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FAST ACOUSTOOPTIC LENS Q SWITCH.(U)
APR 75 L D HUTCHESON, J JERNIGAN, M L SCOTT
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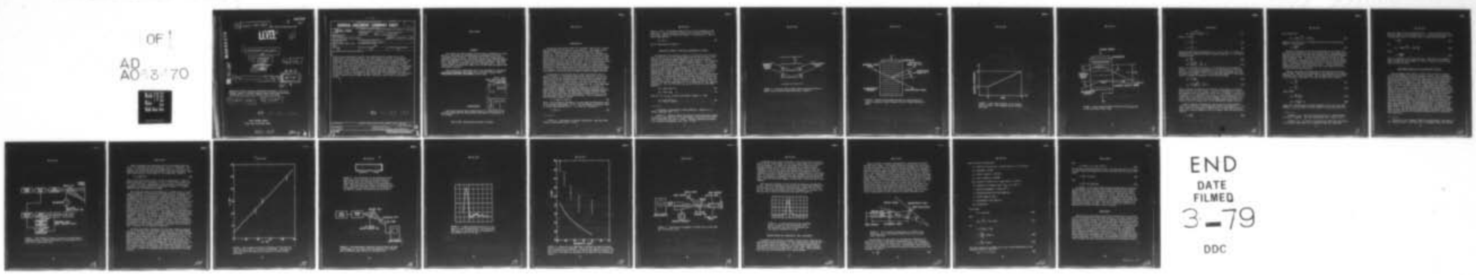

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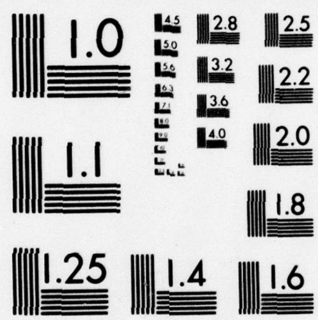

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LEVEL IV

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6 FAST ACOUSTOOPTIC LENS Q SWITCH.

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15. OUTLINE, TABLE OF CONTENTS, SUMMARY, OR EQUIVALENT DESCRIPTION

Analytical and experimental results have demonstrated the feasibility of this acoustooptic Q switching technique. The focal length of the lens is adjusted by varying the rate of frequency variation in a linear FM pulse of acoustic energy. The Q-switched laser output pulse width is adjusted by varying the bandwidth of the FM pulse. The theoretical and experimental results verify that accurate predictions can be made about the operation of the fast acoustooptic lens Q switch. A significant improvement in the operation of the lens Q switch has been presented with a detailed analysis of a typical system. It is anticipated that this technique will be tested in the near future. This technique also offers significant advantages over its electrooptic Q switch counterpart in many situations. In particular, the acoustooptic Q switch requires lower voltages and fewer intracavity parts than an electrooptic switch.

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FOREWORD

This report has been prepared for the timely presentation of information on the analytical and experimental development of the fast acoustooptic lens Q switch. The feasibility of this project was successfully demonstrated with Q switching a Nd/YAG laser with the acousto-optic lens approach. It reports on preliminary findings of the study and is released at the working level for information only. This is an interim report and additional reports will be published as research and development continues.

This research and development effort was performed for the period June through September 1974, supported by the Naval Weapons Center independent exploratory development project funds.

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31 March 1975

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INTRODUCTION

An acoustic wave which travels in a material consists of a sinusoidal perturbation of the density of the material. This change in the density of the medium causes a change in the material's index of refraction. These acoustic waves propagate from a flat piezoelectric crystal into an acoustooptic crystal and form almost planar wave fronts traveling in the crystal. The optical waves enter the crystal approximately parallel to the acoustic wave fronts, and are diffracted by the phase grating formed by the acoustic waves. If the optical beam strikes the acoustic traveling waves at the proper angle, the optical beam appears to be reflected from the acoustic waves in a manner which is analogous to that by which X-rays are reflected from the lattice planes of a crystal. This reflection of the optical beam satisfies the same relationship as the X-ray case and hence is known as Bragg reflection.

Considering an optical beam which strikes the acoustic wave as shown in Figure 1, a necessary condition for diffraction is that the diffraction from any two acoustic phase fronts add up in phase along the direction of the reflected beam.[1] The path difference AB + BC, shown in Figure 1, of a given optical wave front resulting from two equivalent acoustic wave fronts must be equal to the optical wavelength λ or an integral multiple of the wavelength, $n\lambda$. In the case of acoustooptical crystals there exists a sinusoidal variation of the phase fronts as opposed to conventional diffraction gratings where the phase fronts are abrupt. This means that a Fourier analysis yields only one diffraction order for acoustooptic deflectors (i.e., $n = 1$), and many orders exist for the abrupt grating. For an acoustooptical beam deflector, Figure 1 yields

$$\lambda = \Lambda (\sin \phi + \sin \theta) \tag{1}$$

where ϕ is the angle of incidence, θ is the angle of diffraction, and Λ is the acoustic wavelength. If $(\theta + \phi)/2$ is assumed to be small, which is a good approximation since $\lambda << \Lambda$, then Eq. 1 reduces to

$$\theta = \frac{\lambda}{v} f - \phi \tag{2}$$

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[1] Yariv, A. *Introduction to Optical Electronics*. New York, Holt, Rinehart, and Winston, 1971. P. 35.

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where $\Lambda = v/f$, v is the sound velocity and f is the frequency of the sound wave. Each acoustooptic device has an acoustical bandwidth Δf, with which a change in diffraction angle $\Delta\theta$, is associated.[2] This is better described by

$$\Delta\theta = \frac{\lambda}{v}\,\Delta f \tag{3}$$

and is illustrated in Figure 2.

