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19-cores Yb-fiber laser with mode selection for improved beam brightness

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Abstract We propose a new method to control the mode combination at the output of a 19-core fiber laser in order to produce a bright beam with uniform phase. The technique is based on both the selective excitation of the amplifying multicore fiber and on an intra-cavity angular filtering at the output. The excitation of the fundamental in-phase supermode of the 19-core fiber was demonstrated, resulting in the emission of a single-mode beam with M^2 limited to 1.21.

1 Introduction

Fiber lasers are now kilowatt class lasers in the continuous wave regime and deliver good-quality beams [1]. These high performances together with the specific features of the fiber laser like high slope efficiency, reliability, and compactness lead to a high acceptance of this technology in the industrial environment. However, regarding the pulsed regime, fiber lasers have more difficulty in competing with bulk solid-sate lasers. That comes from nonlinear effects and from damages appearing above some intensity thresholds because of the large peak power concentrated in the fiber core. In order to increase the threshold power of these deleterious effects, several strategies have been investigated. The goal is to enlarge the core cross section of the doped fiber while maintaining single-mode operation to preserve beam quality. Most investigations deal with specific fiber designs, sometimes involving microstructured core and/or cladding, to get a large-area fundamental mode [2–4]. Alternatively, fibers with multiple amplifying cores offer another way to reach high saturation powers on large cross sections. Depending on the design, these fibers can be constituted of coupled or independent cores. Nevertheless, in both cases specific techniques must be implemented to select the in-phase supermode of the fiber laser. That point is crucial in view of making lasers with high beam quality. Some methods have been proposed to get laser emission from a single core when using a multiple core fiber (MCF) for the gain medium [5, 6]. Other methods aim at providing phase-locking of the core array to force single supermode operation. The most widespread technique is based on the well-known Talbot effect, which has already been investigated in various geometries [7–9]. With such a technique, mode selection can be ensured by a structured mirror or by reflectors properly spaced from fiber ends. Nevertheless, Talbot effect intrinsically induces high losses more particularly when the periodic pattern (core distribution) is distributed in an axial symmetry. In some other cases, the in-phase supermode emission was observed as a result of a spontaneous organization induced by nonlinear phase shift or supermode gain discrimination [10–12].

In this paper, we report a technique allowing to separately control (i) the modal population of a MCF laser by means of a selective injection, (ii) and its phase-locking through an intra-cavity angular filtering. The proposed architecture was experimentally tested in a laser set-up with a 19-core Yb-

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doped fiber. Both theoretical and experimental results are presented and discussed.

2 Bright multicore fiber laser

The number of supermodes propagating in a MCF depends on the number of individual cores, on the number of modes able to propagate in each core and on the coupling strength between neighboring cores [13]. In particular, with strongly coupled cores and optimized structural parameters MCFs can be very ruggedly single-mode [14]. Otherwise, if the individual cores are single-mode, MCFs usually support a number of modes which is limited by the number of cores. However, proper excitation of such a fiber can reduce the number of excited supermodes and permits to guide low divergence beams [15].

In this paper, we design a ring-cavity laser, including an amplifying multicore fiber which was designed to produce a diffraction limited output beam. The fiber laser scheme is depicted in Fig. 1. It includes an amplifying rare-earth doped multicore fiber (DMCF) pumped by a laser diode (LD). A single-mode feedback fiber (SMFF) ensures angular filtering of the beam at the output end of the DMCF, and serves also for selective seeding at its input end. The DMCF is excited by the fundamental mode from the SMFF, through a first free-space imaging system (lenses L4 and L5) allowing size variation of the launched beam. A small part of the emitted beam is reflected towards the feedback fiber whereas the main part is extracted from the laser cavity through an output beam splitter. A set of lenses (L1 to L3) constitutes a second free-space imaging system which displays the far field of the DMCF onto the input face of the SMFF. Optical isolators in the feedback loop assign a single traveling direction of the radiations in the cavity. Polarization state is fixed by a polarizing cube. Owing to the splitting ratio chosen for the beam splitter, a pre-amplification stage can be necessary in the feedback loop.

