Design and Demonstration of a Ferroelectric Optical Switch

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Abstract: From the telegraph to satellites, the field of telecommunications has grown at an incredible rate. Allowing for huge amounts of data to be transferred at faster speeds than the blink of an eye, thanks to the use of light as the preferred mode of transportation. This paper will examine the interaction between light and a special class of materials called ferroelectrics. Ferroelectrics are materials that have built-in electrical dipoles inside their crystal structure. This report will examine the basic properties of light and of ferroelectrics. Such properties include polarization, total internal reflection, and the electro-optic effect. Then an optical switch will be designed and fabricated based on ferroelectric lithium tantalate, so that it modulates light using a combination of total internal reflection and the electro-optic effect. The performance of this device was tested and compared with theoretical predictions.

INTRODUCTION

Historical Perspective

In the year 1837 Samuel Morse invented the telegraph[1]. This invention only allowed the transmission of data at a very slow rate, only a few Hertz. However, the telegraph itself spread all over the world at a very fast rate. In 1878, Alexander Graham Bell invented the telephone[1], which was handled by an operator. At the same time James C. Maxwell made a very important contribution to the world with his ingenious and simple way of combining four equations into a set of equations called Maxwell's equations. These equations have been applied into many of today's creative inventions. They also explained clearly how light could be described as an electromagnetic wave. As a result in 1895 Guglielmo Marconi discovered that electromagnetic waves did not need wires to travel, they could easily travel through air, thus came the invention of the radio[1]. In 1940 the use of telecommunications increased exponentially due to the invention of satellite communications. Satellite communications allowed the transfer of data at very fast rates and over a very long range. They improved the way in which people could communicate globally. Finally in 1960, "the laser", a bombshell hit the telecommunications industry[1]. This invention has allowed for the improvement of many of today's communication systems. It allows the use of light as a pathway for communication around the world.

Specific Aims

The specific aims of my research are to understand the interaction between light and materials. Also to learn and manipulate properties of light such as Snell's law, index of refraction, total internal reflection and the electro-optic effect in order to design and fabricate an optical device. Once the optical device is fabricated it will be tested in order to verify and gain support from theory.

Significance

Since 1960, when the first laser was developed the field of optics has grown at an incredible rate. This revolution in optics has had a powerful impact on society; thus, making the use of optical devices an every day necessity. Improvements have been made in global communication, health care service, and manufacturing[2]. In the field of telecommunications, optics has played an enormous role in developing systems around the world that include the use of fiber optics to transmit voice, data and video.
Fiber optics are cables made of glass, each wire is the size of a hair strand capable of carrying one million channels of data. Fiber optics cables have advantages over coaxial cables because they do not erode; they also allow large transmission of data and less electromagnetic interference. The greatest advantage of using fiber optic cables over coaxial cables is the fact that light can be used in order to transmit data. However, once the data reaches its final destination electrical components are used and these slow down the entire process significantly by creating bottlenecks. It is thus believed that such electrical components have reached their full potential and it is time for new devices to play an active role in the telecommunications industry. Some of these devices include optical scanners, switches, modulators and telescopes. These devices will allow the use of light to control and manipulate light.

BACKGROUND

Light

A sinusoidal or harmonic wave is composed by wavelength, frequency and amplitude. Wavelength is the length of a single wave or period, frequency is the number of waves per unit time and amplitude is the maximum disturbance, height, of the wave.

Light has been proven to be an electromagnetic wave with an Electric Field, **E**, and a Magnetic Field, **B**, propagating in a direction perpendicular to both of these fields[3] as shown in Figure 1.1. Electric field is force per unit charge, $E = \frac{F}{Q}$ and the magnetic field is force times velocity per unit charge. The following equation best describes the electric field in light in terms of its angular frequency,

$$E = E_0 \cos(kz - \omega t + \delta) n \qquad \textit{Equation 1.1}$$

where k represents the direction in which the wave is moving, ω is the angular frequency, t is the time, δ is the direct displacement of the wave and n is the unit vector.

