200 W Self-Organized Coherent Fiber Arrays

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Abstract: We report producing 200 W coherent fiber laser arrays without active control. This outcome is obtained via self-organization using a non-fiber coupler for two- to ten-laser arrays.

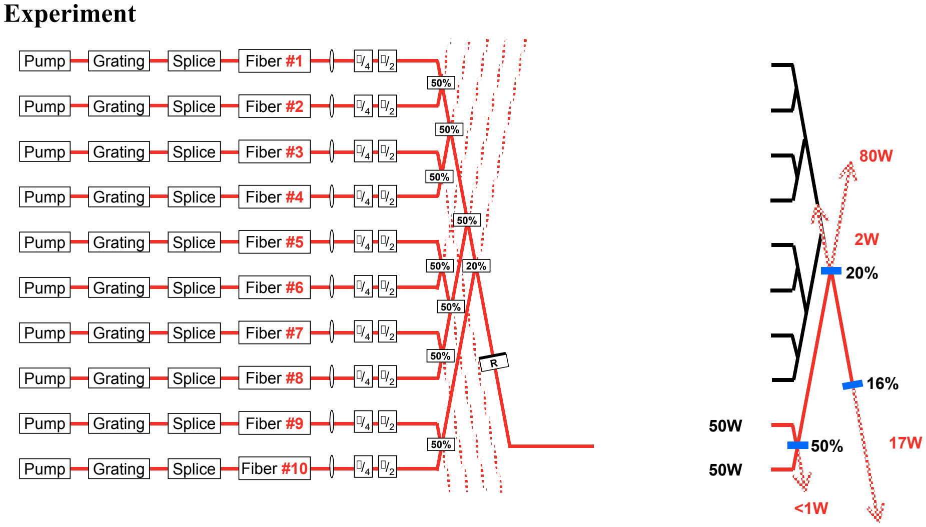
OCIS Codes: 060.4370 Nonlinear optics, fibers 060.2320 Fiber optics amplifiers and oscillators

1. Introduction

Lasers are nonlinear oscillators capable of complex dynamical behaviors. Studies of nonlinear systems have shown that under the correct conditions self-organization phenomena cause groups of dissimilar nonlinear oscillators to passively form in-phase states, without any active control. These studies have further shown that both the correct inherent dynamics and proper oscillator connectivity are required for in-phase states to self-organize. Fiber lasers offer the desirable characteristics of high efficiency, high power per weight, good thermal characteristics, and simple infrastructure; their limited individual output can be overcome by allowing them to form arrays.

We report our experimental demonstration of up to 200 W output from fiber laser arrays. Using a different physical architecture than our initial work [1], we again confirm that fiber laser arrays can self-organize coherent and in-phase states. We observe that self-organization occurs only when the intensity in the fiber is not so large that the optical phase is disrupted by cross phase modulation, as well as when the gain is not so saturated that the Kramers-Kronig-mediated phase adjustment is not also saturated.

2. The Experiment



(a) (b)

Fig. 1: (a) Experimental layout in which up to ten fiber lasers are combined. Fiber lasers are described in text. Optical path lengths external to fibers the same for all lasers. Lenses collimate the beams emerging from fibers. Their polarization are adjusted by the wave plates. Beams then are directed by fold mirrors (not shown) to mirrors (reflectivities indicated) which are chosen to provide uniform all-to-all coupling between the lasers, adjustable by changing the reflectivity of the mirror labeled "R". The 0.4 nm wide gratings overlap spectrally; they were temperature controlled and tuned to center at 1073.5±0.2 nm. (b) The measured output power is shown when only lasers #9 & 10 are operating, at 50 W, as discussed in Section 3 of text.

Fig. 1 shows the coupling approach used – an external mirror arrangement. Table I summarizes the fiber lasers' properties. Separate experiments were done with two different sets of ten Yb-doped cladding-pumped fiber lasers. Each fiber laser uses a diode pump laser bank, which is fiber coupled, with standard industrial 400 µm-core fiber, into a lens module which end-couples this fiber into either the Crystal Fibre™ or, with a different lens module, the Nufern™ fiber. Each Crystal Fibre™ laser, Fig. 2, has a section of non-Yb air-guided fiber to guide the pump; the nearly 100% reflectivity grating is written into its Ge-doped core. Similarly, each Nufern™ lasers also has an internal splice between the, in this case cladding-guided, grating fiber and the gain fiber. The splices to the doped fibers are ~30 cm from the gratings, which are the back reflectors. The Nufern™ lasers have nominally multimode cores, and enforce single mode operation by being coiled inside 10 cm diameter jars. The Crystal Fibre™ lasers have single mode cores, and are packaged wrapped on ~40 cm mandrels.

