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SPIE.

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Abstract. We give a summary of the progress we have made in the fabrication of guided wave devices for use in holographic video displays. This progress includes identifying anisotropic leaky-mode modulators as a platform for holographic display, the development of a characterization apparatus to extract key parameters from leaky-mode devices, and the identification of optimized waveguide parameters for frequency-controlled color display. © *2015 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JMM.14.4.041308]

1 Introduction

Leaky-mode modulators were first introduced as a solution for holographic video display in 2013 and were shown to have distinct advantages over the existing state-of-the-art[1] (a summary of these advantages is given in Table 1). At that time, the spatial light modulators most commonly used for holographic video displays were pixelated modulators[2] and acousto-optic Bragg cells.[3,4] Those using pixelated modulators, such as liquid crystal light valves and MEMs mirrors, had to grapple with problems such as superfluous diffracted orders, conjugate images, and quantization noise[5,6] (see Fig. 1). Bulk wave modulators avoid the artifacts of pixelated modulators because they are analog devices without fixed pixel structure;[7] however, they are expensive to fabricate as they do not lend themselves to wafer-based batch fabrication processes.[8] Leaky-mode modulators are similar to Bragg cells in that they are analog devices, so they also avoid pixel artifacts. Additionally, leaky-mode modulators are readily fabricated using straightforward wafer-based photolithographic processes, which makes it possible to fabricate them inexpensively.[9] Leaky-mode modulators have the additional advantages of polarization rotation of signal light, increased angle of deflection, and frequency control of color. Much of the work done since these modulators were first introduced has focused on optimizing frequency control of color.[10–12]

2 Background

2.1 Modulator Operation

The leaky-mode modulator operates by having light interact with surface acoustic waves in an anisotropic waveguide. As shown in Fig. 2(a), light couples into a waveguide through a prism at one end of the device. Once the light is trapped in the waveguide, it interacts collinearly or contralinearly with surface acoustic waves launched from an interdigital transducer. When the light encounters the surface acoustic waves, it is coupled from the guided mode to a leaky mode of the orthogonal polarization. The momentum diagram for this interaction is given in Fig. 2(b). The leakage occurs because the waveguide is anisotropic and will only guide light of one polarization. Once the polarization of the light is rotated, the light is no longer guided and exits the far face of the substrate.

Waveguides are formed on these devices by immersing X cut, Y propagating lithium niobate in a pure melt of benzoic acid. This step is called proton exchange. The waveguides may then be annealed in a furnace to modify the waveguides properties. By carefully tuning exchange and anneal time, we can form waveguides optimized for frequency control of color.

2.2 Frequency Control of Color

Most displays require dedicated pixels or color filter wheels to multiplex color, but leaky-mode devices are capable of multiplexing color in frequency. This is made possible by the partial confinement of leaky modes. Guided modes are discrete, and free space modes are continuous, but leaky modes, which are only partially confined, allow light to travel in a limited band of modes. Guided modes are separated from leaky modes by a difference in momentum, which can be bridged by having the light interact with a periodic structure (like a surface acoustic wave) with a spatial frequency. This spatial frequency can be varied over a range, resulting in a change in the angle of propagation of the leaky-mode light. This results in a scan at the output. The range of spatial frequencies necessary to couple light from a guided mode to a leaky mode is not, in general, the

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Table 1 This table compares a fast, high-resolution pixelated modulator—MEMs or liquid crystal on silicon modulator—with a five hundred channel leaky-mode modulator. The leaky-mode modulator has a much greater aggregate bandwidth, much lower fabrication complexity, and unique capabilities, such as polarization rotation and frequency multiplexing of color.

