LETTER
IEICE Electronics Express, Vol.13, No.8, 1–6

Resolution of live electrooptic imaging with a very thin (10-μm) sensor plate

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Abstract: Resolution of live electrooptic imaging (LEI) having an ultimately-thinned (10-μm) electrooptic sensor plate has been evaluated experimentally and discussed theoretically. The evaluated resolution value is 30–40 μm, which is the best ever demonstrated for the LEI technique. Through its theoretical analyses, the following three resolution-limiting factors have been quantified and a guideline for resolution improvement has been discussed; (a) the image sensor pixel density, (b) the magnification and resolution of the laser optics, and (c) the electrooptic sensitive volume.
Keywords: live electrooptic imaging, image resolution, evanescent field, thinned electrooptic plate, resolution chart, imaging optics
Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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DOI: 10.1587/elex.13.20160135
Received February 16, 2016
Accepted March 2, 2016
Publicized March 31, 2016
Copyedited April 25, 2016

IEICE Electronics Express, Vol.13, No.8, 1–6

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1 Introduction

It is highly attractive, not only from technological but also from academic points of views, to agilely grasp space-domain behaviors of electrical signals and/or noises in and around circuit boards as well as issues of electromagnetic interferences, where prompt visualization of the electrical signals and/or the noises in their distributions and dynamics should be extremely effective. Besides various numerical visualization approaches, a technique named live electrooptic imaging (LEI) [1, 2, 3] shown in Fig. 1a is unique for approaching the above target experimentally, where high-frequency electric fields are visualized in real-time phase-evolving video formats. The LEI technique is based on the two ultimate properties of photonics [4], i.e., the ultra-parallel [5, 6] and ultra-fast [7, 8] natures, merged in a plate-shaped electrooptic (EO) sensor [9, 10].

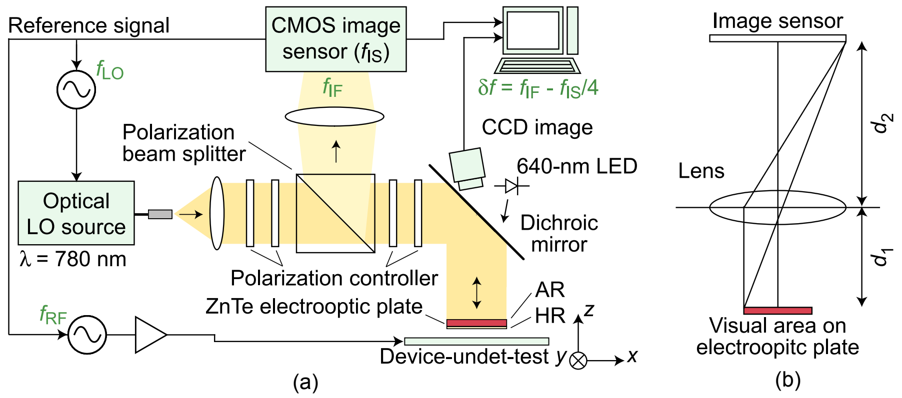

Fig. 1. Shown are schematics of live electrooptic imaging setup (a) and its imaging optics (b). AR/HR: anti-/high-reflection coated, CCD: charge-coupled-device, CMOS: complementary metal-oxide-semiconductor, IF: intermediate frequency, IS: image sensor, LED: light-emitting-diode LO: local oscillator, RF: radio frequency.

Whereas its coming applications are expected in various areas, demonstrated so far have been the following basics: wave vector mappings [11] and their applica-

DOI: 10.1587/elex.13.20160135
Received February 16, 2016
Accepted March 2, 2016
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Copyedited April 25, 2016

tions for high-definition wave imaging and waveguide mode analyses [12], visualizations of rotating electric field vectors and their ellipticity [13], visualizations and decompositions of Bloch states in metamaterial structures [14], visualizations of propagating waves in and around electromagnetic absorbers [15], and packet imaging [16]. Recently, the scheme of detached EO imaging [17] has been added to the list. The present status of the LEI technique is specified by its highest frequency of visualized waves, largest visional area, highest optical magnification ratio, and maximum pixel number, which are 100 GHz [2], 25-mm square [3], 8.5 [2], and $256 \times 256 = 65{,}536$ [18], respectively.

