Millimeter-Wave Active and Passive Microscopies
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Abstract—Millimeter-wave scanning near-field microscopies operating in the active and passive modes are investigated to enhance the sensitivity attainable in these microscopic imaging techniques. For active microscopy, a knife blade with a tip radius of 6 μm and a width of 8 mm was used as a near-field probe. Experiments performed at 60 GHz show that this can enhance the signal intensity by ~20 dB compared with an equivalent metal tip probe. For passive microscopy, a tapered slit-type probe featuring no cutoff was used as a scanning probe. Experiments performed at 50 GHz at various sample temperatures show that our passive microscopy system can successfully image thermal radiation, even in the low temperature range where passive imaging systems in the infrared region are ineffective.

I. INTRODUCTION

Millimeter-wave imaging technologies can be classified into active and passive methods. The former detects transmitted or reflected radiation from a sample using an external millimeter-wave source. The latter observes weak thermal radiation emitted from a sample. The spatial resolution achievable with millimeter-wave imaging systems using conventional optics is limited to below the wavelength of its operating frequency due to diffraction effects. The recent development of scanning near-field microscopy has successfully overcome this resolution barrier by employing sub-wavelength apertures or sharp tipped structures as near-field probes [1]. In comparison with optical waves, the benefit of using radio waves such as microwaves, millimeter waves, and terahertz waves in scanning near-field microscopy lies in the promise of new types of material contrast. A good example is the mapping of electronic transport properties in semiconductors and in biological systems [2]–[5].

We report here the use of a knife blade as a scanning probe for millimeter-wave active microscopy, and of a slit-type probe utilizing a rectangular metal waveguide for passive microscopy in order to improve the sensitivity attainable in these microscopy formats, and hence to reduce the measurement times required to record near-field images. Since these two types of probes have line-like tips for the detection of near-field signals, a scanning method and an image reconstruction algorithm based on computerized tomography are adopted for deconvolution of the tip shapes of the probes to obtain 2-D near-field images.

II. ACTIVE MICROSCOPY USING A KNIFE BLADE

At higher frequencies than millimeter waves, especially in the terahertz and infrared regions, a sharp metal tip is widely used as a scanning probe [4], [6]–[12], [19]. The metal tip is held close to the surface of the sample and evanescent waves are converted to propagating waves. The radiation scattered from the incident radiation is measured for imaging. The metal tip probes are easy to fabricate and permit extreme sub-wavelength resolution because of the simplicity of their structure. However, the signal intensity of the scattered waves is relatively low, and therefore can be submerged within a large background signal.

Fig. 1 is a schematic drawing of our millimeter-wave scanning near-field active microscopy using a knife blade. Since the knife blade is wider than the metal tip (and hence the interaction area between the tip and the sample is larger), an improvement in the signal intensity of the scattered waves is expected. Radiation at 60 GHz (λ = 5 mm) from a circular horn antenna with an aperture diameter of 10 mm is incident on the knife blade probe with p-polarization. The distance between the aperture of the circular horn and the probe tip is 8 mm. Scattered waves from the probe are collected by a polyethylene lens and are then received by a standard-gain rectangular horn antenna. The acceptance angle of the receiver is 20°. Both antennas are connected to waveguide-to-coaxial transformers (not shown in Fig. 1) that are connected via coaxial cables to a vector network analyzer (VNA: Agilent 8510C) to measure the complex transmission coefficient from port 1 to port 2, S21. The sample to be imaged is placed on a sample mount consisting of a hemispherical glass lens and an antireflection layer [13]. The probe-to-sample separation is adjusted between Z1 and Z2 by using a piezoelectric transducer (PZT) and a laser displacement sensor, as depicted in the inset of Fig. 1.

A scanning method and an image reconstruction algorithm based on computerized tomography for 2-D image reconstruction were used in order to facilitate deconvolution of the tip shape of the knife blade [13], [14]. The sample is...
scanned linearly for different sample-rotation angles by a scanner using linear and rotational motor-driven stages. A PC is used to control the scanner and the PZT. The PC saves raw data collected as projections from the VNA, and also executes image reconstruction by implementing a filtered back-projection (FBP) algorithm [15]. Since the raw data that is acquired consists of complex numbers, intensity and phase images are obtained after image reconstruction. For each of the scanning points, two values of $S_{\text{Si}}$ at different tip-to-sample separations, $Z_t$ and $Z_v$, were acquired and the vectorial difference between them $\Delta S_{\text{Si}}$ was calculated and recorded in order to extract pure near-field information by eliminating unwanted background signals. $Z_t$ and $Z_v$ were set at 1 µm and 7 µm, respectively. A commercially available knife made of stainless steel (OLFA Art knife XB157H) was selected for use as the near-field probe. The knife was cleaned and then electroplated with gold. The width and the tip radius of the probe were 8 mm (1.6 λ) and 6 µm (~ λ/1000), respectively.

