Ultrahigh sensitivity electric field detection with a liquid electro-optical film

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In this Letter, an electro-optical probe configuration with polar molecule liquids as the sensing film is proposed to improve the voltage sensitivity. This method exhibited increases in intrinsic sensitivities better than $0.1\,\mathrm{mV}/\sqrt{\mathrm{Hz}}$, 2 orders of magnitude larger than the normal method using a GaAs probe in the same measurement system. Based on the mechanism of orientation polarization, the electro-optic coefficient was measured to be $250\,\mathrm{pm/V}$ by the Teng–Man method at a modulation field of $100\,\mathrm{Hz}$. This technology will be promising in applications of low-frequency field detection.   © 2011 Optical Society of America
    OCIS codes: 280.4788, 120.5060, 190.4710, 190.3270.

Electro-optical probes with negligible perturbation have attracted great attention [1,2] for electric fields sensing, particularly for the diagnosis of integrated circuits. The method consists of sending a laser beam through an electro-optical thin film, where an electric field to be detected is present. The film refractive index modulation by the electric field alters the phase relation between the probe and the reference beam. The local field therefore becomes detectable by analyzing the interference signal of the two beams [Fig. 1(a)]. Despite the clarity of the probing principle, the usefulness of the technology depends largely on the voltage sensitivity, but its improvement has been hampered because (i) the electro-optical coefficients, γ_{ij}, of crystals are generally small, on the order of several pm/V [3]; (ii) the emanating fields from circuits are subject to significant decay by the air gap [Fig. 1(b)] between the electro-optical probe and the circuit under test because of the nature of the noncontact detection mode and the existence of the passivation layer of the circuit surface [4,5]. Efforts have therefore been devoted to exploration of novel electro-optical materials [6,7]. Electro-optical polymer, due to γ_{ij} as high as on the order of hundreds of pm/V [8], has shown promising prospects of enhancing sensitivity. However, problems associated with polymer film include low abrasive resistance and weak adhesion to the glass cone, so that it is difficult for the probe to endure high-speed, multipoint, large area detection as an atomic force microscopic tip does. In this Letter, we propose a electro-optical probe mechanism, which uses liquid-state polar molecules as the sensing film, which is coated onto the circuit surface [Fig. 1(c)] instead of being affixed to the scanning tip end [Fig. 1(b)]. This scheme has not only eliminated the air gap, but also uses molecular orientation as a response to the electric field excitation, leading to a sensitivity of $0.1\,\mathrm{mV}/\sqrt{\mathrm{Hz}}$, 2 orders better than those achieved by solid sensing films.

    The schematic experimental setup based on liquid electro-optical film is shown in Fig. 1(a). In contrast with conventional probes [9,10], where the electro-optical film

is attached to the tip end of a glass cone as a waveguide [Fig. 1(b)], here the electro-optical liquid of polar molecules is pasted on the circuit. The liquid film is then covered by an indium tin oxide (ITO) glass with a 20 nm aluminum reflective coating [Fig. 1(c)], which not only serves as a reflection layer but also screens the emanating electric field in the liquid. The circuit, the liquid, and the ITO glass form a sandwich structure as shown in Fig. 1(c). When the incident light (I_i) is focused on the circuit surface by an objective lens, it is divided into two components. One is reflected by the aluminum reflective coating ($\sim 30\%$) as a reference beam (I_1), while the other, traveling through the liquid film, is reflected by the transmission line of the electronic circuit as a probe beam (I_2). The interfered light intensity (I_{output}), carrying the information of the field-induced phase difference change related to the electric field signal, is detected by a photodiode. The incident beam is a continuous wave of $1.31\,\mu\mathrm{m}$ generated by a semiconductor laser diode, and its power is 1 mW. A polar organic solvent, N,N-Dimethylformamide (DMF), is used as the liquid electro-optical film for electric field sensing. As shown in the inset of Fig. 1(a), an oxygen atom can attain
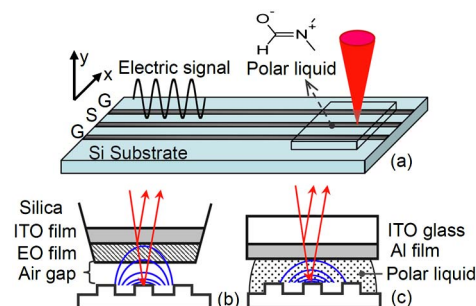

Fig. 1.   (Color online) Illustration of the electro-optical probe. (a) Electro-optical detection system using polar liquids. *G* and *S*, ground and signal line, respectively, of coplanar waveguide circuit. Configuration of (b) solid-state and (c) liquid-state probes. Curves above the signal electrode show schematic contours of the emanating field of the circuit.

