IEICE Electronics Express, Vol.1, No.6, 144–149

A new object mounting structure for use in millimeter-wave scanning near-field microscopy

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Abstract: An object mounting structure has been developed for use in millimeter-wave scanning near-field microscopy in order to efficiently reduce both unwanted signal fluctuations caused by surface waves within the object to be imaged and reflections from outside the object. The object mount comprises a hemispherical lens with an anti-reflection (AR) layer covering the spherical surface. An object mount for use at a millimeter-wave frequency of 60 GHz has been designed and fabricated. Experiments performed at 60 GHz show that signal fluctuations resulting from the above two factors can be dramatically reduced using this object mounting structure.

Keywords: millimeter waves, scanning near-field microscopy, object mounting structures, hemispherical lenses, anti-reflection (AR) layers.
Classification: Microwave and millimeter wave devices, circuits, and systems.

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DOI: 10.1587/elex.1.144
Received May 18, 2004
Accepted May 28, 2004
Published June 25, 2004

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1 Introduction

Microwave and millimeter-wave scanning near-field microscopy have recently attracted much attention as useful tools for investigating material properties, testing circuit performance and failure analysis [1]-[6]. In this technique, a fine coaxial cable with a sharpened central conductor protruding from the outer shielding, microstrip- and strip-lines, or small circular and slit-like aperture in a conducting screen are used as near-field probes. The object to be tested is placed in close proximity of the tip of the near-field probe to achieve sub-wavelength spatial resolution nearly independent of the radiation wavelength λ. To date, a 50 nm resolution has been reported on a sophisticated microscope system operated at a microwave frequency of 2.8 GHz ($\lambda \sim 0.1$ m) [6]. Although the signals obtained from scanning near-field microscopes are strongly affected by the interaction between the near field of probe tip and object, taking place within a volume much less than the radiation wavelength, they are also affected by far field interaction between the propagating waves emitted from the probe and object structures possessing dimensions comparable with, or larger than the wavelength.

In 1981, Rutledge and Muha [7] proposed an efficient quasi-optical coupling structure between free space and a transmitting or receiving antenna array. We have adopted this structure for use in millimeter-wave scanning near-field microscopy in order to efficiently reduce unwanted signal fluctuations caused by the far field interaction, i.e., by surface waves within the object to be imaged and reflected waves from outside the object. The object mount developed here consists of a hemispherical glass lens, incorporating an anti-reflection (AR) layer. The design of the object mount for scanning near-field microscopy at a millimeter-wave frequency of 60 GHz is described, and the performance of the fabricated mount is reported.

2 Object Mounting Structure and Design

Fig. 1 shows (a), a schematic of our millimeter-wave microscope system and (b), a cross section of the object mounting structure proposed here. The object mount is a hemispherical glass lens with an AR layer covering the

DOI: 10.1587/elex.1.144
Received May 18, 2004
Accepted May 28, 2004
Published June 25, 2004

spherical surface of the lens. An object is placed on the flat surface of the hemispherical lens. Experiments have been performed at a millimeter-wave frequency of 60 GHz (λ : 5 mm) in reflection mode. The near-field probe used is of the tapered slit-type probe. The height of the standard waveguide (WR-19) is tapered down to 80 μm to form a slit aperture with dimensions of 4.8 mm ($\sim\lambda$) $\times$ 80 μm ($\sim\lambda/60$) at the probe apex. The probe is connected to a vector network analyzer (HP85106) via waveguide-to-coaxial transformers to enable measurement of S_{11} signals, which are then reconstructed into 2D near-field images. The probe-to-object separation is 10 μm. To achieve sub-wavelength resolutions in all directions, the object to be imaged is scanned linearly at different object-rotation angles. Signals acquired during these linear scans are then processed into 2D images using an image reconstruction code based on computerized tomograpy [8]. The following sections describe the design of this object mounting structure.

