Phase locking and in-phase supermode selection in monolithic multicore fiber lasers

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We report a compact multicore fiber laser that utilizes an all-fiber approach for phase locking and in-phase supermode selection. By splicing passive coreless fibers of controlled lengths to both ends of an active 19-core fiber, we demonstrate that the fundamental in-phase supermode can be selectively excited with a completely monolithic fiber device, instead of conventional free-space and bulk optics, to achieve phase-locked operation for a multiemitter laser device. © 2006 Optical Society of America

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Active fibers with multiple cores have provided a convenient and promising power-scaling solution for compact high-power fiber laser devices.[1] As the gain medium is split at discrete positions inside the cladding instead of all being concentrated in an oversized core, the thermal issue is less of a concern for multicore fiber (MCF), and more output power can be extracted per unit length of fiber.[2] However, there still exists the challenge to effectively obtain high-brightness output beams to make MCF advantageous compared with traditional monocore fibers. For a MCF with a two-dimensional (2-D) core array, if each core is single mode and neighboring cores are optically coupled, the total number of nondegenerate supermodes equals the number of cores. Among all supermodes, only the in-phase mode (all cores emit in phase) has the preferable Gaussian-like far-field intensity distribution.[3] Therefore, the MCF resonator needs to be explicitly designed to establish the exclusive in-phase mode oscillation.

Several coherent beam combining techniques exist to phase lock multiple emitters in fibers, including the use of a Talbot cavity,[4,5] a structured mirror,[6] a collimating lens with a high reflector,[7,8] and a self-Fourier transform resonator.[9] All these approaches involve free-space optics, i.e., air gap and bulk optics, as part of the resonator. The inclusion of free-space optics not only substantially increases the device size and alignment complexity but also decreases the laser efficiency owing to the additional cavity losses. More important, it may cause serious instability problems in high-power operation because of its susceptibility to environmental and thermal disturbances. For one to take full advantage of a fiber device, i.e., of its compact size as well as its robustness against external disturbances, the phase-locking operation should ideally take place inside a confined waveguide. We note that, while there have been all-fiber approaches preferring out-of-phase mode lasing with ring-distributed MCFs[10,11] and in-phase mode amplification (seeded by a pulsed Gaussian beam) with isometric-array MCFs,[3] there is a lack of reports of in-phase mode oscillation through a monolithic fiber device.

In this Letter we report an all-fiber approach that effectively selects the fundamental in-phase supermode of MCF lasers. By combining Talbot and diffraction effects, we show that the preferable supermode can be selected by use of passive optical fibers of appropriate lengths, fusion spliced to both ends of an active MCF (Fig. 1). Based on a 19-core MCF, such an all-fiber device has been fabricated, and its laser emission properties have been studied. The phase-locked laser beam has been observed as a high-brightness on-axis spot in the far field, in sharp contrast with the messy pattern from the same MCF without mode-selecting measures. All components of this device can in principle be incorporated into a single fiber, and the whole system is alignment free in operation. This all-fiber design is robust against environmental and thermal disturbances at all power levels and can be conveniently integrated into compact photonics systems.

MCFs are typically designed to exhibit core arrays either in ring or isometric distributions. It is well known that as one-dimensional (1-D) periodic coherent waves propagate, there exists a Talbot distance $Z_T = 2\Lambda^2/\lambda$ where the periodic structure repeats itself at multiple(s) of Z_T.[12] Here λ is the free-space wavelength and Λ is the periodicity. Therefore, each supermode emission of a MCF repeats itself with a charac-

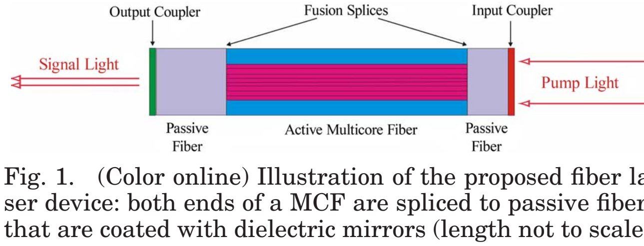

Fig. 1. (Color online) Illustration of the proposed fiber laser device: both ends of a MCF are spliced to passive fibers that are coated with dielectric mirrors (length not to scale).

