# Self-starting femtosecond mode-locked Nd:glass laser that uses intracavity saturable absorbers

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We produced transform-limited pulses as short as 130 fs with 160-mW average output power from a passively mode-locked Nd:glass laser. This is to our knowledge the first demonstration of an intracavity semiconductor antiresonant Fabry–Perot saturable absorber continuously starting a Kerr-induced passively mode-locked laser. The antiresonant Fabry–Perot saturable absorber, even with dispersion compensation, produced only picosecond pulses, and femtosecond performance was observed only with the addition of an intracavity long-pass wavelength filter. We propose a new mode-locking mechanism, which we refer to as Kerr-shift mode locking, in which the wavelength-dependent intracavity aperture and self-phase modulation in Nd:glass combine to produce a self-wavelength shift that reduces intracavity losses for femtosecond pulses.

We have introduced an intracavity antiresonant Fabry–Perot saturable absorber (A-FPSA), which both starts and sustains stable mode locking without self-*Q* switching of a cw-pumped Nd:YLF and Nd:YAG laser.[1–3] Femtosecond pulses were generated with a Kerr-lens mode-locked[4–7] Ti:sapphire laser with the use of resonant passive mode locking as the starting mechanism.[5,8,9] However, intracavity saturable absorbers are more compact and simpler than external coupled cavities. Therefore we suggested,[9] owing to the direct analogy between the A-FPSA and resonant passive mode locking,[1] that an intracavity A-FPSA should work as well.

In this Letter we report what is to our knowledge the first demonstration that an A-FPSA can continuously start a Kerr-effect-based mode-locking process without degrading its steady-state stability. In addition, we give some initial experimental evidence for a new type of Kerr-induced mode-locking mechanism for solid-state lasers, similar to Kerr-lens mode locking[4–7] (KLM). Even with dispersion compensation the A-FPSA alone produced picosecond pulses, and femtosecond pulses were observed only with the addition of an intracavity long-pass wavelength filter. We propose that self-phase modulation (i.e., the Kerr effect) in Nd:glass combined with the fixed loss at shorter wavelengths enhances the observed self-wavelength shift to form transform-limited femtosecond pulses that have reduced intracavity losses. We refer to this proposed new mode-locking mechanism as Kerr-shift mode locking (KSM).

A Nd:glass laser provides sufficient gain bandwidth to support femtosecond pulses. Extension to an all-solid-state practical femtosecond laser is possible because of the strong absorption line at ≈800 nm, where high-power diode-array pump lasers are commercially available. Previously, an additive-pulse mode-locked Nd:glass laser produced pulses as short as 122 fs (Ref. 10) that required an external coupled cavity containing a fiber with active length control. Because both the KSM mechanism and the A-FPSA are intracavity saturable absorbers, no cavity-length control is required for passive mode locking. In addition, the A-FPSA is a bulk nonlinearity that requires no critical alignment into a waveguide or a fiber. The A-FPSA simply forms one end mirror of the Nd:glass laser.

The laser cavity (Fig. 1) is an astigmatically compensated delta cavity. The Nd:glass plate (Schott LG760), 4 mm thick and 2% doped, is at Brewster's angle between two curved mirrors with a 10-cm radius of curvature. One arm of the delta cavity contains a low-temperature molecular-beam-epitaxy-grown InGaAs/GaAs A-FPSA[1] with a 98% top reflector with either a 17- or an 8-ps carrier lifetime. The other arm contains dispersion compensation through the use of two SF10 prisms. The calculated beam radius in the Nd:glass plate is 45 $\mu$m × 30 $\mu$m. The Nd:glass laser is cw pumped with a Ti:sapphire laser at 800 nm with a focused pump beam radius of 20 $\mu$m in the sagital plane. The absorbed pump power is 92% of the incident power. Using a 1% output coupler (30′ wedged), we typically measured

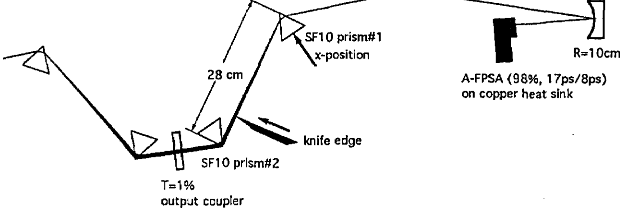

Fig. 1. Nd:glass delta cavity cw pumped with a Ti:sapphire laser.

