Direct observation of Kramers–Kronig self-phasing in coherently combined fiber lasers

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A highly stable coherent beam-combining system has been designed to measure self-phasing in fiber lasers due to nonlinear effects. Whereas self-phasing in previous coherent combination experiments has been principally attributed to wavelength shifting, these wavelength effects have been efficiently suppressed in our experiment by using a dual-core fiber with closely balanced optical path lengths. The self-phasing from nonlinear effects could then be measured independently and directly by common-path interferometry with a probe laser. The Kramers–Kronig effect in the fiber gain media was observed to induce a phase shift that effectively canceled the applied path length errors, resulting in efficient lasing under all phase conditions. This process was demonstrated to result in robust lasing over a large range of pump conditions.

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

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Passive coherent beam combining of fiber lasers has been demonstrated by several groups using a variety of architectures [1,2]. In this technique, an external resonant cavity establishes one or more optical supermodes, where each supermode is a coherent state containing light from a large number of laser emitters. By designing the optical cavity to oscillate in a single supermode, the lasing light field is confined to a single coherent state, and mutual coherence is established across the array. However, the cavity loss to this supermode is a strong function of the individual laser path lengths [3,4], requiring the phase of each laser to be correctly established and maintained for efficient lasing. The light associated with this cavity loss is generally directed out of the resonator and does not contribute to the optical feedback, nor to the useful output.

Early success in passive coherent combining of fiber lasers was reported where the lasers appeared to be selecting the correct phases automatically, even in the presence of time varying path length errors. It is now generally understood that changes in oscillation wavelength can produce phase shifts between unequal length fibers [5]. Lasing at the proper wavelength can then result in phase states that are close enough to ideal to reduce the path-length error loss, resulting in a low lasing threshold and efficient single mode out-coupling and lasing among a modest number of fibers. However, wavelength shifting is not the only passive phase mechanism that can take place in a fiber. In particular, the Kramers–Kronig (K–K) phase shifts that accompany laser gain have long been thought to play a role in self-phasing. Many theoretical models have been suggested that incorporate this and other nonlinear effects into the coupled cavity to predict lasing behavior in large lasing ensembles [6–9]. Unfortunately, experimental verification of these models has been difficult due to the complex behavior of the combined phase effects. In particular, it has been difficult to measure and interpret the phase adjusting role played by the K–K effect 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 utility of these passive techniques have been left largely unanswered. The purpose of this current work is to isolate, measure, and analyze the effect of K–K phase shifting in the absence of wavelength tuning and other nonlinear effects. Understanding the role of this and other nonlinear effects is considered key to understanding and optimizing passive beam combining systems.

Our experimental laser test bed has been designed to remove wavelength tuning effects, facilitate accurate adjustment of differential laser path lengths, and allow for precise interferometric measurements of K–K phase shifts. There are two principal methods available to eliminate wavelength tuning as a phase adjusting mechanism. One is to limit the wave number tuning range of the laser $\Delta k = 2\pi\Delta\lambda/\lambda^2$ by internal spectrally selective optics, where $\Delta\lambda$ is the laser gain bandwidth and λ its central wavelength. A second is to use fiber lengths that are as close to identical as possible. If the optical path length difference between two fibers ΔL is much less than $1/\Delta k = \lambda^2/(2\pi\Delta\lambda)$, wavelength shifts across the allowable tuning range will have a negligible effect on the phase difference between the fibers. Satisfying this condition effectively eliminates wavelength tuning as a confounding variable.

Our experimental setup is shown in Fig. 1. Since we are interested in measuring the influence of the K–K effect under controlled and fundamental conditions, we have chosen to restrict the beam addition to two fiber lasers. The laser gain media, consisting of two ytterbium-doped phosphosilicate glass cores, were contained in a common inner cladding. Stress rods of borosilicate glass were added to remove the polarization degeneracy and promote lasing in a single polarization state, further simplifying the physical system. A core separation of 20 μm was chosen to produce negligible evanescent coupling, ensuring that all beam coupling would take place external to the fiber. The local environment of each core,

