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MODE LOCKED FIBER LASERS AND THEIR APPLICATIONS

KJT, Inc

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13. ABSTRACT *(Maximum 200 words)*

A modelocked fiber laser design was fabricated and tested at Rome Laboratory. Significant features are a fully integrated portable assembly and complete freedom from polarization sensitivity. A remarkable low threshold power of 50 mw enables use of single element laser diode pumping. Extensive optimization of the Multiple Quantum Well Saturable Absorber has resulted in stable 10 pico second pedestal free modelocked pulses in a passive self-starting configuration. Active modelocking was also investigated but was found to generate longer pulses. Synchronization with a second fiber laser was demonstrated to increase the repetition rate by more than order of magnitude. Soliton pulse shaping in the cavity is indicated but requires further work to establish. The signal pulses are transform limited and can support data rates exceeding the limitations of present state of the art diode based laser sources.

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1.0 Introduction

Presently, ultra-fast TDM is limited by the availability of a compact, short-pulse source that is directly compatible with fiber coupled modulator technology. Fiber laser signal sources possess several significant advantages over established diode laser technology. The pico second and sub-pico second pulse widths achievable in fiber lasers are significantly shorter, allowing more efficient use of the full bandwidth available from single mode fiber. The wavelength region and configuration of fiber based lasers are inherently compatible with fiber amplifier technology, thereby greatly facilitating compensation for the distribution and splitting losses encountered in practical systems. Finally, nonlinear soliton type pulse generation and shaping in a fiber can be achieved naturally and can be designed to minimize dispersion induced limits experienced by all fiber systems at the bit rates required by the next generation of communication systems.

Work done by us under previous contracts has been primarily directed towards developing a short pulse fiber laser using a multiple quantum well saturable absorber based on InAlAs/InGaAs structures as a passive mode locker. Using this approach, we have demonstrated the possibility of constructing a rugged, stable, and efficient source of 10 ps. pulses at a repetition rate of about 3.5 MHz. A critical factor in this work has been the reproducibility of the multiple quantum well structure used to mode lock the laser. The proper linear transmission and saturation flux at the laser operating wavelength are required for short pulse duration and a low pump power threshold. These factors have proven difficult to optimize. In order to obtain the information needed to control these parameters during the growth of the structures, correlated measurements of the linear and non linear transmission and mode locked pulse duration in as wide a range of samples as possible were continued as part of this contract.

Furthermore, passively mode locked lasers tend to be subject to pulse frequency jitter, pulse amplitude fluctuations and CW background which can limit their usefulness in high speed communications applications. An analysis of these effects and the limitations they impose on passively mode locked fiber lasers was begun during the present contract. Of particular interest was the degree to which these types of noise can be reduced using a synchronized laser scheme reported on earlier.

2.0 Results

2.1 A Passively Mode Locked Erbium Fiber Laser for Field Use

Work done by us has resulted in an extremely stable laser design which is fiber integrated, rugged, and completely free of alignment and polarization sensitivity.[1,2] The entire system can be enclosed in a 2x3x5 in. package. This linear cavity laser uses fiber gratings to determine the operating wavelength, is passively mode locked with a quantum well saturable absorber and is completely self-starting with a pump power requirement of only 40 mW in the fiber. This is to our knowledge the lowest pump power reported for such performance, and permits operation with standard compact cost effective 980 nm laser diode chips, in marked contrast to the multi stage pump diodes, Ti:Sapphire pumped systems or bulk type Nd-YAG (YLF) lasers generally used in recently reported ultra-short pulsed TDM applications. The pulse width achieved in our laser is 10 picoseconds, corresponding to a potential system limit of 5 gigabits.

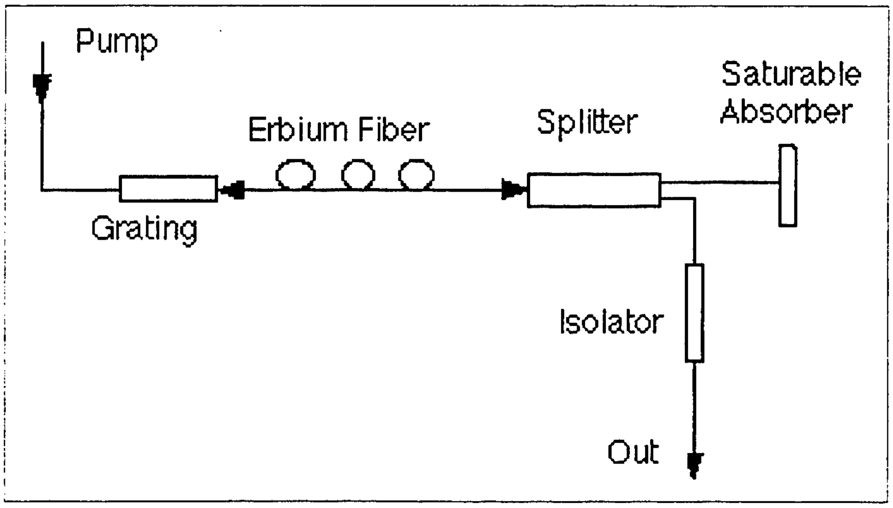


Fig. 1. Fiber laser Design

The laser is based on the linear cavity design shown in Fig.1. Here the Erbium doped fiber is pumped at 980 nm. through a fiber grating. The pump laser was a pigtailed semiconductor laser which produced a maximum pump power of 70 mW. in the fiber. The output coupler was a fiber based splitter. One fiber from this splitter was butt coupled to the surface of the multiple quantum well saturable absorber shown in Fig. 2, and fixed in place with a UV curable epoxy cement. The method of coupling is illustrated in Fig 3. The other output port of the splitter was fusion spliced to an optical isolator through which the output of the laser was taken.

