**Enhancing The Near Field and Transmission Efficiency through Subwavelengh Apertures**

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***Abstract* – The enhancement of the electro-magnetic field and the transmission resonance through the subwavelength coupling apertures are described for the two cases of structures. One is a transmission-resonant aperture type like the aperture of Bow-tie type and the other is a transmission-resonant cavity type. Comparative discussions are given on the two structures with main interest focusing on the performances of the field energy concentration and transmission enhancement through the subwavelength coupling apertures.**

I. INTRODUCTION

According to the Beth’s theory [1], when a uniform plane electromagnetic wave is incident upon the small circular aperture whose diameter is much smaller than the incident wavelength in an infinite conducting plane, the power transmission efficiency of these apertures decays as the fourth power of the aperture size. In more detail, the transmission cross section (TCS) T of the aperture whose diameter D is much smaller than the wavelength $λ$ is proportional to $\left(D/λ\right)^{4}⋅D^{2}$. 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$\left[m^{2}\right]$, i.e., $P\_{t}=P\_{inc}⋅T$. Recent researches have shown that the transmission efficiency can be significantly enhanced by modifying the aperture shape as in the circular ridged [2] aperture (or H-shaped aperture [3]) in the infinite thin conducting plane or by employing a small coupling aperture-to-cavity-to-aperture system [2] 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 $T=3λ^{2}/4π[m^{2}]$ as a upper bound [2]. This means that the incident power on the TCS much larger than the actual aperture area is funneled into the aperture and transmitted through it and radiated into the opposite half space to incident side regardless of the actual aperture shape and area under the transmission resonance where the transmitted power $P\_{t}$ becomes maximum. Aperture-based near-field techniques employ a probe of a subwavelength coupling hole (aperture) 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 (aperture) size of the probe rather than by the wavelength. Several designs of the near-field probe have been used such as a circular aperture [4], rectangular aperture [5], and open wave guide [6] in microwave band for example. 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 for this purpose several kinds of aperture such as long $(\~λ/2)$ resonant slot and annular aperture have been studied to overcome such a low transmission efficiency problem. In general the transmission 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. Traditional near-field optical probes, such as the tapered fiber probe, are effectively magnetic dipoles coupled to free space via a metal plane. Because the magnetic interaction with matter is negligible at visible frequencies, one would rather have a probe based on an electric dipole than a magnetic dipole. So we are going to consider the near-field probe which is essentially an electric dipole coupled to free space via an radiating aperture types. To this end the above two types of transmission resonant structures i.e., transmission resonant aperture (TRA) and transmission resonant cavity (TRC) structures, are considered.

II. Two types of transmission-resonant structures

We are going to deal with the two types of transmission-resonant structures i.e., trans-mission resonant aperture (TRA) type and transmission resonant cavity (TRC) type which are implemented in the rectangular waveguide run.

*A. Transmission-resonant aperture (TRA)type*

The single most important element in any form of scanning probe microscopy is the probe it- self [7]. The spatial resolution of the micro-wave imaging depends on how the electromagnetic field energy is confined and focused [5]. We first obtain geometrical parameters $(w\_{1}=2 mm, $and $w\_{2}=7 mm)$ of the bow-tie type of aperture in an infinite conducting plane so that the transmission resonant frequency may be located roughly in the X-band range(8.2~12.4GHz) by using the numerical analysis of Rao-Wilton-Glisson (RWG) method [2]. Then for experimental work, we fabricated the probe in the waveguide run whose geo-metrical parameters and structure are shown in Fig.1.

(a)



 (b)

Fig.1 Transmission-resonant aperture of Bow-tie type (a) feeding WR90 rectangular waveguide (a = 22.86, b = 10.16, and t = 0.2) (b) Bow-tie type of aperture ($w\_{1}$= 2, $w\_{2}$ = 7, g = 0.4) unit [$mm]$

In order to investigate the reflection characteristics versus frequency, we have calculated them by use of HFSS for the geometrical parameters given above. Figure 2 shows such $\left|S\_{11}\right|$ curve vs frequency.

Fig.2 Scattering coefficient $\left|S\_{11}\right|$ versus frequency

(a)

(b)

Fig.3 Near field (electric) distribution at z = 0.2mm (a) in the x-direction (b) in the y-direction.