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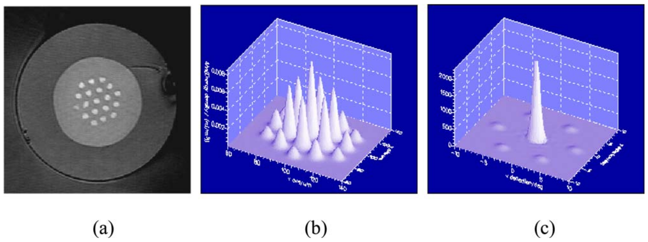

Fig. 2. (Color online) (a) Microscopic image of an active 19-core fiber and calculated (b) near-field and (c) far-field intensity distributions of the fundamental in-phase supermode.

teristic distance after exiting the fiber facet. If we place a mirror at $Z_T/2$ of the in-phase mode, it will be reflected and coupled back into the MCF with minimum loss. The mirror distance Z_M can then be utilized to support or suppress oscillations of selected modes. However, the previous expression of Z_T applies only to the ideal case of 1-D infinitive periodic structure but not for MCF with a 2-D finite core array. In addition, individual supermodes have different diffraction properties that also affect the dependence of the modal reflection coefficient (γ) on Z_M. Rigorous analysis is thus needed to calculate γ as a function of Z_M.[13] Accounting for both Talbot and diffraction effects, it is possible to identify desirable Z_M where the in-phase mode is decisively favored, and this mechanism has been demonstrated with free-space optics for MCF lasers.[4,5]

Nonetheless, the principles described above work no matter what the medium is, air or any dielectric medium, with negligible transmission loss. We thus propose to propagate, reflect, and couple the waves inside low-loss waveguides, e.g., passive optical fiber, to select the in-phase mode and suppress high-order modes. Passive fiber may be spliced to one end of a MCF with an effective wavelength λ/n, where n is the medium refractive index. Furthermore, as the modal suppression effect is finite, we may reinforce the Talbot and diffraction effects by applying them twice: passive fibers of appropriate lengths can be spliced to both ends of a MCF. The detailed structure of the MCF device is illustrated in Fig. 1, with the two cavity mirrors directly deposited onto the passive fiber facets, forming a monolithic all-fiber device. Pump light is launched at one end into the MCF cladding, and the signal exits from the other end.

Prototypes of this MCF laser device have been fabricated and tested to demonstrate the all-fiber mode-selection concept and study the modal properties of the emission. An active 19-core MCF (MC19), as shown in Fig. 2(a), has been used. The MC19 cores are made from heavily Er–Yb-codoped (1.5 wt. % Er_2O_3 and 8.0 wt. % Yb_2O_3) phosphate glass designed for compact high-power fiber lasers.[14] The MC19 has a 200 μm outer diameter and an isometric core array of periodicity 14.4 μm, and each core is 7.6 μm in diameter. The core is single mode (NA of 0.12 at 1.5 μm) with a calculated full angular spread of 0.20 rad. The supermodes of this MC19 have been calculated by using a finite-element method[15] with the near- and far-field intensity distributions of the in-phase mode shown in Figs. 2(b) and 2(c). The Gaussian-like far-field distribution has a full angular spread of 0.04 rad.

In the experiments, a short piece of MC19 (10 cm long) served as the gain fiber. A first fiber laser was built from a piece of bare MC19 without additional modal controlling. By butt-coupling one end of the MC19 to a multimode pump-delivery fiber that had a broadband high reflector (at ~1.5 μm) deposited on its facet, the 975 nm pump light was launched into the MC19 cladding. This MC19 has a lasing threshold of ~4 W pump and a slope efficiency (SE) of 13% with respect to the launched pump power. The output far-field distribution, recorded on a screen 7.5 cm away from the output facet, is shown in Figs. 3(a) and 3(b) with a spread of ~0.19 rad. Note that this angle is nearly identical to that of an individual core, meaning that the cores are only weakly coupled in the short fiber cavity without proper external feedback. The second tested MCF device was fabricated by using the same MC19 with a piece of passive fiber spliced to its output end. The passive fiber had a uniform index distribution (coreless) and a diameter of 200 μm. To sufficiently suppress the high-order modes, a relatively long piece of passive fiber, ~1.7 mm, was spliced. The fabricated device was pumped and tested in the same way as the first one,