Table I. Summary of parameters for fiber lasers.

Laser Brand	Crystal Fibre™	Nufern™
Cladding diameter	225 µm	400 µm
Cladding NA	~0.8	~0.5
Core Mode Diameter (Area)	24 µm (452 μm^2)	13 µm (133 μm^2)
Core Numerical Aperture	0.05	0.06
Grating wavelength	1073.5±0.2 nm	1085±0.2 nm
Laser Position Number	Fiber length calculated from mode spacing	Nominal Fiber length
1	4.06 m	10.5±0.5 m
2	4.00 m	10.5±0.5 m
3	4.04 m	10.5±0.5 m
4	3.63 m	10.5±0.5 m
5	3.98 m	10.5±0.5 m
6	4.85 m	10.5±0.5 m
7	4.60 m	10.5±0.5 m
8	4.05 m	10.5±0.5 m
9	4.04 m	10.5±0.5 m
10	4.04 m	10.5±0.5 m

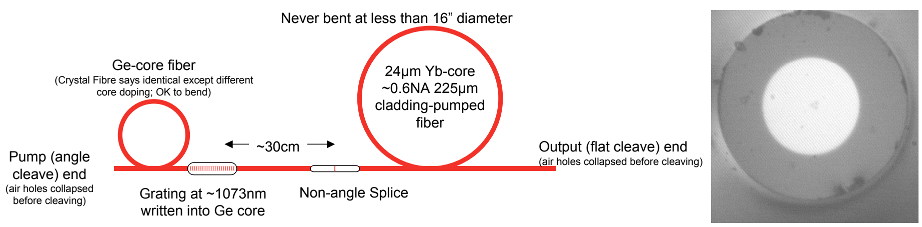
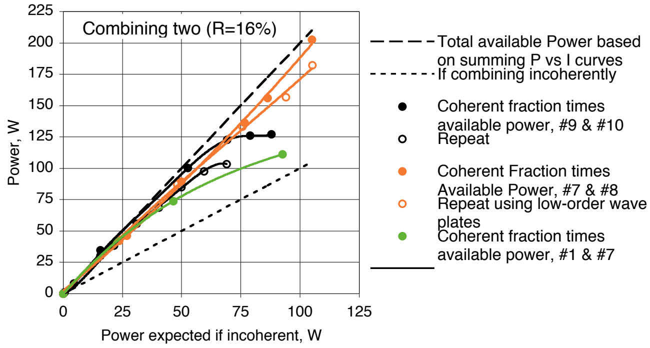


Fig. 2. Diagram of Crytal Fibre™ lasers used in experiments. On right is a photograph of fiber end. Air-guided 225 µm-diameter portion within which pump propagates was illuminated for photograph and is lighter in color. The Nufern™ laser layout is similar, with differences indicated in Table I and text.

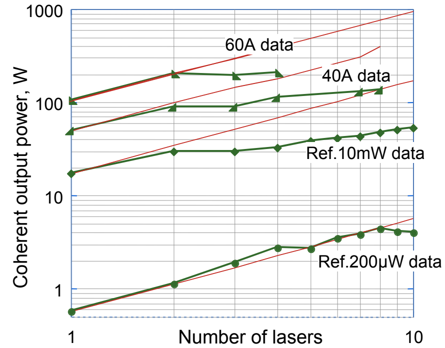
To allow full control of launching and collimation, each fiber end is in a fiber chuck, rigidly fastened to an x-y-z translation stage having coarse and fine adjustment, the fine with submicron resolution. Upon emerging from the flat-cleaved output end, each diverging beam is collimated by a 60 mm focal length lens. It then passes through adjustable $\lambda/4$ and $\lambda/2$ wave plates. To keep them insensitive to temperature at high power, these are special-ordered very thin anti-reflection coated low-order plates. Each beam is then directed into the remainder of the external coupling optics by a nominally >99% reflectivity (specified at 45˚ for 1.06 µm) mirror used at ~52˚ (one at each beam bend in Fig. 1). One polarization is less reflected than the other, and a relative phase shift between the s-and p-polarizations is expected. For this reason we rotate the fiber ends in their chucks and adjust the wave plates, while operating at low power, to have the beams be either entirely either p- or s-polarized. At higher power both polarizations lase. The angle of incidence on the combining mirrors is 14˚, as small as practical, and sufficiently small to minimize polarization sensitivity. Most alignment is done by moving the 52˚ mirrors and the fiber chucks' translation stages. We found monitoring, and minimizing the output from the incoherent output ports to be the most sensitive method to make adjustments.