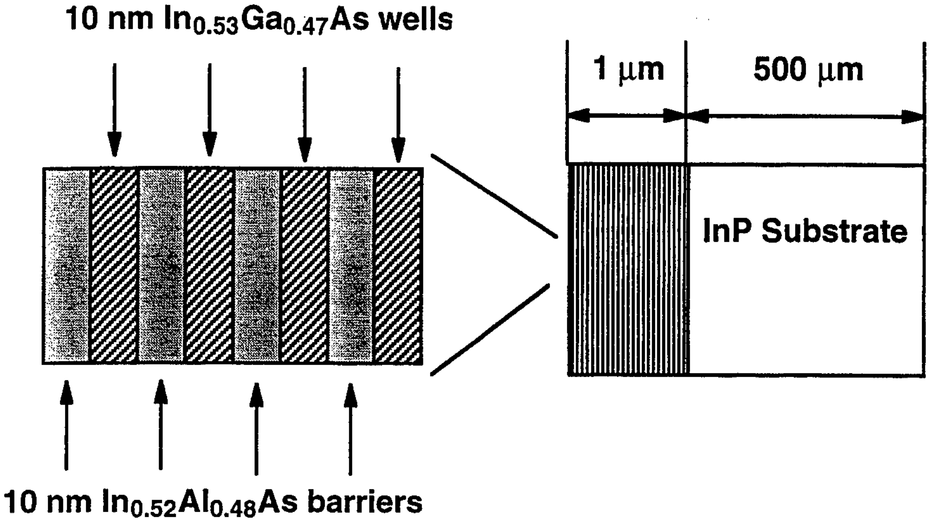


Fig. 2 Structure of the Quantum Well Absorber

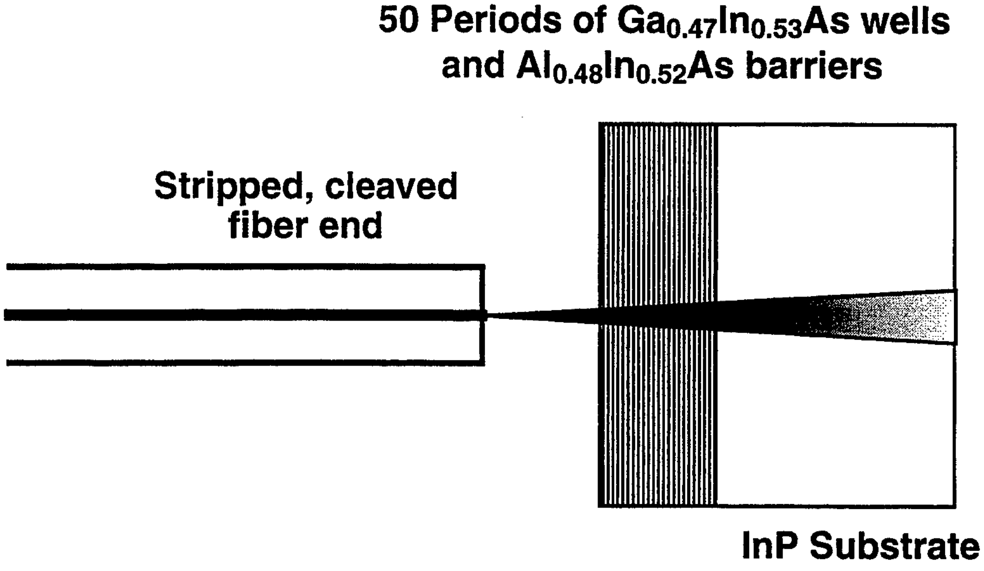


Fig 3. Fiber butt coupled to quantum well saturable absorber

The transmission of the fiber grating used in this laser is shown in Fig. 4.

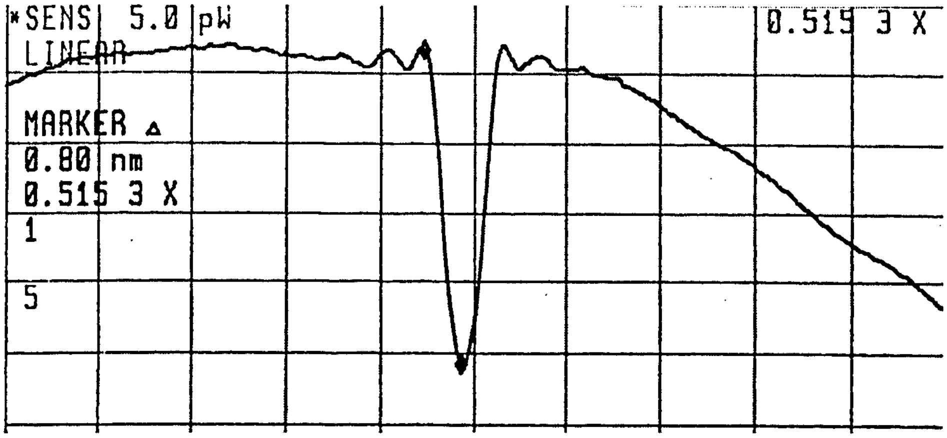


Fig. 4. Transmission of Grating Used in the Mode Locked QW Laser

A typical spectrum and auto correlation trace of the output of the laser are shown in Figs. 5 and 6. Note that these spectra are characteristic of a specific quantum well structure. This data translates into a pulse duration of 8.0 ps., assuming a hyperbolic secant shape, and a spectral width of 0.35 nm or 43 GHz. The resulting time - bandwidth product was approximately 0.35. A summery of the operating characteristics of this laser is shown in Tab.1.

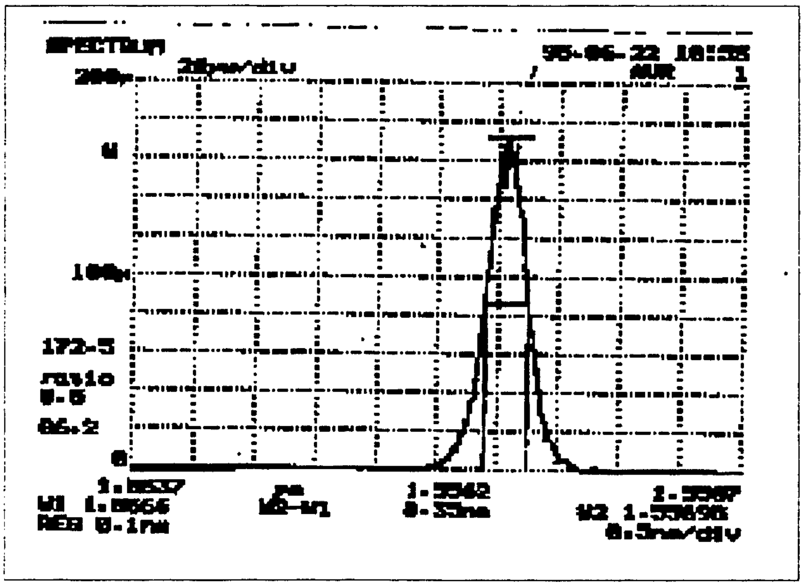


Fig. 5. Optical Spectrum of Mode Locked QW Laser Using Saturable Absorber 1305

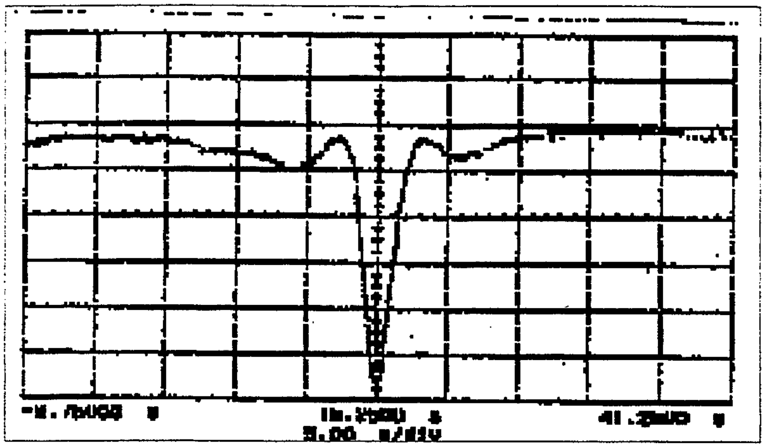


Fig 6. Auto Correlation Trace Corresponding to the Spectrum Shown in Fig. 5. The Pulse Duration from this Data is 8.0 ps.

