Experimental measurements of the origin of self-phasing in passively coupled fiber lasers

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We have directly measured the intensity distribution, gain, and induced phase shift between two fiber lasers that are coherently combined by a Dammann grating. The induced phase shift between the lasers has been shown to approximately cancel out any applied phase error introduced into the cavity, allowing the combined resonator to operate at an efficient low-loss state. We show that the origin of this self-phasing stems from a redistribution of power between the two lasers. The resulting difference in circulating intensity produces a differential change in saturated gain, which in turn produces a differential Kramers–Kronig phase shift that effectively cancels the applied phase error.

OCIS codes: (140.3298) Laser beam combining; (140.3410) Laser resonators; (140.3290) Laser arrays; (140.3510) Lasers, fiber.

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Passive phasing has been observed in coherently combined fiber lasers by several research groups, whereby some physical mechanism appears to automatically adjust the laser phases to an efficient lasing state [1–3]. The origin of this physical mechanism is often attributed to simple wavelength tuning [4]. However, there are many other mechanisms that can provide the appropriate self-phasing, including changes in fiber length with temperature, temperature-induced index of refraction changes (dn/dT), nonlinear optical effects (e.g., the optical Kerr effect), and the Kramers–Kronig (KK) phase shift that accompanies a change in gain. In most experiments performed to date, the observed self-phasing most likely results from a complex combination of many or all of these effects, and as a result is hard to accurately characterize. Theoretically, it has been shown that the presence of resonant (gain-dependent) and Kerr nonlinearities can result in higher coherent beam-combining efficiency than that predicted by a cold-cavity theory [5–8]. Recently, it was experimentally demonstrated that efficient coherent beam combining can be achieved in laser arrays containing more than 20 elements [9,10].

In previous work [11], we carefully controlled against all known phase-adjusting mechanisms except for the KK effect, and directly measured the phase pulling between two coherently coupled fiber lasers as a function of applied path length error. We eliminated the effects of wavelength tuning and temperature-induced length and index changes by fabricating a precision dual-core Yb-doped fiber and equalizing the optical path length difference between the two cores to near zero. From these measurements, we conjectured that the self-phasing mechanism in our experiment was strictly due to the KK effect. Figure 1 shows the experimental demonstration of this self-phasing effect. The x axis corresponds to the applied phase error introduced between the two fiber lasers, whereas the y axis shows the total differential phase between the two coherently locked lasers measured by a probe laser. Since the cavity was designed to have low-loss phase states at integer values of $\pi/2$ radians, the self-phasing mechanism was apparently pulling the total cavity phase to these low-loss points for all applied phase errors. The phase jumps seen in the curve show that the cavity is skipping over the high-loss-phase states, allowing efficient lasing at all applied phase errors.

Although these experiments showed convincing evidence that the KK effect can produce self-phasing, they left open the question of its origin. Indeed, since the lengths of the two cores were virtually identical, the differential phase change between them would depend on the KK effects being different in each core. In this Letter, we show experimental measurements that help identify the origin of this differential KK phase.

Figure 2 shows our experimental configuration for combining two laser gain media and measuring important lasing characteristics. A ~3-m length of custom fiber forms the active part of the laser cavity. The fiber was designed and fabricated to eliminate most sources of self-phasing. It consists of two Yb-doped cores contained in a double-clad structure, and uses stress rods to maintain polarization. The two Yb-doped cores are separated

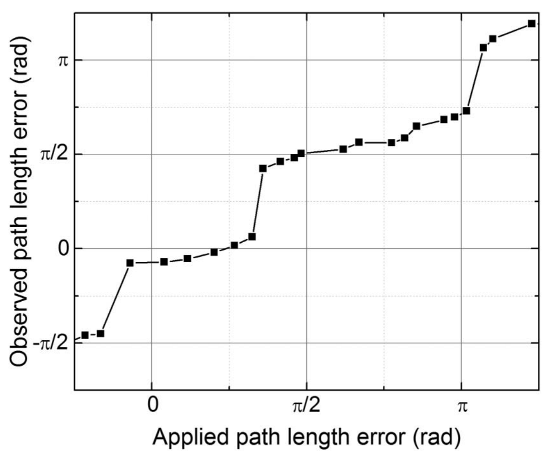

Fig. 1. Experimental data showing self-phasing in the passively coupled laser cavity. The height between the two adjacent phase steps is roughly equal to $\pi/2$.

