Subpicosecond Imaging System Based on Electrooptic Effect

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Abstract—This work presents an ultrafast, interferometric electrooptic sampling system that uses a two-dimensional detector array to image the electric field present on a device. Spatial and temporal resolution are comparable to conventional “point” electrooptic sampling systems, < 5 μm and < 1 ps, respectively. Voltage sensitivity is expected to be 270 V/m and may achieve less than 4 mV with sensor cooling and a more effective electrooptic material. A coplanar silicon structure with 10 μm feature size would have a field sensitivity of 27 kV/m and 400 V/m, respectively. This compares favorably with the reported sensitivity of 104 V/m for prior imagers and 10 V/m for point samplers. Applications for an E-field “imager” include characterization of field distributions in planar passive microwave devices, multiport analog and digital devices, and studying device and materials physics.

I. INTRODUCTION

ULTRAFAST electrooptic (EO) sampling was first demonstrated in 1982 [1] and since then has become a valuable research tool for testing optoelectronic and electronic devices and materials. In an extensive review, Wiesenfeld [2] presented many aspects of EO sampling, including probe configurations, intensity transfer functions, noise sources and dielectric loading effects of nonlinear electrooptic (NLO) probes. Conventional EO sampling of weak electric fields employs a tightly focused, pulsed laser probe beam to measure electric-field-induced birefringence in a NLO; hence, it is referred to herein as “point” sampling.

Many significant achievements using point EO sampling in both room-temperature and cryogenic environments have been reported at our lab and elsewhere. Alexandrou et al. [3] studied dispersion and propagation modes of ultrafast pulses on bent coplanar transmission lines. Wang et al. characterized a silicon photodetector having a 5.7-ps full-width at half-maximum (FWHM) response with λ = 720 nm [4] and measured a single-flux-quantum pulse in a low-temperature superconducting digital circuit [5]. Hegmann et al. [6] measured a 1.5-ps photoinduced transient on superconducting YBa2C3O7−δ, attributed to kinetic inductance. Many groups have studied the physics of photoconductive pulse generation and switching [7]–[10].

Point sampling is analogous to an ultrafast, single-channel sampling oscilloscope. The trend toward more complex circuits and denser packaging of analog and digital devices makes it important to expand the capability of EO sampling, so that it is possible to probe many points simultaneously. This article describes an EO imaging system that is capable of mapping the voltage distribution over a rectangular region. This system is comparable to an ultrafast sampling oscilloscope having more than 180,000 channels.

Some applications of EO sampling require the measurement of data over an extended area, e.g., transmission lines and photoconductive switches, or at several points, e.g., multiport analog and/or digital devices [11]–[14]. Meyer [15] demonstrated the ability to map electric field distributions over an area by scanning the area of interest using a point sampler. Mertin [16] reviews development of two-dimensional (2-D) measurement technologies and presents results from an automated scanning point sampler. Of the groups studying photoconductive switches, the latter two have studied the operation of switches in applications having high fields [9], [10]. Their work is significant because they also pioneered the use of EO imaging, where a spatial map of the field strength is recorded with an area detector array. Their work differs from the present in that the switching events were adequately described with 200-ps temporal resolution, whereas subpicosecond resolution is desired for the present system. Furthermore, the field strength measured in these switches (≈105 V/m) is orders-of-magnitude greater than those present on logic and microwave device structures.

II. SYSTEM DESCRIPTIONS

A. General Requirements

EO sampling requires a pulsed (or gated) laser source to probe the response of the device to the applied transient. Our lab uses a mode-locked Coherent Mira 900 Ti:Sapphire laser. It produces a 76-MHz train of linearly polarized ≈100-fs FWHM pulses, tuned to ≈800 nm, ≈1 W. Devices tested in our lab generally include a photoconductive switch that is excited with a fraction of the pulsed beam, thus providing a trigger for the measurement and eliminating electrical jitter.

B. Conventional Point Sampler

In a point sampler [2], the NLO may be either the device substrate (e.g., GaAs devices) or on an external probe. A
linearly polarized optical probe pulse enters the NLO through the first surface. In transmissive sampling, the probe is transmitted at the second surface after a single pass, whereas in reflective sampling, it is reflected, passing through the NLO a second time. The beam exits the NLO and is passed through a compensator or wave plate to introduce a static polarization bias. The bias is adjusted so that in the absence of an electric field, the probe is circularly polarized at the input of an analyzer, thus giving maximum sensitivity and linearity when a field is applied. The analyzer separates the beam into orthogonal polarization components, which are measured by a pair of detectors connected to a differential lock-in amplifier. Signal-to-noise (SNR) improvements are obtained when the signal is modulated at frequencies approaching the laser 1/f noise floor.