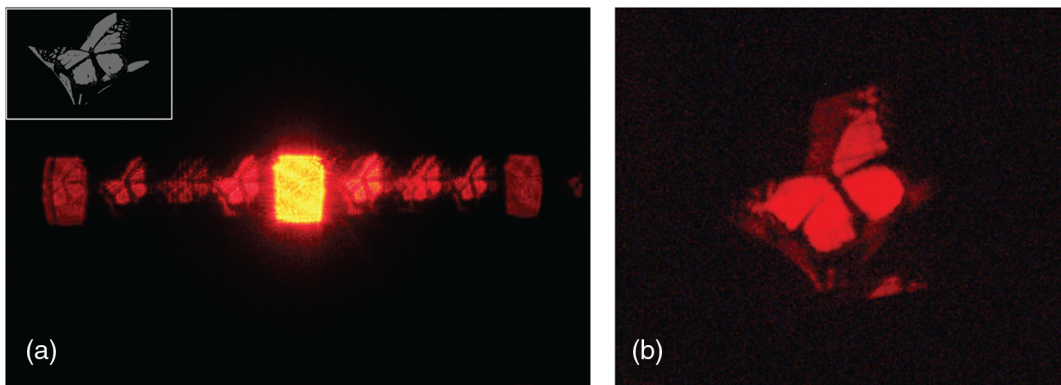| Affordance	Pixelated modulators	Leaky mode modulator
Temporal bandwidth	5 Gpixel/s (8 Mpixels)	50 Gpixels/s (500 channels)
Output angle ($l = 532$ nm, $L = 12$ μm)	2.54 deg	24.7 deg
Signal polarization rotation	No	Yes
Fabrication complexity	~20 patterned layers	Two patterned layers
Superfluous conjugate image	Yes	No
Hologram approximation basis	Quantized pixels	Sinusoidal waves
Color multiplexing	Space/time	Space/time/frequency

Fig. 1 Comparison between (a) the optical output of a pixelated liquid crystal on silicon modulator and (b) the scanned output of a leaky-mode modulator. The pixelated modulator possesses visual artifacts, such as a bright zero order as well as high-order and conjugate images, which are absent in the output produced by the leaky-mode modulator.
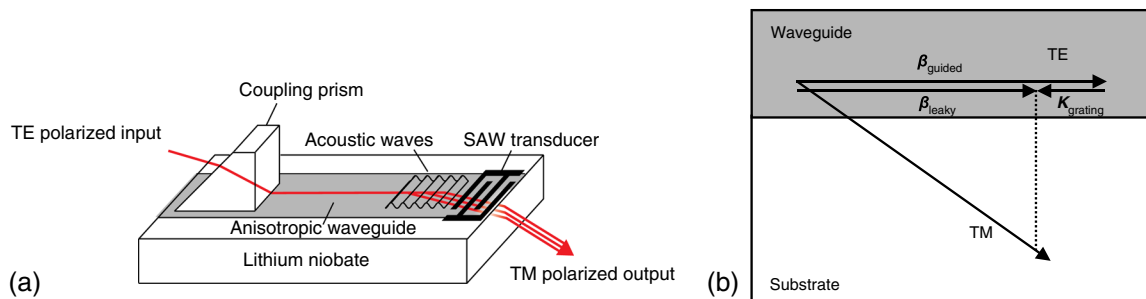

Fig. 2 (a) Anisotropic leaky-mode modualor. Laser light enters though a rutile prism and is evanescently coupled into a waveguide. The light traveling inside the waveguide encounters surface acoustic waves generated by an interdigital surface acoustic wave (SAW) transducer. The light interacts with the sound waves and is coupled from TE guided mode light into leaky TM polarized light. Leaky mode light can be scanned in angle by changing the spatial frequency of the acoustic wave. (b) The momentum diagram for the guided to leaky-mode interaction.

