Phase locking of a two-dimensional laser array by controlling the far-field pattern

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(Received 10 November 2003; accepted 16 February 2004)

We report phase locking of a two-dimensional laser array through beam control in the far field of the emitters. Compared to the near-field techniques, the far-field approach involves simpler beam profiles and does not rely on having a large number of emitters in a perfectly periodic structure. Our experimental results and computer simulation also point to much higher feedback efficiency, less sensitivity to power variations among the emitters, and the ability to repair a missing element. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1699448]

There has been much interest in the mechanisms that will permit phase locking of the elements of solid-state laser arrays to produce a diffraction-limited beam. Various schemes, such as employing an intracavity spatial filter,[1] evanescent coupling,[2–4] or the Talbot effect,[5,6] have been studied. Phase locking in two-dimensional fiber laser array containing 18 elements on an annular pattern has been demonstrated with a Talbot resonator utilizing the self-imaging properties of coherent periodic structure.[5,6] A mirror is placed at the Talbot distance or fractional Talbot distances to project the images back to the emitters to facilitate phase locking. Recently it has been demonstrated that the resonator losses caused by beam spreading in the radial direction in free space can be reduced by employing an annular waveguide.[7] The self-imaging annular Talbot effect is conceptually simple and elegant. However, like other near-field diffraction effects, the Talbot images involve complicated and rapidly evolving beam profiles and wave fronts, which increase the difficulty in alignment and mode control. The emitters must be arranged in a nearly perfect periodic structure.

In this letter, we report phase locking of a two-dimensional laser array through beam control in the far field of the emitters. The beam profiles of laser arrays are much simpler in the far field, especially for the in-phase mode, because all elements in the array interfere constructively at zero degree. We used the self-imaging confocal resonator in which the far-field patterns of the emitters are formed at the output mirror. Using this configuration, Ménard *et al.*[8,9] first demonstrated the phase-locked operation in a two-element system. The application of this technique to a multielement system in a two-dimensional pattern faces new issues including proper patterns of the emitters, deviation from periodicity, and sensitivity to power variations among the emitters. Our experimental results in a 2×2 laser array and computer simulation for an annular array of a large number of elements indicate that beam control in the far field can result in much higher feedback efficiency, higher tolerance to deviations from perfectly periodic structure, and the ability to repair a missing element.

The schematic of the experimental setup is illustrated in Fig. 1. A Nd:YVO_4 crystal is end-pumped by four continuous-wave pump beams from four optical fibers, each delivering 1 W at 808 nm. The resonator terminates on one side in a flat-output mirror (M2) with 6% transmission at 1064 nm and on the other side on the surface of the Nd:YVO_4 plate (M1) coated for high reflectivity at 1064 nm and >96% transmission at 808 nm. Mirrors M1 and M2 were located on the focal planes on each side of the converging lens. 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.

The 1-mm-thick vanadate crystal, containing 2 at. % Nd doping is surface-cooled through contact bonding with a sapphire crystal. The uncoated bonding interface between Nd:YVO4 and sapphire has a 0.4% residual reflectance. The optical fibers for delivering the pump beams have a core diameter of 200 μm and numerical aperture of 0.39. The fibers are symmetrically positioned at the corners of a square with various separations ranging from 0.5 to 1 mm between adjacent elements.

The beam profiles at the gain elements and at the output mirror are related to each other through a Fourier transform. An arbitrary beam profile $E(x,y)$ at the gain elements re-

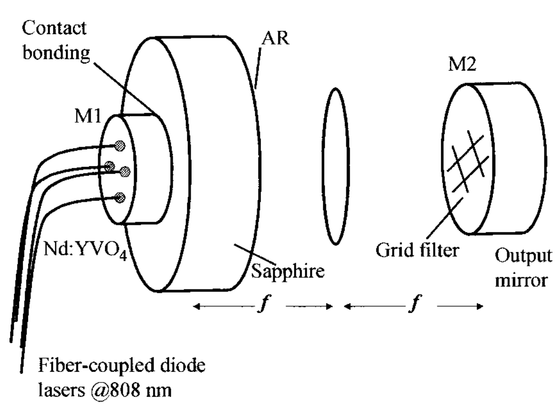

FIG. 1. Schematic of phase-locked 2×2 laser array in a self-imaging resonator.

