Modelocked picosecond pulses from 490 nm to 2 μm with optically pumped semiconductor lasers

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Abstract

We describe tunable cw modelocked laser action from synchronously pumped CdS, CdSSe, CdSe, InGaAsP and HgCdTe lasers[1-4]. The 2-50 μm thick semiconductor platelets are longitudinally pumped and have produced 40 mW at 495 nm unmodelocked and a peak power of 50 Watts modelocked at 1.2 μm. Pulsewidths of 4-6 ps with time-bandwidth products of 0.6-1.7 are obtained using intracavity etalons and Lyot filters. Intracavity tuning achieves a single crystal range of 7 nm in CdS at 495 nm, 29 nm in InGaAsP at 1.2 μm and a range of 60 nm in HgCdTe at 1.8 μm. As many as two dozen crystals have been mounted together on a micrometer stage within the dewar to allow an immediate and wide tuning range. Also tuning from 1.82 to 2.0 μm via the Burstein-Moss shift in a single HgCdTe epilayer has been accomplished by varying the loss in the external cavity. A modelocked threshold as low as 0.3 mW in CdS, a 20% conversion efficiency into the TEM_{00} mode, and lasing in InGaAsP with optical pumping a full 1.5 eV above a 1 eV bandgap shows that an efficient and convenient picosecond source tunable through the visible and near infrared is feasible.

Introduction

Optically pumped semiconductor lasers have the advantage over diode lasers that virtually any direct-bandgap semiconductor can be used. This allows the tuning range to be easily tailored. Dye lasers though effective in the visible have had a slow development beyond 1 μm due to dye instability problems[5,6]. F-center[7,8], Alexandrite[9,10], and transition-metal-doped solid state lasers[11] have appeared, but only the optically pumped semiconductor laser can tune the whole range from 490 nm to 2.0 μm.

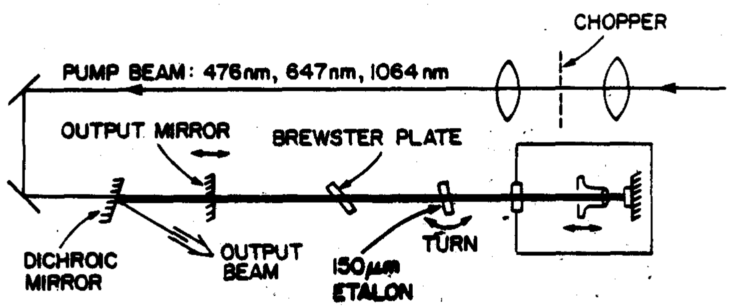

Figure 1. Cavity Design

Figure 1 displays the linear cavity for synchronously pumped modelocking showing a brewster plate to control the laser polarization with LPE grown crystals, an intracavity etalon used for tuning and bandwidth limitation, and a pump beam telescope to correct for chromatic aberration in the intracavity 10X microscope objective. The dewar was operated with liquid nitrogen, or liquid helium which was especially desirable between 1.8 and 2.0 μm.

A modelocked slope efficiency of 31% is shown in Figure 2 and demonstrates the effectiveness of the cavity at 495 nm. The microscope objective exhibits a round trip loss of 33% at 1.7 μm, limiting the laser efficiency in the infrared. Figure 3 shows the output versus input power for a 1.2 μm InGaAsP crystal operating unmodelocked in the lossy cavity, revealing a maximum pump power equal to only twice the threshold power. Overheating the small pump spot (<10 μm diameter) usually results in damage, but this is easily accomodated by sliding to a new spot on the crystal. A maximum unmodelocked output power of 40 mW was obtained from a CdS ring laser[12] using an objective on either side of the crystal, wherein also an interesting damage effect was observed. The presence of the intracavity laser beam, as noted by aligning the cavity, greatly accelerated the degradation of the pumped spot of the CdS crystal, when using large pump powers.

The binary crystals were more tolerant of high average pump powers which suggests an improved thermal conductance contributed to by the intrinsically large thermal conductivity of the binary crystals. Figure 4 shows a shift in the laser wavelength versus time, due to heating, for a single InGaAsP platelet.

