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ABSRACT

A rhodamine 6G dye laser, internally pumped within the extended cavity of an Ar^+ ion laser, is mode-locked when its cavity length is matched to half that of the pump laser: the 5145 Å argon laser line is passively mode-locked by the combination of the saturable absorption and the lasing action of the dye which is in turn synchronously pumped and mode-locked. Tunable (5650 Å to 5950 Å) ∿10 pSec pulses are generated, and the average output power is ∿ 80 mW.

Introduction

cw generation of picosecond pulses from dye lasers which are synchronously pumped by actively mode-locked noble gas ion lasers has received considerable attention in the past few years.[1-7] In such a scheme, an acousto-optically mode-locked cw ion laser (pulse width of ∿ 100 pSec) externally pumps a dye laser whose cavity length is matched to (or one-half[6]) the cavity length of the pump laser. When the lengths of the two cavities are optimally matched (to within a few μm), picosecond pulses are generated. Such pulses have considerably higher average power and wider tuning range than those obtained from cw-pumped passively mode-locked dye laser systems.[8]

In this letter we present preliminary results of the reciprocal passive mode-locking, by an intracavity Rhodamine 6G (R6G) dye laser, of the 5145 Å line of an Ar^+ laser. This mode-locked line, in turn, synchronously mode-locks the dye laser generating tunable ultrashort pulses of duration and average power comparable to those obtained from synchronously mode-locked systems. Our approach, therefore, eliminates the need for actively mode-locking the pump laser with an acousto-optic modulator driven by the amplified output of a stable oscillator. Furthermore, we observe that the pulse width appears not to be too critically dependent on the mismatch of the two cavities.

The Reciprocal Mode-Locking Scheme

Fig. (1) shows a schematic of our mode-locking arrangement. The Ar^+ laser cavity is extended, in a folded configuration, to include the broadband high reflecting mirrors M_1 and M_2 (10 cm radius of curvature R) at the focus of which the dye jet stream is placed at

Brewster's angle. The cavity is completed through prism P and a flat high reflecting mirror M_3. The dye laser beam, which has M_1, M_2 and P in common with the argon beam, is dispersed by the prism P and propagates to a partially transmitting end mirror M_5 ($R = \infty$, transmission T=3%).

The initial alignment of the combined laser cavities is achieved through the following procedure: With the output coupler M_6 in place and M_3 replaced by the wavelength selector, the Ar^+ laser is made to oscillate on the 5145 Å line. M_1 and M_2 are then aligned such that the 5145 Å spot reflected from the Ar^+ laser optics is coincident with the initial spot on M_2. M_5 of the dye laser is then adjusted such that the R6G laser oscillates on its fundamental mode (readjusting M_1 and M_2 may be necessary to obtain a good first order mode). The Ar^+ laser wavelength selector is then replaced by the broadband high reflector M_3. Due to the prism P, only the 5145 Å line is sharply focussed to pump the dye jet under these conditions. At this point, the dye concentration is significantly reduced by the addition of ethylene glycol, and the Ar^+ output coupler is removed. With a slight adjustment of M_3 and/or M_2, the 5145 Å line oscillates with a good TEM_{∞} mode structure. Upon increasing the dye concentration and the Ar^+ plasma current, R6G lases readily.

In this intracavity pumped configuration R6G acts as a saturable absorber of the 5145 Å line. However, its relaxation time ($\sim$ 6 n Sec) is not short enough to induce mode-locking. When M_5 is misaligned such that R6G is not lasing, it is observed that the Ar^+ intracavity intensity is strongly modulated but not completely mode-locked. On the other hand, when M_5 is aligned to allow R6G to lase, short-pulsed operation of the 5145 Å line is obtained as coarsely monitored with a fast photodiode and a sampling oscilloscope. This occurs when the cavity length of the dye laser is optimally adjusted (by the translation of M_5 with a differential micrometer) to a position approximately equal to (or one-half) the cavity length of the Ar^+ laser. The passive mode-locking of the Ar^+ laser is the result of the effective shortening of the relaxation time of the saturated dye absorption as caused by the formation of a dye laser pulse, at the trailing edge of the Ar^+ laser pulse, which stimulates a rapid depletion of the excited S_1 state of the dye. The dye laser pulses, in turn, will also be ultrashort being synchronously pumped by the mode-locked Ar^+ laser pulses (see Fig. 2). This is similar to the previously reported double mode-locked operation.[9, 10]

