# Visualization of Microwave Heatingformesh-Patterned Indium-tin-Oxide by a Thermo-Elastic Optical Indicator Microscope

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**Abstract:** This review highlights advances toward non-destructive thermo-elastic optical indicator microscopy visualization system, with a particular focus placed on the structural type of the optical indicator. We present the electromagnetic field interaction with a thin electrical conductive layer of mesh-patterned ITO which is used as an optical indicator. Depending on the mesh-pattern orientation and electromagnetic field polarization, the microwave heating mechanism and field distribution are different. Visualization was made with a 12 GHz microwave signal and 35 dBm maximum power.

Keywords: Microwave heating, mesh-patterned ITO, thermo-elastic microscopy

#### 1. Introduction

Transparent conductive oxide (TCO) is one of the most important and widely studied classes of advanced applied materials, with applications such as liquid crystal displays (LCD),organic light emitting diodes (OLED), solar cells and touch screens. It is an essential component in modern optoelectronic devices [1-3].In Particular, Indium-tinoxide (ITO) is still the dominant material for transparent conductive electrodes (TCEs) due to high optical transparency together with low sheet resistance [1].

In recent years, there is a great need for fabricating optoelectronic devices with mechanical flexibility due to the replacement of the traditional glass substrates with polymer materials. As important components of flexible electronic devices, electrodes that are transparent, have high electrical conductivity, and display favorable physical stability, such as high flexibility are required. One of the ways to increase the flexibility of a material is the mesh-patterning technique[4,5]. Results indicate that the proposed mesh patterned ITO electrode has a high potential for flexible electronic devices [6,7].

In modern technology non-destructive visualization is an important industrial requirement. Compared with conventional methods of visualization the thermo-elastic optical indicator microscope (TEOIM)[8]visualization system has great potential and advantages, including high sensitivity fast inspection time and spatial resolution. Conventional visualization methods based on a scanning probe technique include eddy current probe microscopy[9], scanning probe microwave microscopy[10], and conducting tip atomic microscopy[11]. The listed methods are still applicable but they have slow measurement process, non-practical equipment, and setup have to configure . The non-scanning probe methods, such us microwave thermography method[12]requires an infrared camera and knowledge of the basic principles of thermography based on the detection of infrared irradiation. In the TEOIM system, the working principle is detecting visible polarized light, which makes the measurement simple.

In this paper, we investigate the phenomenon of microwave heating in the mesh-patterned ITO conductive layer and show the images of heat distribution for different structural types of ITO. The measurements show that the microwave heating mechanism depends on the orientation of the mesh-pattern and the electromagnetic wave polarization.

## 2. Materials and methods

The experimental setup and measurement principle are shown in Fig. 1.The optical indicator (OI) was the glass substrate coated by a 100*nm* ITO thin film for the heat absorption. A microwave signal was generated by a synthesized sweeper (*HP*83620*A*) at the frequency 12*GHz* by 0*dBm* power and then amplified up to 35*dBm* by a power amplifier (*ZVE* – *W* – 183+). The generated microwave signal was transmitted by a rectangular waveguide (10.16*mm* × 22.86*mm* aperture) and interacts with the ITO thin absorbing layer placed in front of the waveguide. 12*GHz* was chosen as an optimal frequency in accordance with the oscillator model (*WR*90,*TE* mod). In order to decrease the noise level and increase the reflection of light, we provided a 1*mm* ceramic plate between the rectangular waveguide and the OI. With this configuration, we have a uniform and monochrome view in a visible area of the camera.

The TEOIM setup is based on the polarized light microscope system [8]. Light was emitted by the light emitting diode (*LED*;  $\lambda = 530nm$ ). The polarization state of the incident light is modulated into circular polarization by a sheet polarizer (90°) and a  $\lambda/4$  wave-plate (45°) (Fig. 1). The incident circular polarized light is reflected from the OI and passes through a second linear polarizer (analyzer) (0° and 45°), and light was finally recorded by a CCD camera (1024*px*×768*px*).



Figure 1.Schematic illustration of visualization system.

