Self-organized coherence in fiber laser arrays

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(Abstract)

We report producing stable, coherent, and same-phase states in arrays of fiber lasers. Provided proper interactions between the lasers are present, arrays will spontaneously self-organize into stable coherent same-phase states. There is no need for active control. Power scaling, power spectra, spatial interference fringes, and temporal data all support this conclusion.

(Body)

As high brightness sources, laser arrays offer robustness, reliability, thermal management, and efficiency superior to monolithic lasers. Maximum spatial brightness is gained from an array that has constant – and zero – relative phases between array members at the output; this is called the inphase state. While the brightness from an incoherent array increases as the number of lasers (N), the brightness of an inphase array will increase as N^2. For these reasons small groups of lasers operating coherently have recently received attention. Several investigators focused on two [1-3] erbium-doped fiber lasers or conventional Nd-crystal lasers [4]. Up to four [5] erbium-doped fiber lasers, as well as up to 19-core ytterbium-doped-fiber lasers [6] have also been reported. This Letter reports our initial experimental findings demonstrating for the first time that inphase states can spontaneously self-organize in arrays of neodymium-doped fiber lasers [7].

We demonstrate inphase combining of even as well as odd numbers, and using asymmetrical couplers, also for the first time verifying the coherence in the same experiment with multiple power, spectral, temporal, and spatial diagnostics. The output power scaling and the spectral dynamics agree with the expectations for an array of inphase lasers. The spectra do not agree with what one would expect if the coherence were only due to coincidental matching of longitudinal modes between the up to five lasers, which may be called the "mode congruence" hypothesis.

The two distinct fiber laser array configurations of this Letter are diagrammed in Fig. 1. Both are assembled from the same components. The essential differences between the setups are from which end the output is taken and what diagnostic information is available. The Fig. 1a output, from the connector, is measured with a power meter. Or, by loosely joining the flat-connector to an angle-connector, the >20dB attenuated connection provides a sample at a power level convenient for the spectrum analyzer, and isolation of the experiment from the instrument. Our spectrum analyzer is an Ando Model AQ6315E with 0.05 nm (13 GHz) resolution. The setup of Fig. 1b has only one grating, on the single-fiber side of the coupler. A CCD camera ~2 m away records spatial patterns from the collimator-array output.

Fig. 2 plots output power measurements, all taken on the Fig 1a setup. The data are compared with expectations for an incoherent and an inphase array. We define available power for an array member as its output when it is a stand-alone laser. When all five lasers are turned on in the experiment, all the available power is observed at the output fiber. That is to say, all the laser oscillators have organized themselves into an inphase state. When two, three, or four are turned on, more power than the incoherent expectation, but not the total available power, appears at the output fiber. We observe stable self-organizing behavior independent of any polarization adjustment on the individual lasers, and even when no effort is made to control the relative fiber lengths. Understanding the coupler will show that Fig. 2-type measurements provide a definitive criterion for distinguishing between incoherent and inphase behavior. The 1–to–5 coupler [8] is made from four 2–by–2 couplers. Light launched into the single-fiber side will divide evenly among the five fibers on the other side. However, light launched in the five-fiber side is mostly lost. When incoherent beams are launched only a fifth of each appears on the other side; when a single laser is on, only one fifth of its available power is seen. The rest is simply lost in the terminated internal fibers. If all five lasers are equal power and incoherent the output will be only five times one fifth of the power, or approximately the power of a single fiber. Alternatively, if the lasers are inphase the output will be five times the power of a single laser. An incoherent array is expected to have linearly increasing power. Our experimental measurements instead agree with the quadratic dependence expected from an inphase array.

Spectra offering further evidence the array is stably coherent are summarized in Fig. 3. They are from the same experiment as the Fig. 2 data, and all data shown were collected without changing the setup. When turned on individually four lasers have single-peaked frequency distributions with indicated means and widths (calculated from the moments); laser #3 is double-peaked. When several lasers are turned on simultaneously, a single-peaked frequency distribution whose mean is not the sum or difference of the individual distributions and whose width is typically less than that of the individual lasers emerges. For example, Fig. 3 shows all five lasers on; the single-peaked frequency distribution is narrower than all but one of the lasers. Note spectral widths are all ~40 GHz, corresponding to about 4,000 longitudinal modes and 7 mm coherence length.