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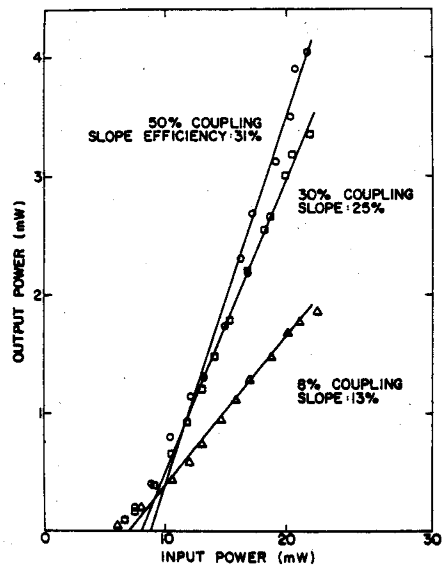

Figure 2. Modelocked Efficiency: CdS

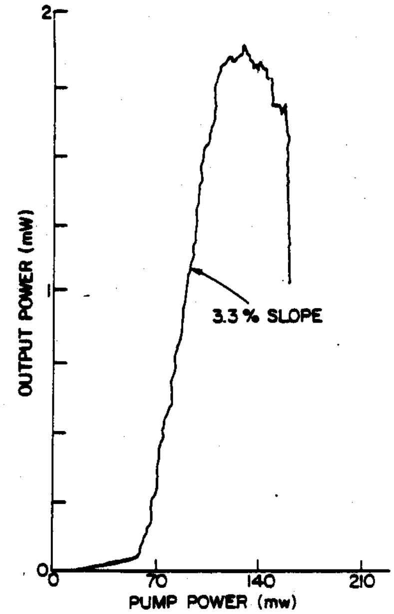

Figure 3. Unmodelocked Efficiency: InGaAsP

The addition of an InP cladding layer improves the transverse thermal path which is somewhat blocked in the longitudinal direction by an oil layer which attaches the crystal to the sapphire endmirror. Figure 5 reveals the rapid wavelength and therefore temperature stabilization.

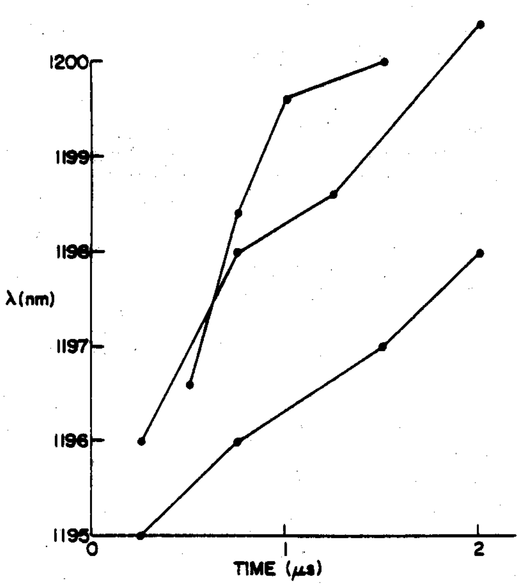

Figure 4. InGaAsP Heating

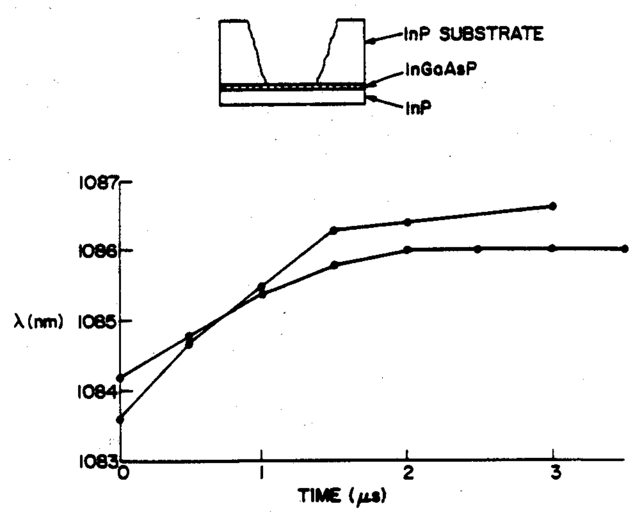

Figure 5. Improved Thermal Behavior

The peak output power observed using a chopped pump beam was about 50 watts modelocked at 1.2 μm in CdTe. However the production of short pulses with large pump powers is accomplished here with a mismatched cavity, which produces a greater gain saturation when the returning laser pulse is delayed. Figure 6 shows the optimum cavity-length mismatch, for producing the maximum output power at 1.8 μm, versus input power. Here a matched cavity length is assumed to yield the minimum laser threshold. The short pulses are produced rapidly in 20 to 30 round trips by repeated noise amplification and by the progressive time shift [13]. Also the observed linewidth corresponds to broadband noise filtered by a few dozen passes through the intracavity bandwidth.

