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Phase locking in a fiber laser array with varying path lengths

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Phase locking has been demonstrated in fiber lasers coupled to a common resonator containing a spatial filter. The phase-locked mode is highly stable despite the phase variations in the individual elements caused by thermal and mechanical effects. The ability to maintain phase locking is attributed to a self-adjusting process, which can be found only in systems with a combination of high gain, long length, low Q, and broad gain bandwidth, all of which can be met in fiber laser arrays. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1826235]

Fiber lasers are becoming the geometry of choice for high-power solid-state lasers because of proven advantages in compactness, efficiency, and beam quality. A single-mode fiber laser producing an output of kilowatts has been demonstrated.[1] The ultimate limitation of power from a single fiber laser is limited by the onset of nonlinear effects such as stimulated Raman scattering and stimulated Brillouin scattering. Further increase in output power will require coherent addition of the outputs from multiple lasers in a laser array. Many researchers have studied beam combination in laser arrays using various techniques, including interferometric addition in fiber couplers,[2–6] the Talbot resonator,[7–9] a self-organization mechanism in evanescent-coupled multicore fibers,[10,11] and active phase correction.[12] Generally speaking, the techniques of combining the output power of multiple fibers into a single fiber through fiber couplers does not remove the limitation to the ultimate power of a single fiber. The Talbot resonator tends to favor the out-of-phase mode and has not yet achieved single-mode operation with diffraction-limited performance. The technique of active phase correction involves complicated interferometric detection and phase modulation for each element.

From the phase control standpoint, the fiber laser arrays are different from laser arrays with monolithic gain elements with fixed lengths, such as diode laser arrays and solid-state (crystal) laser arrays,[13–15,17] in their unequal and ever-changing path lengths among the fiber elements. The lengths of typical fiber lasers range from meters to tens of meters. It is practically impossible to ensure equal lengths. The optical path lengths are also constantly changing due to uncontrollable thermal and mechanical effects. Assuming a thermal coefficient of path-length change of $10^{-5}/°\mathrm{C}$,[16] a temperature drift of 0.01 °C can result in a phase shift of π in a 5 -m-long silica fiber and totally alter the interference condition. An effective phase-locking technique must be able to respond to the changes and maintain a stable beam profile.

In this letter, we report that fiber lasers of arbitrary lengths can be stably phase locked to produce a diffraction-limited beam of the in-phase mode despite constant and random changes in the optical path length in the individual elements. The ability to adapt to the changing environment is attributed to a self-adjusting process that can take place only in systems with a combination of long length, broad gain bandwidth, and low Q resonator, all of which can be found in fiber laser arrays.

The schematic of the experimental setup is shown in Fig. 1. Coherent beam combination of two fiber lasers is performed in a confocal self-imaging resonator, similar to the ones used previously to phase lock one- and two-dimensional laser arrays of fixed lengths.[13,14] The resonator projects the far-field patterns of the fiber emitters located at a focal plane S2 of a converging lens to the output mirror located at the other focal plane S3. When the waves from the emitters have the same phase, the far-field pattern is always simple with constructive interference occurring at zero degree. A matching spatial filter can be placed at the output mirror for mode selection. In the present study, the fiber gain media are the Nufern PM-YDF-5/125 double-clad ytterbium-doped fibers with a core diameter of 5 μm. The fiber lengths are 5.6 and 8.2 m, respectively. The nominal numerical aperture is 0.46 for the inner cladding and 0.15 for the core. The small-signal absorption coefficient is 1.7 dB/m at 975 nm. The fiber lasers are end pumped by two fiber-coupled laser diodes emitting at 972 nm wavelength. The fibers are terminated at S1 with a high reflectivity mirror centered at 1064 nm. The other ends are perpendicularly cleaved with 4% reflectivity. The beams from the fiber ends

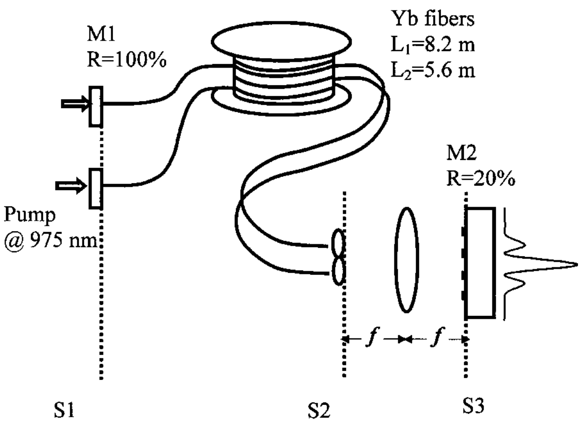

FIG. 1. Schematic of the experimental setup.

