Passive mode locking of a semiconductor diode laser

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By using a GaAs/GaAlAs multiple-quantum-well sample as a saturable absorber in an external resonator, we have passively mode locked a GaAs laser to obtain pulses as short as 1.6 psec, the shortest pulses ever observed to our knowledge from a mode-locked diode laser in a regulator pulse train.

Mode-locked semiconductor diode lasers are, in principle, capable of emitting trains of very short optical pulses. Such sources would be ideal for future pulse-modulated high-speed optical communications systems, and much effort has been devoted to understanding the physical principles involved in mode locking these lasers. A fundamental problem for passive mode locking has been the identification and characterization of a suitable saturable-absorber element. In this Letter we describe the use of a GaAs/GaAlAs multiple-quantum-well (MQW) structure to produce the first reported stable passive mode locking of a diode laser with an external saturable-absorber element.

Most previous attempts to mode lock diode lasers with a saturable absorber have utilized absorption produced by optical damage. By aging a laser to the point of severe degradation, pulses as short as 5 psec have been obtained for a short time before laser failure.[1] Bursts of subpicosecond pulses have been obtained with aged lasers[2] or by proton bombarding one end facet of a laser.[3] Recently, 35-psec pulses were produced in a GaAlAs laser with nonuniform current injection.[4]

In order to study the physical characteristics of a material for use as a saturable absorber, it is desirable to have a configuration in which the absorber is completely independent of the laser structure. In this way one can study the physical mechanisms of absorber saturation and recovery and tailor the absorber to act effectively to mode lock a diode laser.

Haus[5] has analyzed the conditions necessary for mode locking a homogeneously broadened laser with a saturable absorber having a relaxation time longer than the pulse width. He showed that the relaxation time of the absorber must be faster than that of the gain and that one must have

$$\sigma_A/A_A > \sigma_G/A_G, \tag{1}$$

where σ_A and σ_G are the cross sections of the absorber and gain media, respectively, and A_A and A_G are the cross-sectional areas of the laser beam in the absorber and gain media.

The nonlinear optical properties of GaAs/GaAlAs MQW structures in the vicinity of the room-temperature exciton resonance were recently studied extensively.[6] It was found that optical saturation of the exciton absorption was caused by the screening effect of the optically created carriers and that this saturation took place at optical intensities more than a factor of 10 lower than those required to saturate the band-to-band transition. Thus for a MQW absorber we have $\sigma_A \gg \sigma_G$. The recombination time of photoexcited carriers in the MQW sample is much longer (~30 nsec) than the gain recovery time (~2 nsec). In order to reduce the absorption recovery time below 2 nsec, the light beam must be tightly focused on the absorber. The diffusion of carriers out of this excited region then determines the recovery time. For diffusion-dominated recovery we expect that

$$\tau = r^2/C, \tag{2}$$

where τ is the recovery time, r is the radius of the excited spot, and $C = \gamma D$, where D is the diffusion constant and γ is a geometrical constant that depends on the beam shape. From the measurements reported in Ref. 6 we find that $C \simeq 10\ \mu m^2$/nsec for Gaussian beams in GaAs/GaAlAs MQW material.

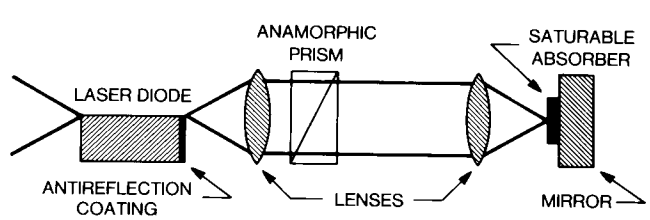

Fig. 1. Experimental setup.

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Experiments were performed using the setup shown in Fig. 1. The commercial GaAs laser diode (Hitachi HLP-1400) was modified by an antireflection coating on one facet. Measurements of output spectra showed that the remaining reflectivity was less than 10^{-3}. The anamorphic prism served to convert the output beam to one with an approximately circular cross section. The MQW absorber consisted of 47 periods of 9.8-nm GaAs layers alternated with 9.9 nm of $Ga_{0.71}Al_{0.29}$ As layers grown by molecular-beam epitaxy on top of a 1-μm $Ga_{0.71}Al_{0.29}As$ etch-stop layer on a GaAs substrate. This sample was epoxied to a high-reflectivity dielectric mirror on a sapphire substrate, and the GaAs substrate was removed by a selective etch. The exposed surface of the MQW absorber was antireflection coated. The reflectivity versus wavelength of the mirror–MQW assembly as measured with a tunable dye laser is shown in Fig. 2. The form of the saturation is in good agreement with transmission measurements.[6] The unsaturated reflectivity of the mirror–MQW assembly was 0.25 at the peak of the exciton resonance (846 nm), and it increased to ~0.50 at the pulse-power levels in the laser resonator under mode-locking conditions.

An 8-mm focal-length lens was used to focus the light onto the MQW absorber. We estimate the spot radius to be ~2 μm at the MQW, which, from Eq. (2), should result in a 0.4-nsec absorption recovery time. The total length of the laser was ~30 cm. By making a small change in the lens–absorber spacing, the chromatic aberrations of the lens–prism combination could be used to tune the laser otuput over a wide spectral range. The output light from the rear facet of the laser diode was simultaneously monitored with a fast photodetector, an optical multichannel analyzer, and a second-harmonic autocorrelator.

