Tapered Multicore Fiber for High-Power Laser Amplifiers

A. V. Andrianov, S. A. Skobelev, A. A. Balakin, E. A. Anashkina, and A. G. Litvak

***Abstract*—The problem of coherent amplification of the out-of-phase mode in tapered multicore fibers with cores arranged in a ring and in a square lattice is studied theoretically. The stability of out-of-phase field distributions with respect to both inhomogeneities of the refractive index and the initial wave field distribution is demonstrated in numerical modeling. Coherent combining of radiation into a single beam with good quality and efficiency of about 80% for ring cores arrangement and more than 90% for square cores arrangement is possible. Achievement of 55 MW of total power at the output of a fiber with 11×11 cores is numerically demonstrated.**

***Index Terms*—Fiber lasers, fiber non-linear optics, laser beam combining.**

I. Introduction

THE development of fiber laser systems with high peak and average power is one of the priorities in modern laser physics. Due to the combination of good mass and size characteristics, high efficiency, reliability, and alignment-free operation, fiber lasers have significant advantages over solid-state ones. However, in terms of achieving high peak power, the capabilities of fiber systems are severely limited by nonlinear effects. Specialized fibers with an increased mode size (LMA - Large Mode Area) can have significantly increased thresholds of nonlinear effects and achieve the average power of the multi-kilowatt level [1] and the peak power of the megawatt level directly in the fiber [2], [3]. Nevertheless, the fundamental limitations associated with self-focusing in the fiber material cannot be overcome by simply increasing the mode size.

Prospects for significant power increase are associated with the use of optical multicore fibers (MCF), in which the signal is distributed over many cores and coherently combined at the output. In an MCF with closely placed cores, radiation propagates in the form of collective modes of all cores (supermodes), while the coherence between the cores is preserved, which greatly simplifies the further combining of radiation into one optical beam. In recent works, it was shown that the use of an out-of-phase field distribution in MCF with a ring of cores [4]–[7] or square grid of cores [8] makes it possible, in principle, to overcome modulation instabilities in a discrete array of cores and increase the total power beyond the self-focusing limit.

However, it is preferable to increase the mode field area in each of the cores in order to significantly increase the output power without excessively increasing the number of cores and complicating the design of the MCF. Note that the maximum diameter of a single-mode core is no more than $10 - 15$ micron at a wavelength of 1 μm for technologically justified values of the difference between the core and cladding indices, which for silica fibers doped with rare-earth ions (e.g., ytterbium ions) are of the order of 10^{-3}. In the work [8], a version of the MCF with step-index cores having a close to maximum size, at which they remained single-mode, taking into account the technologically sound choice of the difference between the refractive indices of the core and the cladding, was analyzed in numerical modeling. In the work [7], the amplification in an active MCF with ytterbium-doped cores, also with a diameter close to the maximum allowable, was experimentally and numerically investigated. A further increase in the size of the cores leads to the fact that each of the cores ceases to be single-mode. This significantly complicates the problem of the beam launching, can lead to complex multimode spatial and spatial-temporal dynamics and distortions of the pulse shape, and also degrades the efficiency of combining at the MCF output. Thus, it is necessary to solve the problem of maintaining single-mode propagation of radiation with an increase in the mode area of each of the cores.

One of the promising technologies that makes it possible to significantly scale the mode field area while maintaining a high single-mode beam quality is the use of tapered optical fibers [9]. A tapered fiber for high-power amplifiers is a fiber with a core and cladding diameter smoothly increasing from input to output. At the input, the core of a tapered fiber is strictly single-mode, which makes it easy to launch radiation without excitation of higher modes; then, the mode structure is adiabatically rearranged with an increase in the core size. With a smooth increase in the diameter and the absence of sharp perturbations of the fiber, the radiation remains practically single-mode, despite the increase in the core size, which is noticeably larger than the single-mode limit. A specific feature of tapered fibers is the relative simplicity of the structure of their cores (in fact, the step-index profile can be used) and the possibility of a completely monolithic structure, as well as the simplicity of implementing a structure with a double cladding for injection of pump radiation [9]. High-power laser systems

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of the kilowatt level [10] with good beam quality [11], [12], high energy Q-switched pulsed lasers [13] and ultrashort pulse amplifiers [14]–[17] are demonstrated using tapered fibers. The possibility of creating a completely monolithic amplifier and laser with a fiberized injection of pump radiation into the tapered fiber is demonstrated [18]. Peak powers of a megawatt level are demonstrated [14]–[17], which are comparable in order of magnitude with the self-focusing limit in silica. At this, up to several tens of MW after compression is shown [15], [19] when using chirped pulse amplification. The paper [20] discussed the possibility of an additional significant increase in the radiation power by using an array of independent tapered fibers. However, in this case it is necessary to solve the problem of radiation synchronization in cores.