We employed a Spectra-Physics Model 171 Ar^+ laser to pump a R6G dye laser. The pump laser output at 5145 Å was 2.6 W at a current I_{Ar} = 40 amperes. The Ar^+ laser cavity length L_{Ar} and that of the dye laser L_D were matched such that $L_D \simeq 1/2\ L_{Ar}$, where L_D corresponds to a cavity round-trip time of $\simeq$ 10 nSec. (100 MHz repetition rate), as can be seen in Fig. 2. Then, a single Ar^+ laser pulse travels in the extended cavity and pumps the dye once every two transits of the dye laser pulse. A dye concentration of 3.8 x 10^{-4} molar in ethylene glycol resulted in an Ar^+ laser threshold current I_{Ar}^{th} of $\simeq$ 40 Amperes.

The pulse width of the dye laser output was measured by the conventional technique of collinear phase-matched second harmonic generation using a 0.1 mm thick KDP crystal (Quantum Technology, Inc.).

Results and Discussion

A typical autocorrelation trace of pulses at $\lambda = 5700\ \mathring{A}$ is shown in Fig. (3). Assuming a $sech^2$ pulse shape, the measured pulse-width is 11 pSec. Similar pulses were observed over a wavelength range of $5650\mathring{A} - 5950\ \mathring{A}$, with a typical average power output of $\underset{\sim}{\sim}$ 80 mW. In general, the pulses have amplitude substructure as evidenced by the 3 : 2 : 1 contrast ratio. The typical FWHM bandwidth of such pulses was $\underset{\sim}{\sim} 4\ \mathring{A}$. Shorter pulses, without substructure, were also observed (3 : 1 contrast ratio) but not easily reproduced, even after the introduction of an iris in the dye laser cavity.

Stable pulses of shortest duration were generally observed near threshold operation of the Ar^+ laser, and when the two focused beams were somewhat noncollinear in the dye jet (as deduced from the relative displacement of the two spots on M_2). We also note that the pulses tended to shorten as the dye concentration and I_{Ar} were increased.

A T = 10% partial transmitter was also used but yielded considerably longer pulses ($\gtrsim$ 50 pSec). Even though, as in the case of synchronously-pumped mode-locked dye lasers[5], it might be expected that higher linear losses would force the dye laser pulses to shorten, in our configuration this effect is counterbalanced by the strong interdependence of the Ar^+ and the dye laser pulses : The higher the intracavity dye laser pulse energy (smaller linear losses) the better mode locked are the Ar^+ pulses (and correspondingly the dye pulses).

The dependence of the pulse width on the cavity mismatch parameter $\Delta \equiv L_D - L_D^{opt}$ where L_D^{opt} is the optimum dye laser cavity length which is $\underset{\sim}{\sim} 1/2\ L_{Ar}$, is shown in Fig. 4. It can be seen that the dependence of the pulse width on Δ is not as critical[11] as in the case of synchronously-pumped mode-locked systems.[12,13] This can be qualitatively explained as follows. In either method, the optimum dye laser pulse forms at the trailing edge of the Ar^+ laser pulse. At each cavity round-trip, the overall nonlinear gain experienced by the dye laser pulse, as a function of its local time, forces it to move forward in time. This must be compensated for by a relative delay with respect to the Ar^+ laser repetition time such that the pulse shape is conserved every round-trip. When $L_D = L_D^{opt}$, this delay is optimum, and the shortest stable pulses are generated. For $\Delta<0$, the dye laser pulse will tend to overlap with Ar^+ pulse, hence it rapidly increases in duration as a function of decreasing Δ. Clearly, since the net gain in the cavity is not high, the forward displacement of the pulse per round-trip can only be a small fraction of the pulse width, and conversely, the pulse width must be considerably larger than Δ/c. Therefore, for $\Delta>0$, the pulse width must increase to conserve the pulse shape at each cavity round-trip. While in synchronously-pumped mode-locked systems the Ar^+ laser repetition rate is fixed, in the present method the Ar^+ and dye pulses are locked in time in the sense that a net delay of the dye laser pulse causes a similar displacement of the Ar^+ pulse. Consequently, relatively large displacements of a short pulse per round-trip can be dynamically compensated for, with the pulse shape and stability being maintained over a wide range of the cavity mismatch parameter Δ.[14]

