Coupled-cavity resonant passive mode-locked Ti:sapphire laser

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We use a nonlinear quantum-well reflective sample in a coupled-cavity configuration for resonant passive mode locking of a Ti:sapphire laser, producing tunable pulses as short as 2 psec. Pulses of less than 10-psec duration are observed over a 50-nm wavelength tuning range using a single-quantum-well reflector, over approximately 2 mm of external cavity length detuning. Stable mode-locked pulse trains are obtained without active cavity length control; however, the optical spectrum depends on the phase. We generate up to the sixth harmonic of the fundamental repetition rate, at 1.2 GHz, by simply decreasing the external cavity length.

Coupled-cavity resonant passive mode locking[1] (RPM) is a new and simple technique to passively mode lock laser media with a small gain saturation cross section, such as Ti:sapphire and Nd:YLF. For these lasers the cross section is small, making intracavity saturable absorber mode locking problematic. We simply add to a cw-pumped Ti:sapphire laser an external cavity with a nonlinear quantum-well reflector (Fig. 1). We call this laser resonant passive mode locked because of the resonant nonlinearity used in the external cavity. Without any dispersion compensation and any active stabilization of the external cavity, we generate stable pulses as short as 2 psec and demonstrate tuning over a 50-nm wavelength range using a single-quantum-well reflector.

The soliton laser[2] is an early example of ultrashort-pulse generation by coupled-cavity mode locking, in which the nonlinear external cavity medium 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, referred to as additive-pulse mode locking[3,4] (APM) or coupled-cavity mode locking,[5] where the pulse formation is based on a nonlinear phase effect with constructive interference at the peak of the pulse and destructive interference in the wings. Therefore, an APM requires interferometric ($\leq\lambda/10$) stabilization of the external cavity length for stable pulse train formation. Recently, an APM Ti:sapphire laser generated 1.4-psec pulses, which were then compressed to 200 fsec with an external grating pair.[6] We first discuss our experimental results, then the operation mechanism of RPM, and conclude with some possible extensions.

We introduce a simple new embodiment of the general concept of coupled-cavity mode locking, in which a cw-pumped gain medium is placed in a high-Q main cavity, and the external coupled cavity contains a near-resonant optical nonlinearity provided by a semiconductor mirror device. A Ti:sapphire laser (Spectra-Physics Model 3900) pumped by a cw argon-ion laser is coupled to an external cavity with a quantum-well reflector[7] as the end mirror (Fig. 1). We used a 5× microscope lens to focus the beam to an $\approx$30-μm spot diameter. Either a pellicle or a folding mirror inside the external cavity was used as the output coupler. The nonlinear reflector was a conventional GaAs/GaAlAs quantum-well structure, which was antireflection coated, and incorporated a AlAs/GaAlAs dielectric mirror centered near 850 nm. The undoped multiple-quantum-well region consists of 75 periods of 9.5-nm-wide GaAs quantum wells and 4.5-nm-wide $GaAl_{0.3}As_{0.7}$ barriers for which the cw exciton saturation intensity at zero bias was measured to be 5–10 kW/cm^2.[8]

We use a real-time noncollinear autocorrelator, a fast photodiode with a sampling scope, and a rf spectrum analyzer for our diagnostics. Without the use of active cavity length stabilization we generate stable 2.1-psec pulses (assuming a sech^2 pulse shape) for which the real-time autocorrelation trace is shown in Fig. 1. The repetition rate was $\approx$250 MHz, and the average output power for the stronger beam was $\approx$90 mW using a 10% output coupler. A clean single pulse train was verified with a fast detector and a sampling scope. The laser operates in a TEM_{00} mode (also verified with a rf spectrum analyzer). The mode locking always self-starts without any problems. We be-

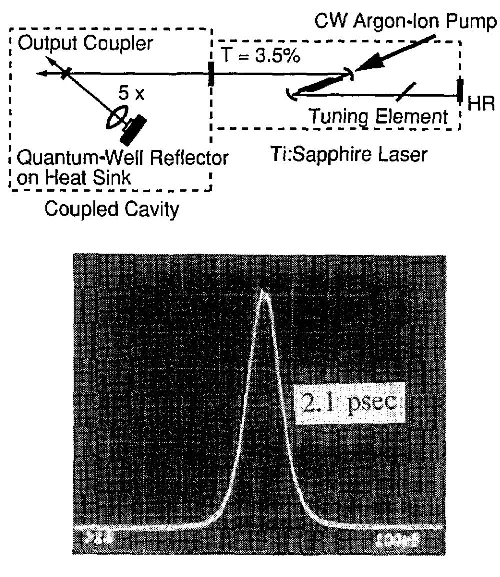

Fig. 1. Cavity design and autocorrelation trace for a 2.1-psec pulse assuming a sech^2 pulse shape. HR, highly reflecting mirror.