In this paper, we study the combination of using multicore fiber and tapered fiber technology for scaling the power. We propose a fiber amplifier based on a monolithic MCF with an array of coupled cores and a diameter increasing from input to output. On the one hand in such fibers efficient launching of radiation can be realized without exciting unwanted modes even if the required input field is inaccurately synthesized; on the other hand, an adiabatic increase in the core mode area when approaching the output helps to reduce the unwanted influence of nonlinear effects. We performed a detailed numerical study of the out-of-phase mode amplification in a tapered MCF, in which the cores are arranged in a ring and in the form of a square lattice, and analyzed the possibility of highly efficient coherent summation of the amplified radiation. We note that passive multicore fibers, including tapered ones, were used previously for studying nonlinear effects [21], [22] and for sensing applications [23], [24].

II. Tapered MCF With Cores Located on a Ring

First, consider the case of a tapered MCF with an even number of identical cores located on a ring. Earlier, we found a number of stable nonlinear solutions [4] for wave beams propagating in MCFs with fixed size cores. In this case, the distribution of spatial supermodes has the simplest forms. The most interesting of them is the out-of-phase mode, in which the field intensity in all cores is the same, and the phase of the field between neighboring cores differs by π, i.e. the amplitude $\propto (-1)^n$. This supermode is resistant to discrete modulation instability at high peak power, and, in principle, can carry total power many times exceeding the self-focusing threshold for single-core fiber [4].

To demonstrate further scaling of the energy and peak power of laser radiation during the amplification of the out-of-phase mode in the tapered MCF, full-scale three-dimensional numerical simulations were performed. First of all, we were interested in the possibility of stable amplification of the out-of-phase mode under conditions of an adiabatically smooth increase in the size of the transverse structure of the fiber. To speed up the simulation, we considered the amplification of continuous-wave radiation, although these results can be applied under the appropriate constraints for the peaks of relatively long pulses (for example, chirped pulses). Numerical simulations were carried out using a previously developed three-dimensional numerical code that allowed us to calculate the evolution of the electric field within the framework of a unidirectional wave equation in a medium with an arbitrary dependence of the refractive index on coordinates, taking into account the Kerr nonlinearity and amplification [4]

$$\mathrm{i}\frac{\partial \mathcal{E}}{\partial z} = \sqrt{k_0^2 n_0^2 + \Delta_\perp}\mathcal{E} + k_0 n_2 |\mathcal{E}|^2\mathcal{E} + k_0 \delta n\, U\mathcal{E} + \mathrm{i}\gamma\mathcal{E} \quad (1)$$

with the refractive index profile $U = \sum_n \exp[-\frac{((x-x_n)^2+(y-y_n)^2)^2}{r_n^4}]$. Here, $x_n(z)$, $y_n(z)$, $r_n(z)$ are the position and radius of the cores, n_0 is the refractive index of the cladding, δn is the difference between the refractive indices of the cores and the cladding, and n_2 is the nonlinear refractive index. The operator $\sqrt{k_0^2 n_0^2 + \Delta_\perp}$ can be easily calculated in the Fourier space and allows one to properly describe wave fields with transverse scales of the order of wavelength by taking into account spherical aberrations. The dimensions of the cores increase adiabatically.