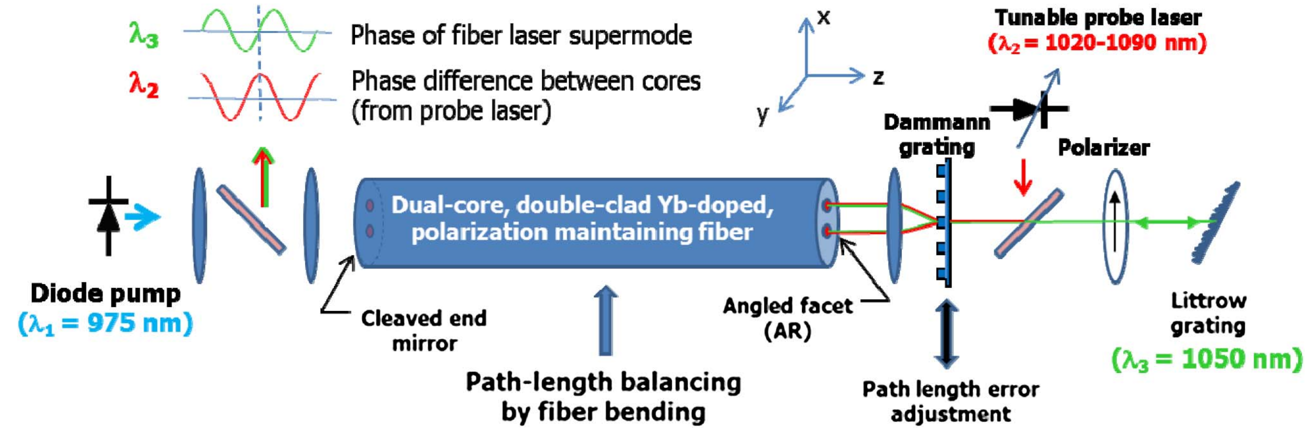

Fig. 1. Experimental setup.

however, was expected to be sufficiently similar to allow common path interferometry to measure small phase differences unperturbed by laboratory noise [10]. A Dammann grating laser cavity was chosen as the coherent beam combining architecture [11]. Splitting one laser beam into two (or combining two beams into one) can be performed by a simple 50% duty cycle square wave grating with a phase depth of π rad. It is easy to show that both the splitting and combining efficiencies η of this grating are given by $\eta = 8/\pi^2 \approx 0.81$. One advantage of the Dammann grating architecture is that it contains only one supermode [12]. This ensures that the cavity will always oscillate in a coherent state, further simplifying physical models of the system.

The left end of the fiber is perpendicularly cleaved to produce a 4% end mirror, whereas the right end of the fiber is angle cleaved to eliminate feedback. The two beams exiting the fiber gain media are collimated by a lens and overlap at the Dammann grating. The common output of the Dammann grating is then passed through a Brewster polarizer to ensure lasing in a single polarization state. A Littrow grating completes the cavity while restricting the lasing bandwidth to a narrow band of wavenumbers $\Delta k \sim 60\ \mathrm{cm}^{-1}$ centered around 1051.6 nm. The inner cladding of the dual-clad fiber is pumped by a fiber-coupled diode laser at a wavelength of 975 nm.

During fiber fabrication, particular attention was paid to balancing the optical paths of the two laser cores. After fabrication, the remaining optical path length difference seen by white light interferometry was minimized by coiling the fiber around a cylindrical mandrel to add a small corrective path length to one core relative to the other. The final path length difference was measured to be $\Delta L = 23\ \mu\mathrm{m}$ across the 3-meter-long fiber, ensuring that $\Delta L \ll 1/\Delta k$ and eliminating the effect of wavelength tuning on the phase of the fiber laser cores.

A tunable semiconductor laser beam was injected into the right side of the cavity to measure the K–K phase shift in the gain media. By passing this probe beam through the Dammann grating, the light was efficiently coupled into the two laser cores. The interference of the probe light exiting the two laser cores on the left-hand side was then used to measure the K–K phase shift inside the cores. In addition, the phase of the coupled fiber laser supermode could be measured by observing the interference of the fiber laser light. These two interference patterns were isolated and independently measured using a spectral filter. The stability of both these phase measurements was estimated to be better than $\lambda/40$ under constant pumping conditions.

