π range.

In recent years it was first predicted theoretically [22,23] and then demonstrated in an experiment [24] that in some types of MCFs with coupled cores there are supermodes stable to transverse instabilities in a nonlinear regime. In particular, MCFs with a square $N \times N$ array of cores support the out-of-phase supermode, in which the phase of radiation is 0 and π in a chessboard-like pattern, and this supermode is stable at high power [25], whereas the in-phase supermode is unstable. Optical beams arranged in a square array with alternating 0 and π phases can be efficiently coherently combined using the out-of-phase regime of the tiled aperture coherent combining scheme [26] without any need for an additional phase mask. When combining radiation from the output of a coupled-cores MCF, the tiled aperture scheme can be significantly simplified due to the absence of the phasing system. Also, since the cores are located close to each other, the fill factor is high, and the lens array typically used in the tiled aperture scheme is no longer needed. These benefits of the out-of-phase supermode make it truly promising for the peak power increase in fiber laser systems. The application area of MCFs supporting the out-of-phase supermode can be much broader than the development of high-power systems and includes studies of nonlinear pulse dynamics at moderate peak powers and broadband wavelength tuning [27]. Dispersion control and zero-dispersion wavelength shifting towards shorter wavelengths can be achieved for the out-of-phase mode, making these fibers promising for soliton propagation in the wavelength regions not supported by standard single-mode fibers [28]. Nevertheless, efficient beam coupling to the MCF and coherent combining of the beams at its output are essential for all these applications.

Recently we demonstrated the possibility of selective excitation and propagation of broadband pulses in different supermodes, including the out-of-phase supermode, in an MCF with a square 5×5 array of coupled cores [29]. We experimentally confirmed that laser pulses can propagate through such MCFs with transverse patterns equal to particular supermodes; the intensity and phase profiles of the supermodes were experimentally measured and found to be in a good agreement with the predicted profiles.

In this paper we demonstrate coherent combining of broadband radiation from all cores of a 5×5 MCF in the out-of-phase supermode propagation regime. To the best of our knowledge, it is the first time when coherent combining of the out-of-phase supermode of a coupled-cores MCF is demonstrated. We show the possibility of efficient coherent combining of the out-of-phase supermode without the use of any special optical elements or systems. In a proof-of-concept experiment the combining efficiency of the out-of-phase supermode reaches 81% with beam quality $M^2 = 1.3$. In numerical modeling we show that combining efficiency can reach 93% in this setup with allowance for the real supermode structure, the beam quality in modeling is $M^2 = 1.1$. The demonstrated optical scheme is easy to scale for a larger number of cores. In particular, with the use of the same optical elements we numerically model combining of the out-of-phase supermode exiting an MCF with 225 cores arranged in a 15 × 15 array; in case of an ideal MCF geometry the combining efficiency is 99%. The presented optical scheme can be used in the reverse direction to split a single beam into a rectangular array of beamlets with a high efficiency. When this regime is used to couple light into the out-of-phase supermode of an MCF with 25 cores, the efficiency of excitation of the out-of-phase supermode reaches 89%.

2. Experimental study

In the proof-of-concept experiment for coherent combining of the out-of-phase supermode (Fig. 1(a)) we use a 25-core fiber, the transverse section photo of which is shown in Fig. 1(b). This MCF was manufactured by assembling the central part using single-core preforms and subsequent drawing [29]. The cores in this MCF are located in a 5 × 5 square array, the diameter of each core is approximately 6 µm; the lattice pitch is ~8.4 µm. The experimental setup for coherent combining of the out-of-phase supermode is shown in Fig. 1(a). Pulses generated by an all-fiber laser system at 1030 nm [30,31] are coupled to the MCF using a specially designed optical scheme based on a spatial light modulator (SLM). In this scheme, the beam emerging from the output fiber of the laser system is first expanded and directed to the SLM. A special phase mask is displayed on the SLM, and then the beam is imaged to the input face of the MCF by a demagnifying telescope. To create a beam with a supermode-like pattern of 25 beamlets, the displayed phase mask contains 25 squares with adjustable flat phases. The rest of the area of the SLM is filled with a strong phase gradient that allows filtering out unnecessary parts of the beam by a spatial filter installed in the Fourier plane of the demagnifying telescope. With this scheme a given supermode in the MCF can be excited, whereas the fraction of power in the other supermodes is low. More details of this setup can be found in [29]. In the considered work this scheme is used to selectively excite the out-of-phase supermode. The length of the 25-core fiber is 67 cm.