The shortest pulses produced were 3.9 ps with a $\Delta\nu\Delta t = 1.7$, using a Lyot filter. In the infrared a 125 μm thick uncoated glass etalon resulted in 6.5 ps pulses with a $\Delta\nu\Delta t = 0.6$ as shown in Figure 7. The cavity length insensitivity shown in Figure 8 allows easy adjustment of the laser (note that the point of zero mismatch is arbitrary), though it has been demonstrated [13] that true modelocking can occur only over a cavity length variation of less than 50 μm for this laser.

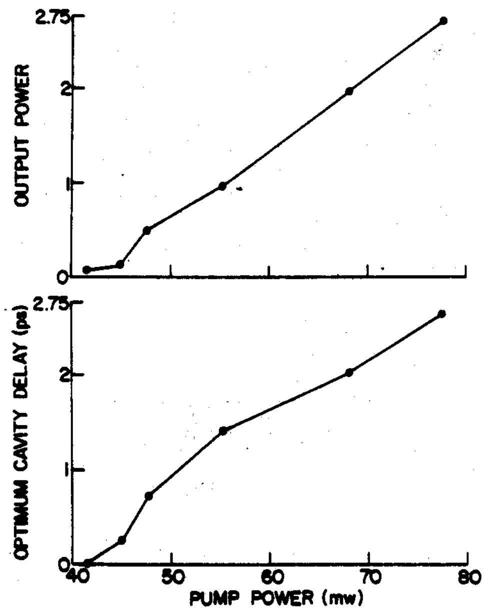

Figure 6. Optimum Cavity Length Mismatch: HgCdTe at 1.8 μm

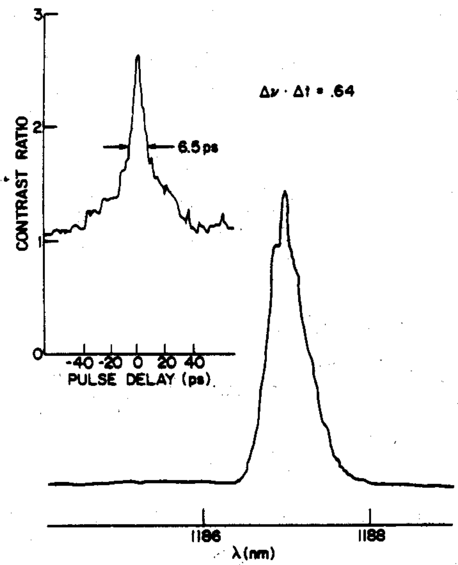

Figure 7. InGaAsP Time-Bandwidth Product

One advantage in using this external cavity laser is that it can be smoothly tuned with an etalon, prism or Lyot filter, in addition to moving to different spots on the crystal as is done with an ultrashort cavity laser [14]. The ultrashort cavity itself is simpler though it further necessitates a powerful subpicosecond pump source to produce 6 ps pulses [15]. The intense excitation produces a Burstein-Moss shift which permits a wider tuning range but also creates a strong chirp [16] in the output as the laser starts from noise for each pulse. This results in a larger time-bandwidth product than is produced by synchronous pumping of the external cavity laser. The external cavity is self-injected by the previous laser pulse and can produce [illegible] pulses by gentle repetitive gain modulation.

