Invited Paper

Recent advances in coupled laser cavity design

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ABSTRACT

External cavity coherent beam combining represents a path forward to higher fiber laser radiance, with several groups demonstrating scalable approaches. In this paper, we review recent advances in coupled laser cavity design. In particular, we compare various designs and describe the pros and cons of each with regard to sensitivity to path length errors. Experimental measurements using a specially designed dual-core fiber demonstrate the modal loss from a superposition architecture. A second area of investigation is concerned with Q-switch suppression in coupled laser cavities. The increased cavity loss that accompanies path length errors in the laser arms can suppress lasing, causing an energy build-up in the laser inversion. When the path length errors are removed and the cavity resumes its low loss state, the stored energy can be released in a manner analogous to Q-switching, creating a giant laser pulse. Since the peak power of this pulse can be many orders of magnitude larger than the cw power, the high instantaneous intensity can cause irreparable damage to optical components. We investigate passive systems that are designed to suppress this unwanted Q-switching by allowing alternative lasing paths to clamp the gain.
Keywords: Laser resonator, Coherent beam combining, Supermodes, Q-switch suppression, Fiber lasers

1. INTRODUCTION

Various laser architectures have been suggested to perform coherent beam addition. In particular, a master oscillator power amplifier architecture has been demonstrated that successfully combines the radiance of several beams[1,2]. Coherence is established by the master oscillator, and the correct phase state is maintained by measuring the phase of each amplifier channel and adjusting it so that a uniform phase is maintained. An alternative architecture utilizes a common cavity to establish coherence and adjust the phases[3,4]. Of course, this architecture can also benefit from measuring the phases of each gain element and performing a path length correction. However, this is not always necessary if the cavity can be designed to be relatively insensitive to path length changes. In these cases, a passive cavity can give rise to a much simpler system. There have been several studies to ascertain the sensitivity of common cavities to path length errors[5,6]. These theories have been verified experimentally using solid-state lasers. However, additional complications arise when fiber lasers are used. The purpose of this paper is to review progress in external beam combining using fiber lasers. In particular, we will show measurements of path length error characteristics where we have extremely good control over the laser wavelength, path length difference, and phase error. In addition, we review a cavity modification that can passively protect a cavity from catastrophic damage due to unintentional Q-switching.

2. PATH LENGTH SENSITIVITY OF BEAM COMBINING ARCHITECTURES

Many optical architectures have been proposed for performing beam combining[7]. These can be generally categorized into superposition architectures and parallel coupled architectures. In superposition architectures, the beams from several lasers are made to overlap in a common plane. An optical element modifies the phase of the resulting interference pattern to couple the light into a single direction of propagation. In contrast, the lasers in a parallel coupling architecture all emit light in the same direction. Coherence is established between the different lasers by coupling a

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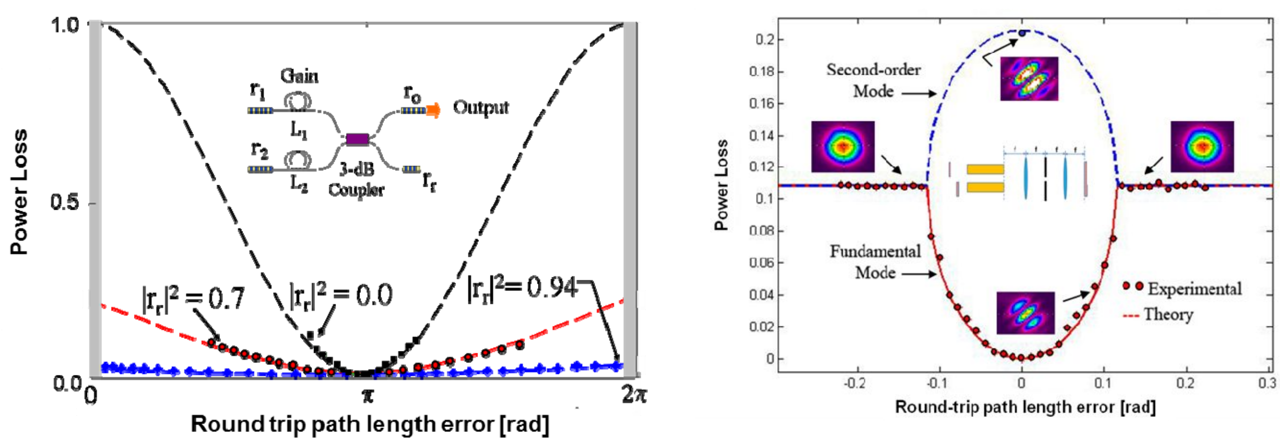
small amount of the light between the various laser cavities. In both architectures, the path lengths (and thus the phases) of the lasers must be chosen correctly to permit efficient lasing. In this section, we briefly review the theory and experimental verification of the path length sensitivity exhibited by coupled laser configurations.

