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Electronic Tuning of a Dye Laser Using the Acousto-Optic Filter*

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A dye laser which is electronically tunable over 780 Å has been obtained by inserting a $CaMoO_4$ acousto-optic filter into the dye-laser cavity. A filter half-power linewidth of 6.8 Å yields a laser linewidth of 1.35 Å. Oscillation at two simultaneous independently tunable wavelengths and electronically variable output coupling has been observed.

We have electronically tuned a dye laser by inserting a $CaMoO_4$ acousto-optic filter into the dye-laser cavity. The tuning of organic dye lasers, which exhibit emission over a broad continuous spectrum,[1] has previously been accomplished mechanically by tilting a dispersive element such as a diffraction grating inside the cavity,[2] or electronically over a narrow range of 4 Å by the electro-optic effect.[3] Using the acousto-optic filter, we have been able to electronically tune the dye laser over 780 Å by varying the frequency of an acoustic wave. A lasing linewidth of 1.35 Å was observed.

The acousto-optic filter[4–6] utilizes a collinear interaction between an ordinary optical wave, an extraordinary optical wave, and a traveling acoustic wave in a birefringent crystal. On a microscopic basis, the acoustic wave couples light of one polarization into the orthogonal polarization. In order for this coupling to be cumulative the optical and acoustic waves must satisfy the phase-matching condition. Changing the acoustic frequency selects the narrow band of optical frequencies that is efficiently diffracted into the orthogonal polarization. In our 2.1-cm $CaMoO_4$ filter, essentially 100% conversion was obtained with an acoustic power density of 150 mW/mm^2 at 5800 Å. Traveling in the same direction as the acoustic wave, the optical band is parametrically downshifted by the acoustic frequency ω_a. On the return pass this same narrow band is diffracted back into the original polarization and is further downshifted by ω_a. Thus, with appropriate polarization selection on each side of the filter, oscillation can occur for light within this narrow band, while all other optical frequencies see a large cavity loss. The repeated downshifting of the optical band yields a chirping cavity mode, which has been analyzed by Streifer and Whinnery.[7]

The $CaMoO_4$ acousto-optic filter requires an S_{13} shear wave propagating along the x axis with particle motion in the z direction. As shown in the schematic of Fig. 1, this shear wave is obtained by longitudinal-to-shear mode conversion at the face in the xz plane. The incident longitudinal wave propagating in the z direction creates, upon reflection from the face inclined at 62°, the desired shear wave propagating in the x direction as well as a quasilongitudinal and a quasishear wave in other directions. An anisotropic analysis shows that 99.1% of the energy in the incident longitudinal wave is converted to the desired shear wave. An optical index-matching fluid surrounding the $CaMoO_4$ crystal reduces the magnitude of the optical refraction angle and the reflection losses. Using the mode-conversion technique, rather than shear-to-shear conversion at a 45° face in the xy plane, permits the use of the dye solution itself for index matching, so that an external dye cell is unnecessary. Furthermore, the fundamentally resonant longitudinal transducer is thicker and does not need to be oriented, as does a shear transducer. The longitudinal transducer was a 72-μm × 1.2-mm plate of 35°/y-cut $LiNbO_3$ that was bonded to the $CaMoO_4$ by a thin layer of phenyl benzoate. Fabricating efficient reliable acoustic bonds proved to be the most difficult operation in the experiment.

In order to minimize the optical losses in the dye-laser cavity, the end faces of the $CaMoO_4$ were cut in orthogonal planes so that the polarization is in the plane of incidence at each face. Mode conversion dictated the angle of 62° in the xz plane for the right-hand face in Fig. 1, while minimization of reflection losses on the left-hand side indicated an angle of 53° in the xy plane. The theoretical reflection loss for the filter was 7.5%. The optical beam is, of course, refracted by transmission through the oblique end faces; the difference in refraction angle for the two polarizations (double refraction) was used as the polarization selection mechanism in the dye-laser cavity. Because of the low birefringence of $CaMoO_4$ (0.01), double refraction at the $CaMoO_4$ faces was not always sufficient to prevent competing oscillations under high-gain conditions; therefore, the Brewster-angle calcite prism was inserted as shown in Fig. 1. A Q-switched internally doubled Nd:YAG laser, providing 100-nsec-long 5-kW pulses in the TEM_{00} mode at 5320 Å, pumped the dye laser longitudinally. The pump laser was mode matched to the dye-laser cavity, which had a confocal parameter of 9.3 cm.