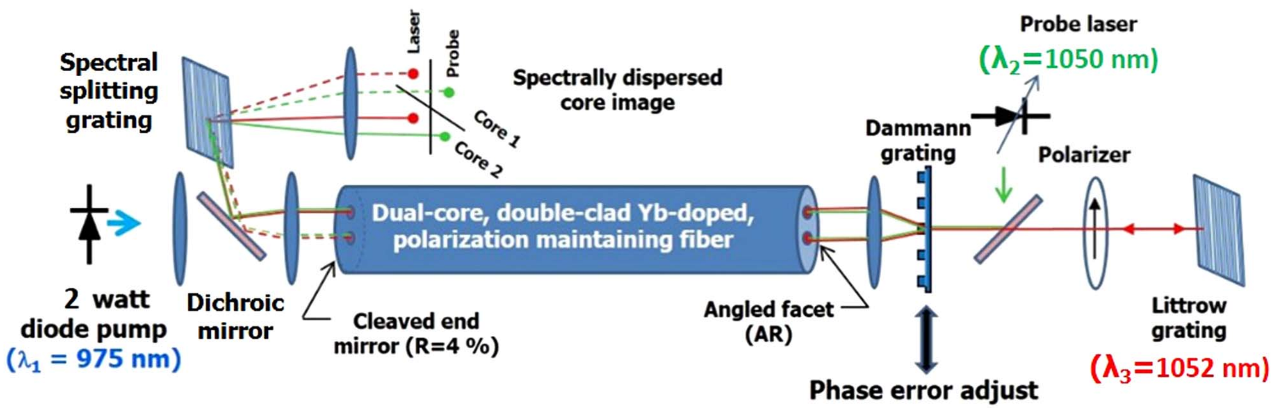

Fig. 2. Experimental configuration of the passively coupled laser cavity with associated diagnostic instrumentation.

by 20 μm and each core has a diameter of 4 μm. The thermal environment is practically identical for the two cores due to their proximity to each other, eliminating virtually all differential thermal-phasing effects. On the other hand, the spacing between the two cores is large enough to avoid significant evanescent coupling. In addition, special care has been taken to reduce the path length difference between the two cores to less than 35 μm over the entire fiber length. Calculations show that, with this small path length difference, the differential phase shift caused by wavelength tuning over the allowable lasing bandwidth of 3 nm is negligible.

The fiber is perpendicularly cleaved at the left end to produce a 4% reflectivity end mirror and angle cleaved at the right end so that lasing does not occur without external optical feedback. The optical fields emerging from the angle cleaved end are collimated by an aspheric lens. A homemade binary phase Dammann grating placed at the back focal plane of this lens serves as a 2×1 beam combiner (or 1×2 beam splitter) with a theoretical efficiency of 81%. The laser cavity is closed by a ruled diffraction grating (used at its Littrow angle) in the far end. A Glan–Brewster-angle polarizer is placed inside the laser cavity to create differential loss in the two polarization eigenmodes of the fiber. As a result, the composite laser cavity only oscillates in a single polarization eigenmode.

The fiber is cladding pumped through a dichroic mirror at the perpendicularly cleaved end by a multimode laser diode array with a wavelength of 975 nm. Probe light (generated by a semiconductor laser tuned to be slightly different than the lasing wavelength) is injected into the fiber from the angle cleaved end through the binary phase grating. The optical signals that exit the perpendicularly cleaved fiber end are reflected off a dichroic mirror and imaged onto a CCD camera, resulting in a spectrally resolved image of the two cores. Thus, independent measurements of the lasing and probe signals can be made for each core. While performing measurements of fiber core phases, this imaging system is replaced by one (not shown) that allows light from the two cores to overlap and produce high visibility fringes of both laser light and probe light. The phase information is then extracted by performing a Fourier analysis of the interference pattern via FFT.

