Phase locking of nanosecond pulses in a passively *Q*-switched two-element fiber laser array

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Phase locking of Brillouin backscattering *Q*-switched laser pulses that are much shorter than the round-trip time of the resonators has been demonstrated in a two-element fiber laser array. Despite the stochastic dynamics of nonlinear pulse generation, simultaneous generation and phase locking of short pulses have been achieved by using diffractive coupling and spatial filtering in an external resonator. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2721390]

High-peak-power pulsed fiber lasers are of interest for various applications, including medicine, remote sensing, and nonlinear optical processes. *Q*-switched fiber lasers based on active and passive techniques[1–3] have been developed to achieve high energy, high peak power, and short pulse emission. The pulse duration of the *Q*-switched pulses generated by conventional active and passive techniques ranges from hundreds of nanoseconds to several tens of microseconds due to the long resonator lengths of typical fiber lasers. Recently, there have been reports of using Brillouin backscattering as a distributed passive *Q*-switching mechanism to generate short pulses that are much shorter than the resonator lengths. Unlike the conventional *Q*-switching fiber lasers, in which the pulse duration is proportional to the photon lifetime in the resonator, the short pulses generated by stimulated Brillouin scattering (SBS) do not depend on the photon lifetime in the resonator but rather on the dynamics of the nonlinear process. For example, short pulses of 2–5 ns duration have been demonstrated in fiber lasers when the power density in the fiber exceeded the threshold for SBS.[4–7] Short pulse generation through SBS in fiber lasers can be a self-starting process that does not require an intracavity modulator, but the occurrence of pulses was found to be highly irregular in pulse energy, shape, and repetition rates.[6,7] There have been reports of pulse stabilization using an acousto-optic modulator[5] and Cr^{4+}:YAG (yttrium aluminum garnet) saturable absorber.[6]

The ultimate peak power achievable in a single fiber gain medium is limited by the threshold of optical damage, which is on the order of 2 GW/cm^2. According to the manufacturer's specifications, the reported power density of peak power of pulses generated by SBS is 20 GW/cm^2, which is already in the regime of optical damage.[5] The potential for further increase in optical power in a single fiber through this nonlinear process thus is limited. Coherent power combination of the output of multiple lasers is a way to extend the upper limit of peak power.

There have been a number of recent reports of phase-locked operation of multiple fiber lasers through the evanescent coupling or when coupled to an external resonator.[8–14] In all previous studies of phase locking of fiber lasers, the lasers were operated in the continuous mode or in the pulsed mode with a pulse duration which was much longer than the round-trip time, and the pulses from the individual lasers overlapped in time to form interference fringes. The control of the relative phase of the laser elements has been achieved by selecting interference fringes that correspond to the desirable relative phase. For example, stable phase locking of multiple fibers has been achieved by using intracavity spatial filters that match the patterns of the interference fringes of the in-phase mode in the near or far field.[11–14] The phase locking of short laser pulses generated by the nonlinear processes, whose development is stochastic, faces the challenge of having to ensure that the short pulses are initiated simultaneously in all the elements. There is also a question of whether the relative phase of laser pulses generated by a high-gain nonlinear process with a frequency shift from the primary laser can be effectively controlled by the same mechanism of phase locking in the resonator of the primary laser. In this letter, we report phase-locked operation of intense short pulses generated by stimulated Brillouin backscattering in two Yb-doped double-clad fiber lasers. The phase locking of two fiber lasers is achieved through interaction with a self-induced loss modulation in a saturable absorber, which also plays the role of initiating and stabilizing the *Q*-switched pulses. This technique opens up the possibility of coherent combination of intense pulses generated by nonlinear processes in multiple fiber lasers to achieve higher brightness much beyond the limitation of optical damage in a single fiber.

The schematic of the experiment setup is shown in Fig. 1. The fiber gain media are two Nufern PM-YDF-5/125 double-clad ytterbium-doped fibers with a core diameter of 5 μm. The numerical aperture is 0.46 for the inner cladding and 0.15 for the core. The two fibers are approximately 6 m long. The small-signal absorption is 1.7 dB/m at 975 nm. The resonator mirrors at the pump end have high transmission at 976 nm and total reflection at 1064 nm. The other ends are angle cleaved at 8° to suppress the optical feedback from the fiber ends. The beams from the fibers are expanded to 3 mm diameter and coupled to a confocal self-imaging resonator, similar to the ones used previously to phase lock one- and two-dimensional laser arrays of fixed lengths.[11,12] A 1-mm-thick Cr:YAG saturable absorber with an unsaturated

