

Journal of Visualized Experiments

Characterization of Anisotropic Leaky Mode Modulators for Holographic Video

--Manuscript Draft--

Manuscript Number:	JoVE53889R1
Full Title:	Characterization of Anisotropic Leaky Mode Modulators for Holographic Video
Article Type:	Invited Methods Article - JoVE Produced Video
Keywords:	holographic video; integrated optics; waveguide; modulators; holography; leaky mode; lithium niobate; proton exchange; electroholography
Manuscript Classifications:	93.31.5: display engineering; 93.31.6: engineering (general)
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Abstract:	Holographic video displays are based on light-bending spatial light modulators. One such spatial light modulator is the anisotropic leaky mode modulator. This modulator is particularly well suited for holographic video experimentation as it is relatively simple and inexpensive to fabricate ¹⁻³ . Some additional advantages of leaky mode devices include: large aggregate bandwidth, polarization separation of signal light from noise, large angular deflection and frequency control of color ¹ . In order to realize these advantages, it is necessary to be able to adequately characterize these devices as their operation is strongly dependent on waveguide and transducer parameters ⁴ . To characterize the modulators, the authors use a commercial prism coupler as well as a custom characterization apparatus to identify guided modes, calculate waveguide thickness and finally to map the device's frequency input and angular output of leaky mode modulators. This work gives a detailed description of the measurement and characterization of leaky mode modulators suitable for full-color holographic video.
Author Comments:	
Additional Information:	
Question	Response
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To the Editor:

I believe that our work is fundamentally a visual one. There are number of steps in the characterization process that are both critical and also difficult to describe in text. These steps include the identification of a wet spot, the understanding of m-lines and the process of evanescently coupling light into a waveguide. For this reason, I believe the work presented is particularly appropriate for video representation.

Thank you for your consideration.

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Standard Manuscript Template

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KEYWORDS:

holovideo, integrated optics, waveguide, modulators, holography, leaky mode, lithium niobate, proton exchange, electroholography

SHORT ABSTRACT:

-This work describes fabrication and characterization of anisotropic leaky mode modulators for holographic video.

LONG ABSTRACT:

-Holovideo displays are based on light-bending spatial light modulators. One such spatial light modulator is the anisotropic leaky mode modulator. This modulator is particularly well suited for holographic video experimentation as it is relatively simple and inexpensive to fabricate^[1-3]. Some additional advantages of leaky mode devices include: large aggregate bandwidth, polarization separation of signal light from noise, large angular deflection and frequency control of color^[1]. In order to realize these advantages, it is necessary to be able to adequately characterize these devices as their operation is strongly dependent on waveguide and transducer parameters^[4]. To characterize the modulators, the authors use a commercial prism coupler as well as a custom characterization apparatus to identify guided modes, calculate waveguide thickness and finally to map the device's¹ frequency input and angular output of leaky mode modulators. This work gives a detailed description of the measurement and characterization of leaky mode modulators suitable for full-color holographic video.

INTRODUCTION:

-Most holographic display technologies, such as pixelated light valves as well as MEMs devices and bulk wave acousto-optic modulators, are too complex to allow for broad participation in their development. Pixelated modulators, especially those with filter layers and active back planes may require dozens of patterning steps to build^[5] and may be limited by fan-out^[6]. The greater the number of patterning steps the higher the device complexity, and the tighter the fabrication protocol must be to achieve reasonable device yield^[7]. Bulk-wave acousto-optic modulators do not lend themselves to wafer based processes^[8,9]. Anisotropic leaky mode modulators, however, require only two patterning steps to fabricate and utilize relatively standard microfabrication techniques^[10,11]. The accessibility of these processes make it possible for any institution with modest fabrication facilities to participate in the development of holographic video display technology^[12].

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The simplicity of device fabrication can be beguiling, however, as the proper function of the devices is strongly dependent upon waveguides¹³ which must be carefully measured and adjusted to achieve the desired device characteristics. For example, if the waveguide is too deep, the device's operational bandwidth will be narrowed¹³. If the wave guide is too shallow, the device may not work for red illumination. If the waveguide is annealed too long, the shape of the waveguide's depth profile will be distorted, and the red, green and blue transitions may not sit adjacent in the frequency domain¹⁴. In this work the authors present the tools and techniques to perform this characterization.

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The leaky mode modulator consists of a proton exchanged waveguide indiffused on the surface of a piezoelectric, x-cut lithium niobate substrate^{15,16}. At one end of the waveguide is an aluminum interdigital transducer, see Figure 1. Light is introduced into the waveguide using a prism coupler¹⁷. The transducer then launches surface acoustic waves which interact contralinearly with light in the waveguide along the y-axis. This interaction couples guided light into a leaky mode which leaks out of the waveguide into the bulk and finally exits the substrate from the edge face^{18,19}. This interaction also rotates the polarization from TE polarized guided light to TM polarized leaky mode light. The surface acoustic wave pattern is the hologram, and it is capable of scanning and shaping the output light to form a holographic image.

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The aluminum transducers are formed by liftoff. After waveguides are formed, an E-beam resist is spun onto the substrate. An interdigital transducer is patterned with an electron beam to form a chirped transducer designed to respond to the 200MHz band responsible for controlling color in waveguide devices. The finger period is determined by $\Lambda f = v$ where, Λ , is the finger period, v , is the velocity of sound in the substrate and, f , is the radio RF frequency (RF). The transducer will have an impedance that must be matched to 50 ohms for efficient operation²⁰.

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The guided to leaky mode interaction occurs at different frequencies for different wavelengths of illumination light and as a result red, green and blue light can be controlled in the frequency domain. The surface acoustic wave pattern is generated by an RF signal sent to the interdigital transducer. The RF frequencies of the input signal translate to spatial frequencies on the surface acoustic wave pattern. The waveguide can be fabricated so that low frequency signals control the angular sweep and amplitude of red light, while middle frequencies control green light and high frequencies control blue light. The authors have identified a set of waveguide parameters that allow all three of these interactions to be separate and adjacent in the frequency domain so that all three colors can be controlled with a single 200MHz signal which is the maximum bandwidth of commodity graphics processing units (GPUs).

By matching the bandwidth of a GPU channel to that of a leaky mode modulator, the system becomes fully parallel and highly scalable. By adding bandwidth matched pairs of GPUs and leaky mode modulator channels, one may construct holographic displays of arbitrary size.

After the device is created, it is carefully characterized to verify that the frequencies for guided-

to-leaky mode transition are appropriate for frequency control of color. First, the location of the guided modes are determined by a commercial prism coupler to confirm that the waveguide has the appropriate depth and the correct number of guided modes. Then, after the devices are mounted and packaged, they are placed in a custom prism coupler which maps the input frequencies of the scanned output light. The resulting data gives the frequency input response and the angular output response for red, green and blue light for the device under test. If the device has been fabricated correctly, the device input response will be separated in frequency and the output response will be overlapping in angle. When this is confirmed, the device is ready for use in a holographic video display.

The first measurements take place before the device has been packaged. The waveguide depth is determined by a commercial prism coupler. This can be accomplished with just one illumination wavelength (typically 632nm red) but authors have modified their commercial prism coupler to allow it to gather mode information for red, green and blue light. After packaging, the device undergoes a second measurement in a custom prism coupler which records deflected output light as a function of input RF ~~frequency~~.

A detailed description of these measurements follows. Fabrication steps are also given, ~~but only briefly and with minimal detail. A more detailed description of the device fabrication will be given in a future publication describing an improved and simplified process.~~

PROTOCOL:

1. ~~Device Fabrication~~Initial Preparation

1.1) ~~Note: Begin with a new clean~~ X-cut lithium niobate wafer. ~~It should be,~~ optical grade, 1mm thick, ~~clean, with nothing deposited on the surface, and both sides double-side polished, and the with top-side~~ marked.

1.2) ~~Using an Electron Beam Evaporator or equivalent machine at a vacuum of 50 μ torr, Evaporate 200nm of aluminum on the wafer at 5 $\text{\AA}$ per sec. To replicate the presented results, position the wafer constellation 65 cm above the aluminum crucible.~~

1.3) Spin ~~on 30 drops of AZ3330~~ photoresist ~~at 3000 rpm for 60 sec. For a detailed description of the mechanics of spinning polymer films see the work by C. J. Lawrence²¹.~~

~~1.4) Softbake the resist at 90°C for 60 sec.~~

~~1.5) Using the proper mask, such as the "Mask 1. Proton Exchange Mask.dxf" file supplied in the appendix, and us expose the wafer using a mask aligner with a 350W mercury bulb or its equivalent for 10 sec as per machine specifications. e a photolithographic mask to pattern waveguides. The wafer should be aligned so that the waveguides should be are parallel to the y-axis.~~

~~1.6) Develop the resist in a solution of MIF 300 for 60 sec.~~

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1.7) Hard bake the wafer for 60 sec at 110°C. ~~Develop the waveguide pattern.~~

1.8) Etch ~~away~~ the exposed aluminum ~~completely by submerging it for 2 min in a 1L solution in~~ with aluminum etch ~~heated to 50°C.~~

1.8.1) CAUTION: Aluminum etch is toxic, corrosive and harmful. See MSDS for proper handling and storage of this chemical. Use proper personal protective equipment for acid when handling this chemical.