The path length sensitivity of coupled laser cavities has been extensively studied[8]. Simple beam superposition of two lasers can be achieved by using a beam splitter or 3-dB coupler[9,10]. Larger numbers of lasers can be most conveniently superimposed by using Dammann gratings. The configuration consisting of two lasers coupled by a 3-dB coupler is shown in the insert of fig. 1a. In this figure, two fiber lasers are placed at one end of the 3-dB coupler and the combined output is taken from one arm at the other end. If the path lengths of the fiber lasers are chosen correctly, all the power can be extracted from this one output port of the 3-dB coupler. The curves in this figure show the effect of laser path length errors on the round-trip power loss of the cavity. When the fourth mirror reflectivity $r_r = 0$ so that there is no reflectivity from this arm, the cavity loss is expressed by a simple $\cos^2(\phi)$ function, where ϕ is the differential path length error. By increasing the value of r_r, the tolerance to path length error can be increased. In this figure, the discrete data points correspond to experimental measurements made using a coupled Nd:YAG laser system rather than fiber lasers.

An example of a parallel coupled beam combining architecture is shown in fig. 1b. The insert shows a spatially filtered cavity, where a spatial filter placed in the back focal plane of the first lens produces a smaller loss to the coherent state than the incoherent state, inducing the two lasers to lock together in a common phase state. The sensitivity of this cavity to path length error is again shown by the curves in the figure, and the discrete points correspond to measurements made with a coupled Nd:YAG laser system. This architecture exhibits distinctly different characteristics when compared with the superposition architecture shown in fig. 1a. Unlike the 3-dB coupled system, the loss curves in fig. 1b show a value where the loss to the first- and second-order modes coalesce. When the phase error is less than this specific value, the two loss curves separate and the cavity lases in the mode with the lower loss. However, phase errors larger than this value produce losses to the two modes that are identical, and the cavity always lases in both modes simultaneously. This is readily seen in fig. 1b, where the far-field patterns are displayed as inserts. The patterns corresponding to small path length errors show operation in either the in-phase mode (lower curve) or the out-of-phase mode (upper curve) depending on the adjustment of the spatial filter. However, the far-field pattern produced by larger path length errors contains both modes lasing simultaneously in an uncoupled manner. The resulting laser operation is incoherent and no increase in radiance is possible.



(a) (b)

Figure 1. Theoretical and experimental plots of cavity loss as a function of round-trip path length error. Experimental data was measured using a Nd:YAG laser system. a) Superposition architecture consisting of a 3-dB coupler. The three separate curves correspond to three different values of the reflectivity (r_r). b) Parallel coupled architecture using spatial filtering. The two curves correspond to the fundamental and second-order modes of the coupled laser system.

3. DUAL CORE FIBER LASER MEASURMENTS OF PATH LENGTH SENSITIVIES

The theoretical curves presented in fig. 1 are based on passive cavities, and do not model the effects of the gain medium, nonlinearities, and thermal effects. The low power Nd:YAG laser used in these tests was found to agree with this simple model quite well. However, experiments using fiber lasers have shown that this passive model may not be sufficient to explain all the observed effects. In particular, there is evidence that Kerr nonlinearities, Kramers-Kronig phase shifts, and thermally induced index and length changes may give rise to a much more complex behavior in real fiber laser systems, particularly at high powers[11]. To examine the physics of this system, we have developed a coupled fiber laser that can be controlled with high precision.