Investigating spatial coherence with the Fig. 1b configuration shows slowly-drifting fringe patterns – three are shown in Fig. 4 – further supporting that the ensemble forms coherent states. Fringe contrast could be optimized by polarization adjustment, and in the data shown is 28%, with 12% standard deviation. Due to the cavity length differences and the thousands of dissimilar frequencies associated with each laser, any accidental coherence would not be apparent on the time scale of the CCD camera and consequently no spatial fringes would be expected. The Fig. 4 data are obtained using a 50%-reflectivity auxiliary mirror immediately in front of the collimator array, enhancing laser interactions. As expected, poorer and less-frequent fringe contrast is indeed observed when the oscillators' front mirrors are only the back-reflections of the collimators themselves, estimated to be <1%. (We note that nearly 100% fringe contrast is intermittently obtained, as the phases thermally drift, when a separate laser is injected into the grating end of the coupler in Fig. 1b, at a wavelength away from the grating's reflection band, and the fibers are forced to operate as amplifiers, all locked to the injected signal.)

Temporally, when all four lasers are turned on, the signal present in the diagnostics tap of Fig. 1b displays irregular pulsations, a few microseconds long, at ~ 90 kHz. The average output power is stable. In homodyne spectra when all four lasers are on (Fig. 5) only a single comb is typically present. The four lasers turned on individually show mode beating at 8.0 MHz, 7.95 MHz, 7.95MHz, and 8.0 MHz, consistent with c/2nL mode spacings. The one-sweep spectrum for an individual laser is typically <50MHz wide (resolution-limited); the peaks are ~200 kHz wide when 100 sweeps are averaged. With all lasers on, the ensemble's comb has 8.2 MHz spacing, with the first peak having ~700 kHz average width. Peak heights are 5X lower at 100 MHz; few peaks occur beyond ~150 MHz. The shared spectral structure indicates the lasers are interacting and mutually coherent. By turning various combinations of the lasers off and on, pulling of the individual modes is observed. These observations are inconsistent with linear accidental mode congruence [5], and we believe are a strong indication that what we are observing is nonlinear self-organization.

In summary, we have demonstrated that an array of lasers may spontaneously self-organize into inphase states without length or polarization control. Our work is the first to show power-combining, spectral, spatial, and temporal inphase behavior for more than two fiber lasers. To our knowledge, supermode or interferometric cold-cavity (no gain element) resonator analyses of an ensemble of different-length fiber lasers cannot predict that the output will form the inphase states we observed. High gain lasers have strong population-inversion-dependent refractive index. Hence power coupled between fibers will dynamically pull the cold-cavity frequencies and phases. Linear analyses seeking lowest-loss modes do not offer a complete description of this situation. We believe it will be much more productive to consider these ensembles as coupled nonlinear oscillators [9]. We acknowledge the help of John Solis and David Hammon with the experimental set up.

References

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Figure Captions

1. Diagrams of two experiments for all-fiber combination of five or four lasers. Gain is provided by ~2 m–long neodymium–doped fibers, each core-pumped by an 815 nm laser diode through a wavelength division multiplexer. The 875±6nm cutoff, 0.19 NA fiber has 4.0 µm core diameter, with 12.6 dB/m absorption at 807 nm and 6.1 dB/km background absorption at 1150 nm. The fiber resonator cavities include polarization paddles and are 12.8 m long, equalized to ±0.1 m. The lasers are all-to-all coupled; each interacts with all the others via a 1-to-5 coupler [8], the shaded box. In (a) each laser cavity is defined by a 98% reflectivity fiber grating (~0.5nm width) spliced to the end of each gain section and by the partial reflectivity of the flat face on the standard FC/PC flat-polished connector spliced onto the fiber on the right; this is the output. Though all gratings are made using the same mask and are kept at the same temperature, the lasing frequencies are a few tenths of a nanometer different. Inverting this produces setup (b), where only four gain sections are used. Diagnostics are attached to the coupler's fifth fiber. The output, indicated by the arrow on the left, is now from a linear array of adjacent, co-aligned 1.25 mm-diameter graded-index lens fiber collimators. Setup (b) allows spatial coherence to be investigated.
2. Experimental measurements of output power as the number of simultaneously turned-on lasers is increased, for setup in Fig. 1a. Expectations for an incoherent array and an inphase array (lines) are compared to the experimental measurements (symbols). Measured power agrees with predictions for an inphase array. The incoherent expectation is the calculated sum of non-simultaneous individual laser powers, measured when the lasers are turned on one at time in the same setup. The total available power, five times the incoherent power (see text), is also plotted.

