Ultrafast Solid-State Mode-Locked Lasers Using Resonant Nonlinearities

Ursula Keller, *Member, IEEE*, Wayne H. Knox, and Gert W. 'tHooft

Invited Paper

***Abstract*—Major advances have occurred recently in ultrafast laser technology using solid-state laser materials. These materials have interesting properties such as room temperature operation, high energy storage density, and broad bandwidth, all of which are desirable for high power tunable ultrafast laser operation. We discuss recent experiments in which resonant nonlinearities are used in order to directly mode lock solid-state lasers or to initiate self-focusing mode locking.**

I. Introduction

DEVELOPMENT of tunable solid-state lasers began nearly 30 years ago. For ultrafast solid-state lasers, a broad bandwidth is one requirement. In general, broadband tunable solid-state lasers can be achieved with a strong electron–phonon coupling of the lasing ion to the host lattice. In 1963, the first tunable "vibronic" transition metal laser, a nickel-doped magnesium fluoride laser, was reported [1]. Many different lasers followed, however they only worked at cryogenic temperatures which was a serious drawback for practical application. In addition, the discovery of the Nd:YAG laser [2] in 1964, and the popularity of dye lasers [3], [4], and of color center lasers [5], diverted research away from tunable transition metal lasers. Renewed research efforts in tunable solid-state lasers produced the first demonstration of the alexandrite laser ($Cr:BeAl_2O_4$) [6] in 1979 and of the Ti:sapphire laser ($Ti:Al_2O_3$) by Moulton in 1982 [7], [8]. The room-temperature Ti:sapphire laser material has an exceptionally wide tuning range of 400 nm (680 to 1100 nm), a relatively large gain cross section (peak value $\approx 4 \times 10^{-19}$ cm^2, about half of Nd:YAG), little excited-state absorption of the laser radiation, and a high optical quality. These properties were the basis for the success of the Ti:sapphire laser, leading to its crucial role in the current rapid developments in femtosecond pulse generation.

Until the late 1980's, subpicosecond laser sources were dominated by dye lasers [9]. The first sub-100 fs pulses were available with colliding-pulse mode-locked (CPM) dye lasers in 1981 [10]. In such a passively mode-locked laser, the gain saturation and absorber saturation work together to form a short net gain window. Because both the gain and the absorber recover rather slowly (typically nanoseconds), and only their combined action forms a femtosecond pulse, this mode-locking technique is referred to as the slow-saturable-absorber mode-locking technique [Fig. 1(a)]. The critical balance between gain and absorber saturation required in slow-saturable-absorber mode locking is very impractical for Ti:sapphire lasers because the saturation fluence $h\nu/\sigma$ of ≈ 0.6 J/cm^2 is much larger than the typical intracavity pulse energy densities (Table I), where σ is the gain cross section of $\approx 4 \times 10^{-19}$ cm^2. Therefore, a fast saturable absorber is required to mode lock a Ti:sapphire laser. In this case, the pulse forming process is determined by the saturable absorber is shown schematically in Fig. 1(b). In addition, because of the low gain in Ti:sapphire lasers, the absorber loss has to be small. Such a saturable absorber was initially not available, and the first passively mode-locked Ti:sapphire laser used coupled-cavity mode-locking techniques. Later, intracavity self-focusing, a reactive or nonresonant nonlinearity, produced a fast-saturable-ab-

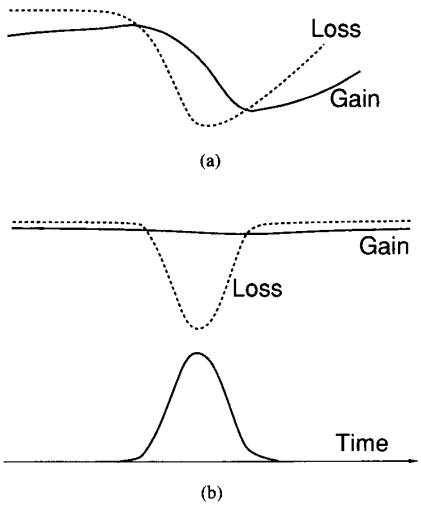

Fig. 1. (a) Slow and (b) fast saturable absorber mode-locking techniques.

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U. Keller and W. H. Knox are with AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, NJ 07733.

G. W. 'tHooft is with Philips Research, 5600 JA Eindhoven, The Netherlands.

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TABLE I
STIMULATED GAIN CROSS SECTION σ AND SATURATION FLUENCE $h\nu/\sigma$ FOR DIFFERENT LASER MATERIALS

Gain Material	σ [cm^2]	$h\nu/\sigma$ [J/cm^2]
GaAs quantum well	$\approx 10^{-14}$	$\approx 10^{-5}$
Rhodamine 6G	1.4×10^{-16}	2.3×10^{-3}
Color Center: NaCl : OH^-	0.9×10^{-16}	1.4×10^{-3}
Ti : sapphire	3.8×10^{-19}	0.7
Nd : YLF	1.8×10^{-19}	1.1
Nd : glass	3×10^{-20}	6.3

sorber-like mode locking with which sub-100 fs pulses from a Ti : sapphire laser were produced [11].

Within only three years, from 1988 to 1991, the pulse duration of mode-locked Ti : sapphire lasers moved from picosecond pulses to 30 fs. During this time many new mode-locking techniques have been introduced.

In this paper, we will discuss three configurations employing resonant nonlinearities: coupled cavity mode locking using a semiconductor nonlinear mirror, a further extension of this including self-focusing mode locking, and the closely related case of an intracavity saturable absorber dye. In the last two cases, the resonant nonlinearity only starts the self-focusing mode locking. Passive mode-locking techniques using resonant nonlinearities have the advantage that they self-start mode locking. We will be concentrating on the Ti : sapphire laser, because many of the new mode-locking techniques have been first demonstrated with this laser. These techniques have been extended to other solid-state lasers such as Nd : YAG, Nd : YLF, Nd : glass, and recently, to Cr : LiSrAlF. The combination of these new mode-locking techniques with diode-pumped solid-state lasers is particularly interesting because of a possible all-solid-state ultrafast laser technology.

