Design and Fabrication of a Color Multiplexing $LiNbO_3$ Device

Abstract—**In an effort to create a full-color holovideo display, a wavelength-multiplexing $LiNbO_3$ crystal is designed. Fabrication parameters are presented. Results of tests and measurements are presented, as well as the procedures used to obtain them. By matching the bandwidth of the $LiNbO_3$ to that of current GPUs, the display is able to efficiently process large amounts of data.**

Index Terms—**Optics and Photonics**

I. Introduction

Holography holds many advantages over other forms of 3D display, including accommodation; which few current displays offer. What has prevented holographic displays from being implemented effectively until now is its dependence on the large amounts of data processing required.

The goal is to create a full-color holovideo device that can process an arbitrarily large amount of data. The output will be controlled by an x-cut $LiNbO_3$ chip which, by modulating the frequency of an surface transducer, changes the angle of the light. The separate colors will be frequency-multiplexed by superimposing multiple frequencies on the same transducer.

200 MHz is chosen as a delimiting bandwidth for the device since it matches most closely the current output of commodity GPUs. By creating a simple, single-waveguide device that runs at this bandwidth, any amount of data can be processed by running multiple devices in parallel. Each device should be capable of scanning RGB light across a similar output angle. This ensures that the output color addresses the same display area and does not require any external modulation to mix properly.

In addition, each device should efficiently utilize the 200 MHz allowed. All three colors passbands need to be as close to each other as possible in order to avoid wasting bandwidth.

To meet the demands listed above, the device's parameters must first be characterized. Means of measuring and evaluating its performance will be presented, as well as the results. Based off of these results, recommended device parameters will be chosen.

II. Background

The device is made from x-cut $LiNbO_3$ in order to take advantage of the crystal's piezoelectric and anisotropic properties. The waveguide itself is formed on the surface of the substrate by means of proton-exchange. For this experiment, a pure benzoic acid bath was used. The depth of the waveguide is proportional to the time of the proton exchange and the quality factor of the acid (D), as given by the equation $d = 2\sqrt{Dt}$, where d is the depth in microns and t is time in hours[1]. The D used in this paper is D= .2993. In order to replicate results given in this paper, it is easiest to match the depth of the waveguide after proton exchanging and index after annealing.

While proton exchanging creates waveguides in the substrate it also damages the material's acousto-optic properties. In order to offset this, an annealing step follows. This creates what is known as an annealed proton exchanged (APE) waveguide. Waveguide depth increases as proton exchange and anneal time increases, and while the refractive index of the waveguide increases proportionally according to proton exchange time, the anneal step reduces the index as it diffuses the doped ions into the substrate.

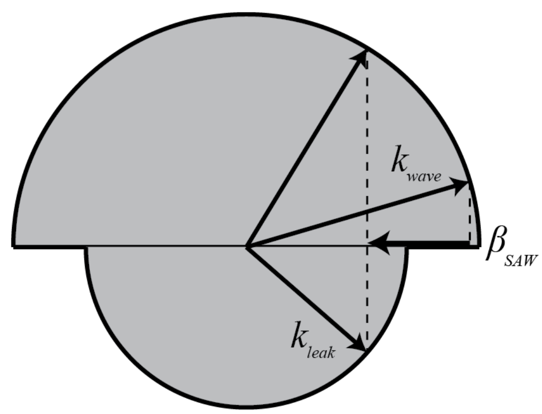

Figure 1. A k-vector diagram of the light-acoustic wave interaction. After the acoustic momentum shifts the optical k-vector back, the light is free to escape into a leaky mode in the bulk of the $LiNbO_3$.

After light is prism-coupled into the waveguide, it is modulated by a comb transducer patterned on the surface of the device. This transducer is designed to operate over a specific range of frequencies. Its bandwidth needs to be designed to match the device's color passband.

The transducer operates by shifting the momentum of the incoming light source according to the equation $k_{wave} - \beta_{SAW} = k_{leak}$. By changing the momentum of the surface acoustic wave (SAW) generated by the transducer, the resulting momentum of the light can be shifted accordingly.

Light once trapped in the waveguide is now free to escape, as can be seen in the k-diagram shown in Figure 1. The number of leaky modes created depends on the strength of β_{SAW} in relation to k_{wave}. The momentum shift also causes a change in polarity; while the incoming light was TE-polarized, the light after the interaction with the SAW is TM-polarized[4]. The light escapes from the waveguide and down into the bulk

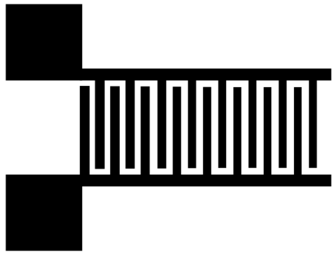

Figure 2. Transducer chirped over a certain bandwidth. The finger width, as well as the spacing between them, determines the frequencies.