A smaller Ar^+ laser (Spectra-Physics Model 165), with $\sim$ 1.8 W from the 5145 Å line was also used in the same configuration described above. For $L_D = L_{Ar}$, the shortest pulses obtained were $\sim$ 35 pSec in duration. Under optimal matching conditions, near $L_D = 1/2\ L_{Ar}$, double-pulsed operation was observed. L_D corresponded to a cavity round-trip time of $\sim$ 7.2 nSec. and the delay between the two pulses was $\sim$ 5.5 nsec. This second pulse was caused by the presence of a secondary Ar^+ pulse 5.5 nSec. after the main one. In this case, the individual dye pulses had no substructure. The measured shortest pulse width was 5 pSec. assuming $sech^2$ pulse shape (Fig. 5). The average power and tuning range were similar to those described above. However, the peak power was lower due to the higher repetition rate.

Conclusions

The reciprocal synchronous passive mode-locking of an Ar^+ laser and a R6G dye laser is reported. Even though the presently generated pulse widths are somewhat longer than those obtained from conventional synchronously-pumped mode-locked dye lasers, our approach has several advantages. First, the active mode-locking of the pump laser is eliminated. Second, our preliminary results indicate that the optimum pulse duration may not be critically dependent on the cavity mismatch parameter. Finally, since mode-locking was achieved at small values of linear cavity losses, cavity dumping techniques can be readily incorporated into this system.

In principle, further band width limiting by an additional prism (or by tuning with a Lyot filter) may eliminate the amplitude substructure. This may also result in shorter pulses. Further work along these directions, and to extend the tuning range, is in progress.

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11. This observation is not yet quite conclusive since the minimum pulse widths presently reported are longer than those obtained by synchronous pumping. However, it seems to be supported by Ref. 13.
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14. Cavity bandwidth considerations should not alter this argument.

FIGURE CAPTIONS

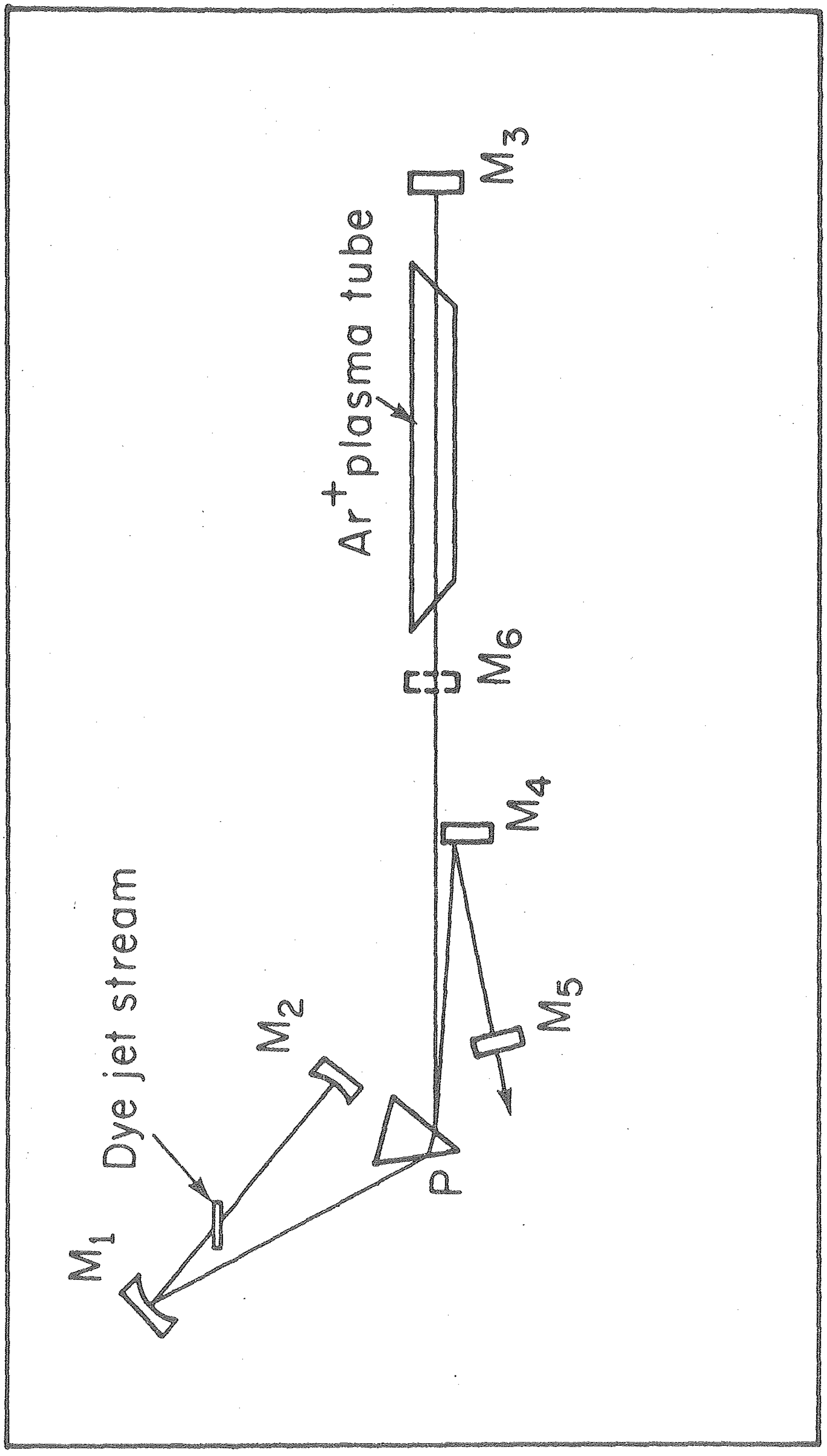
Fig. (1) Reciprocal Mode-Locking Scheme. M_1 and M_2: broadband high reflectors (R = 10 cm). M_4: R6G high reflector (R = ∞). M_5: R6G partial transmitter (R = ∞). M_3: Ar^+ broadband high reflector (R = ∞). M_6: Ar^+ output coupler (removed after initial alignment, see text).

