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Narrow Resonant Double-Ridged Rectangular Waveguide Probe for Near-Field Scanning Microwave Microscopy

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Abstract – In this paper, we propose a narrow resonant waveguide probe that can improve the measurement sensitivity in near-field scanning microwave microscopy. The probe consists of a metal waveguide incorporating the following two sections: a straight section at the tip of the probe whose cross-section is a double-ridged rectangle, and whose height is much smaller than the waveguide width; and a standard waveguide section. The advantage of the narrow waveguide is the same as that of the quarter-wave transformer section i.e., it achieves impedance-matching between the sample under test (SUT) and the standard waveguide. The design procedure used for the probe is presented in detail and the performance of the designed resonant probe is evaluated theoretically by using an equivalent circuit. The calculated results are compared with those obtained using the finite element method (Ansoft HFSS), and consistency between the results is demonstrated. Furthermore, the performance of the fabricated resonant probe is evaluated experimentally. At X-band frequencies, we have measured the one-dimensional scanning reflection coefficient of the SUT using the probe. The sensitivity of the proposed resonant probe is improved by more than two times as compared to a conventional waveguide cavity type probe.

Keywords: Near-field scanning microscopy, Scanning probes, Resonant narrow probes, Double-ridged rectangular waveguide

1. Introduction

Scanning probes for nondestructive evaluation and noninvasive inspection in near-field microscopes have recently attracted a lot of interest, and cover frequency ranges spanning from microwave to optical regions [1-6]. However, the resolution of the imaging system is limited by the wavelength owing to the diffraction characteristic of the waves. A near-field scanning microwave microscope (NSMM) is capable of resolving objects much smaller than the wavelength of the excited wave by using the characteristic of the evanescent electromagnetic wave [1]. In the reactive near-field region of an antenna, the field is non-radiated and localized near the radiator. Therefore, this method can be used to generate evanescent waves and utilize them to implement a microscopic imaging system. The distance between the sample under test (SUT) and the probe is as small as possible to ensure that the SUT is in the reactive near-field region.

In most near-field microwave imaging systems, open-ended rectangular waveguides are used extensively as imaging probes [2, 5, 7, 8]. In the near-field region, the lateral resolution attainable with such probes is inversely proportional to the aperture area of the waveguide [8], i.e., as the aperture size decreases, the sensing area of the probe (or footprint) reduces; hence, small inclusions, defects, and cancers can be resolved in the captured image. In the waveguide-based near-field microwave imaging systems, the aperture of the waveguide is determined by the microwave band over which the probe operates, e.g., X, Ku, K, etc. Hence, there is an increasing demand for new imaging probes that are capable of providing higher spatial resolution than the standard rectangular waveguides while operating at the same frequency [9, 10]. Until now, a resonant slit-type probe and an end wall slot type probe have been proposed for use in the microwave band owing to the simplicity of their structures [5, 11, 12]. The probes have a narrow slot aperture with a height much less than the operating wavelength λ, and a width of the order of $\lambda/2$. These probes result in a high transmission efficiency owing to additional devices as the impedance-matching circuit, i.e., a resonant cavity or / and a screw tuner [11, 12].

In this paper, we propose a new type of narrow probe for the NSMM that can further improve the sensitivity of the measurement. The probe consists of a metal waveguide incorporating the following two sections: a straight section at the tip of the probe whose cross-section is a double-ridged rectangular waveguide (DRWG) and whose height is much smaller than the waveguide width; and a standard waveguide (WR-90) section. The advantage of a narrow DRWG is the same as that of a quarter-wave transformer i.e., to achieve impedance-matching between the SUT and the standard waveguide, thereby allowing high-sensitivity

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measurements. Since the matching section is not additionally constructed inside the probe, the probe itself is compact and does not require any additional tuning components, such as E-H tuners. Further, since there is no flat plate with a slot and screw holes at the tip of the probe, the cross-section of the proposed probe is smaller than that of a conventional probe as shown in Fig. 1.

Furthermore, in this paper, we propose that an equivalent circuit of the proposed probe can be modeled using transmission lines, shunt susceptance, and radiation admittance using scattering parameters obtained from the commercial finite element method(FEM) simulator, Ansoft HFSS. The optimum length of the open-ended DRWG is calculated using the obtained parameters at the operating frequency.