II. RESONANT PASSIVE MODE LOCKING (RPM)

Resonant passive mode locking (RPM) is a coupled-cavity mode-locking technique with a resonant nonlinearity in the coupled cavity [Fig. 2(a)] [12]–[15]. Following early soliton laser experiments by Mollenauer [16] in which a color center laser was coupled to a nonlinear fiber cavity in the soliton regime, Blow and Wood [17] demonstrated theoretically that *any* nonlinear coupled cavity can produce mode locking. Confirming Blow and Wood's theoretical prediction, enhanced mode locking of a synchronously pumped color center laser was simultaneously demonstrated in 1988 [18]–[21] using a fiber with positive group velocity dispersion (GVD) or a semiconductor diode amplifier [21] inside a coupled cavity. Similarly, Fujimoto *et al.* mode locked a CW pumped Ti : sapphire laser [22]. Later, Ippen *et al.* [23], [24] introduced a simple model, called additive pulse mode locking (APM), which explains the pulse shortening process through interference of the pulse in the main cavity with the self-phase-modulated reinjected pulse from the coupled cavity containing a Kerr nonlinearity. This is similar to the previously discussed nonlinear Michelson interferometer [25], [26] with which a CO_2 laser was passively mode locked. Under certain conditions, APM of a CW pumped laser can be self-starting [27], and many different APM lasers have been demonstrated [28]–[34].

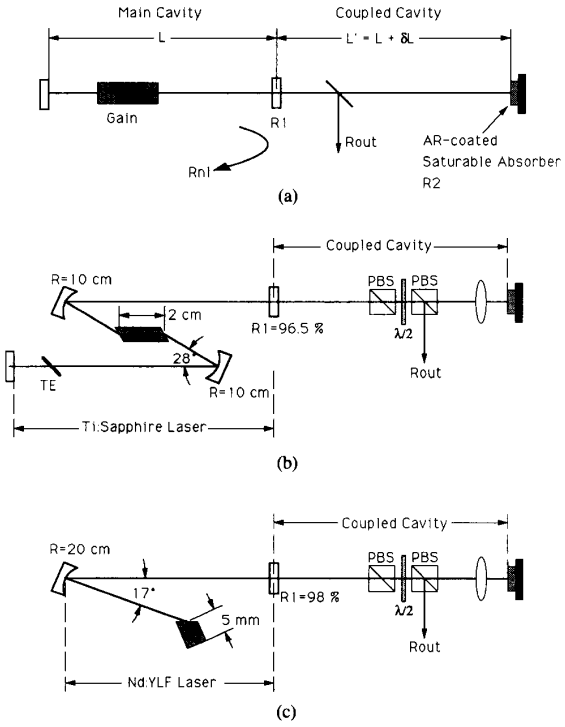


Fig. 2. (a) Schematic RPM cavity. (b) RPM Ti : sapphire cavity setup. (c) RPM Nd : YLF cavity setup.

Blow and Wood's [17] theoretical prediction and the early APM laser results [18]–[22] inspired other coupled-cavity mode-locking techniques using a saturable absorber [12]–[15], an active mode locker [35], and a moving mirror [36] as the nonlinear element in the coupled cavity. We mode locked both a Ti : sapphire [12] and a Nd : YLF laser [14], [15] using a semiconductor saturable absorber in the coupled cavity. The wide-spread success of APM was strongly enhanced by the easy availability of fibers. In contrast to RPM, APM requires a feedback system to control the cavity length and to maintain stable mode locking. However, even with an active feedback loop in place, a CW pumped APM laser has a tendency to drop out of mode-locked operation induced by sudden mechanical vibrations which is difficult to track with a simple feedback circuit [22].

For an all-solid-state ultrafast laser technology, semiconductor saturable absorbers have the advantage that they are compact, fast, and can cover bandgaps from the visible to the infrared. Because the nonlinearity in the coupled cavity is based on a fast intensity dependent reflectivity change of the semiconductor reflector, a resonant nonlinearity, we refer to it as resonant passive mode locking (RPM). Even though RPM is a coupled-cavity mode-

locking technique no feedback system to control the cavity length is required to produce stable mode-locked pulses. RPM is self-stabilized by optical frequency adjustments [12], [13]. This means that coherent superposition of the pulse in the main cavity and the pulse in the coupled cavity is maintained by small optical self-frequency shifts compensating for any relative cavity length fluctuations. The performance of an RPM Nd:YLF laser was subsequently improved using a low-temperature MBE grown multiple quantum-well semiconductor reflector [15], and Jacobovitz-Veselka *et al.* further demonstrated that a bulk semiconductor with a short carrier lifetime can be used for RPM [37]. This opens the possibility of passively mode locking many more solid-state lasers. For example, LT $In_xGa_{1-x}As$ alone covers band-gap wavelengths from 0.87 μm to 3.8 μm depending on x and could be grown on top of an AlAs-GaAs dielectric mirror. The low-temperature growth produces an optically smooth surface even though the InGaAs is strongly lattice mismatched to GaAs [38]. Using a band-gap engineered broad-band saturable absorber, the tunability of a RPM Ti:sapphire laser has been now extended to more than 100 nm [37]. This is significant considering the fact that the mode-locking mechanism is based on a near-band-gap resonant nonlinearity.

The most recent invention of a new intracavity saturable absorber, an antiresonant semiconductor Fabry-Perot, produced self-starting stable CW mode-locked pulses from a Nd:YLF [39] and a Nd:YAG [40] laser. Mode locking with this new intracavity saturable absorber can be considered as "monolithic" RPM, which we will discuss at the end of this section.