To perform a quantitative study of the self-phasing effect, we started by characterizing the gain and phase characteristics of the two doped fiber cores independently. The KK phase shift was measured as a function of the gain by pumping one of the Yb-doped cores using a single-mode laser diode at 976 nm. The optical feedback from the ruled diffraction grating on the right side of Fig. 2 was temporarily blocked during this experiment to prevent the composite laser cavity from lasing. The unpumped Yb-doped core served as a reference for both phase and gain measurements. Probe optical fields at 1050 nm were launched into both fiber cores. Weak optical probe power was used to minimize gain saturation effects, and subsequent tests showed no sign of saturation. Both the total single-pass intensity gain G and the phase shift of the pumped core $\Delta\phi$ were measured with respect to the reference core at a variety of pump powers. The data from this experiment are plotted in Fig. 3, showing the expected linear relationship between the KK phase shift $\Delta\phi$ and the small signal exponential power gain $\ln(G)$. This leads to a direct measure of Henry's alpha parameter $\alpha = 2\Delta\phi/\ln(G) = 7.4$ [12].

Next, we resumed the normal operation of the coherently combined fiber lasers. The pump laser was used to cladding-pump both cores above threshold at a fixed pump current. The single-pass gain of each individual Yb-doped core G was determined by measuring the intensity gain of the probe beam exiting a particular core from the left ($\lambda_{\text{probe}} = 1050$ nm). Simultaneously, we measured the output intensity from the same core at

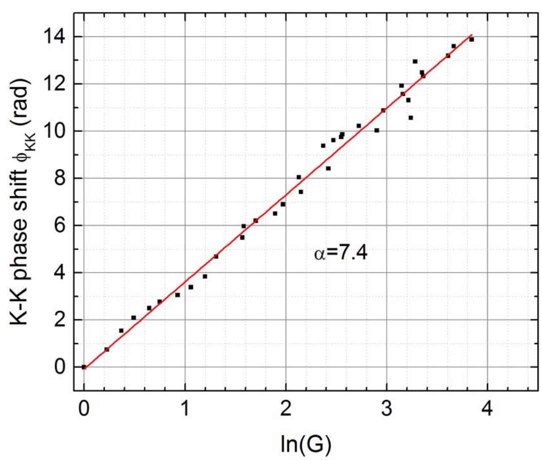

Fig. 3. Kramers–Kronig phase shift versus the small-signal exponential gain $\ln(G)$ (where G is the single-pass power gain).

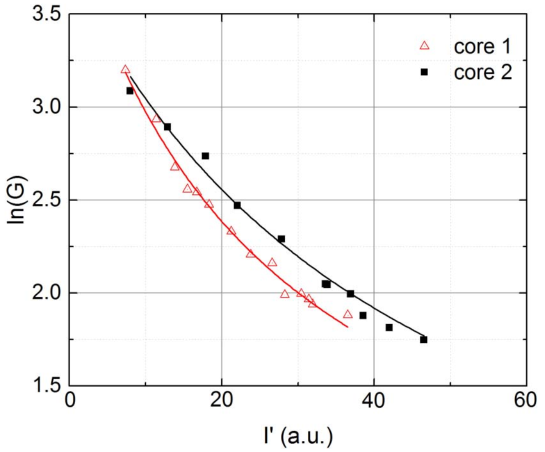

Fig. 4. Small-signal exponential gain versus the optical output intensity I' in each individual fiber core.

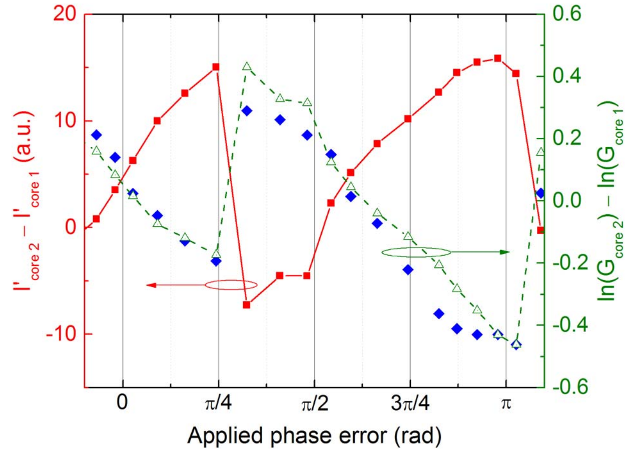

Fig. 5. Difference of the optical output intensities in the two gain arms (red solid squares) and the corresponding difference in exponential gain (blue solid diamonds) measured as a function of the applied phase error. The calculated difference in exponential gain (green open triangles) is obtained by using the experimental data of the output powers (red solid squares in this graph) along with the gain saturation results of Fig. 4.

the lasing wavelength ($\lambda_{\text{laser}} = 1052$ nm). The curve shown in Fig. 4 was obtained by providing a variable cavity loss, allowing the round trip gain to be adjusted. Since the output intensity I' is proportional to the internal lasing intensity I directly behind the 4% output coupler, these measurements can be used to quantify the gain saturation of the two cores [exponential gain $\ln(G)$ versus internal laser intensity]. The differences between the two curves is most likely due to coupling efficiency differences between the two cores.

