The effect of polarization in passive coherent beam combining of fiber lasers

Hung-Sheng Chiang*[a], James R. Leger[a], Emese Huszar[b], Johan Nilsson[c], Jayanta Sahu[c]
[a]Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, USA 55455-0170; [b]Bethlen Gábor Református Gimnázium, Hódmezővásárhely, Hungary 6800; [c]Optoeletronics Research Centre, University of Southampton, Highfield, Southampton, Hampshire, SO17 1BJ, United Kingdom
*chia0078@umn.edu; phone 1 612 625-1574

ABSTRACT

A Yb-doped, dual-core, double-clad, polarization-maintaining fiber is used to demonstrate passive coherent beam combining. A homemade Dammann grating is employed as a passive beam-combining optical element. Self-phasing is observed in this laser system, where we attribute the self-phasing behavior to the Kramers-Kronig effect. We experimentally demonstrate the importance of polarization on coherent beam combining efficiency as well as on Kramers-Kronig induced self-phasing.

Keywords: Coherent beam combining, Yb-doped fiber, Dammann grating, Kramers-Kronig effect, self-phasing

1. INTRODUCTION

Coherent laser beam combining has been shown to be an effective method to achieve high optical radiance from several low radiance sources. For applications where the spectral, spatial, and divergence characteristics of each low radiance source must be preserved in the high power beam, it is necessary to combine the outputs from the individual lasers coherently. To achieve coherent laser-beam combining, the phases of individual lasers must be locked together in the proper phase state. This can be achieved either by actively controlling the phase of each laser electronically or by passive means whereby individual lasers self-adjust by some physical mechanism.

In this paper, we measure the characteristics of passive phasing in fiber lasers. In particular, we report on the effects of polarization on the laser cavity's ability to self phase-lock via the Kramers-Kronig effect.

1.1 Laser cavity

We have designed and fabricated a Yb-doped, dual-core, double-clad, polarization-maintaining fiber to perform our measurements. Each core has a diameter of 4 μm, ensuring single spatial mode propagation at the lasing wavelength of approximately 1050 nm. The separation of the two Yb-doped cores of 20 μm was chosen to place the two fiber cores in similar thermal environments while preventing evanescent coupling between them. The fiber we used to construct our laser was approximately 3 m in length. One end of this fiber was cleaved perpendicularly to serve as a 4 % end mirror. The other end of the fiber was polished at an angle (~ 8 degrees) to reduce back-reflections. This angle-polished facet produced a sufficiently low reflection back into the core to prevent the fiber from lasing without feedback from an external reflector.

Fig. 1 shows our experimental setup. The fiber was cladding-pumped at 975 nm from the left side by a fiber-coupled diode laser array. On the right side, the light emerging from the angled facet was collimated by an aspheric lens. The Dammann grating was placed at the back focal plane of this lens. The laser cavity was completed by placing a ruled diffraction grating at the far right of the figure. We used this grating at its Littrow angle to narrow the lasing bandwidth of the laser. Inside the laser cavity, a Glan-Brester-angle polarizer was used to introduce polarization-dependent loss. Its polarization axis could be aligned along one of the principal polarization axes of the fiber to maintain linearly polarized laser emission.

The difference in the index of refraction between the two fiber cores was made as small as possible in the process of fiber fabrication. In order to eliminate the possibility of wavelength tuning effects as a means of phase adjustment between the two gain arms, it can be shown that the optical path difference ΔL between the two gain arms has to be

Fiber Lasers XI: Technology, Systems, and Applications, edited by Siddharth Ramachandran,
Proc. of SPIE Vol. 8961, 89612B · © 2014 SPIE · CCC code: 0277-786X/14/$18
doi: 10.1117/12.2041012

much less than $\lambda^2/(2\pi\Delta\lambda)$, where $\Delta\lambda$ is the laser gain bandwidth and λ is its central wavelength. The laser gain bandwidth is restricted by the ruled diffraction grating to approximately 1 nm. The lasing wavelength is approximately 1 μm. Thus, wavelength tuning is eliminated when ΔL is significantly smaller than 100 μm. In order to meet this criterion, the residual optical path difference between the two fiber cores was reduced by consistent fiber bending and coiling. In this way, we were able to reduce the optical path difference to 23 μm.

