Passive Coherent Beam Combining of Fiber Lasers: Accurate Measurements of Phase Error Tolerance

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Abstract: A cladding-pumped dual core ytterbium fiber laser is designed and fabricated to measure phase error tolerance in passive coherent beam combining. We show quantitative measurements on the effects of longitudinal modes on phase error tolerance.
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1. Introduction

External cavity architectures offer a simple alternative for coherent beam combining compared to a master-oscillator power amplifier design [1]. In both architectures, it is important to ensure that the phase of each fiber laser is adjusted correctly to promote efficient, high-brightness laser operation. Active phase control has been employed to achieve the required laser phases in both approaches [2,3]. However, under certain conditions the external cavity architecture can also be operated in the passive regime, where no active phase control is needed.

There appear to be several mechanisms responsible for the self-phasing seen in passive systems, with the most obvious one being wavelength tuning. For a sufficiently small number of lasers, the operating wavelengths can adjust to establish the required fiber phases for efficient lasing, even in the presence of significant phase errors. At higher powers, nonlinear effects may also contribute to the behavior of the coupled laser system [4].

Measuring the effects of phase errors and the corrective behavior of wavelength tuning and nonlinear interactions is particularly challenging in passively coupled fiber laser systems. First, since there is no active phase correction, the effects of vibrations and temperature generally make it difficult to accurately measure and maintain the phase of each fiber laser with respect to the others. Second, controlling these phase relationships to the required accuracy takes special care. And finally, the wide gain bandwidth of most fiber lasers allows for significant longitudinal mode hopping, making it very difficult to separate the cavity response to wavelength tuning from other effects. Previous attempts to measure the characteristics of passively coupled laser systems have been plagued by the inability to control many or all of these effects. In this paper, we have engineered and fabricated a custom fiber, together with a specially designed passive beam combining experiment to eliminate all these complications. Our set-up allows us to measure the amplitude and phase of the supermodes as well as the combined laser output characteristics as a function of fiber phase errors, wavelength tuning, polarization, and nonlinear effects independently from each other so that the underlying physics of this complex system can be studied.

2. Fiber design and experimental set-up

The experimental set-up shown in fig. 1 consists of a dual-core double-clad polarization maintaining Yb-doped fiber laser, where the two laser cores are coherently coupled in an external cavity by a Dammann grating. The fiber cores are separated by 20 μm, a distance chosen to keep the environment virtually identical between the two cores while

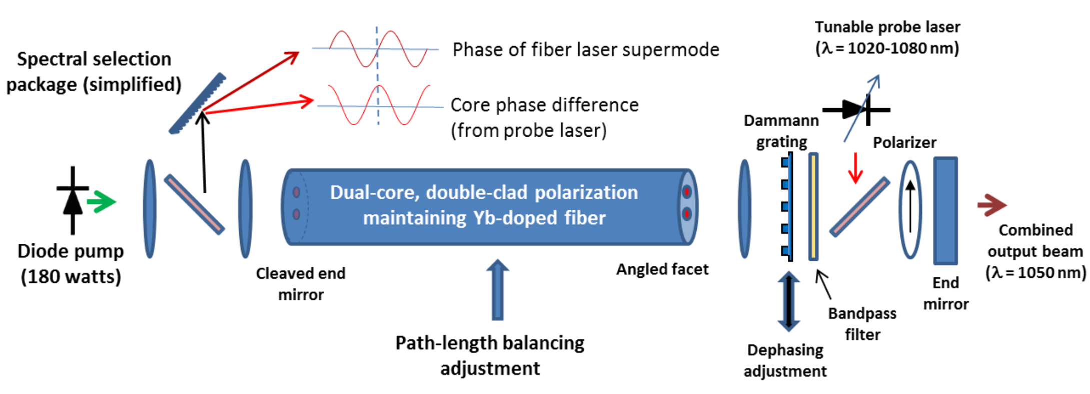

Fig. 1 Experimental configuration for accurate measurement of path length error effects. The path length error can be changed by translating the Dammann grating perpendicular to the fiber. The tunable probe laser permits measurement of absolute phase errors.

suppressing the effects of evanescent coupling. The optical path length difference between the two cores was balanced as closely as possible through process control during fiber fabrication. Further path length balancing was achieved by controlled fiber bending, reducing the residual optical path length difference between cores to 23 μm (out of a total fiber length of 3 meters). The resulting longitudinal mode spectra of the lasers formed by the two cores were sufficiently close so that the effect of wavelength tuning could be easily managed by placing spectral filters inside the cavity. Stress rods were introduced in the fiber to ensure polarization maintaining propagation.

