Resonant Transmission of Electromagnetic Wave Through Small Apertures

Young-Ki Cho
School of Electronics Engineering, Kyungpook National University, Daegu 41566, Korea

Abstract – Two types of transmission resonant structures which can provide both high spatial resolution and high transmission are discussed. One is a transmission-resonant aperture(TRA) type and the other is a transmission-resonant cavity(TRC) type, which are useful in designing so called subwavelength(or nano) aperture for the NSOM(Near field scanning optical microscope) probe. There are two types of TSC structures. One is a conventional TSC structure, a coupling-aperture-type(CA type) TSC which has been used as a band pass filter(BPF) in microwave band. The other is a perforated-aperture-type(PA type) TSC such as narrow rectangular slot and ridged slot structures perforated on the thick conducting screen. The PA type TSC are investigated for the two kinds of transmission resonances, Fabry-Perot(longitudinal resonance) type and transverse resonance type. The desired nano-aperture in the NSOM probe design as a TRA can be found by letting the conductor slab thickness be zero for the transverse resonance condition observed in the PA type TSC on the thick conducting screen.

Index Terms — Transmission resonant aperture(TRA), Transmission resonant cavity(TRC), Transmission cross section(TCS), Coupling-aperture(CA) type TSC and Perforated-aperture(PA) type TSC.

1. Introduction

In the area of Nano-optics, transmission of electromagnetic energy through subwavelength aperture in conducting screen has recently attracted much interest. It is well known that the transmission cross section(TCS) \( T \) of the aperture whose diameter \( D \) is much smaller than the wavelength \( \lambda \) is proportional to \( (D/\lambda)^4 \cdot D^2 \) 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 \( P_{inc} \) and \( T \) as:

\[
P_t = P_{inc} \cdot T.
\]

So far many researches have been done with a view of enhancing the transmission efficiency of small aperture[2]-[4] for various applications such as compact optical data storage, nano-lithography, nano-microscopy. In parallel such research has been done in the areas of design of metamaterial element such as complementary split ring resonator(CSRR)[5] and electromagnetic compatibility(EMC) and interference(EMI)[6].

As the result of the active research work, various transmission resonant structures have been investigated in parallel with extraordinary(or enhanced) transmission[7] phenomena. Here the transmission resonance and the enhanced transmission share the meaning of transmission phenomena in which TCS \( T \) is significantly larger than the physical aperture area. In this presentation, we review various transmission-resonant structures which have been reported so far and look into the relation between the transmission resonant aperture(TRA) and transmission resonant cavity(TRC) types from the viewpoint of TCS or transmission efficiency.

2. Transmission Resonant Structures ; TRA and TSC structures

If we define the transmission resonant structures by the aperture structures whose TCS \( T \) is significantly larger than the physical aperture area, then the resonant structures can be categorized into two classes. One is the TRA type and the other is the TSC type.

It has been found that the transmission efficiency of the small holes or apertures can be significantly enhanced by reforming the aperture shapes as circular ridged aperture[4], [8], H-shaped aperture, C-shaped aperture[2]-[4], and CSRR[5] structure etc.

In addition, also by employing a small coupling aperture-to-cavity-to aperture system[8], [9] like transmission cavity filter in microwave engineering) embedded in a thick conducting screen, transmission efficiency can be enhanced. The former is called a TRA and the latter structure is called a TSC for distinction.

All the above TRAs have a following common feature of diffraction property: when an electromagnetic wave is incident upon the apertures, if geometrical parameters of the aperture are approximately chosen so that the transmitted power \( P_t \) through the aperture may become maximum, the admittance between the port at the aperture center becomes real and the incident power on the TSC \( T \)(much larger than the physical aperture area) is funnelled and transmitted through the aperture and reradiated into the back side half space, irrespective of the aperture shape and size, amounting to

\[
P_{t\text{max}} = P_i \times T = P_i \frac{2g^2}{4\pi} \quad (1)
\]

where \( P_i \) and G mean, respectively, incident power density and directivity.

Also for the case of aperture-to-cavity-to aperture system, we can prove that the TCS is given as \( \frac{2g^2}{4\pi} \) under the
transmission resonance condition by use of the equivalent circuit approach[8]. This means that an equivalence relation holds between TRA and TRC from the viewpoint of TCS or transmission efficiency.

3. Perforated-Aperture-type(PA type) TRC on the Thick Conducting Screen

There are two kinds of TRC, one is the coupling-aperture-type(CA type) TRC which has been mentioned in section 2. The other is a perforated-aperture-type(PA type) TRC[10], [11] to be considered here. The cross sections of PA type TRC can be, as an example, that of rectangular waveguide whose height is much smaller than the wavelength or that of the ridged waveguide. The structure of the PA type TRC are enclosed by electric walls inside the guiding structures(constituting the cavity) between the input and output apertures and lossy magnetic walls at both ends of apertures whose shapes are kept as the same as the cross sections of the guiding structures i.e., both ends are open to air. Here the loss means the radiation loss.

These PA type TRCs have different features from the foregoing CA type TRCs in section 2. In the case of CA type TRC structure in section 2, the TRC works as a BPF(band pass filter) only when the fundamental dominant mode exists inside the guiding structure between input and output coupling aperture. On the other hand, in the case of PA type TRC on the thick conductor whose cross section is of that of the narrow rectangular guide or ridged guide, the transmission resonance phenomena occur even when the guiding structure inside the rectangular guide and the ridged guide are cutoff. Here the operating frequencies are slightly smaller than the cutoff frequencies of the narrow rectangular guide structure and the ridged guide structure under the assumption that the longitudinal length of the rectangular guide and the ridged structures be infinite.

Under the cutoff condition[10], [11], the longitudinal propagation constant along the guide section becomes nearly zero[10], which is similar to the physical situation of epsilon-near-zero medium. So this type of transmission resonance is observed to occur irrespective of the longitudinal length(corresponding to the thickness of the conductor slab).

In the frequency region higher than the cutoff frequency where propagating mode is supported, multiple transmission peaks of Fabry-Perot(FP) type is observed at frequencies where the FP resonance condition holds. In order to distinguish between the two types[10], [11], the former type of transmission resonance is called transverse resonance type and the latter FP types which occur at multiple values of frequencies is called longitudinal resonance type.

The enhanced transmission is explained by two different resonance mechanisms[12], [13], a vertical one which is based on the above transverse resonance and Fabry-Perot(longitudinal type) resonance and a horizontal one which is associated with the periodicity. The transmission resonance type here belongs to the vertical mechanism which is associated with the localized waveguide resonances and is almost independent of the periodicity of the structure. More detailed discussions on the enhanced transmission for both perfect conductor and real metal cases will be given during the conference.

4. Conclusion

Various transmission resonant structures which can produce the enhanced transmission are discussed; TRA, CA type TRC, and PA type TRC on the thick conductor slab. TRA shape is thought to be found by reducing the conductor thickness to zero for the transverse resonance condition observed in the PA type TRC structures on the thick conducting screen.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2015R1D1A1A09058357). This study was supported by the BK21 Plus project funded by the Ministry of Education, Korea (21A20131600011).

References