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Dynamic Laser Wavelength Selection

Abstract: This paper describes the dynamic selection of the emission wavelengths of a laser by insertion of a dispersive tunable electro-optic *Q*-spoiler within the laser cavity. Five different oscillation wavelengths of an argon ion laser have been individually selected by varying the voltage on the KD*P electro-optic crystals in the *Q*-spoiler.

Much interest exists in tuning a laser over a continuous band of wavelengths. This is of especial interest for applications in communications, where the laser is to be frequency modulated. Because the laser transition is between two discrete energy states of an atomic system, frequency tuning by varying the resonance of the oscillation cavity can extend only over a range equal to the line width of the spontaneous emission. The atomic system can be perturbed to a certain extent, and hence the laser oscillation frequency shifted, by the application of electric¹ and magnetic² fields or varying the temperature³ and pressure⁴ on the system. Because of the stability of the atomic system, the range of tuning allowed by these techniques is small. A large shift in wavelength has been obtained, however, by applying a large hydrostatic pressure to a pulsed PbSe injection laser,⁵ but the application of very high pressures does not represent a practical dynamic tuning technique.

Fortunately, many applications do not require a continuous sweeping of the laser frequency, and discretely spaced emission wavelengths are preferred. For example, a laser system capable of emitting three lines properly located in the visible spectrum, which could randomly be selected and their intensities varied, would be useful for multicolor displays. In a memory application,⁶ if one wavelength is used to write upon and another wavelength to erase a reversible photosensitive medium, it would be very advantageous to be able to select these two wavelengths very rapidly. From an analytical viewpoint, the ability to switch from one wavelength to another at high speeds would make possible the study of laser transients or cross-relaxation effects.

Discrete laser wavelengths can be selected by preferentially destroying the cavity feedback at wavelengths where the

atomic system has gain. The most commonly used technique is to place a prism in the laser cavity.⁷ With the prism, the dominance in the 6328Å line of the He-Ne laser is removed and gain exists in the visible at 5940, 6046, 6118, 6293, 6351, 6401, and 7305Å. Suitable mechanical orientation of the prism permits oscillation at any one of these wavelengths. In other laser systems, e.g., the argon ion laser, the prism in the cavity can be used to select any one wavelength out of several which normally oscillate simultaneously. Other previously reported techniques include the use of a feedback mirror with a selective reflectivity,⁸ a Lyot-type filter used to obtain oscillation at the ruby R_2 line,⁹ molecular absorption in a gas cell¹⁰ placed in the laser cavity, and a special type of prism.¹¹ Electro-optic materials could be used in the Lyot-type filter to make it voltage tunable,¹² but the use of such a device in a laser cavity has not been reported.

In this communication a technique used to achieve voltage-controllable dynamic tuning is described. A dispersive medium in conjunction with an electro-optic control device is used inside the laser cavity. This combination acts as a *Q*-spoiler which introduces more loss than gain for each line except the desired one.

The wavelength dependent *Q*-spoiler consists of a crystalline quartz rod, a $\lambda/4$ plate, two KD*P electro-optic crystals and two Brewster angle windows. The arrangement of these optical components is shown in Fig. 1. The light beam as it leaves the laser tube has a plane of polarization that is parallel to its plane of incidence on the Brewster angle window. The window on the *Q*-spoiler is oriented so that the plane of incidence is parallel to the plane of polarization of the light beam. The optical activity of the crystalline quartz rod rotates the plane of polariza-