ANALYTICAL ASPECTS OF THE FAST ACOUSTOOPTIC Q SWITCH

As described in the previous section, if an acoustic wave interacts with an optical wave at the proper angle then the optical beam is diffracted at a particular angle dependent on the acoustic frequency. Instead of applying a constant single frequency signal to the transducer, a chirp signal is applied as shown in Figure 3, where $f_1 - f_2$ is the bandwidth B of the transducer and $t_1 - t_2$ is the acoustic transit time across the optical beam. The uppermost optical ray in Figure 4 encounters an acoustic wave of higher frequency f_1 and the lower optical ray interacts with a lower frequency f_2 acoustic wave. The upper ray is diffracted at a larger angle θ_1 and the lower ray is diffracted at a smaller angle θ_2 since the angle of diffraction is directly proportional to the RF. The rays between these two extreme rays are diffracted proportionately to the RF each ray encounters. The resultant optical beam is focused to a line.[3] If the coordinate system is chosen as shown in Figure 4 then the two dimensions of x and y remain as the only important coordinates. Now the focus point x_F, y_F can be found by using simple geometry,

$$y_F = (\tan\theta_1)x_F + y_1 \tag{4}$$

$$y_F = (\tan\theta_2)x_F \quad y_2 \tag{5}$$

where θ_1, θ_2, x_F, y_F, y_1, and y_2 are shown in Figure 4. Thus,

$$x_F = \frac{L}{\tan\theta_1 - \tan\theta_2} \tag{6}$$

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[2] *Principles of Acoustooptic Light Deflection*. Oakland, N. J., Isomet, September 1970. P. 4.

[3] Atzeni, C. "Optical Signal-Processing by Filtering Fresnel Images of Acoustic Light-Modulators," in *Proceedings, Electro-Optical Systems Design Conference*, ed. by M. S. Kiver. Chicago, Industrial and Scientific Conference Management, Inc., 1970. P. 662.

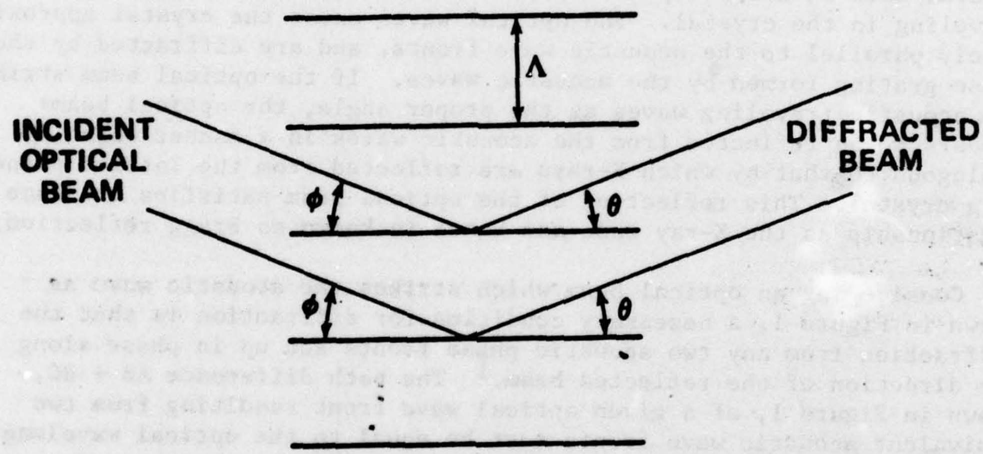

FIGURE 1. An Optical Beam Incident Upon an Acoustical Wave at Angle ϕ and the Optical Beam Diffracted at Angle θ.

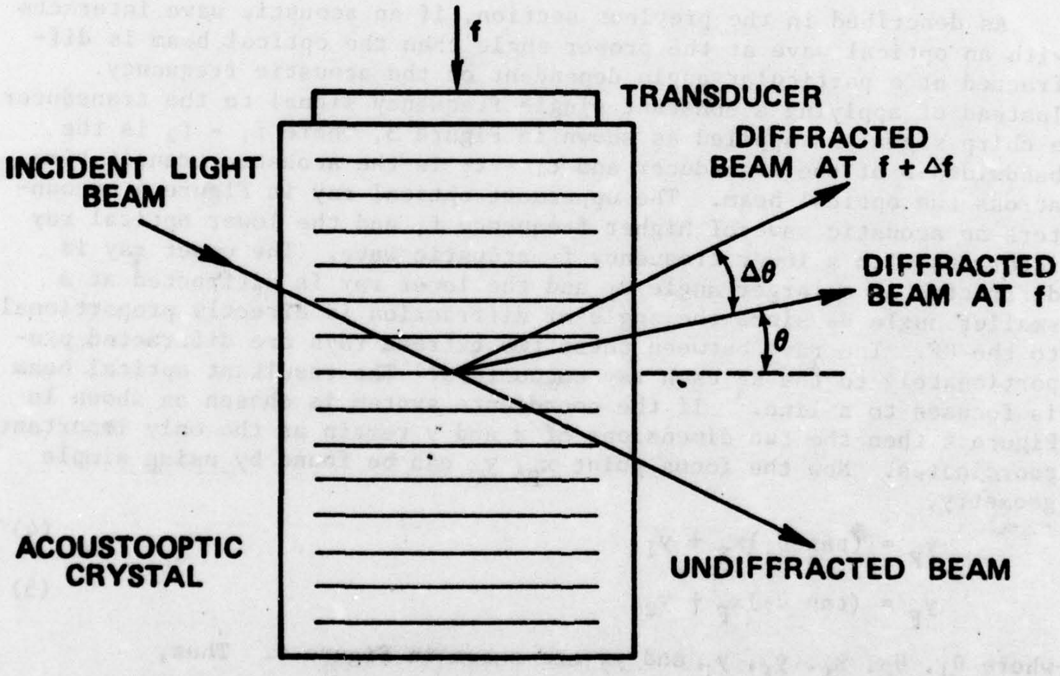

FIGURE 2. Physical Relationship Between the Optical Beam and Acoustic Frequency; Larger Frequency Yields a Larger Diffraction Angle.

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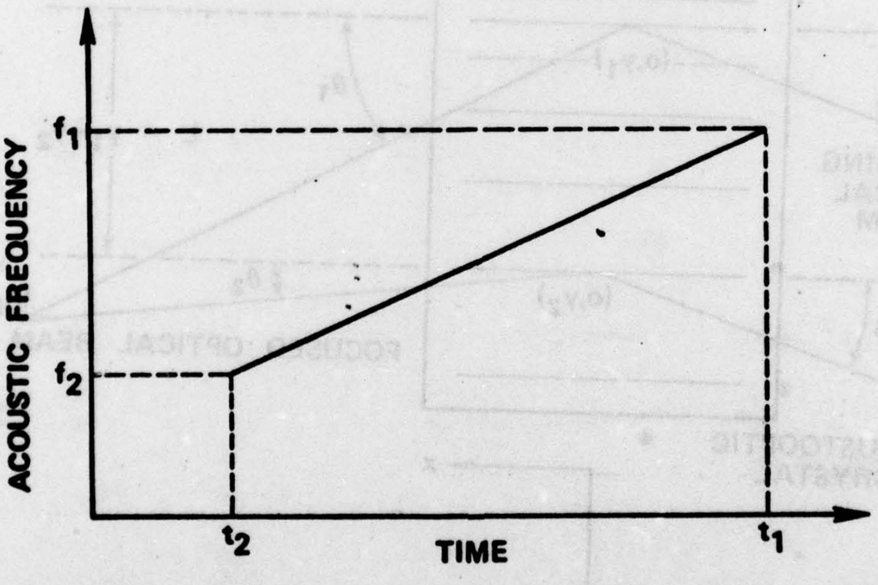

FIGURE 3. Chirp Signal Applied to the Acousto-optical Crystal. The frequency varies linearly with time.