The RPM Ti:sapphire and Nd:YLF laser cavity design is shown in Fig. 2(b) and (c). Typically, R_1 is set at 95 to 98% to achieve pulses of a few picosecond with good stability. A tunable output coupler R_{out}, formed with a half-wave plate and a polarizing beamsplitter, is convenient to optimize RPM. In the case of the Nd:YLF laser, R_{out} as high as 85% is used [15]. The laser beam is then focused onto an AR-coated semiconductor saturable absorber which forms the end mirror of the coupled cavity. This nonlinear semiconductor reflector strongly mode locks a CW pumped laser. It is important to realize that the coupled cavity is a low-Q cavity. The reinjected beam from the coupled cavity is strongly attenuated by the high output coupler R_{out} and the low reflectivity of the saturable absorber.

A full theoretical treatment of RPM has been given by Haus *et al.* [13]. We restrict our discussion with a simple model based on the nonlinear coupled cavity reflectivity R_{nl} [Fig. 2(a)]. This has been discussed in detail in [15]. The frequency dependence of R_{nl} is shown schematically in Fig. 3. This is similar to the transmission characteristic of a Fabry-Perot resonator, however since the two cavities are coupled, the periodicity of the coupled cavity reflectivity is $c/2\,\delta L$ and not $c/2L'$, where L' is the coupled cavity length and δL the cavity length detuning. The lasing center frequency is at maximum reflectivity R_{max}. The

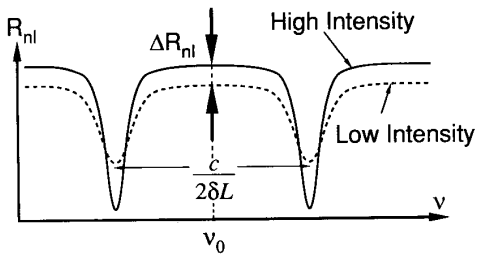


Fig. 3. Coupled cavity reflectivity R_{nl}.

intensity dependent reflector R_2 in the coupled cavity produces a intensity dependent coupled cavity reflectivity. Because R_1 is rather large, the nonlinear coupled cavity reflectivity can be approximated by [15]

$$R_{nl} = R_{max} + \left(\frac{\partial R_{max}}{\partial R_2}\right)\Delta R_2 \tag{1}$$

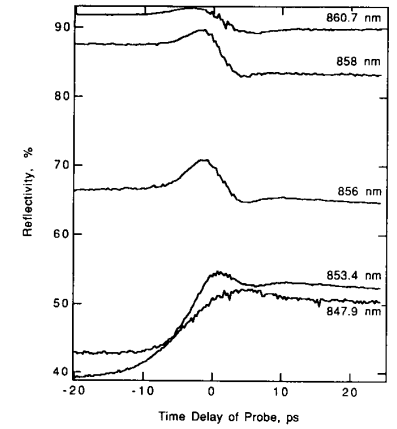
where ΔR_2 is the nonlinear reflectivity change in the semiconductor saturable absorber. The unperturbed R_{max} is given by [15]

$$R_{max} = \frac{(\sqrt{R_1} - (1 - R_{out})\sqrt{R_2})^2 + 4\sqrt{R_1 R_2}(1 - R_{out})}{(1 - \sqrt{R_1 R_2}(1 - R_{out}))^2 + 4\sqrt{R_1 R_2}(1 - R_{out})}. \tag{2}$$

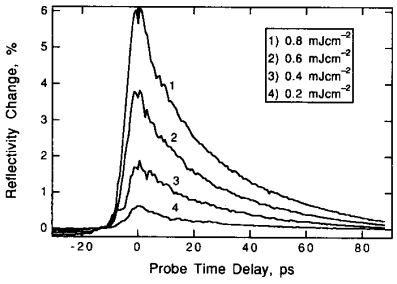
The factor $(\partial R_{max}/\partial R_2)$ in (1) is determined by the laser parameters and defines the coupling strength between the two cavities. For typical parameters used in RPM lasers ($R_1 = 98\%$, $R_2 \approx 50\%$, and $R_{out} \approx 50\%$), the coupling strength is only ≈ 0.008.

Initially, we used a p-i-n multiple quantum-well structure as the saturable absorber. For the Ti:sapphire laser, we used an AR coated AlGaAs-GaAs quantum-well structure grown on top of an AlAs-AlGaAs dielectric mirror centered around 850 nm. The undoped MQW region consists of 75 periods of 95 Å wide GaAs quantum wells and 45 Å wide $Al_{0.3}Ga_{0.7}As$ barriers [12]. Fig. 4(a) shows the measured nonlinear reflectivity of this p-i-n AlGaAs-GaAs MQW reflector. We used a standard noncollinear pump-probe technique and the RPM Ti:sapphire laser to perform this measurement. The wavelength was tuned over the absorption edge of the AlGaAs-GaAs MQW absorber with the strongest fast nonlinearity in the middle of the absorption edge at 856 nm. The maximum reflectivity change was $\approx 6\%$ at an estimated excitation energy density of ≈ 0.5 mJ/cm^2. The nonlinearity observed in Fig. 4(a) scales with the pulse duration and is still under further investigation.

Similarly, a p-i-n InGaAs-GaAs MQW absorber was used to mode lock a Nd:YLF laser [14], however the stability was rather poor. More stable mode locking was achieved using a low-temperature (LT) MBE grown InGaAs-GaAs MQW structure [15]. The absorber layer is MBE grown ≈ 380°C and consists of 50 periods 60 Å thick GaAs barriers and 62 Å $In_xGa_{1-x}As$ wells with $x = 0.29$. The LT MQW structure is grown on top of an



(a)



(b)

Fig. 4. Noncollinear pump-probe measurements on (a) the p–i–n quantum-well reflector initially used for the RPM Ti : sapphire laser and (b) the low-temperature MBE grown InGaAs–GaAs saturable absorber used for the RPM Nd : YLF laser.