1.9) Remove the photoresist mask with a rinse of acetone followed by isopropyl alcohol (IPA). ~~and~~

1.10) Using a 0.016in thick diamond blade with an exposure depth of 0.165in on an automatic dicing saw, cut the wafer into 10x15mm devices with the long dimension parallel to the y-axis.

1.10.1) The blade will not cut all the way through the substrate. To separate each device, simply stress each cut made by the dicing saw.

1.10.2) Note: Each 10x15mm device will individually go through the remaining steps of the protocol.

2. Proton Exchange

2.1) Place an individual device in a test tube with a small hole cut in the bottom to allow interaction between the device and all liquid baths.

2.2) Proton exchange the device by immersing it in a 1L melt of 99% pure benzoic acid at 240°C. In order to achieve the target depth of 0.4504µm, use an immersion time of 10min and 10sec.

2.2.1) Note: The proton exchange immersion time is dictated by the diffusion coefficient, D, which for the authors' melt is currently D=0.2993. The proton exchange immersion time is calculated using the relation $T = d^2 / (4D)$. Where T is the exchange time in hours, d is the waveguide depth in microns and D is the diffusion coefficient. For a detailed description of the mechanics of proton exchange see the work by J. L. Jackel¹⁵.

2.3) Remove the device and allow to cool for 5 min or until cool to the touch ~~remove.~~

2.4) Clean off any ~~remaining photoresist with~~ benzoic acid residue with a rinse of- acetone then IPA ~~solvents.~~

3. Anneal

3.1) Place device in a regular test tube and wrap the tube in aluminum foil.

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3.2) Place the tube in a muffle furnace for 45 min at 375°C.

3.3) Remove the device and allow to cool for 5 min or until cool to the touch.

4. Clean

4.1) Clean the aluminum mask from the device using aluminum etch for roughly 2 min at 50°C.

4.2) Clean the device in acidic piranha etch to remove any organic residues.

4.2.1) CAUTION: Acidic piranha etch is toxic, corrosive and harmful. See MSDS for proper handling and storage of these chemicals. Use proper personal protective equipment for acid when handling these chemicals.

4.3) Rinse the device in acetone, then IPA, and dry with compressed nitrogen.

1.5) Diesaw the wafer into 10x15mm samples with long dimension parallel to the y-axis.

5. Waveguide Measurements

5.1) Using any commercial waveguide analyzer measure the characteristics of the proton exchanged waveguide. A good device will have 2 guided modes using a 633nm laser. See Figure 2 for an example of desired results.

5.1.1) Note: If the device shows more than two guided modes for red illumination then the exchange time in step 2.2 should be reduced. Likewise if the device shows less than two guided modes the exchange time should be increased.

1.8) Anneal the sample by placing it in a muffle furnace for 45min at a temperature of 375 °C [ref]. Clean the sample with solvents.

6. Add Resist

6.1) Spin on 4 drops of a Lift Off Resist (LOR) at 3000 rpm for 60 sec and then bake at 200°C for 1 hr.

6.2) Remove and allow the device to cool for 5 min or until cool to the touch.

6.3) Spin on 4 drops of 3:1 PMMA:Anisole and spin at 3000 rpm for 60 sec and then bake at 150°C for 15 min.

6.4) Remove and allow the device to cool for 5 min or until cool to the touch.

6.5) Spin on 2 drops of a conductive polymer at 1000 rpm for 60 sec, then 6000 rpm for 4 sec to remove any excess.

7. Pattern

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7.1) Use an electron microscope enhanced with a beam blanker to enable writing or an equivalent machine to expose the device.

7.1.1) Under a vacuum of 50 μ torr, expose the conductive layer to an electron beam with an area dose of 30 μ C/cm² that scans the pattern of the interdigital transducers. To replicate the results presented in this paper use a measured beam current of 410 pA.

7.1.2) Write the pattern from a .dxf or equivalent file on the electron microscope as per machine specifications.

7.1.3) Note: For a detailed description of the E-Beam lithography process see the work done by R. E. Fontana²².

8. Develop

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8.1) Remove the conductive layer by rinsing the device in a continuous stream of deionized water for 5 sec.

8.2) Remove the exposed PMMA by dipping the device into 1:3 solution of MIBK:IPA for 45 sec.

8.2.1) Remove from the 1:3 solution of MIBK:IPA and rinse with IPA for 5 sec.

8.2.2) Dry the device with compressed nitrogen.

8.2.3) Repeat steps 8.2-8.2.2 as necessary to fully develop the PMMA. However expose the device to the solution of MIBK:IPA in 5 sec increments only. Complete development should reveal the LOR underneath the PMMA and can be identified by uniform coloration throughout the developed area surrounded by crisp edges and corners.

8.2.3.1) Note: Over development of PMMA leads to small feature blowout and can completely erase the interdigital transducer fingers, leaving a single large developed block. Likewise under development leaves non-uniform residues that will decrease the effectiveness of the liftoff process that follows.

8.3) Remove LOR in exposed region by dipping the device into a 1:1 solution of MIF 300:H₂O for 25 sec.

8.3.1) Remove from the 1:1 solution of MIF 300:H₂O and rinse with IPA for 5 sec.

8.3.2) Dry with compressed nitrogen.

8.3.3) Repeat steps 8.3-8.3.2 as necessary to fully develop the LOR. However expose the device to the solution of MIF 300:H₂O in 2 sec increments only. Complete development should reveal the surface of the substrate underneath the LOR and can be identified by uniform white coloration

throughout the developed area maintaining its crisp edges and corners. Failure to develop the LOR properly also leads to the problems discussed in 8.2.3.1. See Figure 3 for an example LOR development process.

8.3.3.1) Note: switching to a lower dose of MIF 300: H₂O such as 1:2 or 1:3 is helpful as the device nears complete development to allow the fine features to develop without blowing out the device. However, it is not advantageous to start with these doses as total time increases and exceeds optimal time in MIF 300.

9. Deposit Aluminum

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9.1) Using an Electron Beam Evaporator or equivalent machine at a vacuum of 50 μ torr, evaporate 200nm of aluminum on the wafer at 5Å per sec.

10. Liftoff Aluminum

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10.1) Fill a large glass dish with 750mL of water on a hot plate at 90°C.

10.2) Insert a plastic buffer into the water dish.

10.3) In a separate small glass container submerge the device in a 100mL solution of NMP.

10.4) Place the container of NMP solution containing the device onto the plastic buffer insuring that the water level does not exceed the height of the container of NMP.

10.5) Cover and let sit 3 to 4 hours or until aluminum liftoff is complete.

10.6) Remove the device from NMP.

10.6.1) Note: it is advantageous to clean off large sections of aluminum from the device by squirting the device using a pipette filled with NMP while still submerged in the NMP bath.

10.7) Rinse the device in IPA and dry with compressed nitrogen.

10.8) Under a microscope, verify that liftoff is complete.

10.8.1) If unwanted residual aluminum remains, wet the device with acetone and very gently brush with a cleanroom swab coated in acetone to remove.

10.8.2) Rinse in IPA, dry with compressed nitrogen, and recheck under the microscope.

10.8.3) Repeat 10.8.1 and 10.8.2 as needed.

11. Polish the End of the Device

[113.1](#)) Coat the device in a protective film such as a layer of AZ3330 photoresist.

[113.2](#)) Clamp the device so that the end with the transducers is exposed for polishing.

[113.3](#)) Using proper polishing procedures, slowly polish the end of the device to a surface roughness of less than 100nm, so that no surface defects interfere with the light exiting the device.

[113.4](#)) Remove the device from the clamp and clean off the protective film.

[113.4.1](#)) If photoresist was used as a protective film, a generous rinse in acetone and then [IPA](#) ~~isopropyl alcohol~~ will remove it.

[11.4.2](#)) [Dry the sample as necessary with compressed nitrogen.](#)

[412.](#) Mount ~~the Device~~ on a Breakout Board

[124.1](#)) If any assembly is required for the RF breakout board, assemble the breakout board according to its specifications.

[124.2](#)) Build, out of glass slides, a mounting platform to hold firmly both the RF breakout board and the device.

[124.3](#)) Mount the device to the top of the mounting platform with double sided tape. Make sure the end of the device overhangs the end of the mounting platform so that the mounting platform does not interfere with light exiting the end of the device.