The characteristics of the probe, such as spatial resolution i.e., Full Width Half Maximum(FWHM) and reflection coefficient, are examined using a commercial FEM simulator and compared with those of the rectangular waveguide(RWG) probe with a ridge-loaded straight slot(RLSS), which has been used in our previous research [12].

In this study, one-dimensional scanning is conducted, and the measured reflection coefficients of the near-field scanning waveguide probe for a printed circuit board(PCB) with seven metallic strips of width 0.5 mm with a gap of 0.5 mm are presented.

2. Structure of the Open-ended DRWG Probe

In the developed NSMM, an open-ended DRWG probe is designed as a near-field scanning probe. Fig. 1(a) shows the block diagram of the traditional rectangular waveguide cavity probe with RLSS and Fig. 1(b) shows the block diagram of the proposed open-end ed DRWG probe without an impedance-matching section. The probe consists of an open-ended DRWG and a feed section of the RWG. The DRWG is composed of a double-ridged RWG with a ridge width w_r and a ridge gap g_r in an RWG of dimensions $l_s \times w_s$ [in mm^2]. The length of the open-ended DRWG is l_c. Table 1 shows the parameters of the proposed probe. The RWG used as the feed section is a WR-90 waveguide (width a, height b). The structure of the proposed probe is simple because there are no cavities, inductive iris, and plates with ridge-loaded slot unlike the conventional probe (Fig 1. (a)).

The open-ended DRWG is coupled through an interface between the feed RWG and the SUT for the matching of a

Table 1. Dimensions of the proposed probe

Parameters	a	b	l_c	d	l_s	w_s
Values (mm)	22.86	10.16	40.00	1.00	14.50	1.00
Parameters	w_r	g_r	w_{in}	a_o	b_o	$a_1(b_1)$
Values (mm)	12.50	0.50	7.90	22.75	10.00	40.0

probe. By adjusting the length of the open-ended DRWG when the probe points at the substrate portion of the PCB without a strip or patch, this probe can excite a specific resonant mode of the open-ended DRWG.

In order to improve the spatial resolution, we reduced the surface of the end wall of the DRWG section, such that it is smaller than that of the previous probe, expressed as follows:

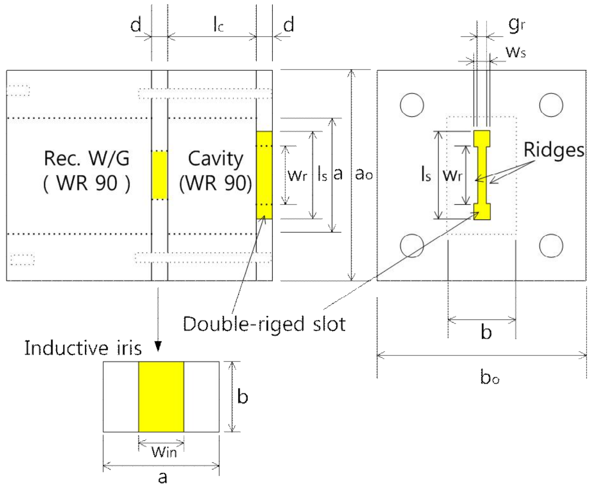
$$a_0 \times b_0(Fig. 1(b)) \ll a_0 \times b_0(Fig. 1(a)), \quad (1)$$

where $a_0 \times b_0(\text{Fig. }1(\text{b}))$ is 1600.0 mm^2 (40.0mm $\times$ 40.0mm), and $a_0 \times b_0(\text{Fig. }1(\text{a}))$ is 227.5 mm^2 (22.75mm $\times$ 10.0mm)