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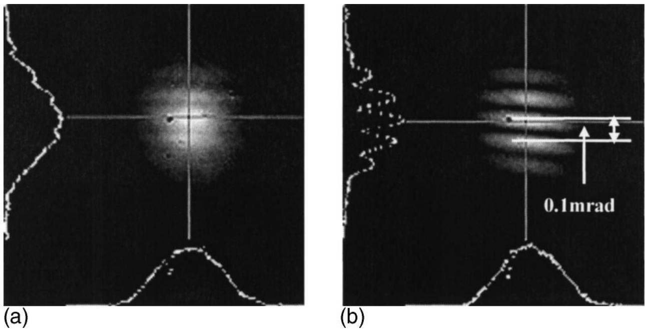

FIG. 2. Beam patterns of the laser array in (a) free running, (b) in-phase modes.

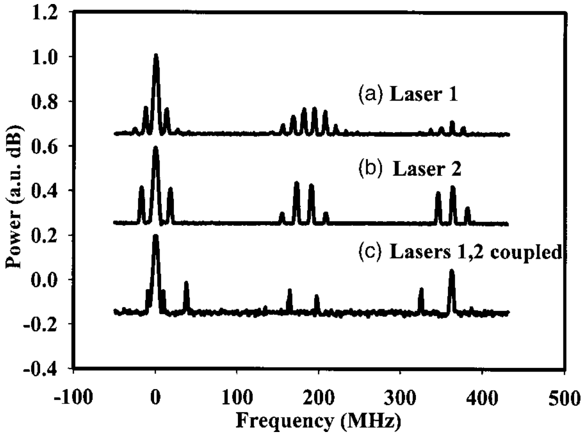

FIG. 3. Spectra of intensity fluctuations of individual and phase-locked lasers.

are expanded to a diameter of 3 mm. The collimated beams are positioned on the focal plane S2 of a converging lens. The center-to-center separation between the two beams is 1.1 cm. The output mirror with a reflectance of 22% at 1064 nm is placed at the other focal plane at S3. For the convenience of being able to construct the spatial filter using easily available thin metal wires, the focal length is chosen to be 40 cm. A much shorter focal length may be used with finer grid patterns made by, for example, photolithography.

With the aid of a charge-coupled device camera and a laser beam analyzer, we examine the beam profile of the output at focal plane S3. Figure 2(a) shows the beam profile at the output mirror of a free-running laser array without a spatial filter. The beam profile exhibits low-contrast interference fringes that are constantly moving with irregular pace and direction. The pace of fringe movement exacerbates and the contrast further degrades when the individual fibers are subject to mechanical perturbations. To stabilize the phase relation, we introduce a single gold wire as the spatial filter in front of the output mirror to create a higher loss for the out-of-phase mode. Ideally, the best effect is achieved with a thinner wire at the first intensity minimum of the in-phase mode. For example, a 5 μm wire at the first intensity minimum of the in-phase mode would introduce an 8% loss to the out-of-phase mode and 0.1% loss to the in-phase mode. For easier handling, we used a 12.75 μm wire at the third intensity minimum of the in-phase mode to create 2.1% loss for the out-of-phase mode and 0.2% loss for the in-phase mode. When the wire is moved across the beam at the output mirror, the position of the intensity minimum simply follows that of the gold wire. Figure 2(b) shows the beam profiles of the in phase. The small width-to-separation ratio of 3:11 of the collimated beams from the fiber emitters is limited by the available collimators, thus considerable fraction of the total energy is found in the side lobes. More energy can be concentrated in the central lobe by increasing the width of the individual beams relative to the separation.

With the spatial filter in place, the phase locking is stable even when the optical path lengths are deliberately changed. For example, no slight fringe movement is observed when the temperature of one of the fibers is raised by 20 °C, which changes the relative optical path length by at least 200 wavelengths. It appears that a self-adjusting process has taken place to adapt to the changing environment.

The self-adjusting process can be understood in terms of selection of common resonances in a compound resonator.[3–6] The position of the spatial filter at the output mirror dictates the relative phase in the laser array. The resonance frequencies of the waves in the fiber laser array, with individual length L_1 and L_2, must simultaneously satisfy the boundary conditions of having nodes at plane S1 and having the same phase at S2. Thus the lasing frequencies are characterized by the common multiples of the free spectral ranges $c/(2nL_1)$ and $c/(2nL_2)$ of the individual fiber lasers. When the optical path length of one of the elements changes, a new set of common resonances of the slightly shifted longitudinal modes must emerge. This self-adjusting process is not always possible, but works best in laser systems with a combination of broad gain bandwidth, long and unequal lengths, and low-Q resonator. The broad bandwidth and long lengths provide a large number of closely spaced longitudinal modes within the gain bandwidth, making it easier to find common resonances. The low-Q values of the resonator broaden the resonance lines to allow those near the common resonance to overlap. In the present case, there are 10^5 longitudinal modes within the gain bandwidth of the fiber laser with 5 m length. The fiber resonators with 100% and 4% reflectance at the end mirrors have a finesse value of 2. Thus all of the favored conditions can be met in fiber lasers.