C. Imaging System

Fig. 1 depicts the imaging system hardware. Reflective sampling was chosen because it doubles system sensitivity, although transmissive sampling is also possible. The laser source is directed through a high-speed modulator followed by a variable-intensity beam splitter consisting of a half-wave plate and polarizing beam splitter. The horizontally polarized "probe" beam is directed back through the polarizer, then into a spatial filter and beam expander. The vertically polarized "excitation" beam passes through a variable-length optical delay and into a fiber coupler.

The probe beam is split into two beams in a small, rigid interferometer. The device-under-test (DUT) is mounted in the device "leg" of the interferometer and a mirror is installed in the reference "leg." The resulting interference pattern passes through a polarizing filter and relay lens and is detected at a camera. The beam splitter in the interferometer is an uncoated, (≈3-mm-thick) BK-7 wedged window. The first surface of the window is aligned at Brewster's angle to eliminate multiple reflections and maximize transmitted intensity. The reference mirror is mounted on a piezoelectric actuator, which is used to modulate the length of the reference leg. The DUT is mounted on a stationary structure. Each leg has adjustments for static alignment.

As in point sampling, measurement of subpicosecond transient electric fields on a DUT is achieved using the linear EO, or Pockels, effect. A propagating electrical transient is launched on the DUT when an optical excitation pulse is applied to a biased, photoconductive switch. A NLO crystal having a high-reflectivity (HR) coating on one side covers the region of interest with the coating in intimate contact with the DUT. "Fringing" fields caused by the propagating transient, which couple into the NLO, produce a temporally and spatially variant refractive index.

The EO-induced index perturbation in the NLO alters the phase of the linearly polarized optical probe as it traverses the device leg of the interferometer. When recombined with an unperturbed reference beam, an intensity pattern results that corresponds to phase differences between the two legs of the interferometer. If the reference beam is static, then changes in intensity at each point can be attributed to spatial phase variations in the NLO, induced by the EO effect.

A video camera (DVC Corp., DVC-0A) having a low-noise, frame-transfer charge-coupled-device (CCD) (Texas Instruments, TC-245) records the intensity pattern created by the interferometer.

Fig. 2 depicts the data acquisition and control hardware. The analog camera output is digitized by a frame grabber (Matrox Corp., Pulser) and stored on a personal computer (Pentium 133 MHz, PCI bus). Timing control for modulation uses custom-built electronics (see also Section VI). Data acquisition is controlled in the LabView programming environment (National Instruments, Inc.), and analysis is performed on the PC using PV-Wave Personal Edition (Visual Numerics).

D. Spatial Resolution

Spatial resolution of the system is determined by the active image area and number of discrete pixels in the image sensor. Image (de)magnification can be adjusted by altering the
position of the relay lens and camera.

The CCD shown in Fig. 3, has 755–8.5-μm pixels horizontal (H) and 242–19.75-μm pixels vertical (V), for an active area of 6.4 mm (H) × 4.8 mm (V). Typical magnification is 4:1, giving a measurement area of 1.6 mm (H) × 1.2 mm (V). The resulting spatial resolution is 2.13 μm (H) × 4.9 μm (V), which is comparable to point sampling. If desired, cylindrical lenses or prisms could be used to correct the pixel aspect ratio.

It is possible to increase optical magnification to 8:1, then digitally average 2 × 2 pixel cells to obtain 4:1 effective magnification. This would reduce noise by 1/2; however, it may prove disadvantageous since more photons from the excitation source will be collected by the sensor (see also Section IV-D).

Important distinctions exist between the imager and scanning point samplers. The imaged nodes must lie within a finite rectangular region, whereas a scanning system can probe random points over an extended area. Furthermore, the imager measures all nodes simultaneously, whereas a scanning sampler probes one node at a time.

III. ELECTROOPTIC INTERFEROMETER

We present the reasons for choosing an interferometer and discuss its operation. We begin by mathematically describing the EO effect, and the relationship between the voltages present on the DUT, fringing fields coupled into the NLO, and resulting phase delay experienced by the optical probe. We then use this information to estimate the temporal resolution of the system. Following this discussion, we analyze the design in Fig. 1 to obtain an estimate of the expected system sensitivity. Finally, we evaluate the linearity of the imager for the operating conditions previously defined.