[124.4](#)) Mount the RF breakout board to the mounting platform so that it is not in the beam path of the light exiting the device. A simple way to do this is to elevate the breakout board with thick tape so that the bottom of the breakout board is above the top of the device.

[124.5](#)) Wire bond the pads on the device to their respective locations on the RF breakout board.

[124.6](#)) Use a 27nH series inductor to impedance match each transducer to the breakout board inputs.

[135.](#) Prism Coupling ~~the Device~~

[135.1](#)) [Use-Select](#) a rutile prism to couple light into the device. The polarization of the light (TE) should be parallel to the optical axis of the rutile the optical axis (Z-axis) of the X-cut lithium niobate.

[135.2](#)) Clean the contact surfaces of both the device and the prism thoroughly with ~~isopropyl alcohol~~ [IPA](#).

135.3) Position the prism so that it is centered on the channel to be tested.

135.4) Press the bottom of the prism firmly against the top of the device with a clamping mechanism.

13.4.1) Note: Do not overtighten as excessive pressure will crack the substrate and damage the coupling prism.

135.5) If successful, a wet spot will appear. A wet spot is a region of frustrated total internal reflection at the interface between the prism and the sample. For an example of proper prism coupling see

146. Mount the Device in the Characterization Apparatus

146.1) Mount the device on the rotating platform of the Frequency division color characterization apparatus for anisotropic leaky mode light modulators discussed by A. Henrie^[4].

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146.1.1) A schematic of the Characterization Apparatus is supplied in Figure 45.

157. Align the Device in the Characterization Apparatus

157.1) Turn on the laser. To replicate the results presented in this paper use 5V for 638 nm, 5.5V for 532 nm, and 6.5V for 445 nm.

157.2) Attenuate the beam for safe alignment.

157.3) Verify the laser polarization.

157.3.1) Place the polarizer in the beam path after the half wave plate so that it blocks horizontally polarized light.

157.3.2) Rotate the half wave plate to achieve maximum attenuation of the laser light signal.

157.3.3) Remove the polarizer.

157.4) Rotate the platform to the proper entrance angle for the wavelength and mode to be measured. See Table 1.

157.5) Using the linear translation stages, align the coupling edge of the prism so that it lies in the focal point of the laser.

157.5.1) At this point, light should be coupling into the device which can be verified either by the characteristic streak of light caused by scattering in the waveguide or by the characteristic mode lines coming out of the end of the device^{[2][3]}. See Figure 56.

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157.5.1.1) If using mode lines to verify coupling, it is helpful to remove the power meter from the beam path. Instead insert a uniformly scattering object, such as a sheet of white paper, into the beam path.

157.5.2) If no coupling is detected, slowly rotate the device while maintaining the coupling edge of the prism in the focal point of the laser. If after five degrees rotation in either direction no coupling can be detected, remove the device from the rotating platform, remove the prism and return to step 134.

157.6) Once coupling is detected, fine tune the rotational platform and linear translation stages to maximize the coupled light into the mode that will be tested.

168. Attach the RF Input and Enclose the Device

168.1) If the power meter was removed during alignment, replace it now. Also remove any obstructions to the beam path used for alignment purposes.

168.2) Attached the RF input to the device breakout board and turn on the RF signal generator. Make sure the amplifier is powered.

168.2.1) Note: to protect the device from burnout, the electrical power of the signal reaching the device should not exceed 1W.

168.3) Remove any attenuation used for safety during alignment. The laser should now be at the optical power levels used for testing.

168.4) Enclose the entire system in an optically isolating box.

179. Run the Provided LabView Testing Program.

179.1) Obtain a laboratory equipment manager that can run the characterization device, such as the Download and open the LabView file AutomatedDeviceCharacterization.vi provided in the appendix.

179.2) Insert all user parameters into the testing software on the control computer.

17.2.1) Note: If using the provided file, Fields in Figure 76 indicates, by a yellow box, the fields that boxed in yellow must be updated before each automated test is run, in order for the provided Analytical program to run properly in step 19.

179.2.2) Note: to replicate the results presented in this paper use the following testing Common testing parameters: are as follows: Initial Frequency: 100 MHz, Final Frequency: 800 MHz, Frequency Step: 10, Rough Initial Position: 0, Rough Final Position: 25, and Position Step: 1.

179.3) Run the testing program.

179.3.1) **Note:** The [provided](#) program drives a power meter along a linear track at user defined intervals. At each position the RF input signal is swept through a set of chosen frequencies and power measurements are made. A measurement is also made with the RF input at its lowest frequency setting and lowest output power which has been experimentally determined as equivalent to no input signal⁴. These measurements are then graphed in real time in a 3D interactive chart.

179.3.2) **Note:** The [provided](#) testing program creates four output files: *config.csv describes the experiment, *data.csv contains the power reading at each frequency, *no_stim.csv contains the background noise reading, and *graph.jpeg contains a copy of the graph on the user interface of the [LabView](#) program as it was when the program ended. See [Figure 87](#).

1810. Repeat steps 157-179 for each wavelength and the TE1 mode described in Table 1.

149. Analyze the Frequency and Angular Output Profiles.

194.1) [Obtain a statistical analysis program or](#) ~~Download~~ the CompareWDMmodes.m MATLAB code provided in the appendix.

194.2) In the folder where [the program CompareWDMmodes.m](#) is located, create a subfolder, ***“Sample Number”*** Where “Sample Number” is the [device identification number](#)~~name~~ entered into the [testing program](#)~~LabView file~~.

194.3) In this folder, “Sample Number,” create three subfolders. Each should be named in the format ***“Sample Number”_“Color”_M1_“Transducer”***, where the names in ***“bold and italics”*** are values entered into the [testing program](#)~~LabView file~~ by the user. (e.g. A16_BLUE_M1_T1, C5_RED_M1_T13, [or](#) D35_GREEN_M1_T18).

194.4) Copy into each subfolder the four files created by the [testing software](#)~~LabView software~~ that correspond with that particular wavelength, mode, and transducer.

194.5) Open [CompareWDMmodes.m](#)~~analytical program~~ and change the user defined variables at the top ~~of the MATLAB code to~~ to reflect the user [LabView-defined](#) values [input into the testing software](#).

194.5.1) **Note:** ~~If using the provided analytical program and~~ ~~For example: If~~ the user defined [Labview-values in the testing program](#) are ***“Sample Number”=A16, “Guided Mode”=1, “Transducer”=1*** the [analytical MATLAB](#) code would be modified to the following:

```
% User Defined Variables
series='A';
sample=16;
```

```
modes=[1];  
transducer='T1';
```

194.6) Run [the analytical program CompareWDMmodes.m](#) in the MATLAB software.

194.6.1) [Note: If using the provided analytical code, among other things it](#) ~~Among other things,~~ [CompareWDMmodes.m](#) creates a figure that compares the normalized frequency response and the angular output for red, green, and blue light. The file it creates is located in the **“Sample Number”** subfolder. See [Figure 9 for an example of the output 8](#).

REPRESENTATIVE RESULTS:

[The principle results of the protocol above are the guided mode measurement from the commercial prism coupler shown in Figure 2, the single frequency, raw input/output data gathered from the customized prism coupler shown in Figure 8 and the multicolor curves shown in Figure 9. In the following paragraphs we discuss the actionable information produced by each of these outputs.](#)

[The guided mode information gleaned from the commercial prism coupler is used, primarily, to establish the waveguide depth, but the number of modes and their spacing contain other useful information relevant to leaky mode operation. For the leaky mode device to work as designed, it must have a guided-to-leaky mode transition for every color, and experimentation has shown this to be true when there exists at least two guided modes for each illumination wavelength. This is particularly relevant for red as it has the fewest guided modes of the three display colors. The proton exchange step 2 should be increased or decreased to make sure there are two red modes. In general, having two modes in red indicates that there are also at least two modes in green and blue. Devices optimized for frequency division multiplexing of color have shown two modes in red, three modes in green and four modes in blue. Fewer modes may appear for green and blue if the anneal time is too long. If fewer than the optimal number of modes appear for green and blue light, then the anneal time in step 3 may need to be extended. Long anneals, however, will also reduce the effective index of the guided modes.](#)

[The raw output of the custom prism coupler as shown in Figure 8 gives one a good qualitative sense for a number of important device parameters such as RF bandwidth, angular sweep, scan linearity, spot size, standing wave period and approximate diffraction efficiency. The projection of the data on the Y axis gives the frequency response of the device from which we can read the center frequency and the approximate bandwidth of operation. The projection of the data on the X axis gives span of the diffracted light output. This position information is nearly proportional to the angular sweep of the device output so the projection on this axis is a good indicator of the angular sweep of the device. The slope of the data on the XY plane of the graph gives us a sense of the linearity of the scan as well as the rate of scan with input frequency. If the X axis is sampled with sufficiently high resolution, then a cross section along the X axis will give the beam profile. If the Y axis is sampled with sufficiently high resolution, then surface acoustic standing wave patterns may become apparent—if they are prominent, it may be beneficial to add an acoustic](#)