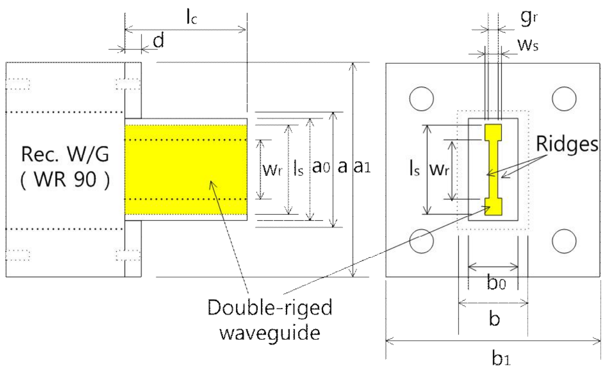
And the ratio of the height to the width of the DRWG is very small, expressed as follows :

$$w_s/l_s \ll 1 \quad (2)$$

The resonant length l_c of the open-ended DRWG for the dominant mode TE_{101} is influenced by the admittances of the two end interfaces, and is slightly smaller than $0.5\lambda_g$ (guided wavelength).



(a)



(b)

Fig. 1. Block diagram of an waveguide probe for near-field scanning: (a) the conventional probe (b) the proposed probe

Near-field enhancement is found in the ridge gap area of the used DRWG. The currents induced on the double ridges of the DRWG are guided toward the terminals. The charge accumulates at the terminals leading to a displacement current across the gap. The field distribution in the ridge gap area strongly depends on the width and gap of the ridges, and the length of the DRWG. The field at the E-plane edges of the proposed open-ended DRWG is enhanced in comparison to the field at the center of the previous RLSS [9].

3. Design of a Rectangular Waveguide Probe

The proposed probe is located at the front of the SUT as shown in Fig. 2 and the equivalent circuits of the probe are presented in Fig. 3. The distance d_s between the probe and the SUT is 0.1 mm. The material of the used SUT is FR-4 (ε_r= 4.3, thickness = 1.57 mm). Fig. 3 depicts an

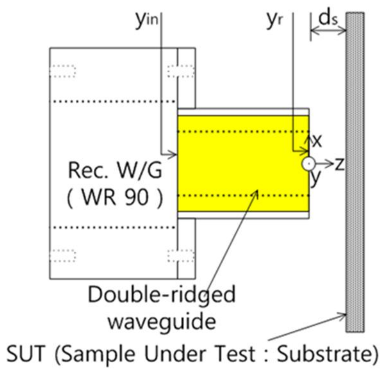


Fig. 2. Waveguide probe and substrate SUT

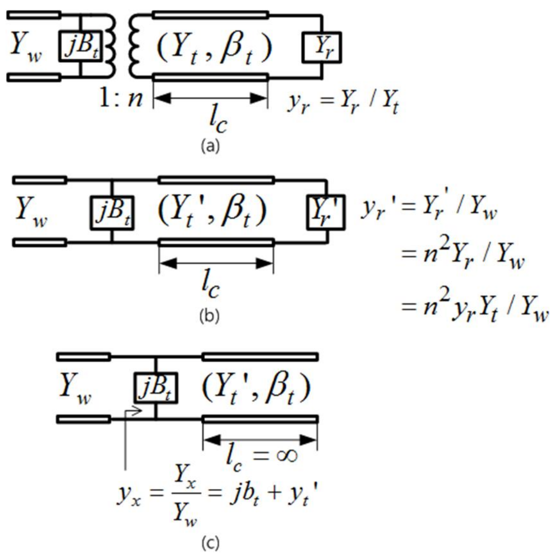


Fig. 3. Equivalent transmission-line model for the proposed probe with open-ended DRWG: (a) with an ideal transformer, (b) without an ideal transformer, (c) if $l_c=\infty$ in the case of Fig. 3(b)

equivalent circuit in which the feed RWG and the open-ended DRWG are modeled using transmission-line sections with characteristic admittances and propagation constants, (Y_t, β_t) and (Y_w, β_w), respectively [17]. Further, the radiation admittance of the open-ended DRWG is Y_r. Fig. 3(a) is a method to model the input interface of the DRWG by using a shunt susceptance and an ideal transformer. In Fig. 3(b), the transformer may be removed if the characteristic admittance of the DRWG and the radiation admittance of the open-ended DRWG are considered to be, respectively,

$$Y_t' = n^2 Y_t \tag{3}$$

$$Y_r' = n^2 Y_r \tag{4}$$

where n^2 is the turn ratio of the transformer. Fig. 3(c) represents a case when the length of the DRWG is infinitely long in the case shown in Fig. 3(b). The normalized input admittance at the input interface of the DRWG in Fig. 3(c) may be expressed as follows:

$$y_x = \frac{1-S_{11}}{1+S_{11}} = jb_t + y_t' \tag{5}$$

Fig. 4 shows the reflection coefficient S_{11} and equivalent parameter y_x at the input interface of the DRWG with infinite length, obtained using Eq. (5). The cut-off frequency of the DRWG is 9.152 GHz [9]. Notably, the tunneling frequency (9.156 GHz) is close to the cut-off frequency when the length of the DRWG is infinite [10]. For the $\mathcal{E}$-near-zero (ENZ) channel using a double ridged RWG with infinite length, the simulated parameters are b_t = -0.1352, y_t' = 9.7453, and β_t= j12.1830 rad/m at the operating frequency of 9.631 GHz.

Fig. 5 shows the turn ratio n^2 of the transformer and the normalized radiation admittance y_r' of the open-ended DRWG in Fig. 3(b) when the proposed probe is located at front of the SUT without strips, where the gap distance

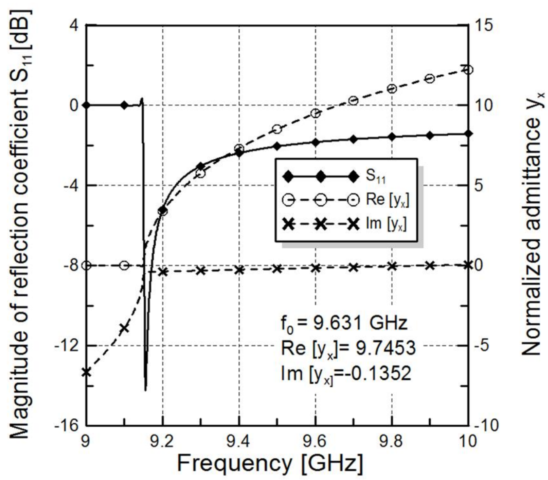


Fig. 4. Reflection coefficient S_{11} and equivalent parameter for DRWG ($l_c=\infty$)

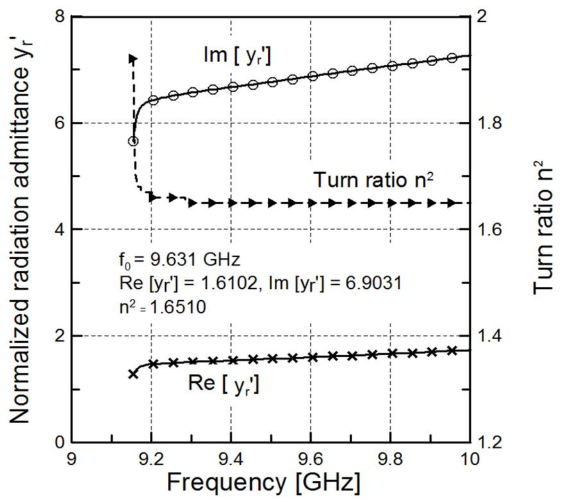


Fig. 5. Turn ratio n^2 of the transformer and the normalized radiation admittance y_r' of the open-ended DRWG in Fig. 3 (b)

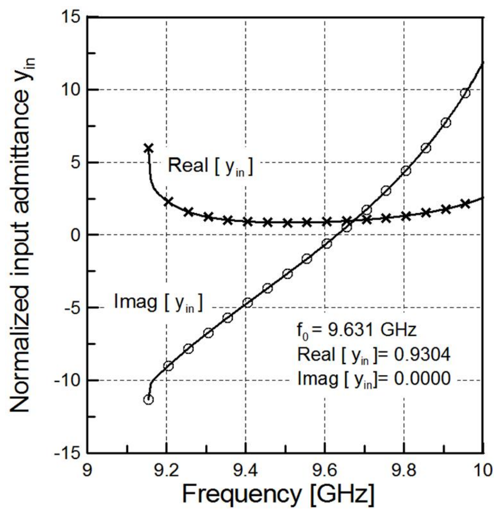


Fig. 6. Normalized input admittance at the interface between the input RWG and the DRWG

d_s is 0.1 mm. At the operating frequency f_0 of 9.631 GHz, the turn ratio n^2 is 1.6510 and the normalized radiation conductance and susceptance, (Re $[y_r']$, Im $[y_r']$) are 1.6102 and 6.9031, respectively.