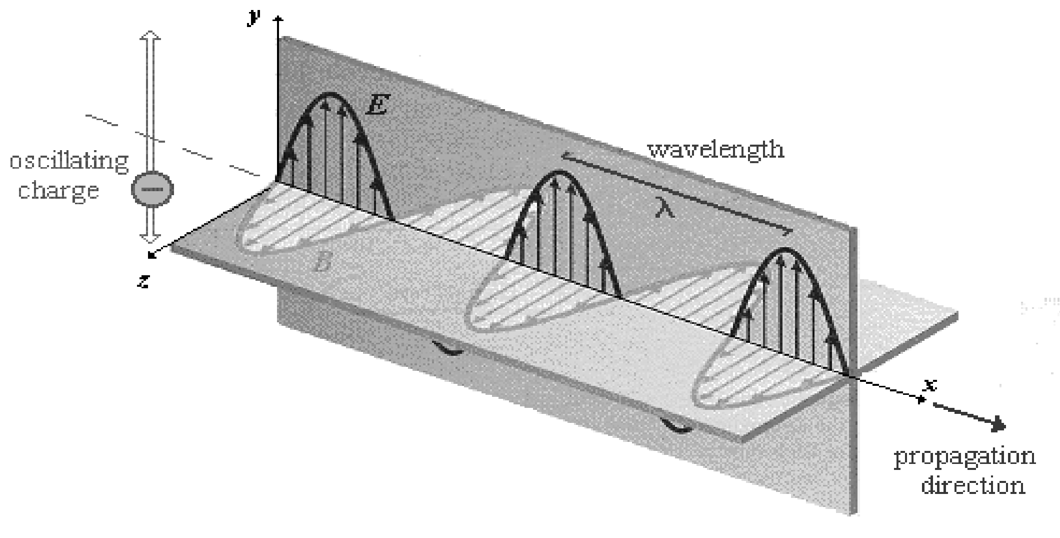

Figure 1.1: The electric field, **E**, travels along the y-axis. The magnetic field, **B**, travels perpendicularly to the **E**, it travels along the z-axis. The wave itself travels along the x-axis; perpendicular to both the **E** and **B**.[4] Light is a transverse wave. The Polarization of the wave is in the direction of the **E.**

Polarizers

Polarization of light is defined as the direction of oscillation of the electric field in the electromagnetic wave. Polarizers are made up of polymers. The polymers are placed in such a way that they allow only certain component of light to pass through. The polymers absorb the other components of light, which do not pass through. If the polarization axis between two polarizers is parallel, certain components of light will be allowed to pass through. If the polarization axis between the two polarizers is perpendicular, all of the light will be absorbed and none of the light will be allowed to pass.

An experiment was conducted with two polarizers (see Figure 1.2). The first polarizer had its optical axis at maximum intensity, the second polarizer or as commonly referred to as the analyzer had a variable optical axis. The optical axis of the analyzer was rotated every ten degrees.

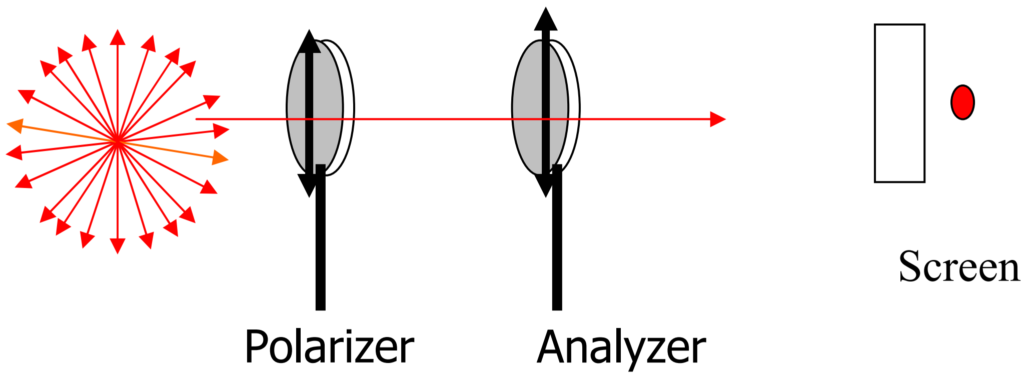

Figure 1.2(a): Experimental set up for experiment between two polarizers, axes are parallel

