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Synchronizable actively mode-locked Nd:glass laser

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With the development of an actively mode-locked Nd:glass laser incorporating dynamic Q control, a single subnanosecond 1.06-μ pulse has been synchronized to a 1-ns-duration 10.6-μ CO_2 laser pulse to within <400 ps.

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Mode-locked Nd:glass lasers of different forms have been developed over the past ten years, with intense study being made of the formation of the ultrashort pulses.[1] However, throughout this period, the mode-locked Nd:glass laser has suffered from two primary limitations. The first of these has been the considerable uncertainty and instability in both the form and intensity of the mode-locked pulses. In addition the use of a saturable absorber as a mode-locking element gives rise to an inherent inability to predict the time of occurrence of the pulse train relative to an arbitrarily triggered event with any precision. These limitations have severely curtailed the application of high-power 1.06-μ picosecond-duration pulses to the diagnosis of many ultrafast phenomena. One such area which has suffered from this limitation has been the optical diagnosis of high-temperature plasmas of thermonuclear interest produced by intense short-duration (~1 ns) CO_2 laser pulses. The provision of an ultrashort optical probe pulse in reliable synchronism with the production of such plasmas would facilitate the precise measurement of the development of the electron density profile, even beyond the critical absorption region ($n_e > 10^{19}$ cm^{-3}), and of the strong self-induced magnetic fields known to be associated with such plasmas.[2]

Although there has been progress recently in the development of ultrafast electro-optical shutters capable of providing synchronizable subnanosecond light pulses,[3] and indeed such pulses have been utilized in microscopic holographic interferometry of plasmas produced by 1-ns CO_2 laser pulses,[4] the extension of this technique to the picosecond range would not appear to be possible at this time.

To overcome the limitations stated above, we have developed an actively mode-locked Nd:glass system, capable of providing a single ultrashort pulse in precise synchronism with a high-power 1-ns-duration CO_2 laser pulse,[5] intended for laser plasma interaction studies. An active modulator, which circumvents the need for a saturable absorber mode-locking element, is incorporated into a ring laser resonator. The latter also includes a second electro-optic element capable of dynamically controlling the effective cavity Q during the buildup of the mode-locked pulse.[6] Finally, provision is also made for switching the single pulse out of the resonator in precise synchronism with an arbitrary external event. In this letter we wish to present some initial results on the operation of this system.

The ring laser resonator, incorporating a 20-cm-long 15-mm-diam Brewster-angled Nd:glass rod, is formed by four Pellin-Broca prisms (Fig. 1). The active loss modulator is a Brewster-angled cylindrical KD*P crystal (PC_2), driven with a 200-μs-duration 60-MHz sine wave voltage providing up to 30% transmission modulation. A second Brewster-angled Pockels cell (PC_1) performed the dual function of providing

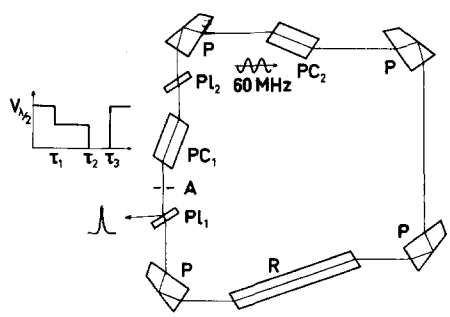

FIG. 1. Schematic diagram of the actively mode-locked Nd:glass ring laser. R, Brewster-angled Nd:glass rod. P, Pellin-Broca prisms, Pl_1, Pl_2, dielectric polarizers. A, aperture. PC_1, three-electrode cylindrical Pockels cell for Q control and pulse switchout. PC_2, cylindrical Pockels cell for active modulation.

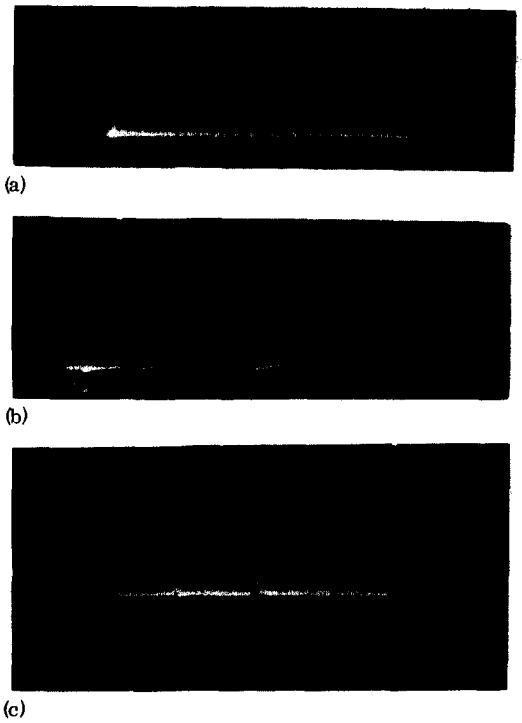

FIG. 2. (a) Development of the mode-locked pulse train in the absence of pulse switchout (50 ns/div). (b) Example of single switched-out pulse (5 ns/div). (c) Display of synchronized 1.06-μ laser pulse (first) and 10.6-μ laser pulse (second) (10 ns/div).