We demonstrated that the intensity of the near-field signal is enhanced by 15.6 dB compared with an equivalent metal tip probe with an equivalent tip radius and the same antenna length as the width of the knife blade, and that image resolution approaching the dimensions of the tip radius of the knife blade can be achieved [16]. Since the knife blade and the sample form a corner reflector, further enhancement in the signal intensity can be expected by enhancing the strength of the near field interacting with the sample when a partial reflector is inserted in the incident beam path in order to incorporate a resonator comprising a partial reflector and a corner reflector in the illumination optics. We positioned a high-resistivity mirror-polished silicon (Si) plate at the aperture of the circular horn antenna, as shown in Fig. 1. The thickness of the plate was adjusted to be 440 µm in order to ensure maximum reflection.

Fig. 2 shows reconstructed images obtained with and without the Si plate. The sample consisted of patterned aluminium (Al) on a quartz substrate, as depicted in the inset of Fig. 2(a). Fig. 2(a) is a plot of the intensity of the near-field signal $|S_{\text{Si}}|$ as a function of the distance between the Si plate and the corner reflector with the probe tip positioned above the center of the sample, as depicted by the dotted line in the inset. This is the relative distance to the point of closest approach of the Si plate to the reflector. This result indicates that this configuration works as a resonator. Data acquisition for the images was performed at the distance that gave the maximum signal intensity in Fig. 2(a). As shown in the intensity images in Fig. 2(b) and 2(c), which accurately reflect the structure of the sample, by incorporating this resonant structure in the illumination optics, the image intensity corresponding to the quartz dot improves by ~2 times (6.0 dB). Since the image intensity is proportional to the signal intensity, this result demonstrates that the intensity of the near-field signal is enhanced by more than 10 times (20 dB) when using a knife blade probe compared with an equivalent metal tip probe [16].

![Image](https://via.placeholder.com/150)

**Fig. 2.** Comparison of reconstructed intensity images obtained with and without the Si plate. (a) Intensity of the near-field signal $|S_{\text{Si}}|$ when the distance between the Si plate and the corner reflector was varied. (b) Reconstructed intensity image without the Si plate. (c) Reconstructed intensity image with the Si plate. The raw data sets for the images were obtained under experimental conditions in which the sampling interval for the linear scan was 10 µm, the number of sampling points was 121, the angle interval for the rotational scan was 1.5˚, and the total number of projections was 121. The image size is 1.2 mm × 1.2 mm.

### III. PASSIVE MICROSCOPY USING A SLIT-TYPE PROBE

We proposed a new type of radiometric imaging technique, known as millimeter-wave passive microscopy, which permits passive imaging with sub-wavelength spatial resolution by using scanning near-field microscopy, and demonstrated the feasibility of this technique at Ka-band (26.5-40 GHz) frequencies at sample temperatures higher than room temperature using a direct receiver [17]. Imaging of thermal radiation with sub-wavelength spatial resolution using scanning near-field microscopy has also been reported in the infrared region [18], [19]. The benefit of using millimeter-wave thermal radiation in this kind of scanning near-field radiometric measurement lies in the promise of achieving thermal imaging in the low temperature range (well below room temperature) where passive infrared imaging systems are ineffective (~230 K). This stems from Planck’s law.

Fig. 3 shows a schematic drawing of our passive microscope system using a slit-type probe operating at a millimeter-wave frequency of 50 GHz (λ = 6 mm). The probe can be operated over a wide frequency range with high transmission efficiency as a near-field probe. The height of a WR-19 rectangular waveguide for U-band (40-60 GHz) frequencies is reduced linearly to form a slit aperture at the tip. The dimensions of the slit aperture were 100 µm in height (h) and 4.8 mm in width (w). The probe-to-sample separation was adjusted to be 10 µm. The experiments were performed in collection mode. The propagating and evanescent components of the millimeter-wave radiation thermally-emitted from the
sample were converted via the slit aperture into propagating waves in the probe waveguide, which were then detected by a receiver. The sample to be tested was placed on a copper sample mount. The mount was temperature-controlled using liquid nitrogen (N₂) as a coolant coupled with an electric heater in combination with a temperature controller operating in on/off or PID mode. The temperature of the mount was measured using a thermocouple built into it just beneath the sample. Because the measured temperature can be considered as being almost equal to that of the back surface of the sample in contact with the mount, we refer to this measured temperature as the sample temperature. The measurement system (except part of the receiver) was sited in a chamber in order to prevent the sample surface from becoming frosted. The chamber was filled with dry N₂ gas evaporated from liquid N₂.