[absorber to the device to produce a smooth, even scan. Absolute diffraction efficiency is not measured but when comparing one device to another, the signal to noise ratio serves as a good indicator of relative diffraction efficiency. This raw data provides a significant amount of information, but it is relevant to only one illumination wavelength.](#)

[To determine if the device is capable of frequency control of color, raw data is processed for several experiments with all three wavelengths to form graphs like the one in Figure 9. The X and Y axis projections are first collected for the TE1 guided modes for all three colors. Then these projections are superimposed on the angle and frequency axes respectively to form a multicolor frequency and angular response like the one shown. If the response for each color is adjacent in frequency and overlapping in angle, then the device is appropriate for frequency control of color.](#)

[By using the characterization steps described in this work, one can both reproduce devices capable of frequency control of color as well as effectively modify their function to meet new optimization criteria such as maximized diffraction efficiency, high signal to noise ratio or high linearity.](#)

FIGURE LEGENDS[Figure Legends:](#)

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Figure 1: Leaky Mode Modulator. As seen on the left, light enters the device through a rutile prism which evanescently couples light into a waveguide indiffused on the substrate's surface. As the guided light propagates toward the far end of the device it encounters surface acoustic waves which outcouple the light from the waveguide and rotate its polarization. The momentum diagram for this interaction is given on the right.

Figure 22: Sample Waveguide Data. Light from the laser is coupled into the prism. It then reflects off the surface of the device and onto a power sensor. When a guided mode is present, instead of reflecting off the device the light is guided through the substrate and out the end of the device. Thus, it is guided away from the power sensor and a [sharp](#) "dip" occurs in the plot. There are two modes identified in this plot. The gradually increasing power reading from left to right can be explained by the gradually increasing transmission efficiency at the air to prism boundary.

Figure 3: Sample LOR Development Process. [Images of the same area of a device as the LOR is developed. The picture on the far left was taken under a microscope after the initial 25 sec development time. The pictures that follow are a sampling of the changes through the iterative process. The final picture is a close-up of the finer features on the device after LOR development to show the clean edges and the exposure of the underlying substrate.](#)

Figure 34: A Prism Coupled Device Mounted to a Breakout Board. A correctly coupled, completed device mounted to its breakout board. At the proper angle, as in this picture the wet spot reflects a rainbow of color.

Figure 54: Characterization Apparatus Schematic. Basic diagram of the characterization apparatus. The laser is sent through a series of optical components before being coupled into the

device through a prism. Once inside a mode in the waveguide SAW waves produced by interdigital transducers and a RF signal knock the light into leaky modes which exit the device at a frequency controllable angle. A linear actuator drives the power meter through a range of positions while the signal generator runs through a range of frequencies creating multivariable graphs which describe the controllability and output of the device.

Figure 65: Identification Techniques of Proper Light Coupling. Proper coupling can be identified by either the presence of the characteristic streak of light caused by scattering in the waveguide, as shown on the left, or by the characteristic mode lines out of the end of the device, as shown on the right.

Figure 76: User Interface for LabVIEW Testing Software. The user interface including all user defined variables. Items boxed in yellow must be updated before each automated test is run in order for the analytical program to run properly.

Figure 78: Sample Frequency vs Position Graph. While the RF frequency input and power meter location are scanned linearly, the experiment software Labview builds and displays this interactive 3D graph of the collected data. Upon completion the current view is saved for quick reference. The MATLAB code provided further graphs and analyses the data.

Figure 98: Sample Mode Comparison Data. The frequency response of the three wavelengths is shown on the left. The sample device has a bandwidth of 200 MHz with individual control for each wavelength. On the right is the output angle response for each sample device. There is good angular overlap for 5-7°.

Table 1: Mode Excitation Parameters. Angle and wavelength parameters for desired the TE1 mode excitations for the 18 channel device discussed in this document.

DISCUSSION:

The design of each device has two critical steps, proton exchange and development of the LOR. Of the two, proton exchange time determines the depth of the waveguide, which in turn determines the number of guided to leaky mode transitions, the controllable frequency bandwidth, and every key design parameter for each color of light. Two guided modes in red is desired. If more exist then bandwidth is sacrificed. If less exist then no guided to leaky mode transition is guaranteed. Follow the note in step 2.2.1 to correct proton exchange times to achieve the desired result.

Proper LOR development is required for proper liftoff and thereby proper function of the interdigital transducers. It is a step best mastered through experience. A non-dilute solution of developer will blow out the fingers of the transducers in 7 sec while a 50% solution will do the same in about 35 sec. The exact time varies from device to device which creates the need to develop the device for 25 sec in a 50% solution followed by repeated quick exposures to more dilute solutions. If blowout occurs decrease development time or solution concentration to

[achieve desired results.](#)

[In the characterization process prism coupling and alignment are the critical steps. If the device is poorly prism coupled or poorly aligned no light will enter the waveguide making it impossible to measure results. Alignment is best achieved with small adjustments. Variations in the scattered light can indicate the approach to a mode line or show the proximity of the interdigital transducer. Experience is the best teacher.](#)

[This protocol is designed for the manufacture of a single device. As such scalability is limited and small variations will be present from device to device. However the authors are actively pursuing the development of a wafer driven manufacture process that will overcome this challenge. Another limitation of this characterization protocol is the reliance on an active testing process. The interdigital transducers must have a large bandwidth to accommodate the changes in the waveguide depth and mode transitions. Once the transition frequencies are determined a narrower bandwidth transducer can be designed. A good model for the process would eliminate the need for this step. Finally, the testing protocol is not completely automatic, requiring human adjustments between changes in wavelength and devices.](#)

[Once a device shows both good angular overlap and frequency control, then it is able to be used in such applications as the 3D holovideo display¹. These devices require only 2 patterning steps to fabricate which is a large improvement on the common display technologies of today, such as pixelated light valves, MEMs devices, and bulk wave acousto-optic modulators. It is the authors' hope that having access to this manufacture, measurement, and characterization protocol will encourage broader participation in electroholographic display research.](#)

Field Code Changed

The authors gratefully acknowledge financial support from Air Force Research Laboratory contract FA8650-14-C-6571 and from DAQRI LLC.

DISCLOSURES:

-The authors have nothing to disclose.

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Figure 1

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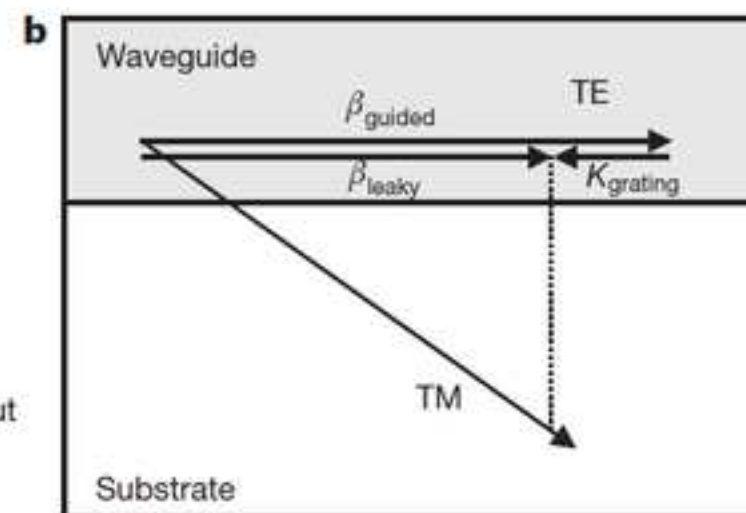
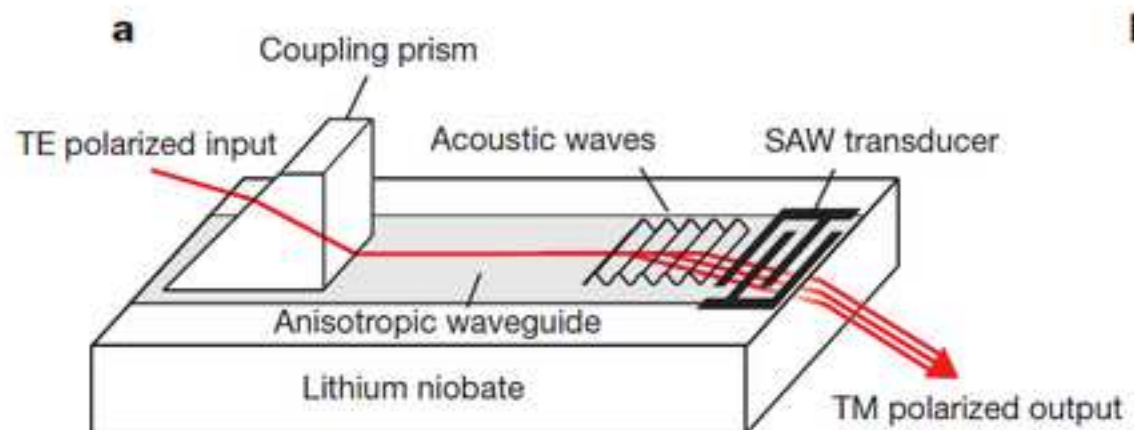