With the dye Rhodamine 6G, 10^{-4} M in ethanol, we tuned the dye laser from 5445 to 6225 Å by varying

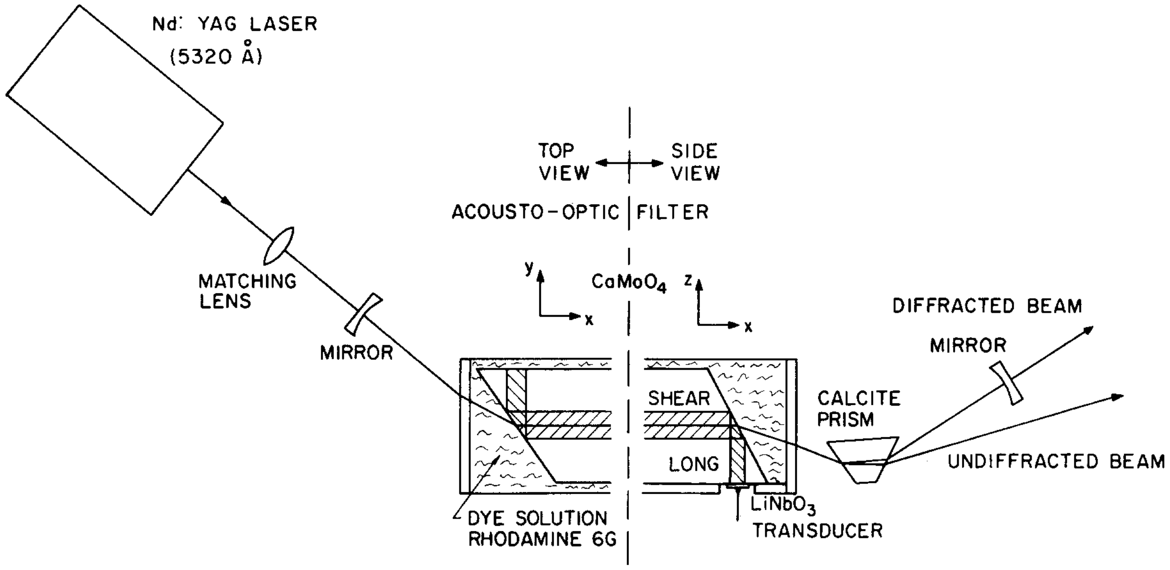

FIG. 1. Schematic of electronically tuned dye laser.

the acoustic frequency from 58.2 to 45.0 MHz. This tuning range of 780 Å included adjustment of the acoustic power to compensate for the transducer response and also some realignment to compensate for dispersion at the extremes of the tuning band. With both the acoustic power and cavity alignment fixed at the optimum settings for 50 MHz, the laser tuned over 520 Å. The large tuning range of 780 Å obtained here for Rhodamine 6G is the result of the close match of the pumping wavelength to the dye absorption peak; by tuning with a 2460-line/mm transmission-type diffraction grating instead of the filter, we obtained a tuning of 835 Å, from 5415 to 6250 Å. With a 2.1-cm $CaMoO_4$ crystal, the filter half-power bandwidth at 50 MHz was measured with a Spex 1704 spectrometer to be 6.8 Å. Regenerative narrowing yielded a lasing-output linewidth of 1.35 Å. Skewing, as predicted by the Streifer-Whinnery theory, was not observed and was not expected to be, since the length of the pump pulse allows for only 280 optical transits through the filter and thus, a possible downward shift of only 0.16 Å with an acoustic frequency of 50 MHz. In order to observe the Streifer-Whinnery shift, it would be necessary to use a pumping laser with significantly longer pulses or, alternatively, to construct the filter using a material with higher birefringence, thereby having both a narrower bandwidth and a higher acoustic frequency.

The acousto-optically tuned dye laser was also made to oscillate simultaneously at two independently tunable wavelengths. The simultaneous presence of two (or more) acoustic frequencies in the filter creates a doubly (or multiply) peaked passband characteristic, with a possible transmission at each band of 100%. The incident acoustic amplitudes are adjusted so that the two wavelengths see approximately equal net gain. That is, the acoustic filter is made somewhat more lossy for a band of frequencies near the center of the dye gain curve than for a band of frequencies further from the center. Under such balanced conditions we found that both wavelengths evolve nearly identically during the course of a pumping laser pulse. The necessary gain balance became more severe as the two frequencies approached each other; independently tunable simultaneous oscillation was observed for separations greater than about 20 Å and up to the tuning-range limit of 780 Å.