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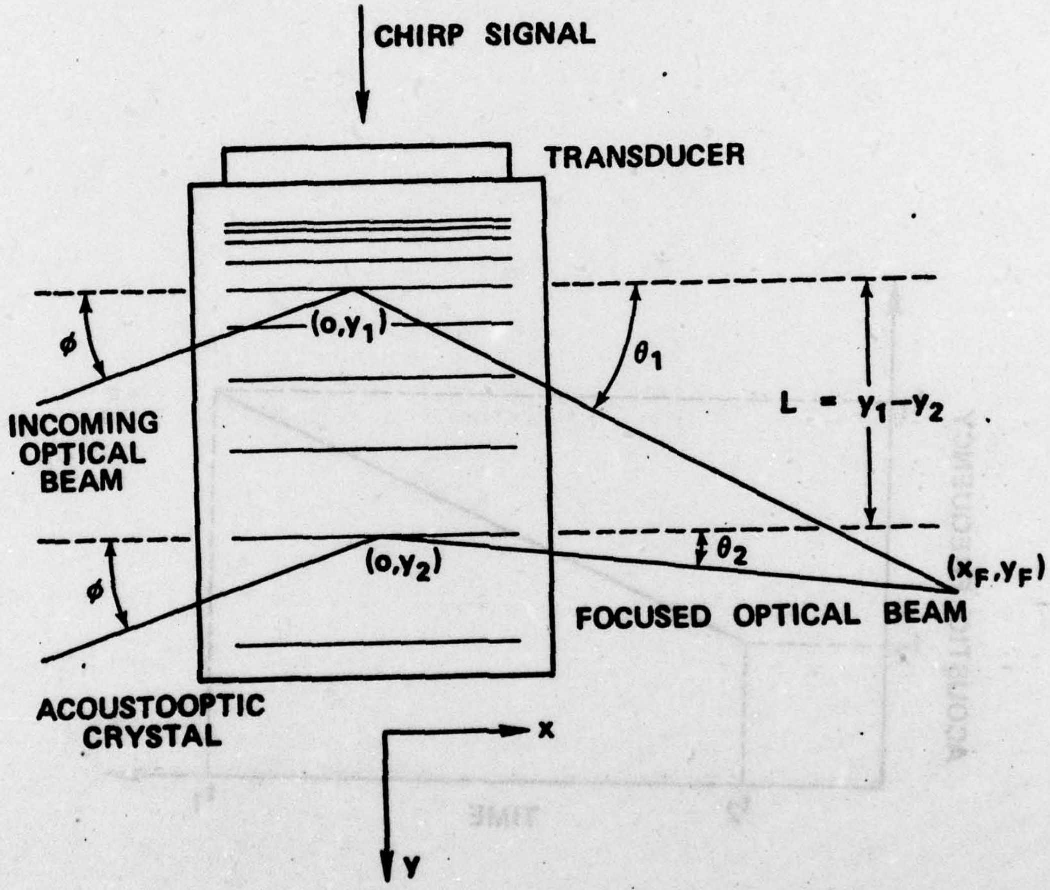

FIGURE 4. Output Optical Beam is Focused at Point x_F, y_F Due to the Traveling Acoustic Wave.

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$$y_F = \frac{L \tan \theta_1}{\tan \theta_1 - \tan \theta_2} + y_1 \qquad (7)$$

and Eq. 2 yields,

$$\theta_1 = \frac{\lambda f_1}{v} - \phi \qquad (8)$$

$$\theta_2 = \frac{\lambda f_2}{v} - \phi \qquad (9)$$

Using the small angle approximation (i.e., $\tan \theta = \sin \theta = \theta$) which is good since θ is typically 50 mrad or smaller using Eqs. 6, 7, 8, and 9, x_F and y_F become

$$x_F = \frac{Lv}{\lambda B} \qquad (10)$$

$$y_F = \frac{Lv}{\lambda B}\left(\frac{\lambda f_1}{v} - \phi\right) + y_1 \qquad (11)$$

where v is the velocity of sound, L is the aperture of the acoustic crystal, λ is the optical wavelength, B is the bandwidth of the transducer, f_1 is the upper frequency, y_1 is the upper coordinate and ϕ is the angle of incidence. If $t = L/v$ is the time required for the sound waves to traverse the aperture L then 10 and 11 become

$$x_F = \frac{v^2}{\lambda}\left(\frac{t}{B}\right), \qquad (12)$$

$$y_F = \frac{v^2}{\lambda}\left(\frac{t}{B}\right)\left(\frac{\lambda f_1}{v} - \phi\right) + y_1 \qquad (13)$$

Since the angles in question are relatively small then x_F is approximately equal to the focal length. Also x_F is independent of f_1 and f_2 but dependent upon the chirp rate (t/B) which is constant for linear FM. In general y_F is a function of f_1 and y_1. y_1 may change in some situations and f_1 is in general a linear function of time, therefore, y_F is also a linear function of time, and is swept, which is the key to the Q switch as will be shown later in the Experimental Results section.

Another important parameter for the use of the chirped acoustic cell for Q switching is the diffraction limited time resolution τ. In other words, if a diffraction limited spot Δy is being swept across a narrow slit (narrow compared to Δy) at a speed v then the time resolution is

$$\tau = \frac{\Delta y}{v} \qquad (14)$$

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For a plane wave[4]

$$\Lambda y = (.887)\ \frac{\lambda x_F}{L} = (.887)\ \frac{v}{B} \tag{15}$$

therefore the device has a switching time which is inversely proportional to the bandwidth,

$$\tau = \frac{(.887)}{B} \tag{16}$$

The above configuration has the disadvantage that the Bragg criterion is not satisfied over the entire optical beam. The Bragg angle is dependent upon the RF and since the frequency is continuously changing over the optical beam $\phi = \phi_B$ at only one frequency (usually at the center frequency, f_c). Therefore, since in general $\phi \neq \phi_B$ the deflection efficiency is degraded, more seriously at the two extreme frequencies. The amount of energy deflected into the focused line decreases which in turn reduces the laser output power.[5] Also the effective bandwidth decreases, which affects both the focal length and the diffraction limited time resolution.