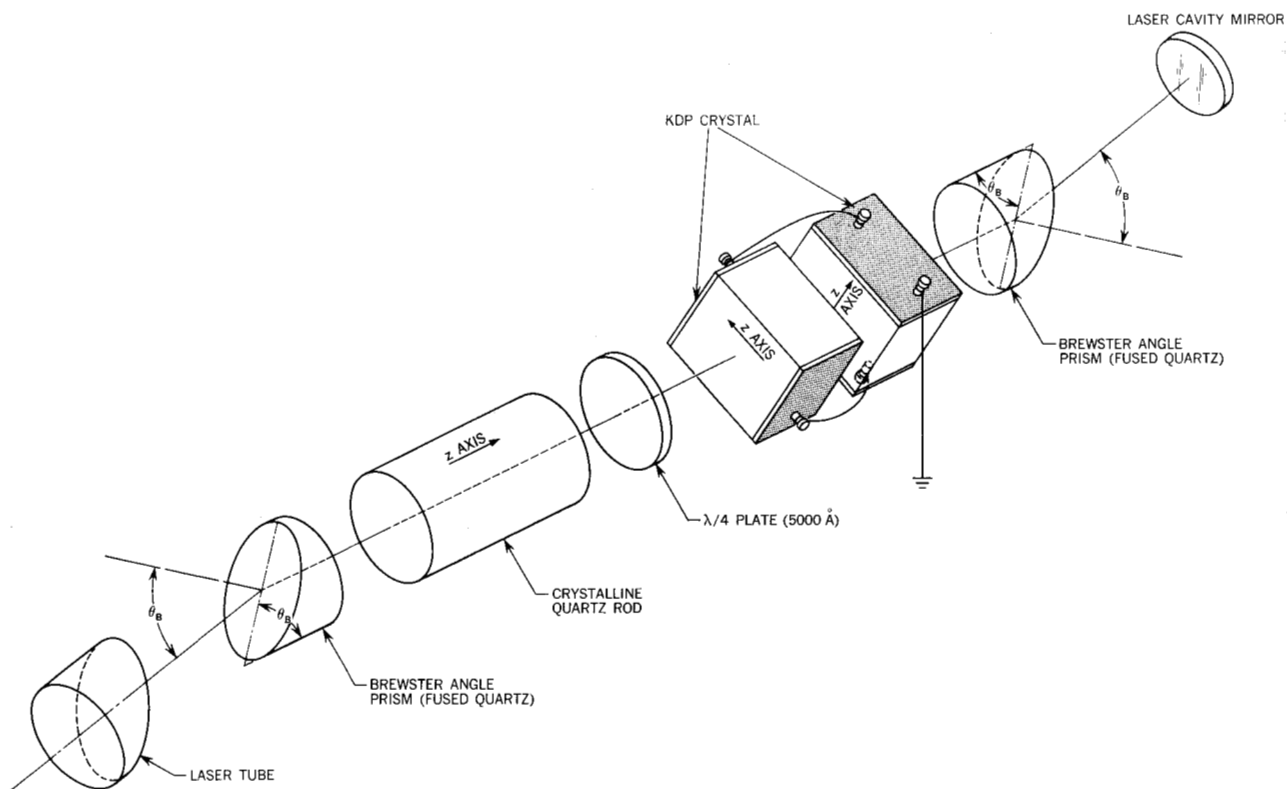
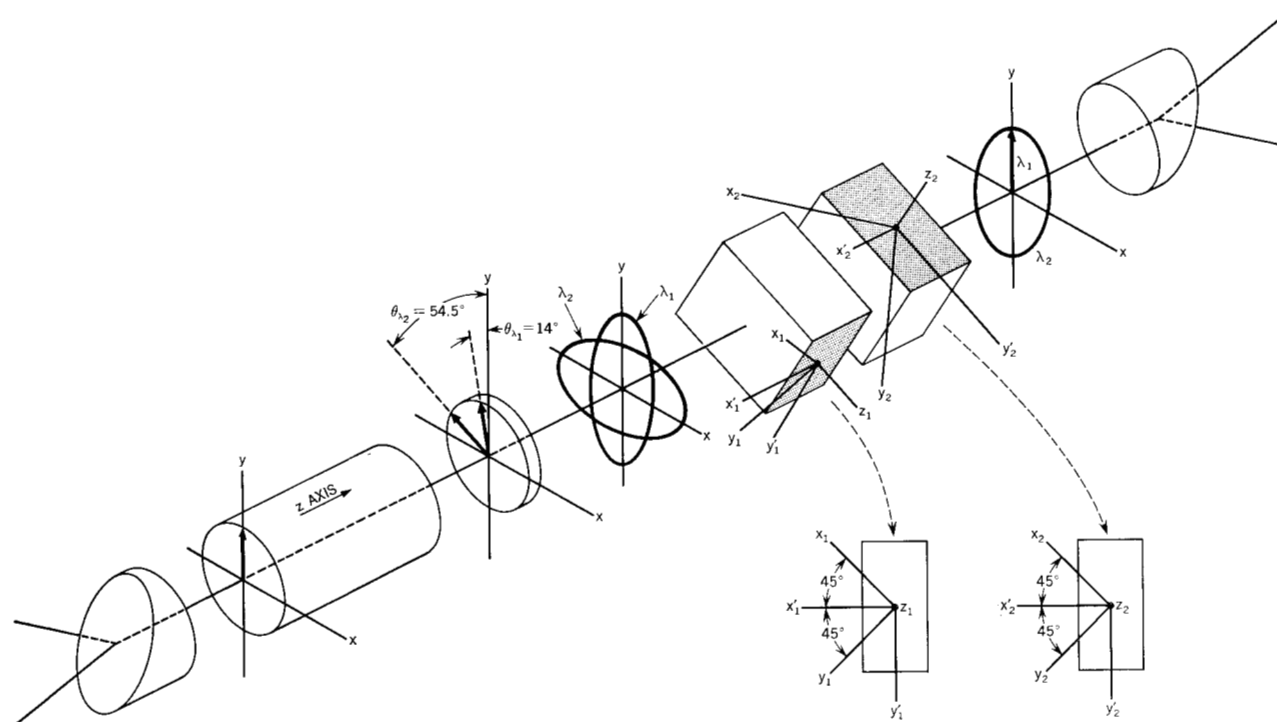


