Two types of near-field microwave imaging probes

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abstract

We consider two types of near-field microwave imaging probes. One employs the small circular ridged aperture and the other employs unsymmetrical transmission cavity whose closed ends comprise the small circular aperture with no ridge and capacitive iris of double ridge type which is placed half waveguide wavelength apart from the circular aperture. The relationship between working principles of the two types of probes is discussed in both transmission efficiency through a small aperture and spatial confinement of the electromagnetic energy.

I. Introduction

when a uniform plane electromagnetic wave is incident upon the small circular aperture in an infinite conducting plane, the transmitted power $P_t$ through the aperture is very small. Specifically, the transmission cross section (TCS) $T$ of the aperture whose diameter $D$ is much smaller than the wavelength $\lambda$ is proportional to $(D/\lambda)^4D^2$ according to the Bethe's theory [1]. Here the TCS $T$ is defined so that the transmitted power $P_t$ through the aperture may be given by the multiplication of the incident power density $P_{inc}$ [W/m$^2$] and $T$ [m$^2$], i.e., $P_t = P_{inc}T$.

It has been found that the transmission efficiency can be significantly enhanced by modifying the aperture shape as in the circular ridged aperture in the infinite thin conducting plane or by employing a small coupling aperture-to-cavity-to-aperture system in a thick conducting plane. It is interesting to note also that the TCS $T$ for both the two structures can be increased to the maximum value of $T = 3\lambda^2/4\pi$ [m$^2$] as a upper bound [2]. This means that incident power on the much larger area than actual aperture area is funneled into the physical aperture and transmitted through it and radiated into the opposite half space to incident side regardless of the actual aperture area under the transmission resonance where the transmitted power $P_t$ becomes maximum.

The near-field microscopy employs a probe of a subwavelength size and an object that is mounted in the near field of the probe, so that the spatial resolution is determined by the coupling hole size of the probe rather than by the wavelength. Several designs of the microwave near-field probe have been used, such as a circular aperture [3] and open waveguide [4]. A smaller coupling circular aperture provides better resolution, although this is not very practical because the transmitted power is very low as mentioned above. So several kinds of apertures such as long resonant slit and anular aperture have been studied to overcome such a low transmission efficiency problem [5]. In general, the transmission efficiency through a small coupling aperture and the spatial confinement of the electromagnetic energy are taken as two conflicting characteristics of the compromise problem which we should solve in the design procedure of near-field imaging probe.

The aim of this work is to consider coupling aperture structures for a near-field microwave imaging probe whose transmission efficiency can be significantly enhanced while the coupling hole size is maintained as small as possible for better resolution.

II. Design of two types of near-field microwave imaging probes and numerical results.

We are going to deal with the two types of probes which are fed by a rectangular waveguide. First, we consider the probe which comprises a small ridged aperture cut in the end plate of the rectangular waveguide.

2-1. Circular ridged aperture type

We first obtain geometrical parameters (ridge width $S$, gap $G$, and aperture radius $RA$ in Fig. 1(b)) of the U.S. Government work not protected by U.S. copyright
resonant circular ridged aperture in an infinite conducting plane so that the transmission resonant frequency may be located roughly midway in the X-band range (8.2 – 12.4 GHz) by using the numerical analysis of Rao-Wilton-Glisson (RWG) method [2]. Fig. 1 shows the structure of the circular ridged aperture under consideration and the geometrical parameters. In order to investigate the reflection characteristics versus frequency, we have calculated them by use of HFSS for the geometrical parameters given above.

Fig. 1. The probe of circular ridged aperture type (a) feeding waveguide \((a = 22.86, b = 10.16, \text{ and } t = 0.2)\) (b) circular ridged aperture \((S = 1.9, G = 0.4, \text{ and } RA = 6.9)\), unit [mm]

Fig. 2. Scattering coefficient \(|S11|\) versus frequency

From the Fig. 2, this type of probe is seen to offer the advantages in both high transmission efficiency for good impedance matching and small spatial confinement of electromagnetic energy for better resolution. Another advantage of this type is, as seen in Fig. 2, its low \(Q\) factor, in comparison with the transmission cavity type appearing later, enabling to transmit short pulses and to achieve good temporal solution.