The laser configuration is designed to filter out the laser field at both the input and the exit of the multicore fiber. As described below, a first selection of the excited supermodes over the whole possible supermodes of the DMCF is performed through the launching conditions. At the opposite end of the DMCF, the filtering achieved by the single-mode fiber provides a feedback signal which is proportional to the intensity of the central peak of the DMCF far field. Intra-cavity losses are therefore minimized for the far field exhibiting the highest brightness and this tends to lock the laser pattern to the mode, or the mode combination, corresponding to the largest number of in-phase emitters. Let us note that high output coupling is chosen for high-power emission. Thus, only a small fraction of the intra-cavity field is sent back to the SMFF, preventing that part of the cavity from damaging power densities. In case the architecture is scaled to very large powers the SMFF should preferably be chosen among the different passive single-mode large mode area microstructured fibers.

The DMCF used in the experiments is a 3-meter long double-clad fiber end-pumped by a laser diode at 980 nm. The inner cladding has a diameter of 480 µm and a numerical aperture of 0.46. The fiber includes 19 coupled Yb-doped single-mode cores: a central core surrounded by two rings of identical cores in a compact triangular arrangement, as shown in Fig. 2. Each core (core diameter $\Phi = 7$ µm) has a low numerical aperture ($NA_{core} = 0.065$), corresponding to a mode field radius in one individual core equal to $\omega_{0c} = 6.3$ µm at $\lambda = 1080$ nm. The centers of neighboring cores are separated by a pitch of 10.5 µm. The overall doped

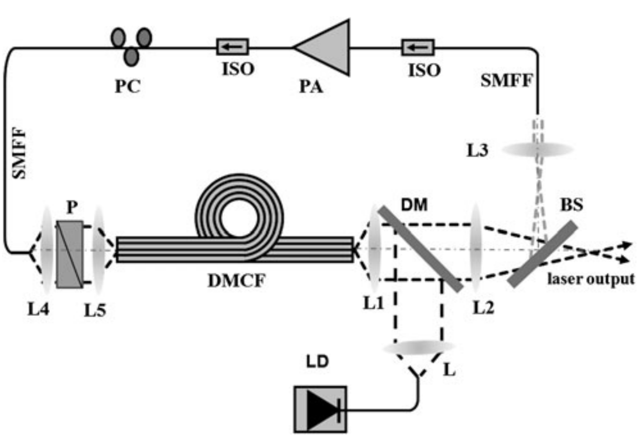

Fig. 1 Experimental set-up. DMCF: doped multicore fiber, SMFF: single-mode feedback fiber, ISO: optical isolator, PA: pre-amplifier, P: polarizing cube, PC: polarization controller, LD: laser diode, DM: dichroic mirror, BS: beam splitter, Li ($i = [1; 5]$): positive lenses

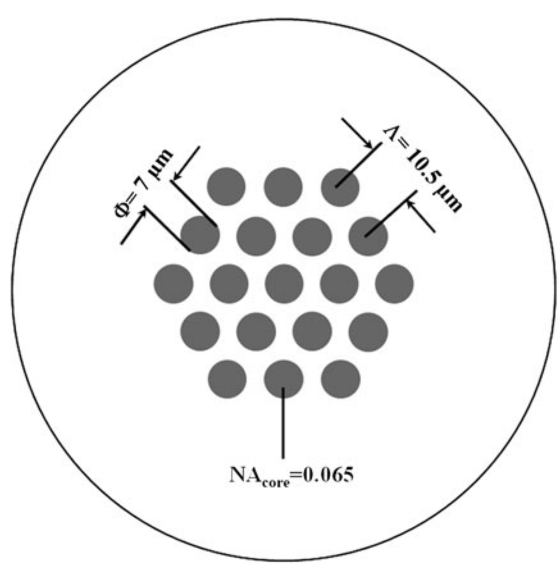

Fig. 2 Geometrical characteristics of the experimental 19-core Yb-doped fiber

area of the multicore fiber section is 731 μm^2, i.e. equivalent to the one of a single core of 30.5 μm diameter. Numerical computations of the different mode field distributions based on the finite element method show that, due to strong coupling between the cores (coupling coefficient = 652 m^{-1}), the fiber can only guide 12 supermodes at the 1080 nm wavelength.