The largest challenge in a fiber laser system is keeping the path lengths of the individual fibers stable to a fraction of a wavelength as the pump current and environmental conditions are varied. However, since the response of the coupled resonator is only a function of the optical path length difference, the effect of pump power and environmental conditions can be minimized by placing the two lasers in the same environment. We have accomplished this by fabricating a fiber that consists of two ytterbium-doped cores in a common, inner, cladding. The inner cladding is surrounded by a lower-index outer cladding to allow for so-called cladding-pumping at high power. In addition, the cores are designed to have a small diameter (5 μm) to enhance any nonlinear effects. The two cores are placed 20 μm from each other, a distance chosen to minimize variation between the two environments while being large enough to effectively eliminate evanescent coupling. Stress rods are also incorporated into the fiber to ensure polarization maintaining characteristics.

One of the key elements of this fiber design is attention to absolute optical path length difference (OPD) between the two fiber cores. When this path length is greater than a few tens of microns, a change in the operating wavelength of the laser can change the relative phase between the two cores. Because of the difficulty of reducing the OPD below this level, most experiments using coupled fiber lasers have been greatly influenced by this wavelength tuning effect, and much of the more subtle physics has been masked. In our experiment, we have taken special care in the fabrication of the fiber to balance the OPD as accurately as possible. After fabrication, the OPD between the two cores was measured by coupling a tunable semiconductor laser into the two cores and observing the fringe shift as a function of laser wavelength. The fiber was then coiled such that one core experienced a larger radius of curvature than the other, effectively increasing its optical path length. In this manner, the OPD was reduced to a level where the effect of wavelength shift on phase could be varied by controlling the bandwidth of the cavity with simple dielectric bandpass filters.

An external laser cavity was set up as shown in figure 2, where the dual-core fiber was pumped by a 975 nm semiconductor laser. The left end of the fiber was cleaved at 90 degrees to provide a 4 % reflectivity, whereas the right end of the fiber was given an angle polish to effectively eliminate reflections from this interface back into the laser cores. The two laser cores were then coupled together with a simple Dammann grating, and the resulting combined beam was passed through a bandpass filter and a polarizer. A flat end mirror completed the external cavity. The relative phase between the two cores could be conveniently adjusted by translating the Dammann grating. The accuracy of this adjustment was judged to be on the order of $\lambda/100$, whereas the differential phase stability of the two fibers when pumped at lower power was approximately $\lambda/40$.

The phase error between the two cores was measured by injecting the light from a tunable probe laser into the fiber from the right-hand side and measuring the fringe shift on the left-hand side. In addition, the phase of the oscillating supermode could be determined by observing the far-field interference pattern at the fiber laser wavelength. Finally, the overall power of the combined laser beam was measured exiting the external end mirror on the right-hand side.

The effect of path length changes can be dramatically seen in figure 3. Using a bandpass filter that is sufficiently narrow (3.8 nm) to eliminate any phase tuning from wavelength shifting, the presence of the two supermodes can be easily seen. Path length shifts resulting in phase errors of zero and π radians produce efficient lasing, whereas intermediate phase errors effectively quench lasing action. However, when the lasing bandwidth is increased to 11 nm (lower red curve in figure 3(b)) or allowed to lase across the entire gain bandwidth (upper blue cure in figure 3(b)), lasing occurs at all possible phase errors, and the effect of the phase error is only to change the output power slightly. Since our current