1.2 Diagnostic instrumentation

In order to directly measure the optical path difference between the two gain arms, we inserted a 70:30 (T: R) beamsplitter into the laser cavity. Probe beams could then be injected into the fiber from the right side of the fiber. The probe laser consisted of a semiconductor chip whose lasing wavelength was tunable from 1020 nm to 1090 nm. On the left side of the fiber, a dichroic mirror was placed at a 45 degree angle to reflect both the probe and fiber laser light (wavelengths of 1020-1090 nm and 1050 nm respectively) while transmitting the pump light (wavelength of 975 nm). The light reflected by the dichroic mirror was further spectrally separated into fiber laser light and probe light, and both optical wavelengths were independently measured by a CCD camera. By analyzing the fringe shift in the interference between the light from the two cores at these two wavelengths, we could measure both the lasing supermode of the fiber and a change in index of refraction induced in the lasing media by the Kramers-Kronig effect.

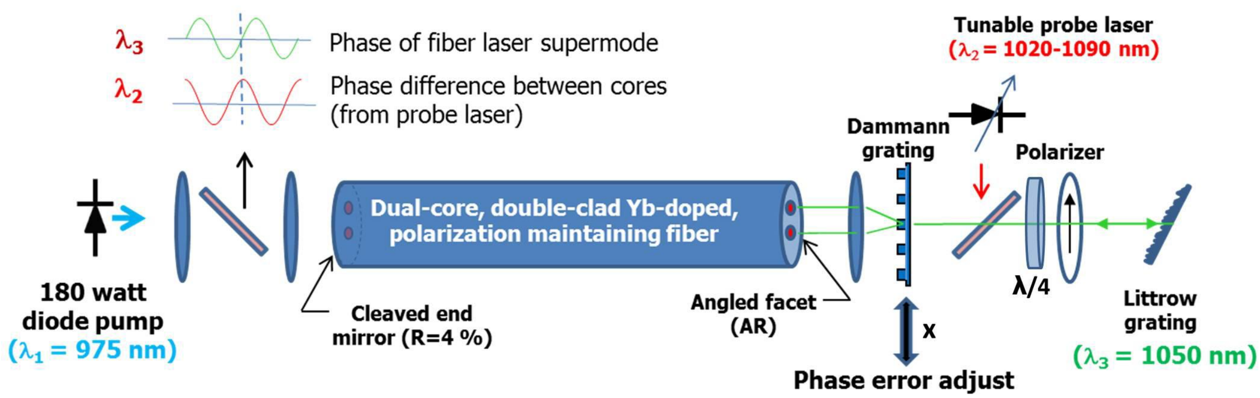


Figure 1. Experimental setup.

2. EXPERIMENTAL RESULTS

2.1 Phase measurement method

The Dammann grating was mounted on a precision translation stage. An additional phase difference $\Delta\varphi$ between the two gain arms was precisely introduced by spatially translating the grating across the laser cavity (*i.e.*, in the x-direction) as shown in Fig. 1. According to the Fourier shift theorem, the phase difference introduced in the +1 diffraction order by a spatial shift Δx of the grating is $\Delta\varphi=2\pi\Delta x/T_g$, where T_g is the period of the grating (~ 1.5 mm). The total phase difference φ_T (which is the sum of the phase difference introduced by the Dammann grating and the phase difference generated inside the fiber) between the two gain arms was measured by sending a probe beam into the laser cavity through the Dammann grating. The interference fringes were recorded and the phase shift was extracted by calculating the Fourier transform of the fringe pattern with a computer and recording its phase at the fringe frequency.