AlAs–GaAs dielectric mirror stack with 10 periods of 905 Å AlAs and 764 Å GaAs layers grown at normal ($\approx$640°C) temperature on a GaAs substrate. We used the RPM Nd : YLF laser and a noncollinear pump-probe technique to measure the nonlinear reflectivity at different excitation energy densities [15] [Fig. 4(b)]. The carrier lifetime is reduced to 25 ps by the low-temperature growth. In addition, the LT growth produces a smooth optical surface even though the InGaAs–GaAs MQW is not lattice matched to the AlAs–GaAs dielectric mirror underneath. In this material system, materials grown at high temperatures exhibit surface striations which strongly diffract the laser beam [14]. The resonant nonlinearity in this LT grown saturable absorber is based on absorption bleaching. Under CW mode-locked operation, the absorption bleaching, and hence the reflectivity, is increased due to the increased numbers of carriers generated within one laser pulse duration. In the short pulse limit (pulsewidth $\tau <$ carrier lifetime) and at a pulse repetition period larger than the carrier lifetime, ΔR_2 is determined by the pulse energy density E_p and is, therefore, independent of τ. The extension of RPM to high repetition rates has been explored with a diode-pumped Nd : YLF laser [41]. More recently, Jacobovitz–Veselka *et al.* [37] demonstrated that even a bulk material, provided it has a "reasonably" fast response time using a low-temperature MBE growth technique, successfully mode locked a Ti : sapphire laser.

The nonlinear response [Fig. 4(a)] of the p–i–n saturable absorber scales with the pulse duration and is based on an ultrafast excitonic nonlinearity. This represents the ideal case of a fast saturable absorber for which a closed form solution exists [42]. However, the nonlinear response [Fig. 4(b)] of the LT semiconductor saturable absorber is determined by the carrier lifetime in the semiconductor which does not scale with the pulse duration. We successfully mode locked Nd : YLF lasers with LT materials having carrier lifetimes between 25 and 70 ps with no significant influence on the final pulse duration of $\approx$4 ps. Therefore, a "semifast" [15] (compared to the final mode-locked pulse duration) saturable absorber was used to mode lock solid-state lasers and numerical simulations may be required to fully explore this regime of operation.

The pulse duration of an RPM laser continuously increases with increased cavity length detuning, shown in Fig. 5 for an RPM Ti : sapphire laser. This is easily explained in the time domain: the total steady-state pulse is a coherent superposition of the pulse in the main cavity and the slightly delayed or advanced reinjected pulses from the coupled cavity. Therefore, at larger cavity length detuning the resulting pulse duration increases.

The RPM laser is self-stabilized by small frequency adjustments [12], [13]. The maximum reflectivity, and therefore coherent superposition at the coupling mirror, can be maintained for any relative cavity length change by a small wavelength shift within the coupled cavity reflectivity period. We demonstrated this self-stabilization scheme with the RPM Ti : sapphire laser [12]. The coupled cavity length was periodically varied by 0.2 μm with a piezoelectric transducer while simultaneously monitoring the optical spectrum. Meanwhile, the laser maintained stable mode locking as monitored on an autocorrelator and a microwave spectrum analyzer. Fig. 6 shows how the peak wavelength is adjusting itself to compensate for the cavity length changes. The maximum range over which the peak wavelength is shifting is determined by the coupled cavity reflectivity period. Fig. 7(a) shows the time-averaged optical spectrum at the center wavelength of 846 nm and over a span of 12 nm. The self-stabilization produces a very structured spectrum when averaged over a longer time period. The optical bandwidth of the time-averaged spectrum was numerically determined from Fig. 7(a). Fig. 7(b) confirms that the bandwidth is determined by the coupled cavity reflectivity period $\lambda^2/2\ \delta L$. Therefore, as theoretically predicted [13] the maximum wavelength shift required to compensate for cavity length fluctuations in a freely running RPM laser is given by the coupled cavity reflectivity period $\lambda^2/2\ \delta L$. These wavelength fluctuations become smaller at larger cavity length detuning. At very small cavity length detunings, the wavelength shifts required for self-stabilization are no longer supported by the gain bandwidth of the laser. Thus, a feedback system for cavity length control would be re-

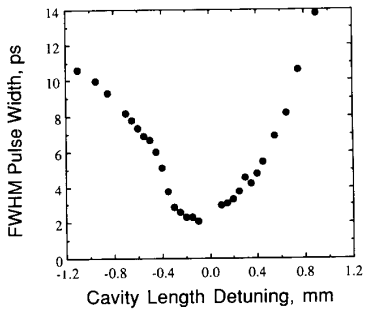


Fig. 5. Pulsewidth as a function of cavity length detuning for the RPM Ti : sapphire laser.

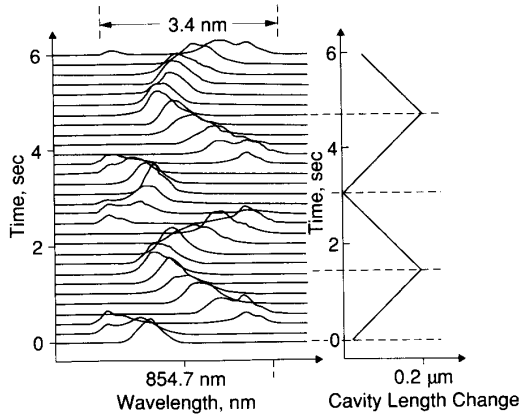


Fig. 6. Self-stabilization by frequency adjustments.

quired to operate the laser at this position. RPM does not require absolute cavity length control, because drifts of several 100 μm are required for significant pulsewidth changes (Fig. 5).

One problem with resonant nonlinearities is that they can restrict the laser tunability. Fig. 8 shows that the pulse duration significantly changes when the wavelength is tuned over the absorption edge of the p–i–n AlGaAs–GaAs MQW absorber. The shortest pulses are achieved close to the absorption edge consistent with the pump-probe measurements [Fig. 4(a)]. However, using a band-gap engineered low-temperature-MBE-grown bulk AlGaAs absorber, the tunability was extended to over 100 nm [37]. The $Al_xGa_{1-x}As$ absorber layer, 1.5 μm thick, is MBE grown at low-temperatures while the x composition is continuously varied during the growth from 0 to 0.22. The resulting absorption edge is broadened from 730 to 870 nm (Fig. 9). Over a 103 nm tuning range, the pulse duration varied by only $\pm 20\%$.