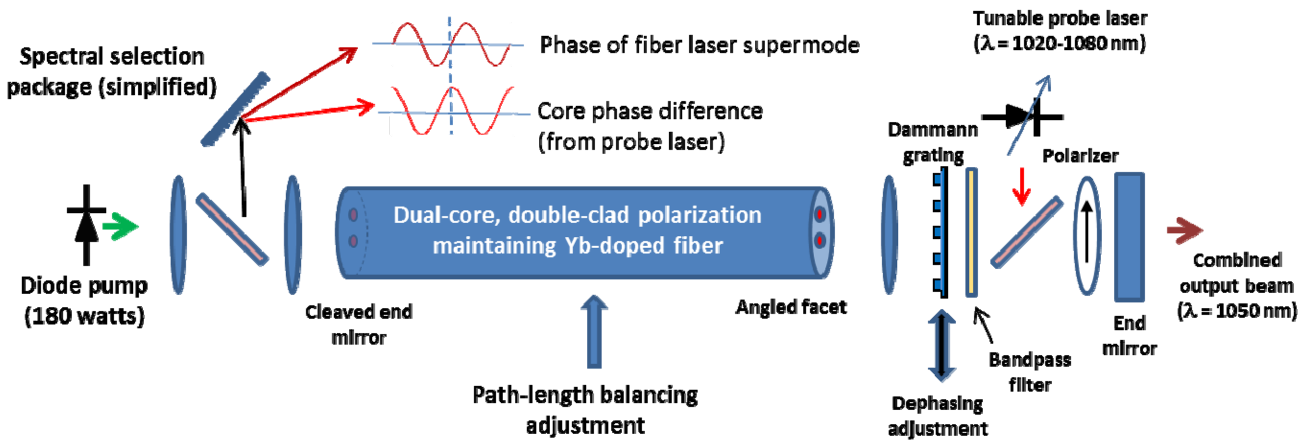


Figure 2. External cavity set-up for coupling two fiber lasers.

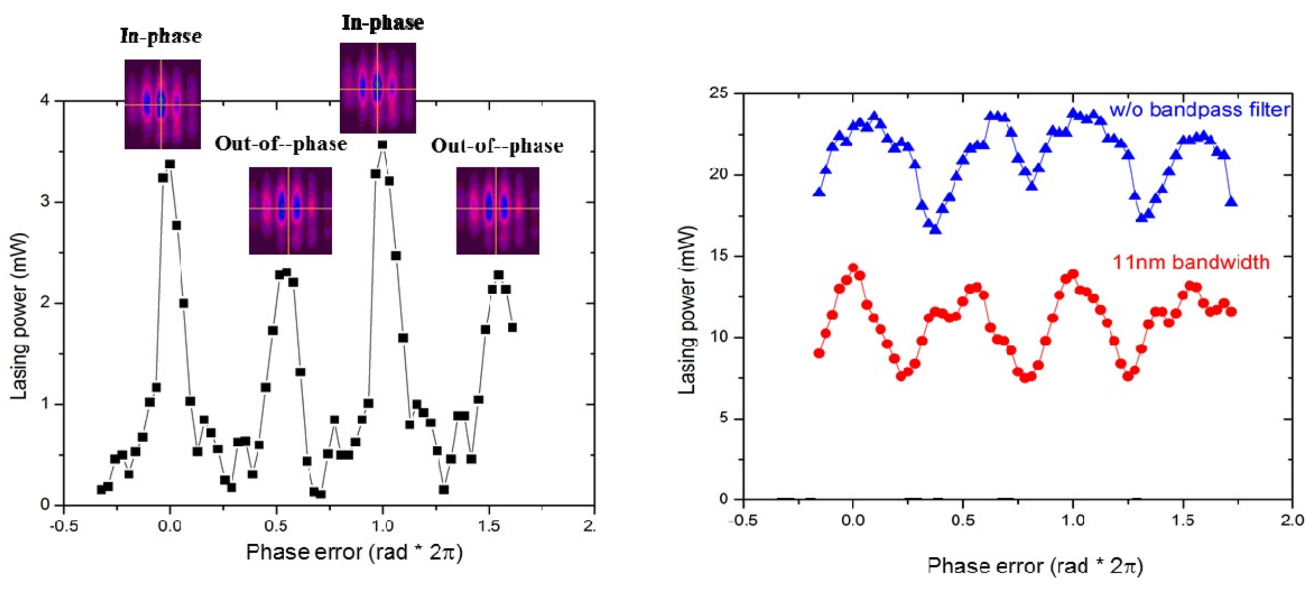


Figure 3. Output power of coupled laser beam as a function of phase error between lasing cores. (a) Lasing bandwidth is constrained to 3.8 nm with a bandpass filter. (b) Lasing bandwidth is increased to 11 nm (lower red curve) and unrestricted (upper blue curve).

fiber is not able to withstand high pump powers, these measurements have all been conducted at pump powers that are only slightly above threshold. However, by replacing the current fiber with one that is designed for high power, we expect to be able to explore lasing characteristics under the influence of several nonlinear effects.