Numerical simulations were performed for an active tapered MCF with a ring structure of ten silica cores ($n_0 = 1.45$) at a wavelength of $\lambda = 1.03$ μm. The following parameters were chosen: the difference between the refractive indices of the core and the cladding $\delta n = 0.002$, the initial core radius $r_n^{(0)} = 5$ μm, the distance between cores 12 μm, the MCF length $L = 40$ cm, gain coefficient $\gamma = 0.16$ cm^{-1}, nonlinear refractive index $n_2 = 3 \times 10^{-16}$ cm^2/W (critical self-focusing power $P_{\text{cr}} = 3.6$ MW). We assumed that the entire transverse fiber structure scales linearly from the input to the output. The radius of the core increased linearly $r_n = r_n^{(0)}(1 + \alpha_r z)$, $\alpha_r = 3.3/40$ cm^{-1}. The core expansion factor is 4.3. Fig. 1(a) schematically shows this MCF. These parameters are in principle achievable using existing fiber manufacturing technologies. The fabrication of such optical fibers does not present much difficulty, since the proven technology of drawing a tapered optical fiber from a solid standard preform [16] will make it possible to fabricate a tapered multicore fiber with the length of tapered section of the order of 0.5-1 m from a corresponding multicore preform in the same way.

The individual cores are strictly single-mode at the input, and the coupling coefficient between adjacent cores (defined as in [4]) significantly exceeds the gain coefficient ($\chi \gg \gamma$) for the MCF under consideration. This makes it possible to efficiently excite the out-of-phase mode in the thin input part of the fiber and amplify the signal in the form of this supermode. Along with this, the following relation holds for the considered MCF

$$\alpha_r \ll \gamma \ll \chi. \quad (2)$$

This ensures adiabatic amplification of the out-of-phase mode and smooth rearrangement of its structure along the tapered fiber with an increase in power and a corresponding increase in the nonlinearity influence.

The results of numerical simulation shown in Fig. 1 confirm attainability of this propagation and amplification regime. Numerical calculations were performed on a grid with 512×512 points in a plane perpendicular to the propagation direction. The calculation step along the fiber axis was chosen as $\Delta z = 8$ μm.