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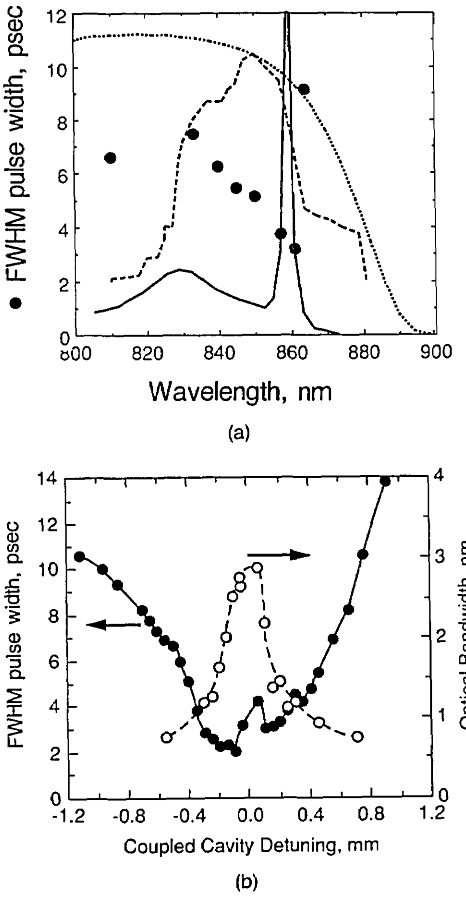

Fig. 2. (a) 50-nm tuning range with less than 10-psec pulses (filled circles). Superimposed onto the graph are the normalized cw output power of the Ti:sapphire laser (dashed curve), the *in situ* luminescence with scattered lasing wavelength at 860 nm (solid curve), and the normalized reflectivity of the AlAs/AlGaAs reflector (dotted curve). (b) The pulse width and optical bandwidth versus external cavity length detuning.

lieve that the self-starting behavior is efficient in the RPM laser, because the quantum well provides an integrating nonlinearity, as opposed to the instantaneous Kerr-type nonlinearity typically used in the APM laser. A low coupling between the two cavities ($T \approx 3.5\%$) was important. Increasing the coupling to 10% increased the pulse width to more than 100 psec.

We achieved a 50-nm tunability by simply rotating a two-plate birefringent tuning plate in the Ti:sapphire laser. Figure 2(a) displays the pulse width as a function of wavelength (filled circles). Superimposed onto this graph are the normalized cw output power of the Ti:sapphire laser cavity alone (dashed curve), the *in situ* measured luminescence from the quantum-well reflector that includes the scattered lasing wavelength near 860 nm (solid curve), and the normalized low-intensity reflectivity of the dielectric semiconductor mirror (dotted curve). Figure 2(a) shows that the 50-nm tunability was primarily limited by the tuning range of the Ti:sapphire mirror set and that the shortest pulse durations are obtained at wavelengths slightly below (a few tens of millielectron-volts) the luminescence peak.

We were able to detune the external cavity length over approximately 2 mm and still achieve pulse durations below 10 psec [Fig. 2(b), filled circles]. The repetition rate, monitored on the rf spectrum analyzer, was changing in the kilohertz regime for millimeter changes in the external cavity length. At exact cavity length matching the laser strongly fluctuates, and no stable mode locking is observed. This shows up in Fig. 2(b) with longer pulse durations at matched cavities, because it was required to average the autocorrelation trace over many scans. In comparison, an APM laser generates mode-locked pulses only for cavity detunings of $\approx 10\ \mu m$.[6]

The pulse width was not sensitive to the argon-ion pump power. By varying the pump power to the Ti:sapphire laser from 6 to 10 W, the pulse duration first decreased slightly to a minimum of 5 psec at ≈ 7 W of power and then increased to 7.5 psec at ≈ 10 W of pump power at a cavity detuning of +0.5 mm.

Figure 2(b) (open circles) displays the time-averaged optical bandwidth as a function of cavity length detuning. By periodically detuning the external cavity by only a fraction of a wavelength, we achieve stable autocorrelation traces; however, the optical spectrum depends on the length of the external cavity (Fig. 3). The external cavity length was changed by a maximum of 0.2 μm by applying a slowly varying sawtooth voltage signal to the piezo transducer that controls the external cavity length. The optical spectrum continuously adjusts itself over a 3.4-nm tuning range in order to maintain stable mode locking, while the actual spectral width ranges between 0.5 and 0.9 nm. The 3.4-nm tuning range depends on the cavity length detuning and is determined by the time-averaged spectral width [Fig. 2(b)]. The resolution of the optical multichannel analyzer used for this measurement was less than 0.3 nm.

