

Subpicosecond mode locking of a Nd³⁺-doped garnet laser

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We demonstrate subpicosecond pulse generation using a GSAG:YSGG:Nd³⁺ crystal. A dispersively balanced nonlinear Michelson interferometer has been used for self-starting mode locking to generate pulses of ~0.5 ps with average output powers of as much as 190 mW.

In recent years Nd³⁺-doped glasses favored for their broad fluorescence band have been widely used for the generation of femtosecond pulses in the spectral region near 1 μm .¹ However, the low thermal conductivity of glasses limits the average output power of both oscillators and amplifiers and has not allowed the use of low-brightness, high-power diode lasers as pump sources. An alternative is to use crystalline materials because of their good thermal, mechanical, and optical properties. However, previously used Nd³⁺-doped crystalline hosts, such as YAG and YLF, have exhibited narrow fluorescence lines, which have limited the obtained pulse widths to 1.7 ps in YAG² and 1.5 ps in YLF.³

Recently the development of a new class of laser-active medium has been reported, namely the crystals of solid solutions of scandium-containing aluminum and gallium garnets GSAG_{1-x}YSGG_x and GSAG_{1-x}GSGG_x.⁴ The disordered nature of these crystals results in a strongly inhomogeneous broadening of both the fluorescence line and the absorption bands.⁴ These characteristics, which are typical of glasses, are combined with thermal and mechanical properties comparable with those of YAG. In addition this new family of hosts allows Nd³⁺ doping levels of more than two times higher than for YAG and a gradual variation of matrix composition in the whole substitution range. These features make this class of laser material attractive for all-solid-state ultrashort-pulse generation.

In this Letter we demonstrate passive subpicosecond pulse generation in a GSAG_{0.33}:YSGG_{0.67}:Nd³⁺ crystal by using the additive-pulse mode-locking (APM) technique. Pulses as short as 500 fs were generated. To our knowledge these are the shortest pulses generated in a mode-locked rare-earth-doped crystalline laser to date.

APM, originally proposed in Ref. 5 and theoretically studied in Refs. 6 and 7, already proved its potential in mode locking of various laser systems, often producing the shortest pulses ever obtained with the corresponding bulk active media.^{2,3,8-10} Because of its better stability and compactness¹⁰ we chose a modification of the APM scheme in the

form of a nonlinear Michelson interferometer.⁹ Following the design considerations of Spielmann *et al.*,⁹ we constructed an astigmatically compensated five-mirror resonator (Fig. 1). The laser was pumped by the 752- and 799-nm lines of a krypton laser. The pump beam was coupled into the resonator through the dichroic mirror M3, which was highly reflective at the laser wavelength (1.06 μm) and highly transmitting at pump wavelengths. Mirrors M1 and M2 were highly reflective at both 1.06 μm and the pump wavelengths and had radii of curvature of 150 and 100 mm, respectively. The crystal was a 4-mm-thick slab, aligned at Brewster's angle, and 90% of the incident pump light was absorbed in two passes. One arm of the laser output was launched into a short piece of a non-polarization-preserving single-mode silica fiber (N.A. = 0.11, core diameter 6.7 μm) having a nonlinear coefficient of $\gamma = 4.0 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$. Mirror M5 ($R = 100\%$) was butted to the fiber end to terminate the nonlinear interferometer arm. To avoid étalon effects, the launching end of the fiber was cleaved at an angle of ~5°. The typical overall reflection from the nonlinear interferometer arm was 50–60%. The high reflector M4 was mounted on a piezoelectric transducer (PZT) in order to compensate actively for the relative length variations of the two interferometer arms, where the error signal was derived from the laser output.¹¹ For 1.1 W of pump power the total output power was 305 mW, the pumping threshold was 120 mW, and the cw slope efficiency was 31%. The 3-dB bandwidth of the first beat note, at ~65 MHz, was ~2.5 kHz, and the laser was therefore well within the self-starting regime.¹²

Mode-locking experiments were carried out by using four different fiber lengths. For the first mode-locking experiments no dispersion compensation was incorporated into the linear interferometer arm (the dashed beam in Fig. 1). However, with this particular arrangement only modes amplified by the main line [peak A in Fig. 3(a) below] of the fluorescence spectrum could be locked. The pulse duration was therefore limited to 1.4 ps (a sech² pulse

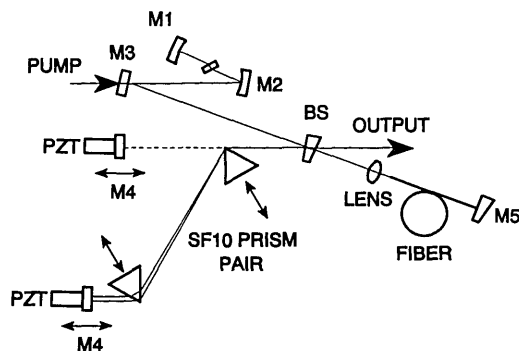


Fig. 1. Schematic diagram of the setup. The dashed beam shows the arrangement without dispersion compensation. Beam splitter BS has a reflectivity of 90%.