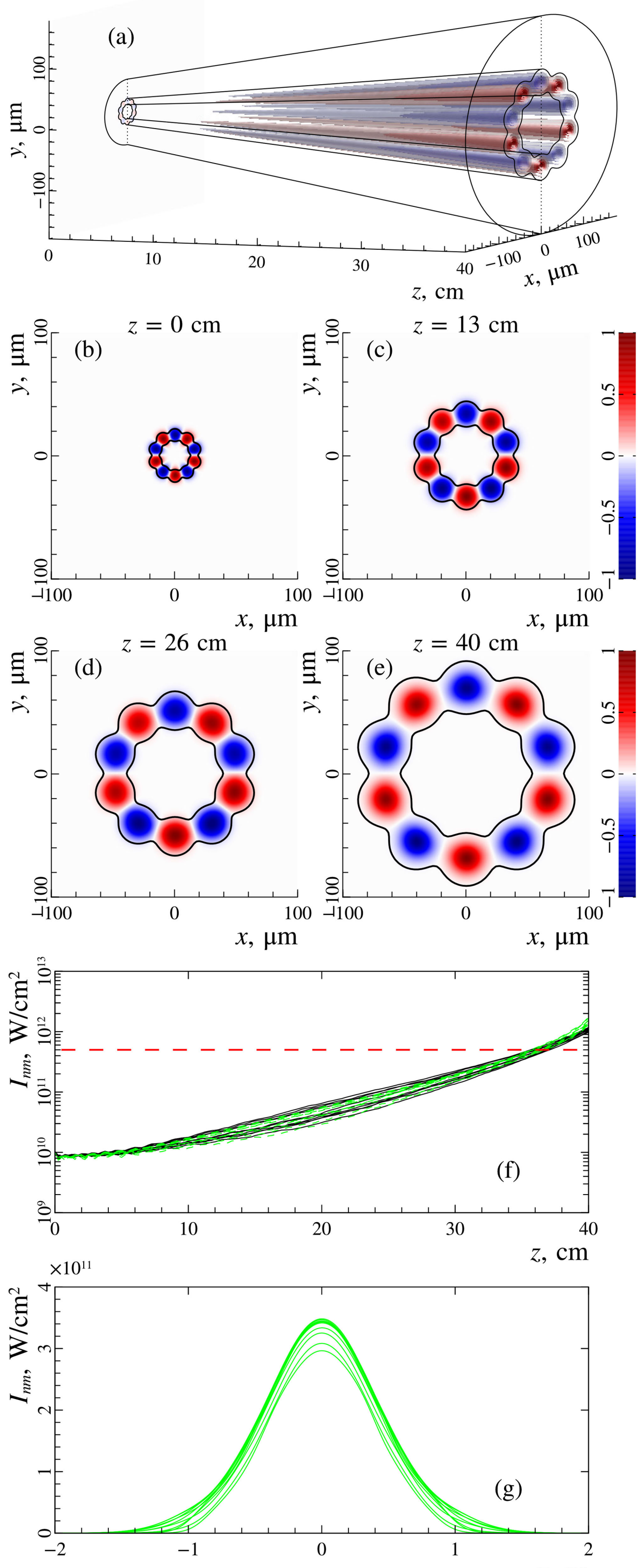

Fig. 1. (a) Schematic representation of a tapered MCF with ten cores. (b)–(e) Wave field distribution in different cross-sections along the fiber: $z = 0$ cm, $z = 13$ cm, $z = 26$ cm, $z = 40$ cm. (f) Change in the wave field intensity in different cores along the fiber calculated in the CW approximation (black curves) and with account for temporal pulse profile (green dotted lines), (g) Temporal pulse profiles in the cores at the MCF output.

We have verified that decreasing steps by half (with a corresponding increase in the number of points along coordinates) does not change results.

To obtain high peak power in fiber systems, amplification of chirped time-stretched pulses is used usually. The characteristic pulse durations are hundreds of ps - units of ns. To estimate the limiting capabilities of the amplifier, it is possible to simulate the amplification of continuous-wave (CW) radiation with a power corresponding to the peak power of the amplified pulse. Since the dispersion is normal at the considered wavelength there is no modulation instability in the time domain.

Radiation with an initial power of 30 kW was injected into the MCF input, which corresponds to the peak power that can be delivered by existing preamplifiers based on LMA or tapered single-core fibers [15], [25]. The field in each core was close to the fundamental mode of the single core. The initial noise level was about 3%. Along with this, to demonstrate the robustness of the regime under consideration, we used a deformed tapered MCF with 1% random variations of the refractive index of the cores. Fig. 1(b)–(e) shows the evolution of the wave beam in different cross-sections along the tapered MCF. Fig. 1(f) shows the evolution of the maximal intensity in different cores. It can be seen from the figure that at the initial stage the distribution of the wave field is inhomogeneous over the cores due to the difference in the refractive indices. The inhomogeneity of the wave field amplitude in different cores decreases with an increase in the total radiation power. When the total power exceeds the threshold value, which was analytically found in the work [26], the amplitude of the wave field in all cores becomes the same (Fig. 1(f)). At the final stage, when the wave field power in individual cores approaches the power of self-focusing, a narrowing of the wave field mode is observed. However, the coherence between the cores is preserved even at the power in the cores $\sim 0.4P_{\text{cr}}$. We justified the applicability of CW approximation by performing full-scale modeling of amplification of 1.1 ns chirped pulses (with Gaussian spectrum corresponding to 200 fs transform-limited duration) with the same peak power as for CW wave. The modeling was based on the unidirectional wave equation with dispersion [20] and a recently developed advanced algorithm for highly chirped pulses [29]. The results shown in Fig. 1 agree very well with the CW approximation, and we did not observe any signs of modulation instability in the time domain because of normal dispersion.

It should be noted that in reality the maximum attainable radiation power at the MCF output is limited by parasitic nonlinear effects, primarily by material damage and stimulated Raman scattering. As the ultimate Raman threshold, we consider a peak intensity at the amplifier output corresponding to the build up of the Raman component becoming comparable to the signal [27]. Due to high laser gain the effective Raman interaction length is very short (less than 10 cm), and the corresponding threshold power in a single core is of the order of 1 MW and the peak intensity is of the order of 0.5 TW/cm^2. We assumed that material damage corresponds to a peak intensity of 0.5 TW/cm^2 [28]. This intensity is shown in Fig. 1(f) by the red dotted line. The threshold intensity in the cores is reached at the fiber length of 36 cm, where the total power reaches 11 MW, which is