A. Pockels Effect

The refractive index in an EO crystal is altered in the presence of an electric field. The perturbed index $n'_{i}$ is dependent on the field-free index $n_{i}$, field strength $E_{i}$, and Pockels coefficients $r$. By applying the techniques of [17] to $x$-cut LiTaO$_{3}$ ($3m$ point group), a material commonly used for EO sampling, we find (neglecting terms quadratic in field strength)

$$n'_{y} = n_{y} - \frac{n_{y}^{3}}{2}(r_{22}E_{y} + r_{13}E_{z}) = n_{y} + \Delta n_{y}$$ \hspace{2cm} (1a)

$$n'_{z} = n_{z} - \frac{n_{z}^{3}}{2}(r_{33}E_{z}) = n_{z} + \Delta n_{z}.$$ \hspace{2cm} (1b)

Numeric subscripts are indices of the tensor elements, and $y, z$ subscripts are direction vectors in crystalline coordinates; $z$ is parallel to the optic axis. These equations show that the refractive index along $y$ is influenced by the electric fringing fields directed along both $y$ and $z$, whereas the index along $z$ is influenced only by fringing fields along $z$. It is also evident that the optical probe polarization must be aligned to measure the desired refractive index perturbation, while the optic axis of the NLO must be aligned on the DUT such that the fringing fields of interest maximize the index perturbation.

If we substitute values for LiTaO$_{3}$ [17] into (1a) and (1b), we find that $\Delta n_z \approx 4.4 \Delta n_{gy}$, and the contribution from $E_{y}$ is negligible. In point sampling, it is common (and convenient) to measure the induced birefringence, which is the difference in index perturbation along $z$ and $y$, or $\Delta n_{2y} = \Delta n_z - \Delta n_{gy} \approx \Delta n_{z}/1.3$.

Since the refractive index change along $z$ is greater than that along $y$ and greater than the induced birefringence, system sensitivity will be maximized by measuring $\Delta n_{z}$. An interferometer was chosen for this purpose.

B. EO Induced Phase Shift

Having determined that we wish to measure the refractive index perturbation using an interferometer, we must consider how it will be used. An interferometer is sensitive to phase delays imposed on a propagating optical wavefront, which in our case is the probe beam. As an optical beam traverses a dielectric material, it suffers a phase delay $\Delta \Gamma$, determined by the refractive index $n$, wavelength $\lambda$, and the material thickness $X$:

$$\Delta \Gamma = \int_{0}^{X} \frac{2\pi}{\lambda} n(x) dx.$$ \hspace{2cm} (2)

We showed above that the refractive index was dependent upon the electric fringing field, but we must also consider that the fringing field is not uniform throughout the thickness of the material. As a result, the refractive index is a function of depth $x$, determined by the penetration depth of the fringing field into the NLO.

Substituting (1b) into (2), we obtain a static phase delay component, $\Gamma_0$ (independent of $E$ fields)

$$\Gamma_0 = \frac{2\pi}{\lambda} n_\varphi X$$ \hspace{2cm} (3a)

and a dynamic phase delay attributed to the EO effect $\Delta \Gamma_\varphi$.

The interferometer measures $\Delta \Gamma_\varphi$ given by

$$\Delta \Gamma_\varphi = \frac{\pi}{\lambda} n_\varphi^3 r_{33} \int_{0}^{X} E_{z}(x) dx.$$ \hspace{2cm} (3b)

1NLO materials from other point groups (e.g., ZnTe, $\bar{3} \bar{3} \bar{m}$) have greater sensitivity when the induced birefringence is measured.
The \( E \)-field distribution within the NLO depends upon the test structure. For this example, consider a coplanar waveguide, on which we wish to probe the \( E \)-field at the center of the gap of width \( g \). In general, if a superstrate having the same relative dielectric constant as the substrate (\( \varepsilon_{\text{sub}} \)) is placed on a coplanar structure, we would expect the fringing fields in the superstrate to be confined to a depth comparable to the gap separating device features. When the superstrate is the NLO (dielectric = \( \varepsilon_{\text{NLO}} \)), the depth of the fringing field, \( g' \), is dependent upon the ratio of the two dielectric constants; the confinement depth becomes \( g' \sim g \varepsilon_{\text{sub}}/\varepsilon_{\text{NLO}} \). The field strength decreases rapidly inside the NLO, so we approximate the integral with the product \( E_{\text{surface}}g' \), where \( E_{\text{surface}} \) is the transverse \( E \)-field magnitude at the surface of the NLO. We then obtain

\[
\Delta \Gamma_{\text{eo}} \equiv \frac{\pi}{n^2 \gamma_{33}} \left( \varepsilon_{\text{sub}} g E_{\text{surface}}^* \right) \frac{1}{\varepsilon_{\text{NLO}}} \tag{3c}
\]

or in words, the measured phase change at any point is proportional to the \( E \)-field at that point. The voltage on the gap \( V^\text{gap} \) is the product of the gap and the \( E \)-field

\[
V^\text{gap} = g E_{\text{surface}}. \tag{3d}
\]

Note that for a given value of \( \Delta \Gamma_{\text{eo}} \), the voltage is independent of the gap, whereas the field depends upon the gap. This can be understood by considering that a device having a larger gap has deeper fringing-field penetration in the NLO. The fields have a longer interaction length with the probe; hence, the field required to produce a given phase change is reduced.