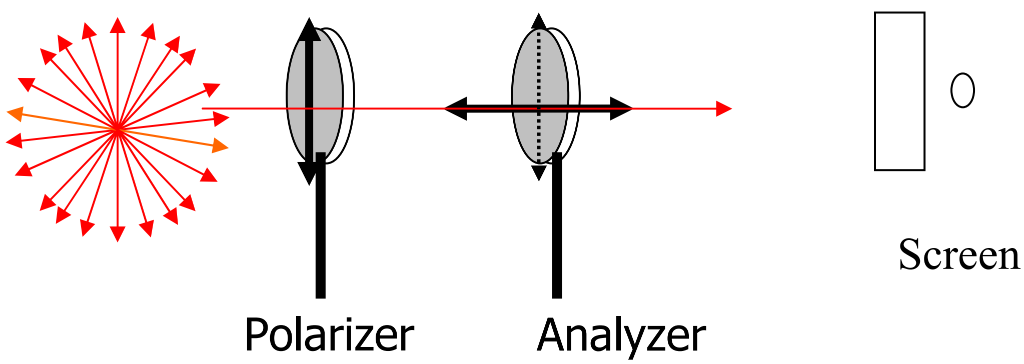

Figure 1.2(b): Experimental set up for experiment between two polarizers, axes are perpendicular.

In Figure 1.2 the relationship between the polarizer and the analyzer is clearly seen. When the optical axes of the two polarizers are parallel (Figure 1.2(a)) maximum intensity is attained, and when the optical axes of the two polarizers are perpendicular

(Figure 1.2(b)) minimum intensity is attained.

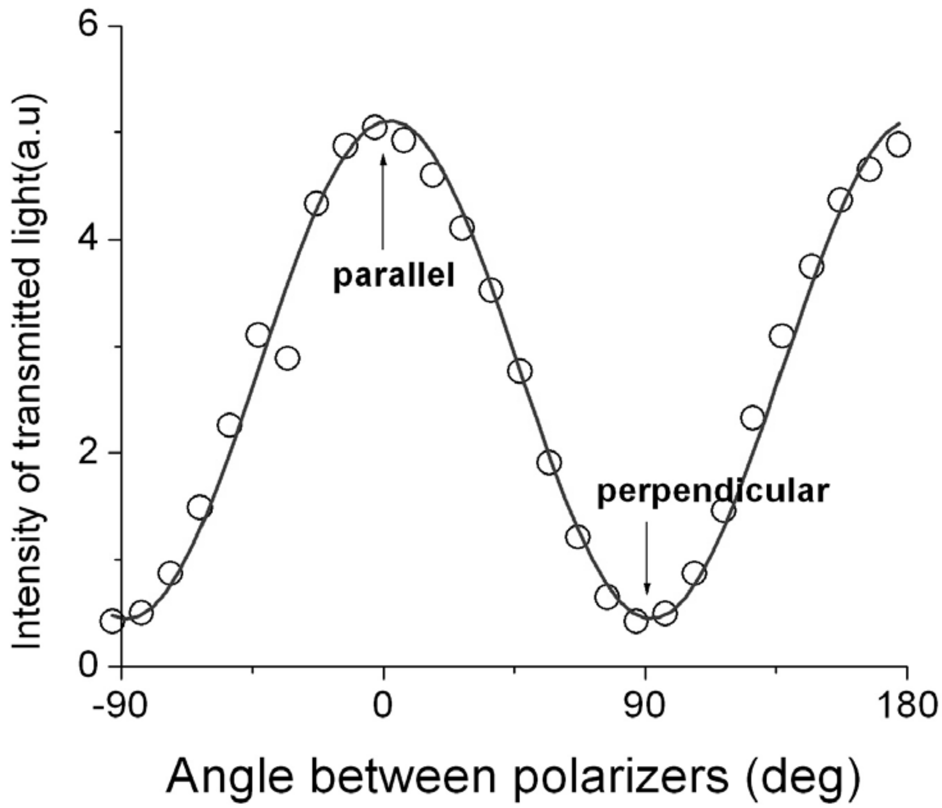

Figure 1.3: This graph represents the relationship between two polarizers and light. Circles are experimental points and the solid line is a theoretical fit.