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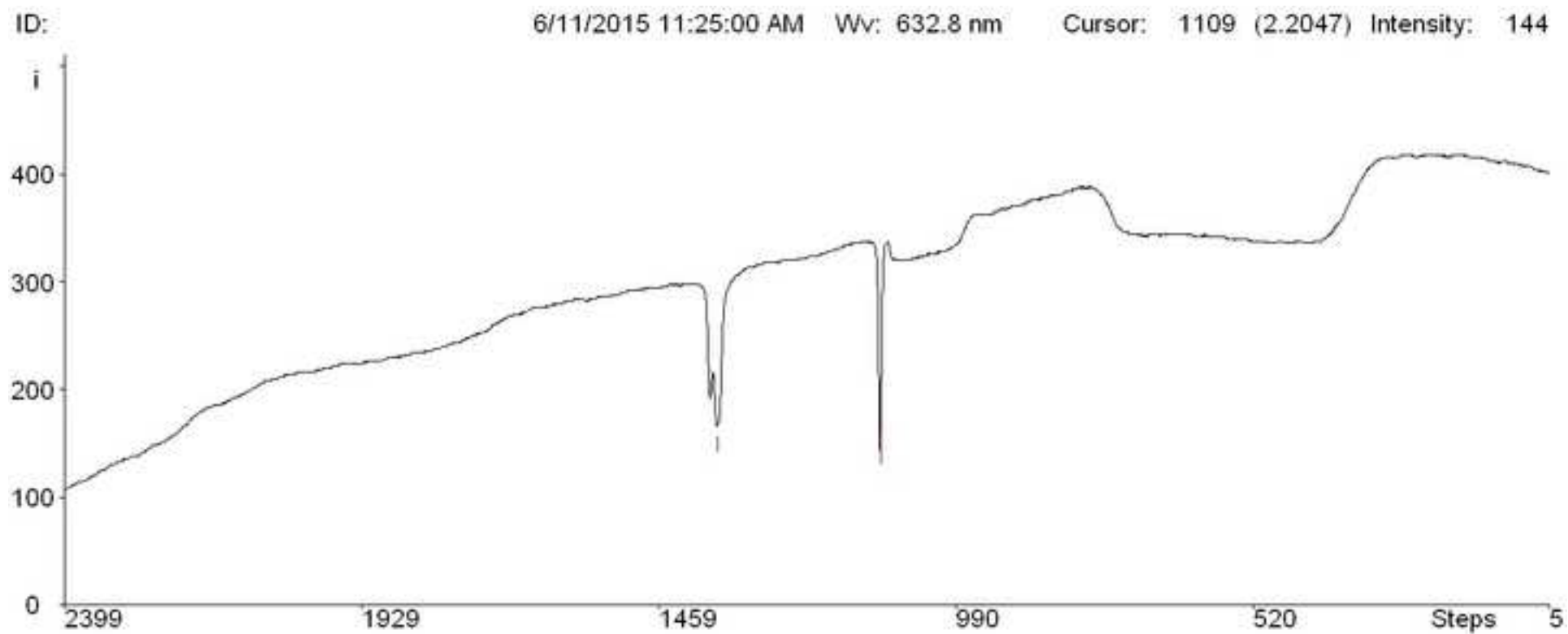


Figure 3

[Click here to download Figure: Figure 3. Sample LOR Development Process.psd](#)



Figure 4
[Click here to download Figure: Figure 4. A Prism Couples Device Mounted to a Breakout Board.psd](#)