**C. Temporal Resolution**

Temporal resolution of the system is determined by the largest of: 1) response time of the EO material, or 2) probe pulse duration convolved with the fringing fields profile; this convolution is approximately equal to the sum of the pulse FWHM and the time-of-flight \( t_{\text{flight}} \) of an infinitely short pulse through the fringing fields. The EO response is limited by phonon resonance, and for LiTaO\(_3\) is of the order of \( 10^{-14} \) s [18]. The probe pulse is \( \approx100\)-fs FWHM, and can be reduced to \( \approx50\)-fs FWHM using a pulse compressor. The optical path length through the fringing fields is \( pL = (2ng\varepsilon_{\text{sub}}/\varepsilon_{\text{NLO}}) \). Time of flight \( t_{\text{flight}} = pl/c \), with \( c \) = speed of light in vacuum. For a coplanar waveguide fabricated on silicon (\( \varepsilon_{\text{sub}} = 11.9 \)) having \( g = 10\mu\text{m} \), and LiTaO\(_3\) (\( n \approx 2.2, \varepsilon_{\text{NLO}} = 43 \)), we find \( t_{\text{flight}} \approx 40 \) fs. From these values, we expect (temporal resolution) \( \approx \) (pulse FWHM + \( t_{\text{flight}} \)) = 140 fs, well below 1 ps.

**IV. INTERFEROMETER OPERATION**

Now that we have described how Pockels effect alters the phase of an optical probe beam, we discuss the interferometer in detail. We begin with its intensity transfer function, and discuss the ideal case. We then consider factors that cause deviations from ideal that reduce system sensitivity, and estimate their magnitude. Finally, we consider how to optimize system sensitivity given these constraints.

**A. Transfer Function**

The normalized intensity measured by the detector, \( I_d = I_{\text{out}}/I_{\text{ref}} \), is the ratio of the output intensity from the interferometer to the intensity present in the reference leg

\[
I_d \equiv \frac{I_{\text{out}}}{I_{\text{ref}}} = (1 + \alpha) + 2\sqrt{\alpha} \cos(\delta) + b, \tag{4}
\]

\( I_d \) depends on \( \alpha = I_{\text{DUT}}/I_{\text{ref}} \), the normalized intensity in the device leg, the phase difference \( \delta \) between the \( E \)-field of the optical probe in each leg, and normalized background illumination, \( b \). Using (3a) and (3c) to expand \( \delta \), we get

\[
\delta = 2(\Gamma_0 + \Delta \Gamma_{\text{eo}}) \equiv 2\Gamma \tag{5}
\]

where \( \Gamma_0 \) was redefined to include both the static phase difference governed by the differing lengths of the interferometer legs, as well as the static phase delay of the NLO. The factor of 2 results from using reflective sampling. The probe passes through the fringing field two times, accumulating twice the phase delay.

**B. Interferometer Operation With an Integrating Detector**

Fig. 4 plots (4) for the ideal case defined as \( \alpha = 1, b = 0 \). In this case,

\[
I_d \propto \cos^2(\Gamma) \tag{6}
\]

which is also the intensity transfer function used to describe point sampling. As a result, all modulation and detection principles described herein apply equally to a system such as that in [2], wherein a variable retarder is used in place of the quarter-wave plate or optical compensator. The variable retarder would take on the modulation function of the piezoelectric actuator, as discussed in Section VI.

In point sampling, the optimum signal sensitivity occurs when the slope of the intensity transfer function is a maximum, as explained in [2]. We will see that this is not the case for an integrating detector such as a CCD since each pixel in a CCD has a finite electron capacity. Sensitivity will be greatest when the ratio \( g/Q \) is maximized, where \( g \) = number of electrons attributed to the EO signal and \( Q \) = total number of electrons. Assuming that the number of electrons in each pixel is linearly proportional the incident radiant flux

\[
Q \propto I_d \tag{7a}
\]

\[
q \propto \Delta I_{\text{eo}} \equiv I_d - I_d|_{\Delta \Gamma_{\text{eo}}=0} \tag{7b}
\]
where $\Delta I_{\text{EO}}$ is the intensity contribution from the EO effect alone. Combining (4), (5), (7a), and (7b) yields

$$\frac{q}{Q} = \frac{\cos 2(\Gamma_0 + \Delta \Gamma_{\text{EO}}) - \cos 2(\Gamma_0)}{p + \cos 2(\Gamma_0 + \Delta \Gamma_{\text{EO}})}$$

where

$$p \equiv \frac{1 + \alpha + \beta}{2\sqrt{\alpha}}.$$ (9)

In the small-signal limit, (8) becomes

$$\frac{q}{Q} \big|_{\text{Lin} \Delta \Gamma_{\text{EO}}}=\alpha = f(p, \Gamma_0) \Delta \Gamma_{\text{EO}}$$

where

$$f(p, \Gamma_0) \equiv \left( \frac{2\sin(2\Gamma_0)}{p + \cos(2\Gamma_0)} \right).$$ (10a)

Equation (10a) describes the fraction of electrons in each pixel attributed to the EO effect. We now consider how to use this information to optimize the system sensitivity.