Out Put Power	1.00 mW
Peak Power	40 W
Wavelength	1.56 microns
Period	300 ns
Pulse Duration	10 ps

Table 1. Laser operating characteristics.

The auto correlation trace shown in Fig. 6 illustrates one of the problems encountered to date with this passively mode locked laser design. The 8.0 ps pulses shown are superimposed on a broad background which involves a sizable fraction of the laser power, thus reducing the peak power of the pulses. The reduction of this background might be substantially reduced by optimization of the saturable absorber and ways of accomplishing this are being explored, as described below. Another problem is that the fundamental frequency of the mode locked pulses in these long cavity lasers is two low for several important applications. The frequency could be increased by shortening the cavity length by perhaps a factor of 10, but a frequency above 100 MHz is probably not obtainable by this means. Active mode locking would provide a way of operating the laser at a high harmonic of the fundamental frequency.

2.2 Active Mode Locking and the Synchronization of a Passively Mode Locked Erbium Fiber Laser.

The synchronization of short pulse fiber lasers is a requirement for their use in high speed optical communications systems where optical clock recovery is important. Also, as mentioned above, a drawback of most pulsed fiber laser systems has been their relatively low repetition rate (a few MHz) due to cavity length. We have demonstrated that mode locked pulses at a gigabit rate can be generated in the laser design described above by injection seeding with a second fiber laser actively mode locked in a very high harmonic.[3,4] This resulted in a completely synchronized gigabit rate output from the two fiber lasers. In our case, synchronization of a passively mode locked laser was accomplished by saturating the multiple quantum well absorber with the signal from an actively mode locked ring laser. A schematic of the system used is shown in Fig. 7.

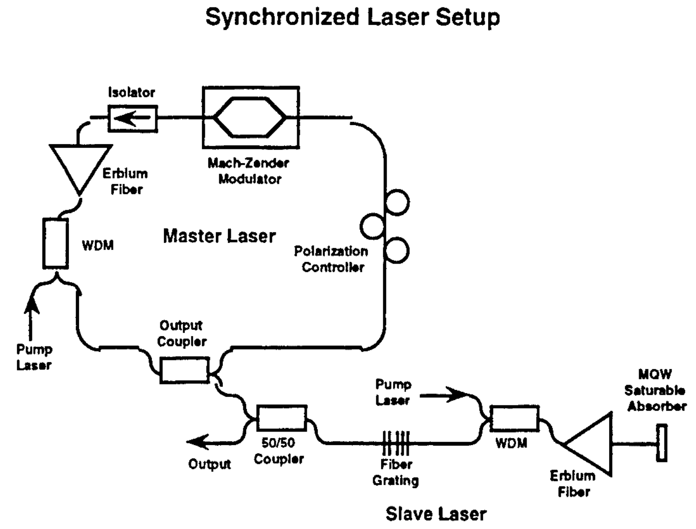
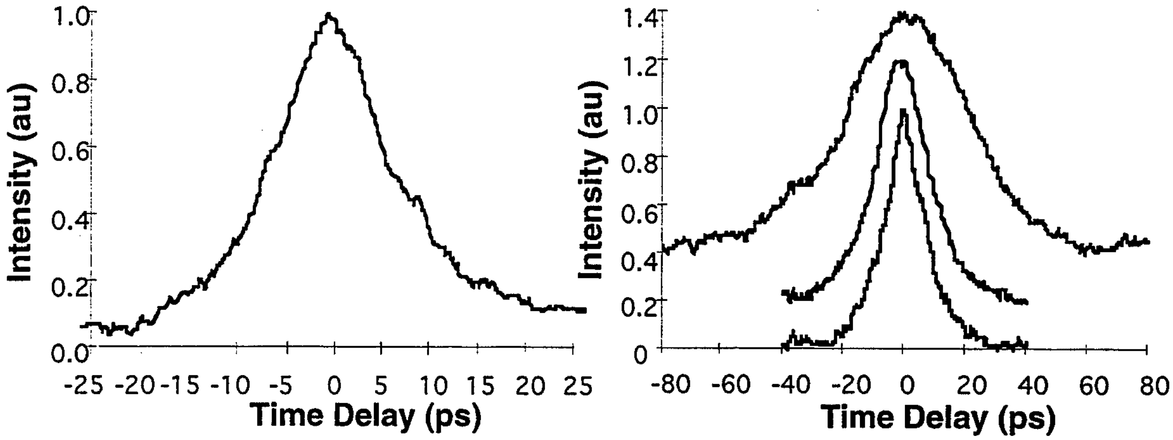


Fig. 7 Setup Used to Synchronize Two Lasers

The master laser was a harmonically mode locked fiber ring laser based on a design previously described by Harvey and Mollenauer.[6] Mode locked pulses from this laser are fed into the passively mode locked laser through a 3 dB coupler.

The slave laser was constructed using a modification of the standing wave design described above. A fiber Bragg grating with a reflectivity of 50% at

1555 nm provided feedback as a cavity mirror and also acted as the output coupler. The laser was pumped through a 980/1550 nm wavelength division multiplexer by a 980 nm laser diode developing 50 mW of power. A multiple quantum well saturable absorber of the type described above was butt coupled to the end of the Erbium fiber and acted as the second mirror of the cavity. The slave laser passively mode locked at a repetition rate of of 3.5435 MHz, corresponding to a cavity length of approximately 30 m. An auto correlation trace of the output of the unsynchronized slave laser is shown in Fig. 8a. The pulse duration varied from 7 to 14 ps depending on the alignment of the end of the Erbium fiber and the saturable absorber. Spectral widths varied from 0.37 to 0.52 nm giving time-band width products ranging between 0.32 to 0.61.



