Experimental Measurements of Self-Phasing Due to Nonlinear Effects in Passively Coupled Fiber Lasers

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Abstract: Nonlinear effects are measured in passively coherently combined fiber lasers. We show that these effects can completely compensate for random fiber path length errors and promote robust lasing under many conditions.
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1. Introduction

Passive coherent laser beam combining has been demonstrated by many groups using a variety of laser gain media, including gas [1], semiconductor [2], and fiber [3]. Since coherent beam combining is an interferometric process, it is inherently phase sensitive and efficient combining requires the maintenance of accurate phase relationships between laser beams. Much of the early success achieved with passively combined fiber lasers is now understood to result from wavelength tuning [4]. When fibers of different lengths are combined, their relative phases are strong functions of wavelength, and the coupled system can often adjust its wavelength to compensate for random time-varying phase errors. However, this is not the only phase shifting mechanism present in a fiber laser. Various nonlinear and intensity-dependent effects can shift the fiber phase, and in some cases these effects can compensate for environmentally induced phase errors and promote robust operation. In particular, the Kramers-Kronig effect, the optical Kerr effect, thermally induced index changes, and thermally induced mechanical changes can all potentially affect the phase relationship between fiber lasers in a coherent ensemble.

Many theoretical models have been proposed to explain the coupled nonlinear optical system that results when both wavelength and nonlinear effects are included in a passive coherent beam combining system [5,6]. However, these models have been difficult to check experimentally due to the complexity of the optical system. In particular, it has been difficult to measure and interpret the phase adjusting role played by nonlinearities in the presence of the phase shifts induced by wavelength tuning. Consequently, questions such as the total number of lasers that can be combined by passive architectures, the optimum cavity design, and the ultimate efficacy of these passive techniques have been left largely unanswered. The purpose of this paper is to measure these nonlinear effects experimentally in a coherent combining configuration that is specially designed to remove all wavelength dependence. By measuring the magnitude of these nonlinear characteristics and directly studying their effect on passive coherent beam combining, we hope to explore new optical architectures that directly utilize the nonlinear fiber characteristics for improved performance.

2. Experimental set-up

There are several conceivable methods to eliminate wavelength tuning as a phase adjusting mechanism in an experimental coherent combining test bed. One possibility is to limit the wavelength tuning range by internal spectrally selective gratings or Fabry-Perot filters. A second is to ensure that the difference in optical path lengths between any two fibers is small. Exploiting both of these methods, it is easy to show that as long as the product between the path length difference between two fibers ΔL and the allowable tuning range Δk satisfies the relationship $\Delta L \Delta k << 1$, frequency shifts across the allowable tuning range will have a negligible effect on the phase difference between the fibers. One way to visualize this condition is to consider the longitudinal mode spectrum of two fibers of dissimilar lengths. Because of the length difference, the spacing between the longitudinal modes of each fiber is different, resulting in an alignment between longitudinal modes that is frequency dependent. For any random phase shift between the two fibers, there will be a frequency where the longitudinal modes align. However, if the fibers are sufficiently close in optical path length, the longitudinal mode spacing of both fibers is almost identical and this tuning mechanism is eliminated.

Our experimental set-up attempts to eliminate as many confounding physical effects as possible to isolate the effects of nonlinearities, while allowing us to make precise interferometric measurements. We therefore have chosen a coherent beam combining system that consists of only two lasers in a Dammann grating combining architecture [7]. A diagram of the experiment is shown in fig. 1. The gain medium consists of two fiber cores in a common cladding.