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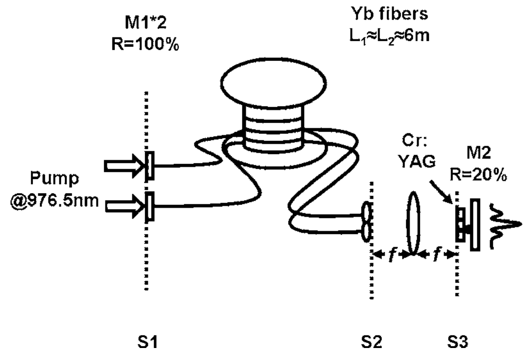

FIG. 1. Experimental setup.

transmission of 50% at 1064 nm is placed in front of the output mirror to induce Q-switched pulses. The pump diode lasers are operated in the quasi-continuous-wave mode with 700 μs duration and 60 Hz repetition rate. When the pump power reaches the threshold of 0.5 W in each fiber laser, a train of Q-switched pulses is observed. The pulse duration is 1 μs and the pulse energy stays nearly constant as the pump power increases. With the aid of a charge-coupled device camera and a laser beam analyzer, we examined the beam profile of the output at focal plane S3. The beam profile exhibits low-contrast interference fringes that are constantly moving from pulse to pulse. The fringe spacing is 18 μm. To stabilize the phase relation, we introduce a 5 μm gold wire in front of the output mirror along one of the dark fringes of the in-phase mode as the spatial filter to create a higher loss for the out-of-phase mode. Figure 2(a) shows the beam profile of the phase-locked laser array when stabilized by a spatial filter. When the output mirror is slightly misaligned from its optimal position, the lasing threshold steadily increases with the misalignment and Q-switched pulses evolve into a train of intense pulses of 1.5 ns pulse duration and much higher pulse energy. The development of the short pulse is attributed to the onset of SBS, which creates a traveling high reflector in the fibers and thereby depletes the energy stored in the gain media through Q switching. The intense SBS pulses have ten times the pulse energy of the long Q-switched pulses that initiate them and truncate the long pulses. With arbitrarily chosen fiber lengths, the giant pulses from the two fiber lasers generally are not phase locked and the beam profile at the output mirror exhibits poor contrast ratio, as shown in Fig. 2(b). The pulses from the individual fibers appear to be generated independent from each other and therefore do not overlap in time, as shown in Fig. 3(a). The interference fringes are stabilized when the difference in lengths of the two fiber resonators is less than 2 cm. Figure 2(c) shows the beam profile at the output mirror when the two lasers are operated in phase. The time series of the oscilloscope traces also confirms the coincidence of pulses

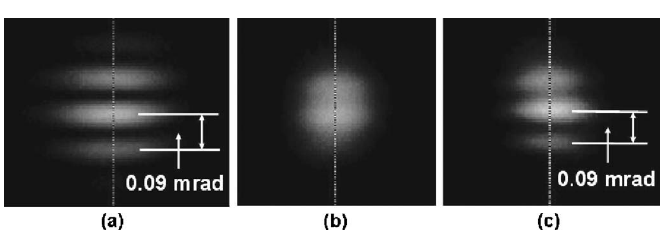

FIG. 2. Beam profiles at the output mirror of (a) phase-locked Q-switched laser pulses, (b) free-running SBS pulses, and (c) phase-locked SBS pulses.

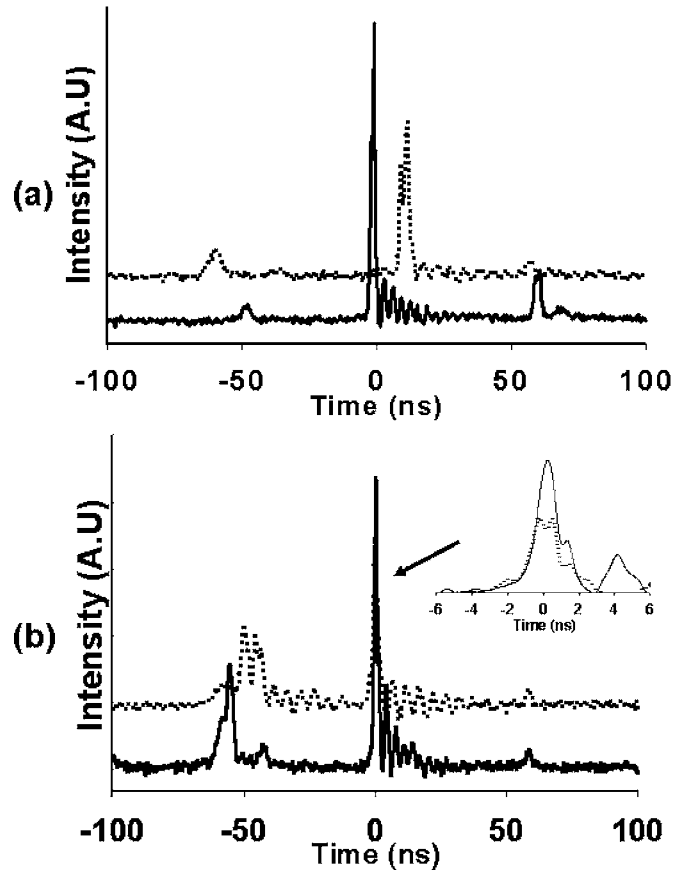

FIG. 3. Oscilloscope traces of the laser pulses from two fiber lasers when they are phase (a) unlocked and (b) locked.