Figure 1.3 depicts the relationship between the angle of the axis of polarization and the intensity or brightness of the light. It is clearly understood that when the axes of polarization for the two polarizers are at zero degrees with respect to one another or parallel, the intensity attained is the highest. Once the axes between two polarizers forms 90 degrees, the intensity attained is the lowest. However, in the figure the intensity never reaches zero completely and this can be attributed to other stray sources of light in the room.

Total Internal Reflection (TIR)

Total internal reflection is a process that occurs when the incidence angle is equal or greater than the critical angle, thus preventing light from being refracted to being completely reflected. According to Snell's Law, there is a relationship between the angle of incidence and the angle of transmittance. This relationship can be best described by the following equation.

$$n_i \sin\Theta_i = n_t \sin\Theta_t \qquad \text{Equation 1.2}$$

However, under TIR, the angle of incidence $\Theta_i = 90^0$, thus $n_i = n_t \sin\Theta_t$. Solving for Θ gives rise to Equation 1.3 or the equation for the critical angle.

$$\Theta_c = \sin^{-1}\left(\frac{n_i}{n_t}\right) \qquad \text{Equation 1.3}$$

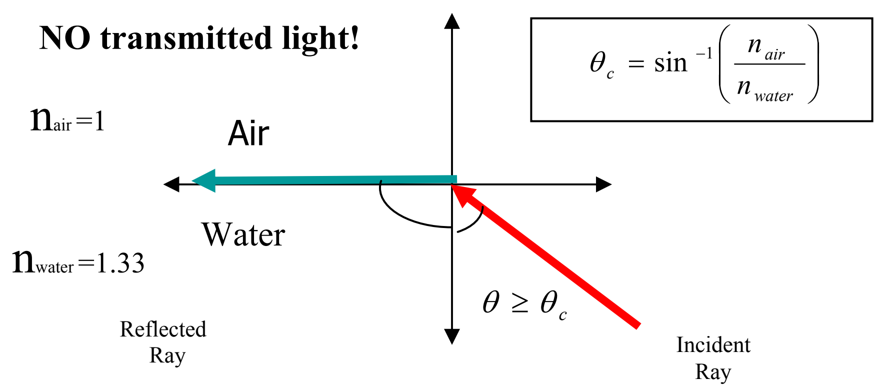

Figure 1.4: Diagram of TIR. Any beams of light equal or greater than the critical angle will not be transmitted.

In Figure 1.4 the angle of incidence happens to be equal to the critical angle. Therefore, the beam of light is refracted parallel to the wafer surface. If the angle of incidence is greater than the critical angle then the light will be completely reflected back into the water medium.

Electro-Optic Effect

The electro-optic effect deals with the interaction of an applied electric field, E, and the change of polarity within a crystal after the field is applied, as a result the index of refraction will change. Equation 1.3 can be expanded into the following;

$$\Theta_t = \sin^{-1}\left(\frac{n_t}{n_i}\right) = \sin^{-1}\left(\frac{n_3 - \Delta n_3}{n_3 + \Delta n_3}\right) \qquad \text{Equation 1.4}$$

However according to the electro optic effect

$$\Delta n_3 = \frac{-1}{2} n_3^3 r_{33} E_3 \qquad \text{Equation 1.5}$$

Where n is the refractive index, r is the electro optic coefficient and **E** is the applied electric field. Subscript 3 refers to a specific direction inside the crystal. Therefore (equation 1.3) becomes

$$\Theta_t = \sin^{-1}\left(\frac{2n - n^3 r_{33} E}{2n + n^3 r_{33} E}\right). \qquad \text{Equation 1.6}$$