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one electron from the nitrogen atom, giving rise to the polar characteristics of DMF molecules. The molecule dipole moment under the action of the external forcing field (DC or AC) is expanded in its power series [11]

$$\mu = \mu_0 + K_1\alpha : E(\omega) + K_2\beta : E(\omega)E(\omega)$$
$$+ K_3\gamma : E(\omega)E(\omega)E(\omega) + ..., \qquad (1)$$

where μ_0 is the molecule permanent dipole moment, and the expansion coefficients $\alpha, \beta, \gamma, \ldots$ are tensors describing the response of molecules to the forcing field $E(\omega)$. There are essentially three basic kinds of polarization mechanisms that lead to the formation and/or orientation of dipoles: electronic, ionic, and orientation polarization. As is well known, due to the contribution of electric polarization in creating the displacement of electric charges or reorientation of the molecules, the bulk reflective index of a material varies with the forcing field [12]. These effects impart a small voltage-dependent optical path variation to the beam traversing the material. Based on this mechanism, we can deduce the electric signal of the circuit from the detected light intensity signal. Unlike solid-state dielectrics, polar liquids have a strong molecular reorientation effect, which intrinsically enhances the voltage sensitivity.

A coplanar waveguide made by photolithography and chemical etching [Fig. 2(a)] served as the circuit under test. Both the middle line, along which the modulation electric signals propagate, and the interline spacing were $100 \mu m$ wide. A 1 kHz sinusoidal signal was applied to the signal line of the circuit. The slightly modulated light signal was amplified by a preamplifier with bandpass filters. The typical data of the output signals were picked up on the oscilloscope, as shown in Fig. 2(c), and the specific measurement was monitored [Fig. 2(b)]. One of the important system parameters is the voltage sensitivity, which is defined by the minimum detectable voltage, V_{min}, in [1]. The minimum voltage is determined by (i) the local field strength determined by the position of the electro-optical film, (ii) the electronic noise of the system, and (iii) the electro-optical coefficient of the material itself. For the first item, the substituted liquid electro-optical material has an intrinsic advantage by eliminating the air gap between the circuit and the electro-optical film. The second item, depending on the whole probe system, is inevitable. We thus introduced a conventional GaAs probe tip in the same system to provide contrast. Limited by the ratio of signal to noise, the minimum detectable voltage (V_{min}) by a GaAs probe was about 1 V (peak-to-peak value) at 1 kHz. When the liquid film was utilized, as indicated in Fig. 2(c), the waveform of the output signal was still inerratic when the applied voltage decreased to about 10 mV. Therefore, the voltage sensitivity was enhanced by 2 orders of magnitude. The noise signal was measured to be about 1 mV in 100 Hz bandwidth, so the sensitivity of the electro-optical system using DMF film was about $0.1 mV/\sqrt{Hz}$. Third, the electro-optical coefficient of DMF was measured by the Teng–Man method at a wavelength of $1.31 \mu m$ [13]. We took an organic–inorganic hybrid material for comparison, a sol-gel-processed silica (SiO_2) film doped with Disperse Red 1 (DR1, Tokyo Kasei Kogyo Co. Ltd., Japan) [14]. After a poling process at temperatures of around $110 °C$, with a poling field ranging from 5000 to $10000 Vcm^{-1}$, the electro-optical coefficient γ_{33} of $DR1/SiO_2$ was about 14 pm/V. However, the electro-optical value of DMF was measured to be as high as 250 pm/V at the forcing field of 100 Hz.