One of the LEI issues needed to elucidate is its ultimate image resolution in the microscopic range. Reported here is experimentally evaluated resolution of the present LEI system equipped with an ultimately-thinned EO sensor plate so as to suppress the fringe field effect, together with the systematic theoretical analyses of the ever-finest LEI resolution for a guideline of its further improvement.

2 Evaluation of LEI resolution

2.1 Factors to determine image resolution

Resolution of the LEI system in Fig. 1 is affected by the following three factors: (a) the pixel density of the complementary metal-oxide-semiconductor (CMOS) image sensor (IS) (Fig. 1a), (b) the magnification power and resolution of the laser optics (Fig. 1b), and (c) the EO sensitive volume V_s described in reference [19].

The (a)-factor is obvious; CMOS-IS having a 100×100 pixel array and a higher sensitivity has been mainly used [1, 18]. The (b)-factor can be dealt with by the conventional optical theory for microscopic images. The definition of V_s, the (c)-factor, is rather obscure, but given primally by the area of one pixel projected on the EO plate and a surface-normal roundtrip of sensing laser light within the EO plate [19]. In order to avoid ambiguity in the definition of resolution, subjects to be visualized in this paper are restricted in evanescent fields originating from planar circuit patterns, where additionally convoluted to V_s are fringe fields from the pattern edges. The fringe fields are generally affected by the thickness and relative permittivity of the EO plate as well as by a mutual adjacency between DUT and the EO plate. This mutual relationship has made conventional resolution evaluations rather delicate.

2.2 EO sensor heads

Whereas it is ideal to have an EO plate with a well-designed set of the above-mentioned three factors as well as sufficiently suppressed invasiveness, its conventional designs have been premature especially in resolution since priority has been placed in their sensitivity and ease of handling.

As shown in Fig. 2, two types of EO sensor heads were tested here so as to estimate the V_s effect. The conventional one (Fig. 2a) contains a 350-µm-thick (100) ZnTe plate of 25-mm square, which is adhered to a 0.5-mm-thick quartz plate for reinforcement with suppressed optical reflection at their interface and accompanies a 0.2-mm-thick Sapphire plate beneath for protection against mechanical damage. The new one (Fig. 2b) consists of a 10-µm-thick EO plate and a 3-mm-

DOI: 10.1587/elex.13.20160135
Received February 16, 2016
Accepted March 2, 2016
Publicized March 31, 2016
Copyedited April 25, 2016

thick glass reinforcement platform, which are both 5-mm-square, together with a 1-mm-thick 25-mm-square glass plate. They are piled vertically with suppressed optical interface reflections. The laser beam incident surfaces of both ZnTe plates are anti-reflection coated while their bottom surfaces are high-reflection coated.

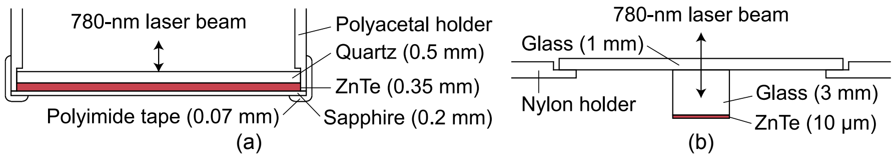
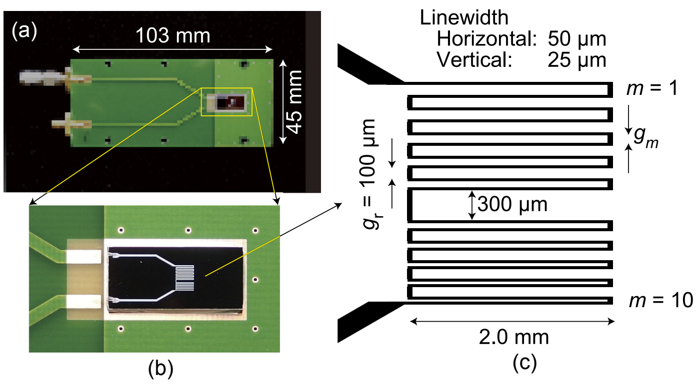


