Millimeter-wave scanning near-field microscope using a resonant waveguide probe

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We demonstrate a millimeter-wave surface imaging technique using a near-field scanning millimeter-wave microscope with a resonant standard waveguide probe. The metallic probe tip in the resonant waveguide was designed to couple energy into and out of the resonant waveguide. By measuring the shift of the resonant frequency and the change of the quality factor in the near-field zone, we obtained millimeter-wave near-field images of YBa2Cu3Oy thin films on MgO substrates with a spatial resolution better than 2 μm. © 2001 American Institute of Physics.

Nondestructive and noncontact imaging techniques with high resolution are very important and attractive subjects due to the possibility of applications in the electronic communication and information industries. For this purpose, various techniques have been developed enabling nano- through microscale imaging of materials, for example, scanning tunneling microscopy, atomic force microscopy, scanning near-field optical microscopy, and various microwave near-field microscopy methods. In this context, using the methods of near-field microscopy, the spatial resolution of microwave imaging can be dramatically increased. Recently, many groups have demonstrated a high spatial resolution imaging technique for conducting materials using a near-field scanning microwave microscope. Resolutions of several thousandths of a wavelength have been achieved by using designs, such as a circular aperture, a modulated scatter probe, an open waveguide, a small loop, and a microstrip resonator. For the millimeter-wave range, several designs were used, for example, a narrow resonant slit, a metal microslit probe, a thin-slit aperture in a convex end plate of a rectangular waveguide, and a small superconducting quantum interference device as a near-field probe at 77 K. The spatial resolution of these probes did not exceed 30–100 μm. However, instead of a slit probe, in the present work, we use a conventional sharpened metallic probe tip coupled to a waveguide resonator as a point-like evanescent field emitter and demonstrate a spatial resolution better than 2 μm at f = 30–39 GHz. The main advantage of this system is its high Q factor and sensitivity, which result in a high spatial resolution. Note that, to improve the spatial resolution, both the quality factor of the resonator and the sensitivity of the probe should be maximized. Another advantage is a high-transmission coefficient at the millimeter-wave frequency range, so the coupling to the sample is much more effective through the conventional metal probe tip than it is through a relative wide slit probe.

In the letter, we will demonstrate a millimeter-wave surface imaging technique using a near-field scanning millimeter-wave microscope with a resonant standard waveguide probe. The metallic probe tip in the resonant waveguide was designed to couple energy into and out of the resonant waveguide probe. We measured the resonant frequency shift using a heterodyne mixing technique as a function of sample-to-probe separation to determine the optimized regime of near-field operation. By monitoring the change in resonant frequency shift and Q as the tip scans over the sample surface, we observed the millimeter-wave near-field image of YBa2Cu3Oy (YBCO) thin films on a MgO substrate. The principal of operation can be understood by perturbation theory of the resonant cavity considering the radius of the probe tip and the charge distribution to depend on the sample–tip distance.

The experimental setup of our near-field millimeter-wave scanning microscope with operating frequencies f = 30–39 GHz is shown in Fig. 1. A rectangular resonant cavity consists of a length L = 10 cm of rectangular waveguide (ER-22) shorted at both ends. A fundamental TE10l mode was excited in the waveguide resonator and the transmitted

FIG. 1. Experimental setup used in performing millimeter-wave scanning near-field microscopy using a resonant waveguide electric probe.
wave was analyzed using a detector and a spectrum analyzer. A mechanically tuned Gunn oscillator was coupled to the waveguide resonator through an attenuator as a source and the other end was coupled to a crystal detector for power measurement and a mixer for a measurement of resonant frequency shift. The PIN switch is used to modulate the input signal for synchronous detection. A PC was used to record the data from the lock-in amplifier, the spectrum analyzer, and the controlled sample stage. The sample was mounted on an $x$–$y$–$z$-translation stage with a resolution of 0.02 $\mu$m. The sharpened probe tip in the rectangular waveguide resonator was designed to couple energy with the waveguide in a manner similar to that used for coupling with resonators. Note that these coupling methods are often used either for measurement of standing-wave patterns or to couple into or out of a resonator. For a resonant waveguide probe, we used an electric-field probe. If this is located at the point where the wire was parallel to the electric field, energy will be coupled into or out of the transmission line.