More recently a new low-loss intracavity saturable absorber element, an antiresonant Fabry–Perot saturable absorber (A-FPSA) was introduced [39]. This A-FPSA starts and sustains stable mode locking of a Nd : YLF [39] and a Nd : YAG [40] laser. The A-FPSA consists of a low-temperature MBE grown InGaAs–GaAs semiconductor saturable absorber, with a bandgap ≈ 1.05 μm, monolithically integrated between two reflecting mirrors. The top reflector is a TiO_2–SiO_2 dielectric mirror with a 98% re-

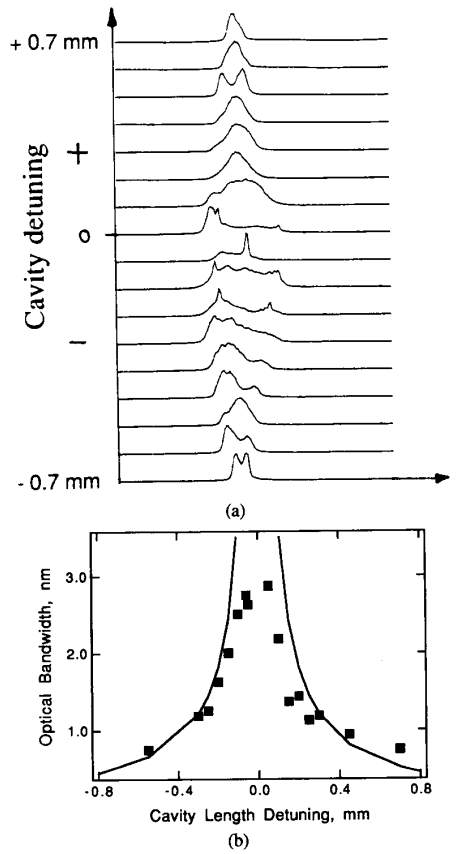


Fig. 7. (a), (b) Time averaged optical spectrum of the RPM Ti : sapphire laser.

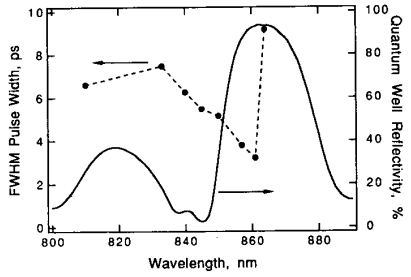


Fig. 8. Tunability of the RPM Ti : sapphire laser using the p–i–n multiple quantum-well reflector in the coupled cavity.

flectivity (Fig. 10). The use of this Fabry–Perot saturable absorber at antiresonance effectively transforms the semiconductor to a high saturation intensity, low-loss absorber as required. This scheme is simpler and more compact than RPM, and avoids issues associated with coupled cavity length control. Because the free spectral range of such a A-FPSA is rather large (i.e., ≈ 140 nm) a broad-band saturable absorber similar to Fig. 9 can be incorporated. This A-FPSA appears to be the best suited for practical applications of RPM.

It was not obvious that a Fabry–Perot structure at antiresonance can produce stable mode locking, and this development was initially motivated by RPM experi-

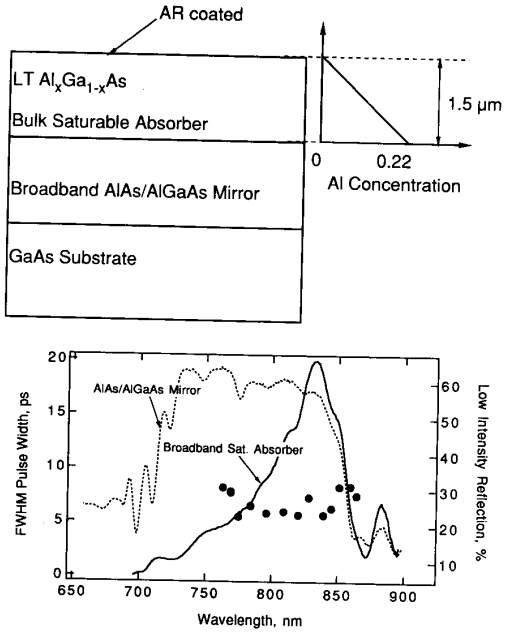


Fig. 9. Tunability of the RPM Ti: sapphire laser using a band-gap engineered broad-band saturable absorber.

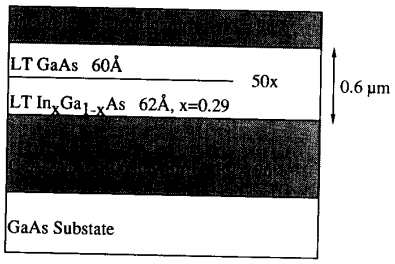


Fig. 10. Intracavity saturable absorber: an antiresonant semiconductor Fabry-Perot saturable absorber.

ments. In fact, mode locking with an A-FPSA is equivalent to "monolithic" RPM (Fig. 11). In this case, 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 of length L and the dielectric mirror underneath the saturable absorber layer forms the end mirror of the nonlinear coupled cavity of length L'. 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 an 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.

III. RPM and Self-Focusing Mode Locking

In 1990 two important experimental results reporting sub-100 fs pulse generation of Ti: sapphire lasers, caught the attention of the ultrafast community. In one experiment, a Ti: sapphire laser was passively mode locked with an intracavity saturable absorber dye jet [43], [44], and in the other experiment, "self-mode locking" of a Ti: sapphire laser was observed by simply misaligning an otherwise empty laser cavity [11], [45].