Stable mode locking was obtained at currents near the laser threshold. Pulses as short as 1.6 psec were observed. The average output power was ~1 mW. Both single and double pulsing per transit time, i.e., pulse repetition rates of ~0.5 or ~1 GHz, could be achieved. Figure 3 shows second-harmonic autocorrelation traces of some of the pulses observed. Incomplete mode locking resulted in very wide pulses, typically 50–100 psec long, as shown in Fig. 3a. The autocorrelation traces were characterized by many coherence spikes, separated by 8 psec, which corresponds to a round trip in the laser diode. Note that, although the reflectivity of the antireflection-coated facet was lower than 0.1%, it could have a major effect on the lasing characteristics. Better alignment yielded much shorter pulses, typically 3 psec long. Such pulses often displayed a three-peak autocorrelation trace, similar to that shown in Fig. 3b, suggesting that the main pulse is accompanied by a weaker satellite pulse. Similar behavior was reported recently for actively mode-locked diode lasers.[7] The satellite pulse is 10 psec away from the main pulse, which is close to, but not exactly equal to, the round-trip time in the diode. The shortest pulses, as shown in Fig. 3c, were observed very close to threshold, and they were extremely sensitive to the system parameters.

The observed spectral width of the mode-locked laser output was typically 3.0 nm, which is about five times wider then the transform limit of our shortest pulse. Optimal pulsing was obtained when the central lasing wavelength was about 5.0 nm above the *room-temperature* exciton absorption peak. We did observe, however, a shift of the absorption peak when the laser was operating, probably resulting from local heating of the

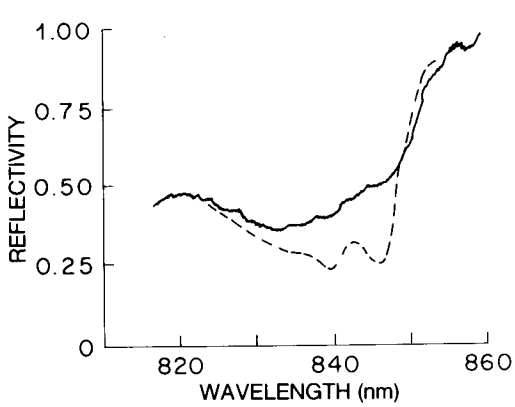

Fig. 2. Reflectivity of MQW–mirror assembly as a function of wavelength. These measurements were taken using a tunable dye laser with a beam that is focused to a 3-μm-diameter spot. The dashed line is the result for an input power of 34 μW and shows the unsaturated reflectivity. The solid line is the result for a power level of 2.5 mW, which corresponds approximately to the saturation under mode-locked conditions.

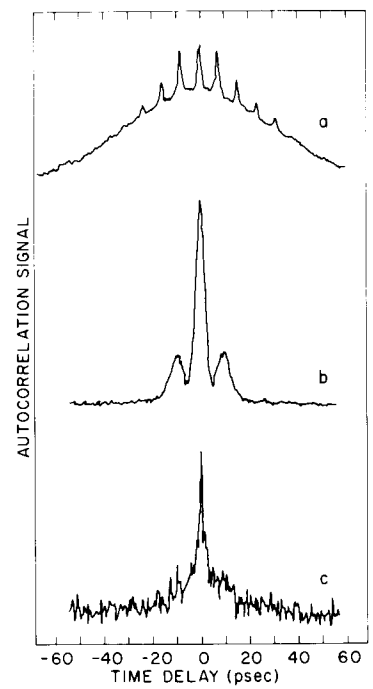

Fig. 3. Autocorrelation traces of the mode-locked laser output. a, Incomplete mode locking; 50-psec-long pulses with superimposed coherence spikes. b, Better mode locking; 3.3-psec pulses accompanied by a satellite. c, The shortest pulses observed; 1.6 psec long. The given pulsewidths were derived from the autocorrelation traces assuming Gaussian pulse shapes.

MQW. The observed shift was +4 ± 1 nm, implying that optimum mode locking occurs when the laser wavelength is very close to the exciton peak.

With most of our samples, it was possible to observe mode locking when any part of the sample was used. The narrowest pulses were observed when the laser beam was focused upon certain specific points on the MQW surface. These points were characterized by higher laser thresholds. We believe that these points may be defects that result in fast recombination of excited carriers.

In conclusion, we have described the use of a GaAs/GaAlAs MQW to produce the first reported stable passive mode locking of a diode laser with an external saturable-absorber element. We have observed the shortest laser-diode pulses ever produced to our knowledge in a regular pulse train (1.6 psec).

We are now investigating the effect of reduced carrier recombination times on the absorption saturation. This will permit the use of larger spot sizes, giving us more control of the relative gain and loss saturation and permitting mode-locked operation at higher laser-power levels.

Some of the research of P. W. Smith and D. J. Eilenberger was performed at AT&T Bell Laboratories, Holmdel, New Jersey.

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