In order to understand why such a high sensitivity becomes feasible, experiments on voltage-response analysis were carried out. According to the typical data of the measured signals in the inset of Fig. 3, the liquid electro-optical film has two simultaneous kinds of voltage responses. One is independent of the direction of the electric field and shows the quadratic frequency of the applied voltage, whereas the other response follows the fundamental frequency. These fundamental and quadratic components of the measured signals are separated by bandpass filters. As is seen in Fig. 3, the amplitudes of the fundamental signals yield a quantity linear to the field strength ($|E(\omega)|$), while the quadratic signals are proportional to $|E(\omega)|^2$. Liquids are ordinarily considered centrosymmetric materials, whose odd rank molecular hyperpolarizabilities are zero [$\beta = 0$ in Eq. (1)] [11]. This means that the liquid film should not create the fundamental components of the measured signals.
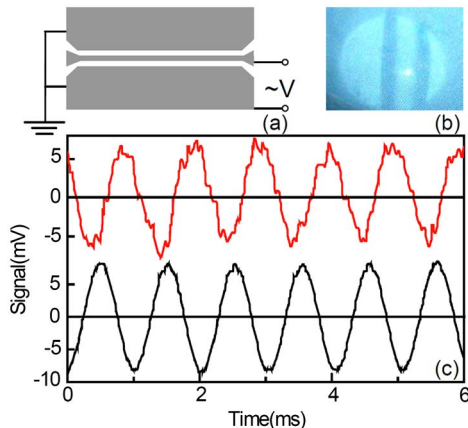

Fig. 2. (Color online) Typical data from the electro-optic probe experiment. (a) Coplanar waveguide serving as circuit under test. (b) Measurement point monitored by a camera. (c) Upper curve, light intensity read by photodiode detector; bottom curve, applied electric signal to line of circuit (a).
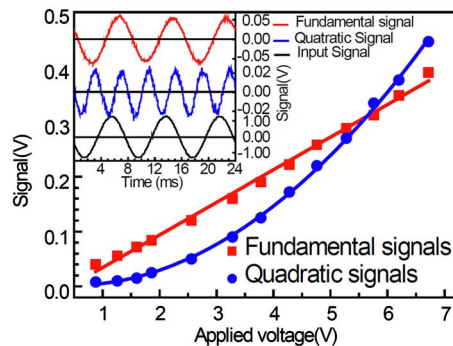

Fig. 3. (Color online) Fundamental and quadratic component amplitudes of the output signals as function of the modulation field strength. Inset shows the two components of the measured signals at the same modulation field. Note that the frequency of the quadratic component is twice that of the modulation field.
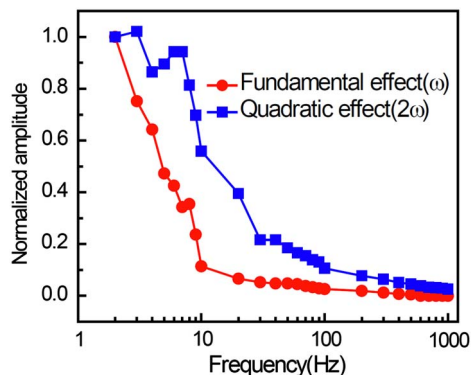
Fig. 4. (Color online) Frequency response spectra of the fundamental and quadratic signals. Output signal declines considerably with increasing modulation frequency.

Therefore, further investigation is necessary to clarify the mechanism.

By measuring the frequency response of liquid electro-optical film, we find the amplitudes of fundamental and quadratic electro-optical signals decline considerably as the applied field frequency increases (Fig. 4). It is evident that either the fundamental or the quadratic components must come from the orientation effect of polar molecules, because the other mechanisms (the electronic and ionic polarization) are nearly frequency-independent in the frequency range we used [15]. As seen in Fig. 4, the measured signals are much larger at low frequencies. It can be interpreted that, with the decrease of frequency, the dipoles of the electro-optical film orient toward the forcing field more completely and give rise to deeper modulation depth. Consequently, we could deduce that the dipoles could not rotate freely to keep up the change of the external field. Therefore, the origin of the anomalous fundamental signals can be reduced to the instantaneous asymmetry of liquid film under the action of the exerting electric field due to the slow-response mechanism. In any case, the anomalously high electro-optical activity of liquid film in a low-frequency range provides an available means in high-sensitivity field sensing.

In summary, a unique electro-optical material was proposed to realize ultrahigh sensitivity in field detection, which not only dispenses with complicated synthesis and poling processes, but also gives excellent performance on field-induced optical modulation. This ultrahigh sensitivity electro-optical detection is promising in practical applications of low-frequency electric field detection, such as biological electric fields (usually <100 Hz), diagnosis of integrated circuit malfunction, and so on. Although integrated circuits operate at high frequencies, the low-frequency detection is important to circumvent the influence of high-frequency parasitic parameters.

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