(a) MQW Laser Output **(b) Synchronized Output**

Fig. 8
a. Auto correlation Trace of the Output of the Unsynchronized Slave Laser
b. Auto correlation Traces of the Synchronized Output of the Slave Laser

The ring laser was initially adjusted to run at the fundamental frequency of the slave laser (3.5435 MHz) and its output was injected into the slave laser through the Bragg grating, which was transparent at the operating wavelength of the ring laser. The output of the slave laser was obtained through the unused port of the 50/50 coupler.

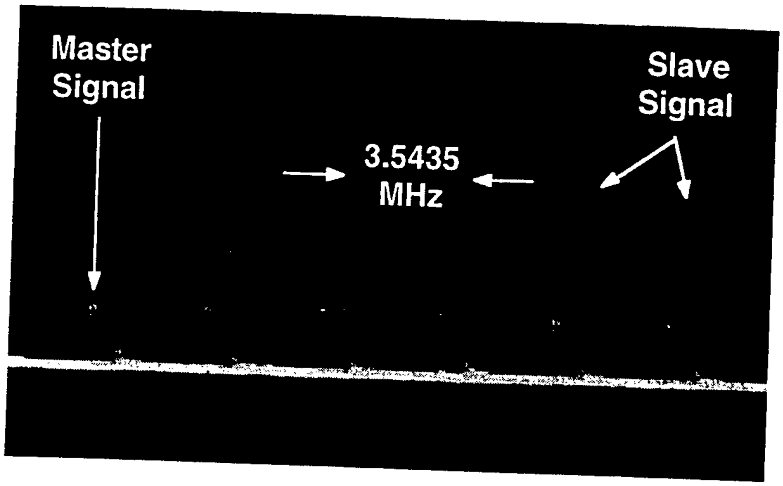


Fig 9. Mode Locked Synchronized Output

Mode locked synchronized output, shown in Fig. 9, was maintained at the fundamental frequency of the slave laser with average injected powers as low as 1.3 mW, corresponding to injected pulse energies of 360 pJ. Below this level the the ring laser signal was insufficient to initiate synchronized behavior. No discernible difference in operation was observed when the injected power was increased above this threshold. Auto correlation traces of the synchronized output at three different positions on the saturable absorber are shown in Fig. 8b. The shortest pulse duration observed was 10 ps. The optical spectrum was always centered at 1550 nm with a band width of 0.32 nm.

2.3 Active Mode Locking Via The Quadratic Stark Effect

It has been shown that if an electrical field is applied to a multiple quantum well stack such as the one illustrated in Fig. 2, the absorption of the wells shifts to longer wavelengths due to a quadratic Stark effect. An example of this effect is shown in Fig. 10. In this case the electric field was applied to the quantum wells by embedding them in a pn junction which could be back biased to the voltages shown in the figure. The measurements shown were carried out by Dr. Mark Kroll as part of his PhD thesis carried out under the direction of Professor Nasser Peyghambarian at the Optical Sciences Center, University of Arizona.[7]

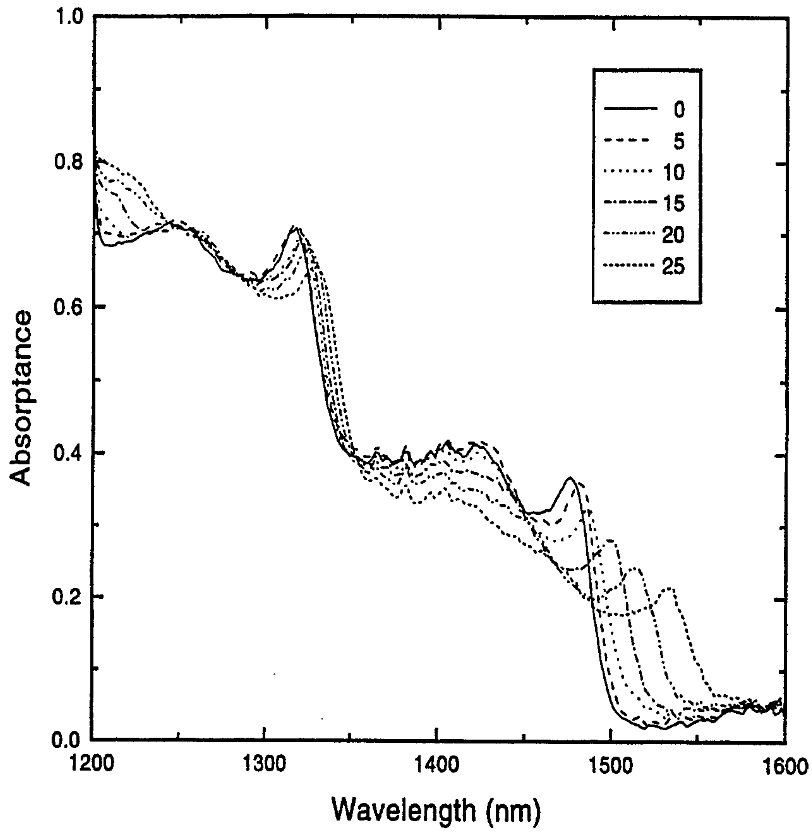


Fig. 10. The Stark Effect in a multiple Quantum Well Structure
From: M. F. Krol, PhD Thesis, Optical Sciences Center, University of Arizona, 1996

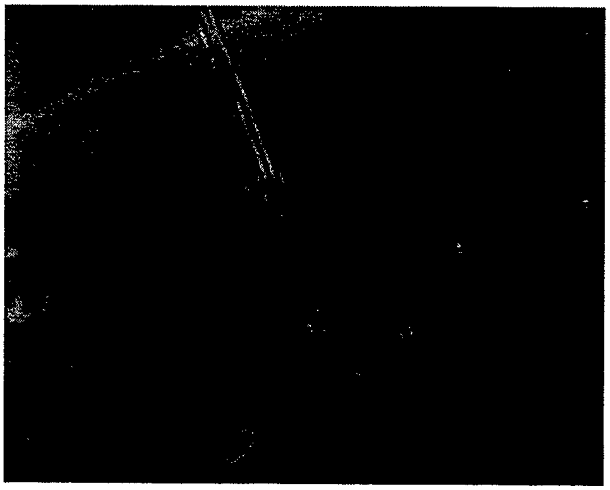


Fig. 11 Photomicrograph of the surface of the quantum well structure used to electrically mode lock a fiber laser.

A microphotograph of the surface of the device used to obtain the data shown in Fig. 10, is shown in Fig 11. The small rings are gold electrodes deposited on the front surface which in our case was doped p type. Beneath this was the quantum well stack illustrated in Fig. 2 and then a layer doped n type. All this was deposited on a substrate of InP which was polished and backed with a gold electrode. In the example shown the material around the electrodes was etched away to produce mesas. This device was supplied to the Photonics Division of Rome Laboratories by Dr. Richard Leavitt of the Army Research Laboratory in Adelphi, MD.