At the interface between the input RWG and the DRWG in Fig. 3(b), the normalized input admittance is given by

$$y_{in} = jb_t + y_t' \frac{y_r' + y_t' \tanh(\beta_t l_c)}{y_t' + y_r' \tanh(\beta_t l_c)} \tag{6}$$

and is shown in Fig. 6. The calculated results of the reflection coefficient for the equivalent circuit and the simulated results obtained by using HFSS are shown in Fig. 7. It can be observed that the reflection coefficients have dip nulling at the operating frequency of 9.631 GHz, and are consistent with the simulated result of 9.633 GHz.

If the transverse cross-sectional shape of the DRWG is

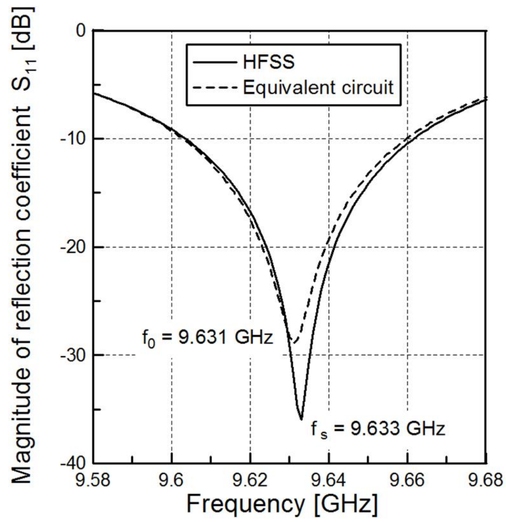


Fig. 7. Calculated reflection coefficients of the proposed probe

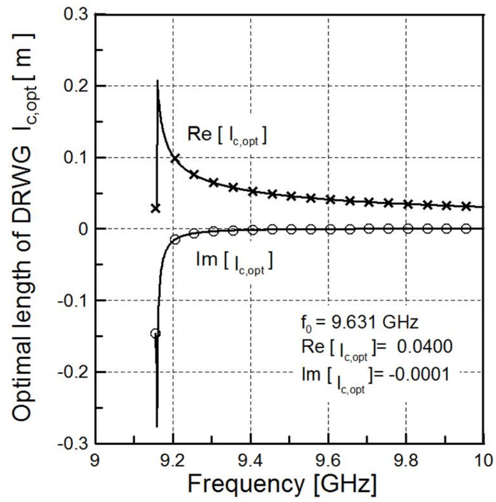


Fig. 8. Optimum length of the open-ended DRWG for the proposed probe

chosen by considering the operating frequency, then the resonance length of the DRWG can be determined theoretically using Eq. (6). When Re $[y_{in}]$ = 1 and Im $[y_{in}]$ = 0 in Eq. (6), i.e., y_{in}= 1, the resonant length is given by

$$l_{c,opt} = \frac{1}{\beta_t}\left[\tanh^{-1}\frac{(1-jb_t-y_r')y_t'}{-y_r'+jb_t y_r'+(y_t')^2} + k\pi\right] \tag{7}$$

where k=1, 2, 3, ... In the case where k = 1, the optimal lengths along the operating frequencies are presented in Fig. 8. At the operating frequency f_0 = 9.631 GHz, the optimum length $l_{c,opt}$ is 40.00 mm. When the operating frequency is close to the cut-off frequency, the optimum length is very long and inaccurate because Im $[l_{c,opt}]$ is large.

