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## Phase-Sensitive and Fast-Scanning Laser Probe System for Diagnosis of High Frequency Acoustic Wave Devices

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### Abstract

This paper describes a phase-sensitive and fast-scanning laser probe developed by the authors' group for the diagnosis of acoustic wave devices used as a platform of highly sensitive sensors. Surface vibration is detected by the Sagnac interferometer, which is insensitive to low frequency vibration. From this feature, we can maximize the scanning speed without influence of low frequency vibration and sacrificing the signal-to-noise ratio of the measurement. It is demonstrated that high quality two-dimensional (2D) image of acoustic wave field patterns can be captured in minutes order. Currently the maximum applicable frequency is 2.5 GHz. Because of the phase sensitivity, the measured field in the space domain is readily converted into the wavenumber domain by the 2D Fourier Transform. It is also demonstrated how effective the wavenumber domain analysis is for the purpose.

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*Keywords:* Surface Acoustic Wave; Bulk Acoustic Wave; Laser Probe; Sagnac Interferometer; Radio Frequency; SAW; BAW

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### 1. Introduction

Currently, use of laser probing systems[1-8] is essential for the research and development of sophisticated radio frequency (RF) surface and bulk acoustic wave (SAW/BAW) devices, which are used widely in various communication systems and sensors[9].

For detecting acoustic vibration, the Michelson and Mach-Zehnder interferometers has widely been used[1-4]. The method detects surface vertical motion through the interference between two beams reflected by the vibrating surface and static mirror. The SAW/BAW field can be visualized by either scanning a laser beam-spot on the vibrating surface or by mechanically translating the device under test (DUT).

One of the drawbacks of these methods is that the sensitivity is independent of the frequency of the vibration, and that the whole system is occasionally affected by a low-frequency vibration caused by the scan. Therefore, the scanning speed is limited so that the mechanical disturbance is minimized[1-4].

This paper introduces a phase-sensitive and fast-scanning laser probe system developed by the authors' group, which is applicable to the diagnosis of RF SAW/BAW devices[10].

For the optical sensing, the Sagnac interferometer[11] composed of micro-optic elements is employed. Although the Sagnac system is able to detect vertical motion of vibration similar to the Michelson/Mach-Zehnder

interferometer, its significant difference is that owing to its intrinsic frequency dependence, RF surface vertical motion can selectively be detected free from the mechanical disturbance. From this feature, we can maximize the scanning speed without sacrificing the signal-to-noise ratio (SNR) and sensitivity of the measurement.

As a demonstration, the system is applied to the characterization of RF SAW/BAW devices operating in 2 GHz range. It is shown that high quality two-dimensional (2D) image of SAW/BAW field patterns can be captured in minutes order.

Because of the phase sensitivity of this system, the measured field in the real space ( $x$ - $y$ ) domain is readily converted to the wavenumber ( $\beta_x$ - $\beta_y$ ) domain by the 2D Fast Fourier Transform (FFT)[12]. It is also demonstrated how effective the wavenumber domain analysis is for diagnosis of RF SAW/BAW devices[13].

## 2. System Setup

Fig. 1 shows the basic setup of the Sagnac interferometer for detecting vertical motion [10,11]. A linearly-polarized laser beam launched from a laser diode (LD,  $\lambda_0=660$  nm,  $P_{\max}=120$  mW) is applied to a  $\lambda/2$  plate to adjust polarization of the incident laser beam  $45^\circ$  off from the base plane. The laser beam transmitted through the non-polarizing beam splitter (NPBS) is incident to the Sagnac loop composed two polarizing beam splitters (PBSs), two static mirrors and the  $\lambda/4$  plate.

From this arrangement, incident two beams circulate the Sagnac loop in opposite directions. Then two beams arrive at the specimen surface with small time difference  $\Delta_t$  while they arrive at the photo detector (PD, Newport AD-200,  $f_1=2.5$  GHz) simultaneously.