Ideally, the Bragg criterion should be satisfied over the entire optical beam. This can be accomplished if the incoming optical beam is divergent rather than collimated. Now the Bragg angle can be matched at all acoustic frequencies. For this case Eqs. 8 and 9 become,

$$\theta_1 = \frac{\lambda f_1}{2v} \tag{17}$$

$$\theta_2 = \frac{\lambda f_2}{2v} \tag{18}$$

which yields

$$x_f = \frac{2v^2}{\lambda}\left(\frac{\tau}{B}\right), \tag{19}$$

$$y_f = vf_1\left(\frac{\tau}{B}\right) + y_1 \tag{20}$$

thus, the x focal distance is again dependent only on the chirp rate, however, x_F is now twice the focal length as in the plane wave case

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[4] Sherman, J. W. "Aperture-Antenna Analysis," in *Radar Handbook*, ed. by M. I. Skolnik. New York, McGraw-Hill, 1970. Chap. 9, p. 9.

[5] Gordon, E. I. "A Review of Acoustooptical Deflection and Modulation Devices," PROC IEEE, Vol. 54 (October 1966), pp. 1391-1401.

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and y_F is swept by the time variation of f_1. Due to an angular multiplication effect in the divergent wave case the diffraction limited spot is being swept across the narrow slit at a speed 2v which yields

$$\tau = \frac{\Delta y}{2v} \tag{21}$$

but

$$\Delta y = (.887)\ \frac{\lambda x_F}{L} = (.887)\ \frac{2v}{B}\ , \tag{22}$$

thus,

$$\tau = \frac{(.887)}{B} \tag{23}$$

which is identical to the plane wave case. Therefore, the divergent waves increase the focal length by a factor of two, but the time resolution is kept the same.

EXPERIMENTAL RESULTS OF THE ACOUSTOOPTIC CRYSTAL

The experimental setup shown in Figure 5 was utilized to measure the various parameters of the acoustooptic crystal. The acoustooptic crystal used in these experiments was made of a relatively new material, tellurium dioxide (TeO_2). TeO_2 has a high figure of merit and a low sound velocity (.617 mm/μsec).[6] The high figure of merit means that a smaller RF power is needed to achieve larger deflection efficiency, while a low sound velocity indicates a larger deflection angle, θ, as shown in Eq. 2. The chirp signal was generated by frequency modulating (FM) a sweep generator. The output frequency of the sweep generator is dependent upon the voltage at the FM input. A linear ramp from a signal generator was the input to the sweep generator. The center frequency and the voltage swing of the linear ramp were all set to give the desired frequency bandwidth. The bandwidth could be varied by changing the peak-to-peak voltage swing of the linear ramp. The output of the sweep generator was gated by an RF switch at the rate of the acoustooptic cell aperture time. The sweep generator has a continuously variable output amplitude with a 10 mW maximum output. Therefore a 40 dB power amplifier is used to boost the RF power into the transducer to about 1 watt. The average power is monitored by a wattmeter to insure that the power does not exceed maximum levels, otherwise, if the maximum power level is exceeded the transducer bonding material is heated and will break down.

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[6] Uchida, N., and Y. Omachi, "Elastic and Photoelastic Properties of TeO_2 Single Crystal," J APPL PHYS, Vol. 40 (November 1969), pp. 4692-95.

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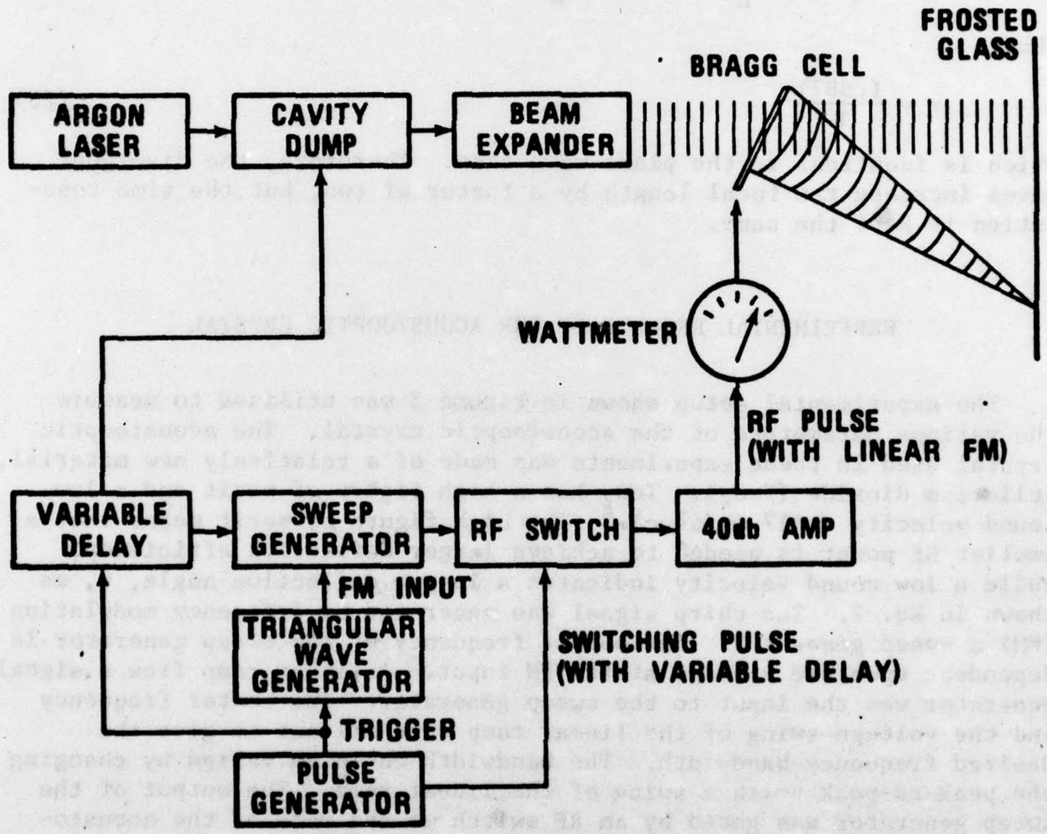

FIGURE 5. This Schematic Diagram Illustrates the Experimental Arrangement Used to Observe and Measure the Coordinates of the Focus of the Acoustooptic Lens.

