

Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber

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We introduce a new low-loss fast intracavity semiconductor Fabry-Perot saturable absorber operated at antiresonance both to start and sustain stable mode locking of a cw-pumped Nd:YLF laser. We achieved a 3.3-ps pulse duration at a 220-MHz repetition rate. The average output power was 700 mW with 2 W of cw pump power from a Ti:sapphire laser. At pump powers of less than 1.6 W the laser self-*Q* switches and produces 4-ps pulses within a 1.4- μ s *Q*-switched pulse at an \approx 150-kHz repetition rate determined by the relaxation oscillation of the Nd:YLF laser. Both modes of operation are stable. In terms of coupled-cavity mode locking, the intracavity antiresonant Fabry-Perot saturable absorber corresponds to monolithic resonant passive mode locking.

Many solid-state lasers (i.e., rare-earth and transition-metal lasers) exhibit a small gain cross section and therefore require a fast and low-loss saturable absorber for passive mode locking. Within an all-solid-state ultrafast laser technology, semiconductor saturable absorbers have the advantage that they are compact, fast, and cover band gaps from the visible to the infrared. Semiconductor saturable absorbers have previously mode locked diode¹ and color-center lasers.^{2,3} However, in rare-earth (i.e., Nd:YLF) and transition-metal (i.e., Ti:sapphire) solid-state lasers, intracavity semiconductors introduce too much loss, have a too small saturation intensity, and have problems withstanding the high intracavity peak intensities. As a result, we have used semiconductors inside a low-*Q* coupled cavity, referred to as resonant passive mode locking⁴⁻⁷ (RPM). However, RPM without an active cavity-length control is self-stabilized only at the expense of small optical frequency fluctuations.^{4,5} An intracavity passive mode-locking technique removes the active stabilization requirement for stable mode locking, and the overall cavity design becomes more compact. More recently an intracavity reactive nonlinearity, such as self-focusing, has been used to produce fast saturable absorberlike mode locking that is, however, not self-starting.^{8,9}

In this Letter we introduce an intracavity saturable absorber element, an antiresonant Fabry-Perot saturable absorber (A-FPSA), that has a relatively fast InGaAs/GaAs semiconductor saturable absorber monolithically integrated between two reflecting mirrors. The top reflector of the A-FPSA is a TiO₂/SiO₂ dielectric mirror with a 98% reflectivity. The use of the A-FPSA effectively transforms the semiconductor to a high-saturation-intensity, low-loss absorber as required. With this new A-FPSA inside a Nd:YLF laser cavity, we produce self-starting 3.3-ps cw mode-locked pulses at a 1.047- μ m wavelength with an average output

power of 700 mW when the laser is cw pumped with 2 W of power.

At antiresonance the intensity inside the Fabry-Perot cavity is always smaller than the incident intensity, which increases the effective saturation intensity (observed before the top mirror) and the damage threshold of the semiconductor saturable absorber. We obtain no bandwidth limitations at antiresonance, because the free spectral range is much larger than the gain bandwidth of the Nd:YLF laser. Additionally, the antiresonance operation is insensitive to thermal loading and provides loose design tolerances. In contrast, a FPSA operated at resonance has a higher intensity inside the Fabry-Perot cavity, has critical design tolerances, and can exhibit bistability effects, which are detrimental for our application.

The saturable absorber inside the Fabry-Perot cavity has a carrier lifetime that is slightly longer than the pulse duration but much shorter than the pulse repetition period. Therefore, under cw mode-locked operation, the absorption bleaching, and hence the reflectivity, is increased owing to the increased numbers of carriers generated within one laser pulse duration. The dielectric top mirror significantly reduces the net reflectivity change, however, protects the semiconductor from the high intracavity intensity, and significantly reduces the intracavity losses. The nonlinear reflectivity is still large enough to strongly mode lock the Nd:YLF laser. In addition, the intracavity A-FPSA can be explained in terms of coupled-cavity mode locking. In fact, the A-FPSA corresponds to monolithic RPM, which is discussed later in this Letter.

Figure 1 shows the laser cavity setup. The laser consists of a standard, end-pumped, linear-folded, astigmatically compensated cavity. A 5-mm Nd:YLF rod has its flat end coated for high reflection at the lasing wavelength of 1.047 μ m and antireflection coated for the pump wavelength. The other

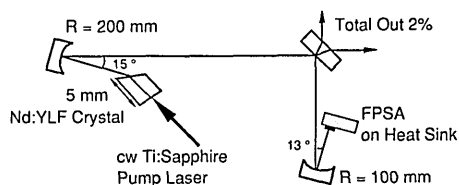


Fig. 1. End-pumped Nd:YLF laser cavity design.