3. Measured power spectra when individual fiber lasers are pumped or when all five are pumped simultaneously; nothing else was changed between measurements. Each spectrum is an average of 100 readings. Center wavelengths and variances (a measure of the line widths), calculated from the data files, are listed. The lowest five curves are recorded when the five are turned on individually. The highest curve is measured when all five are on simultaneously. Note it is ~25 times higher than any individual laser. For comparison, the intermediate curve, simply the calculated sum of the lower five curves, is the power spectrum expected if the lasers were incoherent. There is a fixed attenuation between the output from the connector and the optical spectrum analyzer used for these measurements; the ordinate is scaled by aiming the connector into a power meter for reference, instead of connecting it to the spectrum analyzer.
4. Three transections, taken at indicated times, of the far field fringe patterns, inserts, for Fig 1b setup with four lasers on. Intensity is plotted versus spatial position; both scales are arbitrary. The fringe pattern spacings are consistent with the array dimensions.
5. Homodyne spectrum for Fig 1b setup. The signal from a fast fiber-coupled photodiode is fed to an RF spectrum analyzer. The horizontal scale is 0–500 MHz, and the vertical scale 0–90 μV. Closer examination at other sweep rates and resolutions shows that the closely spaced peaks are ~8.5 MHz apart; they are observed even when the RF sweep time is only 30 msec.

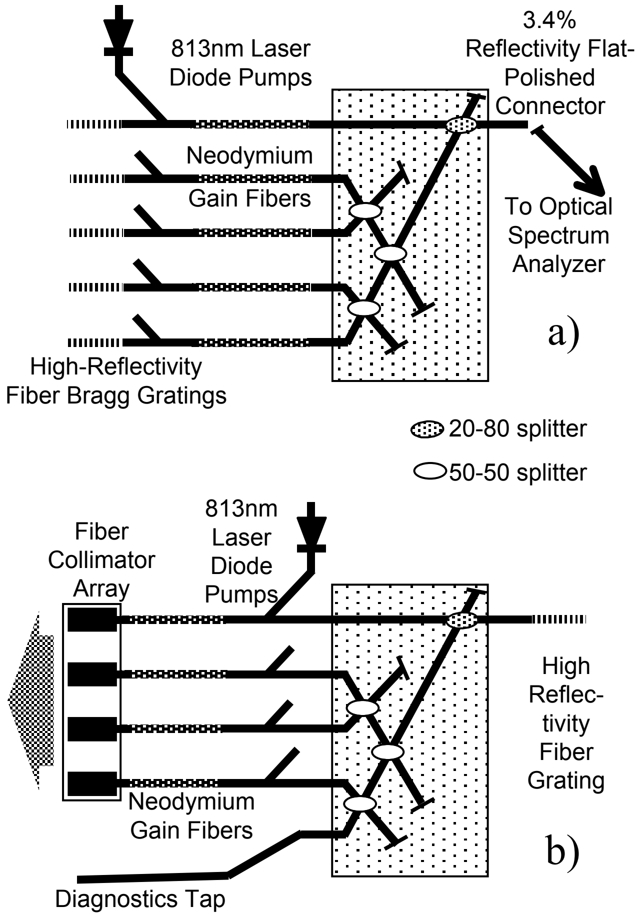
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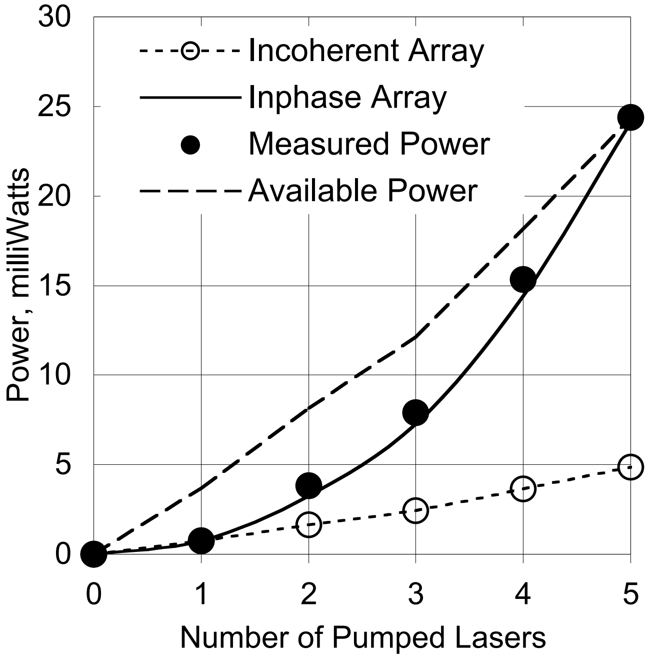
Figure 1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10
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Incoherent Array
Inphase Array
Measured Power
Available Power