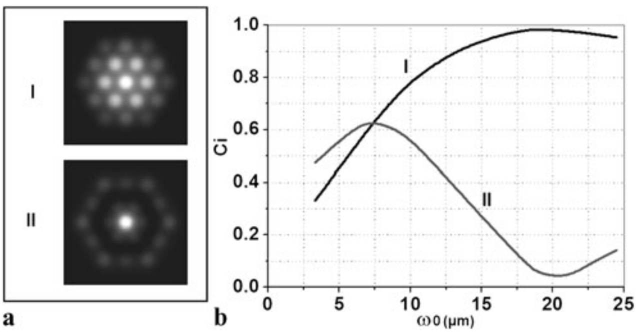

Fig. 3 **a** Intensity distributions of supermode I (fundamental) and supermode II guided by the 19-core fiber under on axis excitation; **b** Coupling coefficient C_i of a Gaussian input beam into the supermodes I and II of the multicore fiber versus the input beam mode field radius

3 Multicore fiber laser: phase-locked dual mode operation

The coupling coefficient C_i of an input beam into the supermode of the multicore fiber labeled "i", is the normalized overlap integral between the input beam and this supermode. The fraction of the input power coupled into the supermode is equal to C_i^2. When a Gaussian beam is launched on axis into the DMCF, the overlap integral with the supermodes exhibiting an azimuthal modulation is zero, and such supermodes are not excited. In other words, the only supermodes to be excited are those with an axial symmetry. In the considered 19-core fiber, the two excited supermodes are shown in Fig. 3a (supermode I = fundamental supermode, and supermode II). The coupling coefficient obviously depends on the mode field radius ω_0 of the input Gaussian beam, as shown in Fig. 3b. With $\omega_0 = 6$ μm, 65% of the input beam power is found to be coupled in a balanced manner, into the two above-mentioned supermodes. The phase velocities of the two supermodes being different ($\beta_I = 8.4360 \times 10^6$ m^{-1}, $\beta_{II} = 8.43438 \times 10^6$ m^{-1}), the intensity pattern at the DMCF output alternates in-phase and out-of-phase combinations depending on the selected wave-

