Coupled-cavity resonant passive mode-locked Nd:yttrium lithium fluoride laser

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We report coupled-cavity resonant passive mode locking of a Nd:YLF laser. This technique has produced 4-ps pulses at a wavelength of 1.047 µm with 390-mW average power at a 250-MHz repetition rate, corresponding to a 1.6-nJ pulse energy. The Nd:YLF rod was pumped with 1.5 W of power at 798 nm from a Ti:sapphire laser. The nonlinear reflector used in the coupled cavity was an InGaAs/GaAs strained layer multiple-quantum-well sample.

We introduce a new technique for passive mode locking for a cw pumped Nd:YLF laser, using an InGaAs/GaAs quantum-well reflector as a nonlinearity in an external coupled cavity. This mode-locking technique is called resonant passive mode locking (RPM) because of the resonant nonlinearity in the coupled cavity. The first demonstration of this novel method was with a Ti:sapphire laser and an AlGaAs/GaAs multiple-quantum-well (MQW) reflector.[1,2] RPM is markedly different from coupled-cavity mode-locking techniques with a nonresonant nonlinearity (i.e., Kerr type) in the extended cavity and does not need any active cavity-length control for stable pulse trains.[2] It promises to become a simple and effective way for passive mode locking of laser materials with a high saturation fluence such as Ti:sapphire and Nd^{3+}-doped crystals (YAG, YLF, BEL) and glasses.

An early example of coupled-cavity passive mode locking was the soliton laser,[3] for which the nonlinear external cavity medium, an optical fiber, supports soliton pulse formation in a net negative group-velocity dispersion regime. This technique has been extended to an external nonlinear coupled cavity with positive group-velocity dispersion, now referred to as additive-pulse mode locking[4,5] (APM) or coupled-cavity mode locking.[6] The pulse formation is based on the coherent superposition of a pulse in the main cavity and a pulse from the coupled cavity that have experienced a nonlinear phase shift (i.e., self-phase modulation in an optical fiber) leading to constructive interference at the peak of the pulse and destructive interference in the wings. In case of RPM, the coupled cavity has negligible dispersion and the nonlinear quantum-well reflector generates a rapid amplitude modulation that strongly induces mode locking. This fast amplitude nonlinearity has been observed in pump–probe measurements.[7] A recently developed theory on coupled-cavity mode locking with a resonant nonlinearity[8] suggests that this fast amplitude modulation is enough to mode lock the laser.

This study of the RPM Nd:YLF laser is motivated primarily by the need for practical high-power, high-repetition-rate pulsed laser sources with pulse ener-gies ranging from 1 pJ to 1 nJ, for potential communication and computing applications. At present, high-speed photonic switching elements require switching energies of the order of 1 pJ.[9,10] Diode-pumped mode-locked solid-state lasers offer a practical alternative to mode-locked semiconductor lasers for high-power short-pulse laser sources with clean spatial and spectral mode properties. The output power of active or passive mode-locked semiconductor lasers is typically low, in the maximum range of a few milliwatts, because the laser must be operated near threshold to generate short pulses. Therefore, picojoule-pulse energies are achieved only for repetition rates that are ≤1 GHz. Amplifier stages are required for picojoule energies at higher repetition rates. For example, with one semiconductor amplifier stage following a mode-locked semiconductor laser having a 960-MHz repetition rate and 1.2-mW average output power, 1.3-pJ pulses were amplified to 45 pJ.[11] In contrast, with high-power diode-laser pump arrays, solid-state lasers can easily supply high power levels, and most difficulties center around mode-locking technqiues. Both active and passive methods have been used. Active mode locking of a diode-pumped Nd:YLF laser at a 2-GHz repetition rate with 7-ps pulses and $\approx$70-pJ pulse energy[12] and of a diode-pumped Nd:YAG laser at a 1-GHz repetition rate with 60-pJ pulse energy[13] has been demonstrated. Passive mode locking is generally preferable, as it offers potential for increased repetition rate, greater ease of use, and economy. The passive APM technique applied to a Nd:YAG laser produced 1.7-ps pulses with 25-mW average power when diode pumping was used,[14,15] and 9 ps with 1.3-W average output power when flash-lamp pumping was used.[16] An APM Nd:YLF laser produced 2-ps pulses with 10-mW average power with diode pumping[14] and 3.7-ps pulses with 7-W average output power with flash-lamp pumping.[17] A krypton-laser-pumped APM Nd:glass laser produced 380-fs pulses.[18] The fiber length (a critical parameter in an APM laser) used in these APM's was ~90 cm, limiting the compactness of this mode-locking scheme. In the case of the RPM Nd:YLF both the crystal and the quantum-
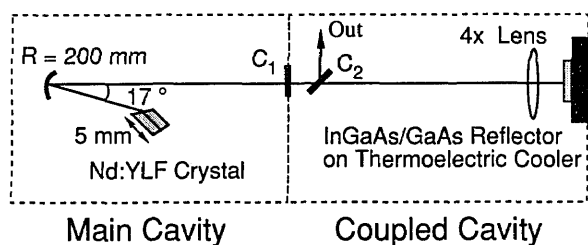
Fig. 1. Cavity design.

well saturable absorber are small, so the laser should be scalable to high repetition rates.