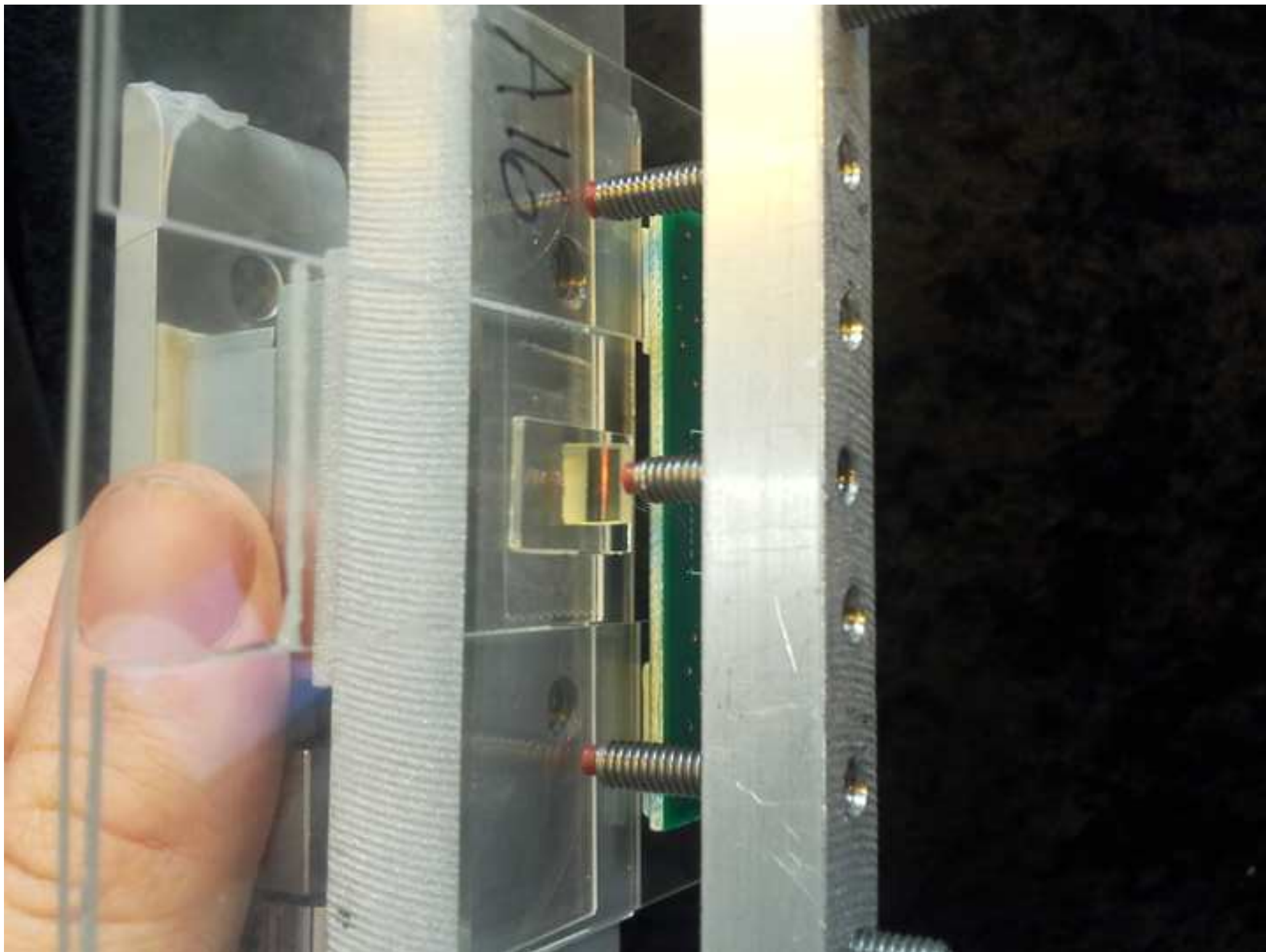


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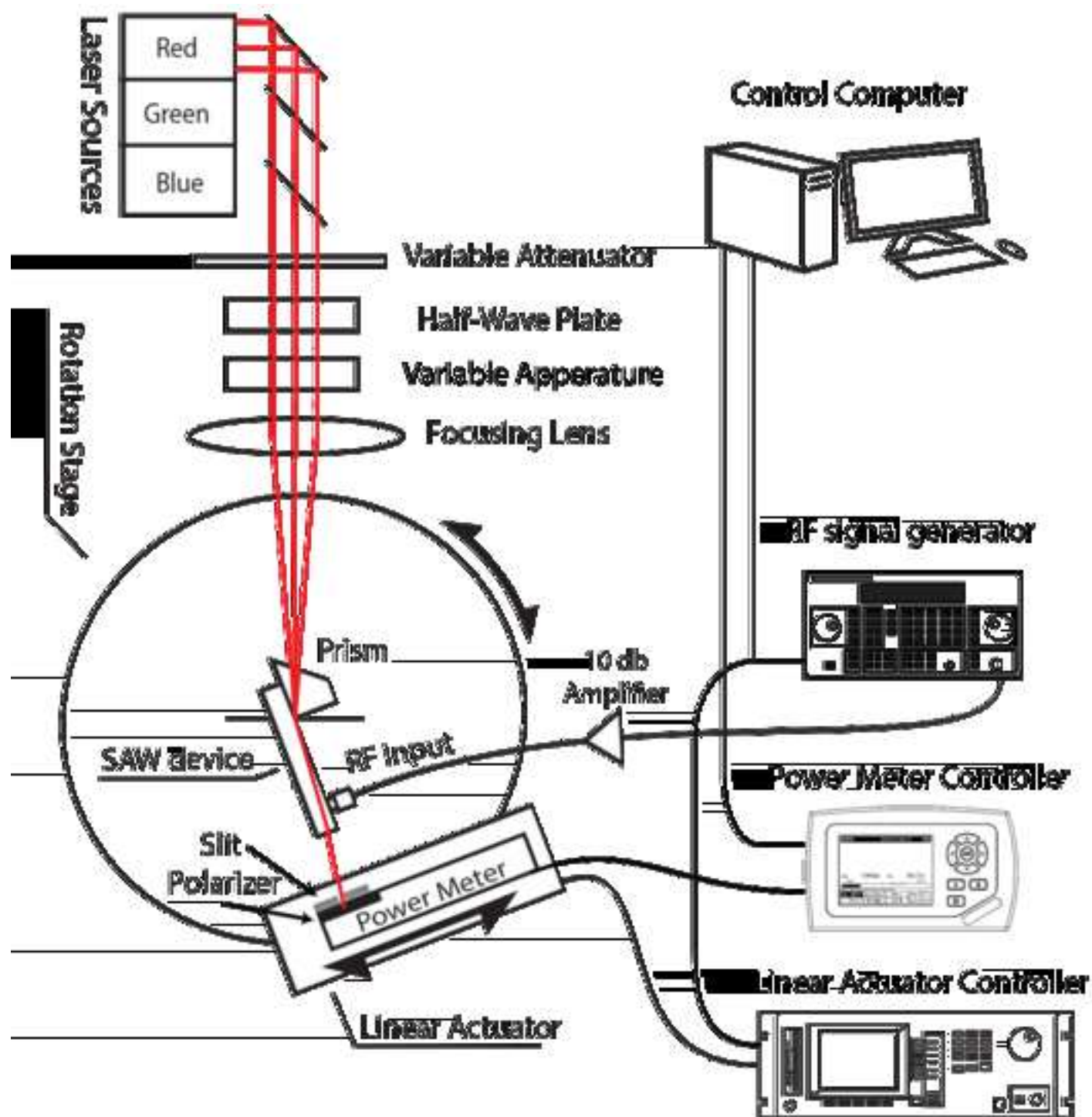


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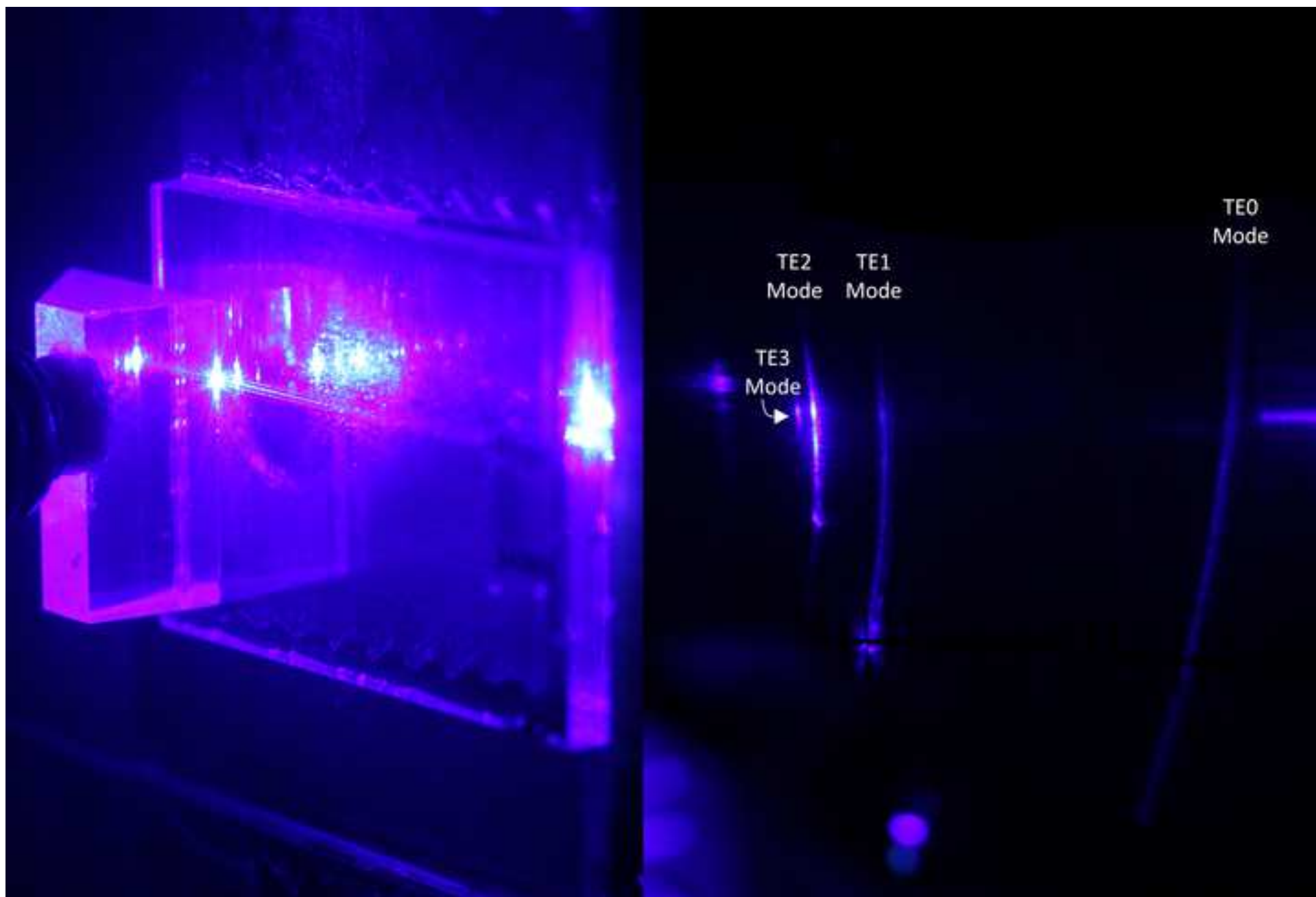


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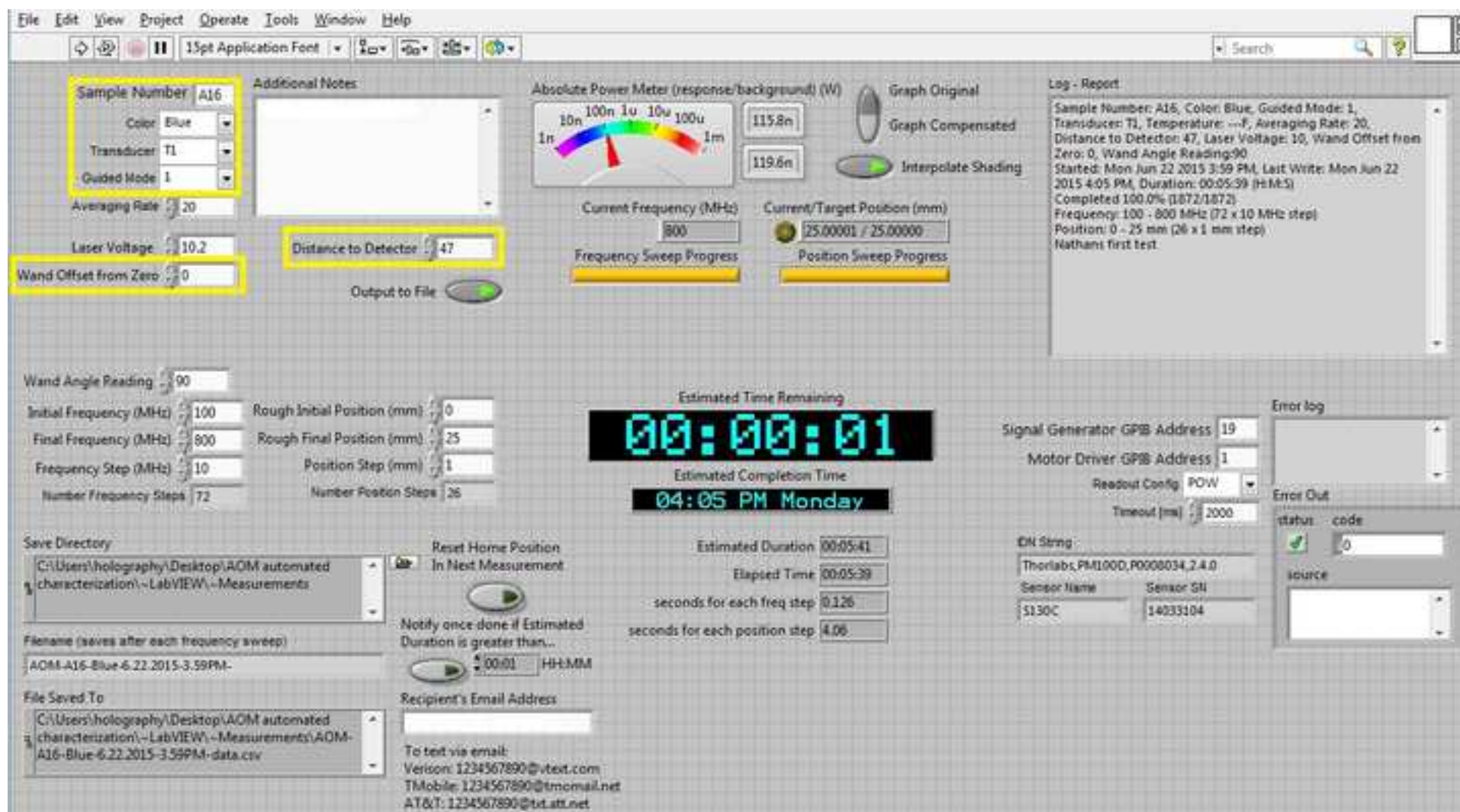