The passive saturable absorber used in the cavity design shown in Fig.1 was replaced by this device and the fiber at one end of the cavity was butt coupled to the inside of one ring electrode. A negative voltage was then applied to this electrode to back bias the device. At lower voltages the laser operated in a DC mode. When a DC voltage of about -25 V was applied to the device the mode locked pulse train shown in Fig. 12 was observed.

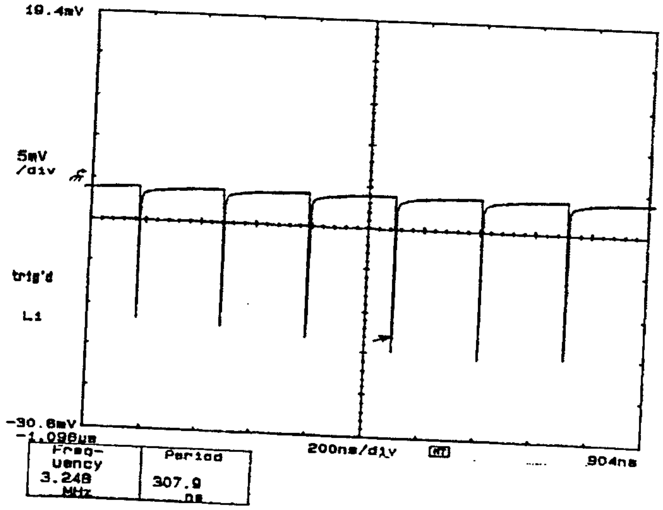


Fig. 12. Pulse Train from Laser Using Electrically Controlled Saturable Absorber

The output spectrum when the laser was mode locked is shown in Fig 13. Assuming that the pulses are transform limited, the spectrum shown implies a pulse duration of about 30 ps. Thus mode locking could be switched on and off by the application of a DC voltage.

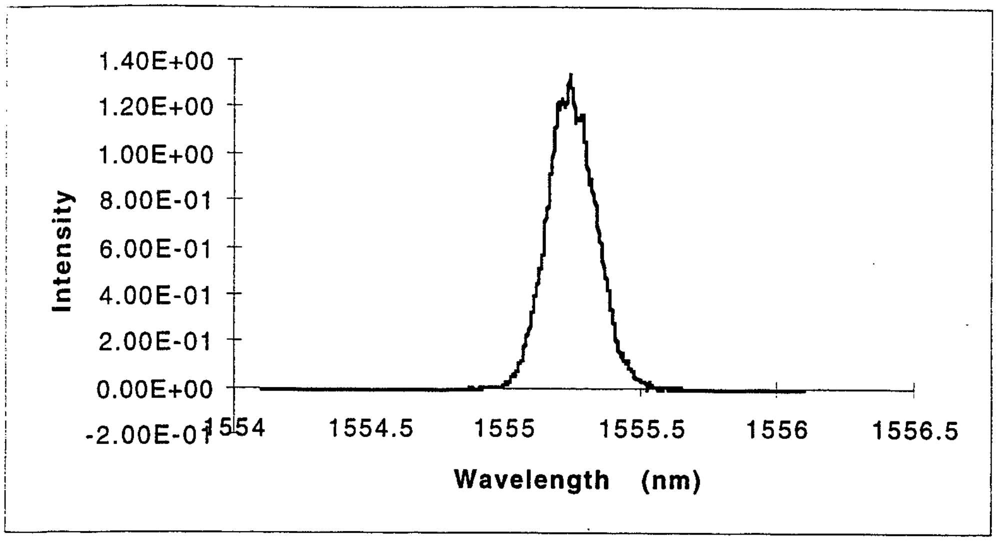


Fig 13. Optical Spectrum of Electrically Controlled Laser

If a sinusoidal AC voltage at twice the fundamental frequency of the laser cavity was superimposed on the DC voltage, a mode locked pulse train at this frequency was produced. In this case the pulse widths appeared to be substantially longer than in the case where the laser was simply switched on.

2.4 Optimization of Multiple Well Saturable Absorbers.

During this contract period emphasis was also placed on improving the performance of the multiple quantum well saturable absorber used to mode lock the fiber lasers described above. The objectives of this work were to achieve a reduction of pulse duration in passively mode locked operation and the elimination of the pedestal or background shown in Fig 6. To this end several samples of the multiple quantum well structure shown in Fig. 2 were grown. The first of these to be characterized was the original sample labeled 1305. Two others, namely 1442 and 1590 were also studied. All these samples were grown under slightly different conditions. In each case the number of quantum wells, their thickness, and the thickness of the substrate were kept constant. Photoluminescent measurements, linear absorption as a function of wavelength, measurements of the non linear absorption at a given wavelength and the temporal duration of the non linear absorption were made for each sample.These results were compared to measurements of pulse duration during mode locking.

Auto correlation traces of mode locked pulses obtained for each sample are shown in Figs 14a, 14b, and 14c. It can be seen that, as stated above, sample 1305 produced the shortest pulses.