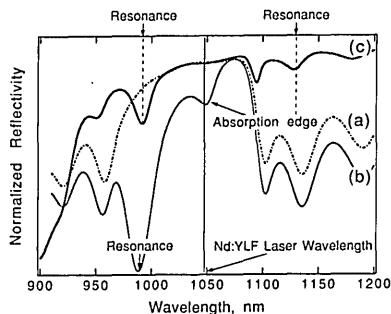


Fig. 2. Low-intensity reflectivity: curve (a), AlAs/GaAs dielectric mirror; curve (b), InGaAs/GaAs saturable absorber layer (uncoated) and AlAs/GaAs dielectric mirror; curve (c), A-FPSA with a free spectral range of ≈ 138 nm.

end is cut at Brewster's angle. The A-FPSA, indium soldered onto a copper heat sink, forms the end mirror of the laser cavity. A highly reflecting mirror with a 100-mm radius of curvature focuses the laser beam onto the A-FPSA to produce a calculated beam diameter of $80 \mu\text{m}$. The cavity output coupler consists of a flat turning mirror at a 45° angle of incidence and 1% transmission, which results in a total output coupling of 2%. The laser is pumped with a cw Ti:sapphire laser at a wavelength of 798 nm. We measured a slope efficiency of 35% (the sum of both output beams) and a pump threshold of 43 mW. A Z-shaped cavity design with a Nd:YLF crystal cut on both sides at Brewster's angle would produce only one output beam and hence would be more desirable.

The A-FPSA consists of a GaAs/AlAs dielectric mirror (16 periods of 76.4-nm GaAs layers and 90.5-nm AlAs layers) with a reflectivity of $\approx 96\%$, grown by molecular-beam epitaxy at normal temperatures ($\approx 640^\circ\text{C}$) on a GaAs substrate. The saturable absorber layer, $0.61 \mu\text{m}$ thick with a band gap close to the $1.047\text{-}\mu\text{m}$ Nd:YLF lasing wavelength, is grown at low temperatures of $\approx 380^\circ\text{C}$ on top of the GaAs/AlAs dielectric mirror and consists of 50 periods of GaAs barriers and $\text{In}_x\text{Ga}_{1-x}\text{As}$ quantum wells ($x = 0.29$) with nominal thicknesses of 6 and 6.2 nm, respectively. Finally, a $\text{TiO}_2/\text{SiO}_2$ dielectric mirror with 98% reflectivity is evaporated onto the absorber layer. The low-temperature growth reduces the carrier lifetime and produces a relatively fast saturable absorber. We measured a 69-ps carrier lifetime of the low-temperature InGaAs/GaAs saturable absorber using our newly developed passively mode-locked Nd:YLF laser in a standard noncollinear pump-probe experiment. Thus the response time of the saturable absorber is somewhat longer than the 3.3-ps pulse duration but much smaller than the pulse repetition rate of ≈ 4.5 ns.

Figure 2 demonstrates the FPSA operation at antiresonance. We measured the wavelength depen-

dence of the GaAs/AlAs dielectric mirror [curve (a)] through the GaAs substrate, which clearly shows that the mirror is centered at $\approx 1.03 \mu\text{m}$ with a FWHM of ≈ 120 nm. Before we deposited the top mirror, we measured [curve (b)] the reflection through the saturable absorber layer; this curve shows a strong Fabry-Perot resonance peak at 988 nm and the absorption edge of the InGaAs/GaAs layer at approximately $1.05 \mu\text{m}$. The 988-nm peak corresponds to a Fabry-Perot resonance with a 7-half-wavelength spacing (i.e., the seventh resonance order), if we take into account the $1.56\text{-}\mu\text{m}$ optical penetration depth into the AlAs/GaAs dielectric mirror and the $1.9\text{-}\mu\text{m}$ optical thickness of the InGaAs/GaAs multiple-quantum-well layer. The thickness of the InGaAs/GaAs layer was chosen such that an antiresonance of the final FPSA is close to the Nd:YLF lasing wavelength of $1.047 \mu\text{m}$. The final A-FPSA reflectivity [curve (c)] shows an eighth-order Fabry-Perot resonance peak at 992 nm if we take into account a $0.5\text{-}\mu\text{m}$ optical penetration depth into the $\text{TiO}_2/\text{SiO}_2$ dielectric mirror. The total optical thickness of this Fabry-Perot structure is $4 \mu\text{m}$, which produces a free spectral range of 138 nm and an antiresonance at $1.06 \mu\text{m}$ close to the laser wavelength of $1.047 \mu\text{m}$.

To monitor the laser operation fully we used a fast photodiode on a sampling scope and on a microwave spectrum analyzer, a noncollinear real-time autocorrelator, and an optical spectrum analyzer. Figure 3 shows a 3.3-ps measured autocorrelation (solid curve) and an ideal hyperbolic-secant autocorrelation (dashed curve) for comparison. We measured the autocorrelation trace while the sampling scope was simultaneously monitored, which indicated a clean detection-system-limited pulse width of ≈ 40 ps. The optical spectrum had a FWHM of 0.66 nm, which reveals that the pulses were 1.9 times transform limited.