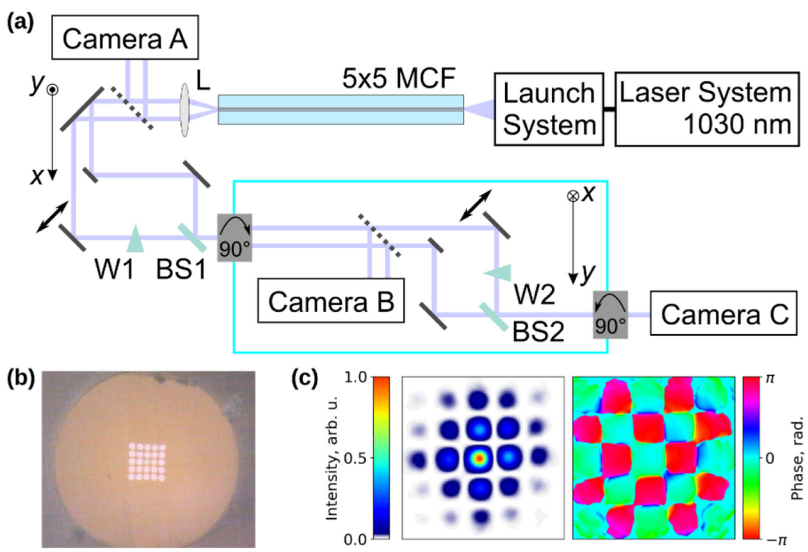

Fig. 1. (a) Scheme of experimental setup. L – lens, BS1, BS2 – 50/50 beamsplitters, W1, W2 – wedges. The part of the scheme in the blue rectangle is rotated by 90° with respect to the other parts of the scheme for clarity, in fact the two combined beams are one above the other. (b) A microphotography of the 25-core MCF used in experiment. (c) Experimentally measured transverse distributions of intensity and phase of the out-of-phase supermode in the used MCF.

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The transverse intensity and phase distribution of radiation in the out-of-phase supermode is shown in Fig. 1(c). In an ideal case, these distributions should be vertically and horizontally symmetric, but as a result of small inaccuracies during MCF assembly and drawing the symmetry is slightly broken. However, it is still possible to coherently combine this structure into a single beam with high efficiency. The beam is a square array of small beamlets whose phases are close to 0 and π in a chessboard-like pattern, so when it propagates in free space, four intensity maxima are formed in the far field, the power is almost equally distributed in these four beams [26]. After that it is possible to coherently combine these four beams in two similar steps using standard 50/50 beamsplitters. It is worth noting that the number of beams with non-negligible intensity in the far field is always four when the square array of out-of-phase emitters with a high fill-factor is combined, regardless of the number of emitters. This result follows from the fact that the size and shape of maxima in the far field are determined by the Fourier transform of the beamlets envelope in the near field, while the envelope of the maxima in the far field is determined by the Fourier transform of a single beamlet. The distance between the maxima is determined by the fill factor of the emitters, and the locations of maxima in respect to the envelope are controlled by the phase shifts between the neighboring beamlets: when all beamlets are in phase, there is a maximum in the center of the envelope, containing up to 80% of power, and side maxima of lower, still non-negligible power [32]. When the phases of the neighboring beamlets differ by π, the maxima in the far field are shifted by half a period relative to the envelope. As long as the fill factor is high, which is always the case of coupled-core MCFs, the ratio between the envelope width and the maxima pitch in the far field is low, resulting in the formation of only four (two in each dimension) maxima with equal intensities carrying most of the total power, whereas higher-order maxima are very small and carry a negligibly small portion of the total power. A detailed explanation of this effect can be found in [26].