Let us assume that the surface of the DUT vibrates as a form of  $A_{RF}\sin(2\pi f_{RF}t)$ , where  $A_{RF}$  is the vibration amplitude, and  $f_{RF}$  is the frequency. Due to asymmetry of the Sagnac loop, the surface vibration causes optical phase difference given by  $4\pi\lambda_0^{-1}A_{RF}\sin(\pi f_{RF}\Delta_t)\cos(2\pi f_{RF}t)$ , where  $\lambda_0$  is the optical wavelength. Since  $A_{RF}$  is much smaller than  $\lambda_0$ , the PD output is proportional to the phase difference. Thus when  $\Delta_t$  is set at close to  $(2f_{RF})^{-1}$ , we can maximize the sensitivity and make the system insensitive to low frequency vibration. In the developed system,  $\Delta_t$  is fixed at 1/6 ns for all the measurement targets since the frequency dependence is not so obvious.

Two-dimensional fast-scan is carried out by the following procedure[8,9]. The translation stage moves continuously along the longitudinal ( $x$ ) direction between the specified starting and ending points. The high-precision linear scale attached to the stage outputs two-phase pulse trains every 40 nm movement. Then analog output signals of the detection circuit are acquired by the high-speed data-logger synchronously with the pulse trains. After one  $x$  scan is completed, the stage returns to the original position, moving simultaneously along the lateral ( $y$ ) direction at a given step. This process is repeated until the two-dimensional scan is completed. In the present system, the translation stage moves at its maximum speed of about 1.0 mm/s, and the sampling rate of 25 kS/s is theoretically achievable.

For the fast-scanning, high-speed heterodyne detection system was also developed [14]. It allows us to detect both amplitude and phase information of the output signal in high sensitivity upto 2.5 GHz.

The authors also developed a focus adjustment technique particularly for our laser probe[15]. The focus adjustment is carried out by the following procedure. First, the objective lens is manually adjusted into focus at three different points on a surface of a device, and the lens heights and their corresponding device positions are recorded. If the surface is flat enough, the relation between the lens height and surface position (inclination) can be modelled mathematically by the recorded data. Then, in accordance with the measuring position during the fast mechanical scanning, the height of the objective lens is controlled continuously by using the mathematical model. In practice, the lens height should be controlled monotonically to avoid problems occurring with the mechanical backlash.

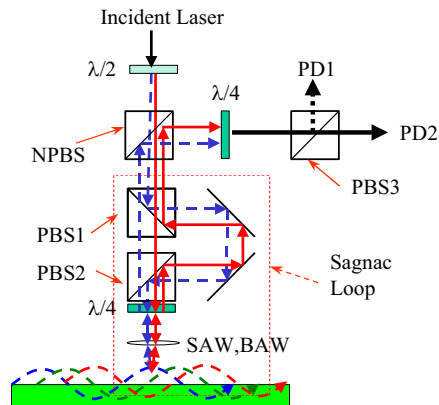


Fig. 1 Sagnac interferometer for detecting vertical vibration.

### 3. Measurement Examples

Effectiveness of this laser probe was examined by using an RF BAW resonator[16] operating in a 2 GHz range. Fig. 2(a) shows a surface image of the RF BAW resonator used as the DUT. In the oval region, a piezoelectric AlN thin film is sandwiched between two Ru electrodes, and the structure is floating on the Si substrate through the air gap. The major axis length of the resonance area is 115  $\mu\text{m}$ , and the minor axis length is 95  $\mu\text{m}$ .