When the microwave signal is applied the conductive layer of OI heats up. After being reflected, the circularly polarized incident light changes to an elliptically polarized state due to the photoelastic effect of the glass substrate caused by thermal stress [13].We detected the linear birefringent (LB) distribution images by choosing the analyzer orientation to be  $0^0$  or  $45^0$ . By solving the inverse problem of the mechanical stress formation, one can calculate the initial heat distribution causing those deformations:

$$q = C \left( \frac{\partial^2 \beta_1}{\partial x^2} - \frac{\partial^2 \beta_1}{\partial y^2} + 2 \frac{\partial^2 \beta_2}{\partial x \partial y} \right), \tag{1}$$

where, q is the heat source density, C is a constant parameter related to physical properties of the OI, and the wavelength of the light source,  $\beta_1$  and  $\beta_2$  is the linear birefringence distribution image related to the normal and shear stresses of the OI, respectively. The calculated heat distribution in our experiment will correspond to the absorbed microwave power by the ITO[14].

Mesh patterned ITO coated glass with different structural types of conductive thin layers was made for visualization. Structures were patterned by the laser ablation technique. Figure 2 (a), (e), (i), and (n) are an optical image of optical indicators. The geometries of patterned ITO are shown in Fig. 2(b), (f), (k), and (o). Sample S1 is ITO coated glass with a uniform conductive layer. Sample S2 has only one conductive line with *1mm* width. S3 and S4 are arrays of conductive lines where lines of the S3 indicator are not connected but in the case of S4 the lines are connected after every *4mm*. The width of the conductive lines is 0.14*mm* and the distance between the lines is 0.06*mm*.



**Figure 2.**(a), (e), (i), and (n) The optical image of indicators with (b) (f) (k) (o) structural type, respectively. Thermal distributions in sample when the direction of alternating electric field coincides with (c) (g) (l) (p) *y*-axis, and (d) (h) (m) (q) *x*-axis. Dashed white rectangles show the orientation of the waveguide.

# 3. Results and discussion

ITO coated glass has been placed in the front of a rectangular wave guide to explore the microwave heating behavior of a thin conductive film. The microwave heating process can be divided into volumetric heating (i.e., dielectric loss heating) and surface heating (i.e., eddy current heating) [12]. For conductive materials, like metals and carbon fiber composites, microwave heating is dominated by eddy current heating. Since ITO is electrically conductive, the principle microwave heating is eddy current heating. Energy is radiated to the thin, conductive surface by microwaves, an alternating electric field is generated, and then induced surface currents are excited from the alternating electric field resulting in an alternating magnetic field. Next, a vortex electric field is generated by this alternating magnetic field; the vortex electric field promotes the movement of electrons which will generate Joule heat inside the metallic layer. Finally, the conductive material is heated by Joule heat as shown in Fig. 2 (c) and (d). These two images are the results of microwave heating distribution in the S1 sample. Since the S1 sample has a uniform conductive surface, in both cases, detecting the heat distribution is possible, when the electric field is perpendicular and parallel to the x-axis, respectively. Sample S2 contain only one conductive thin line with a width of 1mm. In this case, when the conductive line and electric field polarization are perpendicular to each other, the ITO line is not heated by the microwave (Fig 2 (g)). Fig. 2 (h) shows the microwave heat distribution in one conductive line, where alternating electric field polarization and the direction of the ITO line are coinciding. The intensity scale was normalized with a different range of value. The maximum value of the intensity scale is about ten times higher. It means that the line strongly heats up when the area of the conductive surface is smaller and the microwave field is localized on the conductive line. For the S3 sample results are predictable.S3 contains an array of conductive lines. Again, the surface is not heated when the conductive direction is perpendicular to the direction of E-field polarization (Fig. 2 (1)). The pattern of microwave heat distribution is detectable when the directions of the conductive lines coincide with the E-field (Fig. 2 (m)). Unlike S3, all conductive lines in S4 are connected. The distances between connector lines are 4mm. For the configuration as in Fig. 2 (p) the connector lines are strongly heated up by the microwave. This configuration is comparable with the result of Fig. 2 (h) when E-field direction coincides with ITO conductive line. For these two images intensity scales were normalized in the same range. Figure 2(q) is similar to the Fig. 2 (m) with small noises caused by the connector lines. In conclusion, when the non-conductive direction is parallel to the electric field polarization, visualization did not show a heat distribution result: mesh-patterned ITO is almost not heated in this case.

## 4. Conclusion

The basic principle of microwave heating for the mesh-patterned ITO was discussed. We visualized the heat distribution in the ITO by anon-contact and non-destructive TEOIM visualization technique. According to experimental results, we found out that the microwave heating distribution is strongly changed depending on the orientation of mesh-pattern and electromagnetic field polarization. TEOIM exhibits great potential, including high resolution, high sensitivity and fast inspection for investigation of symmetric structural materials. This technique can be an important tool for the testing and analysis of material properties.

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