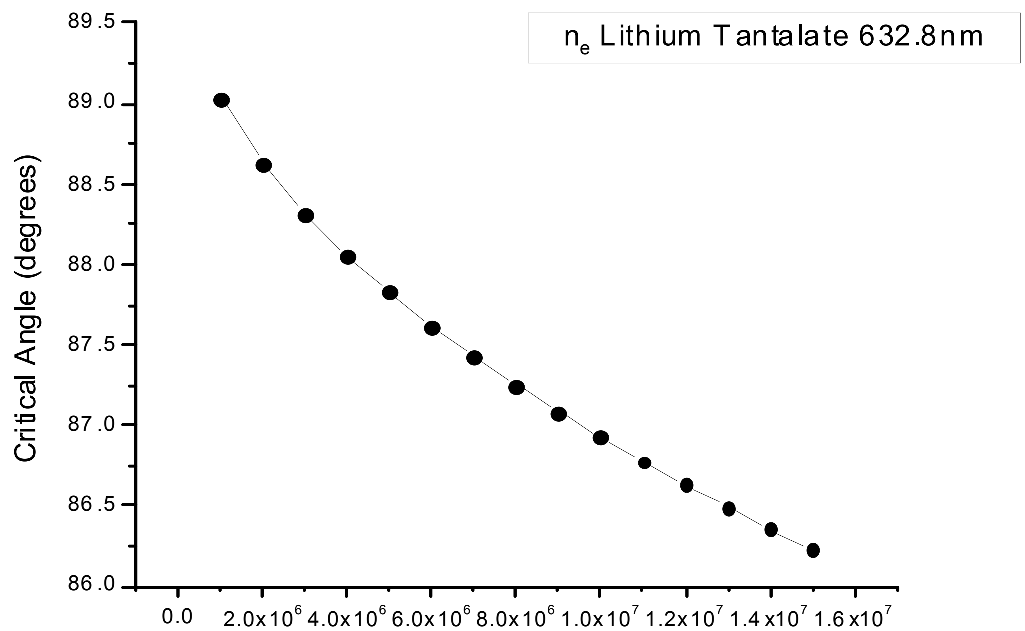

Figure 1.5: Graph describing the relationship between the electric field, **E**, and the critical angle, according to the electro-optic effect in single crystal lithium tantalate.

According to Figure 1.5 it is clearly seen that the applied electric field, E, is inversely proportional to the critical angle. In other words the greater the applied electric field the smaller the critical angle will be. By substituting the applied voltage into equation 1.6, a theoretical prediction can be attained for the critical angle. Then this value can be compared to the experimental value.

Optical Switch

Multiplexing is when telephone calls or data channels are transmitted in a simultaneous process[2]. Optical switches are devices that have been invented in order to perform multiplexing at very fast speeds and with less delay than by using the customary electronic signals. This will allow the processing of millions of signals at a speed of terahertz. An optical switch will be created using the electro-optic effect, total internal reflection (TIR) and a ferroelectric crystal with a single domain wall.

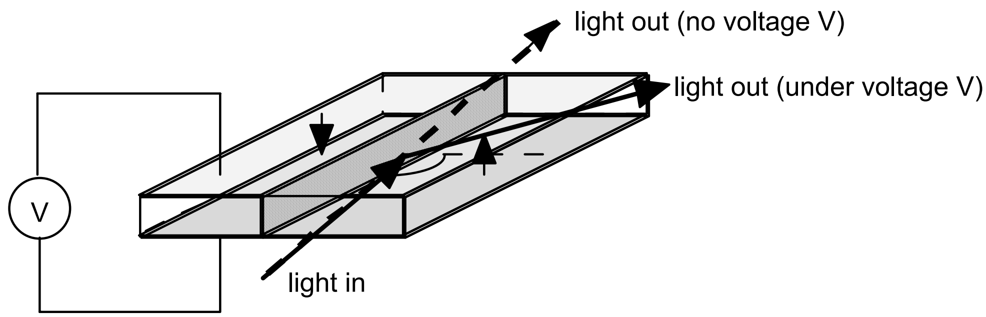

Figure 1.6[6]: Schematic of an optical switch based on a single domain wall interface inside a ferroelectric across which field indiced index change occurs. This is used to totally internally reflect a light beam on the same side of the wall.

In Figure 1.6 the domain wall will be created by applying the necessary voltage in order to create the electro-optic effect and therefore creating total internal reflection within the optical switch.