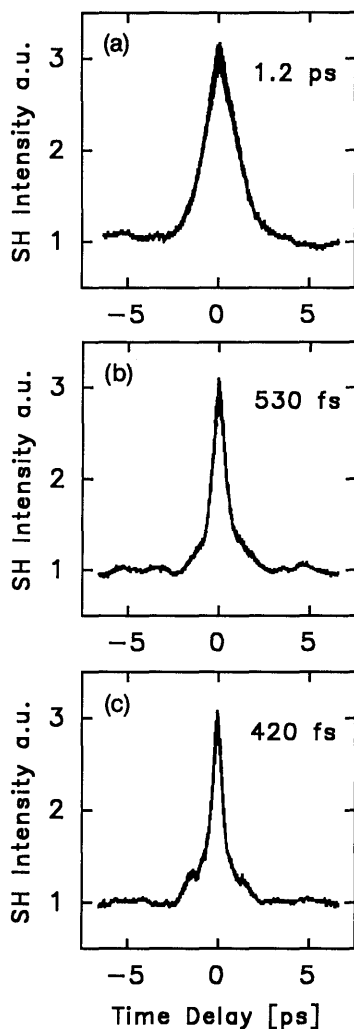


Fig. 2. Pulse intensity autocorrelation measurements of (a) a pulse where the laser is mainly operated at line A, (b) a pulse where the whole spectrum is mode locked, and (c) the shortest pulse obtained, exhibiting more distinct shoulders. Pulse widths are given under the assumption of a hyperbolic-secant shape.

shape is assumed) under these experimental conditions. The mode-locked bandwidth was 1.15 nm, which yielded a time-bandwidth product $\Delta\tau\Delta\nu$ of 0.43. The maximum mode-locked output power was 190 mW at a pump power of 1.1 W. The pulses

had slight shoulders, which may be attributed to an excess nonlinearity. Fringe-resolved autocorrelation measurements showed that the pulses were slightly chirped.

As a next step, we introduced a dispersive delay line into the linear interferometer arm. A pair of SF10 prisms (separation 70–90 cm) was incorporated (the solid beam in Fig. 1) to allow a solitonlike pulse-shaping mechanism. The intracavity group-delay dispersion could be controlled by varying the prisms' glass path. With the prisms inserted into the cavity and the negative dispersion optimized, a second feature appeared in the mode-locked spectrum, which coincided with peak B [see Fig. 3(a) below] in the fluorescence spectrum. A frequency chirp was also eliminated. At a fiber length of 76 cm and a pump power of 1.2 W, pulses of ≈ 1.2 ps were generated [Fig. 2(a)] with a time-bandwidth product $\Delta\tau\Delta\nu = 0.32$, which indicated that the pulses were bandwidth limited. The minimum pulse width of 650 fs at this fiber length was achieved for a pump power of 670 mW. The relative magnitude of the smaller peak in the mode-locked spectrum could be increased by reducing the fiber length. The shortest pulses were generated by using the 45-cm fiber and were 420 fs [Fig. 2(c)]. The self-starting threshold pump power was ≤ 0.4 W with fiber lengths ≥ 45 cm. Long-term mode-locked stability was degraded at the shortest pulse width with stabilizer locking times reduced from tens of minutes to a ≤ 1 -min scale. Cutting down the fiber to 30 cm did not lead to a further reduction of pulse duration, which indi-

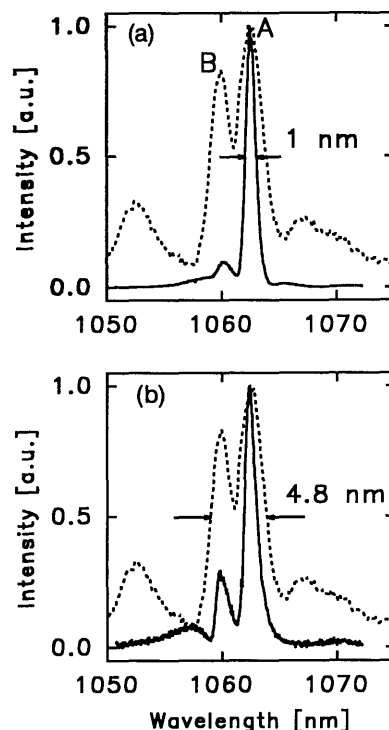


Fig. 3. Spectra corresponding to the pulses of Fig. 2. (a) Spectrum corresponding to the pulse in Fig. 2(a) (solid curve) and the fluorescence spectrum of the crystal (dashed curve). (b) Spectrum corresponding to the pulse in Fig. 2(b) (solid curve) and the fluorescence spectrum of the crystal (dashed curve).

cated that the gain bandwidth limited further pulse shortening at these pulse durations. For the pulse displayed in Fig. 2(b) both lines were mode locked, which yielded pulse durations of 530 fs. The laser was operated at a pump power of 750 mW, and the output power was 90 mW. However, when the laser was operated on both lines simultaneously the pulses always exhibited shoulders that we attribute to the double-peaked structure of the mode-locked spectrum. As the full mode-locked spectrum displayed in Fig. 3(b) consists of separate lines, it is difficult to define the bandwidth correctly, and $\Delta\tau\Delta\nu$ cannot be used as a measure of pulse quality in the conventional sense. Fringe-resolved autocorrelation measurements did not indicate any linear chirp; however, the shoulders of the pulses were clearly visible. These shoulders became even more distinct when a length offset (in a range of $\pm 20 \mu\text{m}$) between the two interferometer arms was introduced. Similar phenomena were investigated recently in a Nd:YLF system.¹³

In conclusion, we have demonstrated what is to our knowledge the first subpicosecond pulse generation with a Nd³⁺-doped crystalline material. Pulse durations below 0.5 ps were observed, and further pulse shortening was limited by the double-peaked structure of the fluorescence line.

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Note added in proof: Recently we generated 260-fs shoulder-free pulses by using a GSAG_{0.67}:YSGG_{0.33}:Nd³⁺ crystal.⁴

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