# NIOBIUM COMPOUNDS IN ACOUSTICS AND ELECTROOPTICS

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Abstract

Niobium compounds, mainly mixed oxides, have found wide application in ultrasonics, acoustooptics, electrooptics, and nonlinear optics. Ultrasonic applications include transducers, wideband microwave delay lines, filters, and a variety of surface acoustic wave (SAW) signal processing devices, largely based on single crystal lithium niobate. The acoustooptic (AO) applications of niobates include beam scanners and deflectors, modulators, Q-switches for lasers, tuneable optical filters, and a number of more exotic signal processing devices. Electrooptic (EO) applications of niobates include optical polarization and phase modulators for communications, Q-switches for lasers, holographic storage, and integrated optical circuits. Niobates are used in nonlinear optics for optical frequency doubling, optical mixing, and parametric oscillation. ?or virtually all of these applications, the niobium compounds are prepared as large, high quality single crystals, and are then appropriately processed by orienting, cutting, and polishing.

## Introduction

Niobium compounds, primarily mixed oxide single crystals, have found very wide application in the areas of ultrasonics, surface acoustic wave devices, acoustooptics, electrooptics, and nonlinear optics. The most useful material is predominantly lithium niobate, although the list of niobium compounds used in these applications is impressive for a single element. In Table I is listed a number of niobium compounds and their applications obtained from the literature over the last twenty years. While many niobium coumpounds have been prepared and studied on an experimental basis, lithium niobate has been utilized on a large scale in both commercial and military systems. Therefore, this paper will deal mainly with the uses of lithium niobate. Applications of other, but less widely utilized, niobium compounds in electrooptics will be described.

Lithium niobate is one of those rare materials, such as silicon, that has a multitude of useful properties and yet can be readily grown, processed, and used in devices. It is a transparent, moderately hard, and relatively dense material that physically resembles clear glass. The physical, acoustic, electrooptic, and nonlinear properties of lithium niobate are summarized in Table II.

## Preparation of Crystals

Lithium niobate single crystals are grown by the Czochralski process from a high temperature melt contained in a platinum crucible heated by radio frequency induction or by platinum resistive heater elements. Figure 1 shows a schematic diagram of a typical Czochralski crystal growth station that is used to grow niobate single crystals. The melt is prepared from the appropriate reagents, an oriented single crystal seed is dipped into the melt, and then withdrawn very slowly. The furnace is designed to control temperature gradients in the space over the melt to avoid strain and cracking in the crystal boule.

The niobate crystals used in many applications are ferroelectric in the temperature range of interest. That is, they exhibit a spontaneous dielectric polarization in a similar way as a ferromagnetic material exhibits a magnetic polarization. A ferroelectric such as lithium niobate undergoes a phase transition from the paraelectric to the ferroelectric state as the temperature is reduced below the Curie point. Upon cooling through the Curie point from the growth temperature, the crystal becomes polarized in a mosaic pattern of oppositely polarized domains so that the average polarization is zero and the net free energy is minimized.

Unfortunately, the performance of virtually all the devices depends critically upon having single domain, single crystal specimens. The crystals must, therefore, be "poled" in a furnace similar to the one shown in Figure 2. The crystal is polished on the polar faces, usually the faces normal to the c-axis, and conducting platinum paste electrodes applied. The crystal is heated to a temperature above the Curie point and sufficient voltage is applied to produce a current density of the order of $1mA/cm^2$ in the crystal. The crystal is then cooled slowly through the Curie temperature to produce a single domain specimen. After poling is finished, the crystal can then be cut and polished to fabricate samples of the desired size and shape.

## Table I. Niobates Used as Piezoelectric Transducers.

| Material | DIELECTRIC CONSTANT LOW FREQUENCY $\varepsilon_1/\varepsilon_o$ | $\varepsilon_2/\varepsilon_o$ | $\varepsilon_3/\varepsilon_o$ | ELECTROMECHANICAL COUPLING FACTOR LONGITUDINAL k | ORIENTATION | SHEAR k | ORIENTATION |
|---|---|---|---|---|---|---|---|
| $LiNbO_3$ | 43 | 45 | 29 | 0.49 | 36° rotated X-cut | 0.67 | X-CUT |
| $Ba_2NaNb_5O_{15}$ | 225 | 225 | 32 | 0.54 | Z-Cut | 0.25 | X-, Y-CUT |
| $PbNb_2O_6$ | 760 | 90 | 130 | 0.48 | 2-cut | 0.74 | Y-CUT |

## Table II. Acoustooptic Properties of Niobates.

| MATERIAL | MODE | ACOUSTIC WAVE DIRECTION | V $(10^5 cm/s)$ | Γ $(dB/cm/GHz^2)$ | OPTICAL WAVE DIRECTION | POLARIZATION | n | FIGURE OF MERIT $(10^{-18} s^3/g)$ |
|---|---|---|---|---|---|---|---|---|
| $LiNbO_3$ | L | [100] | 6.57 | 0.15 | [010] | [001] | 2.20 | 7.00 |
| | L | [001] | 7.33 | 0.15 | [100] | [010], [001] | 2.29 | 4.50 |
| | S | [001] | 2.59 | 2.6 | [100] | [010] | 2.29 | 2.29 |
| $Sr_{0.75}Ba_{0.25}Nb_2O_6$ | L | [001] | 5.50 | 4 | [100] | [001] | 2.30 | 38.6 |
| $Sr_{0.5}Ba_{0.5}Nb_2O_6$ | L | [001] | 5.50 | 4 | [100] | [001] | 2.27 | 8.6 |
| $Ba_2NaNb_5O_{15}$ | L | [001] | 6.25 | 15 | [100] | [010], [001] | 2.25 | 1.2, 4.2 |
| | S | [101] | 3.68 | 20 | [010] | [001] | 2.25 | 9.2, 49.5 |