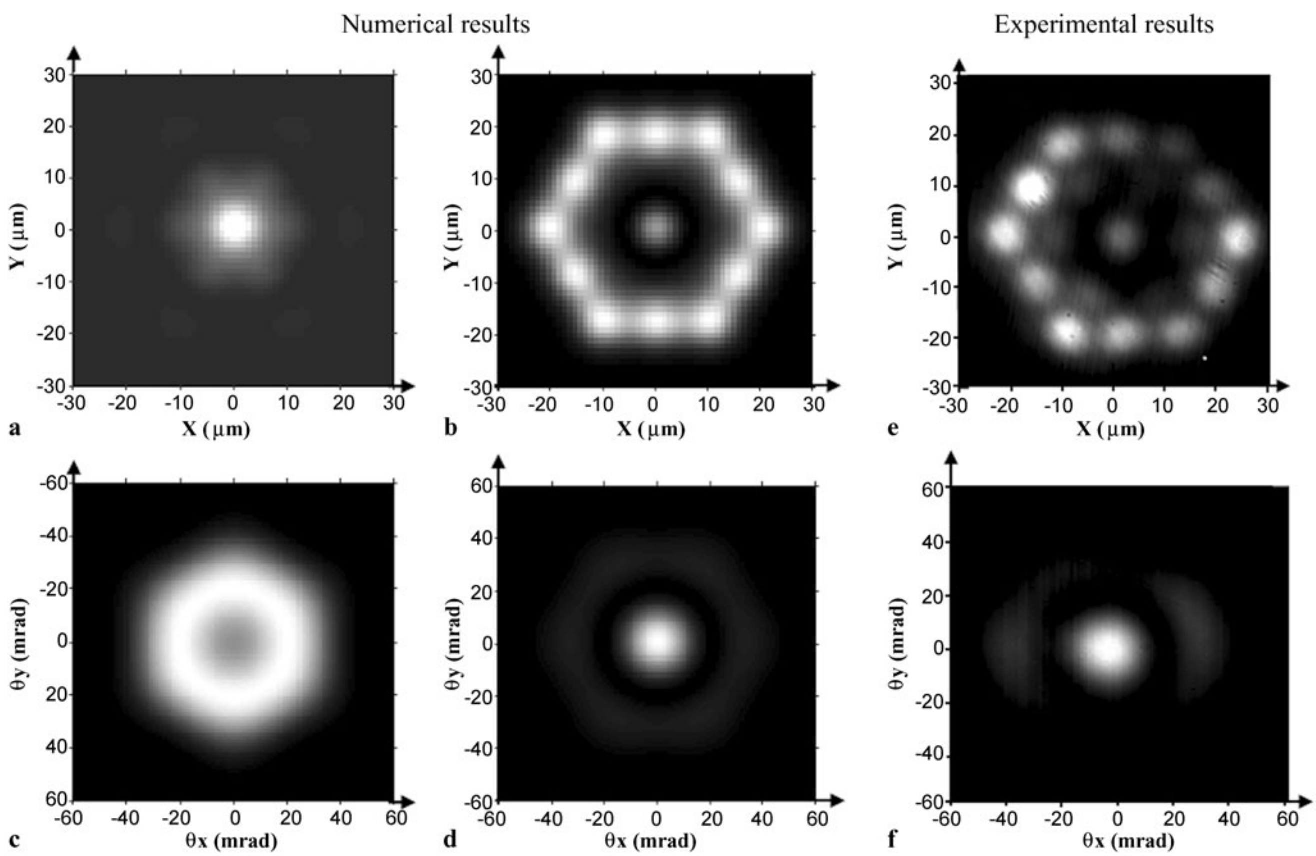

Fig. 4 Theoretical near fields and far fields at the exit of the DMCF when excited by a centered Gaussian beam of 6 μm mode field radius: **a** and **c** in-phase combination of the two supermodes, **b** and **d** out-of-phase combination. Experimental **e** near-field and **f** far-field patterns recorded in the out-of-phase situation

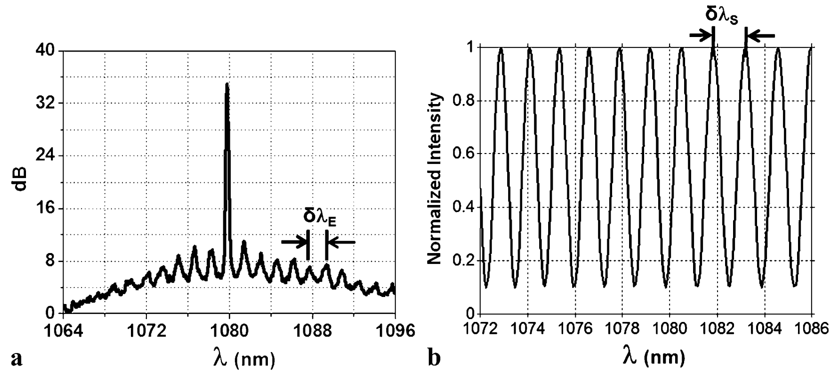

Fig. 5 **a** Experimental laser spectrum. Periodic modulation ($\delta\lambda_E$) corresponds to supermodes beating; **b** Numerical calculation of the spectral response of the 19-cores fiber combined to the SMFF showing a spectral filtering period $\delta\lambda_S$

length, as shown in Figs. 4a and 4b respectively. The corresponding theoretical far fields are shown in Figs. 4c and 4d respectively. In the far field, the beam with the brightest central lobe results from superposition of supermodes with opposite phase (Fig. 4d).

In the experiments, the magnifying telescope L4, L5 (focal lengths respectively equal to 6.2 mm and 11 mm) is chosen to give a ∼6 μm diameter Gaussian spot on the DMCF input face. Positioning stages are then used to center the input beam on the axis of the multicore fiber. Therefore, the main part of the energy is coupled into the two expected modes. At the output end, the resulting field strongly differs depending on in-phase or out-of-phase supermodes superposition. In the out-of-phase case, the far-field pattern (Fig. 4d) better matches the Gaussian mode of the feedback fiber than in the in-phase case (Fig. 4c). As a consequence, the lowest losses experienced by the laser field correspond to the set of wavelengths giving rise to out-of-phase modal interferences at the DMCF output. For the wavelengths yielding to in-phase situation, the far field has a depressed intensity pattern on axis and results in very high losses. Hence, by proper selection of the wavelength, the architecture locks the laser on the two excited DMCF supermodes, in the out-of-phase combination. The experimental data confirm the expected behavior. Figure 4e displays the DMCF near field recorded at the laser output and Fig. 4f shows the corresponding far-field pattern. Both images are very similar to the field distributions derived from numerical computations (Figs. 4b and 4d). The laser delivers a single peaked narrow spectrum centered at 1080 nm (Fig. 5a). A further signature of the strong spectral filtering operated by the laser scheme is visible in the periodic modulation $\delta\lambda_E \approx 1.4$ nm in the background around the main peak. It results from the spectral modulation of losses due to the two-mode interferences being itself related to the propagation constant difference $\delta\beta = \beta_I - \beta_{II}$. By means of the overlap integrals between the two-mode interference patterns and the mode of the SMFF, we have computed the field intensity collected by this SMFF, as a function of the wavelength (Fig. 5b). As expected, the computed spectrum is found to be modulated with a modulation period $\delta\lambda_S \approx 1.4$ nm, in perfect agreement with the experimental results.