$LiNbO_3$, favoring this direction over escaping up into free space due to the lower index contrast. After a short time in the substrate, the light exits the end of the device. The angle at which it exits varies according to the frequency of the SAW.

III. Fabrication

Individual waveguides are embedded into the $LiNbO_3$ chip by depositing an aluminum hard mask onto a wafer and then dicing it into individual pieces. Only the areas which are not covered by the aluminum will be affected by the proton exchange.

In order to characterize the responses of various waveguide depths and indexes, 15 samples were prepared and proton exchanged for the times shown in Table 1. Proton exchanging takes place in a two-neck flask nested inside a heating mantle. The mantle is heated to 238° C. After proton exchanging, the aluminum hard mask is removed.

Annealing is performed in a dry muffle furnace at 375° C for the times specified in Table 1. After annealing, the samples are measured in a Metricon 2010/M prism coupler in order to find the number of modes and refractive indexes. The indexes of each sample are also listed in Table 1.

	Proton Exchange Times				
Anneal Times	*10 (m)*	*20*	*30*	*45*	*60*
30 (m)	2.2379	2.2734	2.2863	2.2877	2.2877
45	2.2346	2.2640	2.2798	2.2849	2.2870
75	2.2214	2.2437	2.2679	2.2793	2.2849

Table I
Refractive indexes of the waveguides in the 15 samples after proton exchange and annealing.

The transducer, a representation of which is shown in Figure 2, is patterned onto each sample using an ESEM e-beam lithography process and aluminum deposition.

IV. Testing

In order to test the devices, a custom setup was required. Shown in Figure 3 is the design that was chosen after iterating through previous models[2]. By sweeping through all angles and frequencies supported, the output data gathered is able to shed light on both the expected output angles of the colors as well as their respective bandwidths.

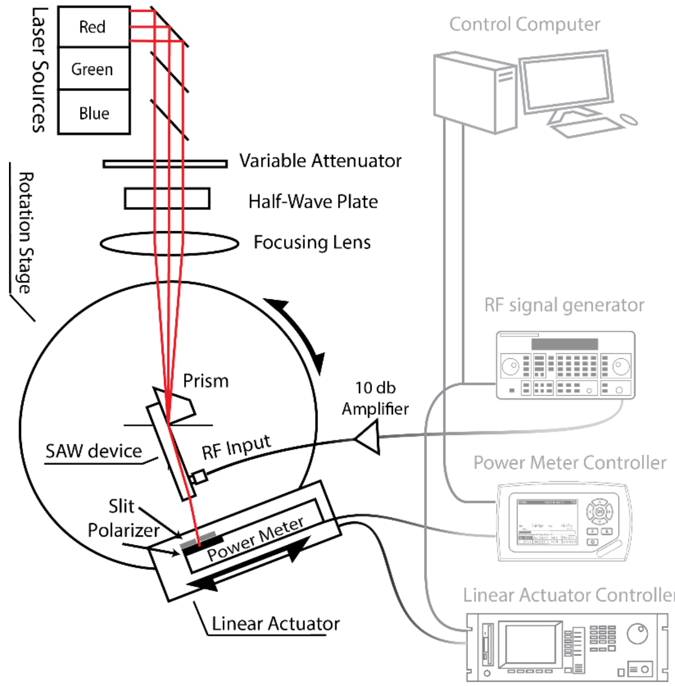

Figure 3. Setup for the measurements given hereafter. One of the lasers fires into a series of lenses and other optical components to couple into the $LiNbO_3$ crystal. The SAW transducer is controlled by the external RF signal generator and sweeps over the range of frequencies supported by the transducer. The light exits the bulk crystal at some arbitrary angle(s). The power meter is controlled by the linear actuator, and for each sweep of frequency, moves normal to the plane of the $LiNbO_3$ waveguide. As the light exiting the crystal is detected by the meter, the data is transmitted to the external computer, where it is compiled.

Figure 4 shows a sample output from the measurements for a given color (red). After normalizing the output, it is shown that the power output is limited to only a certain frequency and angle area. In order to make a full-color device, the angles for all three devices should be similar, but the frequencies these colors use to acheive such angles should be separate. After analyzing the data, it was found that the 10-min. proton exchanged, 45-min. annealed device had the parameters desired. The results for this device are shown in Figure 5.

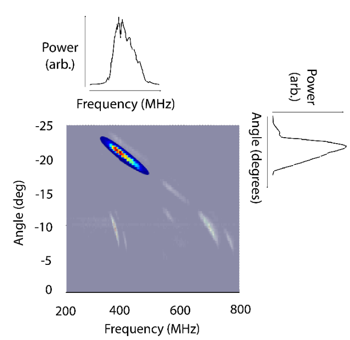

Figure 4. Frequency vs. angle output for a given device. The normalized intensity shows that the power is limited to only a specific range of frequencies and angles.