$\lambda$ = 0.633 μm, $M_2$ (Fused Silica) = 1.5 x $10^{18}$ $s^3$/g

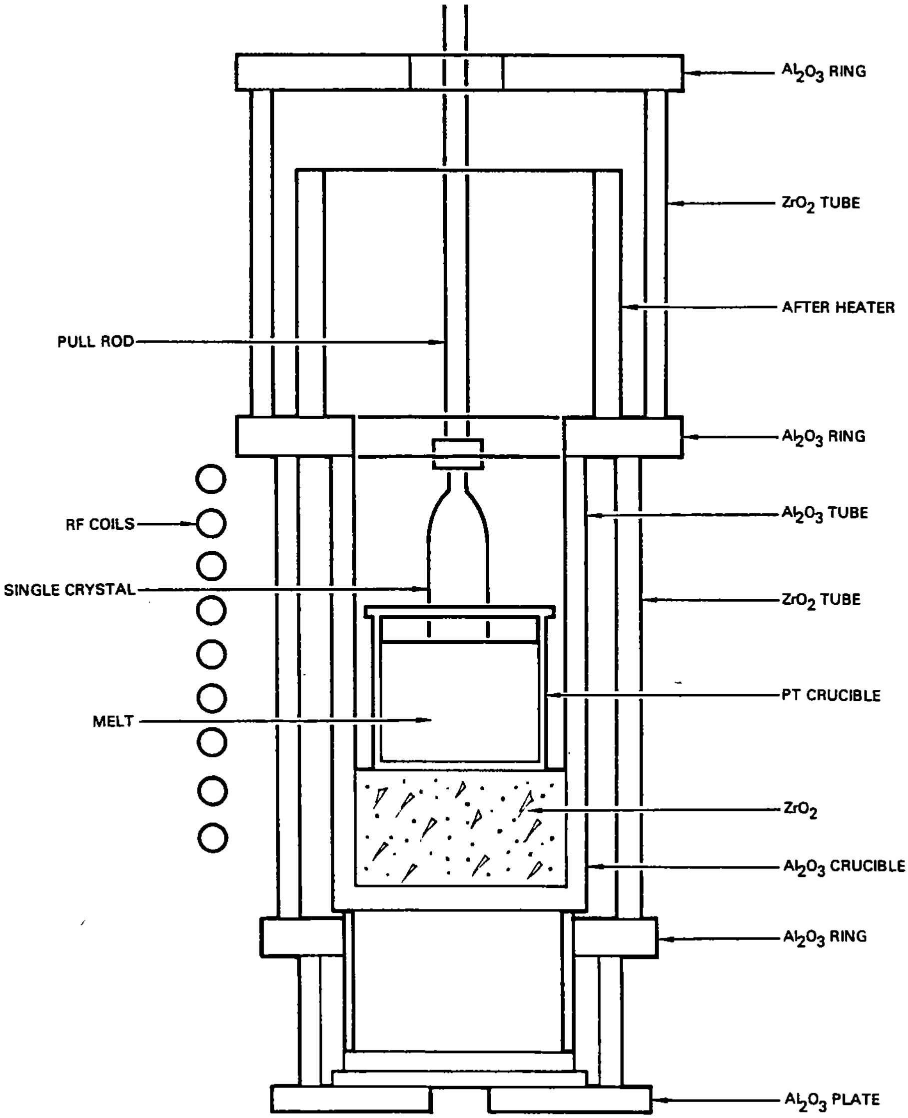



Figure 1. Crystal Growth Furnace.

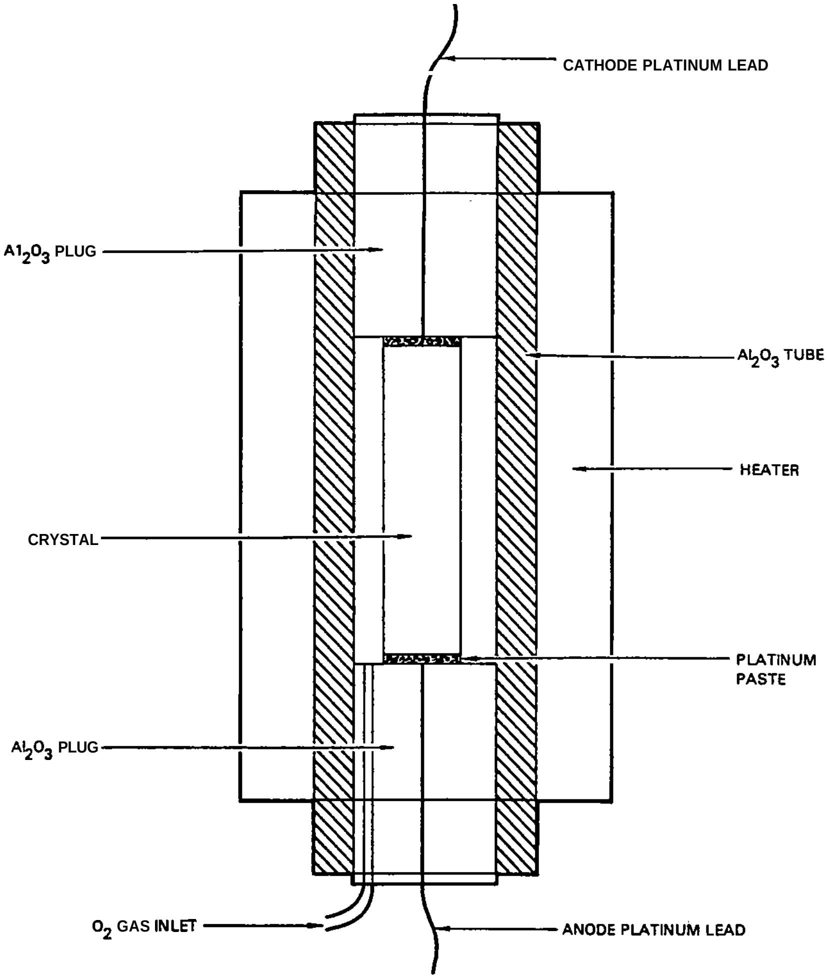



Figure 2. **Poling Furnace.**

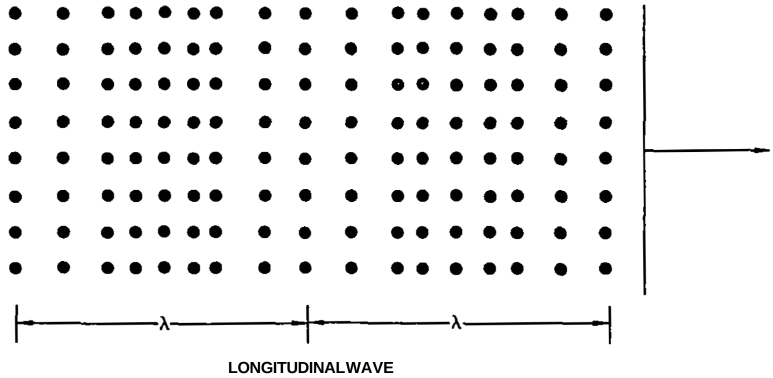
## Acoustics

Acoustic devices fall into one of two basic categories, namely, bulk wave or surface wave devices. Bulk acoustic waves are either longitudinal waves, similar to sound waves in air, or shear waves, for which the medium motion is normal to the direction of wave propagation. Figure 3 illustrates the two types of bulk acoustic wave motions. Several parameters characterize an acoustic medium such as a niobate single crystal. These include the velocity of propagation for each wave type, the polarization of the shear waves, the acoustic impedance, and the acoustic attenuation. The elastic wave velocities were reported by Spencer (1) for lithium niobate.

The generation of bulk acoustic waves is accomplished by a device called a transducer. The most common version consists of a thin plate of piezo-electric material with electrodes bonded to both surfaces of the acoustic medium. The transducer plate is cut to a thickness of one half of an acoustic wavelength at the design center frequency. In operation, radio frequency voltage is applied to the electrodes through an appropriate matching network, and the plate expands and contracts through the piezoelectric effect, launching an acoustic wave into the medium. A bulk wave transducer is shown schematically on each end of a delay medium in Figure 4, for which acoustic pulses representing binary data are depicted. The transducer acts as a source of acoustic waves on the transmitting side and as a receiver on the opposite end. Delay lines, which form the bases of major applications for acoustic device technology, are used for temporary data storage in various signal processing applications.