As evident from Fig. 9, the electric intensity calculated by HFSS on the SUT has a peak value around the E-plane edge of the open-ended DRWG, where the incident power

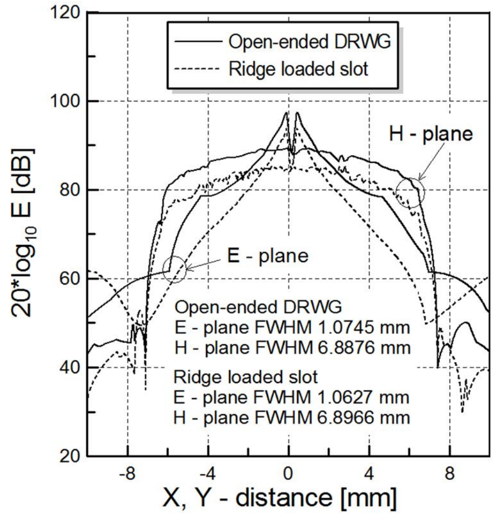


Fig. 9. Electric field intensity distribution on the SUT surface (d_s=0.1 mm)

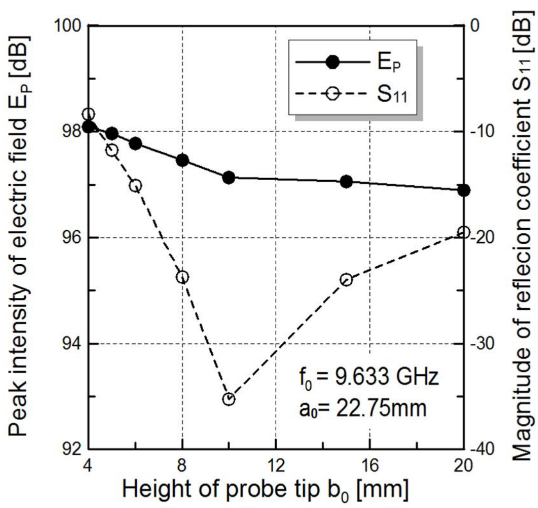


Fig. 10. Peak intensity of electric field E_p and magnitude of reflection coefficient S_{11} against the height of the proposed probe tip: f_0=9.633 GHz and a_0= 22.75 mm

is 1 W and d_s = 0.1 mm. Notably, on the surface of the SUT, the electric field intensity of the proposed probe is more strongly concentrated as compared with the conventional probe with the RLSS, because the surface current density increases on the end wall of the narrow probe tip. The peak values of the electric field intensity are 97.13 dB for the proposed probe and 93.49 dB for the conventional probe. The FWHM of E and H -planes are approximately 1.07 mm and 6.89 mm, respectively, in both cases.

Fig. 10 shows the simulated peak intensity of the electric field E_p and the reflection coefficient S_{11} against the height of the proposed probe tip at the operating frequency f_0 = 9.633 GHz and the fixed tip-width a_0= 22.75 mm. It can be observed that the peak intensity increase gradually

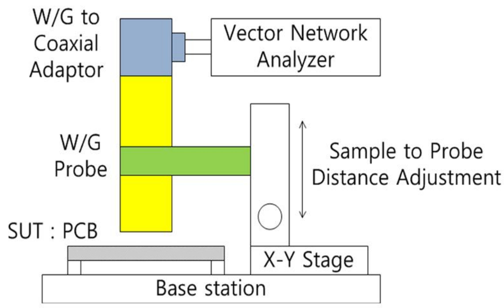


Fig. 11. Experimental equipment arrangement

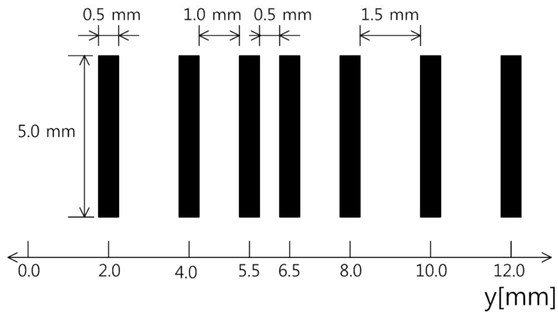


Fig. 12. Layout of a PCB with seven strips with width of 0.5 mm

as the tip-height b_0 reduces from 20.0 mm to 4.0 mm. The minimum reflection coefficient is obtained at b_0=10.0 mm.