4. PASSIVE Q-SWITCH SUPPRESSION

In the previous two sections, we have shown that proper phasing is important for effective beam combining. Whether the phasing is provided by an active or passive system, the loss of proper phasing can have catastrophic consequences to the lasing system. A possible failure mechanism proceeds in the following manner. The pumped laser system shifts for a short time from a high-Q cavity condition (with lasers maintaining the proper phase state) to a low-Q condition (when one or more of the laser paths introduces a significant path length error). The Q is sufficiently low to interrupt lasing, and the pump energy starts to build up the inversion. The path length error then corrects itself and a giant laser pulse is induced as the built up energy in the inversion is converted into optical energy in a few cavity lifetimes. This Q-switched pulse can have a peak intensity that is many orders of magnitude larger than the cw lasing intensity. In a high power laser system where the components are designed to work only at the cw intensity, the Q-switched pulse can exceed the damage threshold and cause catastrophic failure of the optical components. It is therefore desirable to design a system that can suppress this unwanted Q-switching.

One simple system that can provide passive Q-switch suppression is shown in figure 4. Although this figure shows the combination of only two lasers, the concept can be extended to include an arbitrary number. The system consists of a conventional Dammann grating beam combiner with two fiber laser inputs and a main output beam. The lasing wavelength of this system is chosen to be $\lambda_{primary}$. In addition to this conventional beam combiner, volume Bragg gratings (VBG) are added to each arm of the laser and tuned to reflect at λ_{aux}. The threshold of lasing at λ_{aux} is chosen to be slightly higher than the threshold to lase at $\lambda_{primary}$. Hence, in normal operation (no path length errors), the laser will operate in the coherent beam combining mode and the VBG will not diffract any light. However, if the threshold of the main output port goes up because of a path length error, each individual laser arm will start to lase at λ_{aux} through the VBG. This secondary lasing path keeps the energy from building up in the fiber gain media by clamping the gain. When the path lengths return to normal and the laser starts to last through the main output coupler, the stored energy will be largely absent and the Q-switched pulse will be significantly attenuated.

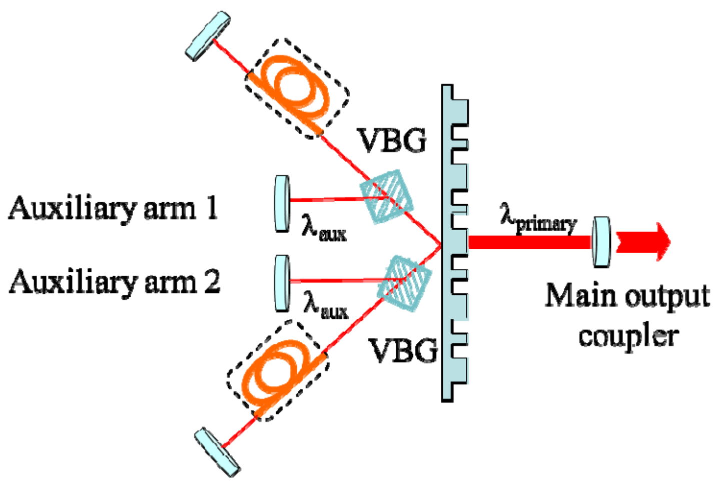


Figure 4. Passive Q-switch suppression devices placed on both arms of a two-beam coherent beam addition cavity.

Figure 5 shows the experimental set-up that was used to test this system. Rather than testing an actual coherent beam combining system, we used an acoustooptic modulator to simulate a beam combining cavity that was abruptly changing from a low-Q state to a high-Q state. A quarter-wave plate and a polarizing beam splitter were used in the auxiliary arm to control the relative loss of this arm with respect to the main lasing arm.