Transducers are an important application for niobates because these materials exhibit large electromechanical coupling factors, k, which is a measure of the degree to which an applied electric field induces mechanical strain in a piezoelectric material. If this factor is large, a transducer can convert electrical energy to mechanical energy with good efficiency over a wide frequency range. Acoustic transducer design is a complex subject in its own right and will not be treated in detail here. It suffices to say that a designer can select a transducer material based on its k value, dielectric constant, acoustic impedance, and acoustic dissipation, then control the thickness of the transducer plate, the area of the electrode, and the nature of the bonding layers to tailor the response of the transducer for a specific requirement. Generally, the center frequency, bandwidth, and conversion loss are the design parameters of concern. To illustrate these considerations, in Figure 5 is shown the normalized electrical input conductance of a lithium niobate transducer bonded to fused silica designed for a mechanical resonant frequency of 185 MHz (2). The computer generated curves were computed for a range of k values. Transducers have been operated at MDAC with resonant frequencies as high as 2 GHz. In Table I, are listed some of the niobates that have been used for transducer application.

Because single crystal niobates are anisotropic materials, the crystallographic orientation of the transducer plate strongly affects its performance. The reasons for this behavior are complex, but have been analyzed (3). Figure 6, shows the computed variation of electromechanical coupling factor with transducer orientation for several niobate crystals along with experimental values where available. As can be seen from the dissimilar behavior for shear and longitudinal waves, orientations that produce pure shear or pure longitudinal waves can be found.



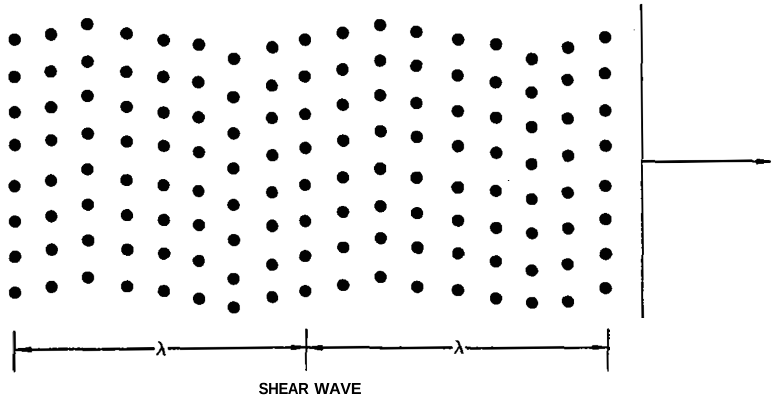




Figure 3. Particle Motions for Bulk Waves.

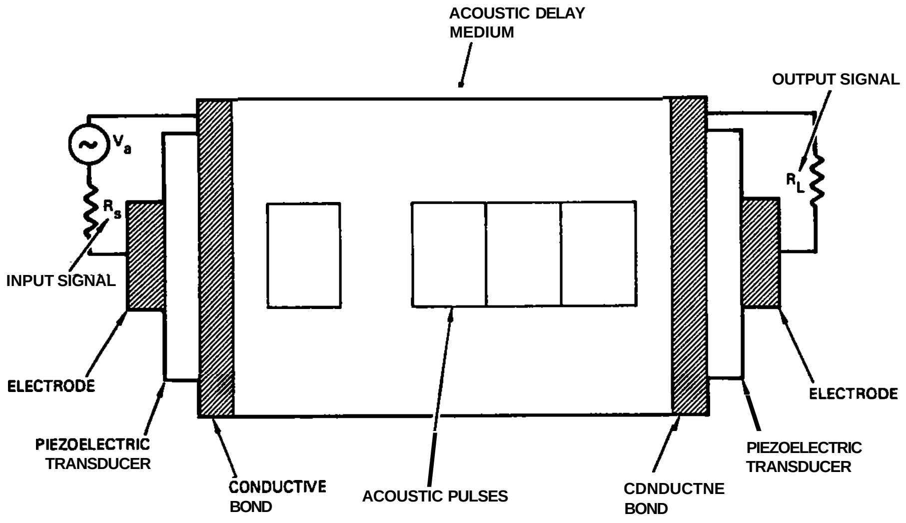



Figure 4. Acoustic Delay Line.

An important application for single crystal niobate compounds is as substrates for surface acoustic wave (SAW) devices, such as delay lines and filters, which are utilized in radar, communication systems, and even television receivers and video games. Single crystal niobates, particularly lithium niobate, are attractive for SAW substrates because of their large electromechanical coupling factors and low high frequency losses for surface acoustic waves. Surface acoustic waves are acoustic waves that are physically bound to the interface between the substrate and air, much as the ripples on a pond. Surface acoustic waves are usually generated using interdigitated electrode pairs like those shown in Figure 7. A radio frequency voltage applied between the electrodes causes the surface of a piezoelectric substrate material like lithium niobate to distort periodically and launch a bound surface wave as shown. A SAW transducer is designed so that the finger spacing is one half of a surface acoustic wavelength at the center frequency. Transducer efficiency drops off on either side of the resonant frequency, but the precise response depends upon the transducer design and coupling factor of the substrate. A transducer can act as a receiver as well as a transmitter, so that SAW delay lines can be fabricated on a common substrate. If the frequency response of the transducers in this configuration is properly engineered, a filter can be fabricated with impressive performance characteristics. SAW devices have operated to frequencies in excess of 1GHz, but are limited at higher frequencies by scattering from surface imperfections.

## Acoustooptics

Several niobate single crystals are used as acoustooptic (AO) materials in a variety of devices, again with lithium niobate being the most useful. In an AO device, a light wave interacts with an acoustic wave through the photoelastic effect and is scattered. The photoelastic effect is an optical phenomenon wherein the velocity of light in the AO medium is linearly proportional to applied strain (4). The change in refractive index n, which is the ratio of the speed of light in vacuum to that in the medium, is given by:

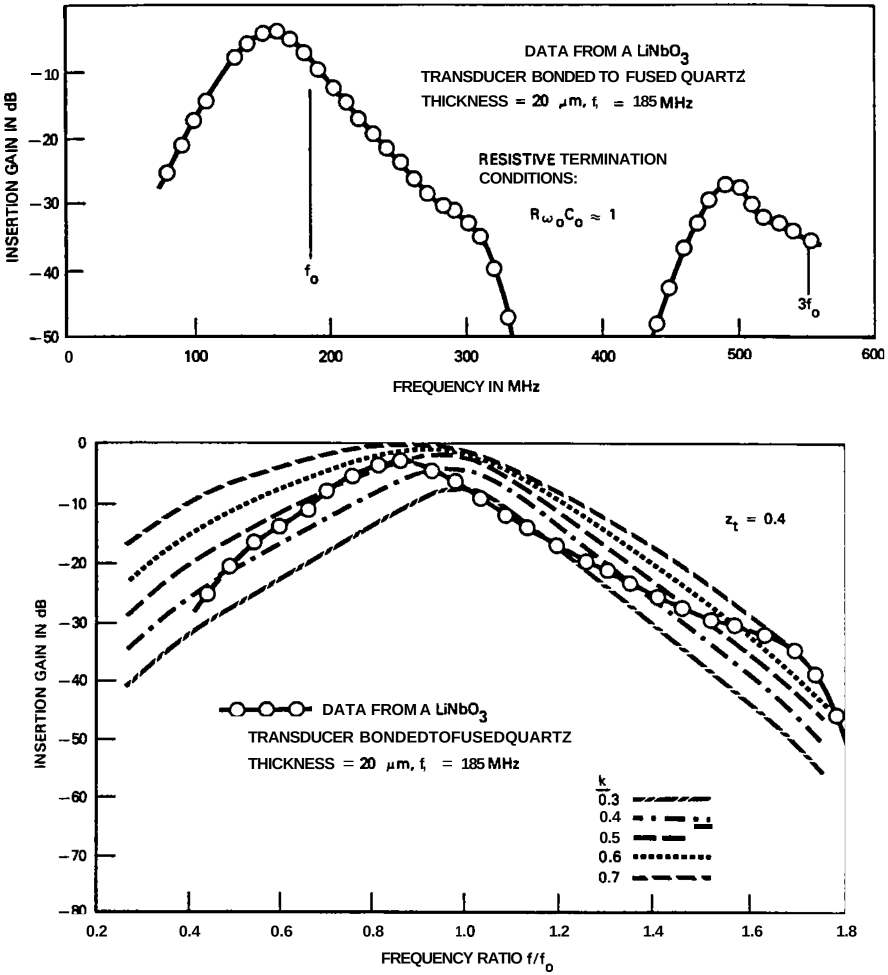



Figure 5. Insertion Gain vs Frequency Data for a $LiNbO_3$ Transducer Bonded to Fused Quartz (top) and insertion Gain Data from a Bonded $LiNbO_3$ Transducer Normalized and Plotted on a Field of Computer Curves (above).

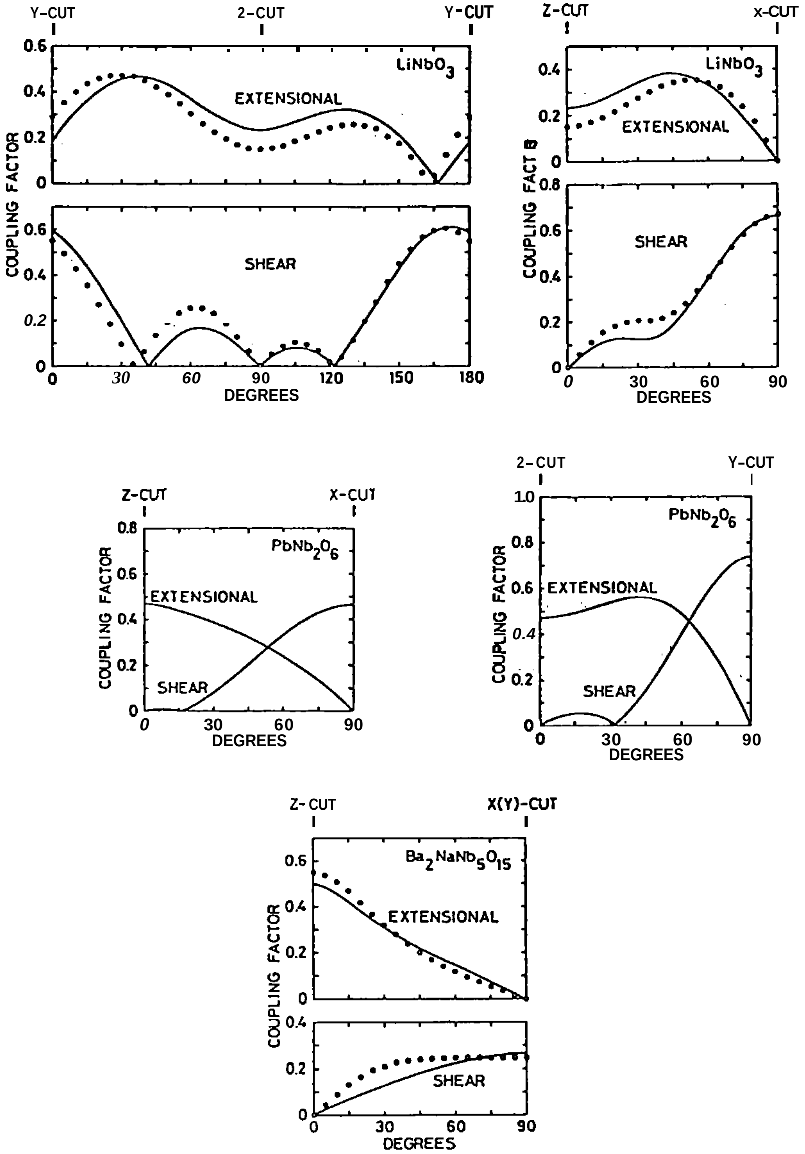



Figure 6. Variation of Electromechanical Coupling Factor with Transducer Orientation for Several Niobate Crystals.

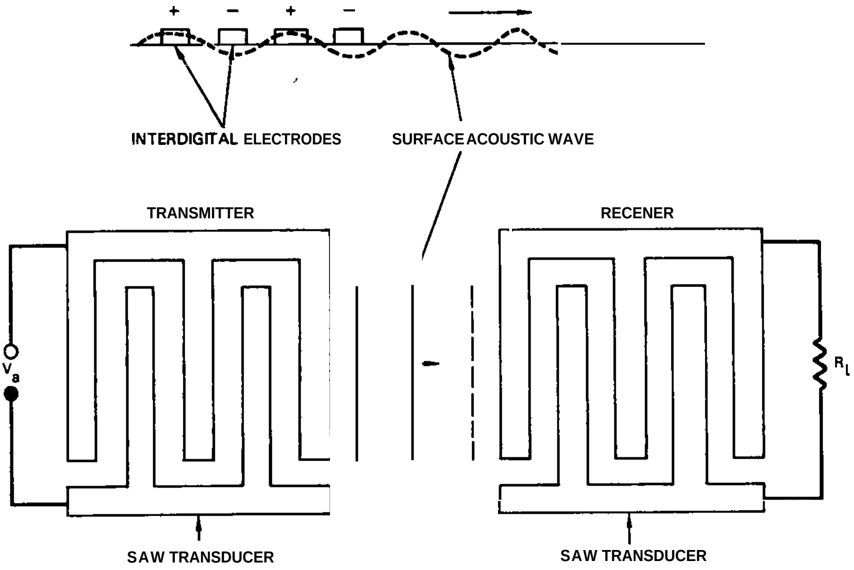



Figure 7. Saw Delay Line.

$$\Delta n = -\frac{1}{2} n^3 pS \qquad (1)$$

where p is the photoelastic coefficient and S is the applied strain. The photoelastic coefficient, applied strain, and refractive index are all tensor quantities, and must be manipulated by tensor analysis; however, the relationship expressed by Equation (1) is conceptually valid. A planar acoustic wave in a solid medium consists of alternating regions of positive and negative strain, whether shear or longitudinal, moving along at the phase velocity of the wave. The strain in an acoustic wave is related to the acoustic power P by:

$$|S|^2 = \frac{2P_a}{\rho v^3 LH} \qquad (2)$$

where $\rho$, $v$, L, and H are the density, acoustic velocity, beam width and beam height, respectively.