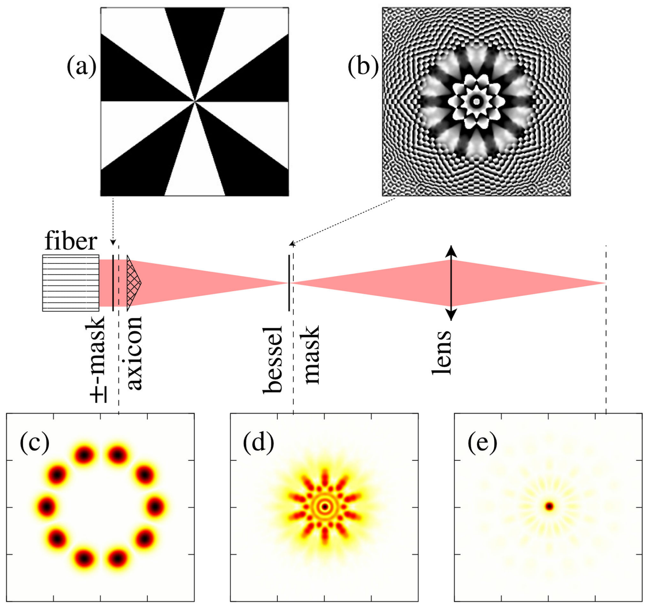

Fig. 2. Scheme for combining the out-of-phase wave field distribution at the MCF output to the single beam.

three times higher than the critical self-focusing power in silica. The amplified spontaneous emission (ASE) can also limit the performance of the amplifier, however, since we assume quite high input pulse power and not very high overall gain (about 500), the fraction of the ASE in the output power is small. The ASE can lower the Raman threshold by seeding the Raman wave. However, even with the ASE seed being about 500 times higher than the quantum noise, the Raman threshold is about two times lower (resulting in about 500 times lower Raman gain), still giving the possibility of achieving the total output power above the self-focusing limit. Thus, it has been shown that it is possible to amplify the out-of-phase mode in a tapered multicore amplifier to a value of the total peak power that significantly exceeds the self-focusing threshold. We note that close to 1 MW peak powers were demonstrated experimentally in a single-core tapered fiber without Raman instability and a small contribution of the ASE [15], [16], so power scaling to multi-megawatt level in tapered MCFs looks feasible.

To conclude this section, consider a well-scalable and efficient scheme for coherent combining of wave beams at the output of the MCF under consideration (see Fig. 1) into one coherent beam. We define the beam combining efficiency η as the ratio of the power of the useful combined beam to the total power of the beams at the MCF output. Fig. 2 shows a beam combining scheme for an MCF of ten cores. The wave beams at the MCF output pass through the phase mask shown in Fig. 2(a), at the output of which the out-of-phase distribution of the wave field becomes in-phase one (Fig. 2(c)). The resulting ring-type wave beam is focused by an axicon lens. The distribution of the wave beam near the axicon focus (intersection of the rays, corresponding to the centers of the initial beams) is shown in the figure 2(d). At this point a special phase corrector is placed (Fig. 2(b)). This corrector makes the wavefront more or less flat so that high quality beam can be formed in the far-field zone by an ordinary thin lens. Fig. 2(e) shows the resulting far-field distribution. Optional circular diaphragm can be placed at the focus of the thin lens. In numerical simulations, we found the optimal conditions leading to the efficiency of radiation combining in the central spot of more than 80% with a sufficiently high beam quality ($M^2 < 1.2$). The considered scheme is also suitable for combining ultrashort laser pulses.

III. Tapered MCF With Cores Located on a Square Lattice

MCFs with a large number of cores arranged in a ring are not so efficient in terms of utilization of the fiber cross-section area. Therefore, it is of interest to generalize the out-of-phase distribution to the case of MCF with more dense packaging of cores. In the paper [8], we considered a square lattice of $N \times N$ coupled cores. Such MCFs are relatively easy to manufacture and allow for a more dense core packing compared to the circular and hexagonal geometry of the lattice [6]. Exact stable analytical solutions were found for the out-of-phase mode, which describes the coherent propagation of wave beams in the lattice under consideration. At low powers, the maximum amplitudes in the cores are sine-distributed along each horizontal and vertical row, similar to the case of a linear rectangular waveguide. With increasing power, the wave field amplitudes in different cores become equal. Note that an MCF with a square matrix of 5×5 coupled cores supporting coherent out-of-phase supermode propagation has been demonstrated experimentally in paper [32].