The fiber was right-angle cleaved at the pump end to form a 4%-reflecting end mirror. The other end of the fiber was polished at an angle to reduce reflection, and light from the two fibers cores was combined with a Dammann grating. Translation of the Dammann grating provided an easy and very accurate method of controlling the phase difference between the two fiber cores [5]. A tunable semiconductor laser was injected into two fiber cores to measure the total optical path length difference and to provide a real-time measurement of the fiber phase error.

3. Effects of fiber phase errors on passive combining

The fiber was pumped at low power and the output power, wavelength and far-field intensity were recorded as a function of path-length error. The path length error could be adjusted with an accuracy of approximately λ/100 by translating the Dammann grating, and path length stability between the two cores of the fiber (at a constant pump current) was judged to be approximately λ/40. Three different spectral filters were placed in the cavity to control the number of longitudinal modes that were available for lasing. Figure 2 shows a plot of the output laser intensity as a function of applied path length error for three different spectral bandpass filters. Limiting the lasing bandwidth to 3.8 nm (fig. 2a) eliminates the effect of wavelength tuning, and the two distinct lasing modes (the in-phase and out-of-phase modes) are clearly visible in the inserts. Path length errors between these two modal peaks quench lasing. When more longitudinal modes are permitted to lase (fig. 2b), the sensitivity to path length error is reduced and lasing is possible over a larger set of path lengths as the spectrum of the laser adjusts to compensate for the phase errors. Our approach allows us to measure the effects of nonlinearities (e.g. phase shifts up to 2π radians introduce by the optical Kerr effect) and differential heating while minimizing the impact of environmental disturbances, and thus better understand the limits and potential optimization of passive beam combination.

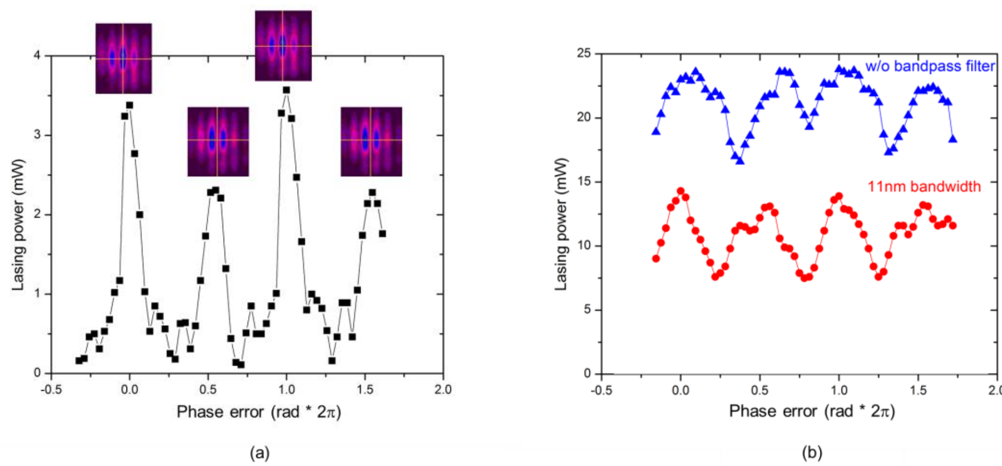

Fig. 2. Measurements of combined laser output power as a function of path length error. (a) Lasing bandwidth limited by 3.8 nm bandpass filter. Inserts show far-field intensity of fiber supermodes. (b) Lasing bandwidth limited by 11 nm bandpass filter, and without filter present.

4. References

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