Through the photoelastic effect, a refractive index variation is associated with the regions of varying strain in the acoustic wave that propagates along at the phase velocity. Such a pattern represents a moving optical phase grating that can diffract and doppler shift a laser beam incident at the proper angle. In Figure 8, is shown an acoustooptic device operating in the Bragg regime which occurs for relatively long interaction regions and results in a single diffracted beam. The propagation vector $\vec{k}$ of the diffracted light ($k = 2\pi/\lambda$) is the vector sum of the incident wave vector and the acoustic wave vector. When the angle of incidence between the incident beam and the acoustic wave is equal to the Bragg angle, the diffracted beam intensity is maximum. The Bragg angle is given by:

$$\sin\theta_B = K/2k \tag{3}$$

where K is the acoustic wave propagation constant. When the intensity of the diffracted beam is measured as a function of angle of incidence, a $\mathrm{sinc}^2(\theta-\theta_B)$ dependence is observed.

The intensity of the diffracted beam depends upon the acoustic power, the dimensions of the acoustic beam, the wavelength of the light, and the properties of the AO medium itself. The intensity of the Bragg diffracted beam is given by:

$$I_d = I_o \sin^2\left[\frac{n}{\lambda}\left(\frac{M_2 P_a L}{2H}\right)^{1/2}\right] \tag{4}$$

where $M_2$ is called the figure of merit ($M_2 = n^6p^2/\rho v^2$) and depends only on the AO material parameters. Because of the tensor nature of the material parameters, the value of $M_2$ depends on the direction of propagation of the acoustic wave, the polarization of the light wave, and the nature of the acoustic wave, i.e. its type and polarization. The orientational variation in $M_2$ for a given crystal can be very substantial, so that $M_2$ is not quoted for a material without specifying the experimental configuration.

The acoustooptic properties of several niobate single crystals are shown in Table II along with reported applications (5). The common generic applications for AO devices include modulators, beam deflectors, and optical frequency translators. Modulators operate by diffracting light out of the incident beam when radio frequency is applied to the acoustic transducer attached to the crystal, and the mode of operation can either be analog or digital. The parameters of interest are the rise time or bandwidth, extinction ratio or modulation depth, and the drive power required. AO modulators are used in many diverse applications such as data transmission, laser recording, acoustooptic multiplexing, and cavity dumping of lasers. Lithium niobate has a moderate value for $M_2$ for acoustic waves propagating in the (001) direction, an acoustic propagation direction for which $M_2$ is essentially the same for light polarized parallel or perpendicular to the (001) direction; therefore, this crystal cut can be used for polarization insensitive Bragg cells.

Lithium niobate is used as an AO medium for applications that require very high acoustic frequencies and large fractional bandwidths. This is

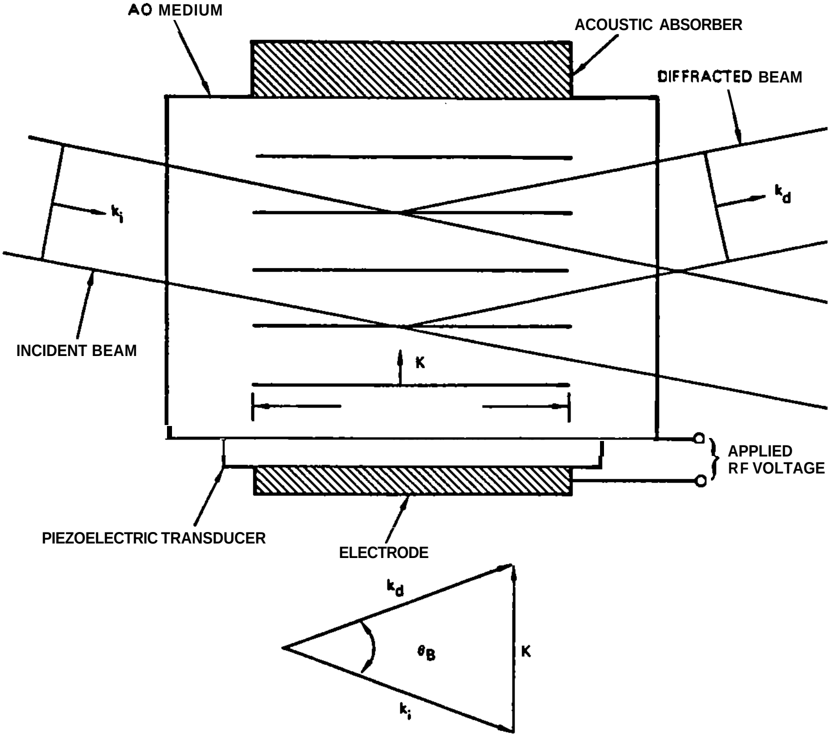



**Figure 8. Acoustooptic Bragg Device.**

because, while lithium niobate has only a moderate value of $M_2$ (7.0 x $10^{-18}$ $s^3/g$), the acoustic losses are very low and a polarization insensitive device can be built. Wideband modulators have been built with center frequencies between 1 GHz and 2GHz using lithium niobate with fractional bandwidths as great as 1 GHz. Another niobate crystal used for AO modulators is $Sr_xBa_{1-x}Nb_2O_6$, with a value of x equal to 0.75, for which the value of $M_2$ is reasonably high (38 x $10^{-18} s^3/g$).

The angle between the incident and diffracted beams depends upon the acoustic frequency, and therefore an AO beam scanner can be constructed. The wave vector of the diffracted light is always equal to the vector sum of the wave vector of the incident light and the acoustic wave vector. The maximum diffracted intensity occurs when the Bragg condition, Equation (3), is satisfied, but significant diffraction occurs over a band of frequencies. Figure 9 shows the situation that occurs for frequencies above, at, and below that which satisfies the Bragg condition for a fixed angle between the incident beam and the acoustic beam. The bandwidth of the device is defined as the frequency interval over which the diffracted beam intensity is within 50 percent (3 dB) of the peak value. It is given for small peak diffraction efficiencies by:

$$\Delta f \approx 1.8\ nv2/\lambda f_o L \qquad (5)$$

where $f_o$ is the frequency for which the Bragg condition is satisfied. To achieve even wider Bragg bandwidths, multiple acoustic beams are utilized.

Ream scanning is a major application for AO deflectors, and lithium niobate is used in some of these instances where large values of $f_o$ are required. One very important application for Bragg cells that is virtually dominated by lithium niobate is for wideband AO signal processors for advanced military applications. Two such applications include the radio frequency spectrum analyzer and the AO time integrating correlator.

Since the diffracted beam intensity is proportional to acoustic power in the small signal limit, and the angle of diffraction is proportional to the acoustic frequency, diffraction of a laser beam by an acoustic beam produces a diffracted beam that accurately represents the spectrum of the acoustic signal. In Figure 10, is shown a schematic diagram of a radio frequency spectrum analyzer and an AO time integrating correlator. The radio frequency signal to be analyzed is mixed with a local oscillator, and an IF signal is generated within the bandwidth of the AO Bragg cell; thus, the acoustic beam generated has the same spectrum as the initial radio frequency signal. The distribution of diffracted power with respect to angle is linearly proportional to the radio frequency power as a function of frequency, i.e. the radio frequency spectrum, for the input signal. The Fourier transform lens collects the diffracted light and brings it to focus at the back focal plane, where intensity versus transverse position is linearly proportional to radio frequency power versus frequency.