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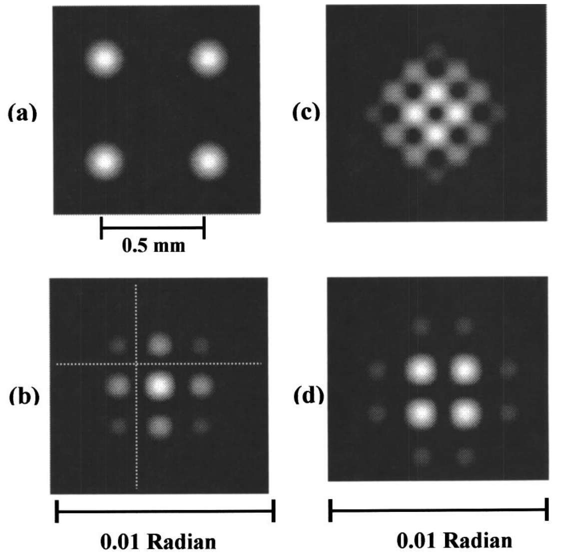

FIG. 2. Beam profiles (a) at the emitters, and in the far field for four coherent Gaussian beams with various phase difference between adjacent elements. (b) $\Delta\phi=0$, (c) $\Delta\phi=\pi/4, 3\pi/4$, and (d) $\Delta\phi=\pi/2$. The dotted lines mark the position for spatial filter for mode control.

turns as $E(-x,-y)$ after each round trip. Thus a symmetric beam profile about the axis of the resonator reproduces itself after every round trip. The emitters do not need to be periodically positioned. For coherent beams originating from the gain elements, the calculated beam profiles in the far field for various phase differences between adjacent elements are shown in Fig. 2. The physical dimension of the beam at the output mirror equals the beam divergence angle multiplied by the focal length. The calculation was done for a separation of 500 μm between adjacent elements and an individual beam waist of 150 μm. The in-phase mode is the only pattern with constructive interference at the center. Thus, mode selection can be done by placing a pair of cross hairs along the intensity minima of the in-phase mode, marked by the dotted lines, at the output mirror.

For the inter-element separation of 500 μm, the evanescent coupling results in the operation in the out-of-phase mode at the threshold when a uniform output mirror is used. As the pump power increases, the competition among the transverse modes results in beam instability. By placing a pair of tungsten cross hairs of 20 μm diameter along the intensity minima of the predicted modal patterns at the output mirror, the laser operates stably in the in-phase or out-of-phase modes, shown in Fig. 3, at all pump powers up to twofold excess of the threshold, without mode competition or beam movement. The full width at half maxima of the

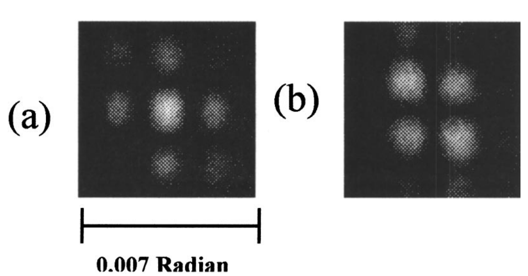

FIG. 3. Beam profiles of (a) in-phase mode and (b) out-of-phase mode at 500 mW output power.

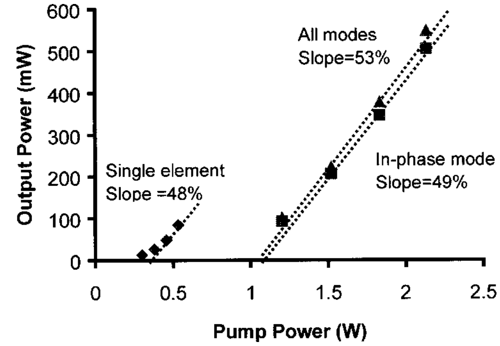

FIG. 4. Output power vs input power characteristics of the four-element laser array. Also shown are the characteristics when only one element is operating.

central lobe of the in-phase mode is 1.1 mrad and remains unchanged with pump power. The output power versus input power of the laser array operating in all modes, without the spatial filter, and in the in-phase mode are shown in Fig. 4. The slope efficiency is 53% for all modes and 49% for the in-phase mode. The presence of the spatial filter results in a slight increase in threshold however the slope efficiency of the in-phase mode is still higher than the slope efficiency of 48% when only one element is operating.