The inset in Fig. 3 shows a block diagram of a superheterodyne receiver, which operates in a Dicke-switched mode. The input to the receiver was switched by a PIN diode switch between the probe and a termination with a repetition frequency of 1 kHz. The output port of the switch was connected to a low-noise amplifier, LNA (Gain: 50 dB, NF: 3.2 dB) via an isolator. The remainder of the millimeter-wave and microwave components that comprise the receiver were installed outside the chamber. The output of the LNA was down-converted to an IF signal with a center frequency of 1 GHz by a single-sideband mixer. The IF bandwidth was 400 MHz. The IF signal was amplified and then detected using a diode detector. The voltage difference between the outputs from the detector when the probe and the termination were connected was measured by using a lock-in amplifier. The same scanning method and image reconstruction algorithm as those employed for the active microscopy were used to acquire 2-D images. A 2-D spatial resolution that is equivalent to the height of the slit aperture can be achieved [14]. Because the measured data are proportional to the line integral of the power of the thermal radiation emitted from the sample in the width (w) direction of the aperture, the image reconstructed by the FBP algorithm is a reflection of the 2-D power distribution of the thermal radiation in the field of view [17].

Figs. 4(a) and 4(b) show a schematic of the sample used in the experiments. The sample was a mirror-polished, 2.5 mm thick, 30 mm diameter substrate made of radar-absorbing material (RAM) with a diameter of 1.0 mm, and a 1.5 mm deep hole. The refractive index of the RAM as measured at 50 GHz by a transmission measurement technique in free space was 3.20 – 0.51. The emissivity of the sample was calculated to be 0.72 from this refractive index. Fig. 4(c) shows one-dimensional scans of the sample when the sample temperature was varied from 300 K to 160 K. The step-size that was used for the linear scans was 50 μm. The output voltage of the lock-in amplifier is plotted in this figure. The observation of a negative output voltage means that the output of the diode detector is smaller when the probe is connected than when the termination is connected. This result indicates that the signal intensity decreases as the sample temperature becomes lower. We confirmed from this result that the signal intensity is proportional to the sample temperature, indicating that the probe can detect millimeter-wave thermal radiation emitted from the sample. By using the DC output voltage of the diode detector when the termination was connected (-10.9 mV), the emissivity of the sample (0.72), and the result shown in Fig. 4(c), the system noise temperature of the receiver system was calculated to be 8000 K using the Y-factor method, resulting in the temperature resolution of the receiver being 0.8 K when the integration time was set to 1 second. These calculated values are not good enough for a sensitive radiometric receiver. This is due to the relatively low power transmission efficiency of the probe that was used in the experiments (27%). The temperature resolution and also the spatial resolution can be improved, for example, by attaching a micromachined silicon chip that we have developed to the tip of a slit-type probe. The chip works as a tuning circuit to enhance the transmission efficiency and has a slit aperture with a smaller height than that of the original slit-type probe to achieve better spatial resolution [20].

Reconstructed millimeter-wave images when the sample temperature was varied from 260 K to 200 K are shown in Fig. 5(a). The hole in the sample, whose diameter is less than the
wavelength of the 50 GHz radiation, can be clearly seen in these images. It can also be noted in these images that the image intensity becomes smaller as the sample temperature becomes lower. Fig. 5(b) plots image intensities for three distinct points of the images shown in Fig. 5(a) as a function of the sample temperature. This result shows that the image intensities, as well as the signal intensities, are proportional to the sample temperature, and that the straight lines fitted to the image intensities for the three points intersect at the laboratory temperature of 300 K at which the microscope system was in thermal equilibrium.

IV. CONCLUSIONS

A novel type of millimeter-wave active microscopy using a knife blade as a scanning probe was investigated. Experiments performed at 60 GHz ($\lambda = 5$ mm) showed that 2-D millimeter-wave images with subwavelength spatial resolution can be successfully reconstructed and that the signal intensity is enhanced by ~20 dB compared with an equivalent metal tip probe. The format of the active microscopy investigated here should enable samples to be observed with higher sensitivity than that achieved using a metal tip and should reduce the measurement times required to record near-field images.

We demonstrated near-field imaging of thermal radiation by millimeter-wave passive microscopy using a slit-type probe, even in the low temperature range where passive infrared imaging systems are ineffective. Since this microscopy format enables thermal imaging with subwavelength spatial resolution, it should be a potential candidate to complement the imaging function of infrared thermography for microscopic examination in the low temperature range.

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