same for red, green, and blue light. By carefully engineering the waveguide, we can achieve a waveguide system that allows us to independently control the angle and magnitude of light out-coupled from a grating structure simply by modifying its spatial frequency components which act as color-selective filters (see Fig. 3). In guided wave modulators, the spatial frequency of the surface acoustic wave is proportional to the temporal frequency of the radio frequency (RF) input to the surface acoustic wave (SAW) transducer. Thus, by altering the frequency and magnitude of the RF
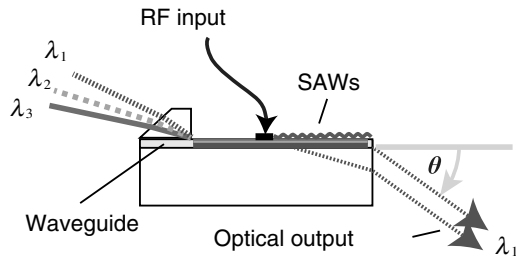
Fig. 3 A leaky-mode device filtering color. The spatial frequency of the SAW determines the wavelength, λ, of the output and the output angle, Θ.

input signal, we can independently control the red, green, and blue outputs of the device. This is the mechanism responsible for the frequency control of color in leaky-mode devices. With the frequency control of color, we are able to simultaneously modulate superimposed red, green, and blue light to create color holographic images (see Fig. 4).

3 Characterization

In order to realize the advantages of leaky-mode devices, such as frequency control of color, we need the ability to characterize the frequency response and angular output of fabricated devices. To this end, we have developed a semi-automatic characterization apparatus.[12] Figure 5 shows a diagram of the characterization apparatus.

The characterization apparatus is a prism coupler that introduces light into a leaky-mode modulator and then sweeps frequencies through the RF input. For each frequency during a sweep, a light detector records the power at a specific output location. Before each frequency sweep, the detector is moved to a new location, gradually scanning the entire output of the device. With this information, we can create a datamap showing the output of the device as a function of drive frequency. From this datamap, we can, for each color, extract the frequency response and angular output of the device as well as determine the scan linearity,
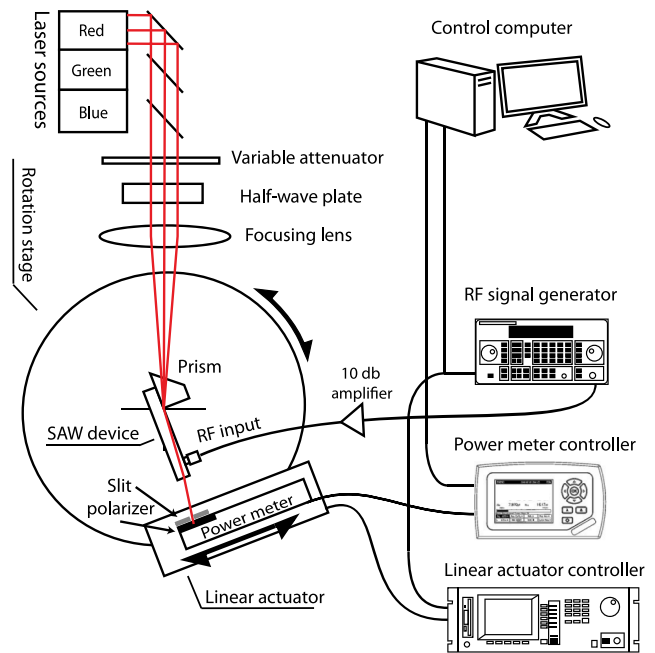

Fig. 5 The leaky-mode device characterization apparatus. One color at a time is coupled into the leaky-mode modulator. The output light is sampled at one angular position defined by a slit on the detector of a power meter. Then the RF input to the modulator is scanned and the power at the slit is recorded for each RF frequency. The slit is advanced one step and the RF frequencies are scanned again for a map relating input frequency with power at every angle of output. We call these graphs datamaps.

angular point spread, and standing wave period as shown in Figs. 6 and 7.