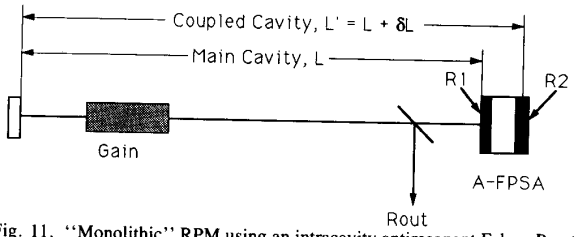
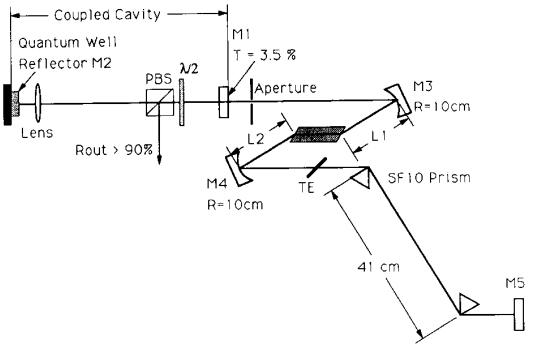


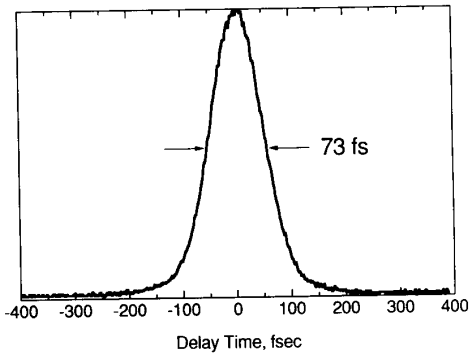
Fig. 11. "Monolithic" RPM using an intracavity antiresonant Fabry-Perot saturable absorber.

The "self-mode-locked" Ti: sapphire laser appeared to be the simplest femtosecond laser ever invented, and at the same time had the potential for far higher output power, and tunability, even though the laser intermittently self-mode locked and then fell back into CW operation. Piché *et al.* [46], [47] suggested that a nonlinear phase effect, such as self-focusing, can lead to lower losses at high intensity. For certain resonator parameters, the nonlinearity can compensate for the linear misalignment introduced in the self-mode-locked Ti: sapphire laser. The initial experiment by Spence *et al.* [11] has since been reproduced by many researchers. The starting was somewhat mysterious using a certain misalignment of the laser cavity and a certain amount of mechanical perturbation. Kafka *et al.* [48] discussed the starting mechanism of misaligned cavity based on enhanced mode beating noise due to higher transverse modes. Using a weakly coupled nonlienar quantum-well cavity (i.e., weak RPM), we achieved a clear separation of the mode-locking and starting processes [49], [50]. This experiment showed for the first time that a resonant nonlinearity could self-start the mode locking, but not participate in the mode locking. In addition, with an intracavity aperture, we demonstrated that no misalignment of the laser cavity is necessary and that self-focusing is important in mode locking. Simultaneously, Negus *et al.* [51] specifically redesigned a Ti: sapphire cavity to take full advantage of the self-focusing effect and demonstrated with an intracavity slit (similar to our intracavity aperture) fast saturable-absorber-like mode locking.

We modified the RPM Ti: sapphire laser cavity [Fig. 2(b)] and added intracavity GVD compensation, an adjustable aperture, and adjusted the tunable output coupler (formed by a half-wave plate and a polarizing beamsplitter) to more than 90% reflectivity [Fig. 12(a)]. In this case, the semiconductor saturable absorber in the external cavity still drives the pulse shortening by a standard saturable absorber mode-locking mechanism, as described for RPM, however the intracavity peak power eventually becomes high enough to initiate self-focusing mode locking. In the RPM case, the dispersion-limited pulsewidth is long enough so that self-focusing is not important. After the self-focusing mode locking has been initiated, the



(a)



(b)

Fig. 12. (a) Cavity setup of the femtosecond Ti : sapphire laser using self-focusing mode locking and weak RPM as the starting mechanism. (b) Autocorrelation trace of the ≈70 fs mode-locked pulse.

semiconductor absorber cavity can be blocked and the mode locking sustains in the main cavity until the cavity is interrupted or larger mechanical vibrations occur. If the main cavity is then opened with the semiconductor absorber blocked, only CW behavior is obtained. It is necessary to maintain a very weak coupling between the main cavity and the coupled cavity, or else RPM and self-focusing mode-locking mechanisms interfere and produce unstable pulse trains. In this mode, weak RPM action created by the semiconductor absorber subcavity clearly acts as a continuous self-starting mechanism for the self-focusing mode locking.

Using a p–i–n AlGaAs–GaAs MQW reflector we obtained stable 70 fs pulses with R_{out} larger than 90% [50] (Fig. 12). In this mode, RPM only serves as a starting mechanism. Because the nonlinear coupled cavity is only a very weak perturbation, no optical self-frequency shifts are induced by relative cavity length fluctuations. The optical spectrum is stable and indicates a transform limited bandwidth.

The tunability of the self-starting is determined by the saturable absorber in the coupled cavity [50]. With the p–i–n AlGaAs–GaAs MQW reflector, the tuning range over which the laser is continuously self-starting is approximately 30 nm and is limited by the resonant nonlinearity in the external cavity as in case of the RPM Ti : sapphire laser (Fig. 8). The broad-band AlGaAs saturable absorber (Fig. 9) should increase this tuning range to more than 100 nm. In addition, when we block the quantum-well reflector the laser sustains mode locking and can be tuned beyond the self-starting range.

Without misalignment of the main cavity, the intracavity aperture [Fig. 12(a)] was necessary for femtosecond pulses. We observed that the average output power increases by ≈10% from the CW power level when the laser is mode locked [50]. The high peak power inside the Ti : sapphire rod allows self-focusing to modify the cavity mode in such a way that the beam waist at the aperture becomes smaller which lowers losses in favor of a mode-locked operation.