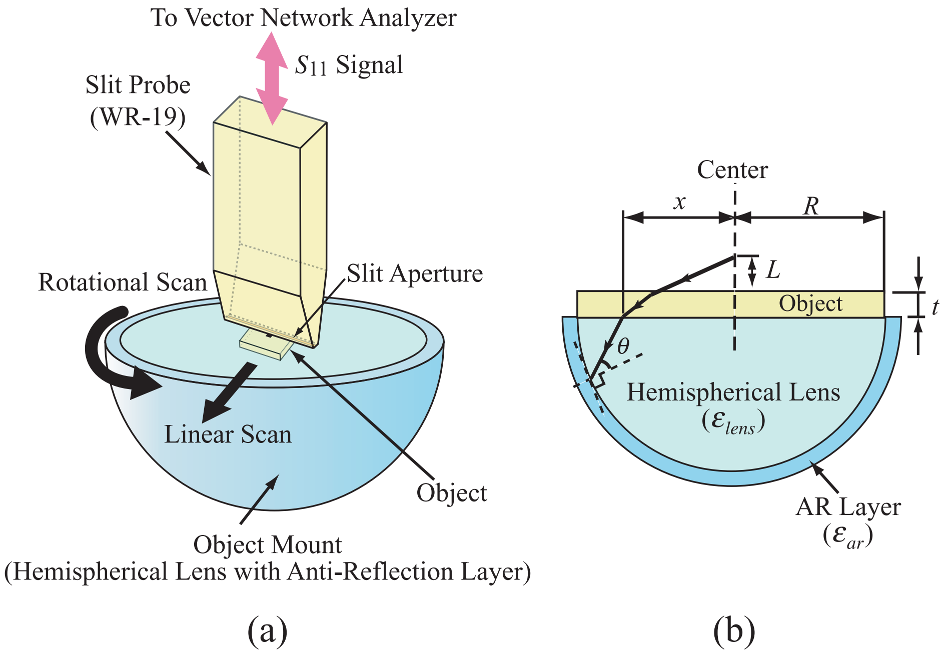


Fig. 1. (a) Schematic of the millimeter-wave microscope system using a metal slit-type probe. (b) Cross section of the object mounting structure.

2.1 AR layer

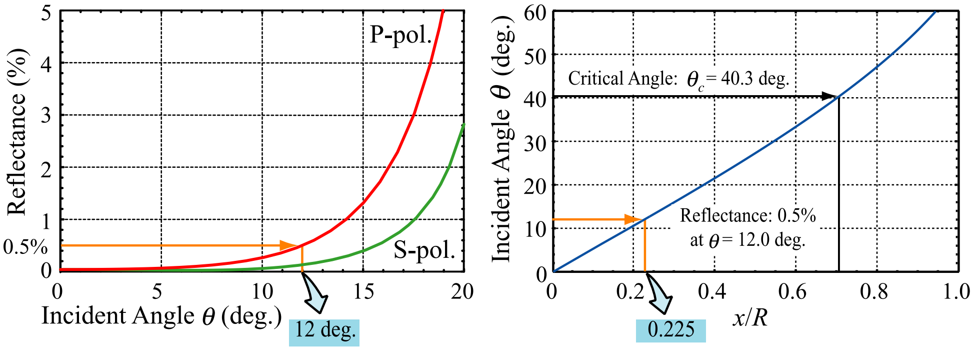
The AR layer is a quarter-wave transformer, preventing reflection from the lens surface. BK7 has been selected as the lens material. This material is a variety of borosilicate glass, with a dielectric constant ε_r of 6.19-j0.01, selected for its ease of mechanical processing and relatively high dielectric constant. In this case, the dielectric constant of the AR layer of 2.49-j0.02 is ideal for achieving perfect matching between the lens and air. After testing several materials, polymethylmethacrylate (PMMA, $\varepsilon_r = 2.56$-j0.03) has been found to be a suitable material for use as a material for the AR layer. The thickness

DOI: 10.1587/elex.1.144
Received May 18, 2004
Accepted May 28, 2004
Published June 25, 2004

of the AR layer is selected as 2.4 mm, being three quarters of the wavelength within the layer at ∼ 59 GHz. This ensures mechanical rigidity and prevents possible mechanical damage during the fabrication. Reflectances (reflection powers) of the AR layer at 60 GHz as a function of the incident angle θ of the radiation emitted from the probe aperture at the lens surface for P (TM) and S (TE) polarizations have been calculated and are shown in Fig. 2 (a). In the calculation, the *Fabry-Perot etalon* effect [9] is taken into account. It is considered that 0.5% reflectance is sufficiently small not to affect the measured S_{11} signal. With this constraint, it is found from Fig. 2 (a) that the incident angle should be less than 12 degrees. The next step of the design is to determine the lens radius in order to limit the incident angle to less than this 12 degrees.

2.2 Hemispherical Lens

As illustrated in Fig. 1 (b), the ray tracing method [9] is used to calculate the incident angle θ of the radiation at the lens surface. In Fig. 1 (b), x, R, L, and t are distance from the lens center, radius of the lens, probe-to-object separation, and thickness of the object, respectively. In the calculation, object is assumed to cover whole the flat surface of the lens. L and t are assumed to be 10 μm and 1 mm, respectively. The calculated results have revealed that the incident angle becomes greater as the dielectric constant of object is reduced. The incident angle as a function of x/R is plotted in Fig. 2 (b) using air ($\varepsilon_r = 1$) as the object. From this figure, x/R should be less than 0.225 to meet the requirement mentioned above, and also should be less than ∼ 0.7 to maintain the incident angle less than the critical angle θ_c of 40.3 degrees at the lens/AR layer boundary. As the dimension of object is usually 20 mm × 20 mm in our experiments, corresponding to $x = 10$ mm, the radius of the hemispherical lens has been determined to be 50 mm ($x/R = 0.2$).