3. Results

All data presented here were obtained on the above setup, using R=16%. When not all lasers are operating, not all the coherent power comes out the front flat. Some, often most, of the coherent power comes out the other indicated paths. When “200 W” is plotted, therefore, this is not the power out of the front mirror. Our scientific purpose was to investigate the limits to coherent combining of fiber lasers. The most important measurement is therefore what fraction of the total output is coherent. Coherent fraction is determined by monitoring a sample of the beam coming out the front reflector using a large dynamic range linear photodiode. In each experiment the photodiode voltage is recorded for each individual laser and also for the various combinations of multiple lasers. When the lasers are completely coherent with one another, the voltage on the detector will be the square of the sum of the square roots of the individual voltages. In contrast, when the lasers are mutually incoherent, the voltage when several are turned on is simply the sum of the individual lasers'. We define coherent fraction as the experimentally measured voltage divided by the square of the sum of the square roots of the individual voltages. The coherent output power of the laser ensemble can then be asserted to be the coherent fraction times the total power output of whatever lasers are turned on.



(a)



(b)

Fig. 3. (a) Two-laser experiments with Crystal Fibre™ lasers. (b) Summary of data from similar experiments using up to ten of these lasers. The total power available from the lasers (sum of powers when operating alone) is plotted as a thin red curve. The output powers (calculated from the coherent fraction) are plotted as data points connected by thick green curves, which are guides to the eye. Corrected for the number of lasers, these curves are expected to not change with number (flat, horizontal line) when the lasers are incoherent. If the lasers are coherent, the curves show a linear increase of power.

Fig. 3a plots some two-laser results. For some pairs – eg. #7 and #8 – we obtain nearly perfect coherence up to the full 200 W of available power. Other combinations do not remain coherent above ~100 W. It was not always possible to repeat the data. The performance deteriorated as the lasers aged, over a period of approximately a month. Several Nufern™ fiber pairs combined with a maximum total power of only 50 W, and did not age. The maximum coherent power is limited by optical nonlinearities in the core. These are directly proportional to fiber length and inversely proportional to core area; from Table I information this product calculates to be 8.5 times smaller for the Nufern™ fibers.

Fig. 3b summarizes additional experiments with more lasers operating. The lasers are coherent at low power, or when just two are on. The coherence fails when both many lasers and high power are simultaneous. Two observations help in understanding this: 1) At low power the lasers are single polarization. At higher power they are not. Two lasers can be contemplated forming a polarization-independent oscillator that is more like a compound cavity than a simple coupling between independent lasers; three doing this is unlikely. (2) The lasers in this free-space coupling experiment must satisfy multiple cavity-mode congruencies, some in gain-free cavities. Because we had to straight-cleave the fibers so that misalignment of the output reflector would not leave the high-gain medium unsaturated, we created a competing cavity with comparable reflectivity to that of the free-space feedback.

4. Conclusions

The low power results do not support the linear axial mode congruence hypotheses of Shirakawa [2] and Siegman [3]. Their hypotheses predict that the large number of lasers we combined coherently should not have been possible given the limited bandwidth available from the fiber gratings. Our hypothesis is that the lasers do indeed self-organize, utilizing the phase change associated with gain change (Kramers-Kronig) to bring about an inphase coherent state. It is our hypothesis that when the lasers run in a more gain/phase saturated condition at higher power, insufficient nonlinear phase adjustment via Kramers-Kronig is available to bring the cavities back to resonance. Then only mode congruence remains to allow coherence. When the gain nonlinearity supporting self-organization saturates, the gradual reduction to two in the number of lasers that can be locked with increasing power is understandable. We elsewhere report measurements of wavelength-dependent saturation, at high pump levels, of the phase change relative to the gain change that supports this hypothesis [4].

5. References

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3. Anthony Siegman, private communication.
4. Monica Minden, Hans Bruesselbach, and Anson Au, submitted to CLEO 2005.