Figure 8

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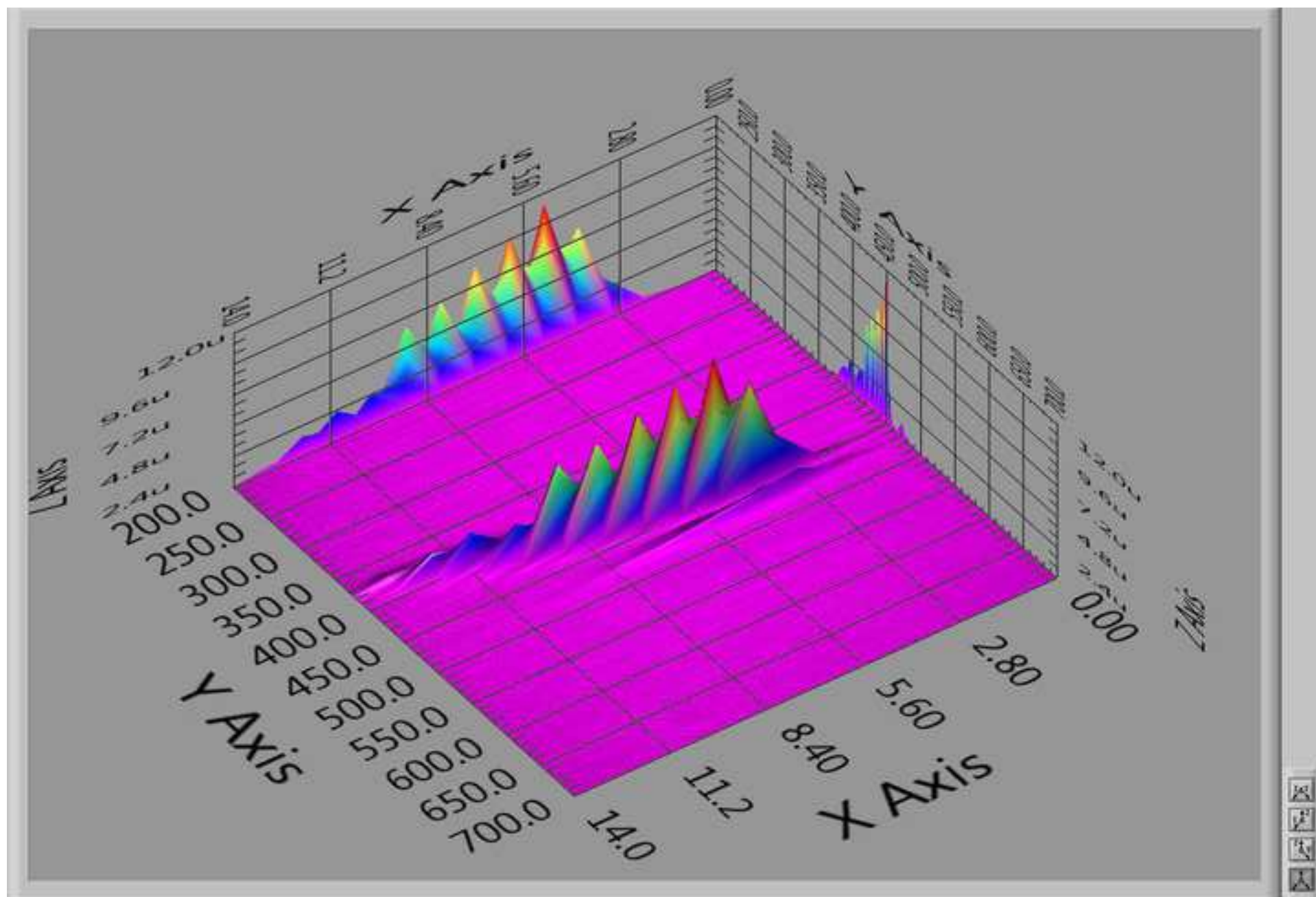
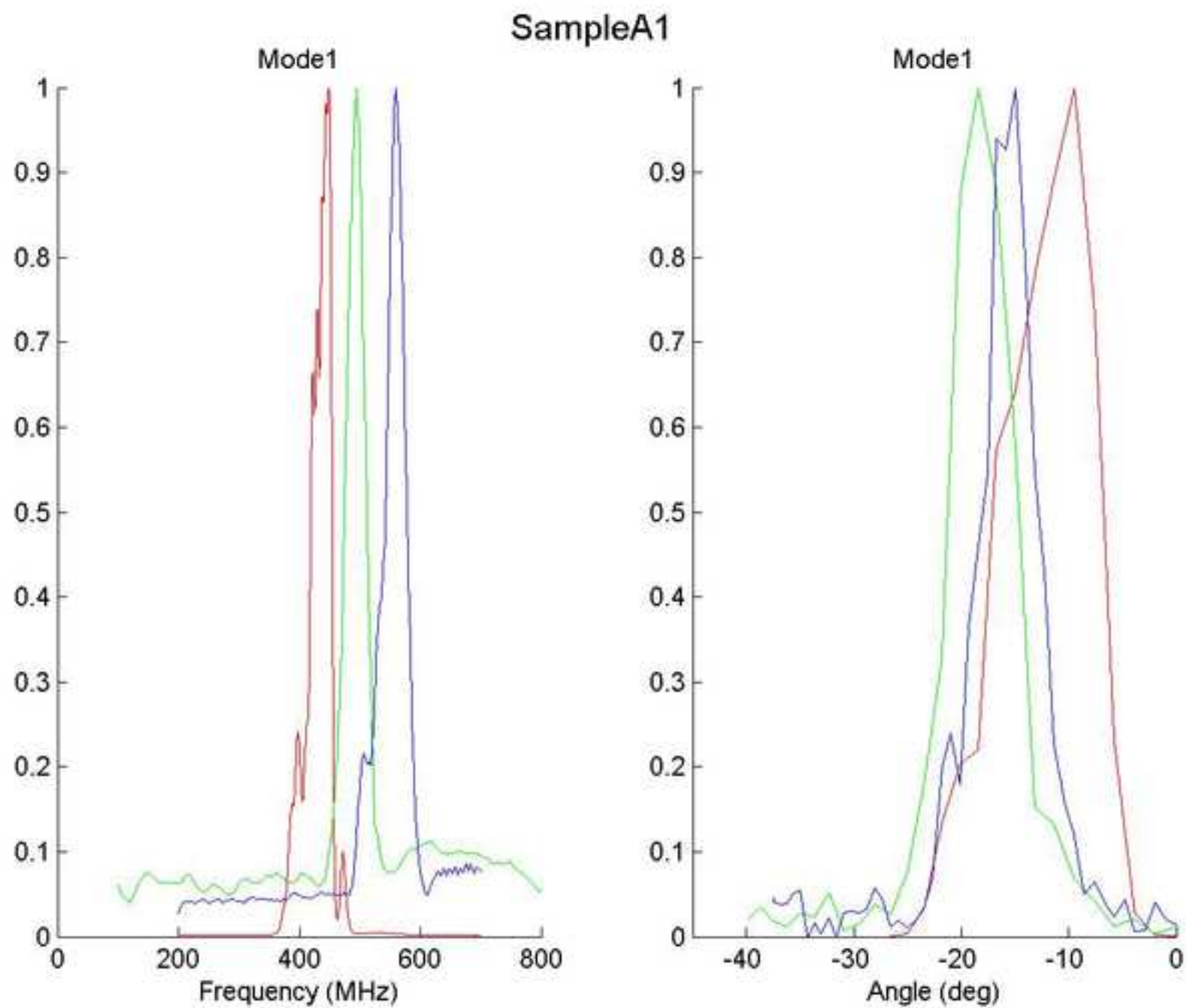