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These experiments were performed with a cavity-dumped argon-ion laser (λ = .5145 μm) and a CW helium-neon laser (λ = .6328 μm). The output of the argon-ion laser was expanded such that the entire cell aperture was filled and the incoming laser light was collimated. Under these conditions the focal length of the acoustooptic crystal is

$$F = \sqrt{x_F^2 + y_F^2} \tag{24}$$

where x_F and y_F are given by Eqs. 10 and 11 respectively. Figure 6 gives a plot of y_F vs. x_F where L = 1 cm, $v = 6.17 \times 10^4$ cm sec^{-1} and $\lambda = 5.145 \times 10^{-5}$ cm. A photograph of the deflected (focused) beam alongside the undeflected beam is indicated in Figure 7. A frosted glass was used to visualize this image.

The second experiment was performed with a CW HeNe laser at a wavelength of 6328 Å. In this case the incoming light on the Bragg cell was made divergent by using a pair of prisms as shown in Figure 8. The arrangement of the pulse generator, signal generator, sweep generator, and RF switch indicated in Figure 5 was used to generate the pulsed linear FM signal. The length of the FM pulse was adjusted to equal the length of the aperture in the Bragg cell. The rate of change of frequency within the pulse was adjusted so that a change in frequency just equal to the desired bandwidth was accomplished. A narrow slit with a photomultiplier tube immediately behind it was placed at the focal coordinates given by Eqs. 19 and 20. The output of the photomultiplier was viewed on a fast oscilloscope. A representative oscilloscope trace is shown in Figure 9. The results of this experiment are summarized in Figure 10. The solid line in this figure indicates the diffraction limited case predicted by Eq. 23. The values of τ that were measured are consistently higher than the diffraction limit. This is primarily attributable to small errors in alignment of the optical system and any nonlinearity of the frequency modulation. The data clearly indicates that τ decreases for an increase in bandwidth.

The third preliminary experiment that has been conducted involved the use of the TeO_2 cell to Q switch a Nd/YAG laser. The experimental arrangement is shown in Figure 11. A knife edge rather than a slit was used in front of the mirror due to alignment difficulties with a slit. Mirrors of 100% reflectivity were used at both ends of the cavity. In this configuration there are two output beams from the cavity. The desired output beam is the undeflected plane wave from the Nd/YAG rod which passes straight through the Bragg cell. An undesirable output is also present in this configuration. The undeflected portion of the returning divergent wave is energy lost to both the feedback and output beam paths. A method of preventing this loss is discussed in the next section.

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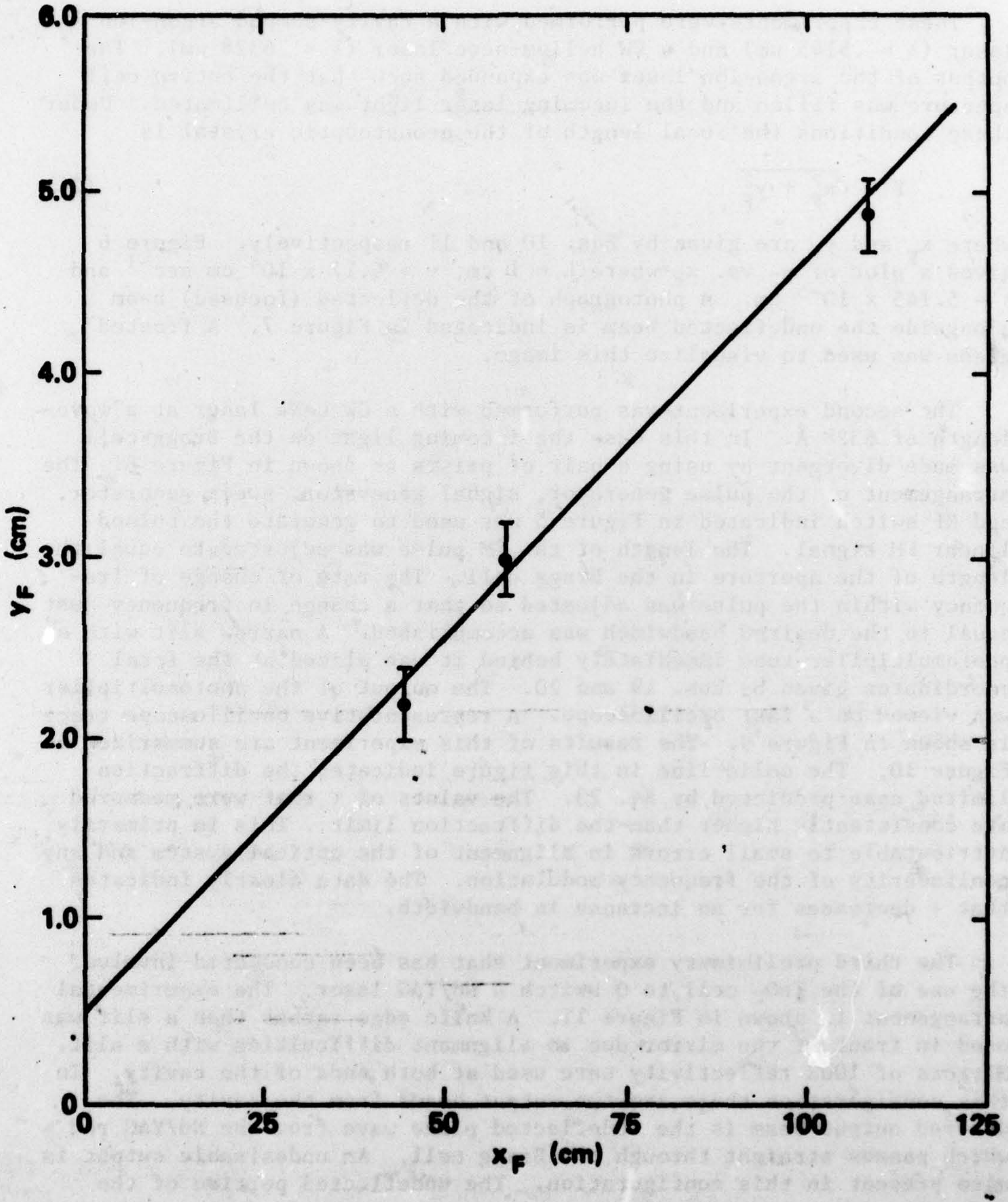

FIGURE 6. The Straight Line Gives the Position of the Focus of the Acoustooptic Lens as a Function of Bandwidth. From left to right, the three data points were measured at 30 MHz, 20 MHz, and 10 MHz.