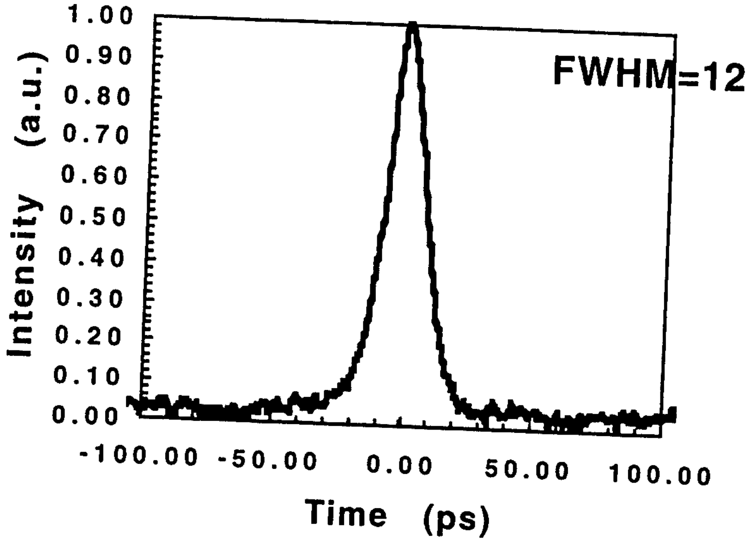


Fig 14a Sample 1305. Pulse Duration = 12 ps

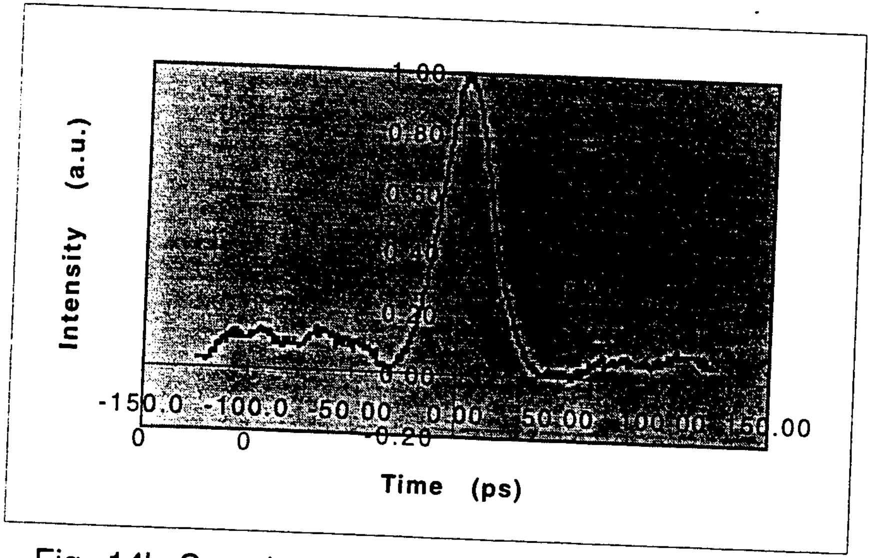


Fig. 14b Sample 1442. Pulse Duration = 18.18 ps

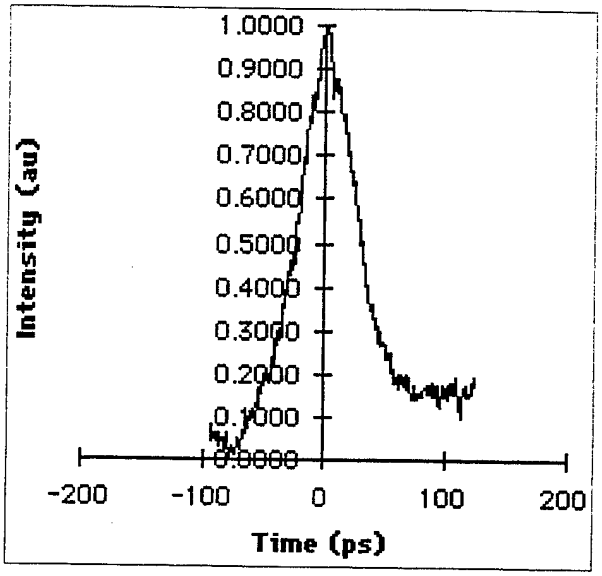


Fig 14c. Sample 1590. Pulse Duration = 30 ps.

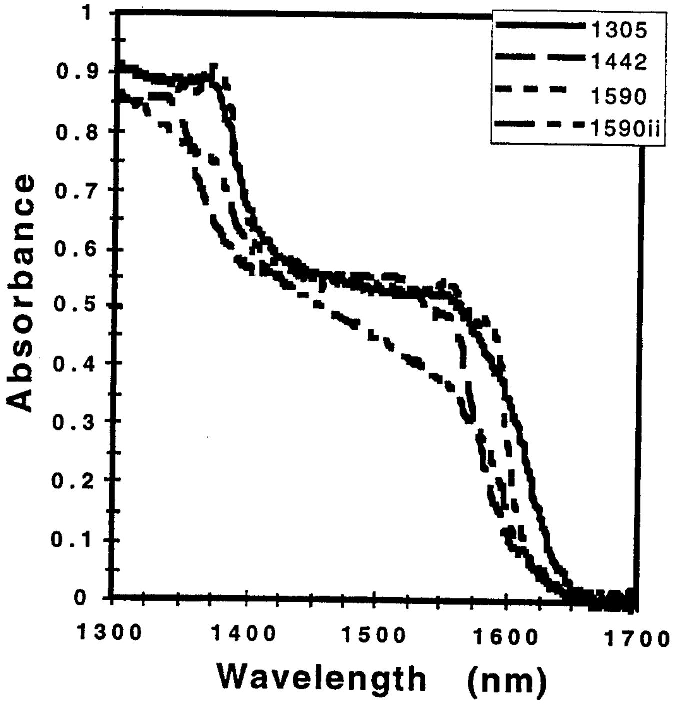


Fig. 15. The Linear Absorption of the Three Saturable Absorbers Studied to Date

Fig. 15 shows the linear absorption of the three samples. The absorption edge of all three samples was different. Also, the width of the exciton lines at approximately 1550 nm and 1305 nm varied from sample to sample. Sample 1590 shows the sharpest or best resolved structure while in 1305 the lines were broader. It should be remembered that sample 1305 produced the shortest mode locked pulses when used in the cavity configuration shown in Fig. 1.

Room temperature photo luminescence spectra were measured on the three samples1305, 1442 and 1590, each excited with the same wavelength and with the same input power. The spectra are shown in Fig.16. They were obtained by exciting the multiple quantum well structures with light of photon energy well above the band edge of the host material. The luminescence shown can thus be associated with the recombination of carriers at the bound states of the quantum wells. If the luminescence decay rate consists of both radiative and non radiative processes, the relative intensity of the photo luminescence can be correlated with the decay time of carriers in each sample. An interpretation of the data shown in Fig.16 is that the importance of non radiative process increases as we go from sample 1590 to sample 1305 and hence the decay rate increases, shortening the lifetime of the carriers. A decrease in carrier lifetime of almost a factor of five is indicated by this data. Since the saturation flux depends reciprocally on the decay rate, sample 1305 should have the highest saturation flux of the three samples studied. It is not obvious that this prediction is born out by the non linear transmission data shown in Figs. 15 - 20. However it is clear that the photo luminescence data provide the clearest distinction between the three samples. Since it was found that sample 1305 had the lowest threshold for mode locking, and produced the shortest pulses, this data provides some indication of one parameter that might be monitored during the MBE growth process to optimize performance.