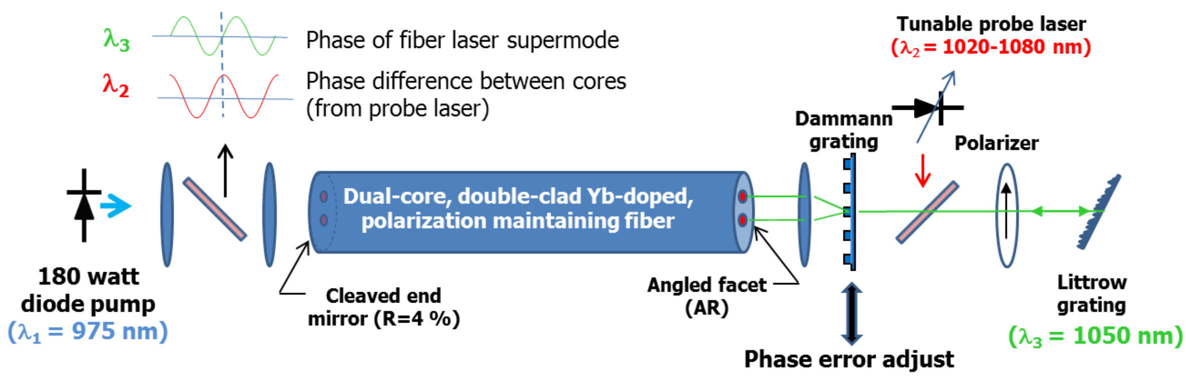

Fig. 1. Experimental set-up for measuring the effects of nonlinearities on a coherently combined laser using a Dammann grating cavity.

Calculations were performed to estimate the closest core spacing that would result in negligible evanescent coupling, ensuring that laser beam coupling would take place only external to the fiber. The local environment of each core, however, was expected to be sufficiently similar to allow common path interferometry to measure small phase differences unperturbed by laboratory noise. Each core consisted of ytterbium-doped phosphosilicate glass, and stress rods were added to ensure polarization maintaining performance (to eliminate the added complexity of multiple polarization modes). An external Brewster polarizer ensured a single polarization state in the fiber. The core diameters were deliberately chosen to be small (5 μm) to enhance nonlinear effects. The dual-clad fiber was pumped by a fiber-coupled multi-emitter diode laser at a wavelength of 975 nm. The 180 watts of available pump power was chosen to enable a range of nonlinear optical effects.

The most significant feature of this fiber system is the accurate balance between path lengths of the two fiber cores. The fiber was specially designed and fabricated to minimize these path length variations, and the residual path length difference was minimized by bending the fiber around a cylindrical mandrel to add a small correcting path length to one core relative to the other. The residual path length error of the three meter fiber was measured by white light interferometry to be 23 μm. The left side of the fiber was right-angle cleaved and served as a 4% end mirror. The right side of the fiber was angle-polished to eliminate back reflections, and the light from each core was collimated and directed onto a Dammann grating by a lens. The Dammann grating was designed to couple the two collimated laser beams into a common on-axis beam. A Littrow grating established the end of the external cavity, and reduced the laser bandwidth to satisfy the $\Delta L \Delta k << 1$ condition.

A tunable semiconductor laser (1020-1080 nm) was injected through the Dammann grating and coupled into the two laser cores. The interference of the light exiting the two cores on the left-hand side of the fiber could be analyzed at two wavelengths, one corresponding to the coherently combined laser wavelength and one corresponding to the tunable probe laser. The probe laser allowed us to measure nonlinear effects of the fiber directly as a function of cavity parameters. A measurement of fringe stability under constant pumping conditions showed a phase measurement accuracy of approximately $\lambda/40$.

By translating the Dammann grating perpendicular to the orientation of the grating lines, a phase shift could be imparted to the two laser arms, where one arm gained phase and the other arm lost phase proportional to the amount of grating translation. A grating translation of one complete period (1.5 mm) corresponded to a round-trip differential phase shift of 4π. Since we could control the grating position to better than 5 μm, this corresponded to a phase adjustment accuracy of better than $\lambda/150$.

3. Experimental measurements of self-phasing by nonlinear effects

The laser cavity was adjusted to produce efficient lasing at 1050 nm by adjusting the grating to null out the path length error between the two laser arms. Simple coupled resonator theory (where wavelength and nonlinear effects