(a) (b)

Fig. 2. (a) Calculated reflectance of the AR layer at 60 GHz as a function of the incident angle of the radiation emitted from the probe aperture at the lens surface for P and S polarizations. (b) Calculated incident angle as a function of x/R.

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3 Experimental Results

The object mount designed above was fabricated and tested. Fig. 3 shows one-dimensional scans of a uniform quartz plate with dimensions of 20 mm × 20 mm, 1 mm in thick, mounted, in turn, as an object, on a soda glass plate (70 mm × 70 mm, 5 mm in thick, $\varepsilon_r = 6.50$), a lens without an AR layer, and a lens with an AR layer (proposed object mounting structure). All the scans were taken at a millimeter-wave frequency of 60 GHz. A one-dimensional scan of an Alumina substrate with the same dimensions as the quartz plate, mounted on a lens with an AR layer, is also shown in Fig. 3. This scan shows that a surface wave propagates in the Alumina substrate, because Alumina has a higher dielectric constant ($\varepsilon_r = 9.48$) than the BK7 material of the hemispherical lens. It is found from this figure that, when using the object mounting structure proposed here, unwanted signal fluctuation vanishes completely, if the dielectric constant of the object is less than that of the material of the hemispherical lens.

In the experiment, only the reflected signal S_{11} was received and the transmitted wave from the object mount was absorbed using Eccosorb material. As the intensity of the transmitted wave is maximized by the AR layer, this object mounting structure can also be of use in transmission microscopy, in which transmitted wave from object is received and utilized for the reconstruction of near-filed images. We have developed a resonant slit-type probe to improve measurement sensitivity [10]. With this resonant probe, in con-

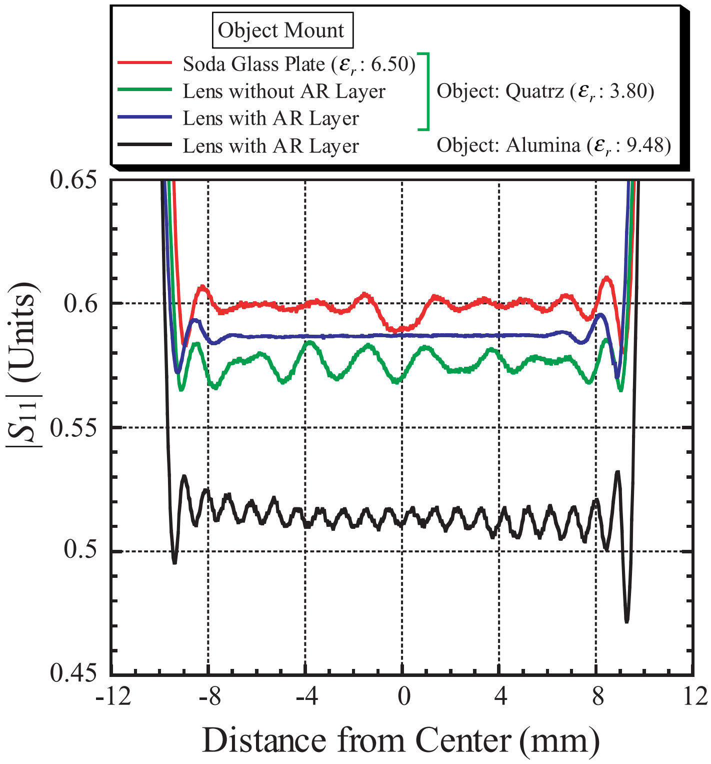

Fig. 3. Measurements of one-dimensional scans of uniform planar objects using different object mounting structures.

DOI: 10.1587/elex.1.144
Received May 18, 2004
Accepted May 28, 2004
Published June 25, 2004

junction with the above mentioned object mounting structure, it is estimated that a dielectric constant sensitivity $\Delta\varepsilon_r/\varepsilon_r$ of $\sim 3 \times 10^{-4}$ is achievable.

4 Conclusion

A new type of object mounting structure has been developed to reduce unwanted noise signals caused by both the surface waves in the object to be imaged and reflections from outside the object. The object mount was designed, fabricated and tested at a millimeter-wave frequency of 60 GHz. Experiments performed at 60 GHz show that signal fluctuations caused by these two factors can be dramatically reduced if the dielectric constant of the object is less than that of the material of the hemispherical lens.

The object mounting structure proposed here has revealed itself to be useful for millimeter-wave scanning near-field microscopy and may be suitable for use in characterizing the uniformity of planar dielectric and semiconductor substrates for various millimeter-wave components, with a sub-wavelength spatial resolution at the frequency of operation. This mounting structure can also be used in the optical region, where implementation of AR coating layer is much easier.

Acknowledgments

This work was supported in part by a Grant-In-Aid for Scientific Research, No. 15360181 from the Japan Society for the Promotion of Science (JSPS), the Support Center for Advanced Telecommunications Technology Research, Foundation (SCAT), Japan, and a Strategic Information and Communications R&D Promotion Programme (SCOPE) of the Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT), Japan.

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