Ferroelectric Materials

In nature most materials are neutrally charged, meaning that their positive and negative particles are placed in such a way that there is no charge within the actual molecule. However, there are some materials such as ferroelectric materials that are structured in such a way that their positive and negative particles are slightly off centered, therefore creating a dipole or as commonly referred to as a frozen dipole. Optical switches are made with ferroelectric materials because the electro-optic effect is large and fast (GHz). In addition, by applying a voltage, one can change the direction of the polarity thus allowing the creation of a domain wall within the crystal.

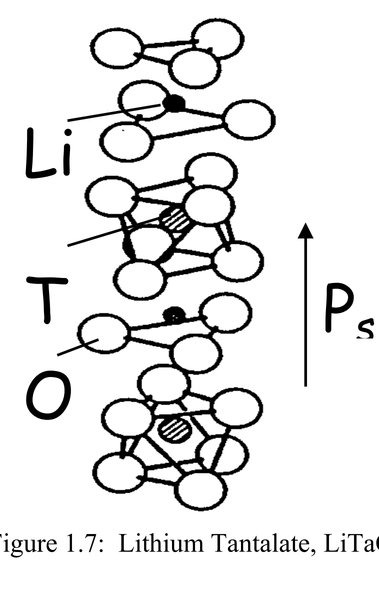

Figure 1.7: Lithium Tantalate, $LiTaO_3$

Figure 1.7 is a picture of the ferroelectric material that will be used for the device, Lithium Tantalate ($LiTaO_3$). In this molecule the Lithium and Tantalum atoms are positively charged and the Oxygen atom is negatively charged. The Oxygen atoms sit slightly lower than the other atoms in the molecule, therefore creating a dipole in the upward direction. Once voltage is applied, the Oxygen atoms will be pushed upward and they will sit slightly higher than other atoms, hence changing the direction of the dipole.

FABRICATION

Small pieces of crystal are cleaned with acetone. In the clean room the samples are carefully placed on top of silicon wafers, which are slightly larger than the sample itself. Following this step both, the wafer and the crystal, are placed on a spinner and three to four drops of 1811 photoresist are added to the sample. Photoresist is a polymer film which breaks up some structural bonds as ultra violet light is applied. This part allows for a very thin and uniform film of photoresist to be placed on the sample as the wafers spins around. Then the sample and wafer are placed on a hot plate and baked at 100^{o} C for two to three minutes. This process is called soft bake. Soft bake is needed in order to dry off any solvent from the photoresist; it improves adhesion and uniformity and it optimizes the light absorbance characteristic of the photoresist[2].

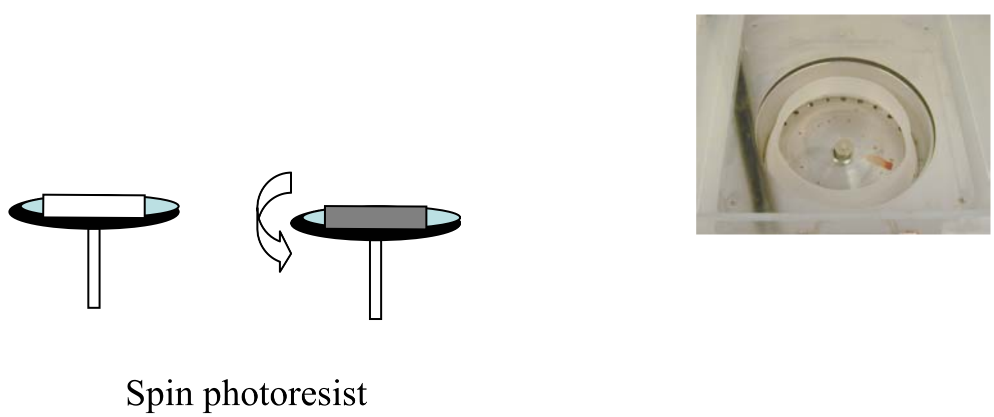

Figure 2.1: (a) Sample placed on wafer, photoresist added. (b) Picture of spinner.