### C. System Optimization

Fig. 5(a) presents a plot of (9), and Fig. 5(b) shows $f(p, \Gamma_0)$ defined in (10b) for the arbitrary nonideal case $p = 1.05$. From Fig. 5(b), we see that $f(p, \Gamma_0)$ has two points for which the amplitude is a maximum. We wish to find $\Gamma_0^{\text{opt}}$ — bias points for which this function is optimized. To do so, we take the derivative of $f(p, \Gamma_0)$ with respect to $\Gamma_0$, equate to zero, and solve

$$\Gamma_0^{\text{opt}}(p) = \frac{1}{2} \cos^{-1}(-p^{-1}).$$ (11)

Equation (11), plotted in Fig. 5(c), shows a distinct $\Gamma_0$ that depends on $p$ which maximizes $q/Q$. Therefore, we wish to optically bias the interferometer at this point, about which the small EO signal is superimposed. We note that for an ideal interferometer, $\{\alpha = 1, \beta = 0\}$ making $p = 1$, giving $\Gamma_0^{\text{opt}} = \pi/2$ where the slope of Fig. 4 is zero! This conclusion is very different from wide-bandwidth detectors used in point sampling, which achieve maximum sensitivity when $\Gamma_0 = \pi/4$, where Fig. 4 has maximum slope. In the general case of a nonideal interferometer, two solutions exist [as originally expected from Fig. 5(b)], one on either side of $\pi/2$.

Substituting (11) into (10b), we find

$$f(p, \Gamma_0) \big|_{\Gamma_0=\Gamma_0^{\text{opt}}} = \frac{2}{p\sqrt{1-p^{-2}}} \equiv f^{\text{opt}}(p).$$ (12)

The factor $f^{\text{opt}}(p)$ is also plotted in Fig. 5(c). It has the greatest value for an ideal interferometer and decreases as we depart from ideal.

### D. Nonideal Factors

Until now, we have ignored sources of optical phase-front distortions to the probe beam. Each optical component has a finite surface accuracy, and refractive index inhomogeneities. These inaccuracies are stationary in time, and spatially random, so the cumulative error is the root-mean-square (rms) combination of all components. These errors will make it impossible to achieve optimum system sensitivity at every
Fig. 6. Factors that degrade interferometer performance: (a) multiple reflections from windows and lenses \[ R = \text{intensity reflection coefficient}, T = \text{intensity transmission coefficient} = (1 - R) \], (b) Fresnel reflections at the surface of the NLO, (c) light escaping from excitation fiber.

pixel simultaneously, but the following observations can be made.

1) As the region-of-interest (ROI) is decreased (within diffraction limits), the magnitude of phase distortions will decrease.

2) As a system, sensitivity will be maximized when the median optical bias point in the ROI corresponds to the optimum bias conditions.

We have shown that there exists an optimum bias point about which we must modulate our signal. In order to determine this bias point, we must understand the origins of \( \alpha \) and \( b \) and estimate their magnitudes.

In an ideal interferometer, the beamsplitter would be infinitely thin, so that reflections occur only at one surface, and the intensity measured at the detector for either the DUT or reference probe pulse is exactly equal. This does not imply that the beamsplitter must be 1:1 (transmission : reflection). Pellicle beamsplitters are very thin but are subject to acoustic and mechanical vibrations, making them unsuitable for this application.

The probe pulses in an interferometer having a thick beam splitter traverse different paths because of interactions with the second surface. Reflections from one surface are desired, while reflections from the second surface must be eliminated.

Coated optics are an option, but the method we chose to eliminate unwanted reflections was to use a wedged window. The two surfaces of the window are not parallel; hence, it is possible to make the beam at one surface incident at Brewster’s angle, where reflectivity of p-polarized radiation is zero. The beamsplitter then behaves ideally, i.e., \( \alpha = 1.0 \).