A lens L (f = 25 mm) is installed at the output of the MCF so that the fiber face is in its focal plane. This focal length is much larger than the far field boundary ($w^2/\lambda \approx 1.6$ mm), so in the lens plane four beams are already formed, they diverge from the optical axis by the corresponding angles. The lens compensates for the divergence, and the four beams propagate collinearly after the lens. After that we have two similar steps of combining, in each of them the multi-beam structure is split in two halves with D-shaped mirrors (horizontally at the first step and vertically at the second), then both parts of the structure are recombined on 50/50 beamsplitters. The intensity profiles of the beams just after the lens L, and after each step of combining are shown in Fig. 2(a,b,c) (in comparison with the results for the corresponding numerical modeling shown in Fig. 2(d,e,f), which will be described in the next section). At each step of combining there is a movable mirror for group delay control and a wedge for precise phase control in one of the paths. It is important to note that the setup uses only simple off-the-shelf elements, and the number of elements does not depend on the MCF parameters.

The resulting combined beam is shown in Fig. 2(c). The total combining efficiency, defined as the ratio between the power in the combined beam and the power just after the MCF, is 73% (corrected for losses at non-coated wedge surfaces and gold-coated D-shaped mirrors). Also, about 10% of the pulses power is contained in other supermodes due to a non-ideal launch system, as measured in [29]. In our combining scheme the power contained in other supermodes is not combined, reducing the overall efficiency. Thus, we calculated the coherent combining efficiency of the out-of-phase supermode to be 81%, when corrected for the reflection losses and power scattering into other supermodes. The remaining losses are most probably caused by the non-ideal structure of the out-of-phase supermode, non-ideal matching of the combined beam profiles at the beamsplitters, and non-ideal group delay matching in the two steps of combining, because the coherence length of our source is only 30 µm. The beam quality M^2 for the combined beam is 1.48 because some side maxima are partially in the combined beam. When the diaphragm with 3 mm diameter is installed in the output beam, the beam quality becomes $M^2 = 1.22 \times 1.35$

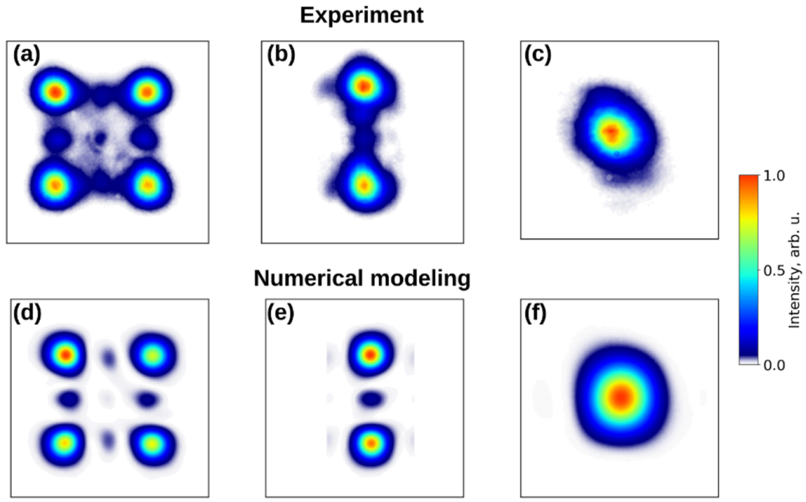

Fig. 2. Measured in experiment (a, b, c) and modeled (d, e, f) intensity distributions of the beam before (a, d), after one (b, e), and after two (c, f) steps of combining; (a, d) correspond to camera A in Fig. 1, (b, e) correspond to camera B, (e, f) to camera C.