Three-dimensional numerical simulations were performed to demonstrate the scaling of the laser radiation power during the amplification of the out-of-phase mode in a tapered active MCF of 11×11 silica cores ($n_0 = 1.45$) at a wavelength $\lambda = 1.03$ μm. The following parameters were chosen: the difference between the refractive indices of the core and the cladding $\delta n = 0.002$, the initial core radius $r_n^{(0)} = 5$ μm, the distance between the cores 12 μm, the MCF length $L = 75$ cm, gain coefficient $\gamma = 0.12$ cm^{-1}, nonlinear refractive index $n_2 = 3 \times 10^{-16}$ cm^2/W (critical self-focusing power $P_{\rm cr} = 3.6$ MW). The core radius increased linearly $r_n = r_n^{(0)}(1 + \alpha_{\rm sq} z)$, $\alpha_{\rm sq} = 1/80$ cm^{-1}. The core radius increased 2 times from the input to the output. Fig. 3(a) schematically shows this MCF.

Numerical simulations were carried out on a grid with 1024×1024 points in a plane perpendicular to the propagation direction. The calculation step along the fiber axis was chosen as $\Delta z = 16$ μm. A wave beam with an initial power of 20 kW was injected into the MCF input. The field in each core was close to the fundamental mode of the single core. The initial noise level was about 3%. The wave field is nonuniform in the transverse direction for a given power [8]. The field amplitude over cores u_{nm} is distributed according to the law $u_{nm} \propto (-1)^{n+m} \sin \frac{\pi n}{N+1} \sin \frac{\pi m}{N+1}$. Efficient excitation of an out-of-phase mode and wave field amplification in the thin input part of an active MCF with a square lattice, where individual cores are strictly single-mode, should be expected to be adiabatic

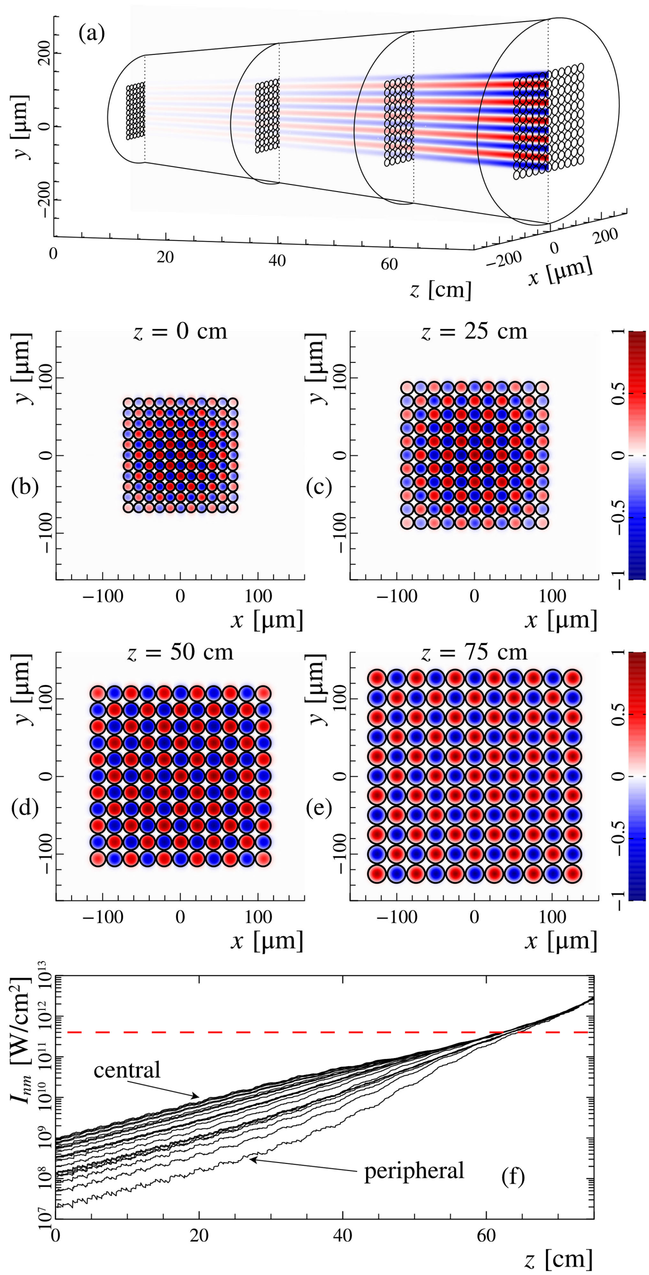

Fig. 3. (a) Schematic representation of a tapered MCF with 11×11 cores. (b)–(e) Wave field distribution of the in different cross-sections along the fiber: $z = 0$ cm, $z = 25$ cm, $z = 50$ cm, $z = 75$ cm. (f) Change in the wave field intensity in different cores along the fiber.