We can model the self-focusing effect inside the laser cavity [Fig. 12(a)] using an ABCD matrix approach [47], [52]. The intensity dependent refractive index in the Ti : sapphire rod can be modeled with a Gaussian duct [52], using a parabolic approximation for the lateral refractive index change, and assuming a constant average beam size in the laser crystal. The laser cavity is astigmatically compensated, the output coupler of the main cavity M_1 is ≈3.5%, the coupled cavity length is equal to the main cavity length, the mirror distance M_1M_3 is equal to 230 mm, the radius of curvature is 10 cm for both mirrors, M_3 and M_4, the mirror distance M_4M_5 is 760 mm, the Ti : sapphire crystal length is 20 mm, L_1 is 46.5 mm and L_2 is 48 mm. A typical intracavity peak powers of ≈1 MW (average output power ≈330 mW at ≈5 W pump power, repetition rate 134 MHz, pulse duration 70 fs), the reduction of the beam radius in the tangential plane is close to 10%. This reduction only happens in the tangential plane, which makes a slit more appropriate than a round aperture [53]. The slit acts as an intensity dependent loss when the mode is reduced with increased intensity. Therefore, combining an intracavity slit close to mirror M_1 with the self-focusing effect inside the Ti : sapphire laser rod produces a fast saturable absorber. The nonlinear phase shift $\Delta\phi = kl\,\Delta n$, where k is the propagation constant, l is the crystal length, and Δn is the refractive index change due to self-phase modulation, gives some first indication about the importance of self-focusing. In our case, $\Delta\phi$ is ≈0.7 radians in steady state with a peak power of ≈1 MW. Thus, the wave plane will experience a significant phase shift variation while propagating through the gain media.

It is important to emphasize that the mode-locking process based on self-focusing is not self-starting and another starting mechanism has to be applied, however once started the stability of these sub-100 fs pulses is excellent [49], [54]. Different starting mechanism have been used such as higher-order transverse mode beatings [11], [48], weak RPM [50], moving mirror [55], mode-dragging (same as moving mirror) [53], acoustooptic mode locker [56], [57], regenerately-driven acoustooptic modulation [58], [59], and synchronous pumping [60]. Some of these techniques have been extended to other lasers [61], [62]. By minimizing higher-order intracavity dispersion in

Ti : sapphire lasers several groups produced pulses as short as 50 fs [63] and <30 fs [64]–[66] pulses.

In addition, a fast saturable-absorber-like mode locking is achieved with a nonlinear polarization rotation. An intracavity birefringent Kerr material combined with a polarizer results in higher transmission at higher intensity. Pulses as short as 38 fs were produced with a Nd : glass fiber laser [67] and 230 fs pulses with a Ti : sapphire laser [68], however being based on the Kerr nonlinearity, this mode locking technique is not self-starting.

Nonlinear effects such as Kerr nonlinearities in laser cavities were discussed as early as 1968 [69], [70]. In addition, Kerr-induced polarization rotation for passive mode locking has been proposed and demonstrated as early as 1972 [71], followed by other applications [72]. With the newly available femtosecond solid-state lasers, the intracavity peak intensities are sufficiently high to seriously exploit this relatively weak nonresonant nonlinearities. The Kerr nonlinearity has the advantage of being broadband and fast, but the disadvantage of not producing self-starting mode locking.

Although the fast-saturable absorber mode-locking model has been successfully used to explain the mode locking of Ti : sapphire lasers in the self-mode-locked limit, some interesting points are not yet fully explained. In Fig. 13(a), we show the variation with respect to dispersion of the pulsewidth and bandwidth of the Ti : sapphire laser which uses the quantum-well coupled cavity starting mechanism. In comparison, when the exact same prism pair is introduced into the cavity of an infrared CPM laser [73] the variation of the pulse width is much stronger [Fig. 13(b)]. Theoretical work is continuing on this subject. Current master equation theories of mode locking [74] do not include higher order dispersion, which is certainly important for these conditions.

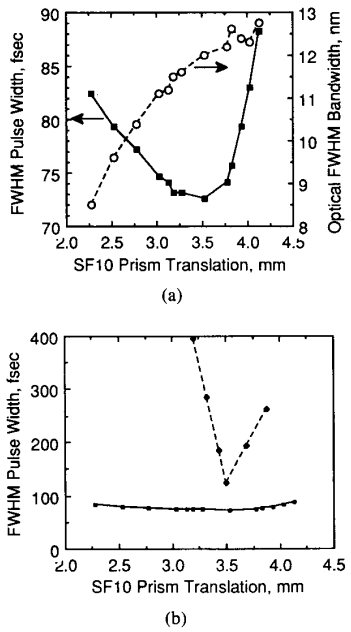


Fig. 13. (a) Pulsewidth (solid line) and optical bandwidth (dashed line) as a function of relative intracavity dispersion. At zero translation of the prism the beam is going through the apex. More negative GVD is introduced at lower prism translation. (b) Comparison of Ti : sapphire laser and CPM dye laser.

IV. Intracavity Dye-Jet Absorber and Self-Focusing Mode Locking

Dyes have been used for many years as gain and saturable absorber media for femtosecond lasers. A careful balance of gain and absorber saturation forms a short net gain window in a passively mode-locked CPM laser shown schematically in Fig. 1(a). This slow-saturable-absorber mode-locking technique has been additionally used in semiconductor diode lasers [75] and in color center lasers [76] which have comparable gain cross section to the dye lasers (Table I). Ti : sapphire is a material with an emission cross section which is about 1000 times smaller than that of laser dyes. We would expect that a laser consisting of a Ti : sapphire crystal as the gain medium and a dye jet as the saturable absorber medium would not operate like a CPM laser, since the saturation energy of the gain medium is 1000 times higher than the saturation energy of the absorber, therefore the absorber would be incapable of shaping the pulse. In spite of this, Sarukura *et al.* [43], [44] passively mode locked a Ti : sapphire with an intracavity HITCI absorber dye and produced stable sub-100 fs pulses. With no significant gain saturation in the Ti : sapphire laser, the ≈ 1.2 ns recovery time of the HITCI absorber dye is not fast enough to explain the short pulse duration.