4. Experimental Results

Fig. 11 shows the experimental arrangement of the scanning near-field microwave microscope similar to a previous study [12]. In this study, the SUT was made of a PCB with seven metallic strips on the FR-4 substrate, which has an area 160.0 x 160.0 mm^2, a thickness 1.6 mm, a permittivity 4.3, a tangent loss 0.02 and a cu cladding thickness 0.017mm. An Agilent E8364B VNA was used to measure the reflection coefficient of the probe. For a specific geometric characteristic of the SUT such as metallic strips, the measured reflection coefficient showed a specific pattern when the location of the scanning probe varied in the direction of y-axis.

The sample is a PCB with seven 0.5 mm narrow metallic strips as shown in Fig. 12. After positioning the probe such that there is a gap d_s of 0.1 mm between the PCB and the probe After positioning the probe such that there is a gap d_s of 0.1 mm between the PCB and the probe as in Fig. 2, when the probe points at the substrate portion of the PCB without strip, the measured frequency responses of the probe are resonant modes at 9.642 GHz (the proposed probe case: open ended DRWG) and 10.330 GHz (the conventional probe case: RLSS [12]), respectively.

The measured one-dimensional scanning reflection coefficients at the two resonant frequencies are shown in

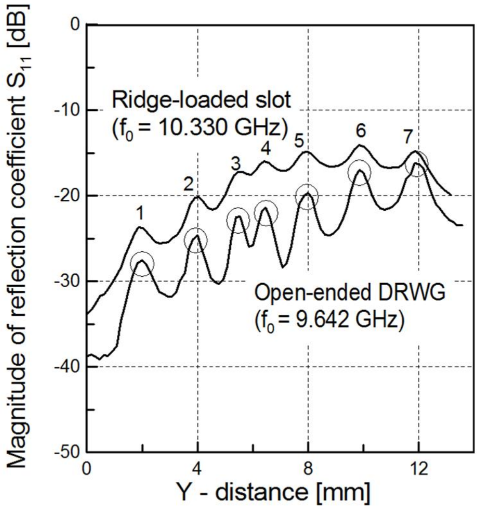


Fig. 13. Measurement results of the SUT in Fig. 12 at resonant frequencies of 9.642 GHz and 10.330 GHz

Fig. 13. From these measurement results, it can be determined that the probes can resolve the two lines at No. 3 and No. 4, wherein the gap between these two strips is 0.5 mm, which is the same as the gap of the DRWG. When the probe is located over a strip, the measured reflection coefficient show a peak, and it can be observed that Fig. 13 has seven peaks at the locations of 2.0, 4.0, 5.5, 6.5, 8.0, 10.0, and 12.0 mm which are consistent with the locations of the strips. Further, it can be observed that the depth of the nulling dips is increased by more than 3.0 dB owing to the increase of the peak intensity of the electric field by using the proposed resonant probe as compared to the conventional probe that employs an RLSS. In both cases, a spatial resolution of 500 μm (~λ/62) has been achieved.

As discussed in [5], it is evident that the image reconstruction with the proposed resonant probe is much brighter than that obtained with the conventional probe using RLSS. The image intensity is proportional to the absolute value of the vector difference between the reflected field intensity at each of the strips and the substrate on the SUT. It can be observed from these profiles that the image contrast is improved by more than twice by using the proposed resonant probe as compared with the conventional probe using RLSS.

5. Conclusion

In this study, a microwave microscope system using a rectangular waveguide probe without cavity was developed. Further, an open-ended DRWG was implemented to enhance the spatial resolution as a near field scanning probe. In order to remove the additional screw tuner and impedance transformer for the impedance matching of a probe, the optimum length of the DRWG was selected for the best resolution to measure the geometric characteristics of the SUT while pointing at the substrate of the PCB. The design procedure used for the probe is presented in detail and the performance of the designed resonant probe is evaluated theoretically by using an equivalent circuit.

From the measurement results, the geometric structures of the SUT can be identified from the measured reflection coefficient. Hence, this method has the potential to image the geometric structures of the metallic patterns as a contactless and non-destructive testing tool. The image resolution and contrast of the proposed resonant probe are much more enhanced than those of the conventional probe using RLSS.

Further research in this area has to be performed to improve the spatial resolution of metallic strips with a small gap and width; therefore, studies on the small foot-print structure of the open-ended DRWG will be required.

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