The laser cores on the right side of the fiber were placed in the front focal plane of the collimating lens (see Fig. 1) and the Dammann grating was placed in the back focal plane. As such, the field distributions in these two planes are two-dimensional spatial Fourier transforms of each other [13]. The effect of a spatial translation of the grating in the x direction by an amount Δx can be calculated by the Fourier shift theorem to produce a phase shift at the fiber cores of $\pm\Delta\phi$ in a single pass, where $\Delta\phi = 2\pi\Delta x/T_g$ and T_g is the period of the grating [13]. One of the two grating orders (coupled into one fiber core) receives a positive phase shift while the other receives a negative phase shift. Although this same shift can be created by physically making one fiber core longer than the other (e.g., by bending the fiber), it is far more accurate to introduce the phase shift external to the fiber by a Dammann grating translation. Since a translation of one complete grating period (1.5 mm) corresponds to a phase shift $\Delta\phi$ of 2π and we can control the grating position to better than 5 μm, this corresponds to a phase adjustment accuracy of better than $\lambda/300$.

In the absence of wavelength phase shifting and all nonlinear effects, the loss to the coupled laser cavity supermodes can be determined by calculating the round-trip system propagation matrix and solving for the matrix eigenvalues and eigenvectors. In the case of the two-laser Dammann grating cavity used in this experiment, the cavity loss L as a function of path length error $\Delta\phi$ is given by

$$L = 1 - \frac{64}{\pi^4}\cos^2(2\Delta\phi).$$

Thus, in the linear regime, the cavity has minimum loss at phase values $\Delta\phi = n\pi/2$, where n is an integer. Figure 2 shows the results from operating this coherently combined laser at 1.2 W of pump power for applied path length errors ranging from 0 to 2π rad. At this low pump power, the laser output power is seen to approximately follow the simple theory, with maximum output power

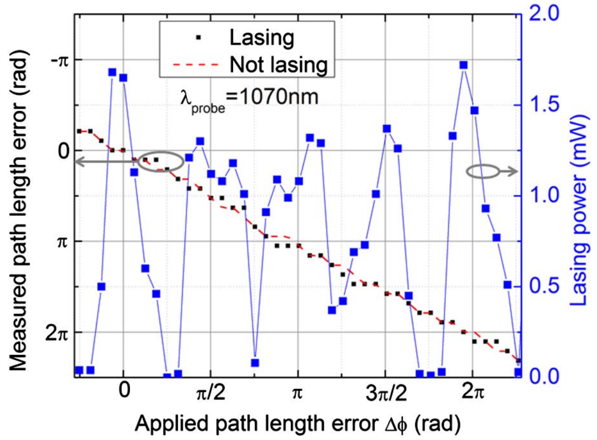

Fig. 2. Measured lasing power and single-pass path length error as a function of applied path length error $\Delta\phi$ at low pump powers (1.2 W).

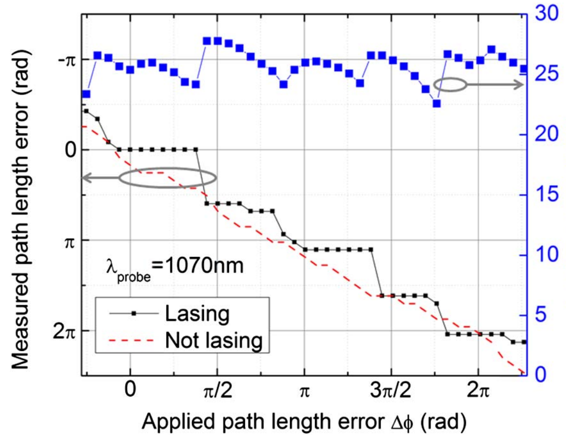

Fig. 3. Measured lasing power and single-pass path length error as a function of applied path length error $\Delta\phi$ at elevated pump powers (2.2 W).

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 (and sometimes lasing stops) due to the loss introduced by path length error. Also shown in this figure is a measurement from the probe laser of total single-pass path length error as a function of applied path length error $\Delta\phi$. 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 (i.e., the sum of the phase error applied by the grating shift and any phase shifts induced in the fiber cores). Figure 2 shows that the single-pass path length error measured by the probe is approximately equal to that introduced by the Dammann grating shift, as expected for laser cores with fixed phases.