dynamic Q control during the buildup of the short pulse, and for switching out the single pulse from the resonator at any desired time. This Pockels cell, which is situated between two multilayer dielectric polarizers, is a three-electrode cylindrical KD*P crystal. One half of the crystal is used for the Q control, while the other half is used for switching of the pulse from the ring resonator, with the center electrode being grounded. During optical pumping of the Nd:glass rod, the half-wave voltage (6.8 kV) is applied to the Q-control Pockels cell (PC_1), inhibiting oscillation within the resonator. When peak inversion has been reached in the rod, the 60-MHz singal, corresponding to the natural frequency of the resonator is applied to PC_2. After a short period (~70 μs) at time τ_1, the potential applied to PC_1 is reduced, thus establishing a small net gain within the resonator (Fig. 1). This permits the original noise pulse to build up linearly, its duration being progressively reduced on each passage through the oscillating modulator. After a period of 1.8 μs, at time τ_2, the Q-control potential is reduced to zero. Approximately 20 resonator transits are necessary for the pulse amplitude to reach its maximum value, at which time τ_3 (Fig. 1) a fast half-wave voltage step is applied to the second half of the Pockels cell, PC_1. This causes the single pulse to be switched out of the resonator by polarizer Pl_1.

Thus the buildup of the mode-locked pulse is rigorously controlled from the point when the cavity Q is switched on, permitting net gain within the resonator. Since the buildup of the pulse can be controlled both by the voltage level applied to PC_1 and the time interval between τ_1 and τ_2, the precise time at which the pulse within the resonator reaches its peak amplitude can be accurately controlled. This was checked by monitoring the leakage radiation, caused by natural and induced birefringence in the resonator elements, reflected by the second polarizer Pl_2. In the absence of pulse switch-out, the mode-locked pulse train has a (FWHM) duration of ~200 ns [Fig. 2(a)] and is synchronized to time τ_1 to within 100 ns. With the activation of the second half of Pockels cell PC_1 the mode-locked pulse reflected from polarizer Pl_1 can be arbitrarily synchronized to any external event to within a jitter time of less than the cavity transit time (in this case 8.3 ns).

However, for the present studies, a much higher degree of synchronization was desired and obtained. For the purpose of investigating plasmas produced by the large high-power dual beam, 1-ns-duration CO_2 laser (COCO-II),[5] jitter times of much less than 1 ns are required. This was achieved by integrally phase locking the 60-MHz active modulator of the Nd:glass system with the acousto-optic modulator of the CO_2 oscillator. The latter modulator provides a short train of 1-ns-duration 100-MW 10.6-μ laser pulses separated by 25 ns.[7] One of these pulses is selected by means of an infrared GaAs electro-optic gate switched by a laser-triggered spark gap.

To synchronize the single 1.06-μ and 10.6-μ pulses, a sample of the selected 10.6-μ pulse is used to trigger a second laser triggered spark gap, with a jitter time of < 1 ns. This provides the half-wave voltage step pulse applied to PC_1 to switch the 1.06-μ pulse out of the ring resonator. The 1.06-μ pulse [Fig. 2(b)] has an energy of ~1.5 mJ, and with the aid of a saturable filter having a linear transmission of ~2%, a pulse intensity to background intensity ratio of $> 10^3$ was achieved. Although detailed picosecond-resolution pulse measurements have not yet been made, the pulse duration is consistently less than the resolution limit of a fast biplanar photodiode-Tektronix 519 oscilloscope detection system. The synchronizability of the two pulses is only dependent on the degree to which the two active modulators can be phase related, and not on the jitter in the switching time of the laser-triggered spark, so long as the latter is less than half the ring resonator transit time (~4 ns). An example of the synchronization between the two pulses is given in the oscillogram, Fig. 2(c), showing the single 1.06-μ pulse followed by the 10.6-μ pulse. A set of measurements made over many successive shots verified that the degree of synchronization between the two pulses was less than the measurement accuracy (400 ps). Experiments are now in progress to determine the limits to the degree of synchronizability, and, in addition, further study of the progressive formation of the ultrashort pulse within the ring resonator is underway.

The provision of an ultrashort 1.06-μ pulse in precise synchronism with the high-power 1-ns output from the COCO-II laser system should provide a valuable means of optical plasma diagnosis. With the incorporation of second or higher harmonic generation, ultrafast optical diagnostics such as interferometry, Schlieren,

and shadowgraph photography as well as Faraday rotation measurements of the CO_2-laser-produced plasmas should be possible. Variation of the duration of the 1.06-μ output pulse should be controllable by suitable adjustment of the depth of modulation, and the Q-control conditions. The use of auxiliary pulse shortening saturable absorber dye cells,[8] and perhaps the use of a dispersive resonator to limit the development of self-phase modulation, should lead to the generation of pulses of a few picoseconds duration.

In addition, the synchronization of a 1.06-μ picosecond laser pulse with a CO_2 laser pulse should permit many other investigations such as the generation of ultrashort 10.6-μ pulses utilizing either the optical Kerr effect[9] or solid-state switching,[10] the ultrafast investigation of infrared molecular processes, and other spectroscopic phenomena.

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