Figure 1 Optical elements in the voltage-tunable Q-spoiler.

Figure 2 Relative orientation of axes and light polarization at various points in the voltage-tunable Q-spoiler.



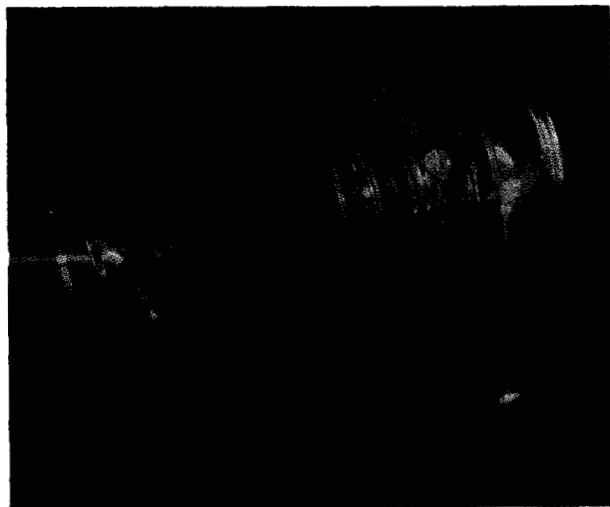


Figure 3 Color photographs of four different argon laser lines dynamically selected in the laser cavity. The wavelengths are (a) 5145, (b) 4765, (c) 4579 and (d) 4965 Å. The photograph (e) is of the voltage-tunable *Q*-spoiler which is placed in the laser cavity.

tion by an amount that depends on the wavelength. The planes of polarization for two arbitrary wavelengths after the light has passed through a length of quartz are shown in Fig. 2. These planes make angles θ_λ with respect to the y -axis.

The light then enters a crystalline quartz $\lambda/4$ plate whose optic axis is parallel to the y -axis. (This plate will not be an exact $\lambda/4$ plate for a band of wavelengths, but that error will be neglected at present.) The light leaving the plate will have an elliptical polarization according to the equation

$$\frac{x^2}{A^2 \sin^2 \theta_\lambda} + \frac{y^2}{A^2 \cos^2 \theta_\lambda} = 1,$$

and this ellipticity is shown in Fig. 2.

The electric field in the two KD*P electro-optic crystals is along the z -axes, which are rotated by 90° relative to each other so as to cancel the temperature dependence of the birefringence. The light travels down the x' -axis of each crystal. The z -axes of the two crystals are rotated 45° relative to the optic axis of the $\lambda/4$ plate. For an applied electric field E_z , the phase shift, ϕ , between a component, $A \sin \omega t$, along the z -axis of one electro-optic crystal and a similar component along the z -axis of the other electro-optic crystal is

$$\phi = \frac{2\pi}{\lambda} n_1^3 f_{63} t E_z,$$

where t is the light path length in each crystal, n_1 is the ordinary index of refraction of KD*P and f_{63} is the electro-optic constant for the field along the z -axis. After the light has passed through the electro-optic crystal, the components along the orthogonal z -axes are

$$Z_1 = (1/\sqrt{2}) A \sin(\omega t + \theta_\lambda),$$

$$Z_2 = (1/\sqrt{2}) A \sin(\omega t - \theta_\lambda + \phi).$$

By placing an appropriate electric field on the electro-optic crystals so that

$$\phi = 2\theta_\lambda,$$

the light of wavelength λ will again be linearly polarized along the y -axis. Light of all other wavelengths will remain elliptically polarized.