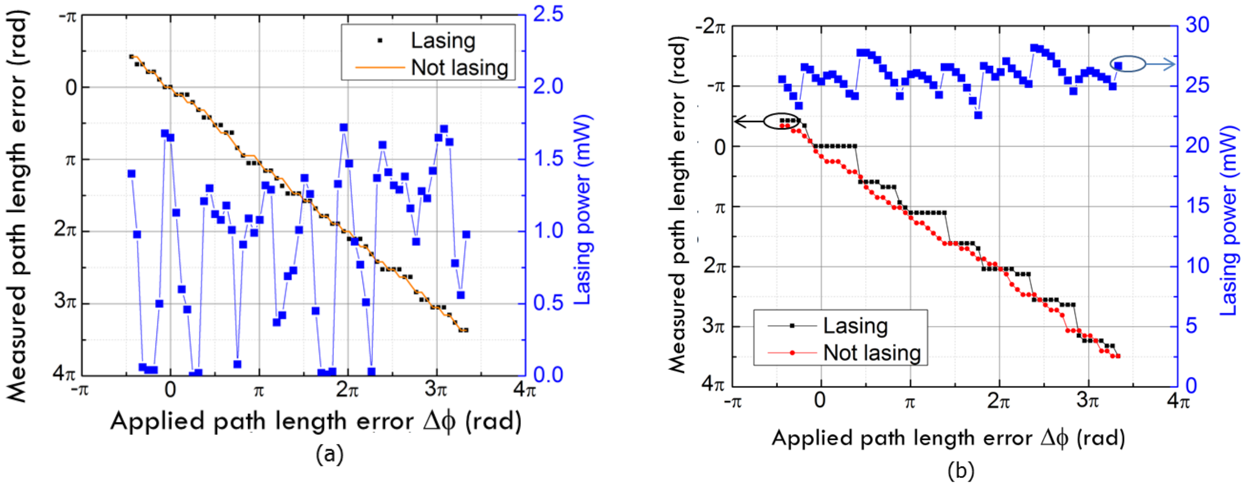

Fig. 2. Measurements of laser power (right axis) and differential path length errors (left axis) for lasers coherently combined in a Dammann grating cavity as a function of path length error. a) 1.2 watts of pump power, b) 2.4 watts of pump power.

are not considered) predicts that efficient lasing will only take place at differential path length errors of $n\pi/2$ (where n is an integer) corresponding to low-loss cavity states. Figure 2 shows the results from operating this coherently combined laser at 1.2 W (fig. 2a) and 2.4 W (fig. 2b) of pump power. At the lower pump power, the laser output in fig. 2a is seen to approximately follow this simple theory, with maximum output power occurring at the low loss path length error states 0, $\pi/2$, π, $3\pi/2$, etc. Between these states, the laser power drops considerably due to the loss introduced by path length error. Also shown in this figure is a measurement from the probe laser of path length error. Because the probe laser passes through both the Dammann grating and the two laser cores, it measures the total path length error between the two lasing arms of the cavity. Fig 2a shows that the path length error measured by the probe is approximately the same as that introduced by the Dammann grating shift.

Fig. 2b shows a dramatically different result when the pump power is increased to 2.4 watts. In this case, the laser is able to lase quite efficiently at all applied path length errors. This ability of the laser to correct for phase errors implies that the laser gain medium itself is changing phase to correct the applied path length errors. To investigate this further, we measured the path length error directly by the probe laser and observed the stair-case shaped graph in fig. 2b. Although the applied path length error introduced by the grating translation varies from 0 to 2π, the laser gain medium is self-adjusting to maintain the total cavity phase at the low loss states of 0, $\pi/2$, π, $3\pi/2$, etc. To show that these phase changes are a result of the laser itself, we also measured the path length errors when the coherently combined laser light was blocked at the Littrow grating. When lasing was interrupted in this way, the gain media no longer provided phase tuning and the measured path length errors were again approximately equal to those applied by the translated grating. We have performed additional experiments that indicate this self-phasing mechanism is due to the Kramers-Kronig effect in the fibers. We have also seen that the effect is quite robust, and appears to select the proper phase states under a wide variety of pump powers and coupling conditions. Future experiments at higher pump powers will explore the nonlinear behavior associated with the optical Kerr effect, thermally induced changes in index and length, and the effects of larger laser ensembles. We expect that these fundamental measurements will be valuable in evaluating theoretical models of more complex laser systems, and may lead to improved passively combined laser cavity designs.

4. References

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