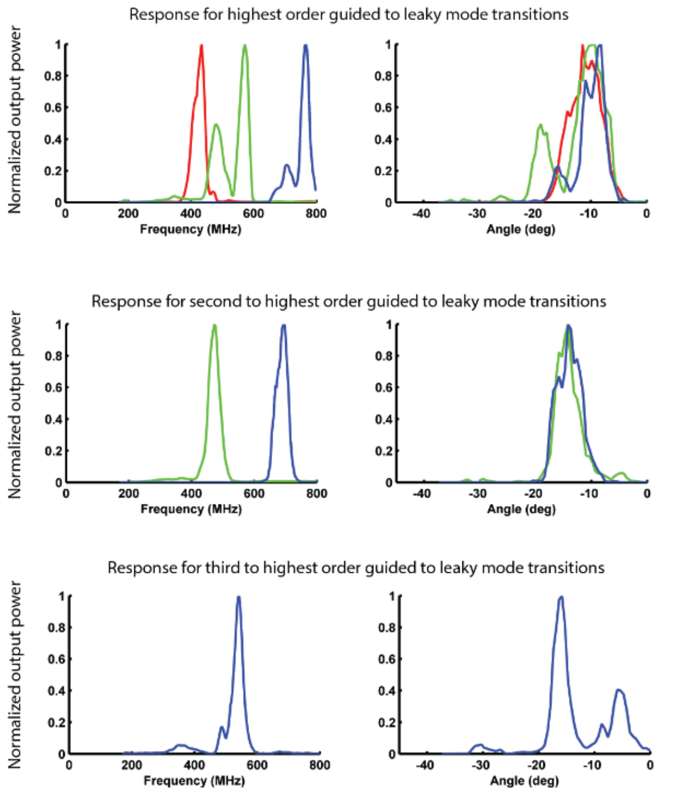

Figure 5. Data collected for the 10-min. proton exchanged, 45-min. annealed device. Only one leaky mode existed for red. Also, the overlapping angles are shown in the second column.

V. Results

From the data collected, it became apparent that the bandwidth of the guided to leaky mode transition decreased inversely with waveguide depth[3]. It was also necessary to find a device with a leaky mode for red, which was not always present in the shallower waveguides. This led to the selection of the 10/45 device mentioned above, which had the best bandwidth while also supporting one red mode. The depth of this waveguide before annealing was 0.4467 µm.

Figure 5 shows that the highest order modes have good angular overlap. Further, higher order mode transitions are more efficient than those from lower orders. However, the the bandwidth required to create all three transitions is roughly 400 MHz, which is double of what was allowed for. By instead choosing the second order green transition and the third order blue transition (again, shown in Figure 5), the bandwidth can be reduced to 200 MHz. This scenario is depicted in Figure 6.

In addition to optimizing bandwith usage, the angular output requirement has been met. Although the overlap shown in Figure 6 is not as complete as that shown in Figure 5 (for the highest-order transitions), the overlap can be further increased by polishing the output end of the device at an angle, which will cause the outcoupled angles to shift based on color, and their curves will draw closer together.

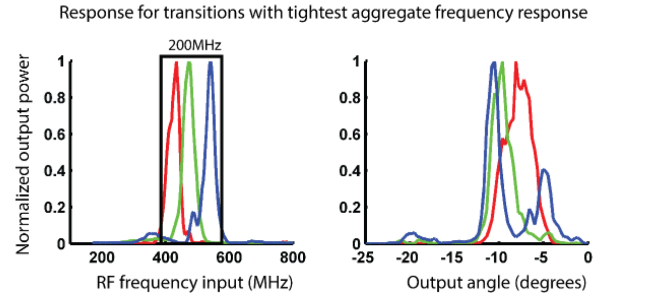

Figure 6. By selecting the correct mode transitions, all three colors are able to be fit into 200 MHz with minimal frequency overlap. The output angles are also acceptable.

VI. Conclusion

After designing and testing multiple devices, a set of standard parameters have been found that produce a full-color light steering source. While replicating these results depends on several variables, by matching refractive index and waveguide depth, the device can be duplicated. The 200 MHz bandwidth requirement has been met, enabling each device to be driven by commercial GPUs. By making small improvements in the future, this device will be capable of being the central component in a full-color, holovideo display.

References

[1] N. T. Do et al. High-efficiency acoustooptic guided-mode to leaky-mode conversion in proton-exchanged lithium niobate waveguides. 1999 IEEE Ultrasonics Symposium.

[2] A. Henrie, B. Haymore, and D. E. Smalley. Frequency division color characterization apparatus for anisotropic leaky mode light modulators. *Review of Scientific Instruments*, 86(2), 2013.

[3] S. McLaughlin et al. Optimized guided to leaky mode device for gpu controlled frequency division of color. *Applied Optics*, 2015.

[4] H. Nishihara et al. *Optical Integrated Circuits*. McGraw-Hill Book Company.