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Millimeter-Wave Near-Field Imagery With A Bow-Tie Antenna

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Abstract—A near-field reflectometry experiment operating at 60 GHz is built in view of material and circuit inspection. The bow-tie near-field probe acts as a linearly-polarized electric dipole and allows strongly subwavelength resolution of $\approx \lambda / 150$. Its interaction with sample is shown polarization dependent and sensitive to both the local topography and the local dielectric constant or metal conductivity. Resonant and non-resonant probes are both evaluated.

Near-field scanning microwave microscopy (NFSMM) is a well-established technique to characterize material properties such as conductivity, dielectric permittivity or magnetic permeability at centimeter and millimeter wavelengths [1]. Owing to very small probe sizes as compared to wavelength, high spatial resolutions at the micron scale have been achieved [2], [3]. Fee et al. [4] first demonstrated the advantage of near-field probes built from tips bonded on open-ended waveguides and later Grober et al. [5] showed a great increase in resolution by using a bow-tie antenna, especially if this probe is resonant with the incident wavelength.

Very few NFSMM experiments have been proposed at mm-waves [6]–[9]. First two use a slit or 1D tapered waveguide as probes that do not allow for direct 2D imaging. Last two are close to GHz NFSMM experiments and use resonant tips. At 100 GHz, one of us previously used tip probes eventually associated to wire modes that guide the mm-wave up to the tip end of a near-field scanner [10].

In view of material and circuit inspection, we chose to develop a new NFSMM operating at 60 GHz. The experimental setup involves a Gunn source diode feeding a directional coupler connected to the near-field probe and we collect the reflectometry signal via a Schottky detector. Since we are interested in samples for which the imaging result may depend of the electromagnetic field ($E$ or $H$) and polarization [11], we manufacture our own probes on the basis of nano antennas attached to the waveguide. This process involves the assembly of small pieces obtained from laser cutting of thin noble metal sheets. As a proof of principle we first study the pyramidal tip or bow-tie antenna [5], [12].

Realizations of the 60 GHz $E$-probe are shown in Fig. 1. It was obtained by bonding two equilateral triangles fabricated by femtosecond laser cutting at the end of a WR15 waveguide. Final assembly is done manually and the air gap $g$ between tips is adjusted at the end of the process. Two such probes with two different gap sizes were fabricated.

First tests with the smallest probe of $g = 18 \mu$m are summarized in Fig. 2. The sample in that case is simply a GaSb substrate edge and we acquired the near-field reflected signal with a lock-in referenced to the $\mu$m vibration prescribed to the sample for various probe-sample distances $h$.

Although we have already obtained good images with a $g = 25 \mu$m probe producing $\approx 35 \mu$m spatial resolution by this technique [13], profiles of the upper row of Fig.2 are quite complicated and depict polarization-dependent features with a strongly varying oscillatory signal when crossing the sample edge at the shortest $h$ distances. This is a known behavior of optical near-field microscopy that was identified as the near-field intensity of a point dipole. The response then varies...
depending of the \( s \) or \( p \) polarisation and \( h \) [14]. Our results are in perfect agreement with these predictions, especially the oscillatory feature at edge crossing that occurs only for a \( p \)-polarized dipole.

Previous results were obtained with a non-resonant probe, \textit{i.e.} the probe was directly connected to the coupler. In the lower row of Fig. 2 we compare this behavior with that of a resonant probe obtained by introducing a E-H tuner between the coupler and the probe [13]. As seen the resonance increases the contrast by a factor of \( \times 3 \) but the oscillatory feature at the edge still remains for \( p \)-polarized field.

The benefit of these first experiments is to illustrate the non-trivial nature of topological near-field imaging in the mm-wave range. Extreme care must be taken in image interpretation as it strongly depends on the field polarization and \( h \).

In a second experiment we investigate NFSMM as an efficient technique for material characterization [1], [2]. We then use a bow-tie probe with gap \( g = 50 \mu \text{m} \) to measure the reflectivity of three \( 400 \mu \text{m} \) wide metallic lines on Si substrate. These lines were fabricated using different metals, namely Al, Au and Cu, and their DC conductivities were measured at \( 16.9 \times 10^6 \text{ S/m} \), \( 26.0 \times 10^6 \text{ S/m} \) and \( 24.4 \times 10^6 \text{ S/m} \) respectively. The near-field profiles are given in Fig. 3 for \( p \)-polarization and two heights, \( h = 5 \mu \text{m} \) and \( h = 15 \mu \text{m} \).

For both conditions, the detected signal suddenly increases above the line because of a change of imaginary part of the dielectric constant in the close vicinity of the probe tip. For the smallest \( h \)-value the profile is affected by the oscillatory feature already seen in Fig. 2 although it is less pronounced because of the largest gap size of the probe. Again a very small \( h \)-distance may induce spurious unwanted features, so we preferably use the measurement at \( h = 15 \mu \text{m} \) for a quantitative analysis because profiles are smoother and correspond to the homogenous nature of the metallic lines.

The near-field response registered for the Al line is measured at \( \approx 63\% \) of that measured for Au and Cu lines, both having very close conductivities. This ratio is in very good agreement with the 65% and 69% ratios calculated for the conductivities of Al-line \textit{vs} Au- and Cu-lines respectively. It confirms that our NFSMM allows quite accurate quantitative comparisons between local dielectric constants, even complex. At that point, absolute measurements are not possible without acquiring additional data that would solve the convolution between topography and conductivity in the measured near-field intensity, and in fact we take here benefit of the large probe-sample distance as compared to line thicknesses. Nonetheless, valuable local comparative measurements of conductivity or permittivity are possible with our NFSMM operating at 60 GHz.

We have described a new NFSMM operating at 60 GHz. A special effort is done in designing and fabricating the bow-tie antenna probe. Near-field intensity profiles clearly depict a true near-field detection with dipolar nature that may induce difficulties in image interpretation. It is also shown that this NFSMM is not only topological dependent and that measurements can be quantitatively related to the conductivity in the near-field.

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