Fig. 2. Configurations of EO plates and their holders: the conventional [17] (a) and the present (b).

Another contrived feature of the new EO sensor head is the lift-up mechanism embedded in its holder, eliminating the Sapphire protection plate used in the conventional. Mechanical damage of the EO plate is thus prevented even if it is pressed down to DUT surfaces severely, and its more intimate contacts are provided. It should be noted that such a thinned EO plate in a close contact to DUT can make high resolution and suppressed invasiveness compatible.

2.3 Resolution chart

As a resolution chart, a planar circuit sample in Fig. 3a was prepared, which contains a meander-patterned microstrip line shown in Figs. 3b and 3c, where two series of meanders are included and their individual gaps vary in width as listed in Fig. 3d. The image resolution is defined here to be finer than a gap width if evanescent fields from both sides of the gap are distinguished from each other.



g_m (μm)

m	g_m	m	g_m
1	100	6	50
2	90	7	40
3	80	8	30
4	70	9	25
5	60	10	20

(d)

Fig. 3. Picture of DUT as a resolution chart (a), its magnification around the Si substrate part (b), the included meander pattern (c), and sizes of meander gaps g_m (d).

Using a photolithography technique, the meander pattern was formed of 1-μm-thick sputtered Al layer on a 525-μm-thick (100) n-type silicon substrate with a 9.0-μm-thick sputtered SiO_2 layer on its top. As shown in Fig. 3b, the Si substrate was die-bonded on a printed circuit board (PCB) with its own microstrip lines patterned and receptacles of sub miniature type A mounted. The microstrip lines on the Si-substrate and on PCB are connected by Au bonding wires.

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Received February 16, 2016
Accepted March 2, 2016
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2.4 Experiment

Here, the highest magnification power available in the present LEI optics (Fig. 1b), which is 3.4, was chosen, where an area of 2.94-mm-square on an EO plate is imaged on the pixel plane of CMOS-IS, whose array area is 10 mm × 10 mm. For reference, the standard magnification power is 0.4, which is given by a different set of optics normally used for a standard 25-mm-square EO plate projected to the pixel array area.

Figs. 4a and 4b show phasor video images of electric field E_z in the z-direction at 1 GHz obtained experimentally using the two sensor heads. The result obtained with the conventional (Fig. 4a) indicates image resolution around 300 µm, where the upper set of the meanders is distinguished with difficulty from the bottom. Each of the meanders patterns did not appear.