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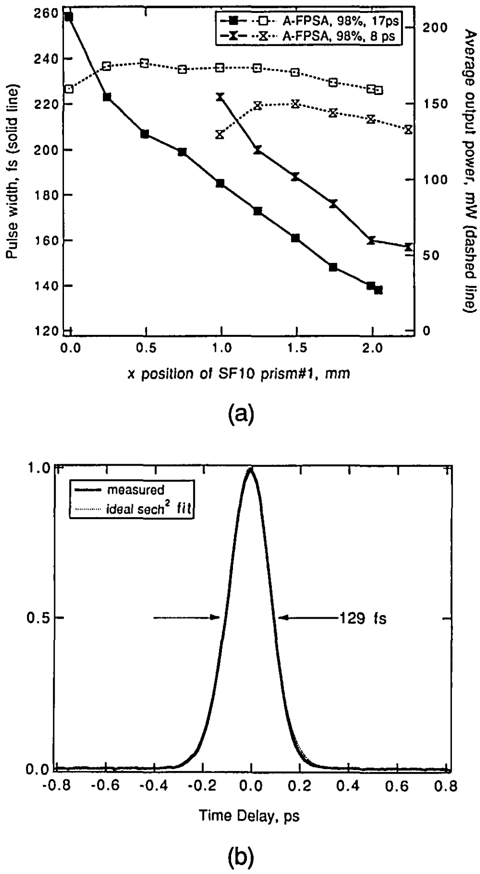


(a)

(b)

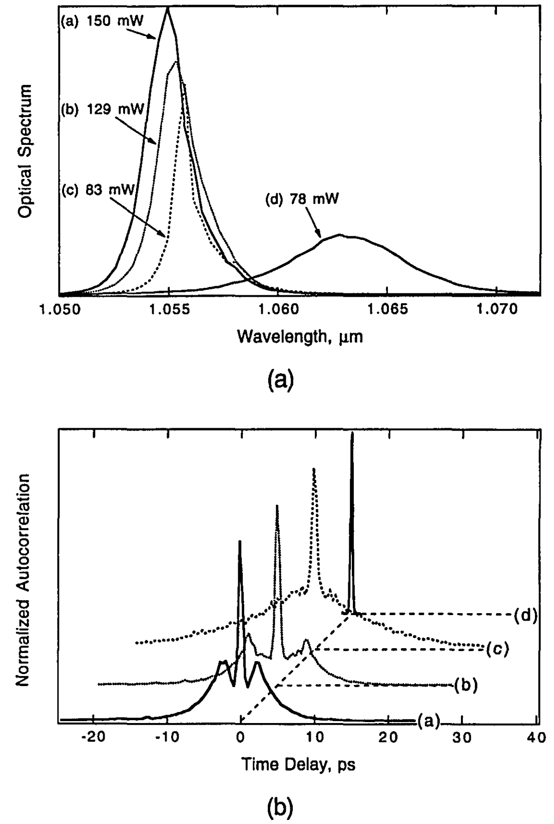
Fig. 2. KSM Nd:glass laser with two different A-FPSA samples with a carrier lifetime of 17 or 8 ps but both with a top reflector of 98%. (a) Pulse duration and average output power as a function of dispersion compensation (SF10 prism apex-to-apex distance 28 cm, $x = 0$ when the laser beam is at the apex of prism #1; prism #2 is used as the wavelength-dependent aperture). (b) 129-fs autocorrelation trace (prism apex-to-apex distance 24 cm).

a lasing threshold of ≈30-mW absorbed pump power and an initial slope efficiency of 24% because of the low losses (i.e., <1%) introduced by the A-FPSA.

Picosecond pulses were obtained with an A-FPSA sample used as one of the end mirrors. The laser beam was focused onto the A-FPSA with a highly reflecting mirror with a 10-cm curvature, resulting in a focused beam radius of ≈34 $\mu$m. We expected that, with dispersion compensation, the A-FPSA would start femtosecond pulses similar to resonant passive mode locking in KLM Ti:sapphire lasers.[5]

However, *ABCD* matrix calculations showed that the Kerr lens induced no significant beam radius reduction when the cavity was close to the middle of its stability regime. We attempted to obtain femtosecond pulses by using an intracavity aperture in either arm of the delta cavity, and, indeed, no femtosecond pulses were obtained. However, when we translated prism #2 (Fig. 1) partially out of the laser beam the output power dropped from 210 to ≈160 mW, and the laser moved from picosecond pulses to femtosecond pulses. Similar results were also obtained by moving a knife edge into the laser beam (Fig. 1). By optimizing the intracavity dispersion with prism #1 and the strength of the starting mechanism by using an A-FPSA with a longer carrier lifetime[2] [Fig. 2(a)], we obtained transform-limited pulses as short as 129 fs [Fig. 2(b)]. The stability as observed with a microwave spectrum analyzer shows amplitude noise sidebands as low as with KLM Ti:sapphire lasers.[11,12]

Intracavity spectral apertures have been used before to adjust the bandwidth or the central wavelength of the transmitted laser beam.[13] The difference here is that we use a single-sided aperture that acts as a long-pass wavelength filter and is formed by either moving prism #2 partially out of the laser beam or moving a knife edge partially into the beam. A long-pass wavelength filter is formed because the angle of refraction from prism #1 is larger for shorter wavelengths. As the knife edge is moved into the laser beam, the average output power decreases, and the center wavelength is shifted owing to the fixed losses at shorter wavelength, but no significant new bandwidth is produced at longer wavelengths [Fig. 3(a), traces a–c], and pulse durations remain in the picosecond regime and even increased slightly [Fig. 3(b), traces a–c]. However, when we move the knife edge further into the laser beam, the laser suddenly jumps into femtosecond transform-limited pulses with a significant shift of its center wavelength and a significant (i.e., 24%) increase in its average output power (Fig. 3, trace d). As soon as the laser jumps into femtosecond pulsing, the noise sidebands as observed on a microwave