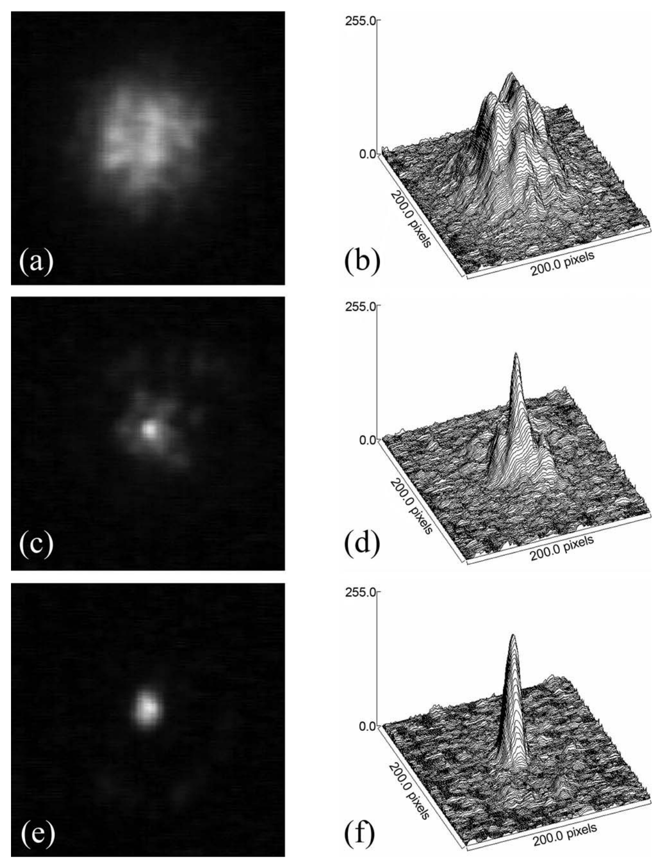

Fig. 3. Far-field intensity distributions of MC19 laser emissions: (a), (b) bare MC19; (c), (d) one end spliced with passive fiber; (e), (f) both ends spliced with passive fibers. (b), (d), and (f) are three-dimensional views of (a), (c), and (e), respectively. All photos are taken at an output level of ~200 mW.

and the resulting far-field pattern is shown in Figs. 3(c) and 3(d). Note that the on-axis intensity is considerably enhanced but contributions from high-order modes are still significant. To reinforce the mode-selecting effect, a third device was fabricated by adding another piece of passive fiber, ~0.5 mm, to the pump end of the second device. Tested in the same manner, the far-field pattern of the output beam is shown in Figs. 3(e) and 3(f). A clean and well-confined on-axis spot with a horizontal spread of 0.04 rad is observed, which is identical to the predicted value of the in-phase mode of MC19. The beam is a little elongated vertically, and we believe that the manufacturing defects of the MC19, e.g., noncircular core shapes and cleaving marks as seen in Fig. 2(a), are responsible. In all, the clear distinction between Figs. 3(e) and 3(a) demonstrates the effectiveness of our all-fiber supermode selection approach. This third MCF laser had a threshold of ~6 W pump and a SE of 4%, due to extra losses at the splices and inside the passive fibers. However, when we later added an output coupler with a pump reflectivity of >99% and a signal reflectivity of 54%, the laser SE increased significantly to 14%.

Typical output spectra from both the first (bare MC19) and third (MC19 spliced with dual passive fibers) devices are shown in Fig. 4. The latter has a much narrower emission spectrum, providing further evidence for the reduced number of supermodes and the phase-locked status. The spectral narrowing of the latter is substantial (3 dB linewidth of ~0.2 nm), considering that all the mirrors used are broadband reflectors. This indicates the potential of our approach as single-frequency fiber laser with large power-scaling capability if linewidth-narrowing elements were incorporated.

Finally, we point out that the mode-selecting fiber lengths at both ends of the MC19 are not chosen arbitrarily. We tested MC19 samples with spliced passive fibers of various lengths, from 200 to 2000 μm, and found that the previous length combination, with a tolerance of ~50 μm, gave the best output beam quality. It seems that longer passive fiber does not

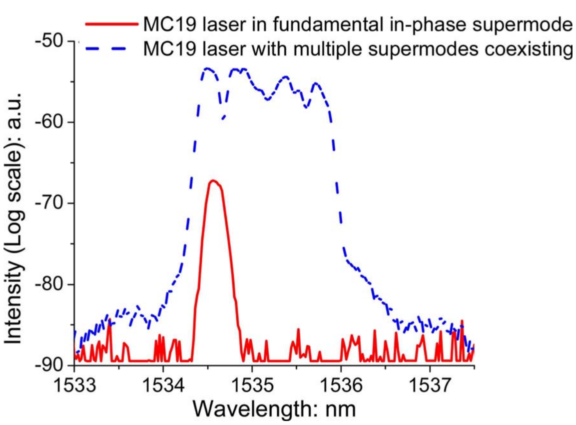

Fig. 4. (Color online) Spectra of MC19 lasers with dual spliced passive fibers (solid curve) and with no modal controlling elements (dashed curve).

necessarily lead to better mode selection. As passive fiber length increases, multimode interference comes together with Talbot and diffraction effects.[16] A systematic study is currently under way, and a detailed analysis will be reported elsewhere.

In conclusion, we have proposed and demonstrated an all-fiber approach, by adding passive fibers at both ends of a MCF, to fabricate a MCF laser that selectively oscillates in the fundamental in-phase supermode. This approach is not limited to the specific 19-core fiber used for demonstration and should be applicable to MCFs with general core array designs.

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