From the Fig.2, the Bow-tie 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 through the small aperture for better resolution. Another advantage of this type is, as seen in Fig.2, its low Q factor, in comparison with the transmission-resonant cavity type appearing later, enabling to transmit short pulses and to achieve relatively better temporal resolution. This Bow-tie type of aperture is essentially the same as the H-shaped aperture. The H-shaped aperture can be taken as a ridge waveguide whose longitudinal length is very short. As is well known in microwave engineering, the ridge waveguide is a broadband device and has a property that its cutoff wavelength in the TE10 mode can be much larger than twice that of the rectangular waveguide size. And the above Bow-tie type of aperture (and the H-shaped aperture) has a transmission resonance feature near the cutoff frequency of TE10 mode of infinitely long ridge waveguide. This feature explains physically why the above Bow-tie type of aperture can provide both a high trans-mission efficiency and a small near field spot size. It is worthwhile to note that the above Bow-tie type of aperture is superior to the $λ/2$ slot dipole in smaller near field spot size whereas the two apertures have almost the same transmission efficiency. As mentioned above, aperture-based near field technique can achieve lateral spatial resolution on the order of the aperture size of the probe because the electromagnetic field energy is squeezed through a tiny aperture and is collimated over a small confined region. So it is interesting to investigate the near field (electric field) distribution just outside the aperture. Fig. 3 (a) and (b) shows the electric field distribution respectively in the $x$ and y directions at z = 0.2 $mm$ in front of the aperture. In Fig.3, the near field spot size (FWHM - full width at half maximum) of the electric field in the x-directions and y-directions are seen roughly to corresponds to the gap size in respective direction.



*B. Transmission-resonant cavity (TRC) type*

Recent research [8] showed that the field is enhanced in the gap between triangles in a bow-tie antenna in the microwave regime and suggested the possibility of extending this principle to visible wavelength. In that work, the Bow-tie type antenna as a kind of an optical antenna, with it’s feeding port open-circuited is used to concentrate the beam for high spatial resolution. What is more, the separation S between the waveguide end aperture and the bow-tie antenna is chosen to be approximately half wavelength$(=λ/2)$ and in-between region constitutes a transmission cavity with relatively low Q. By employing the above optical bow-tie antenna type, the desired beam confinement can be achieved but transmission efficiency still remains to be improved further. In order to do so, the Q of the transmission cavity is to be increased. Fig.4 shows a possible solution of such a desired high Q structure which can be implemented in the microwave frequency band.



Fig.4. Illustration of the transmission resonant cavity type with the input inductive (small rectangular hole) and output capacitive diaphragms (Bow-tie type) spaced by 1/2 waveguide wavelength

Fig.5. Return loss of the transmission resonant cavity type

Fig.5 shows the return loss (impedance matching characteristics) and Fig.6 shows the highly confined electric field distribution which is required for better resolution. It is worth while to note that the large E-field confinement to the small area near the gap (corresponding to the effective subwavelength aperture) is a combined result of the transmission cavity resonance effect and lightning rod or tip effect. For reference Fig.7 shows the comparison of E-field configuration between the transmission resonant cavity (TRC) type and the transmission resonant aperture (TRA) type. The blue line represents the curve for the TRA type and the red line for the TRC type. It is seen that both the two type allow to implement the high transmission efficiency as well as the field enhancement in a very small area.

(a)

(b)

Fig.6. Electric field distribution along the gap at output z=0 of the transmission resonant cavity type (a) X-axis (b) Y-axis

Fig.7. Comparison of the electric field configuration between the transmission-resonant aperture type and the transmission-resonant cavity type.

As expected the transmission resonant Q for TRC type is higher than that for TRA type and the field intensity at the output for TRC type is seen to be much larger than that for TRA type.

VI. CONCLUSION

We have considered two types of near field microwave imaging probe with a small coupling apertures whose transmission efficiency and output electric field can be significantly enhanced for better resolution and better interaction. One type of the coupling aperture is a Bow-tie type of aperture. The other is a transmission cavity type whose both ends comprise the small rectangular aperture and a bow-tie optical antenna type as a probe output iris. 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 (aperture) and spatial confinement of electromagnetic energy for the better resolution.

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