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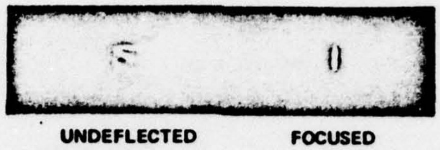

FIGURE 7. This Photograph of the Undeflected Argon Laser Beam on the Left and the Focused Deflected Beam on the Right was Observed Through a Frosted Glass Placed in the Focal Plane of the Acoustooptic Lens. The argon laser was pulsed in synchronism with the presence of the acoustic pulse in the Bragg cell in order to "freeze" the motion of the focal line.

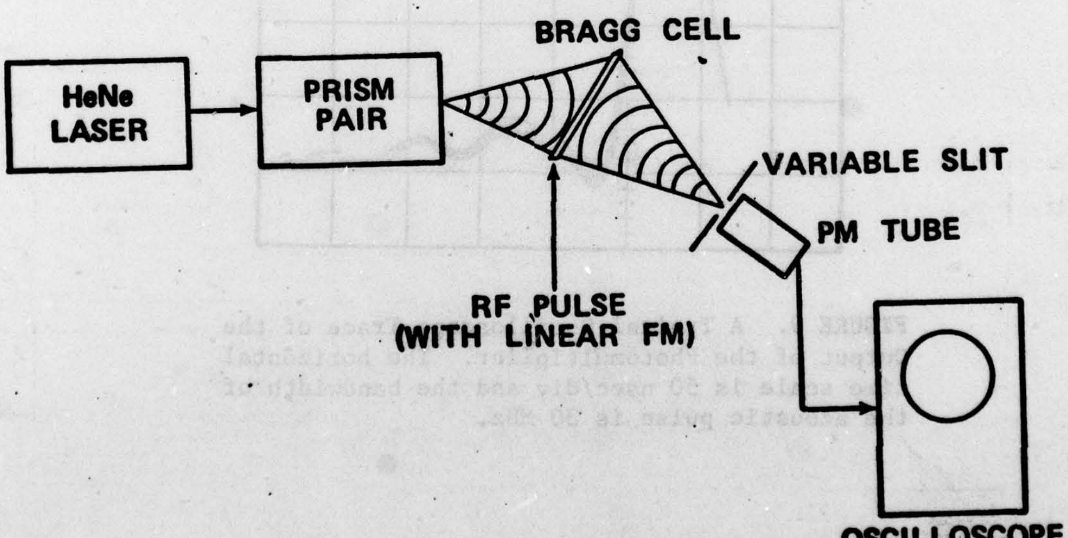

FIGURE 8. The Experimental Apparatus Indicated Here was Used to Determine the "on" Time of the Acoustooptic Lens Q Switch with a Divergent Beam Incident on the Bragg Cell.

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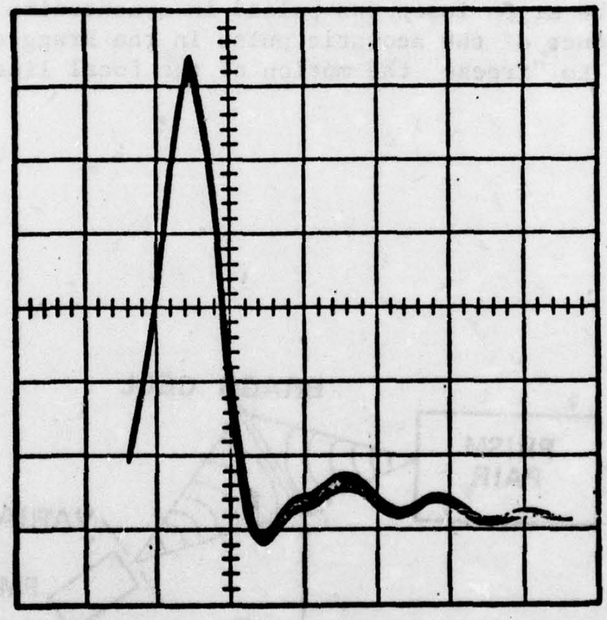

FIGURE 9. A Typical Oscilloscope Trace of the Output of the Photomultiplier. The horizontal time scale is 50 nsec/div and the bandwidth of the acoustic pulse is 30 MHz.