(Fig. 3(a)) and the power drops by 5%. The spectrum of the combined beam is shown in Fig. 3(b) in comparison with the source spectrum. Small deviations in the combined spectrum are caused by the presence of other supermodes in the MCF with a different group delay.

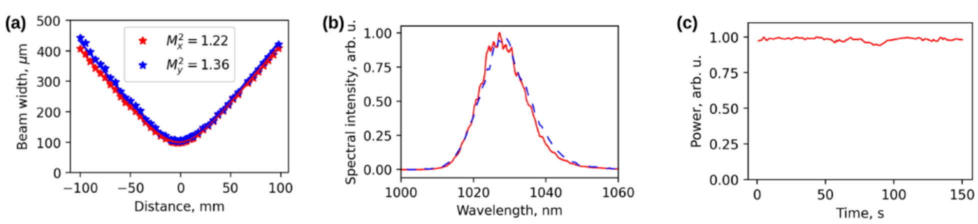

Fig. 3. (a) M^2 measurement of combined beam. (b) Source spectrum (blue dashed curve) and combined beam spectrum (red continuous curve). (c) Power stability during 150 seconds.

An important advantage of coherent combining of the radiation transferred through a coupled-cores MCF, as compared to an array of independent fibers, is that the phase in the channels is locked, so we don't need the high-bandwidth phase stabilization system. We confirmed this in our experiment: we measured the power in the combined beam for 150 seconds and, as shown in Fig. 3(c), the power fluctuations during this period were 5% at the most. This result is obtained without any active stabilizing system, so it proves the phase stability in the cores of the MCF. The main source of the instability here is the drift of our free-space four-beam combining scheme made of standard components.

3. Theoretical study

We performed numerical modeling to determine maximum combining efficiency which we could obtain with our experimental MCF in an ideal combining setup. We simulated the propagation of the measured out-of-phase supermode through the described optical scheme for coherent combining, starting from the output face of the MCF. The intensity and phase distributions shown in Fig. 1(c) were 2D Fourier transformed to find the far field. Its intensity profile is

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shown in Fig. 2(d). We can see that side maxima arise due to a non-ideal structure of the MCF. The subsequent two-step combining of four obtained beams on two ideal beamsplitters was modeled by parallel translation of one part of the picture onto the other and summing up complex amplitudes of the corresponding points. Before combining, the common phase of one part of the beam was shifted so that intensity maxima in both beams had equal phase. A possible mismatch in the optical path length of the combined beams was not taken into consideration in the modeling, i. e. the source was regarded to be absolutely coherent. Beam images in the far field before combining, after the first step and the final combined beam are shown in Fig. 2(d,e,f). The power of the combined beam (Fig. 2(f)) was 93% of the initial beam power. 7% of the power was lost due to unequal intensities of the four combined beams, and also due to presence of side maxima. Note that the phases of the side maxima do not necessarily match at the beamsplitters, thus the side maxima can interfere constructively or destructively at each step of combining. In the modeling, most of the side maxima interfered destructively, leading to a better shape and lower M^2 parameter of the combined beam. The M^2 parameter in modeling, calculated over a large region that includes the remains of the sidelobes, was 1.09 in both directions.

Importantly, the proposed and experimentally validated scheme for coherent combining of the out-of-phase supermode from the output of an MCF without a lenslet array and the active feedback system for phase stabilization is suitable for coherent combining of beams from the MCF with an arbitrary number of cores in a square array. In this case, absolutely the same experimental scheme can be used without additional elements, which indicates perfect scalability of the system for a large number of channels. To demonstrate such scalability in numerical simulation we modeled coherent combining of the out-of-phase supermode from an MCF with 225 cores arranged in a 15×15 square lattice, assuming ideal structure of the fiber (Fig. 4(a)). The combined beam is shown in Fig. 4(b). The combining efficiency is 99% in this case, beam quality is $M^2 = 1.16$.