4 Optimization

4.1 Optimization Criteria

Armed with the information provided by our characterization apparatus, we can begin to optimize leaky-mode devices for specific criteria, such as maximum output angle, maximum
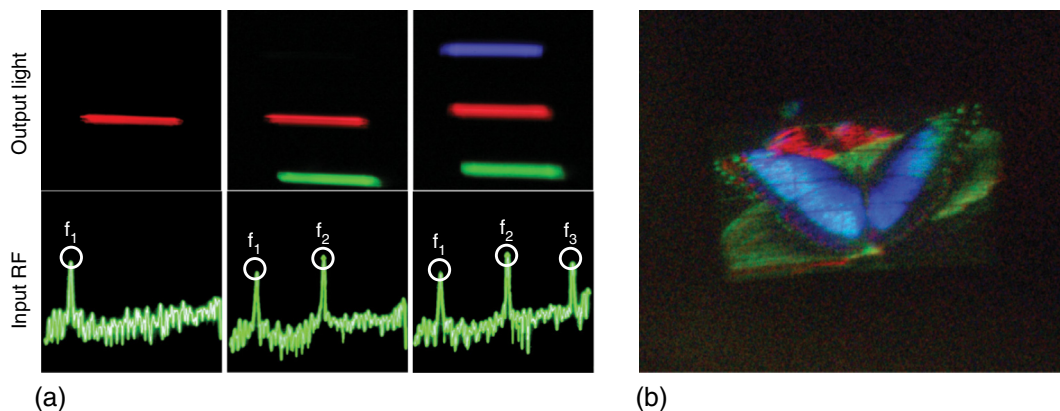

Fig. 4 (a) The output color of the leaky mode is determined by RF frequency input. Red, green, and blue light can be controlled simultaneously and independently in the frequency domain. (b) A holographic stereogram image view formed a single channel leaky-mode modulator using frequency domain control of color.

scan linearity, and maximum diffraction efficiency or for optimal packing of red, green, and blue signals in frequency space. We chose the last of these as our first optimization criterion.[10]

Specifically, we sought to create a device that had bands of operation for red, green, and blue light that were adjacent in the frequency domain and overlapping in angular output. We wanted the individual color frequency bands to be as large as possible without causing the bands to overlap. We also wanted the total range of frequencies spanned by all three color bands to be <200 MHz so that the device could be controlled by commodity graphics processing units.[13]

4.2 Waveguide Parameters

We prepared a number of samples with varying waveguide depths and found that the bandwidth of the guided to leaky-mode transitions increased as the waveguide was made less shallow. This result is consistent with the literature.[14] The limit on how shallow we could make waveguides was provided by the red guided to leaky-mode transition. If the waveguide became too shallow, the red transition would disappear. This occurred at waveguide depths just under one half micron for waveguides protons exchanged in pure acid melts.[10]

4.3 Choosing Guided to Leaky-Mode Transitions

With the individual color bands made as large as possible, we then tried to select the transitions that would result in the most adjacent red, green, and blue frequency responses (see Fig. 8). In practice, selecting a transition is accomplished by modifying the input angle of the target color
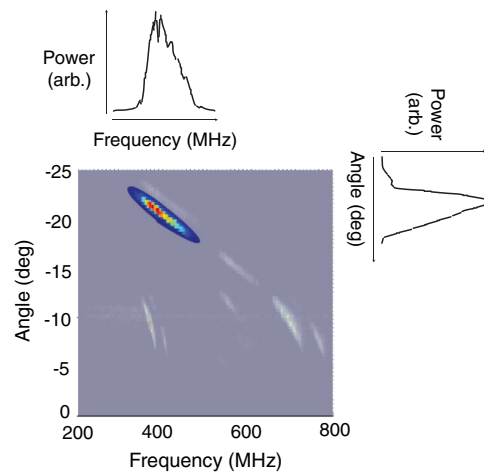

Fig. 7 The X and Y projections of a datamap give the RF input frequency response and the angular power ouput response, respectively, for one color. These projections can be combined with the projections from datamaps for other illumination wavelengths to give us a full-color description of the device's operation.