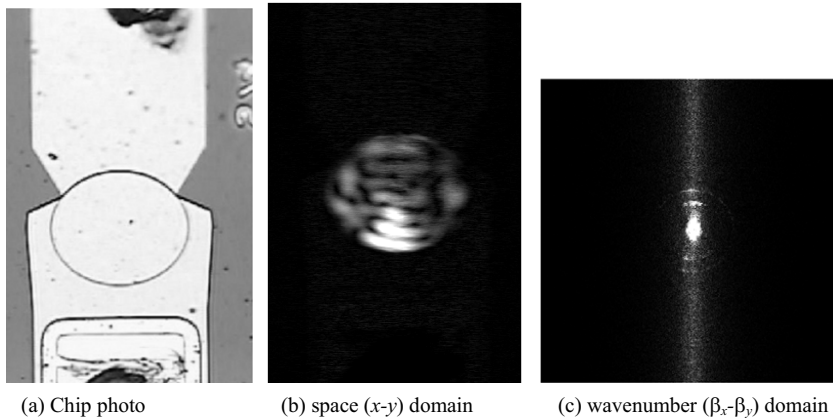


Fig. 2 DUT used for the experiment and measured field distribution (1.816 GHz)

Fig. 2(b) shows a 2D image acquired by the laser-probe at 1,860 MHz. It took about 17 minutes to scan  $500 \times 750$  ( $x \times y$ ) points with 0.4  $\mu\text{m}$  step. The transversal resonance pattern is clearly observed in the oval region where the resonator is placed. For this measurement, the RF input power was set at 13 dBm.

Next, the wavenumber domain analysis was performed by using the integrated software developed by the authors[17]. Fig. 2(c) shows the result in wavenumber ( $\beta_x$ - $\beta_y$ ) domain obtained by the FFT conversion of the data shown in Fig. 2(b). Horizontal and vertical directions represent  $\beta_x$  and  $\beta_y$  components, respectively, where the origin ( $\beta_x, \beta_y$ )=(0,0) is located in the middle. Several concentric circles are seen. Lack of the angular dependence indicates isotropic propagation of acoustic waves.

We extracted spectral data corresponding to each circle numerically, and the inverse FFT was applied to reconvert to real ( $x$ - $y$ ) space. Fig. 3(a) shows the result when only the inner portion in the FFT image was extracted and inverse Fourier transformed. The result is almost identical with Fig. 2(c). Since  $|\beta|$  is small, this portion corresponds to the thickness vibration of the longitudinal wave.

Fig. 3(b) shows the result when the image processing was applied to the second largest circle in the FFT image. It is seen that the energy of the mode leaks through the upper electrode of the resonator. Since  $|\beta|$  is relatively large, this circle corresponds the Lamb mode generated at the resonator

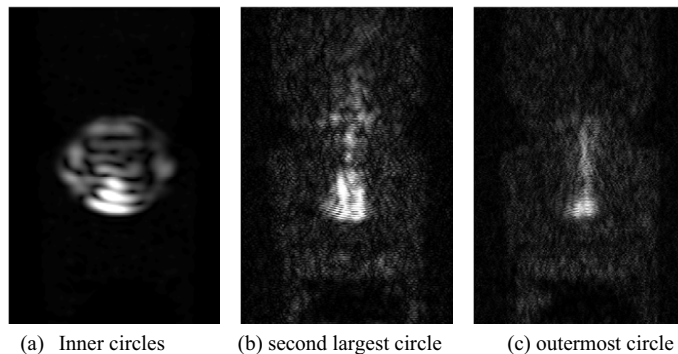


Fig. 3 Field distribution reconverted from extracted data.

edge. It should be noted that the AlN layer extends under the upper interconnecting electrode, which is not mechanically isolated from the AlN layer in the resonator area.

Fig. 3(c) shows the result when this image processing was applied to the outer-most circle in the FFT image. Lamb wave generation at the resonator edge is clearly visible also in this case.

#### 4. Conclusions

The paper introduced a phase-sensitive and fast-scanning laser probe system developed by the authors' group, and demonstrated how effective the system is for the diagnosis of RF SAW/BAW devices.

As a next step, we are attempting to speed up the measurement, to increase the maximum frequency, and to enhance the sensitivity. Calibration of the measured data, namely estimation of the absolute vibration amplitude, should be realized for further enhancement of the usefulness of this system.

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