Fig. 2

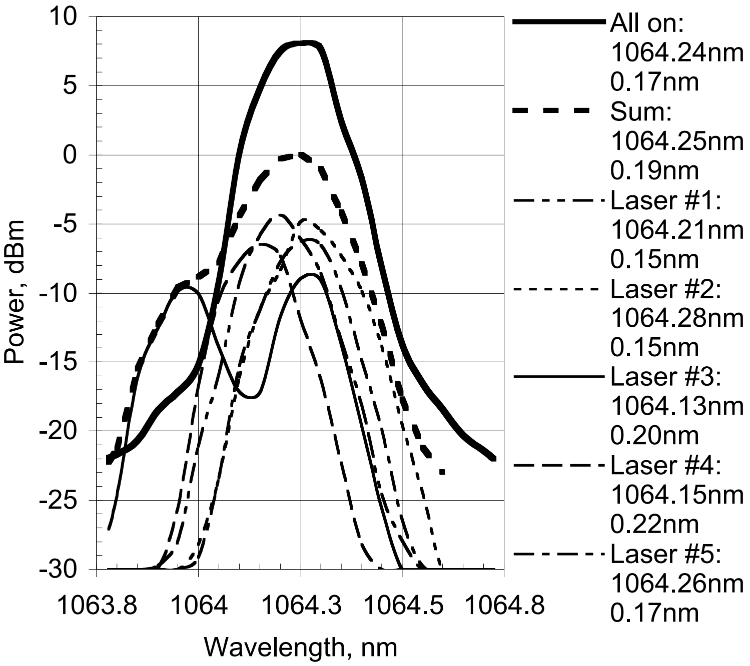

10
5
0
-5
-10
-15
-20
-25
-30
Power, dBm
1063.8
1064
1064.3
1064.5
1064.8
Wavelength, nm
All on: 1064.24nm 0.17nm
Sum: 1064.25nm 0.19nm
Laser #1: 1064.21nm 0.15nm
Laser #2: 1064.28nm 0.15nm
Laser #3: 1064.13nm 0.20nm
Laser #4: 1064.15nm 0.22nm
Laser #5: 1064.26nm 0.17nm

Fig. 3

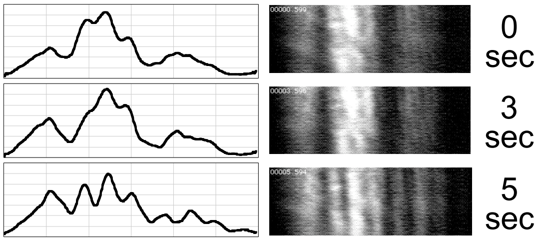
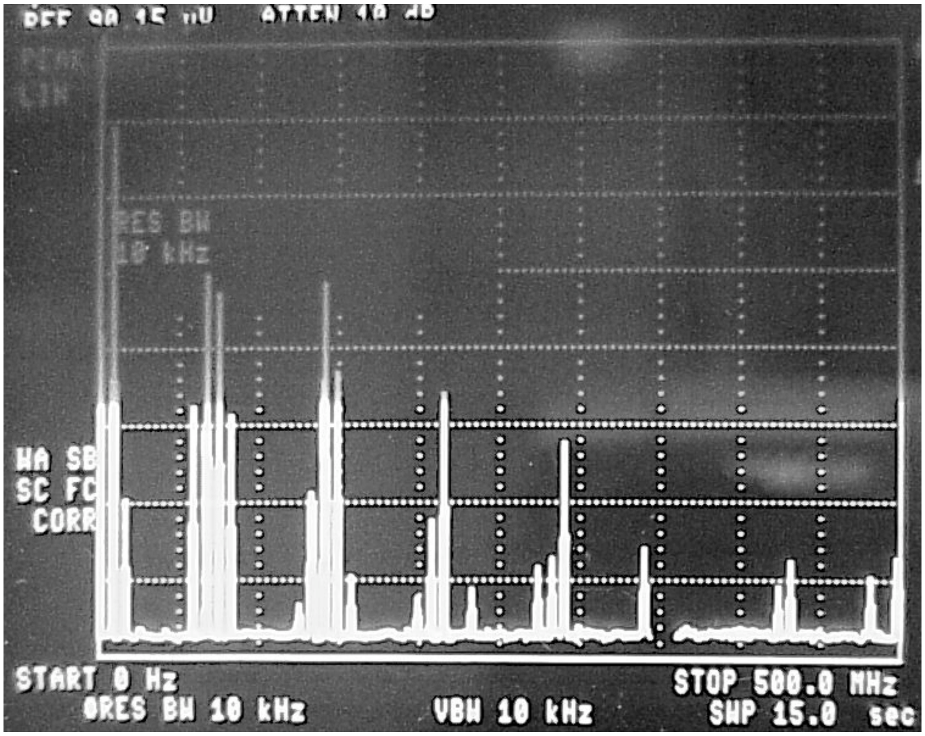


Figure 4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PEAK
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Figure 5