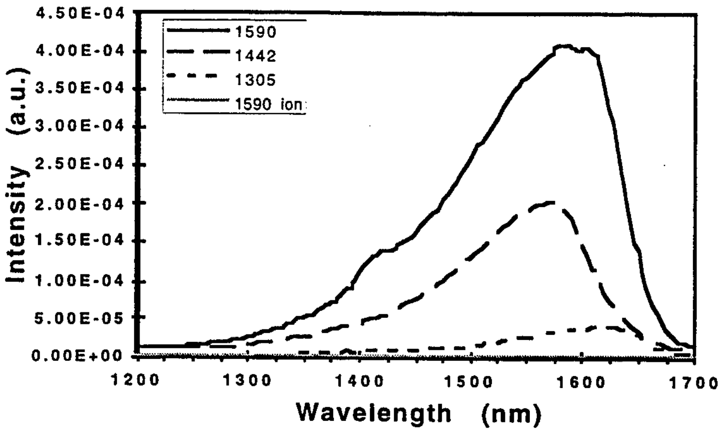


Fig 16. Photo luminescence Spectra of the Three samples

The non linear transmittance of the samples was studied using a tunable Cr^{4+}:YAG laser described elsewhere.[8] In these the DC output of the laser was focused into a μm spot on the surface of the sample and the fraction of the light transmitted was measured as a function of laser power. The intensity of the incident light was calculated from the measured output power of the laser and the known spot size. Measurements were made at 1550 nm. Preliminary results are shown in Figs. 17 a,b and c. The data indicates that the saturation flux, or threshold for saturation, was highest for samples 1305 and 1590. It is interesting to note that the the transmittance of sample 1305 did not seem to reach saturation over the range of incident intensities used.

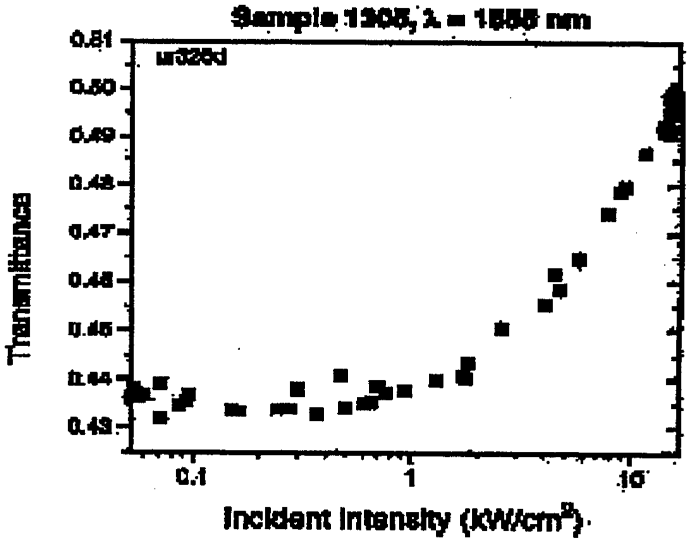


Fig. 17a Sample 1305

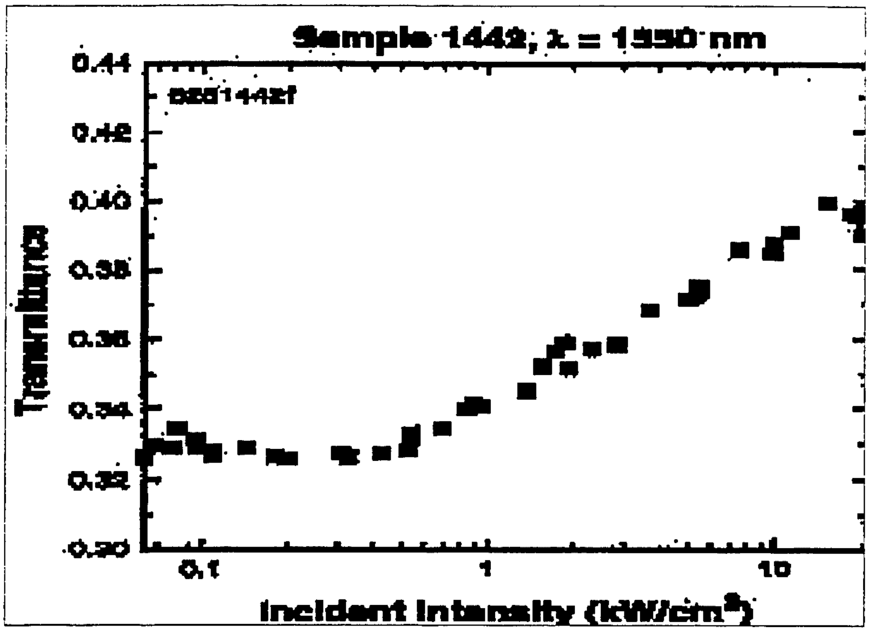


Fig 17b Sample 1442

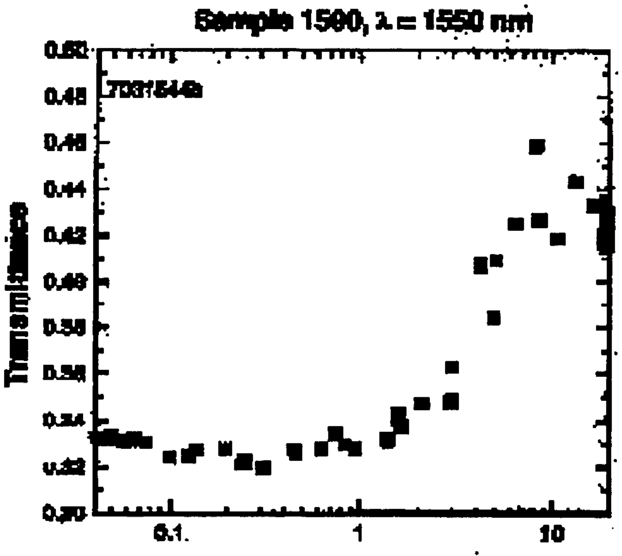


Fig 17c Sample 1590

Fig. 17 Non Linear Transmittance of Three Saturable Absorbers

The time evolution of the saturated absorption of the three sample is shown in Figs. 18 a, b, and c. These measurements were made by initially saturating the absorption with a femtosecond duration pulse from a mode locked Cr4+:YAG and then probing the decay of the transmission as a function of time using delayed pulses from the same laser.