Figure 2.1 shows a schematic of how the photoresist was added onto the sample. It also shows a picture of the actual spinner. Now the samples undergo photolithography. In this process the pattern of a mask is developed onto the surface of the sample with the help of ultraviolet light in this case the source is Mercury light. However, the mask does not touch the sample. The sample is placed on a stage, which is then raised to a very finite distance from the mask. This distance is so minimal that the design from the mask is transferred onto the sample with very close detail. This technique is referred to as soft contact. The sample is now developed for 20 seconds in developer and 40 seconds in deionized water. After all samples have been exposed and developed they are ready for sputtering.

In order to deposit Tantalum on to samples, they are mounted on a silicon wafer and taped with vacuum tape. The tape is placed along the edges of each sample without covering the design that has already been exposed on to the sample during the lithography. 1000 Amperes of Tantalum are deposited on to the sample surface through radio frequency magnetic sputtering.

In order to remove unwanted Tantalum and uncover the design, the samples are soaked on acetone. This step is very delicate because some particles of the Tantalum will lift off by themselves others have to be cleaned by applying gentle pressure with cotton swabs. However, one has to be very careful while rubbing in order to avoid scratching the surface of the actual design. A layer of photoresist in applied once again to the surface of the sample. Now comes the critical step, poling.

During poling a voltage is applied to the surface with the electrode, or layer of Tantalum. This voltage allows for a change to take place in the two areas of the device and facilitating the creation of a domain wall in the middle. A voltage of ~21KV/mm was applied to create the domain wall.

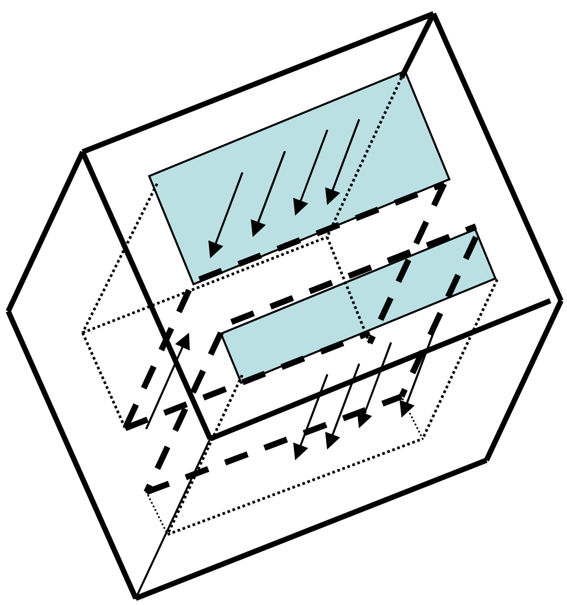

Figure 2.2: Poling of Lithium Tantalate Crystal

In Figure 2.2 voltage is applied so that the direction of the dipole is changed in the two areas where the electrode was deposit. In the area in the middle no voltage is applied therefore the dipole continues to be in the upward direction. This is how the domain wall was created in the crystal.

Next comes polishing, which is the one step that requires a lot of patience. The samples are placed in a sandwich between pieces of glass and rubber. Each piece of glass has to be cut slightly larger than the actual sample size. Then the entire stack is placed in a holder. The edges of the sample are polished with diamond polish of 14.5 um down to 0.5 um by moving the holder in the shape of an eight in order to attain a uniform polish.

After the sample has been poled, photoresist in once again applied to both surfaces of the sample and then it is packaged in a holder. Carbon leads are attached to each side of the electrode by using silicone glue, and pulled up through each side of the holder so that it will facilitate for voltage to be added to the device during testing.

Figure 2.3: Sample in holder.

Figure 2.3 shows a picture of the actual holder. The device sits in the middle and each of the carbon leads goes up through the respective sides.

Testing and Conclusion

The device was tested by using a Helium Neon Laser with a wavelength of 632.8 nm and by applying 300V/0.27mm. It took some time to determine the best value for the voltage so that optimal results could be attained. The set up was similar to that of the polarizers, and the holder was placed behind the polarizers so that the laser could go through the device. Then a camera was placed directly behind the holder so that the results could be recorded easily.