A metal probe of radius $r_0$ extended a distance ($x$) through the center of the top wall of a rectangular waveguide resonator operating in the TE$_{10}$ mode. According to perturbation theory, the fractional change in resonant frequency ($\Delta f$) can be written as

$$\frac{\Delta f}{f_0} = \frac{-2x\pi r_0}{abl},$$

where $a$ and $b$ are the lengths of waveguide, and $l$ is the cavity length. The denominator is the volume of the unperturbed resonant waveguide cavity while the numerator is the volume of the probe tip in the resonant waveguide cavity. This relation indicates that volume increase in a waveguide cavity will decrease the resonant frequency. For our experimental setup, inserting a probe tip in a resonant cavity can be considered as a change in volume of the cavity. If the probe tip is in the near-field zone, the propagating power of the TE$_{10}$ mode will be perturbed by small changes in electric impedance due to the interaction between the tip and the conducting surface. If the TE$_{10}$ mode is the only propagation mode in the waveguide, the mode carries the average power $P$, which can be written as $P = I^2 R_{\text{in}}/2$, where $I_0$ is the terminal current at the probe tip and $R_{\text{in}}$ is the input resistance into the probe tip. The input resistance from the probe tip can be written as $R_{\text{in}} = bZ_1/a$, where $Z_1$ is the wave impedance. The propagation amplitude in a resonant cavity may be varied by the small change in input resistance of the probe tip. By measuring the changes in input power and the resonant frequency changes while scanning the surface, it is possible to map the electrical properties of conducting surfaces.

In order to achieve higher coupling between the probe and the resonant waveguide, we adjusted the insertion length ($x$) of the electric probe in a resonant waveguide at frequency $f=36$ GHz. As can be seen in Fig. 2, for $x=0.3b$, the detector output shows monotonous behavior. As the insertion length increases, the slope of the detector output shows a sharp decay. As expected, the change in detector output increases as the insertion length $x$ of the probe in the resonant waveguide increases. This fact indicates that a larger $x$ gives the probe greater sensitivity. If we consider the tip geometry depending on the sample–tip distance, according to Tabib-Azar, Katz, and LeClair, the sensitivity of the probe can be written as

$$S_d = \frac{\alpha A_{\text{eff}} f_0}{C_0 d^2},$$

where $A_{\text{eff}}$ is the probe tip’s effective interaction area, $C_0$ is the coupling capacitance, $d$ is the distance between the probe tip and the sample, and $\alpha$ is a coupling factor dependent on the cavity–probe geometry. The sensitivity has $1/d^2$ dependence on the distance between the probe tip and sample. Using Eq. (2), the theoretical fit to the experimental data is shown in the inset. The radius of the probe tip in this case was 5 $\mu$m.

When the object is placed in the vicinity of the probe, the reflection coefficient of the probe tip in the resonator is changed. Here, both the resonant frequency and detector output are affected by the presence of the tip–sample interaction. The change in resonant frequency in this case depends on the changes in electric impedance due to the interaction between the tip and conducting surface. In order to observe the dependence of resonant frequency upon the tip–sample separation, we measured the mixing signal of the detector output using a millimeter-wave receiver system. The millimeter-wave receiver system consisted of a local oscillator with a tunable Gunn oscillator at center frequency $f_{\text{LO}} = 37$ GHz and a mixer. It served the function of down-converting the resonant frequency to an input frequency (IF). A spectrum analyzer traced the down-converted mixing signal with input frequency $f_s = 35.289$ GHz. Figure 3 shows the mixing signal as a function of sample–tip distance and the mixed IF signal with $f_{\text{IF}} = 1.711$ GHz is shown in the inset. The insertion length of $x$ of the probe tip was $x = 0.8b$. This heterodyne signal indicates the response to the resonant frequency shift depends on the sample–tip distance.
This trend can be also understood in terms of the perturbation in the resonant cavity. The observed resonant frequency shift was about 30 MHz. This frequency shift was a larger value than that observed in the near-field microscope in the microwave range. The observed mixing data also show a 1/d^2 dependence on the distance between the tip and the sample.

Figure 4 demonstrates a 36 GHz image of a patterned YBCO thin film with a linewidth of 20 µm and a thickness of 50 nm on a MgO substrate. The sample–tip separation was 2 µm. The tip radius and the insertion length were about 5 µm and 0.8b, respectively. Figure 4 shows a one-dimensional intensity variation along the arrow line a–b and the scan image is indicated in the inset. From these results, the spatial resolution is estimated to be 2 µm (the width of the observed full width at half maximum, 22 µm, minus the strip linewidth, 20 µm). In addition, as expected, a direct correlation between spatial resolution and the distance d was observed. As the distance d decreased, the spatial resolution increased as the sensitivity increased and has 1/d^2 dependence behavior. Note that it may be also expected that spatial resolution would be increased as the tip radius decreases and the coupling between the probe and cavity increases. Detailed experiments on the relation between probe tip and spatial resolution are underway.

In summary, we have demonstrated a millimeter-wave scanning near-field microscope with a resonant waveguide probe. The metallic probe tip in the resonant waveguide was designed to couple to the resonant waveguide. By measuring the shift of the resonant frequency and the change of detector output in the near-field zone, we obtained scanning millimeter-wave images of YBa2Cu3O6 thin films on MgO substrates with a spatial resolution better than 2 µm. These results indicate that the near-field imaging microscope using a standard waveguide probe has potential as a near-field imaging technique in the millimeter-wave range. Our future efforts include extending our measurement to lower temperature.

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