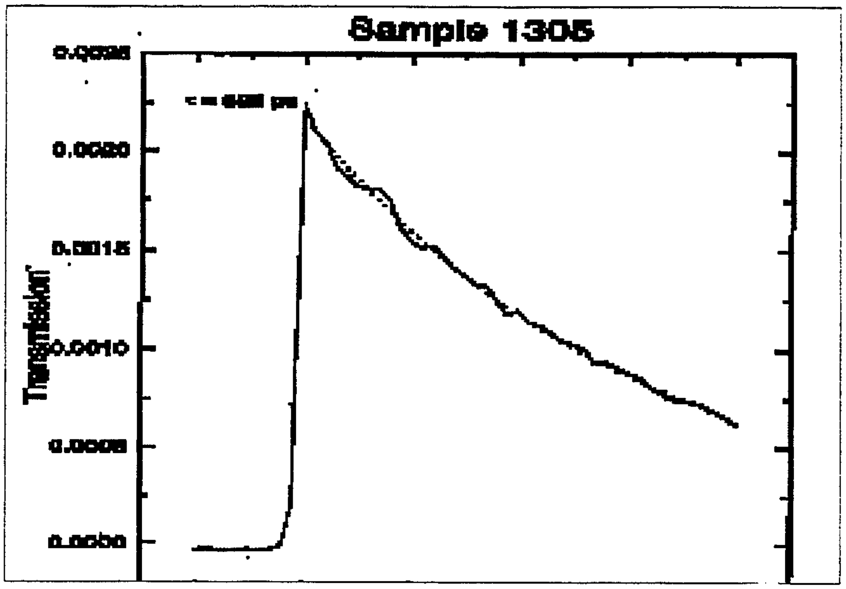


Fig 18a. Decay Times of Saturated Transmission of Sample 1305

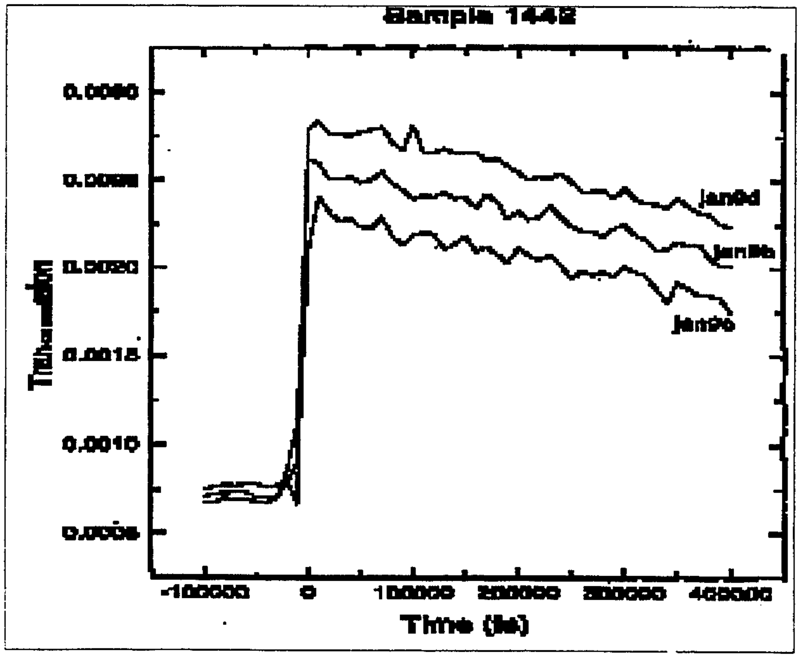


Fig 18b. Decay Times of Saturated Transmission of Sample 1442

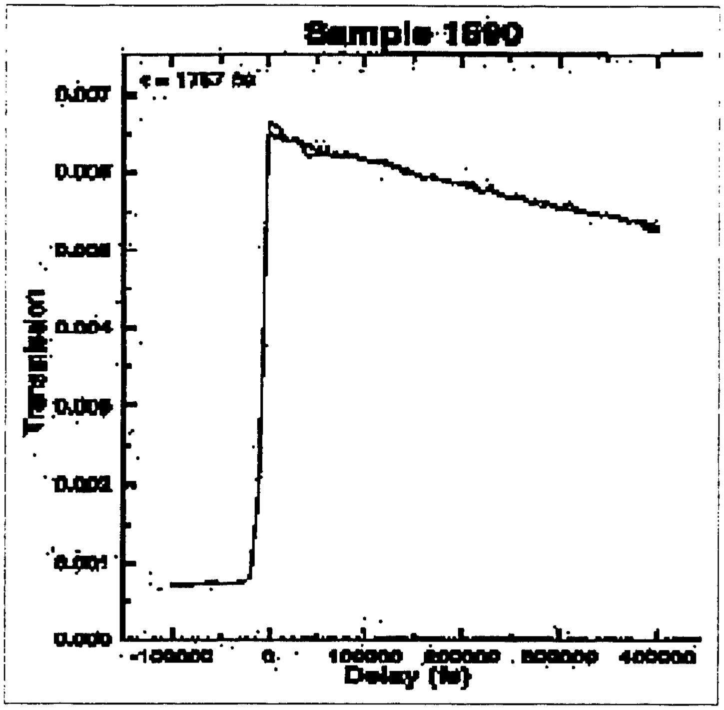


Fig. 18c. Decay Times of the Saturated Transmission of the Samples

The decay times of the saturated transmission inferred from this data are indicated on the figures. Of the three sample 1305 had the shortest decay time of 325 ps. However, all of the decay times are much longer than the duration of the mode locked pulses obtained. All of the samples can therefore be classified as slow saturable absorbers. Mode locking is initiated by the saturation of absorption but other non linear mechanisms operating in the gain medium of the laser or in the passive fiber portions of the laser cavity must contribute significantly to pulse shaping. Optimization of the saturable absorber itself should continue to insure reproducibility in the processes used to grow the samples, but a parallel investigation into the effect of the fiber grating band pass and non linear dispersion in the fiber and in the saturable absorber should be initiated to determine pulse shaping mechanisms.

3.0 References

1. R. Erdmann and K. Teegarden, " A compact mode locked Erbium doped fiber laser for field use." Laser 95 Congress, Munich, Germany June19-23, 1995
2. K.J. Teegarden and R.K. Erdmann," Self-Starting mode-locked Erbium fiber laser using fiber gratings," SPIE Vol. 2481, Photonic Device Engineering for Dual Use Applications, 1995
3. Final Technical Report RL-TR-96-249, KJT Inc. Contract # F30602-95-C-0058
4. R. Erdmann, W. Kaechele, and R. Fork, "Synchronization of passively and actively mode locked Er^{3+} fiber lasers," Presented at the OSA Annual Meeting, Portland, Oregon, 1995
5. W. Kaechele, W. Haus, M. Hayduk, R. Erdmann, and K. Teegarden, "Synchronization of Active/passive Mode- locked Erbium Fiber Lasers," SPIE Vol. 35
6. M. Kroll, "Ultrafast Carrier Dynamics and Enhanced Electroabsorption in (Ga,IN)As/(Al,In)As Assymetric Double Quantum Well Structures" PhD Thesis, Optical Sciences Center, University of Arizona,
7. G. T. Harvey and L.F. Mollenauer, Opt. Lett., Vol.18, p.107, 1993
8. M.J. Hayduk, S.T. Johns, M.F. Kroll, C.R. Pollock, and R.P. Leavitt, "Self- starting passively mode-locked tunable femtosecond Cr^{4+}:YAG laser using a saturable absorber mirror". Opts Comm. Vol. 137, p. 55, 1997