The expected value for the critical angle when applying 300 Volts is 87.2538 degrees. Using basic geometry the value of the critical angle came out to be 86.8391 degrees ± 0.48% error. Therefore our theoretical value comes very close to the experimental value. In Figure 3.1 it is clearly seen that our experimental value fits well with our theoretical data.

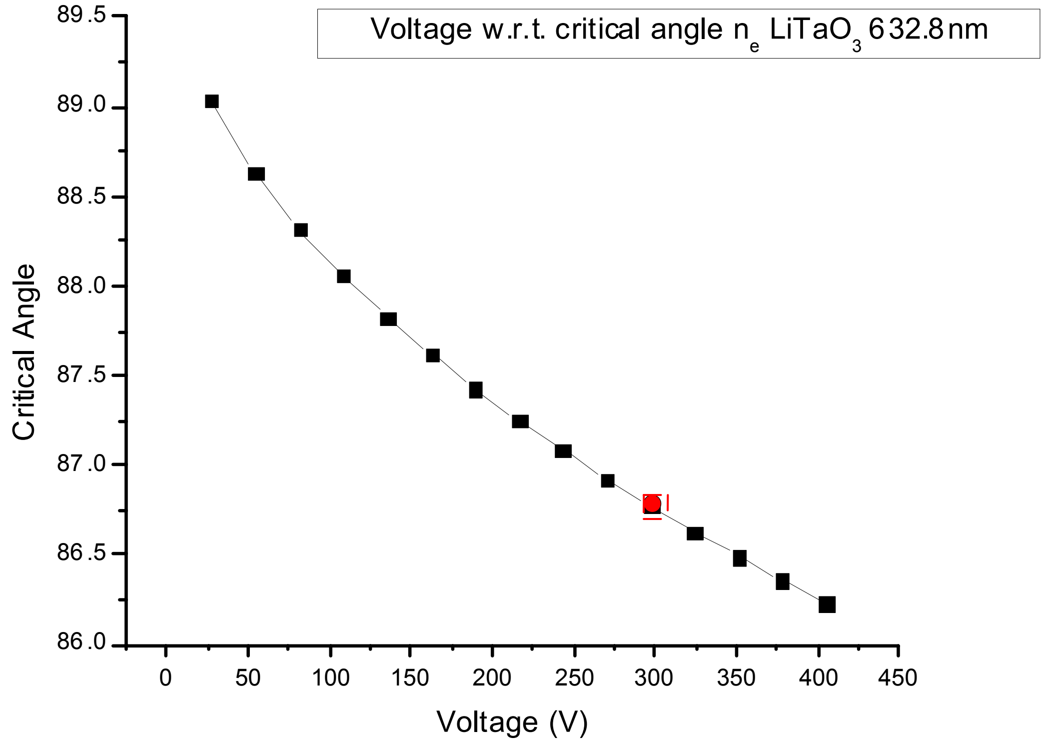

Figure 3.1: Graph describing the relationship between the applied voltage and the critical angle, according to the electro-optic effect in single crystal lithium tantalate. The red circle represents the experimental value surrounded by its' respective error bars.

Only one experimental value was plotted in Figure 3.1 because this was the only value that was accurately measured.

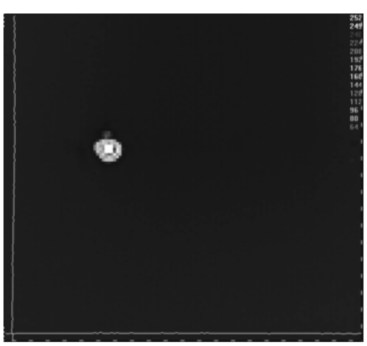

Figure 3.2(a): 0 V

Figure 3.2(b): 300 V

Figures 3.2 (a) and (b) are pictures from video clip of device in motion.

In Figure 3.2(a) the voltage applied was 0 V, meaning that the device is allowing for the light to be transmitted straight through. In Figure 3.2(b) the voltage applied was 300 V, in this case the electro-optic effect took place thus allowing for TIR to occur. In conclusion a device that obeyed optical properties was fabricated and tested. The results attained came fairly close to theoretical predictions and the optical switch behaved the way it was expected to.

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