Fig. (2) Sampling scope display of dye laser pulses detected with a photodiode. Combined rise time $\simeq$ 400 pSec. Horizontal scale = 2 nSec./div.

Fig. (3) Intensity autocorrelation trace (with background, $sech^2$ pulse shape) of a typical dye pulse.

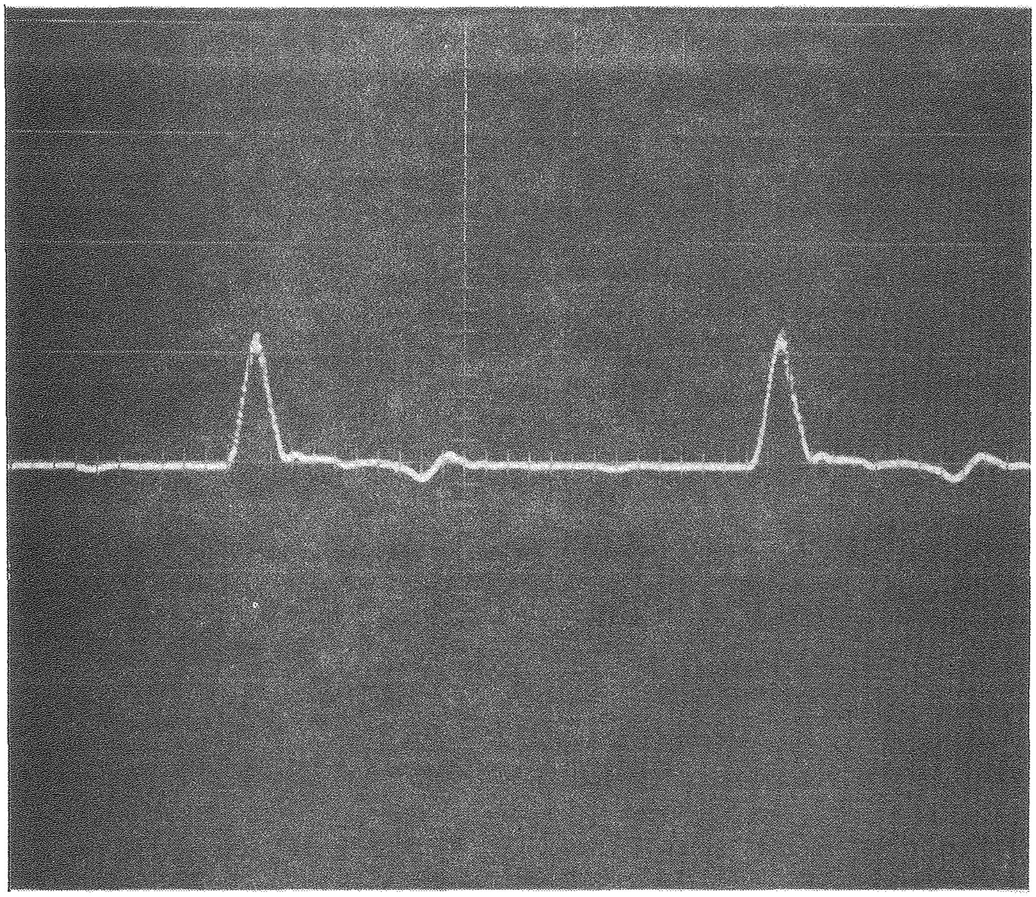
Fig. (4) Autocorrelation width vs. cavity length mismatch parameter