2.2 Observation of Kramers-Kronig self-phasing in linearly polarized fiber

The experimental data shown in fig. 2 resulted from adjusting the polarizer in fig. 1 so that the polarization state of the laser light was aligned with one of the principal polarization axes of the fiber. The fiber was cladding-pumped at ~ 2.2 W. At this pump power level, the cavity lased at all values of path length phase error between the two gain arms. The lasing power stayed at roughly the same level (± 10 %) over the entire range of path length errors. The actual path length error as measured by the probe laser showed a distinct staircase-like behavior. Despite the fact that the applied path length error $\Delta\varphi$ changed continuously through all the possible values, the total path length phase error φ_T (applied phase error plus phase shifts from propagating through the two fiber cores) changed in a semi-discrete manner. Theoretically, it can be shown that this laser cavity has a loss minimum whenever the total path length error φ_T equals $k\pi$, where k is an integer. It is apparent that self-phasing is occurring in our experiment, and that this self-phasing cannot be explained by wavelength shifting or thermal effects.

In our experiment, we observed that the phase plateaus in fig. 2 (measured with the probe laser) disappeared at lower pump power levels or when the laser was not lasing[1]. The existence of plateaus in the measured path length error is an indication that there is a self-phasing mechanism which can effectively compensate for the applied path length error. Since this self-phasing mechanism doesn't manifest at low pump power levels and is also absent when the laser is not lasing, we conjecture that this self-phasing mechanism originates from the Kramers-Kronig effect, *i.e.*, a change of index of refraction due to a change in gain. An applied path length error changes the loss of the cavity. In order to sustain lasing, the gain has to change accordingly. The change in gain results in a change in the index of refraction of the fiber cores and thus the optical path length also changes. The optical path length will adjust itself in such a way that the cavity remains at its lowest loss. This means that the self-adjustment of the optical path length will always try to restore the total path length error to $k\pi$.

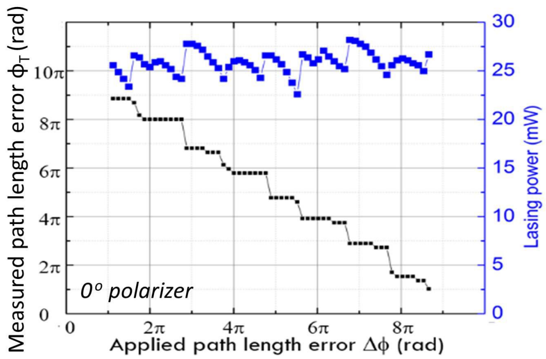


Figure 2. Measured path length error (black curve) and lasing power (blue curve) vs. applied path length error. The pump power was ~2.2 W. The wavelength of the probe laser was set to 1070 nm to measure the Kramers-Kronig phase shift.

2.3 Measurements of the Kramers-Kronig phase shift in a single fiber

To further explore whether the observed self-phasing originates from the Kramers-Kronig effect or is due to various thermal effects, we pumped a single fiber core using a single-mode laser diode (wavelength = 976 nm) and used the un-pumped core as a reference. In this way, we were able to measure the phase shift of the pumped core relative to the un-pumped core.

Fig. 3(a) shows the phase shift of the pumped core relative to the un-pumped core as a function of the core-pumping power. The phase shift increases more or less linearly with the pump power until the point where the pumped core starts to lase. Once lasing starts, the phase shift becomes approximately constant, with further pumping having only a small effect on phase. If the phase shift were purely due to the Kramers-Kronig effect, the slope of the curve should be zero above lasing threshold because of gain clamping. We believe that the shallow negative slope above lasing threshold is most likely due to a heating effect. Thus, we conclude that the Kramers-Kronig phase shift is the dominant phase-shifting mechanism under our experimental conditions.

Although the gain at 1070 nm is significantly smaller than the gain at the lasing wavelength (~ 1050 nm) of the fiber, previous studies[2] on the resonant nonlinearity in Yb-doped fiber show that the Kramers-Kronig phase shift at these two wavelengths differs by less than 10 %. Therefore, we believe our phase measurement is a reasonably accurate assessment of the phase shift at the lasing wavelength of the fiber.