Background illumination, factor \( b \) in (4), is radiation collected by the detector that does not contribute to the desired signal. Fresnel reflections occur at each dielectric interface (window or lens) as in Fig. 6(a). Each transmitted beam is the superposition of many reflections. Beams that experience multiple reflections will be delayed more than the coherence length of the probe pulse, so will not interfere. To estimate \( b_{\text{rms}} \), we compare the intensity of transmitted light delayed by more than the coherence length of the probe pulse, so will not interfere. To estimate \( b_{\text{rms}} \), we compare the intensity of transmitted light delayed by more than \( n_1 t \) to that delayed by exactly \( n_1 t \). For a system of \( M \) windows and lenses,

\[
b_{\text{rms}} = (1 - R^2)^{-M} - 1.
\] (13)

Since system sensitivity decreases with increasing \( b \), it is advantageous to minimize the reflection coefficient \( R \) at each optical element by using coated optics. A conservative estimate for the system shown in Fig. 1 (not all optics shown) having seven uncoated BK-7 windows \( (R = 0.04) \) gives \( b_{\text{rms}} \approx 1.2\% \).
Fresnel reflections occur also at the surface of the NLO. Most EO materials used for sampling have a large refractive index, giving large reflections. The following expression for background contributions from the NLO, \( b_{\text{NLO}} \), is evident from Fig. 6(b) 

\[
b_{\text{NLO}} = 1 - (1 - R_{\text{NLO}})^2. \tag{14}
\]

Reflections from the top surface of the crystal are potentially the most detrimental to system performance. Uncoated LiTaO\(_3\) has \( R_{\text{NLO}} \cong 14\% \), making \( b_{\text{NLO}} \cong 35\% \); antireflection (AR) coatings, which make \( R_{\text{NLO}} \cong 0.03 \), yield \( b_{\text{NLO}} \cong 6\% \). \( R_{\text{NLO}} \) also effectively reduces \( \alpha \) to \( \alpha' \) by 

\[
\alpha' = \frac{I_{\text{DUT}}}{I_{\text{ref}}} (1 - R_{\text{NLO}})^2 = \alpha (1 - R_{\text{NLO}})^2 \tag{15}
\]

since only a fraction of the incident pulse makes exactly one round-trip through the NLO.

Uncoated LiTaO\(_3\) makes \( \alpha' = 0.74\alpha \), whereas coated LiTaO\(_3\) produces \( \alpha' = 0.94\alpha \). To minimize these detrimental effects, the NLO requires a nearly perfect AR coating on the first surface \( (R_{\text{NLO}} = 0) \) and perfect HR coating \( (R = 1) \) on the second surface.

The final source of background is the light reflected by the DUT from the fiber-coupled beam used to trigger the photoconductive switch. A conservative estimate assumes that the fiber is positioned at the DUT and pointed directly toward the interferometer beam splitter [Fig. 6(c)]. The results of this analysis will be at least an order of magnitude too large because the analysis neglects the following facts.

1) The fiber is directed toward the DUT, and will shadow reflected light.
2) The DUT will absorb incident photons.
3) The polarizing filter will attenuate reflected (scattered) light that is depolarized.
4) The photoconductive switch may be located outside the image area.

From the above argument, the results of the following simplified analysis will be reduced by a factor of 10.

The divergence angle of the beam is determined by the fiber diameter and wavelength. A fraction of the light is reflected off the beam splitter toward the camera. The distance between the relay lens and DUT is determined by the desired magnification and lens focal length \( f \). The lens has a finite aperture and collects only a fraction of the diverging beam from the fiber, \( b_{\text{fiber}} \). Assuming a gaussian beam from the fiber tip, this simplified approach yields 

\[
b_{\text{fiber}} \approx \frac{I_{\text{exc}} R_{\text{bs}}}{I_{\text{ref}}} \exp \left( \frac{D}{D'} \right) \tag{16a}
\]

where 

\[
\frac{D}{D'} = \frac{\lambda D m}{2 df (m + 1)}, \tag{16b}
\]

and where \( I_{\text{exc}} \) = intensity of the excitation pulse \( (\approx 1 \text{ mW}) \), \( I_{\text{ref}} \approx 10 \mu\text{W} \) (for pixel saturation), \( R_{\text{bs}} \) = beamsplitter reflectivity, \( D \) = lens-aperture diameter, \( D' = 1/e \) beam diameter at the lens, \( \lambda \) = wavelength, and \( d \) = fiber-core diameter.

Clearly, \( R_{\text{bs}} \) and \( m \) should be minimized, and \( f \) should be large. From (16a) and (16b), typical operating conditions give \( b_{\text{fiber}} \approx 13\% \), which we reduce to 1.3\%, as discussed above.

We have considered several factors that contribute to the nonideal terms \( \alpha \) and \( b \) in the interferometer transfer function. It is essential to use precision optics, and minimize front-surface reflections from the NLO to prevent system degradation. Proper adjustment of the excitation beam intensity and fiber placement will limit background contributions from the excitation source. Finally, coated optics will reduce multiple reflections from other system optics. For a well-designed system having an AR-coated NLO, we obtain \( b = b_{\text{NLO}} + b_{\text{fiber}} + b_{\text{fns}} \approx 0.06 + 0.012 + 0.013 = 0.085 \), and \( \alpha = 0.94 \), thus making \( p \approx 1.044 \). This value for \( p \) will be used in the remaining discussion.