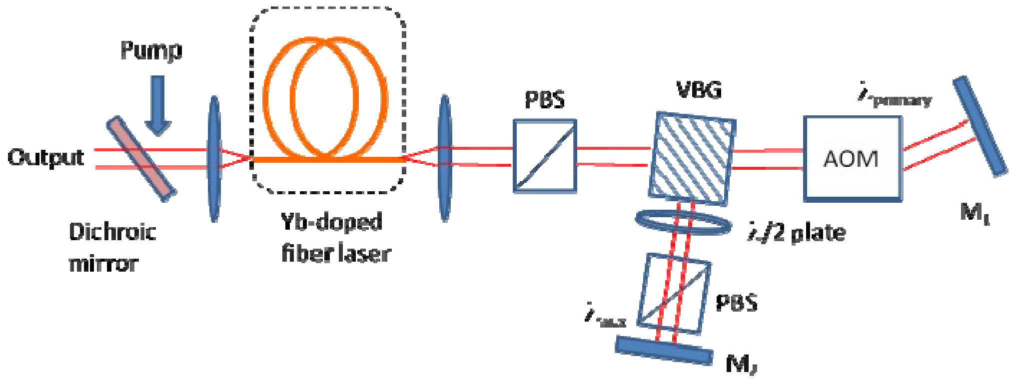
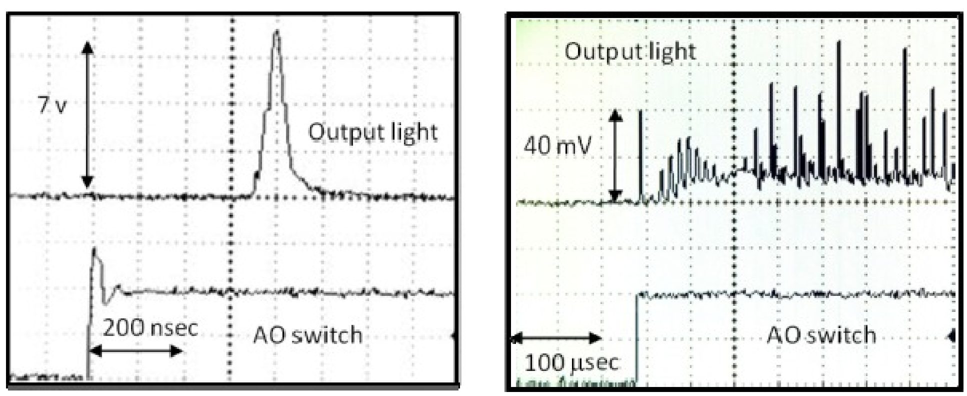


Figure 5. Experimental set-up to demonstrate Q-switch suppression.

Figure 6 shows the result of abruptly turning on the acoustooptic modulator both without and with the Q-switch suppression in place. With no Q-switch suppression, the initial lasing pulse consisted of a giant spike that registered a value of seven volts on our uncalibrated detector. With the Q-switch suppression in place, the Q-switch spike was reduced by 175 times to a value of 40 millivolts, a level lower than the self-pulsation pulses in the cw operation of the laser.



(a) (b)

Figure 6. Experimental results from Q-switch suppression experiment. a) No Q-switch suppression. b) Q-switch suppression employed.

5. CONCLUSIONS

This paper has reviewed three recent advances in passive coherent beam combining. The first consisted of a comparison of the path length sensitivity between a 3-dB coupled cavity and a spatially filtered cavity for performing coherent beam addition. It was noted that the two cavities had very different responses to path length errors. The 3-dB cavity was able to establish coherence at any path length error, although increased error resulted in increased cavity loss. The spatially filtered cavity, in contrast, was only able to establish coherence for a small range of path length errors. Larger errors resulted in incoherent cavity operation. The second section outlined a fiber laser experiment for measuring path length sensitivity in a fiber-based system. Care was taken to control the effect of wavelength tuning, and two regimes were explored. In the first regime, wavelength tuning had little effect on the path length errors, and the combined laser power was significantly influenced by path length error. In the second regime, the wavelength tuning had more influence on the cavity path lengths, and the path length error was largely compensated by this tuning. Finally, the third section introduced a new method for suppressing undesired Q-switching. Alternative lasing paths were provided for each lasing arm, effectively clamping the gain of the arms and preventing the build up of a Q-switch pulse. An experiment was shown that reduced the peak intensity of the Q-switch pulse by a factor of 175 times.

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