The time integrating correlator, also shown in Figure 10, is somewhat more complicated. The laser beam intensity is modulated with a reference signal $S_1(t)$, and the input signal $S_2(t)$ is impressed on a radio frequency carrier and applied to the AO device. The acoustic beam is imaged on an array of detectors by the Fourier transform lens. The intensity of the light

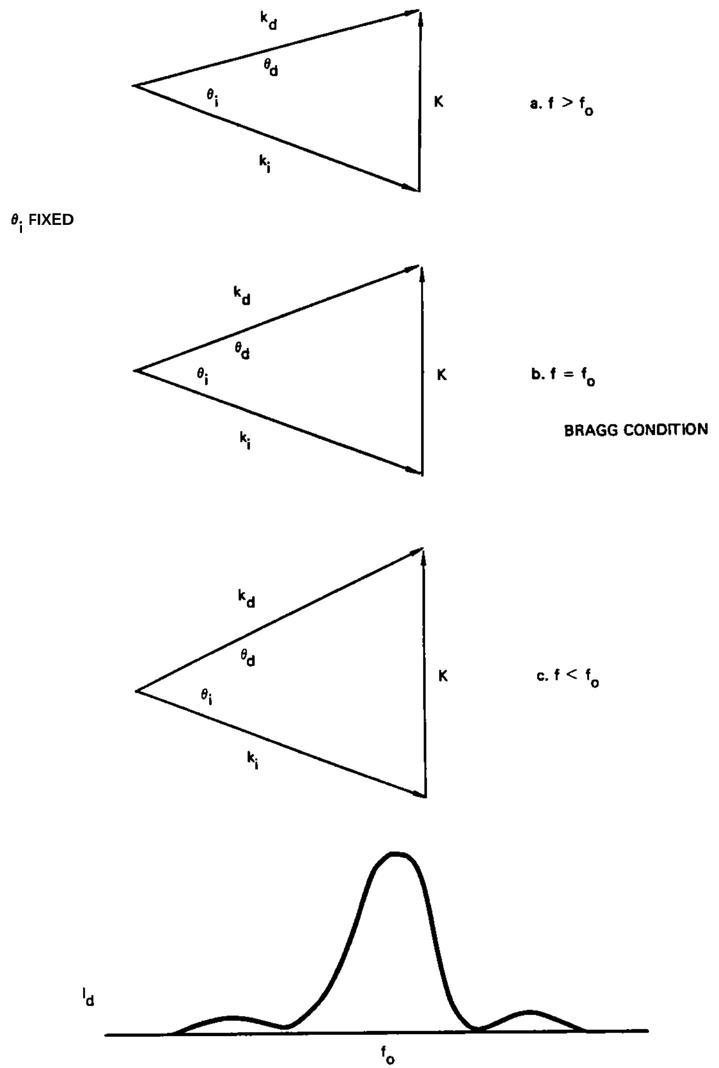



Figure 9. AO Beam Deflector.

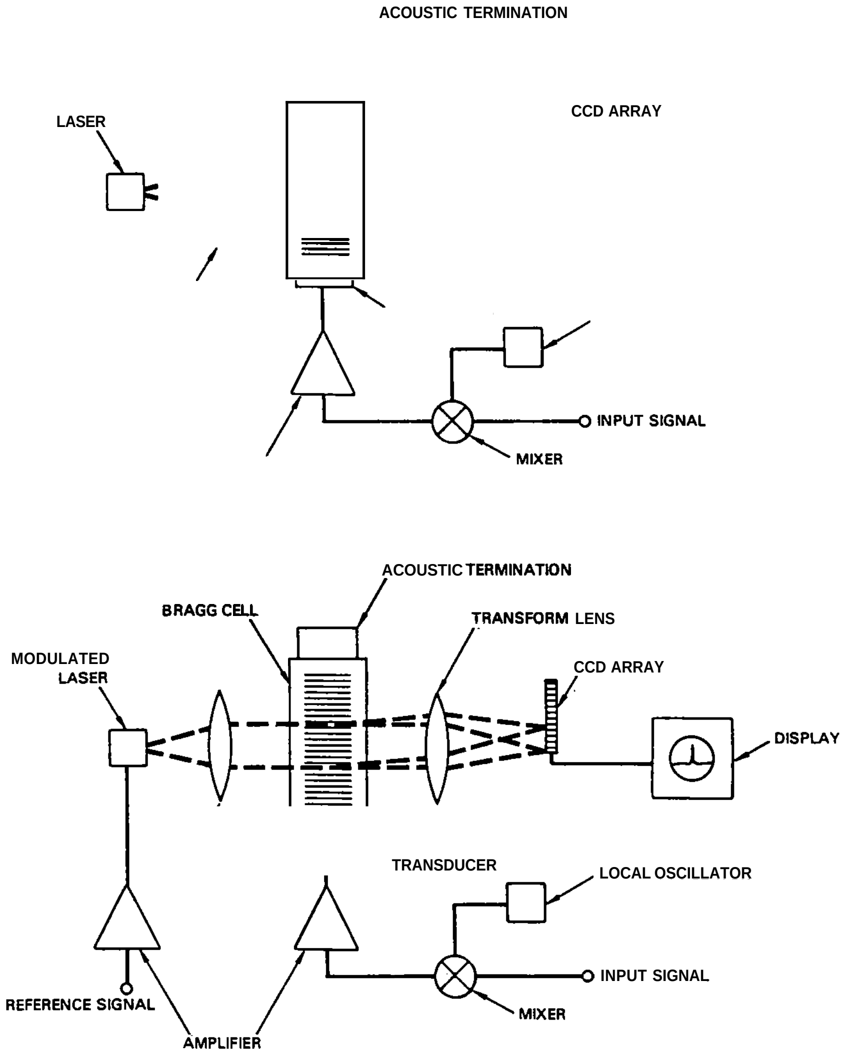



Figure 10. Acoustooptic RF Spectrum Analyzer (above) and Time Integrating Correlator (below).

at a position x in the transform plane is proportional to $S_1(t) \cdot S_2 (t - \frac{x'}{v})$, where $x'$ is position within the acoustic beam and v is the acoustic velocity. The value of x and $x'$ are related by the system magnification m, $(x = mx')$, which can readily be adjusted to unity. If the detectors in the array are allowed to integrate the received signal for a time T, the output of the detector at position x is

$$v(x) = K \int_0^T S_1(t)\ S_2 \left(t - \frac{x'}{v}\right) dt \tag{6}$$

where K is a proportionality constant. The integral is simply the correlation between the two signals with the delay parameter $\tau$ being $\frac{x}{v}$. If signal $S_2$ is identical to $S_1$ within a delay range of D/v, where D is the optical beam aperture, a strong correlation peak is detected by the appropriate detector. A laboratory breadboard time integrating correlator that used a lithium niobate AO Bragg cell and a modulated GaAlAs laser diode as an optical source has been produced.