Figure 9

[Click here to download Figure: Figure 9. Sample Mode Comparison Data.psd](#)



Wavelength	Mode	Angle
638 nm	TE0	23°
	TE1	28°
532 nm	TE0	26°
	TE1	31°
	TE2	32°
445 nm	TE0	31°
	TE1	36°
	TE2	38°
	TE3	39°

Name of the Material	Company	Catalog Number
X-Cut Lithium Niobate	Gooch and Housego	99-00630-01
Positive Photo Resist 1	EMD Performance Materials	AZ 3330 F Photoresist
Photoresist Developer	EMD Performance Materials	AZ MIF 300
Aluminium	International Advanced Materials	AL13
Aluminium Etch	Transene	Type A Aluminum Etchant
Benzoic Acid	Sigma Aldrich	109479-500G
Acetone	Fisher Chemical	UN1009
IPA	Fisher Chemical	UN1219
Acidic Piranha etch	Cyantek Corperation	Nanostrip
Under Layer Resist	Micro Chem	LOR 3A
Positive Photo Resist	Micro Chem	950 PMMA A9
Anisole	Micro Chem	A Thinner
Conductive polymer aqueous solution	Mitsubishi Rayon Company	AquaSAVE
MIBK (4-Methyl-2-pentanone)	Sigma Aldrich	360511
NMP (1-methyl-2-pyrrolidone)	Sigma Aldrich	328634

Name of the Equipment	Company	Catalog Number
E-beam Evaporator	Denton Vacuum	Integrity 20
Thin Film Spinner	Laurell Technologies Corporation	WS-400A-6NPP-LITE
Mask Aligner	Karl Suss America Inc.	MA 150 CC
Automatic Dicing Saw	Disco Corperation	Disco Dad 320
Muffle Furnace	Thermo Scientific	FB1415M
Electron Microscope	FEI	XL30 ESEM
Dehydration Oven	Lab-Line Instruments	Ultra-Clean 100 (3497M-3)
Hot Plate	Thermo Scientific	SP131325
Polisher	Ultra Tec Mfg., Inc.	Ultrapol End & Edge Polisher
Class IIb 12V RBG Lasers: Wavelengths(nm): 638, 532, and 445 Signal Generator	Agilent	8648D
Signal Amplifier	Mini-Circuits	TB-17
Power Meter Controller	ThorLabs	PM100D
Linear Actuator Controller	Newport	ESP7000

AutomatedDeviceCharacterization.vi

LabView

Experimental Control

CompareWDMmodes.m

MATLab

Software by BYU

Analytical Software by
BYU

Comments/ Description

Lithium Niobate 3" Diameter X-CUT Wafer 1mm Polish/Polish

Used in the creation of the proton exchange mask.

Develops AZ3330 and LOR 3A

99.999% Pure

99% Pure

99.5% pure Isopropyl Alcohol

Bottom layer used for liftoff.

Top layer used for liftoff

Develops PMMA

Used for liftoff

Comments/ Description

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Any equivalent equipment would suffice.

Bought second-hand. Probably pulled from a laser projector. Any equivalent equipment would suffice.

Now found at Keysight. Obsolete. Any equivalent equipment would suffice. Needed Frequency sweep 9 KHz-1000 MHz.

Necessary only to overcome the limitations of the signal generator.

With power meter model S130C. Any equivalent equipment would suffice. Needed sensitivity 500pW

With linear actuator model MFN25PP. Any equivalent equipment would suffice. Needs 0.1mm accuracy.

Found in the appendix

Found in the appendix



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Editorial comments:

1. Please provide details in the protocol section. For instance. Please specify the action item in step 1.1., is aluminum already present on the wafer? If so please specify. If not please mention how aluminum was added?

- Step 1.1 was a non-action step designed to understand the starting point of the protocol. It has been reworded for clarity and added instead as a note.

2. In step 1.2 how was aluminum evaporated? What were the conditions used?

- Vacuum pressure, distance, deposition rate, and final thickness were added.

3. In step 1.3 how was the photoresist spun? Which photoresist was used? What were the conditions? How was it masked on parallel waveguides? Please provide a reference for this step.

- Drop count, rpm, photoresist type, time, and Reference 21 were added to the spin step with the mask step becoming its own step with a provided sample file.

4. In step 1.4, how was the exposed aluminum etched? How were the remaining photoresist removed? Which solvents were used? How much and what concentrations? Please provide more details.

- Time, volume, temperature, and depth were added to the Al etch, Photoresist removal became its own step and solvents were specified.

5. In step 1.5 how is the wafer diesawed?

- Diesaw parameters were provided as well as simple instructions.

6. In step 1.6 how much of benzoic acid is used? What's the purity? Please provide more details as to how the Proton exchange is carried out?

- Volume and purity of the benzoic acid were added with a reference added for clarity.

7. In step 1.7, how is the sample cleaned? What is the sample used (same as step 1.1?) How is the remaining aluminum etched?

-Solvents were specified. Step 1.10.2 defines the device for the rest of the protocol. The Al Etch was described in depth in 4.1.

8. In step 1.8, how is the sample cleaned? What solvents are used? Please provide more details.

- Cleaning is covered with all solvents and order in step 4

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- Aquasave, MatLab, LabView and all other references to commercial products were replaced.

10. In step 1.10 what are the conditions?

- 6.5 describes the drop count, rpm, time and process for the conductive layer.

11. In step 1.11 please provide a reference for how e-beam process takes place. Please provide details on how the sample is developed.

- Note 7.1.3 provides the reference for E-Beam Lithography. Step 8 provides in depth discussion of development.

12. In step 1.12 what are the evaporating conditions?

- Step 9.1 gives the same deposition information as Step 1.2 since the process is the same.

13. In step 1.13, how is the sample cleaned? What solvents are used? What grade and volume?

- Liftoff and cleaning are discussed in length in Step 10.

14. Using the comments for section 1 as an example, please similarly address the rest of the protocol section to provide more details. Please ask yourself the "how" question to obtain more details.

- The entire protocol was checked for needed clarification. Surface roughness and power readings are provided.

15. After you have made all of the recommended changes to your protocol (listed above), please re-evaluate the length of your protocol section. There is a 10 page limit for the protocol text, but there is a 3 pages limit for filmable content. If your protocol is longer than 3 pages, please highlight (in yellow) 2.75 pages (or less) of text to identify which portions of the protocol are most important to include in the video; i.e. which steps should be visualized to tell the most cohesive story of your protocol steps. Please see JoVEs instructions for authors for more clarification. Remember that the non-highlighted protocol steps will remain in the manuscript and therefore will still be available to the reader.

- The protocol is 8.6 pages long with 2.3 pages highlighted.

16. Please expand your representative results in the context of the technique you describe; i.e. how do these results show the technique, suggestions about how to analyze the outcome etc. This text should be written in paragraph form under a "Representative Results" heading and should refer to all of the results figures. You may include the figure captions under this heading but the captions and figure text must be separate entities.

- The discussion section, which touched on analyzing outcome was placed in the place of the Representative Results section.

17. If your figures and tables are original and not published previously, please ignore this comment. For figures and tables that have been published before, please include phrases such as "Re-print with permission from (reference#)" or "Modified from.." etc. And please send a copy of the re-print permission for JoVE's record keeping purposes.

- All figures and tables are unique

18. Please make sure that the "Discussion" section covers the following points.

- a. Critical steps within the protocol.
- b. Modifications and troubleshooting.
- c. Limitations of the technique.
- d. Significance of the technique with respect to existing/alternative methods.
- e. Future applications or directions after mastering this technique.

- A new discussion section was written giving 4 critical steps, troubleshooting, limitations, alternative methods, and future applications.

19. Please make sure that your references comply with JoVE instructions for authors. In-text formatting: corresponding reference numbers should appear as superscripts after the appropriate statement(s) in the text

of the manuscript. Citation formatting should appear as follows: (For 6 authors or less list all authors. For more than 6 authors, list only the first author then et al.): [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. **Volume**(Issue), FirstPage – LastPage, doi:DOI, (YEAR).]

- References were reformatted

20. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

- A final revision was completed

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