The phase locking is quite insensitive to power variations among the pump beams. For example, with the spatial filter in place, the beam profile of the in-phase mode is nearly unaffected when one of the pump beams is completely turned off. The combined pump power at threshold also remains unchanged because the other three elements deliver 33% higher pump power to compensate for the missing

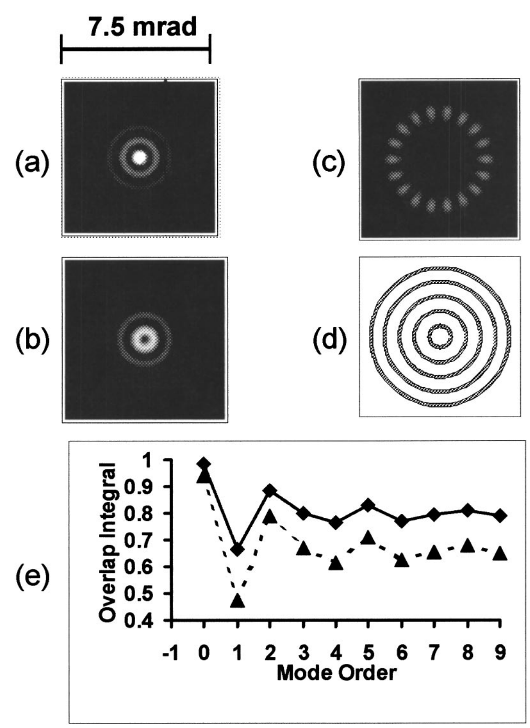

FIG. 5. Calculated modal patterns at the output coupler of an 18-element annular laser array for (a) $\Delta\phi=0$, (b) $\Delta\phi=\pi/9$, (c) $\Delta\phi=\pi$, (d) the spatial filter consisting of concentric rings along the minima of the in-phase mode with an angular width of 0.25 mrad, and (e) calculated overlap integral when the widths of the rings of the spatial filter are 0.15 mrad (diamond) and 0.25 mrad (triangle).

fourth element. The missing element appears to be ''repaired'' by the image of the diagonal element after one round trip.

The simplicity of the modal pattern, the efficiency of the feedback, and the relaxation of the requirement from exactly periodic to inversion symmetric placement of the emitters make the present far-field approach very attractive for laser arrays with a large number of elements. For comparison purposes, we calculated the beam profiles for an 18-element laser array equally spaced on an annulus of 776 μm radius, with an individual beam waist of 100 μm. The selected modal patterns are shown in Figs. 5(a)–5(c). Also shown in Fig. 5 is the amplitude reflection coefficients of various supermodes, calculated from the overlap integrals of the emitted wave field and the reflected wave field with a spatial filer in place. The filter, shown in Fig. 5(d) consists of a set of concentric rings placed along the intensity minima surrounding the central peak of the in-phase mode. The amplitude coefficients and the difference between the highest and next highest values depend on the width of the spatial filter. The values for the in-phase mode are generally higher than 90%, which is considerably higher than theoretical limit of 70% for the Talbot resonator with an annular waveguide. The difference between the two highest values is 12%, which is comparable to the value of approximately 12% for the Talbot resonator. Thus, our approach has the advantage of higher efficiency and the ability to promote the in-phase mode while providing comparable modal discrimination against other supermodes.

In conclusion, we demonstrated phase locking in a two-dimensional array through beam control in the far field of the emitters. Compared to the Talbot resonator, which utilizes diffraction in the near field, the far-field approach involves simpler beam profiles and does not rely on having a large number of emitters in a perfectly periodic structure. Our experimental results and computer simulation also point to much higher feedback efficiency, less sensitivity to power variations among the elements, and the ability to repair a missing element.

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