The microwave spectrum analyzer on a 1-MHz frequency span and a 10-kHz resolution bandwidth centered on the pulse repetition rate of 219.4 MHz demonstrate unambiguously that the laser is not self-Q switched [Fig. 4(a)]. A Nd:YLF laser self-Q switches at the relaxation oscillation rate, which produces extremely strong modulation sidebands on a microwave spectrum analyzer. At a cw pump power of 2.2 W, Fig. 4(a) shows that the relaxation oscillations are approximately 55 dB below the first laser harmonic at a 10-kHz resolution bandwidth. This is typical for any active or passive mode-locked

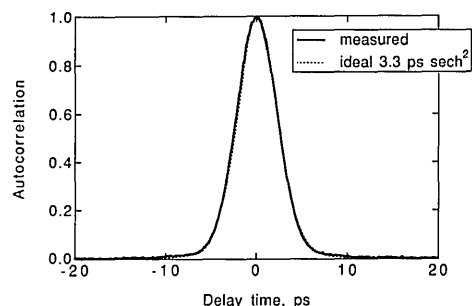


Fig. 3. Autocorrelation of the cw mode-locked Nd:YLF laser.

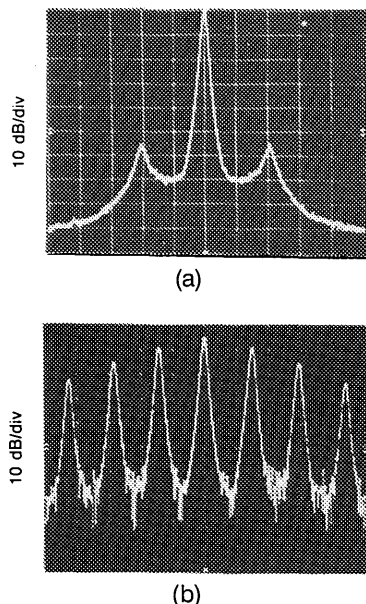


Fig. 4. Microwave spectrum analyzer results: relaxation oscillations appear as modulation sidebands around the pulse repetition frequency of 219.4 MHz for (a) a cw mode-locked Nd:YLF laser (2.2-W pump power) and (b) a cw mode-locked and Q-switched Nd:YLF laser (1.4-W pump power). The frequency span is 1 MHz, and the resolution bandwidth is 10 kHz.

Nd:YLF lasers. Higher pump power results in smaller relaxation oscillation strength. At a pump power of less than 1.6 W but greater than 0.8 W, the laser is stably self-Q switched [Fig. 4(b)], producing 4-ps cw mode-locked pulses within a 1.4- μ s Q-switched pulse at the relaxation oscillation rate of the Nd:YLF laser. For both cases we measure a peak-to-peak amplitude noise of no more than 2% observed over 250 ms on an oscilloscope with a greater than 1-MHz detection bandwidth. The high-frequency AM noise above a few hundred kilohertz is limited by the Ti:sapphire pump laser. It is important to note that spurious intracavity reflections strongly affect the stability of the passively mode-locked Nd:YLF laser. For example, a slightly wedged antireflection-coated Nd:YLF laser rod or a focusing lens instead of a curved highly reflecting mirror prevented mode locking.

The method of operating a Fabry-Perot structure at antiresonance is not obvious and has been motivated by our previous research with RPM.⁴⁻⁷ In terms of coupled-cavity mode locking, the A-FPSA forms a monolithic coupled-cavity configuration for which the A-FPSA determines the end mirrors for the two coupled cavities that spatially overlap. The top mirror of the A-FPSA forms the end mirror of the main cavity, and the dielectric mirror underneath the saturable absorber layer forms the end mirror of the nonlinear coupled cavity. Because of monolithic integration of these two end mirrors within the same element, no relative cavity-length fluctuations exist. Thus there is no need for active cavity-length stabilization. In addition, the A-FPSA design minimizes the cavity-length difference and hence the pulse duration. Although this

formal relation with RPM exists, it is simpler and equally correct to view the entire A-FPSA as an effective intracavity saturable absorber.

In conclusion, we have demonstrated a stable, self-starting, intracavity passive mode-locked Nd:YLF laser and produced a 3.3-ps pulse duration. In addition, stable Q switching is achieved. The intracavity A-FPSA represents a saturable absorber for which we can custom design the effective saturation intensity for a given material by simply choosing the appropriate top reflector. Because the FPSA is operated at antiresonance, we obtain a low insertion loss (top reflector is 98%), a high damage threshold, no bandwidth limitation (free spectral range of \approx 138 nm, which is much greater than the gain bandwidth of the laser of \approx 0.7 nm), a high effective saturation intensity, insensitivity to thermal loading, loose design tolerances, and the possibility of designing a broadband saturable absorber. Both at cw and at mode-locked operation the laser mode is a clean TEM₀₀ mode as observed with a microwave spectrum analyzer and an infrared viewer. The cavity alignment is optimized for maximum power, and no intracavity aperture or slit has been used. However, some small self-focusing mode-locking contributions might affect the steady-state pulse duration owing to the effective gain aperture introduced by longitudinal laser pumping,⁸⁻¹¹ which is under further investigation.

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