so that it propagates in a new guided mode. The required frequency to couple the light to the leaky mode will then be shifted. Annealing was also used as a way to shift responses as necessary to get a set of adjacent frequency bands. We met our optimization criteria by choosing the first-order guided mode, TE_1, for each color. The optimal device has a 0.4505 micron waveguide depth modified by a 45-min anneal at 375°C. Notice that the aggregate response in Fig. 9(a) meets our optimality criteria for adjacent bands in frequency with an aggregate bandwidth <200 MHz.
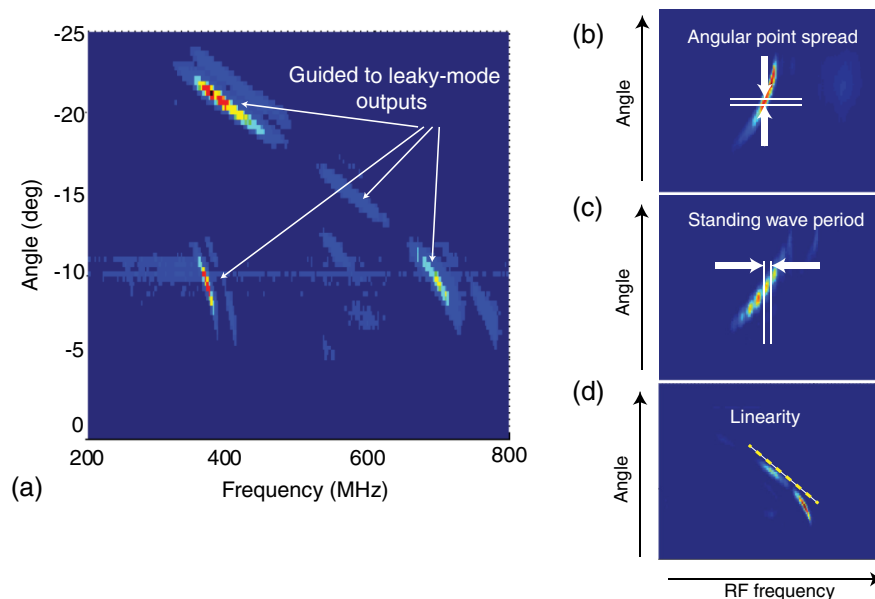