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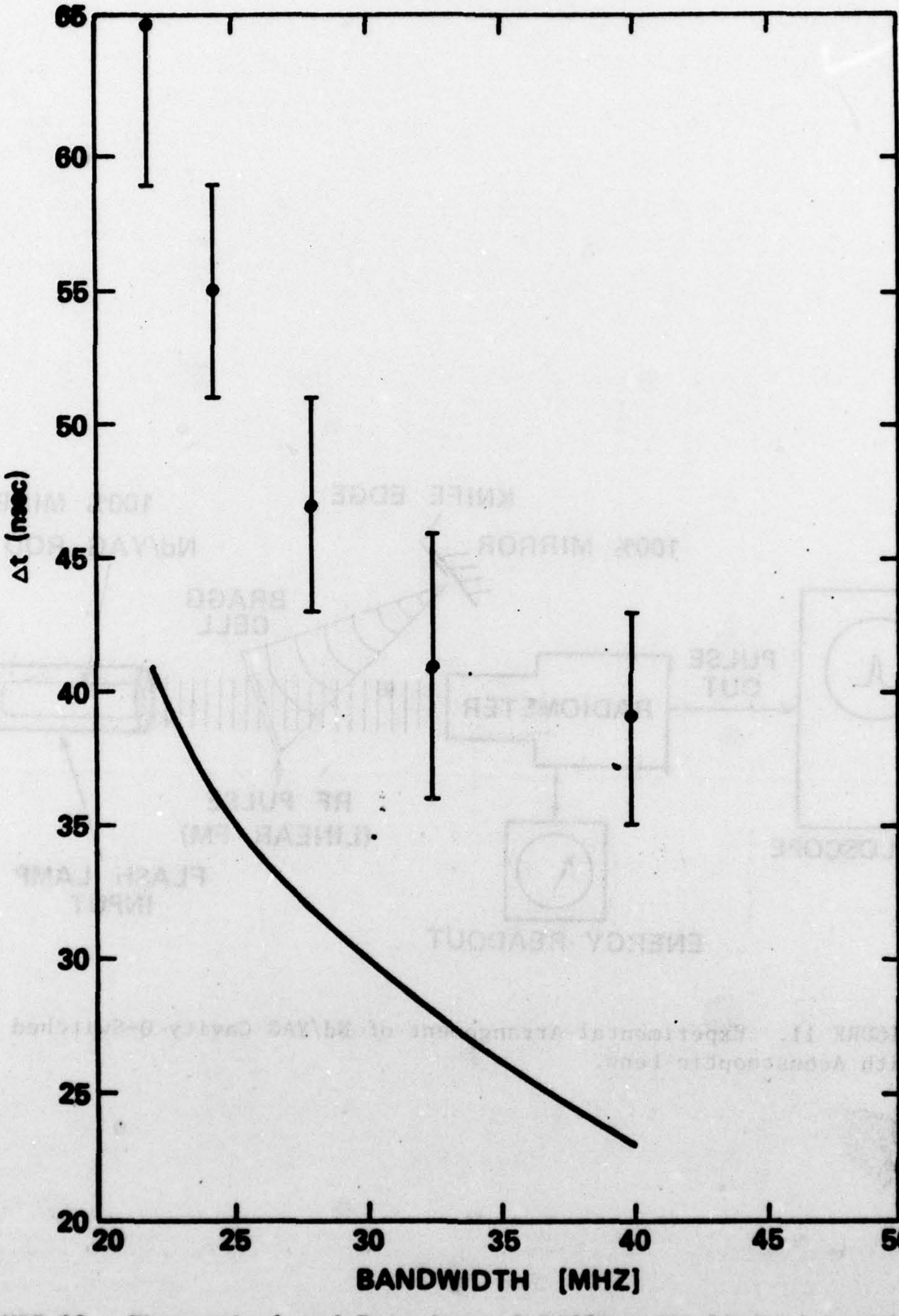

FIGURE 10. Theoretical and Experimental Diffraction Limited Aperture Time as a Function of Bandwidth. The solid line indicates the theoretical diffraction limit for the "on" time of this type of Q switch. The error bars on the data are estimates of the widths of the oscilloscope traces.

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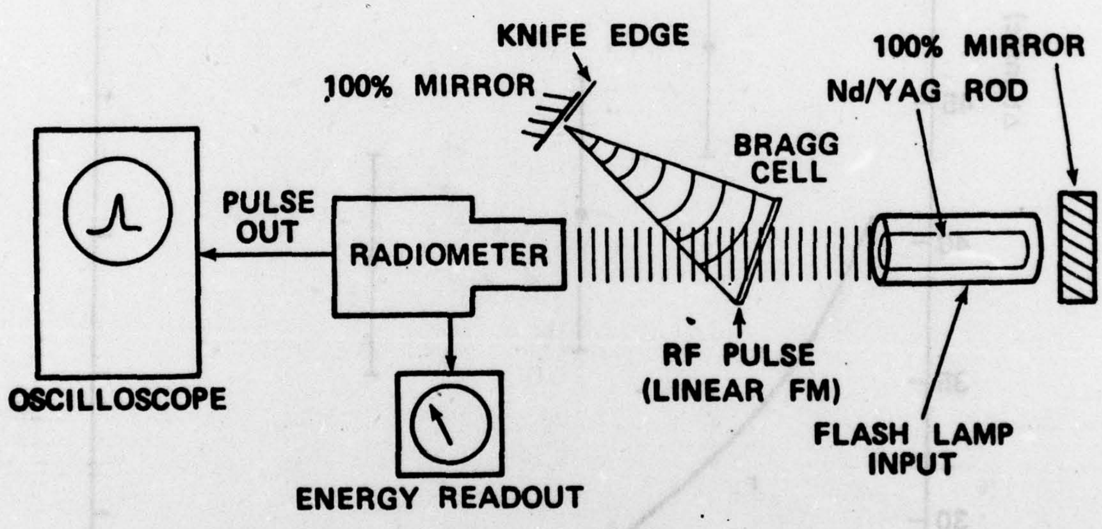

FIGURE 11. Experimental Arrangement of Nd/YAG Cavity Q-Switched With Acoustooptic Lens.

A radiometer was placed in the path of the output beam to provide a measure of the energy output, as well as a pulse signal to be viewed on the oscilloscope. The TeO_2 cell was coated with an antireflection coating suitable for the 10.6 μm wavelength of the Nd/YAG output. Alignment of the optical cavity was facilitated by using a partially reflective mirror in the output beam between the Bragg cell and the radiometer to achieve lasing action with no signal applied to the Bragg cell. As the power to the Bragg cell was increased, the deflected beam could be located for placement of the 100% reflective mirror and knife edge. Once the cavity was aligned, the partially reflective mirror was removed.

The effective bandwidth of the acoustic RF pulse was approximately 33 MHz. Since the configuration used involves a plane wave incident on the Q switch cell, this gives a switching time of about 30 nsec from Eq. 16. The Q-switched output from this arrangement is a 50 nsec, 100 kW pulse with a typical Q-switched pulse shown in Figure 12.

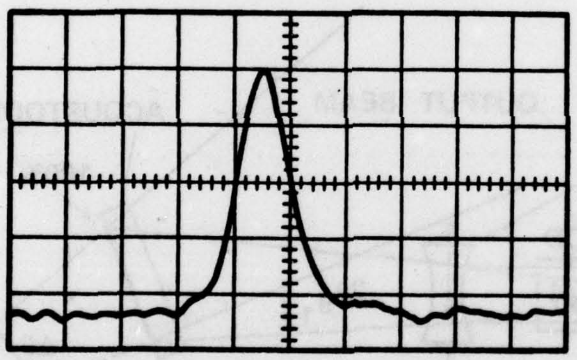

FIGURE 12. A Q-Switched Pulse From the Nd/YAG Cavity is Shown in This Oscilloscope Trace. The horizontal time scale is 50 nsec/div and the acoustic bandwidth is 33 MHz.