The RPM Nd:YLF laser (Fig. 1) consists of a linear folded cw Nd:YLF cavity with a 3% output coupler, C_1, which is coupled to an external low-Q cavity with a nonlinear InGaAs/GaAs quantum-well end reflector with a band gap near the lasing wavelength of 1.047 μm.[19] A tunable output coupler consisting of a half-wave plate and a polarizing beam splitter inside the external cavity is used as the overall output coupler, C_2. The Nd:YLF cavity is end pumped with a Ti:sapphire laser at 798 nm. This 5-mm Nd:YLF rod has its flat end high-reflection coated for the laser wavelength at 1.047 μm and antireflection coated for the laser pump at 798 nm, while the other end is cut at Brewster's angle. The linear folded cavity design with an angle of 17° corrects for the astigmatism arising from the 200-mm radius of curvature of the turning mirror.[20] Output coupler C_1 is slightly wedged to minimize unwanted étalon effects in the cavity. The nominal Nd^{3+} concentration is 1.5%. The calculated cavity beam waist in the Nd:YLF rod is elliptical, with a beam radius of 66 μm in the saggital plane and 93 μm in the tangential plane. To produce a TEM_{00} mode, the Ti:sapphire pump laser beam is focused to a smaller spot size of ≈46-μm radius by an 88-mm focusing lens. The Nd:YLF laser cavity with its 3% output coupler forms a stable cw laser with a slope efficiency of 57% and a pump threshold of ≈48 mW. This high slope efficiency and low threshold are possible because of the small pump laser area. The mode-beating frequency (i.e., the cavity repetition rate) of the cw Nd:YLF laser is ≈250 MHz. We used a microscope lens with a focusing length of 30.6 mm to focus the beam to an estimated ≈30-μm diameter spot onto the nonlinear MQW reflector that forms the end mirror of the coupled cavity. The nonlinear quantum-well reflector is an $In_xGa_{1-x}As$/GaAs MQW optical modulator with a band gap near 1.047 μm, described in more detail in Ref. 19 as sample D. Because there is no dielectric mirror grown underneath the MWQ structure and the GaAs substrate is transmissive at 1.047 μm, we evaporated a gold mirror onto a MQW layer consisting of ≈5 nm of chrome as the sticking layer and ≈250 nm of gold. The reflector is indium bonded onto a copper substrate, which is mounted onto a thermoelectric cooler.

The pulse width is measured with a noncollinear autocorrelator (Fig. 2, solid curve) and compared with an ideal 4.0-ps FWHM $sech^2$ pulse (Fig. 2, dashed curve). The Nd:YLF rod is cw pumped with 1.5 W of power, generating 390 mW of average output power P_1

at an ≈250-MHz repetition rate, corresponding to 1.6-nJ pulse energy with an ≈48% overall output coupler C_2. The pulses are simultaneously monitored with a noncollinear autocorrelator, a sampling scope, a rf spectrum analyzer, and an optical spectrum analzyer. The pulse on the sampling scope is well defined, and its width is limited by the overall time resolution of photodiode and sampling head to ≈50-ps pulse duration. The stability of the mode-locked pulses is not so good as for the RPM Ti:sapphire laser.[2] We observe as much as 30% amplitude fluctuations on the autocorrelation trace. The pulse width remains constant. The average power reflected from the quantum-well absorber and injected back into the main cavity is only 3% because of significant diffraction from surface striations on the quantum-well reflector.[19] This diffraction also contributes to the poor mode quality of the reflected beam. The poor reflection from the quantum-well sample may also be the reason for the excess wings in the autocorrelation trace (Fig. 2).

The 4-ps pulses are achieved at a slightly detuned cavity length of −0.22 mm. When the two cavities are exactly matched, the laser is extremely unstable, with no defined pulses on the sampling scope, which is consistent with the theoretical model.[8] Mode locking in this regime would require active cavity-length control. Increasing the cavity-length detuning increases the pulse width, and at more than ≈0.9-mm detuning the autocorrelation traces begin to break up into multiple ≈4-ps pulses superimposed upon a longer pulse. These pulses are separated by the cavity-length detuning time. At even larger detunings these short pulses do not overlap anymore, and they show a 2:1 intensity ratio of peak to background, which implies that they are coherence spikes. Therefore at larger cavity detunings the laser is not properly mode locked. We believe that the detuning range over which mode locking is observed can be improved with better reflector quality, as discussed above.