## Electrooptics

A few niobate crystals, notably lithium niobate, have been utilized as electrooptic modulator materials for use in the visible and near infrared (6). The electrooptic effect, also called the Pockels effect, is an optical phenomenon in which the refractive index of a medium varies linearly with an applied electric field, much as the refractive index varies with strain in the photoelastic effect. The refractive index change is given by:

$$\Delta n = - \frac{1}{2} n^3 rE \tag{7}$$

where r is the pertinent electrooptic coefficient and E is the applied electric field. Again, the electrooptic coefficient is a tensor quantity and the observed effects are orientation dependent. The Pockels effect can be used to operate either a phase or amplitude modulator, but the most common application is amplitude or polarization modulation since coherent detection is required for a phase modulated system. Figure 11 shows a typical electro-optic intensity modulator, which also functions as a polarization modulator if the analyzer is removed.

The incident beam is polarized at 45° to the fast and slow birefringent axes of the crystal, so that the beam is resolved into two components of equal amplitude polarized in these directions. The two beams propagate with different phase velocities so that a differential phase retardation $\Gamma$ accumulates upon transversing the crystal. The value of $\Gamma$ is given by:

$$\Gamma = \frac{a\pi\ell}{\lambda_o} (n_s - n_f) \tag{8}$$

where n and $n_f$ are the slow and fast refractive indices respectively and $\ell$ is the crystal length. When an electric field is applied, the fast and

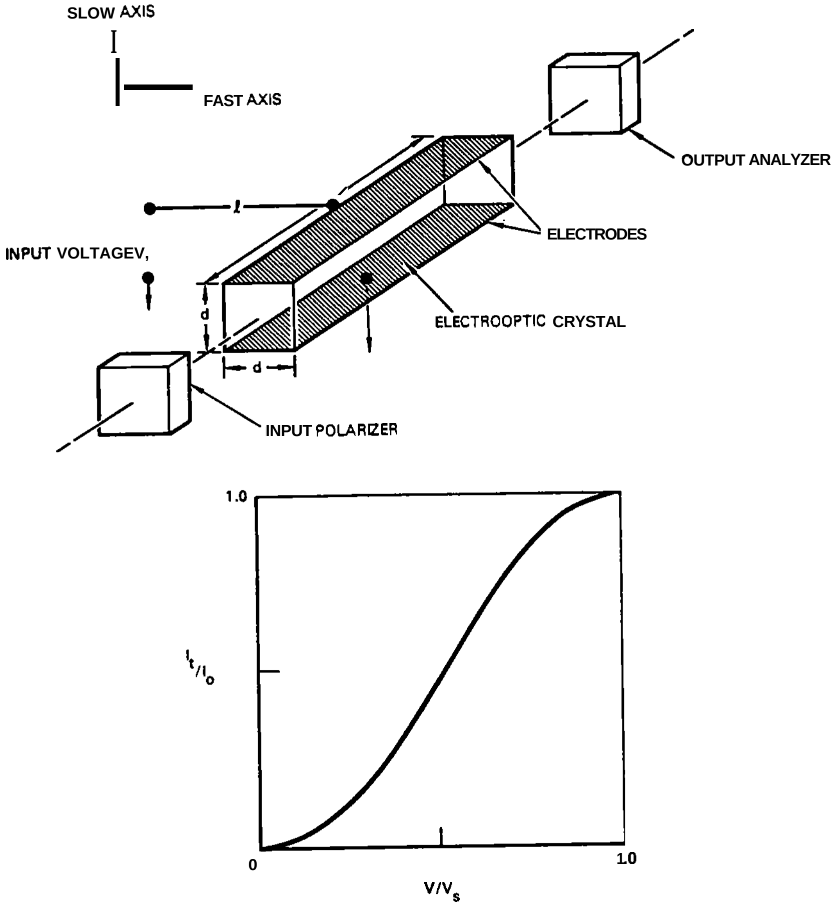



**Figure 11. Pockels Cell Modulator.**

slow refractive indicies change by different amounts, so that the retardation is proportional to the field as given by:

$$\Delta\Gamma = \frac{2\pi\ell}{\lambda_o} (\Delta n \; - \Delta n_f) \tag{9}$$

Thus, from Equation (7), we have a retardation change that is given by:

$$\Delta\Gamma = \frac{\pi\ell}{\lambda_o} (n_f^3 r_f - n_s^3 r_s)E \tag{10}$$

The polarization of the beam emerging from the crystal is unchanged for an even number of half waves of retardation, but it is rotated by $90°$ for an odd number of half waves since the sign of one of the optical electric field components is reversed. The transmission through the crossed analyzer is given by:

$$I = I \sin^2 \left[\frac{\pi}{\lambda} \left(\frac{n_f^3 r_f - n_s^3 r_s}{2}\right) \frac{\ell}{d} V\right] \tag{11}$$

where d is the cross section of the crystal and V is the applied voltage. The switching voltage for the modulator is the voltage required to induce a half wave retardation and turn the transmission on by rotating the polarization of the beam by $90°$. The half wave voltage $V_\pi$ for the material, defined as the voltage that must be applied to a cube shape sample ($d = \ell$) to induce a half wave retardation, is given by:

$$V_\pi = \frac{\lambda_o}{n_f^3 r_f - n_s^3 r_s} \tag{12}$$

The lower $V_\pi$, the lower will be the switching voltage for a given modulator configuration. Table III lists the value of $V_\pi$ for several niobate crystals that have been used in EO modulators.

Electrooptic modulators are used for modulating or encoding information on laser beams for laser communication systems, for modulation of the writing beams in laser recorders, and for a variety of other specialized applications. Optic axis cut lithium niobate crystals are supplied in a standard 9 x 9 x 25mm configuration for use as an intracavity polarization modulator for Q-switching Nd:YAG lasers used in military range finding applications. The Q-switch application is the largest single use for electrooptic modulators, and lithium niobate is the most widely used EO material for this application. Lithium niobate has been used in EO modulators with bandwidths exceeding 1 GHz for experimental wideband communication systems. Most applications of EO modulators has been in experimental or laboratory systems, so that the quantity of material grown and utilized for this purpose has been relatively small, the Q-switch application being the exception.

## Table III. Electrooptic Properties of Niobates.

| MATERIAL | APPLIED FIELD DIRECTION | DIELECTRIC CONSTANT | LIGHT BEAM DETECTION | HALF WAVE VOLTAGE ($V_\pi$, VOLTS) |
|---|---|---|---|---|
| $LiNbO_3$ | [001] | 29 | [100] or [010] | 2950V |
| | [010] | 45 | [001] | 4000V |
| $Sr_{0.75}Ba_{0.25}Nb_2O_6$ | [001] | ~$10^4$ | [100] or [010] | 50V |
| $Sr_{0.5}Ba_{0.5}Nb_2O_6$ | [001] | 500 | [100] or [010] | 400V |
| $Ba_2NaNb_5O_{15}$ | [001] | 30 | [100] or [010] | 1850V |

$\lambda = 0.633\ \mu m$ $T = 25°C$ $f = 1KHz$

Three niobate crystals, $LiNbO_3$, $Ba_2NaNb_5O_{15}$, and $KNbO_3$, have been widely used in nonlinear optics in recent years. There are two basic applications of these crystals, namely, harmonic generation and parametric oscillation. In harmonic generation, the output of a near infrared laser, primarily Nd:YAG operating at 1.06 μm, is frequency doubled to the visible, which is highly desirable for many applications. In parametric oscillation, a visible source, usually a dye laser or even a frequency doubled Nd:YAG laser, is used to generate tuneable output in the near infrared. To a considerable extent tuneable dye lasers have supplanted optical parametric oscillators, but limited work is still reported in this area. Considerable need exists for efficient solid state sources operating pulsed and continuously in the visible, so a considerable amount of effort is presently devoted to the development of frequency doubled Nd:YAG and Nd:Glass lasers. The advantages of such sources when compared to alternatives include high overall efficiency, high output levels, high reliability and low cost.