2.2 Bisected unsymmetrical transmission cavity type

It is well known that the resonant transmission cavity type using aperture input and output coupling of the same sized small hole can be incorporated as a filter in a waveguide run. The irises form the closed ends of the cavity and the small holes in the center allow coupling into and out of the cavity. The magnetic field along one side of the iris couples through the hole to the other side, and provided that the length between the two irises is waveguide wavelength \(\lambda_g\), the resonant mode will be set up which couples through to the output (free space) side, as shown in Fig. 3(a).
If the resonant transmission cavity type using aperture input and output coupling of the same sized small holes is incorporated in the waveguide run, when maximum transmission occurs, the strong resonant mode is established. That is, the $x$-component magnetic field (corresponding to tangential magnetic field) on the two irises at $z = -\lambda_y/2$ and $z = 0$ becomes maximum and $y$-component electric field becomes maximum roughly at $z = -\lambda_y/2$. So without change in the transmission resonance frequency, we can bisect the original transmission cavity $\lambda_y$ long by putting the capacitive iris of Fig. 3(b) which can support the original maximum $y$-component electric field at at $z = -\lambda_y/2$ midway inside the original cavity, as shown in Fig. 3(a). Under the situation, the field configuration inside the bisected transmission cavity ($-\lambda_y/2 \leq z \leq 0$) remains almost the same as that in the original symmetrical cavity.

Note that transforming the capacitive iris at $z = -\lambda_y/2$ through the length of $\lambda_y/2$ to the small coupling circular hole (corresponding to inductive circuit element) leads to the formation of parallel LC resonant circuit under the assumption of high $Q$ resonant circuit. From this, we expect the single ridged aperture can be synthesized in terms of the unsymmetrical transmission cavity structure, as shown in Fig.3(a) through some adjustments of geometrical parameters of the circular hole and capacitive iris. Here "unsymmetrical transmission cavity" is used in the sense that different coupling irises are used as in Fig. 3(a) instead of the same small sized aperture coupling for both ends of the conventional symmetrical transmission cavity. Fig. 4 shows the reflection characteristics versus frequency.
It can be seen from Fig. 4 that, also in the transmission cavity type of Fig. 3, impedance match can be achieved at 11.05 GHz, i.e., all the incident power from the feeding rectangular waveguide can be made to be radiated through the small coupling hole at \( z = 0 \).

The difference between the circular ridged aperture type and transmission cavity type is that the transmission resonance frequency (10.872 GHz) for the former is somewhat lower than that for the latter and that the frequency selectivity \( Q \) for the former is much smaller than that for the latter as seen in Fig. 2 and 4, under the assumption that \( R_A \) in Fig. 1 be the same as the radius \( R \) of the coupling hole in Fig. 3. As mentioned above, the transmission cavity type of Fig. 3 tends to show relatively larger \( Q \) than that for the circular ridged aperture type in Fig. 1. The \( Q \) can be, however, lowered to any desired value by increasing the radius of the coupling hole of one closed end of the transmission cavity or by decreasing the width of the vertical conducting strip with a gap which corresponds to the capacitive element of the other end of the cavity.

### III conclusion

We have considered two types of near-field microwave imaging probe of a small coupling holes whose transmission efficiency can be significantly enhanced while the coupling hole size is maintained as small as possible for better resolution. One type of the coupling hole is a circular aperture with double ridge. The other is an unsymmetrical transmission cavity type whose closed ends comprise the small circular aperture (obtained by removing the ridge structure from the above circular ridged aperture) and capacitive iris, located \( \lambda_g / 2 \) (half guide wavelength) apart from the small circular ridged aperture. This study may help to understand the working principles of filter and small aperture antenna as well as the near-field probe with main interest centering on the compromise between two conflicting physical characteristics. The two conflicting characteristics for the filter and antenna problems correspond to impedance matching bandwidth and frequency selectivity. On the other hand those for near-field probe design problem mean the transmission efficiency of the small coupling hole and spatial confinement of electromagnetic energy for the better resolution.

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