Another interesting type of simultaneous two-frequency tunable output was obtained by operating the acoustic filter at an acoustic power level somewhat higher than that required for 100% conversion. For acoustic powers in the range $2.64P_0 < P < 8.17P_0$, where P_0 is the acoustic power required for 100% conversion, the amplitude of the symmetrically split side peaks of the filter-transmission characteristic exceeds the amplitude of the central peak, and the dye laser should oscillate at these two simultaneous frequencies. Through a spectrometer we observed a single narrow line with $P = P_0$, which decreased in intensity as the acoustic power was increased, then suddenly split into two lines that increased in intensity as the acoustic power was further increased.

The use of double refraction for polarization selection also allows electronically variable output coupling from the dye laser. If the acousto-optic diffraction into the orthogonal polarization is less than 100%, but still high enough to allow the tunable dye laser to reach threshold, the undiffracted light can be coupled out of the cavity as useful output by virtue of its angular separation from the resonated diffracted beam, as illustrated in Fig. 1. In our experiment, a filter conversion level of 80% provided optimum output coupling, while threshold was reached at 40% conversion. The best fit of these experimental data to theory implies the experimental condition of 13% one-way cavity loss, comprised mostly of the 7.5% filter reflection losses and the 4% transmission of the right-hand mirror.

In another experiment, actually performed before the experiment described thus far, a Rhodamine B dye laser, 5×10^{-3} M in ethanol, was transversely pumped with an Avco C-950 nitrogen laser with a pulse width of 10 nsec and peak power up to 100 kW at 3371 Å. In this case, the acousto-optic filter utilized shear-to-shear conversion at 45° faces and was surrounded by a silicon-based index-matching fluid ($n = 1.625$). The maximum transmission was 50%. Electronic tuning of about 244 Å, from 6156 to 6400 Å, was obtained. Probably as a result of the smaller number of optical passes available, the output linewidth in this first experiment was found to be 4.7 Å.

The acousto-optically tuned dye laser provides electronic tuning over a broad continuous spectrum with an output linewidth comparable to that obtainable with grating-tuned dye lasers. We believe that the output linewidth could be reduced by an order of magnitude by using an acousto-optic crystal with higher birefringence, and that further narrowing could be obtained by using a longer pumping laser pulse. The simultaneous optical outputs could be used for excited-state spectroscopy, and amplitude or frequency modulation could be imposed on the acoustic wave.

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$In_{1-x}Ga_xP$ *p-n* Junction Lasers*

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The laser operation of $In_{1-x}Ga_xP$ ($x \sim 0.27$) *p-n* junctions is demonstrated at 4.2 and 77 °K. The *n*-type material for the junctions is grown at a fixed temperature (900—950 °C) from an In solution with the InP and GaP source crystal introduced into the solution at slightly higher temperature. The *p-n* junctions are formed at 700 °C by Zn diffusion from an In + 10% Zn source. In comparison with InP, the threshold currents for $In_{1-x}Ga_xP$ junctions are large, which is attributed to the problems associated with introducing Zn into the In-Ga sublattice.

Since the advent of the *p-n* junction laser, considerable effort has been expended to develop direct crystal systems that might lase at wavelengths shorter than 6400 Å, which is about the practical limit of direct $GaAs_{1-x}P_x$ junctions. In contrast to $GaAs_{1-x}P_x$, $In_{1-x}Ga_xP$ is direct over a larger range ($0 \le x < 0.74$)[1] and should lead to laser junctions operating from the infrared (~9000 Å) to the yellow (~5800 Å). Thus far, however, the laser operation of $In_{1-x}Ga_xP$ has been reported only for optically pumped homogeneous *n*-type samples,[2] and not for *p-n* junctions in spite of the fact that rather high-quality diffused junctions have been fabricated in $In_{1-x}Ga_xP$.[3] In this letter we discuss the difficulties that arise in forming high-quality diffused junctions in $In_{1-x}Ga_xP$,[4] and report here the laser operation of *p-n* junctions in this ternary system.

As previously described,[5] the crystals for this work are grown by a modified Bridgman solution-growth technique employing a small temperature gradient established on the In solution between the source InP and GaP and the $In_{1-x}Ga_xP$ deposited at fixed temperature (900—950 °C). In a period of 20 to 30 days a polycrystalline ingot of 1—2 g and of large grain size is grown. Most of the laser data to be presented here were obtained on a Te-doped ingot with $x \sim 0.27$, $N_d \sim 4.5\times10^{18}/\text{cm}^3$, and $\mu \sim 1000\ \text{cm}^2/\text{V sec}$.