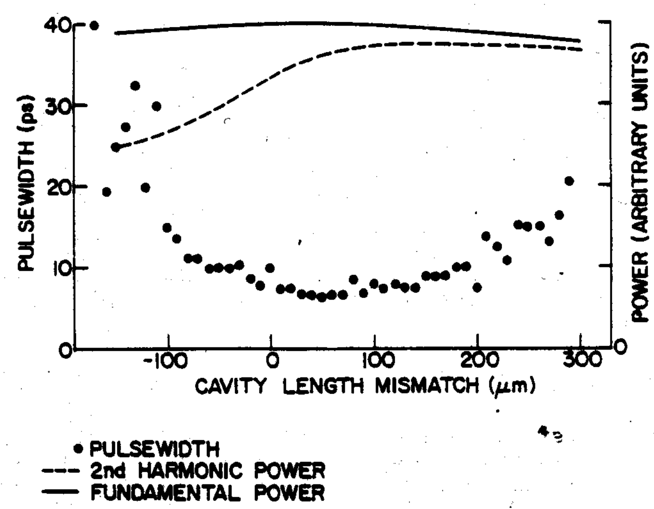

Figure 8. Cavity Length Sensitivity: InGaAsP

Lasing in the ultrashort cavity formed by the crystal platelet between the cavity end-mirror and the crystal front surface was observed occasionally in InGaAsP. Figure 9 shows two lasing spectra obtained from the same spot on an InGaAsP crystal, and with the same average pump power, but with the pump modelocked in one case and unmodelocked in the other. A broad spectrum is produced by the 125 ps-long pump pulses in the ultrashort cavity.

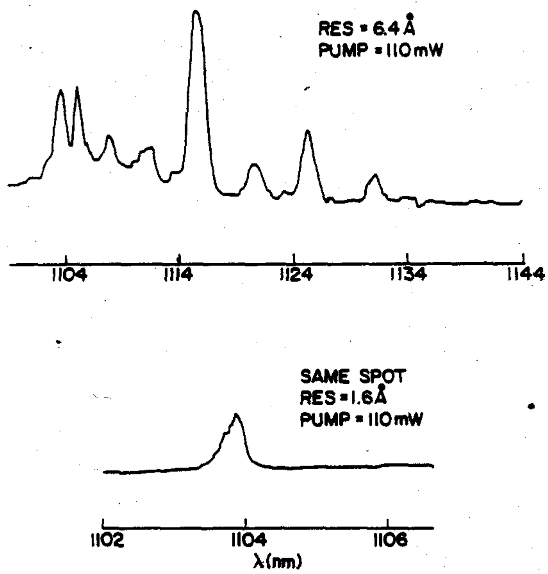

Figure 9. Ultrashort Cavity Lasing: InGaAsP

Pulse chirp has also been observed in the modelocked external cavity laser by a modified autocorrelator. A monochromator was inserted between the 2nd harmonic crystal and the photomultiplier, and the "pulsewidth" was observed as a function of the monochromator detuning. Figure 10 shows 10 ps pulses with the monochromator centered on the 2nd harmonic spectrum. Detuning the monochromator reduces the apparent pulsewidth to a minimum of 3 ps. The low frequency portion of the 2nd harmonic spectra which shows the 3 ps pulse is produced only by the low frequency components of the original pulse, whereas the center portion of the 2nd harmonic spectra is produced by both the center and combined high and low frequencies of the original pulse. A chirped pulse can produce the effect observed in Figure 10, as induced by group velocity dispersion or possibly a time varying Burstein-Moss shift in the semiconductor crystal. Figure 11 shows an intracavity pulse compressor used with the modelocked InGaAsP laser. The etalon has a ~100% back reflector, a front reflector of 4% and a piezoelectrically controlled 50 μm air gap. Without internal loss the etalon is intended to exhibit frequency dependent phase, without frequency dependent loss[17]. The result was a series of three 2 ps pulses, suggesting that some pulse compression was accomplished, though the pulses were subsequently too short to adequately saturate the gain.