To see how much change in gain is needed to induce a specific Kramers-Kronig phase shift, we core-pumped the fiber again and used a 1050 nm probe to measure the induced phase shift. To prevent the pumped core from lasing, we blocked the return light from the ruled diffraction grating. The data are presented in Fig. 3(b). We see that there is a linear relationship between Kramers-Kronig phase shift and the change of gain. This relationship was previously predicted by Charles Henry as $\Delta\varphi=(\alpha/2)\Delta g$, where $\Delta\varphi$ is the Kramers-Kronig phase shift, Δg is the intensity gain change, and α is a dimensionless parameter[3]. The value of α is measured to be approximately 3.5 at 1050 nm based on the data shown in Fig. 3(b). We are currently working on a theoretical model that takes into account both the path length error-dependent loss and the Kramers-Kronig phase shift to explain the observed self-phasing behavior.

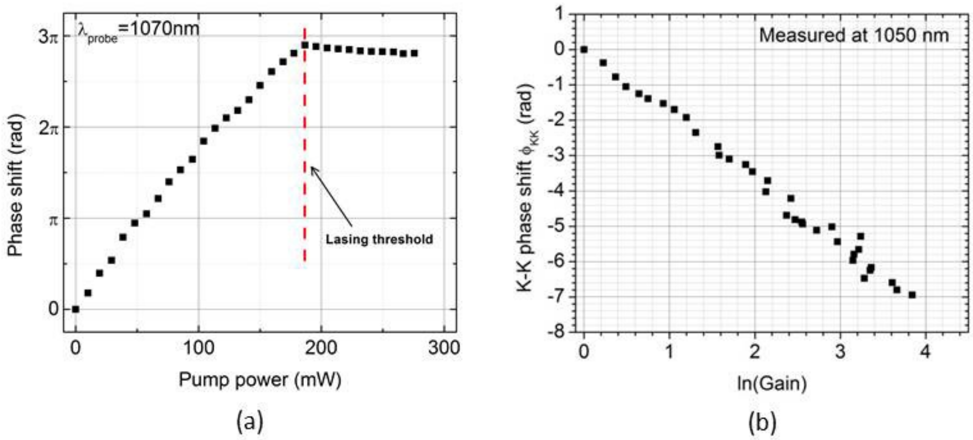


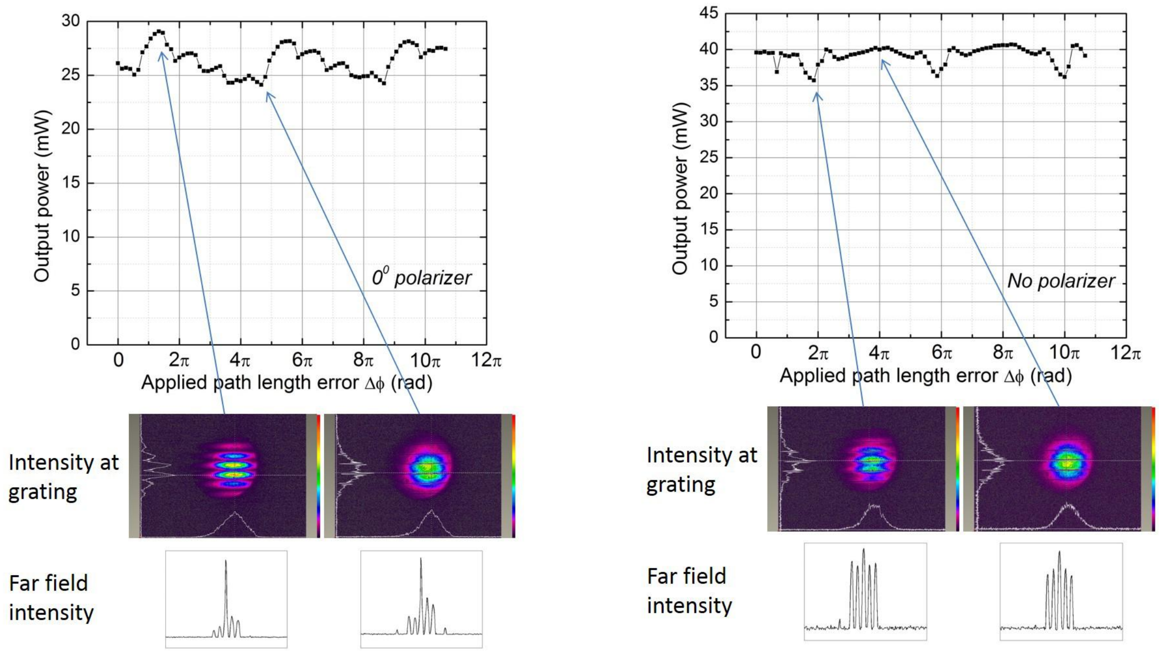
Figure 3. (a) Phase shift of pumped core relative to the un-pumped core vs. core-pumping power; (b) Kramers-Kronig phase shift measured as a function of gain.