4 Multicore fiber laser: fundamental mode operation

The fundamental supermode of a MCF structure with a dense array of cores is usually characterized by (i) a field amplitude with a broad Gaussian envelop, (ii) only weak modulation from the individual cores, (iii) and by a uniform phase. The corresponding emitted beam exhibits high brightness thanks to its large cross-section area and low divergence. Selective excitation of this fundamental supermode is then of high interest. We propose to perform such an excitation enhanced by spatial filtering, in a laser configuration. The Gaussian input beam launched in the DMCF was set to a width ω_0 equal to 21 μm, so that almost all the injected power is coupled to the in-phase supermode as indicated by the curve of Fig. 3b. Its theoretical intensity pattern and the associated far field are depicted in Figs. 6a and 6b, respectively. The coupling coefficient obtained for $\omega_0 = 21$ μm being close to 1, we can deduce that the mode field radius of the in-phase supermode $\omega_{0\text{sm}}$ is ∼21 μm. We have experimentally investigated this situation by simply changing the pair of lenses in the telescope L4, L5 (focal lengths respectively equal to 4 and 25 mm). As expected, we observed that the transverse distribution of the field at the laser output changed from the previous situation (Fig. 6c). It was now similar to the theoretical fundamental mode of the DMCF (see Fig. 3a). The filtering performed by the SMFF serves in particular in case of injection misalignment or in case of coupling to high order modes in the DMCF itself. If there is no coupling between the individual cores, the fiber no longer supports supermodes. However in-phase emission of the core array can still be obtained with the above laser configuration thanks to self-adjustment of the laser wavelength for lowest loss operation.

The M^2 parameter of the emitted beam was calculated from Siegman's definition based on the near-field and far-field patterns [16, 17]. The experimental M^2 value was derived from the near-field and far-field patterns (respectively