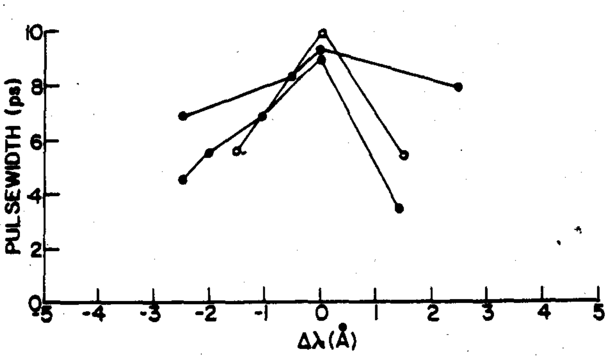

Figure 10. Autocorrelator Modified to Observe Chirp

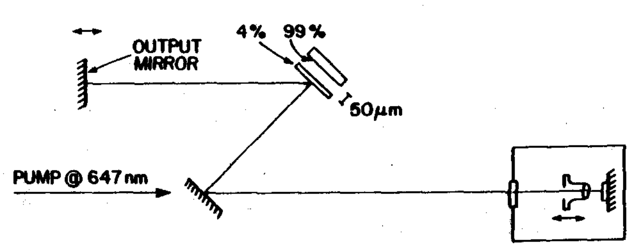

Figure 11. Intracavity Pulse Compressor: InGaAsP

The above-bandgap pump source is probably absorbed within a few microns of the surface and Figure 12 suggests that the penetration of the excited carriers is less than 10 μm. The shift in lasing wavelength towards the red with increasing thickness is due to the loss in the unpumped portion of crystal. A large jump in wavelength seems to occur at a thickness of less than 10 μm. Figure 13 shows the modelocked lasing spectrum of HgCdTe on a CdTe substrate displaying numerous etalon modes. The optical thickness is calculated based on the mode spacing and shows a strong increase at the high frequency side. This corresponds to the optical loss from the unpumped region of the <10 μm thick HgCdTe crystal.

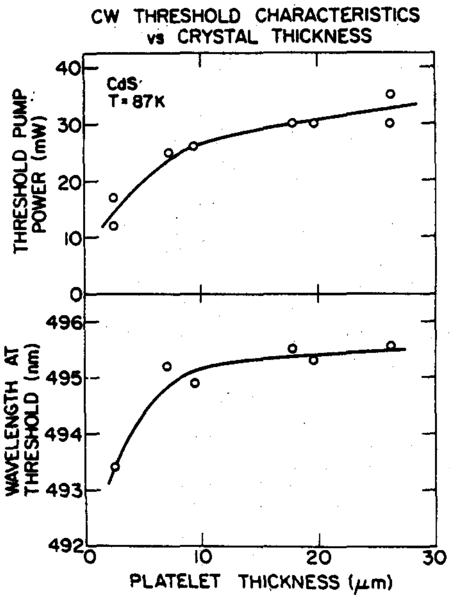

Figure 12. Pump Penetration: CdS

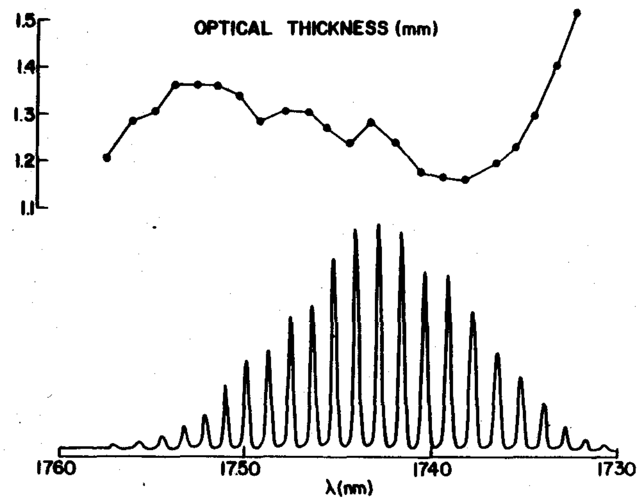

Figure 13. Short Wavelength Absorption: HgCdTe

Mounting many crystals to tune from 490 nm to 2 μm necessitates a rather broadband dielectric mirror. However CdS has been modelocked adequately with an aluminum mirror sputtered on its back surface, and epoxied to a copper heat sink. Though aluminum makes an unsatisfactory mirror against a high index material, a single $\lambda/4$ SiO_2 layer would correct this. Similarly gold mirrors are appropriate for the longer wavelength crystals.

A limitation to the tuning range of this laser is Auger recombination which increasingly becomes a problem for higher electron densities and longer wavelengths, though the effect is lessened by lowering the temperature. The design of the laser yields a gain path of only 2-3 μm which demands a large inversion density, unless the optical loss in the cavity can be kept extremely low.

We have described a modelocked picosecond source that is tunable and has operated in the range from 490 nm to 2 μm using CdS, CdSSe, CdSe, InGaAsP and HgCdTe. The laser exhibits a TEM_{00} output beam, is reasonably efficient, and can readily accept an assembly of direct-bandgap semiconductor platelets. The laser may be tailored to a specific wavelength region or spread across the entire visible and near infrared spectrum.

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