(a)

(b)

Fig. 3. Self-wavelength shift of the optical spectrum when a knife edge (see Fig. 1) is moved into the laser beam, producing successive traces a–d: (a) measured optical spectrum (0.1-nm resolution), (b) measured autocorrelation trace from a noncollinear autocorrelator.

spectrum analyzer drop drastically in comparison with that under picosecond pulsing, similar to the behavior that we observed with a KLM Ti:sapphire laser.[5] Moving the knife edge further into the laser beam continuously reduced the output power, but stable femtosecond pulses were observed until the intracavity power was too low to support stable mode locking.

We believe that increased self-phase modulation of femtosecond pulses (i.e., by a factor of ~100) supports the required wavelength shift, which is then balanced by the lower gain at longer wavelengths. Self-phase modulation alone only broadens the spectrum, but because of the fixed loss at shorter wavelength, the extra bandwidth created by self-phase modulation effectively shifts the center wavelength. Because of the fixed loss at shorter wavelengths the center wavelength has to shift by a large amount to permit the much larger spectral bandwidth required for femtosecond transform-limited pulses. This red shift is ultimately stabilized by the reduced gain at longer wavelengths. This hypothesis is experimentally supported because, as long as the laser operates in the picosecond regime, no significant bandwidth is produced at longer wavelength, and only when the laser moves into the femtosecond regime do we observe a new bandwidth at longer wavelengths (Fig. 3). Under femtosecond operation the spectrum is peaked near 1.063 $\mu$m, whereas a freely running Nd:glass laser is peaked at 1.054 $\mu$m. Therefore self-phase modulation combined with an intracavity long-pass wavelength filter and the reduced gain at longer wavelengths produces an intensity-dependent transmission with a new gain maximum at longer wavelength. This forms an effective fast saturable absorber similar to that with KLM. However, it is important to note that KLM cannot explain the observed center wavelength shift.

Because both KLM and KSM are based on the Kerr nonlinearity, we would expect similar mode-locking performance. In both cases the amplitude noise sidebands are low, as observed on a microwave spectrum analyzer. In addition, in comparison with colliding-pulse mode-locked dye lasers, both mode-locking processes show a weak dependence on intracavity dispersion [Fig. 2(a) and Ref. 5], and KSM requires an excess of negative dispersion for stable mode locking: At the stability limit for stable mode locking [$x = 2$ mm in Fig. 2(a)] the prism pair still produced a negative group-delay dispersion of 1.9 fs/nm, whereas the Nd:glass plate introduces a positive group-delay dispersion of only $-0.2$ fs/nm.

Because KSM is very weak for initial mode-beating fluctuations, it requires an additional starting mechanism such as an A-FPSA. This is confirmed by the fact that an A-FPSA with a 99% top reflector was insufficient to start KSM or even mode locking in the picosecond regime. In addition, we observed that an A-FPSA with a longer carrier lifetime (i.e., a stronger mode-locking driving force[5]) resulted in shorter femtosecond pulses [Fig. 2(a)]. This suggests that the A-FPSA may also play a role in the femtosecond pulse formation. However, without a sufficiently strong long-pass wavelength filter and with the A-FPSA alone we obtained only picosecond pulses (Fig. 3). Because of the absorption edge of the InGaAs/GaAs saturable absorber, the unbleached absorption of the A-FPSA is reduced by a fraction of a percent at longer wavelengths.[1] In addition, because the A-FPSA has a bitemporal absorption response,[2] we would expect a somewhat stronger bleaching at femtosecond pulses. However, this effect was not sufficient for the laser to produce femtosecond mode locking. The free-spectral range of the A-FPSA is ≈140 nm, which is much larger than the 10-nm wavelength shift and should not be an effect. Further investigations of different starting mechanisms should clarify this issue.

In conclusion, we have demonstrated self-starting stable transform-limited 129-fs-long pulses from a Nd:glass laser. Owing to the extremely low losses (i.e., <1%) introduced by the A-FPSA, we obtained 160-mW average output power at an absorbed pump power of ≈1 W. In addition, this laser's performance could not be explained by KLM theory, because of the large center wavelength shift and the single-sided aperture. We have proposed an explanation for this laser's behavior, which we call Kerr-shift mode locking. KSM can be independent of the specific cavity design and, for example, can operate near the middle of a laser cavity's stability range, where KLM may not provide a strong enough mode-locking force. An intracavity semiconductor A-FPSA provided the starting mechanism for KSM. An A-FPSA combined with KLM or KSM is expected to provide a reliable, intracavity, passive mode-locking mechanism for many broadband solid-state lasers.

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