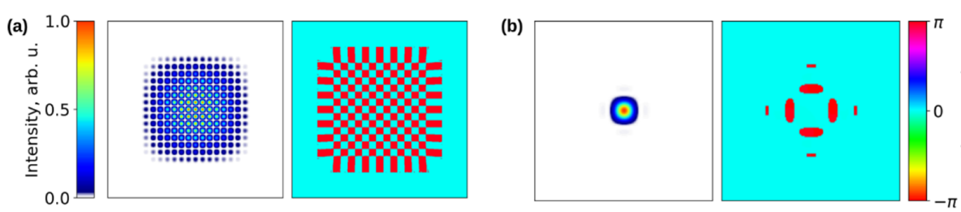

Fig. 4. (a) Transverse intensity and phase distributions of the out-of-phase supermode of the MCF with 225 cores, arranged in a square 15×15 lattice. Diameter of each core is 6.5 μm, step-index is 0.005, lattice pitch is 8.4 μm. (b) Modeled intensity and phase distributions of coherent combining of the out-of-phase supermode shown in (a).

The proposed optical scheme for coherent combining is fully reversible and allows splitting a single beam into a rectangular array of beamlets with simple optical elements. The resulting array of beamlets can be used to excite an out-of-phase supermode in MCFs with high efficiency or for other purposes. The number of beamlets in the array is determined by the ratio between the size of the initial beam and the distance between four beams obtained by the beamsplitters. The numerically simulated intensity and phase distributions of the array of beams obtained by splitting a Gaussian beam into 25 beamlets are shown in Fig. 5. When this array of beams is directed to the input face of the 5×5 MCF we used in experiment, the calculated efficiency of the out-of-phase supermode excitation will be 89% in case of an ideal MCF structure. 4.5% of the power will be coupled to other supermodes, and 6.5% of the power will be coupled to the cladding. It is worth noting that it is also possible to efficiently excite some other supermodes using this scheme with an additional large-scale phase mask directly in front of the MCF.

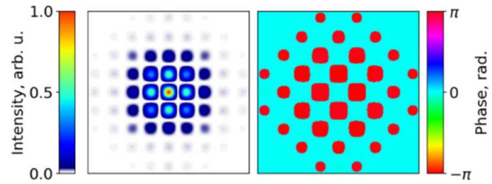

Fig. 5. Intensity and phase distributions of the array of beams obtained by splitting a Gaussian beam into a 5 × 5 array of beamlets (modeling).

4. Conclusion

In this paper we proposed a lenslet array-free scheme for coherent combining of radiation propagating in the out-of-phase supermode regime through an MCF with an arbitrary-size square array of cores. In a proof-of-concept experiment we demonstrated coherent combining of broadband pulses transmitted through an MCF with a 5 × 5 square array of cores with a transverse structure of the out-of-phase supermode. We demonstrated, for the first time to the best of our knowledge, coherent combining of radiation from 25 cores without any special optical elements and without the phase stabilization system. The combining efficiency of the out-of-phase supermode was 81%, and the beam quality was $M^2 = 1.3$. Our numerical modeling showed that combining efficiency can reach 93% with allowance for distortions of a real MCF structure, beam quality being $M^2 = 1.1$. Modeling on an example of MCF with 225 cores (15 × 15) also demonstrated that the proposed scheme is easy to scale for a larger number of cores. Assuming the ideal geometry structure of the MCF, combining efficiency reaches 99% in this case.

The proposed optical scheme can be used in reverse direction for highly efficient beam splitting into an arbitrary-size array of beamlets, in particular, to excite MCF supermodes. In case of an MCF with 25 cores (5 × 5), the out-of-phase supermode coupling efficiency is 89%.

The obtained results confirm that the radiation shaped as an out-of-phase supermode of an MCF with a square array of coupled cores can be efficiently combined using a simple optical scheme providing a beam of good quality. This result is an important step toward future research in the area of high-power fiber laser systems.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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