We believe that the resonant nonlinearity in coupled-cavity mode locking yields a new mode of operation. The laser operates in stable mode-locked pulse trains by self-adjusting its optical frequency in response to phase shifts due to external cavity length variations, which is, in fact, a simple property of a

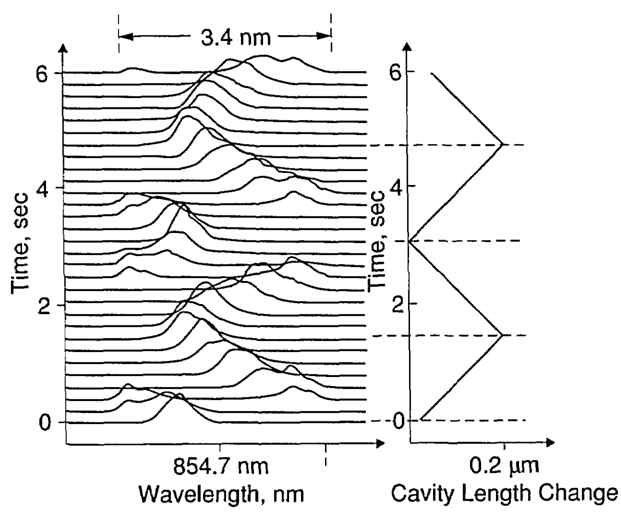

Fig. 3. Optical self-frequency shift versus the external cavity length detuning that ensures coherent superposition of the pulses at the coupling mirror.

linear Fabry–Perot coupled cavity. The near-resonant amplitude nonlinearity is distinctly different from the nonresonant Kerr-type nonlinearity used in previous techniques. APM lasers operate with a pure phase nonlinearity.[3–6] In contrast, our results suggest that in RPM the primary pulse-forming mechanism is based on an amplitude nonlinearity. To this end, we have demonstrated the non-APM operation of our laser.[1] We believe that the quantum-well reflector generates a rapid amplitude modulation[9] that is responsible for the pulse-forming mechanism. The intensity on the reflector is estimated to be $\approx$110 kW/cm^2, which is well above the cw exciton saturation intensity. Gain saturation is most likely negligible because the fluence per pulse is only approximately 0.3% of the saturation fluence of Ti:sapphire ($\approx$0.6 J/cm^2), assuming a 30 μm $\times$ 50 μm elliptical beam waist inside the Ti:sapphire rod.[10] In the case of a nonlinearity with a rapid partial recovery, gain saturation is not necessary for stable mode locking. This operation is between the two limits discussed by Ippen *et al.*[11] RPM operation is not obtained with a Kerr medium in the external cavity, because in APM lasers the phase (the external cavity length) corresponding to maximum power is not the same phase as that for stable mode locking and self-starting.[12]

Initially motivated by the large time-averaged spectral width [Fig. 2(b)], we added a prism pair for dispersion compensation (SF-11 prisms spaced by 40 cm) inside the Ti:sapphire laser cavity to correct for the positive dispersion of the Ti:sapphire rod and possibly to generate femtosecond pulses. In the case of a passively mode-locked Ti:sapphire laser with an intracavity absorber dye jet, the prism-pair compensator compressed the pulses from 10 psec to 190 fsec (Ref. 13); however, in our case we were not able to achieve significantly shorter pulses with an intracavity prism pair, because, as demonstrated in Fig. 3, in reality the pulses have a much narrower optical bandwidth than the time-averaged spectrum [Fig. 2(b)] would have implied. Using an external grating pair for further pulse compression, we generated some preliminary subpicosecond pulse durations of $\approx$700 fsec, which requires an $\approx$1-nm spectral width assuming a sech^2 pulse shape. If required, the spectrum could be locked with an active cavity length stabilization scheme that is controlled by a detector behind a wavelength-selective element.

The pulse repetition rate is determined by the external cavity length, provided that it is matched within a few millimeters to an integer fraction or multiple of the main cavity length. By successively decreasing the external cavity length to an integer fraction of the main laser's cavity length, we produced pulse repetition rates up to the sixth harmonic (1.17 GHz) of the fundamental repetition rate (194 MHz). For mechanical reasons, we had to extend the Ti:sapphire cavity length from $\approx$250- to $\approx$190-MHz repetition rate. The average output power remained constant. For all harmonics the fundamental mode beating signal was suppressed by more than 40 dB.

The full tuning range of the Ti:sapphire laser from 700 nm to above 1000 nm could be reached by bandgap engineering of the quantum-well reflector. Several different reflectors could then be mounted on the same heat sink. By actively heating or cooling the sample, one can achieve a fine wavelength tuning for the optimum pulse duration. We have not attempted to optimize the output power. We believe that the focusing lens and the thickness of the nonlinear quantum-well reflector can be custom designed for maximum output power and shortest pulses.

In conclusion, we introduce a completely new and extremely simple technique of short-pulse generation. Stable autocorrelation traces were generated without any active cavity length stabilization. The RPM Ti:sapphire laser self-stabilizes its operation by small optical frequency adjustments. An advantage of RPM is its extremely low complexity with a compact bulk nonlinearity that requires no critical alignment. The repetition rate can easily be changed by choosing different external cavity lengths. Another advantage is that the near-resonant nonlinearity can be custom designed by band-gap engineering, different thicknesses of the nonlinear absorber layer, and different focusing lenses.

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