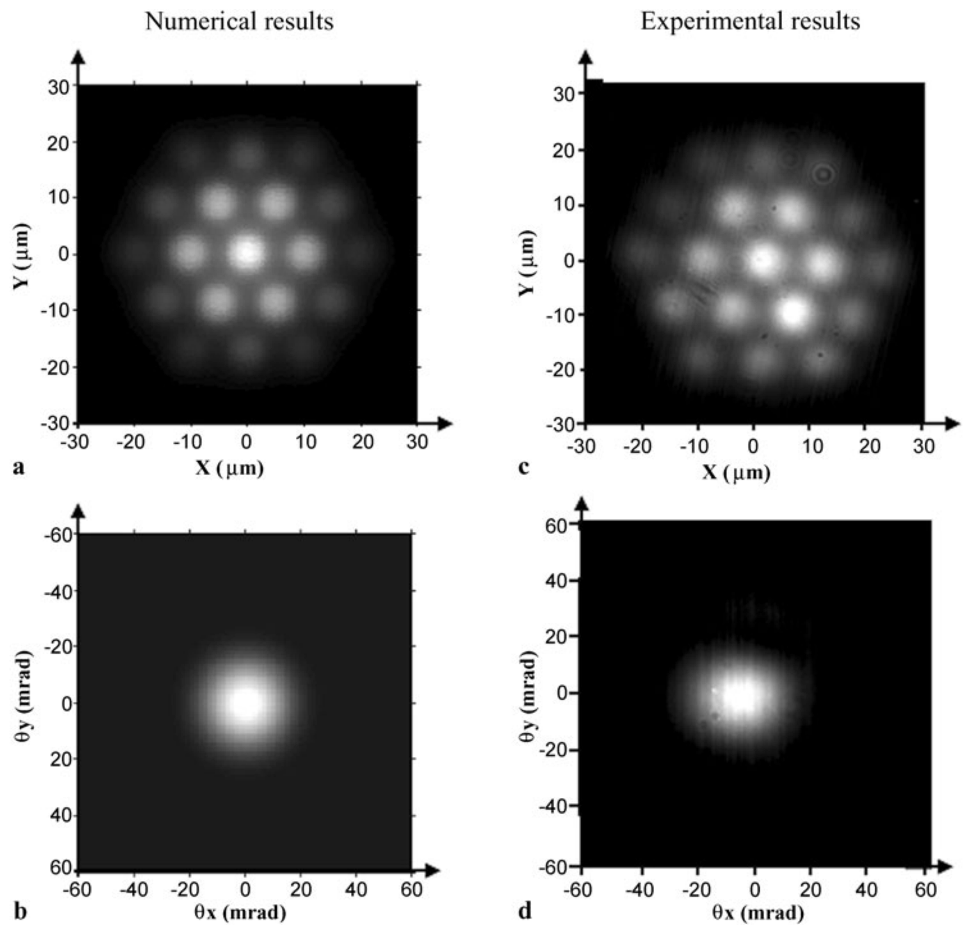

Fig. 6 Theoretical and experimental fundamental mode emitted by the DMCF when excited by a centered Gaussian beam of 21 μm mode field radius: **a** and **c** near fields; **b** and **d** corresponding far fields

Figs. 6c and 6d) recorded by means of a high resolution IR camera. It was found to be ∼1.21, i.e. close to that of a Gaussian diffraction limited beam and in good agreement with the theoretical value of 1.17. The numerical aperture of the beam was measured to be ∼0.02, i.e. 3 times lower than that of a single core. Considering that $\omega_{0sm} \sim 3\omega_{0c}$, this measurement confirms that the beam divergence is minimized and close to the one of a diffraction limited beam of Gaussian profile. These observations attest that the proposed laser configuration actually succeeds in locking its output on the DMCF fundamental supermode. The laser spectrum remains narrow and single peaked at 1078 nm (Fig. 7). We no longer observed periodic modulation in the laser spectrum like in the previous situation with two excited modes (see Fig. 5a). This gives an additional proof that the laser operates on a single transverse mode. The ring laser generates a maximum power of 2.3 W when pumped with 17.5 W of diode laser power at 980 nm. The rather poor conversion efficiency can be attributed to losses from various origins. First, several components of the set-up are not optimized for the 1078 nm operating wavelength. Second, the gain peak of the preamplifier and of the multicore amplifying fiber significantly differs by 45 nm. We can now estimate the potential interest of using a multicore fiber in view of making a bright

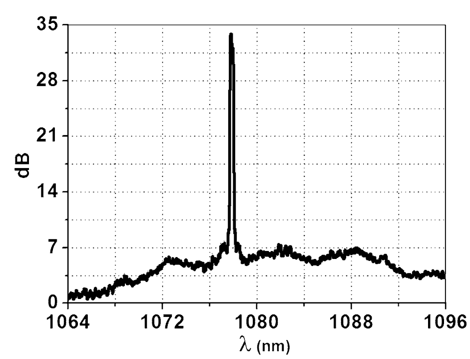

Fig. 7 Experimental spectrum of the 19-cores fiber laser when operated on the pure fundamental supermode mode of the multicore fiber

laser source. By definition the beam brightness (or radiance) is the ratio of the power by the beam cross-section area (S) and by its solid angle (Ω). As indicated above, the product S.Ω of the field from an individual core is almost identical to that of the fundamental supermode of the 19-core fiber. Therefore, the potential gain in brightness should only come from the gain in power. The extractible power from the DMCF cannot reach 19-fold the power available from a single emitter due to the non uniform intensity of the supermode cross section. More precisely, we have calculated that each inner ring core delivers ∼80 of the power emitted by the central core and that each outer ring core delivers only ∼40% of this power (see the in-phase supermode pattern in Fig. 3a.I). Considering this power distribution, a ∼11-fold power increase should be expected leading to ∼11-fold increase in brightness.

5 Conclusion

In this paper, we report a multicore fiber laser configuration suited to the generation of high-brightness beams. The hybrid laser architecture is based on ring geometry including a modal control by both selective injection and angular filtering. Dual mode and single fundamental mode operations were experimentally demonstrated with a double-clad ytterbium-doped 19-core fiber. Observations in terms of near-field and far-field patterns as well as in term of spectral features are in good agreement with the expectations deduced from computations. When operated on the fundamental supermode the laser delivers a beam with a measured M^2 of 1.21, a value indicating a beam quality very close to that of diffraction limited Gaussian beam. The supermode being emitted by the whole array of cores, the extractible power is evaluated to be 11-fold the one of a single core, and the beam brightness can thus be enhanced by a factor 11. The technique could be scaled to amplifying fibers with a larger number of cores or to microstructured fibers with multiple cores of large area. In this paper, the method has been demonstrated with a coupled core amplifying structure but it applies as well to fibers with non-coupled cores. In addition, as a modulator can easily be inserted in the single-mode branch of the resonator, this laser set-up should also be well appropriate for Q-switched regime.

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