To study the longitudinal mode spectra, we analyzed the intensity fluctuations of laser output using a radio-frequency spectrum analyzer. First, we align the output mirror to decouple the two fiber lasers. The spectra of the beat waves of the individual lasers, shown in Figs. 3(a) and 3(b), consist of equally spaced peaks with an envelope modulation of 180 MHz, which is caused by the 0.8-m-long external cavity. The beat frequencies of 12.53 and 18.35 MHz are the free spectral ranges of the fiber lasers of length $L_1 = 8.2$ m and $L_2 = 5.6$ m, respectively. When the output mirror is aligned to create the phase-locked mode, the spectrum of the beat waves exhibits fewer peaks at 38 MHz and its multiples at 153 and 198 MHz, respectively. In the present coupled system with a length difference of $\Delta L = 2.6$ m, the minimum common multiple is predicted to be $\Delta\nu = c/(2n\Delta L) = 39$ MHz, which is consistent with the observed value of 38 MHz.

Figure 4 shows the measured ouput versus pump power relation of the individual fiber lasers and for the phase-locked array operating in the in-phase mode. The slope efficiencies are 39%, and 40% for laser 1 and laser 2, respectively, and 43% for the phase-locked mode. The efficiency of coherent power combination is 92% for a pump power of 600 mW.

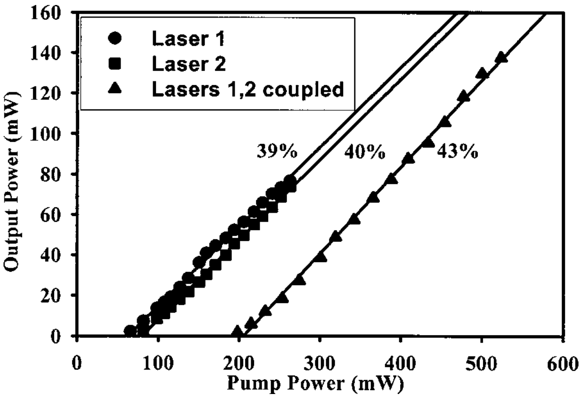

FIG. 4. Output vs pump power relation of the laser array and the individual element.

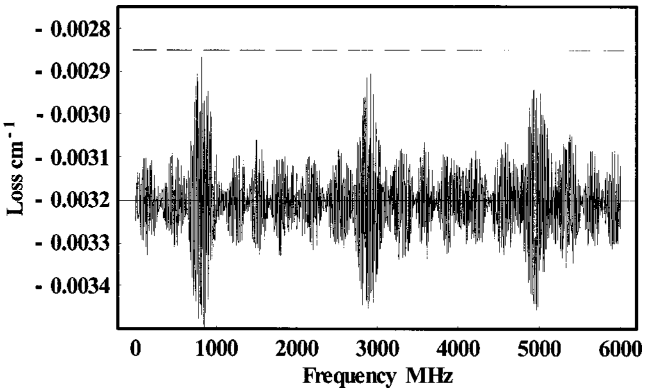

FIG. 5. Simulation of average resonator loss for a ten-element fiber resonator coupled in parallel. The individual lengths range from 4.8 to 5.25 m with a 5 cm increment and 0.5 cm random length uncertainty. The dashed line indicates the loss of the individual resonators.

The use of the self-adjusting process for stabilizing phase locking in a common external resonator is applicable to laser arrays containing a large number of fibers whose ends are arranged in a rectangular grid or annular formation and coupled in parallel to a common resonator.[14] The resonator loss of a system of N resonators coupled in parallel is the average value of those of the individual resonators given by

$$\alpha = \frac{1}{N}\sum \frac{1}{2L_i}\ln\left(\frac{R}{(1-\sqrt{R})^2+4\sqrt{R}\sin^2(kL_i)}\right), \qquad (1)$$

where k is the wave vector and L and R are the length and mirror reflectivity of the individual resonator. We have simulated the resonance condition for a system of ten optical-fiber resonators whose lengths range from 4.8 to 5.25 m with a length increment of $\Delta L = 5$ cm and a random uncertainly of 0.5 cm. The low-Q resonators are assumed to have mirrors with 100% and 4% reflectivity. Figure 5 shows a spectrum of the loss of the composite resonator as a function of frequency. The spectrum exhibits an envelope modulation of 2 GHz, corresponding to the length increment of 5 cm $[\approx c/(2n\Delta L)]$, while the loss at common resonances is approximately the same as that of the individual resonators. When the optical path lengths of the individual elements change, a new common resonance can always be found with a frequency shift of less than 2 GHz.

The outputs of the individual fiber lasers as well as the phase-locked laser array are unpolarized. In the present experiment, no special effort was made to align the polarization axes of the polarization maintaining fiber of the two fibers because a polarization eigen state can always be found in a two-element system regardless of relative orientation.

In conclusion, we have successfully phase locked two fiber lasers with unequal and varying optical path lengths with high efficiency. The stable phase locking is attributed to a self-adjusting process by which the laser array prefers to operate in common resonance frequencies of the composite system. This is mainly due to the specific virtues of fiber lasers of having long length, broad bandwidth and low Q resonator. The study points to the possibility of phase locking of a large number of fiber lasers without the needs for active phase control.

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