Two regimes were exhibited by a Ti : sapphire laser incorporating a HITCI jet and two Brewster dispersion compensation prisms (Fig. 14). As the pump power is increased, a long-pulse regime is first obtained, then above a critical pump power of a few watts, a femtosecond pulse train abruptly appears. In this regime, only a very weak dye solution is required (typically 100 times weaker than a CPM laser), and the operation of the laser does not critically depend on the focusing into the dye jet as in a CPM laser.

At low concentrations the dye jet only starts the self-focusing mode locking. This can be shown in a number of ways. Sarukura *et al.* [77] have investigated the starting characteristics as a function of the dye concentration and found a direct correspondence between the starting time and the dye concentration. Although the self-starting tuning range was originally reported to be 750–820 nm, we have found that it is possible to extend this range using different dyes, or even a mixture of dyes. Fig. 15 shows the absorption spectra of HITCI and IR140 dyes. We confirmed that with only HITCI in the jet, the self-starting range is 750–820 nm as indicated, however the laser will sustain mode locking up to 870 nm if carefully tuned without introducing any perturbations. This is analogous to the weak RPM starting mechanism discussed previously, since the HITCI is effectively being "removed"

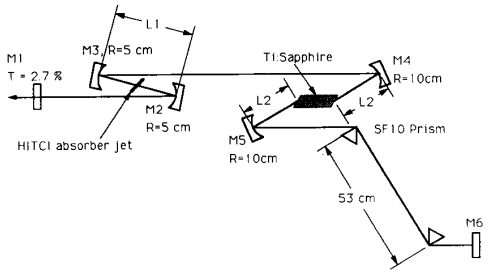


Fig. 14. Cavity setup for femtosecond Ti : sapphire laser using self-focusing mode locking and an intracavity HITCI dye jet as the starting mechanism. L_1 is ≈ 50 mm, distance M_1M_2 is ≈ 240 mm, $M_3M_4 \approx 630$ mm, L_2 is ≈ 49 mm, the Ti : sapphire crystal length is 2 cm, and the pulse repetition rate is 74 MHz.

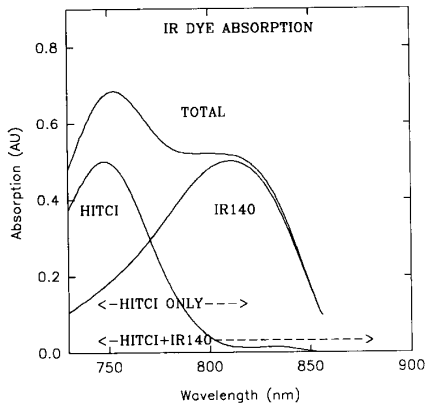


Fig. 15. Absorption of the dye saturable absorbers HITCI and IR140 with the self-starting tuning range.

by the operation of tuning to long wavelengths. Therefore, the HITCI is only self-starting the laser, and not participating significantly in the pulse shaping or the mode locking in steady state. When IR140 is added, the self-starting range is extended to 870 nm, as indicated in Fig. 15. Also by analogy with the weak-RPM starting process, we find that if the dye concentration is too high, complex unstable operation is observed, suggesting that the dye mode locking is interfering with the self-mode-locking process.

V. Conclusion

We have discussed the use of resonant nonlinearities in the mode locking of solid-state lasers. In the coupled cavity configuration, RPM operation has been explored in a regime in which the intracavity peak power is limited by the dispersion and self-phase-modulation effects are not important. This case is analogous to APM operation. A recently developed intracavity saturable absorber, an antiresonant Fabry–Perot semiconductor saturable absorber, corresponds to "monolithic" RPM [39]. This scheme is simpler and more compact than an external coupled cavity, avoids issues associated with coupled cavity length control, and will be the practical application of RPM.

When dispersion compensation is added, higher peak powers are achieved. In this case, the self-focusing becomes the dominant mode-locking mechanism and the weakly coupled quantum-well cavity becomes only a starting mechanism. Although resonant nonlinearities can, in principle, restrict the tuning range, band-gap engineering enables the tuning range to be extended significantly [37]. Finally, we discussed the closely related case of the intracavity dye jet Ti : sapphire laser in which the self-focusing mode locking is started by weak saturable absorber action. Similarly, to the broad-band semiconductor saturable absorber the self-starting range is extended by dye mixing.

In conclusion then, we have shown that the new class of widely tunable high power solid-state materials are qualitatively well understood, and the relation between various modes of operation are becoming clear. Some interesting details remain to be understood, such as mode-locking stability and dispersive limits. New materials continue to be developed and we expect that significant advances are yet to come in this field.

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Ursula Keller (M'89), for a photograph and biography, see p. 1721 of the July 1992 issue of this JOURNAL.

Wayne H. Knox was born in Rochester, NY, in 1957. He received the B.S. and Ph.D. degrees from the Institute of Optics, University of Rochester, in 1983, while performing research at the Laboratory for Laser Energetics.

He worked as a post-Doctoral member of the technical staff at AT&T Bell Laboratories, Holmdel, NJ, from 1984 to 1985 and is now a member of the technical staff in the Photonic Switching Device Research Department. His research interests include the physics of semiconductors and defects in insulating and semiinsulating crystals, nonlinear optics, femtosecond spectroscopic and optoelectronic measurements, and coherence properties of optical fields.

Dr. Knox is a member of the Optical Society of America, the American Physical Society, and the Lute Society of America.

Gert W. 'tHooft was born in Hooge Zwaluwe, The Netherlands, in 1952. He received the B.S., M.S., and Ph.D. degrees in physics from the State University Leiden, Leiden, The Netherlands, in 1972, 1974, and 1978, respectively.

In 1979 he joined Philips Research Laboratories, Eindhoven, The Netherlands, to work on the characterization of III–V compounds for optoelectronic applications. Since 1985 he has been involved in the development and application of ultrashort spectroscopy. During 1990–1991 he spent a sabatical year at AT&T Bell Laboratories, Holmel, NJ.