2.4 The effect of polarization on Kramers-Kronig induced self-phasing

Our previous experiments have been performed with polarization maintaining fibers and external polarizers. The reason we chose to design the experiment in this way was to study the simplest possible physical system consisting of two lasers operating in a single polarization state. However, many beam combining experiments in the past have been designed without particular attention to polarization. In fact, in many applications the polarization state of the final beam is not important. It is natural to ask whether the polarization state has an influence on the Kramers-Kronig self-phasing we have observed. To study this, we have performed a variety of experiments whereby we have placed a quarter-wave plate and polarizer in the cavity as shown in fig. 1. This combination allows us to enforce any elliptic polarization state we desire on the circulating beam. We can also remove the polarizer and quarter-wave plate entirely and let the beam choose its own polarization state.

In our first experiment, we cladding-pump the fiber with approximately 2.4 watts of 975 nm pump light. With the polarizer in place and oriented along one of the principal axes of polarization in the fiber, the data in fig. 4(a) was recorded. As in the previous case shown in fig. 2, we see that the overall laser power (measuring all diffraction orders exiting the Dammann grating) is approximately constant with respect to applied phase error. A check of the circulating polarization showed that the fiber was indeed maintaining the initial polarization state. We expect there to be peaks at every integer value of π in applied phase error, and indeed this is seen in the figure. The fact that the peaks are not all of equal intensity is most likely a result of unequal coupling into each core as well as a Dammann grating phase modulation that is not exactly π radians.

For each value of applied phase error, we also recorded the fringe pattern at the Dammann grating and the far-field pattern. The fringe pattern visibility is a measure of the coherence of the supermode, with a low visibility indicating that multiple supermodes are oscillating in the cavity. The far-field pattern indicates the phase state of the supermode, with a large central spike indicating that the supermode is uniform in phase. Two representative points are shown in fig. 4(a). The first at the peak of the intensity curve shows a high visibility fringe at the grating and a very large central peak. Similar fringe and far-field patterns are observed for virtually all the other points in this curve, with the exception of the points at the bottom of the intensity trough. At this value of phase error, the fringe visibility was seen to degrade somewhat, the central peak of the far-field pattern was slightly reduced, and the asymmetry of the diffraction pattern was accentuated. Thus, we see that over most of the applied phase error range, the Kramers-Kronig phasing appeared to be compensating for the phase errors, resulting in effective coherent beam combining.



(a) (b)

Figure 4. Total output power as a function of applied path length phase error. The interference pattern of the light exiting the fiber cores and illuminating the grating is shown at two phase error points, as is the far-field output intensity. a) Polarizer placed between Dammann grating and Littrow grating, b) Polarizer removed.