from pulses from the individual lasers, as shown in Fig. 3(b).

The time series of the output power also shows that the pulse duration in the final stage of development leading to the strongest pulse is much shorter than the round-trip time. The round-trip amplification is about 10. Thus a two-element laser system is essentially a two-armed laser amplifier for free-propagating pulses during the final stage. Any unevenness in the waveguide and pump level can result in unbalanced output pulse energy from each fiber. This explains the lower contrast ratio of the beam profile at the output mirror, compared to those for the conventional Q-switched laser pulses.

Based on the experimental results, we can describe the mechanism by which the phase-locked stimulated Brillouin pulses are generated in the two-element fiber laser array. At the beginning of the cycle, a passively Q-switched pulse is generated due to the action of the saturable absorption in Cr:YAG. The interference fringes at the output mirror created by the leading edge of the Q-switched pulse bleach the Cr:YAG crystal and establish a loss grating which provides the diffractive optical feedback for the individual fiber lasers and cross coupling between the lasers. The diffractive feedback has a self-coupling efficiency η_S, and cross coupling has a cross coupling efficiency η_C, as illustrated in Fig. 4. When the intensity of the conventional Q-switched laser pulses is high enough to trigger the SBS process, a frequency shifted seed pulse is generated. In a two-element fiber laser array with lengths L_1 and L_2 coupled to an external resonator, there are three resonators, with gain lengths L_1, L_2, and L_1+L_2, sharing the common gain media. In the absence of the self-coupling η_s, the resonator with length L_1+L_2 has the

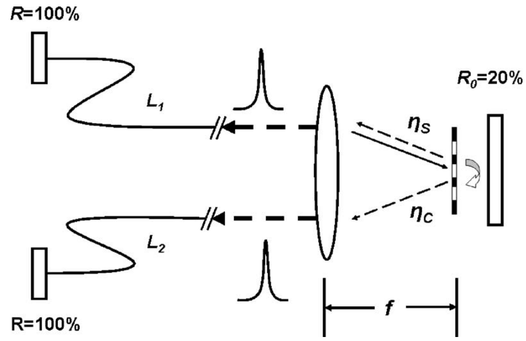

FIG. 4. Two-element laser coupled through a diffractive element in an external resonator.

largest gain length and the lowest threshold for the SBS process. The SBS pulses thus created would be propagating in the two fibers sequentially and the output from the fibers cannot be phase locked. In the present experiment, the first order diffraction of the loss grating in the saturable absorber provides a self-coupling strength of approximately 30% and cross coupling strength of 70%, assuming a full saturation of the saturable loss. This enables the SBS pulses initiated in one of the arms of the gain media to become the seeds for amplification in both arms of the gain medium simultaneously and their interaction through the diffractive element in the common external resonator can result in-phase locking. Since the pulse duration of the SBS pulses is much shorter than the round-trip time in the individual resonator, effective phase locking also requires that the difference in fiber lengths be much less than the pulse duration.

In the present study, the combined peak power is 6.67 kW, corresponding to a power density of 17 GW/cm^2 in each fiber. Further increase in pulse energy in each fiber laser, achievable by increasing the energy storage in a lower-Q resonator, results in optical damage in the fiber ends. The pulse energy of the phase-locked mode for the coherently combined pulses is 10 μJ, which is two times the pulse energy of the individual fiber lasers. The efficiency of the coherent beam combination is high. This points to the possibility of a coherent combination of intense laser pulses generated by nonlinear processes in multiple fiber lasers to achieve higher brightness much beyond the power density of optical damage of a single fiber.

In conclusion, we have demonstrated phase-locked operation of the output of two Brillouin backscattering Q-switched fiber lasers whose pulse durations are much shorter than the round-trip time of the resonators. Despite the stochastic nature in the dynamics of nonlinear, simultaneous generation and phase locking of short pulses have been achieved through diffractive coupling and spatial filtering in an external resonator. Investigation of phase locking of two-dimensional fiber laser array based on these same techniques is underway and will be reported in due course.

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