ANOTHER METHOD FOR ACOUSTOOPTIC LENS Q SWITCHING

As stated in the previous discussion on the Q switch there are two simultaneous Q-switched outputs. In that configuration a substantial loss in laser energy is encountered. The following configuration is one possible method for eliminating the loss of laser power, thereby increasing the Q-switched output power of the laser. This discussion will also give the calculations for a typical system.

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Figure 13 shows a proposed configuration of achieving only one Q-switched laser output. The primary difference between this configuration and the previous one is the back face of the Bragg cell has a 100% reflection coating. Now the transmitted Bragg reflection is combined with the reflected Bragg reflection to yield a more efficient Q-switched laser. The energy density inside a Q-switched laser cavity is usually very large. Consequently the divergent lens not only improves the Bragg angle matching condition in the acoustooptic cell but also decreases the energy density in the Bragg cell which reduces the possibility of damage. Another advantage of the divergent beam inside the laser cavity is that the output beam has a better chance for single mode operation. The higher order modes are more divergent than the lower order modes, consequently the higher order modes will diverge out of the laser cavity and only the lowest order mode will remain inside the laser cavity. Figure 13 also shows the output beam to the divergent, but the output can be recollimated by using a long focal length convergent lens.

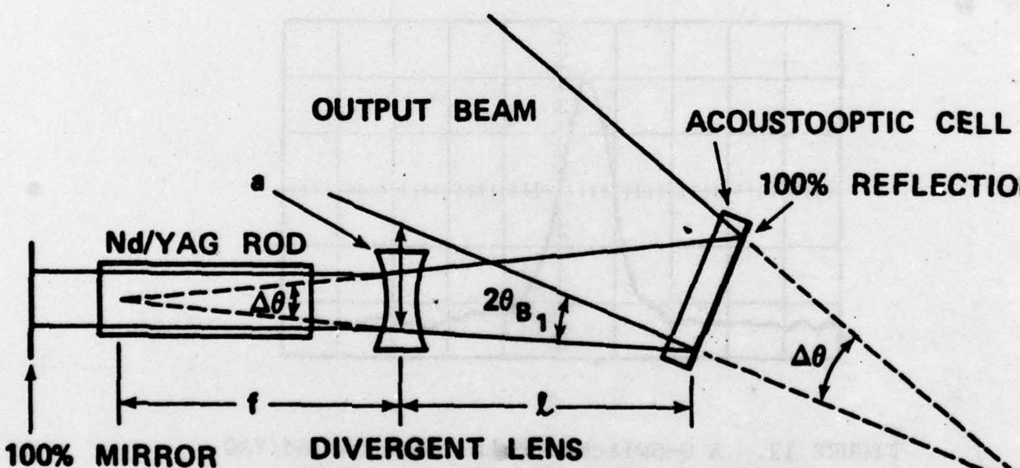

FIGURE 13. This Proposed Configuration of a Nd/YAG Cavity Eliminates one of the Undesired Output Beams and Increases Laser Efficiency.

The following is a calculation of the important parameters of a laser system using a fused quartz acoustooptic cell. The limiting factors of the size of the laser cavity is determined by the distance ℓ and the focal length (f) of the lens. The distance ℓ has to be sufficently long such that the diffracted beam is not obscured by the lens. From Eqs. 17 and 18

$$\Delta\theta = \frac{\lambda B}{2v} \qquad (25)$$

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where for these calculations:

v = velocity of shear wave in fused quartz = 3.7×10^3 m/sec

B = bandwidth = 20 MHz

f_c = center frequency = 200 MHz

f_l = lower frequency = 190 MHz

d_B = diameter of Nd/YAG rod = laser beam = 6×10^{-3} m

L = diameter of divergent lens = $2d_B$ = 12×10^{-3} m

λ = optical wavelength = 1.06×10^{-6} m

ℓ = distance between lens and Bragg cell

f = focal length of lens

A = acoustooptic cell aperture

Θ_B = Bragg angle

this yields

$$\Delta\Theta = 2.86 \text{ mrad} \tag{26}$$

and

$$2\Theta_B = \frac{\lambda f_1}{v} = 54.4 \text{ mrad} \tag{27}$$

for

$$a = \ell(2\Theta_{B_1}) = 2d_B$$

$$\ell = \frac{2d_B}{2\Theta_{B_1}} = .2206 \text{ m} \tag{28}$$

$$f = \frac{d_B}{\Delta\Theta} = 2.098 \text{ m} \tag{29}$$

The focal length of the Bragg cell is not of much importance in this configuration but is given by

$$x_F = \ell + f = 2.32 \text{ m} \tag{30}$$

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and

$$A = \Delta\theta(\ell + f) = 6.64 \times 10^{-3} \text{ m} \tag{31}$$

For the above calculated aperture size A the time allowed for the chirp to travel across the Bragg cell (t) and the chirp rate (R) can be calculated

$$t = \frac{A}{v} = 1.79 \ \mu\text{sec} \tag{32}$$

and

$$R = \frac{B}{t} = 11.2 \text{ MHz}/\mu\text{sec} \tag{33}$$

In summary, if the above design constraints were used to construct an acoustooptic lens Q switch, the divergent cylindrical lens must be spaced .22 meter from the Bragg cell and the lens must have a focal length of 2.09 meters with a diameter of 12 mm. The aperture of the quartz cell must be 6.64 mm which will yield an aperture time of 1.79 μsec and a chirp rate of 11.2 MHz/μsec. Although the focal length of the Bragg cell is long, the presence of the divergent lens and the 100% reflection coating on the rear of the cell increase the length of the laser cavity by only .22 meter. The size of the laser itself may be decreased by folding the laser cavity if desired.

CONCLUSIONS

Analytical and experimental results have demonstrated the feasibility of this acoustooptic Q switching technique. The focal length of the lens is adjusted by varying the rate of frequency variation in a linear FM pulse of acoustic energy. The Q-switched laser output pulse width is adjusted by varying the bandwidth of the FM pulse. The theoretical and experimental results verify that accurate predictions can be made about the operation of the fast acoustooptic lens Q switch. A significant improvement in the operation of the lens Q switch has been presented with a detailed analysis of a typical system. It is anticipated that this technique will be tested in the near future. This technique also offers significant advantages over its electrooptic Q switch counterpart in many situations. In particular, the acoustooptic Q switch requires lower voltages and fewer intracavity parts than an electrooptic switch.

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