The data in fig. 4(b) were obtained by removing the polarizer and quarter wave plate from the system and allowing the laser to oscillate at its natural polarization state. We observed that the laser generally selected an elliptical polarization state which did not change polarization significantly as a function of applied phase error.

We observed that the total power in this laser cavity was significantly higher than the power observed with the polarizer inserted. This appears to be caused by one or more polarization sensitive elements in the cavity that were adding loss to the beam in the polarized case. In particular, the Littrow grating is quite polarization sensitive, resulting in a reduced reflectance when illuminated with the state of polarization chosen in the first experiment.

The second obvious difference is that the visibility of the fringe pattern at the Dammann grating was degraded significantly over most of the values of path length phase error. The two values shown in fig. 4(b) were representative of almost all the phase error points. Even more remarkably, the far-field patterns of the laser were significantly degraded, indicating a loss of coherence between the two lasers.

As a final experiment, we measured the total phase shift in the cavity as a function of applied path length phase error in a manner identical to that described in part 2.1. The stair-case shaped phase response shown in fig. 2 was observed when the polarizer was placed in the cavity as shown in fig. 1. However, when the polarizer was removed, the staircase shape was almost entirely eliminated. The data are shown in fig. 5, where the cases with and without polarizers are plotted on top of each other. It is clear that the influence of Kramers-Kronig phase adjusting has been severely attenuated when the polarizer was removed.

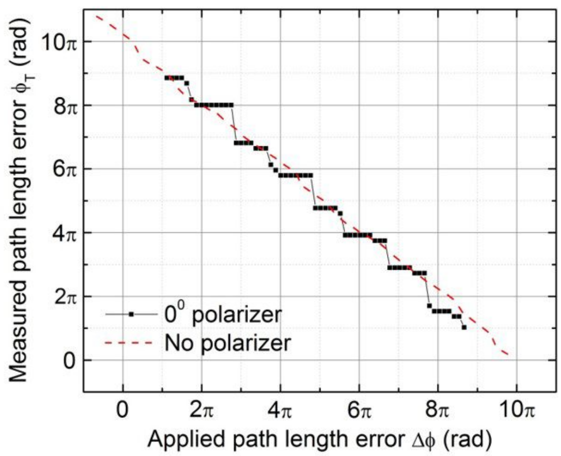


Figure 5. Measurements of the total phase difference between the two laser cores as a function of applied phase error. The solid black line corresponds to measurements with a polarizer inserted in the cavity, whereas the dashed red line corresponds to measurements with the polarizer removed.

3. CONCLUSIONS

We have observed efficient coherent beam combining that is insensitive to path length errors when the polarization of the cavity is controlled by a polarizer aligned to correspond to one of the principal polarization states of our PM fiber. Furthermore, we have shown that this insensitivity comes from the Kramers-Kronig effect, which was observed to produce a phase shift that cancelled the applied phase error, permitting the cavity to operate in a low-loss phase state. However, when the polarizer was removed and the cavity was allowed to lase in an arbitrary polarization state, the effect of the Kramers-Kronig self-phasing was considerably compromised. In fact, the far-field diffraction patterns measured from the unpolarized cavity showed very little coherence between the two laser cores under most phase error conditions. These experiments indicate that it is important to maintain polarization when making fundamental measurements of the Kramers-Kronig self-phasing effect.

REFERENCES

[1] Chiang, H.-S., Leger, J. R., Nilsson, J. and Sahu, J., "Direct observation of Kramers-Kronig self-phasing in coherently combined fiber lasers," Opt. Lett. 38(20), 4104-4107 (2013).

[2] Arkwright, J. W., Elango, P., Atkins, G. R., Whitbread, T., Digonnet, M. J. F., "Experimental and theoretical analysis of the resonant nonlinearity in Ytterbium-doped fiber," J. Lightwave Technol. 16(5), 798-806 (1998).

[3] Henry, C. H., "Theory of the linewidth of semiconductor lasers," IEEE J. Quantum Electron. QE-18(2), 259-264 (1982).