V. SYSTEM SENSITIVITY AND LINEARITY

A. Linearity

We now derive an expression for the linearity of our measurement system. Let us define linearity \( L \) as the ratio of (10a) and (8)

\[
L(p, \Delta \Gamma_0) = \frac{\left( \frac{2 \Delta \Gamma_0}{p \sqrt{1 - p^2}} \right)}{\left( \frac{p^{-1} \cos(2\Delta \Gamma_0) - 1}{p^{-1} \cos(2\Delta \Gamma_0) - \sqrt{1 - p^{-2} \sin(2\Delta \Gamma_0)}} \right)} \tag{17}
\]

where \( \Gamma_0 \) has been replaced with \( \Gamma_0^{\text{ref}} \), and \( \Delta \Gamma_0^{\text{ref}} \) is a small-signal perturbation about \( \Gamma_0^{\text{ref}} \). Fig. 7 shows \( L(p = 1.044, \Delta \Gamma_0) \), from which we see that the measured response is linear within \( \pm 5\% \) for \( |\Delta \Gamma_0| < 0.015 \text{ rad} \); this is more than adequate for expected signals.

B. Sensitivity

We have obtained an expression for the optimum sensitivity factor \( f^{\text{opt}}(p) \) and numerical estimates of the parameter \( p \). The next step is to determine the measurement resolution of the system given this information. First, we determine the system dynamic range and minimum resolvable phase change, then the voltage and \( E \)-field needed to produce this phase change.
Fig. 8. Modulation: (a) expansion of Fig. 4 about an interferometric null shows EO modulation about $\pm \frac{\Delta \Gamma_0}{2}$ bias points; (b) modulation and image capture timing diagram.

From (10), we can determine $D_{\text{signal}}$ if we assume that the pixel is nearly saturated so that $Q \approx Q_{\text{well}}$. The CCD has an electronic noise equivalent signal, $q_{\text{elec}} = 30$ electrons, shot noise, $q_{\text{shot}} = 40$ electrons, and well capacity $Q_{\text{well}} = 80 \times 10^3$ electrons [19]. Setting $q_{\text{noise}} = (q_{\text{elec}}^2 + q_{\text{shot}}^2)^{1/2} = 50$ electrons, we find

$$D_{\text{signal}} = 20 \cdot \log \left( \frac{Q_{\text{well}}}{q_{\text{noise}}} \right) \left( \frac{\Delta \Gamma_0}{\Delta \Gamma_{\text{lin}}} \right).$$

For $\Delta \Gamma_0 = \pm 0.015$ radians (the limit of “linear” range) and $p = 1.044$, we find $f_{\text{opt}}(p) = 6.25$, and $D_{\text{signal}} = 43$ dB.

The minimum detectable signal $\Delta \Gamma_{\text{min}}^\text{lin}$ is that which makes $q/Q = q_{\text{noise}}/Q_{\text{well}}$

$$\Delta \Gamma_{\text{min}}^\text{lin} = \left( \frac{q_{\text{noise}}}{Q_{\text{well}}} f_{\text{opt}}(p) \right)$$

which gives $\Delta \Gamma_{\text{min}}^\text{lin} = 100$ $\mu$rad, corresponding to $\lambda/6 \times 10^4$ resolution.

We relate $\Delta \Gamma_{\text{min}}^\text{lin}$ to the voltage necessary to produce it using (3c) and (3d)

$$\Delta \Gamma_{\text{min}}^\text{lin} \approx \frac{\pi}{\lambda} n_2^3 g_{33} \left( \frac{\varepsilon_{\text{sub}}}{\varepsilon_{\text{NL}}} \right) (V_{\text{gamma}} \min).$$

The minimum detectable voltage $V_{\text{gamma}} \min$ is constant for any (coplanar) gap geometry. $E_{\text{surf}} \min$ is the minimum field, which if present at the surface of the NLO, could be resolved by the system

$$E_{\text{surf}} \min = V_{\text{gamma}} \min / g.$$  

When testing a device fabricated on silicon ($\varepsilon_{\text{sub}} = 11.9$) using LiTaO$_3$ ($\varepsilon_{\text{NL}} = 43$, $g_{33} = 33$ pm/V, $n_2 = n_\gamma = 2.180$) [17], and $\lambda = 800$ nm, we find $\Delta \Gamma_{\text{min}} = 3.7 \times 10^{-4}$ $V_{\text{gamma}} \min$. By equating $\Delta \Gamma_{\text{min}}$ to $100$ $\mu$rad, $V_{\text{gamma}} \min$ = 270 mV, which corresponds to 27 kV/m on a $10^{-4}$ $\mu$m gap.