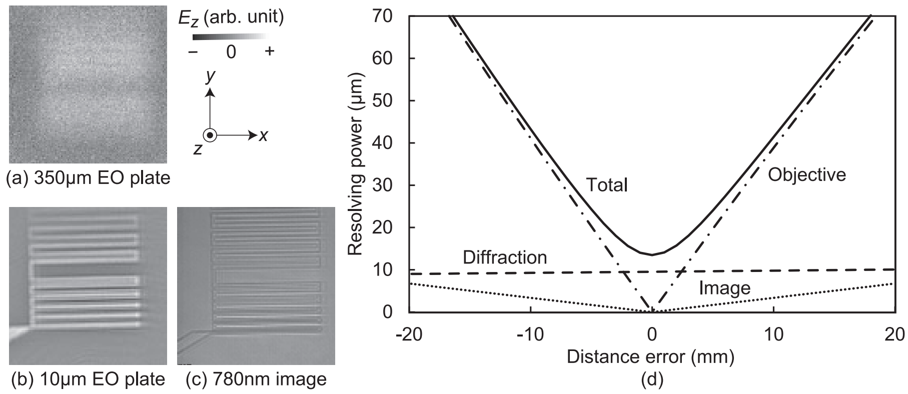

Fig. 4. Electrooptic (EO) images derived by a conventional 350-µm-thick EO plate (a) and by a 10-µm-thick EO plate (b). Corresponding optical image taken by the CMOS image sensor in Fig. 1a with 780-nm laser illumination (c) and theoretical plots of resolving power against distance error (d).

In contrast, the resolution improvement in Fig. 4b is impressive, where the 50-µm gap of the $m = 6$ meander is completely resolved without severe sacrifice of image signal power. The resolving limit stays between meanders of $m = 7$ and 8, suggesting resolution of 30–40 µm, which is the finest ever obtained in the LEI technique. It has been thus clarified that the (c)-factor has been dominant so far.

3 Discussions and analyses

3.1 Doubled images

As a result of the resolution improvement, it was found that the image of the meander evanescent fields in Fig. 4b is laterally doubled with a distance of several tens microns. The image doubling is not a feature of electric field distribution since a 780-nm image of the meander pattern taken by CMOS-IS without the EO sensor head (Fig. 4c) is also doubled in the same direction by the same amount of distance, indicating that the doubling originates from the laser optics.

Furthermore, it was found that the cause of the doubling exists within the housing of CMOS-IS. This is because the doubling direction was fixed to the image azimuth even if CMOS-IS was rotated around the optical axis. It would be thus

DOI: 10.1587/elex.13.20160135
Received February 16, 2016
Accepted March 2, 2016
Publicized March 31, 2016
Copyedited April 25, 2016

reasonably attributed to double reflections of laser beam at the surfaces of CMOS-IS and its cover glass if these surfaces could be non-parallel by a few degrees.

3.2 Quantification of limiting factors

Theoretical curves for resolution of the LEI optics (Fig. 1b) are plotted in Fig. 4d as functions of deviations from ideal optical lengths. The solid line indicates a convolution of the following three. The diffraction limit, $0.61\lambda/\mathrm{NA}$ for λ of 780 nm, is shown by a broken line, and is 10 µm or less independently of the distance error, where the NA value was evaluated from the effective laser beam diameter of 36 mm at the lens. The dashed line and the dotted line are, respectively, defocuses given by errors in the objective distance d_1 and the imaging distance d_2, where the former is dominant.

The image resolution experimentally derived in Fig. 4b agrees fairly well with a composite of the defocusing by the d_1 deviation, which is unavoidable in the present system and is estimated 5 mm, the diffraction limit, and the (a)-factor, which is 30 µm on the image. Furthermore, some residual of the (c)-factor might be added, which would be minor since the thickness of the EO plate is less than the evaluated image resolution.

To obtain further improvement in the image resolution, the followings should be effective; firstly, the laser optics should be improved for higher magnification power, higher resolution, and suppressed defocusing; secondly, the EO plate should be made as thin as possible to reduce the fringe effect; and finally, unnecessary reflections of the laser beam in front of CMOS-IS should be eliminated.

4 Conclusion

Record-high image resolution has been experimentally evaluated for the live electrooptic imaging system, which has been brought about by an ultimately thinned EO plate. Theoretical analyses of the image resolution have led to the quantification of the three limiting factors, suggesting possibility of further improvement of the image resolution.

Acknowledgments

The authors appreciated Dr. N. Maeda and Mr. K. Akiyama of Nippon Soken Inc. and M. Tsuchiya has appreciated Profs. T. Shiozawa and J. Hamasaki for their encouragements.

DOI: 10.1587/elex.13.20160135
Received February 16, 2016
Accepted March 2, 2016
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