Fig. 6 (a) An example of a datamap that shows the location of guided to leaky-mode transitions in frequency and output angle. From datamaps, one can, at a glance, determine a number of important device parameters, including the (b) point spread, (c) standing wave period, and (d) linearity of a guided to leaky-mode transition.
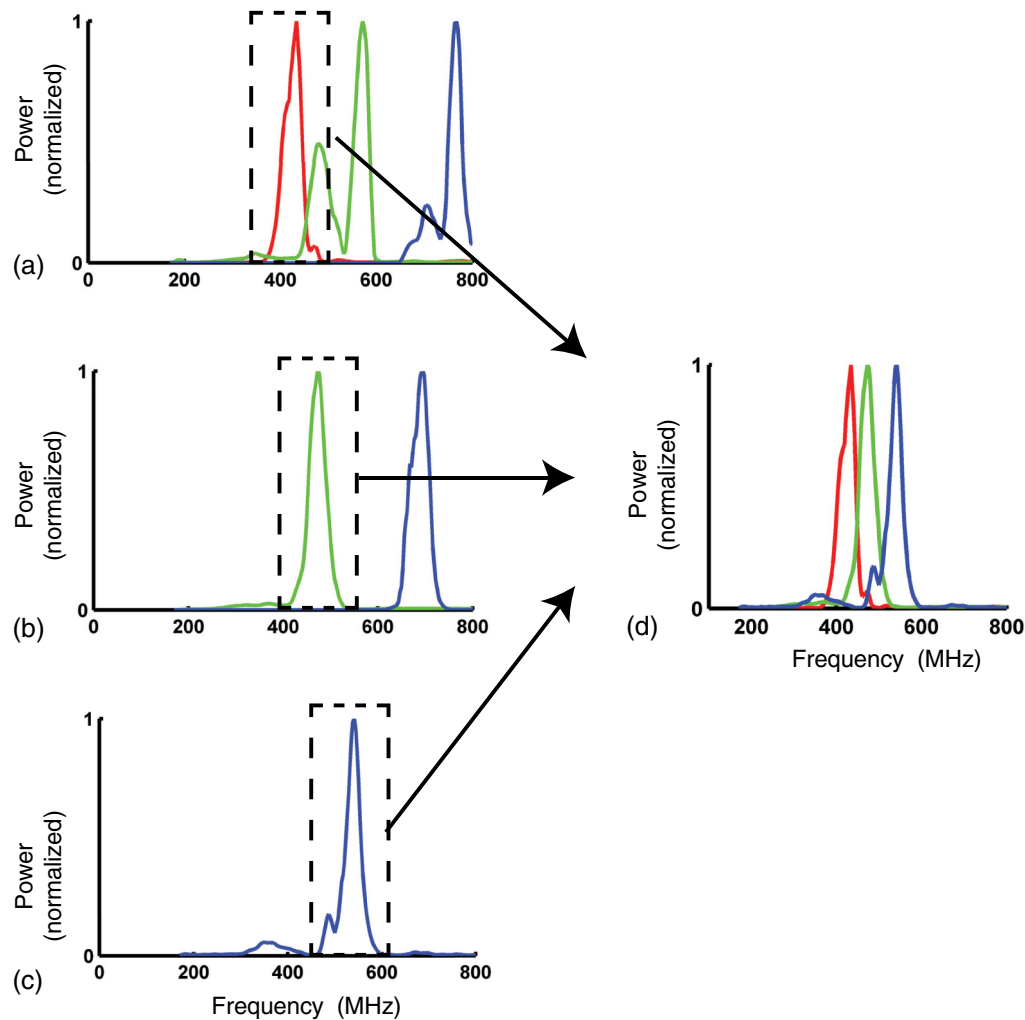
Fig. 8 The guided to leaky-mode transitions for each color are shown in (a) to (c). The optical output power as a function of frequency for the guided to leaky-mode transitions from the highest-order guided modes for red, green, and blue light are shown in (a). The transitions from the second highest-order guided modes are shown in (b) and from the third highest are shown in (c). The frequency response for guided to leaky-mode transitions from the second highest-order modes for green and blue (red only has one transition). (d) The aggregate frequency response for the TE_1 to TM_{leaky} transitions for each color. Note that they sit adjacent to each other in frequency.
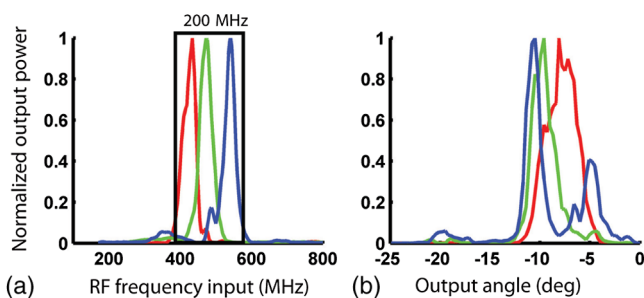

Fig. 9 (a) The frequency response for red, green, and blue light for the TE_1 to TM_{leaky} transitions for each color. Note that they are adjacent to each other in frequency and that they fit within a 200 MHz band. (b) The angular output for these transitions. The angular output is overlapping for all three colors at −10 deg. The angular bandwidth for the current amount of overlap is <3 deg, but it could be increased to almost twice that amount by placing a prism at the output to push the blue curve right and the red curve left.

5 Conclusion and Future Work

Now that the device parameters required for frequency control of color have been established, we turn our attention to diffraction efficiency and the achievable number of points that can be scanned. Brightness and signal-to-noise ratio are first-order considerations for holographic video displays. We will seek to improve the waveguide quality and geometry to maximize diffraction efficiency. As a second-order concern, the number of points that can be scanned relates to the numerical aperture of a diffractive system and limits the achievable depth of a holographic image. We will maximize this parameter by extending the light/sound interaction distance to the limits imposed by optical loss and acoustic attenuation.[15]

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