When we vary the output coupler C_1 of the cw Nd:YLF laser, the mode-locking performance is improved as the output coupler C_1 is changed from 10% to 5% and then to 3%. For an output coupler of 10% the nonlinear coupled cavity produces strong noise sidebands up to ≈10 dB below the first laser harmonic
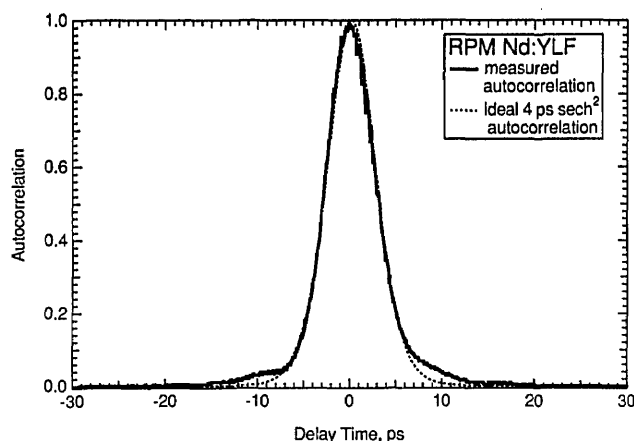
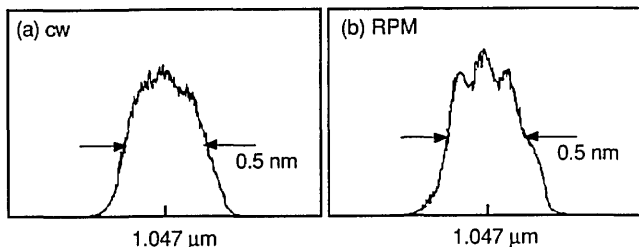Fig. 2. 4-ps autocorrelation trace assuming a $sech^2$ pulse shape.

Fig. 3. Time-averaged optical spectrum under (a) cw operation and (b) mode-locked operation.

owing to enhanced relaxation oscillations of the Nd:YLF cavity. Decreasing the output coupler decreases these noise sidebands, which are greatly mitigated with the 3% output coupler. We observe optimized performance with an overall output coupler C_2 (Fig. 1) in the range of 50% to 60% at the above-mentioned power levels.

Monitoring the output of the laser with the rf spectrum analyzer, we observe a well-defined first laser harmonic near 250 MHz that is ≈ 60 dB above the mode beating signal from the cw Nd:YLF laser with the external cavity blocked. By shortening the external cavity we increase the repetition rate. This pulling effect is larger with smaller output couplers C_2 in the coupled cavity. Typically, with a $\approx 50\%$ output coupler C_2 and with 0.1-mm cavity detuning we measure a pulse-repetition-rate change in the kilohertz regime. This frequency pulling effect is easy to understand: At a cavity length detuning of -0.22 mm, the 4-ps pulse in the main cavity is still overlapping the reinjected advanced (by ≈ 1.5 ps) pulse from the external cavity. The total pulse, which is the sum of the two, will have a slightly advanced timing depending on the amplitude of the reinjected pulse.

The time-averaged optical spectrum for cw operation with an optical spectrum analyzer is shown in Fig. 3(a), and for that mode-locked operation in Fig. 3(b). The time-averaged optical spectrum has a FWHM of ≈ 0.5 nm, which would imply that the 4-ps pulses are ≈ 1.7 times transform limited. However, in RPM the time-averaged optical spectrum [Fig. 3(b)] includes the self-frequency shifts of the laser to maintain stable pulse trains that do not correspond to the bandwidth of the mode-locked pulses. The optical bandwidth of the mode-locked pulses decreases with increased cavity length detuning, and a more structured time-dependent optical spectrum under the mode-locked condition is consistent with stabilization of coupled-cavity operation by self-frequency adjustments.[2,8]

In summary, we have demonstrated RPM of a Nd:YLF laser and achieved 4-ps pulse duration. This introduces a new technique of mode locking Nd^{3+}-based solid-state lasers. With only 1.5 W of pump power at 798 nm, we have generated pulses with energies as high as ≈ 1.6 nJ at a repetition rate of 250 MHz. As we have demonstrated with the RPM Ti:sapphire laser,[2] the pulse energy scales inversely with the repetition rate because the average power remains constant. Here the RPM Nd:YLF laser is pumped by a Ti:sapphire laser. Diode pumping is a straightforward extension. However, owing to the poor spatial

and spectral mode properties of high-power diode arrays, the diode pump power cannot be focused so tightly as the Ti:sapphire pump power. Therefore the mode volume in the Nd:YLF crsytal has to be enlarged to guarantee TEM_{00} mode operation, which will increase the pump threshold. Diode pumping may produce a practical high-power laser source with hundreds of picojoules of pulse energy at repetition rates well above 1 GHz for applications requiring high-energy, high-repetition-rate laser sources such as photonic switching for optical communication and computing.

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