Fig. (5) Intensity autocorrelation trace (with background, $sech^2$ pulse shape) of double pulsed operation.



XBL 8010-2264

Fig. (1)



XBB 811-200

Fig. (2)

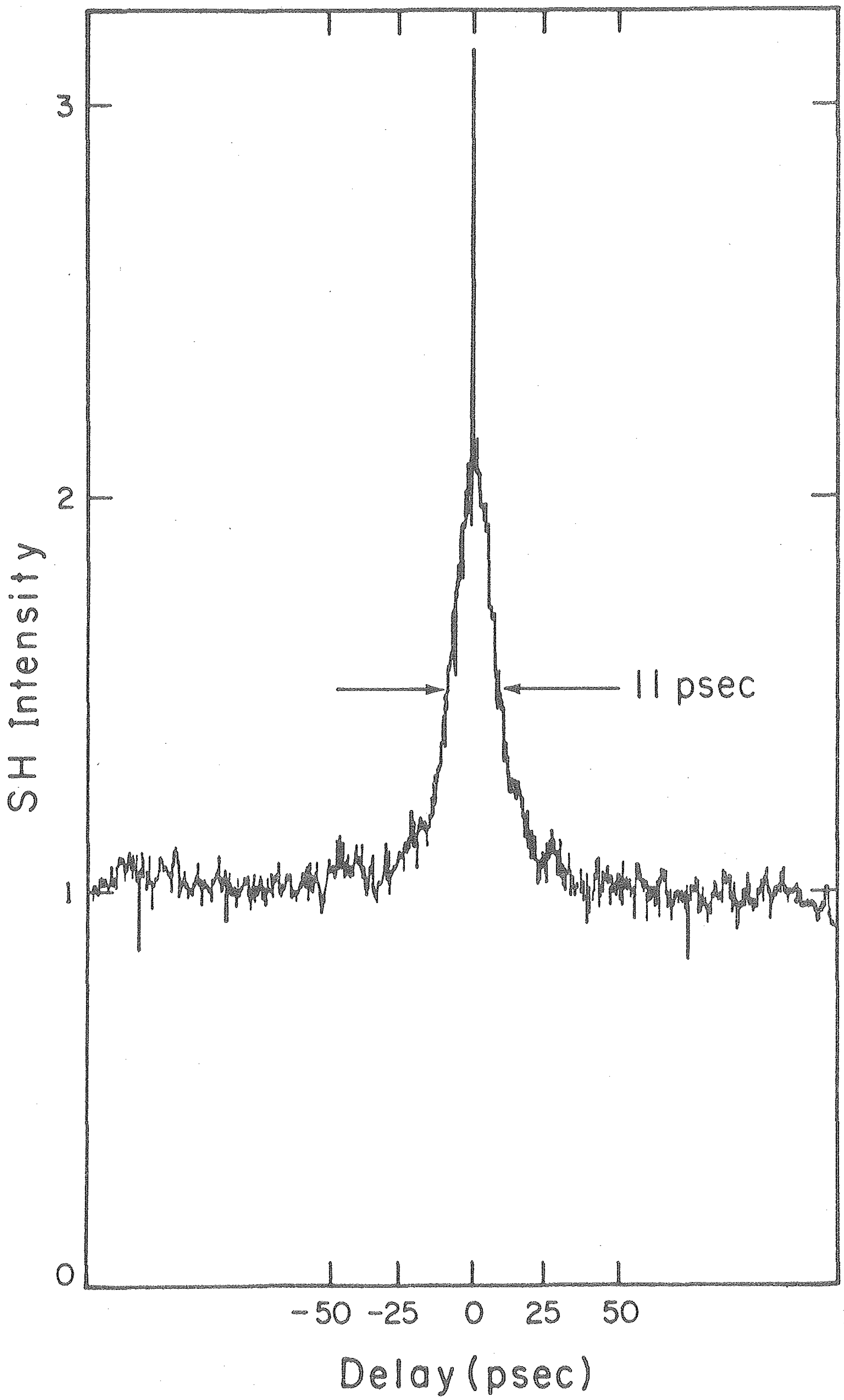
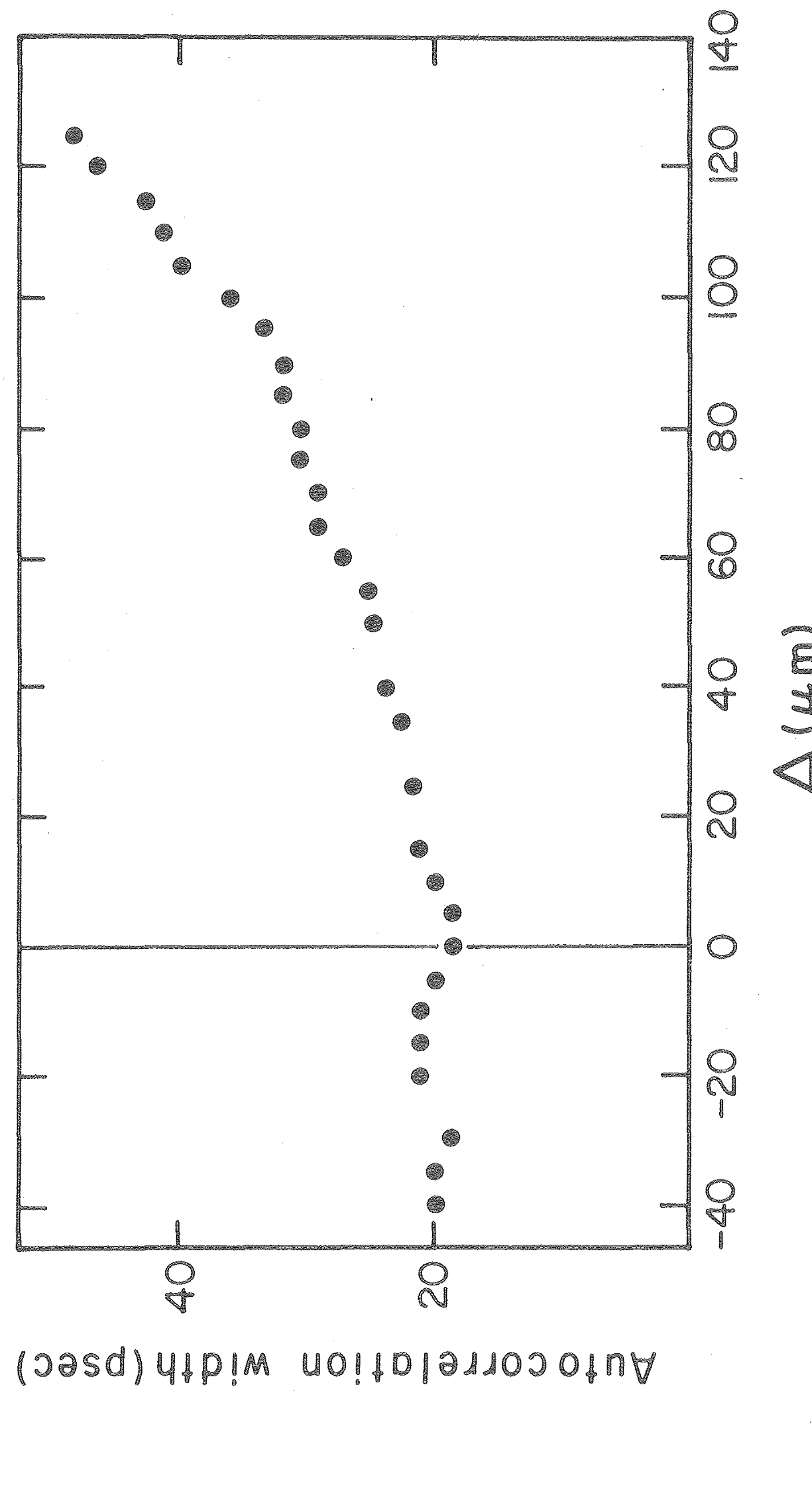
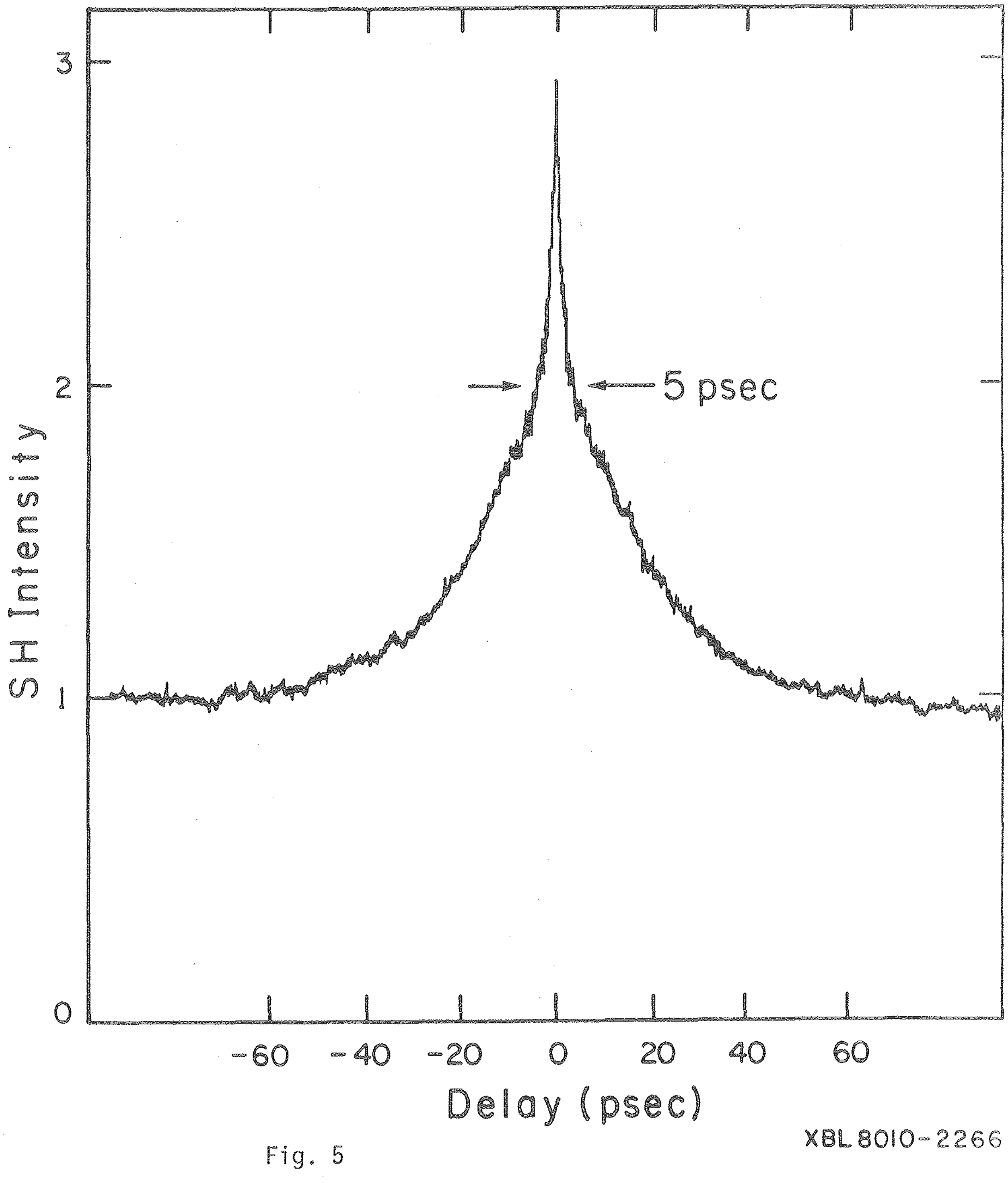


Fig. (3) XBL 8010-2267



XBL 8010-2265

Fig. (4)



3
2
1
0
SH Intensity
5 psec
-60
-40
-20
0
20
40
60
Delay (psec)
XBL 8010-2266

Fig. 5