In Figure 12 is shown a typical experimental configuration for frequency doubling a Nd:YAG laser with a nonlinear niobate crystal. The laser emits a beam at the fundamental frequency $\omega$ which is presumed to be Gaussian in profile for simplicity, and the beam is focussed into the crystal using an appropriate lens. The power generated at the second harmonic wavelength varies quadratically with input fundamental power and is given by:

$$P_{2\omega} = 2\left(\frac{\mu}{\varepsilon_o}\right)^{3/2} \frac{\omega^2 d^2 \ell^2}{\pi w_o^2 n^3} \frac{\sin^2(\ell \Delta k/2)}{(\ell \Delta k/2)^2} P_\omega^2 \qquad (13)$$

where the following definitions apply:

$\omega$ = fundamental wave frequency ($\omega = 2\pi c/\lambda$)

$\mu$ = permeability of free space ($4\pi \times 10^{-7}$ mks units)

$\varepsilon_o$ = permittivity of free space ($8.85 \times 10^{-12}$ mks units)

$n$ = refractive index of nonlinear crystal

$w$ = radius of Gaussian beam waist

$d$ = nonlinear optical coefficient

$\ell$ = length of nonlinear crystal

$\Delta k$ = wave vector mismatch between fundamental and second harmonic

This configuration is appropriate for frequency doubling a Q-switched laser with the crystal outside the laser resonator. For frequency doubling a continuous Nd:YAG laser, the nonlinear crystal is usually coated for low reflectivity and placed within the cavity of the laser to increase the incident power. In Table IV we present the nonlinear optical properties of the three niobate crystals normally used for harmonic generation or parametric oscillation.

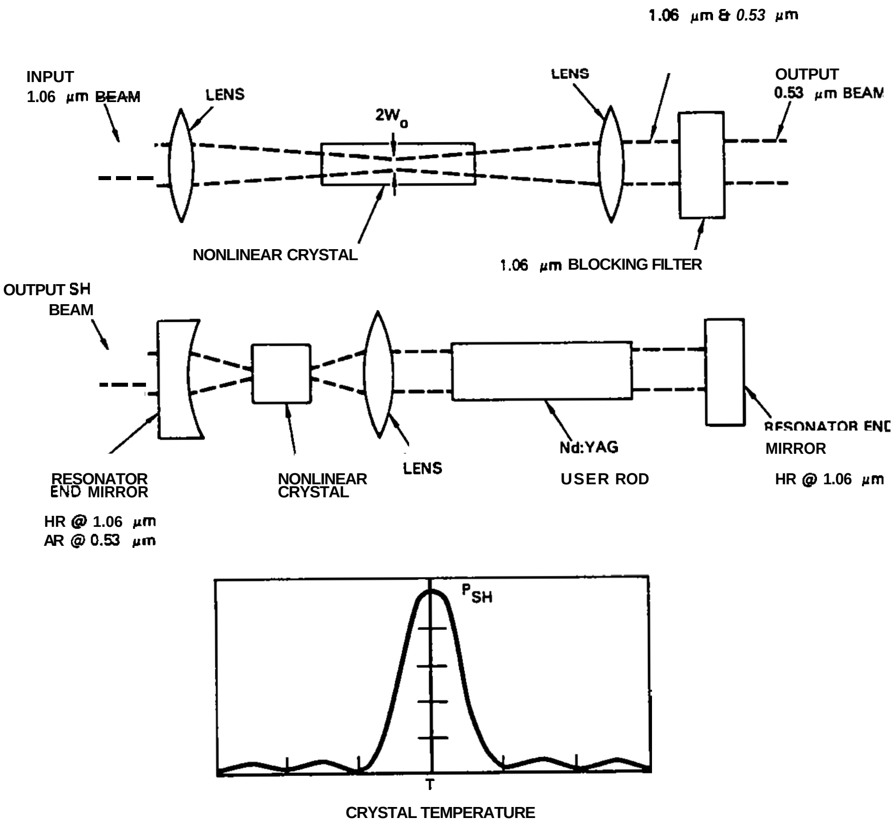



**Figure 12. External and Internal Frequency Doubling of Nd:YAG Using Niobate Crystals.**

Table IV. Nonlinear Properties of Niobates.

| MATERIAL | FUNDAMENTAL WAVE DIRECTION | FUNDAMENTAL WAVE POLARIZATION | SECOND HARMONIC WAVE DIRECTION | SECOND HARMONIC WAVE POLARIZATION | NONLINEAR COEFFICIENT d(RELATIVE TO QUARTZ) | PMT (°C) |
|---|---|---|---|---|---|---|
| $LiNbO_3$ | [100] | [010] | [100] | [001] | 14 | 150°C |
| | [010] | [100] | [010] | [001] | 14 | 150°C |
| $Ba_2NaNb_5O_{15}$ | [100] | [010] | [100] | [001] | 40 | 80°C |
| $KNbO_3$ | [010] | [100] | [010] | [001] | 36 | - |

PMT - Phase Matching Temperature for SHG with 1.06 μm Nd:YAG

The nonlinear output coefficient and the refractive indices for the fundamental and harmonic wavelengths are tensor properties, so therefore the crystal must be crystallographically oriented prior to fabrication. The crystal is then cut and polished on the faces normal to the input laser beam. The surfaces are polished to $\lambda/10$ surface flatness and a 10Å rms surface, and are then antireflection coated for the fundamental and second harmonic wavelengths. The niobate crystals listed in Table IV are all oriented so that the 1.06 μm beam propagates down the $x_1$ or $x_2$ direction. By controlling the temperature of the crystal, the phase mismatch $\Delta k$ can be adjusted to zero and the $\mathrm{sinc}^2(\ell\Delta k/2)$ factor can be maximized for peak conversion efficiency. When operated within the cavity of a Nd:YAG continuous laser, high quality $Ba_2NaNb_5O_{15}$ crystals can produce sufficient nonlinear loss to optimum couple the laser at the harmonic wavelength (7). Under these conditions, as much harmonic power at 0.5320 μm is obtained as could be obtained at the fundamental wavelength at optimum output coupling. Similar results have been reported for $KNbO_3$ crystals. Repetitively Q-switched Nd:YAG lasers have been externally doubled using $LiNbO_3$ crystals with a 40 percent conversion efficiency (8). Second harmonic power levels as high as 1W have been obtained from intracavity frequency doubled Nd:YAG lasers, using $Ba_2NaNb_5O_{15}$ and average powers as high as 30W have been achieved using $LiNbO_3$ to externally double a repetitively Q-switched Nd:YAG laser.

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