With the setup in Fig. 2 still configured to coherently combine the two laser cores, we measured the output intensities I'_1 and I'_2 and their respective gains as a function of applied path length error between the two laser cores. This path length error could be easily adjusted by translating the Dammann grating as indicated in Fig. 2. Whereas a simple analysis of the Dammann cavity predicts that an applied path length error only alters the phase of the supermode (i.e., the intensity distribution between the two cores should not be effected), we observed that this intensity distribution was indeed influenced by the amount of applied phase error. The origin of this intensity redistribution is currently being investigated and will be the subject of a future report. For this Letter, we have simply measured the intensity difference $I'_2 - I'_1$ and have plotted it in Fig. 5 as a function of path length error. It is apparent that an increase in path length error leads to a discontinuous increase in this intensity difference. We expect that this increase should lead to a corresponding decrease in the respective gain difference $\ln(G_2) - \ln(G_1)$ through the gain saturation effect measured in Fig. 4. In fact, a direct measurement of this saturation effect was made and is shown in Fig. 5 as blue diamonds. As a crosscheck, we also plot (dashed green curve) the calculated gain difference using the measured intensity difference and the gain saturation curve shown in Fig. 4. The close correspondence between these data is evident. Clearly, this differential gain will produce a differential KK phase shift, leading us to the conclusion that the origin of the self-phasing behavior comes from a redistribution of supermode intensity between cores as a function of path length error.

As a quantitative measure of the above mechanism, we calculate the expected KK phase shift for a particular path length phase error by converting the exponential gain ratio data from Fig. 5 into a KK phase shift using the gain-phase relationship measured in Fig. 3. The result is plotted in Fig. 6 (blue open-triangles). Note that this calculated phase shift originates from a measured change in the supermode intensity distribution. This calculated result can be compared with the actual observed phase shift contained in Fig. 1. Since the measurement in Fig. 1 is of the total phase difference between the two cores (the applied phase error plus the induced KK phase shift), the KK phase shift alone can be obtained simply by subtracting the applied phase shift from the data in Fig. 1. This result is also plotted in Fig. 6 (the black solid-squares). The correspondence between the two curves both in shape and in quantitative value is notable.

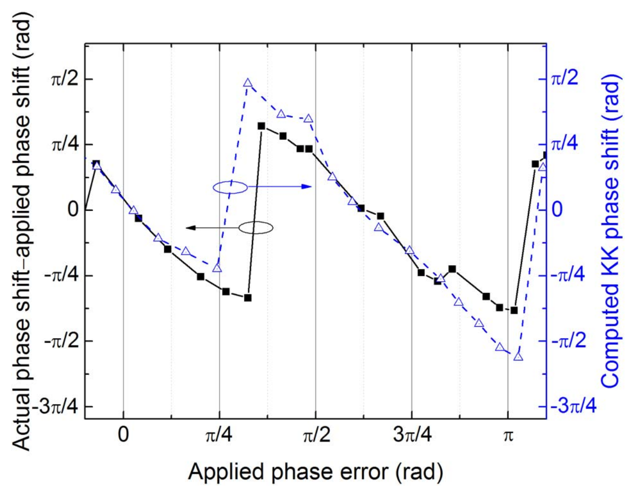

Fig. 6. Experimentally observed self-phasing (black solid squares) and the computed KK phase shift (blue open triangles) plotted as a function of the applied phase error. The computed KK phase shifts are inferred from the applied phase error versus output intensity data in Fig. 5, the output intensity versus gain relationship in Fig. 4, and the gain versus phase relationship in Fig. 3.

To conclude, we have presented data that explicitly links the self-phasing in our coherently combined fiber lasers to a change in the supermode intensity distribution (i.e., a redistribution of intensity between the laser cores). A differential change in fiber core intensities results in a corresponding change in gain. This gain difference produces a phase shift via the KK effect that approximately balances the applied phase error and keeps the cavity in a low-loss regime for efficient lasing. We believe that the work presented here is an important step toward fully understanding the physical mechanisms behind self-phasing in passively coherently combined fiber lasers.

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