Figure 3 shows a dramatically different result when the pump power is increased to 2.2 W. In this case, the laser is able to lase quite efficiently at all applied path length errors, as evidenced by the almost-flat output power curve. This ability of the coupled laser system to correct for phase errors implies that the laser gain medium itself is changing phase to correct the applied path length errors. To verify this, the probe laser was used to measure these phase shifts directly, and the resulting total cavity phase measurements are shown as the stair-case shaped graph in Fig. 3. 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, or near, 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 beam-combining architecture, we also measured the path length errors when the coherently combined laser light was blocked at the Littrow grating. These measurements are shown in Figs. 2 and 3 as dashed lines. 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 introduced solely by the translated grating.

There are several mechanisms that could be responsible for the self-phasing observed in these fibers. Besides the K–K effect, we have also considered thermal expansion $\Delta l/l = \alpha_L \Delta T$ and thermal effects on core index of refraction $\Delta n/\Delta T$ as possible causes, where l is the fiber core length, T is the temperature, α_L is the coefficient of thermal expansion, and n is the refractive index. To differentiate between all these effects, we cladding-pumped the fiber in a manner similar to our main experiment. However, rather than combining the power from the two laser cores, we let each lase independently and at slightly different thresholds. We then observed the differential phase shift between the cores with the probe laser as before. Figure 4 shows the differential phase shift as a function of pump current. We note that when both fibers are below lasing threshold, they exhibit phase shifts that are slightly different from each other, giving rise to the slowly varying function on the left side of the graph. However, when one laser achieves threshold and starts to lase, the differential phase changes quickly and linearly at a rate of approximately 7.5 rad per ampere of cladding pump current. This continues until the other laser achieves threshold, whereupon the differential phase no longer changes with pump current. We interpret this to indicate that the K–K effect is most likely responsible for the observed phase shift. When both lasers are below threshold, they both exhibit similar K–K phase shifts. The small difference in rate gives rise to shallow

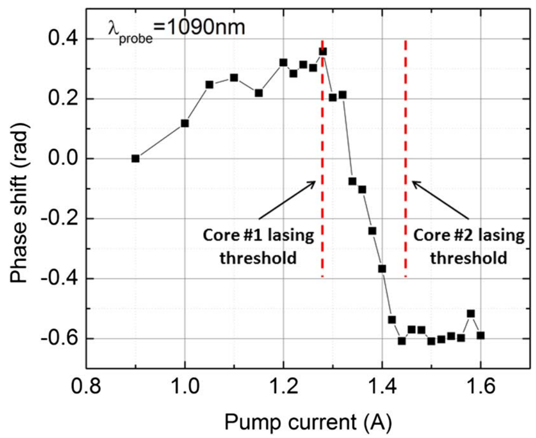

Fig. 4. Measured differential phase shift between independently lasing fiber cores.

slope in the left part of the curve, and probably comes from slightly different pumping or loss conditions. However, when one laser starts to lase (clamping its gain and phase shift), the K–K phase shift from the nonlasing fiber exhibits a strong linear function of current. Finally, when both fibers lase, both gains and phase shifts are clamped and we no longer observe any phase change as a function of pump current.

We believe that the self-phasing results can be explained by considering the simultaneous effects of the cavity loss as a function of phase shift, and the K–K phase shift as a function of cavity gain (or loss). This model will be the subject of a future paper.

In summary, we have observed and measured K–K self-phasing in a passive coherently combined laser cavity. Whereas the K–K effect has undoubtedly influenced previous passive coherent combining experiments, we believe we have, for the first time, isolated and quantified its influence on passive phasing in the absence of other confounding effects. Importantly, the K–K self-phasing appears to correct for all applied phase errors accurately and virtually completely under a variety of pump conditions and levels, and only fails when the pump power is too low to excite a sufficient number of Yb-ions to produce the required phase shift. A fundamental understanding of this phasing mechanism should prove valuable in evaluating more complex laser systems, and may ultimately lead to improved passively combined laser cavity designs.

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