in the case of [8]

$$\gamma \ll \chi \sin \frac{3\pi}{N+1} \sin \frac{\pi}{N+1}. \quad (3)$$

To satisfy this condition we assumed that our MCF with square lattice has a lower gain coefficient and longer length, compared to the ring-shaped MCF. Along with this, for the considered MCF $\gamma \gg \alpha_{\text{sq}}$, which provides adiabatic amplification of the out-of-phase mode and smooth rearrangement of its structure along the tapered MCF with increasing power and a corresponding increase in the nonlinearity influence.

Fig. 3(b)–(e) shows typical distributions of the wave field in different cross-sections of a tapered MCF from a square lattice. Fig. 3(f) shows the evolution of the wave field amplitudes in different cores. One can see the equalization of amplitudes in all cores as the wave field intensifies increases. Oscillations of amplitudes in cores depending on the coordinate z are associated with the initial noise. At the final stage, when the power of the wave field in individual cores approaches the power of self-focusing, a narrowing of the wave field mode is observed. If we restrict ourselves to the field intensity in the cores at the level of 0.4 TW/cm^2, then the achievable power at the MCF output of 63 cm long is 55 MW. The value of about 0.4 TW/cm^2 is due to both the breakdown limit of the material and the threshold for the development of Raman instability. Thus, the results of numerical simulations confirm the possibility of stable adiabatic amplification of the out-of-phase mode in a tapered MCF from a square lattice. We note that in recent experimental studies normal dispersion of the out-of-supermode in square-lattice MCF at the wavelength of 1.03 μm was measured directly [30], ensuring the absence of modulation instability in the time domain.

It should be noted that the radiation combining from a square matrix of cores turns out to be more efficient than in the case of their circular arrangement. The paper [31] discussed a scheme for coherent combining of wave beams with an out-of-phase wave field distribution at the output of a square fiber lattice. In this scheme, radiation from the output of individual cores is collimated using an array of microlenses with a specially selected focal length. In the far field four beams of equal intensity are formed containing more than 98% of total power. With the correct choice of the focal length of the microlens array, the power fraction of the side peaks in the far field can be reduced to less than 3%, regardless of the fill-factor of the aperture directly at the fiber output. These four beams can be then coherently combined using a standard scheme with two beam splitters. Based on numerical simulation, the optimal conditions were found that made it possible to achieve an efficiency of beams combining of more than 90% for an unlimited number of cores and in the presence of errors and disturbances. This is significantly more efficient than coherent combining of the in-phase distribution resulting in formation of single main beam and several side-lobes carrying significant amount of energy.

IV. Conclusion

Summing up the results we conclude that coherent amplification of the out-of-phase mode in tapered multicore fibers is attractive for high power laser systems. The out-of-phase distribution of the wave field turned out to be stable with respect to both inhomogeneities of the refractive index in the cores and to inhomogeneities of the initial wave field distribution in both considered configurations of MCF cores: ring-shaped and square lattice. The main condition for the stability is that the characteristic length of the taper diameter increase should be larger than the characteristic length of the signal amplification, which, in turn, should be larger than the characteristic coupling length between the cores. Numerical simulation of the wave beams amplification in the MCF with 11×11 cores with realistic parameters demonstrated that 55 MW of total power at the output of the fiber can be achieved even with noticeable variations in the parameters of the fiber and the input distribution of the wave field.

Radiation combining in the form of an out-of-phase mode from the MCF output is most efficient for fibers with cores arranged in a square lattice [31]. Satisfactory combining efficiency can also be achieved in the case of a circular arrangement of cores using the scheme shown in Fig. 2, which requires two phase masks, one of which has a relatively complex form.

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