The Brewster angle window on this end of the Q -spoiler introduces reflection losses for all polarization components which are not parallel to the plane of incidence. Elliptically polarized light of all other wavelengths will be partially reflected out of the laser cavity. The light in the laser cavity propagates to one of the feedback mirrors of the cavity and is reflected back to the Q -spoiler window where all polarization components not parallel to the plane of incidence will again suffer loss.

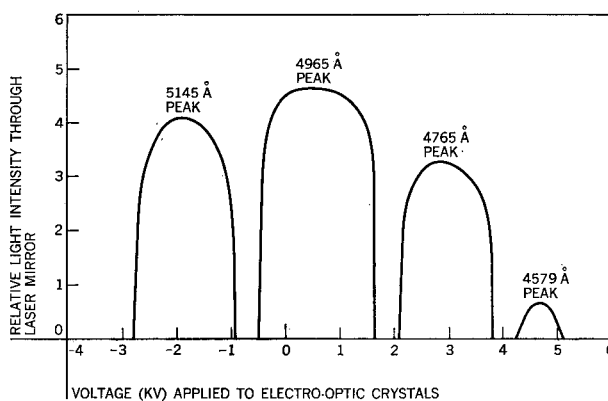


Figure 4 An experimental plot of the laser light intensity output as a function of the voltage applied to the electro-optic crystals in the voltage-tunable Q -spoiler. The four peaks correspond to four different wavelengths of laser oscillation.

An argon laser system consisting of a gas tube and feedback mirrors will have a net gain G_λ for $\lambda = 4579, 4658, 4765, 4880, 4965, 5017$, and $5145\text{\AA}$ at a fixed current in the electrical discharge. Normally, the gain in the $4880\text{\AA}$ line is much higher than in any of the other lines. For the purpose of frequency selection, the spectral reflectivity of one of the feedback mirrors has been tailored so that the single pass gain is approximately equal for all lines. The crystalline quartz rod is chosen to be of sufficient length that the polarization planes for the various lines are angularly well separated. The selection of one particular laser wavelength is accomplished by applying an electric field to the electro-optic crystals so that the light of the desired wavelength is linearly polarized and passes through the Brewster angle window with no loss. The laser lines of all other wavelengths suffer reflection losses at the Brewster angle window which are greater than G_λ ; hence oscillation in these other lines is prevented. Figure 3 shows four different lines dynamically selected in the laser cavity. The light intensity through one of the laser mirrors as a function of the voltage applied to the electro-optic crystals is shown in Fig. 4.

The most difficult task in developing operational capability for dynamic laser line selection is the reduction of optical losses in the optical components which compose the tunable Q -spoiler. The single pass gain for most of the lines in the argon laser is of the order of 15 percent. Therefore, the single pass losses in the Q -spoiler must be less than this figure, and should preferably be as low as possible to obtain a large usable power output. The windows to the Q -spoiler are prisms made of high quality fused quartz. The quartz rod is free of all optical and electrical twinning. The quartz $\lambda/4$ plate is constructed for $5000 \pm 50\text{\AA}$. The optical elements are stacked tightly

against each other with a film of DC-705* silicone oil between them for refractive index matching. The losses present in the Q -spoiler are now mainly due to crystalline inhomogeneities and scattering at the interfaces.

Braslau and Hardy¹³ have reported some measurements and calculations of the transient response of a Q -spoiled He-Ne laser. Switching times from below threshold to equilibrium of 20 to 100 μ sec were reported. The switching time for ionized argon is in the range of nanoseconds.¹⁴ These times would limit the dynamic tuning role assuming that electro-optic crystals can be switched with pulse rise times less than these relaxation times. A transition time of 8 μ sec has been measured in switching from the 5145 to the 4965 Å line. This is the maximum rate at which the control signal used in this experiment could be switched, however, and faster response is expected as the applied voltage switching time is decreased. In addition to the four argon lines shown in the photographs, we have been able to select the strong 4800 Å line.

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Acknowledgement

The authors wish to acknowledge the contributions of Mr. Robert Knechtel in the design and construction of the voltage-tunable Q -spoiler.

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Received April 29, 1966.