This sensitivity is well suited to measurement of microwave devices and complex transmission line structures. Several enhancements can be made to improve suitability for digital applications. A nonlinear organic salt known as DAST$^2$ has $\varepsilon_{\text{NL}} = 7.0$, Pockels coefficient $r_{11} = 160$ pm/V, and $n = 2.460$. From (20), this would increase sensitivity by a factor of 43. Cooling the sensor reduces shot noise so that $q_{\text{noise}} \approx q_{\text{elec}}$, thus by (19), increasing sensitivity by a factor of 1.6. In combination, these produce $V_{\text{gamma}} \min \approx 4$ mV, and $E_{\text{surf}} \min \approx 400$ V/m.

VI. MODULATION

Having discussed the attributes of an integrating detector, we now show how the signal is modulated about the desired operating bias point. We first discuss how the signal is modulated in each image, and the timing required. We then discuss the characteristics of a frame transfer sensor, and how to use these characteristics to our advantage.

Fig. 8(a) is an expanded view of Fig. 4, about $\pi/2$. In the absence of an electric field, points A and B have equal intensity when the PZT$^3$ actuator is displaced equally on either side of the null. The optical phase bias at points A and B are adjusted to $\pm \frac{\Delta \Gamma_0}{2}$. When an electric field is present on the DUT, the resulting EO phase shift is added to $\Delta \Gamma_0$. This causes the intensity at point A to increase to C, while that at point B decreases to D. Analysis of the data is achieved by subtracting field D from B, and C from A.

The data acquisition system and modulation control hardware (Fig. 2) are used to acquire images with the timing shown in Fig. 8(b). Timing is synchronized with the camera’s pixel and field clock signals. The electrical bias on device’s photoconductive switch is synchronously modulated at the 30-Hz camera field clock frequency, thus decreasing 1/f noise (both laser and mechanical vibrations of the interferometer). The piezoelectric actuator is modulated at 1/2 the bias frequency. A trigger pulse is generated on the mutual rising edge of bias and actuator signals. This triggers the frame grabber to digitize four fields in succession, corresponding to points C, A, D, B$^4$ in Fig. 8(a). The resulting images are digitally subtracted as describe above to construct the $E$-field image.

$^2$Molecular Optoelectronics Corporation, 877 25th St. Watervliet, NY 12189. DAST has a different Pockels coefficient matrix than the (31m) point group, so substituting $r_{11}$ for $r_{33}$ is an approximation.

$^3$The piezoelectric material in the actuator is lead-zirconate-titanate (PZT), hence, the actuator is called a PZT for brevity.

$^4$Ideally, it is unnecessary to collect images corresponding to points A and B, however the information captured in these images may be useful for digital removal of vibration-caused artifacts.
A frame transfer CCD (Fig. 3) has two discrete sensor regions: an active-pixel site and a storage site of equal size. Each field is acquired over a 1/60-s integration period. An advantage of using a detector with an integration period of 1/60 s is that 60-Hz electrical noise will be integrated over one complete cycle, thus averaging to zero. During integration, the active pixels integrate charge proportional to photon flux, while electrons in the storage site are clocked to the output amplifiers. During frame transfer, charges in the active pixels are transferred vertically via “bucket brigade” into the storage site. Charge transfer causes slight smearing due to transfer inefficiency, and distortion occurs for charge packets that are transferred through brightly illuminated pixels.

A high-speed modulator “gates” the laser “on” immediately before and after alternate frame transfer cycles, and “off” at all other times. This eliminates charge smearing during frame transfer and reduces the effective laser and vibration noise bandwidth significantly. The limiting speed for this modulation is governed by the frame transfer period (1.27 ms for our camera). If the laser is gated “on” for ~100 pulses, the effective modulation frequency would be ~750 Hz.

VII. SUMMARY

We have described and analyzed an ultrafast EO imaging system that uses an interferometer and CCD detector to map 2-D electric fields on an optoelectronic device. It is comparable to an ultrafast sampling oscilloscope having more than 180 000 channels. Limitations caused by use of an integrating detector are reviewed, and optimum operating conditions are identified. Techniques are presented that allow modulation of the signals at 750 Hz, which will reduce sensitivity to laser and mechanical 1/f noise. System sensitivity in the absence of laser noise is estimated to be 270 mV, corresponding to 27 kV/m for a 10-μm coplanar structure. These values make the system well suited for testing microwave devices. Sensor cooling and use of alternative NLO materials should improve sensitivity by factors of 1.6 and 43, respectively, making the minimum resolvable voltage 4 mV. The system then would be easily capable of digital (e.g., CMOS) circuit evaluation.

REFERENCES


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Roman Sobolewski, for a biography, see this issue, p. 677.

Thomas Y. Hsiang, for a biography, see this issue, p. 677.