CHAPTER I

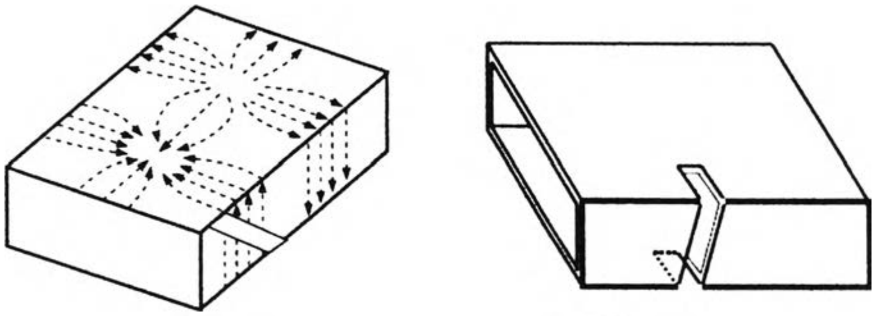
INTRODUCTION

1.1 Background

The inclined slot cut on the narrow wall of rectangular waveguide, known as edge slot, is one of radiating typed slots that can be made on the rectangular waveguide. As shown in Fig. 1.1(a), the tilted slot perturbs the wall current distribution of the waveguide [1]. Thus, a part of energy in the waveguide radiates out through the slot. Taking the benefit of its radiating characteristic, the edge slot can be implemented as antenna, waveguide coupler or other waveguide radiators.

As an antenna, the slot length must be adjusted to get resonance in order that the antenna radiates efficiently the desired frequency in a specific bandwidth. Unfortunately, the width of the narrow-side of the rectangular waveguide is substantially shorter than a half free-space wavelength, thus the inclined slot must often extend to the adjacent top and bottom walls of the waveguide to obtain the required resonant length, Fig. 1.1(b).

The edge slot waveguide antenna possesses some advantages as follows.



(a) (b)

Figure 1.1: (a) Edge slot cuts the waveguide wall current lines, (b) resonant edge slot.

- Lightweight, compact structure and relative easy for accurate fabrication
- High power handling due to its waveguide excitation
- High radiating efficiency and reliability
- Broader bandwidth over the broad-wall slots

In addition, since the slot is machined in the narrow rather than the broad wall, neighboring slots in a planar array can be more closely spaced in the H-plane to avoid multiple beams while scanning.

Based on these benefits, edge slots have been widely used in the realization of antenna array for numerous radar and communication systems. It has been successfully designed at S, X, and Ka bands. In the future, it has opportunities to develop at higher frequency and other applications, such as wireless and millimeter wave communications.

In order to have a good array design, it requires accurate information of individual edge slot, such as resonant length, inclination angle, network equivalence parameters, etc. However, there is no adequate theory regarding the behavior of edge slots. The theoretical formulation cannot be determined accurately because the existence of broad wall parts that makes the structure of the edge slot become complicated to express in an exact formulation. Consequently, the designer has to refer to the measurement results so far.

Designing an array by empirical method needs hundreds of measurements to adjust the slots in just one waveguide or single dimension array. This number will increase in the design of multi-dimensional array. Hence, it is strongly desirable to predict by numerical computations to solve this designing difficulty.

Some numerical approximations have been investigated, but they have difficulties. They are partly caused by folded part of edge slot on the broad-wall and partly from the effect of wall-thickness that must be included in the analysis [2]. So far, the results are still less satisfactory than practical measurements. Therefore, the analysis of the edge slot is still a challenging problem at this moment.

1.2 Research Motivation

The effort to build the theoretical analysis of the slot has been pioneered by Stevenson as reported in 1948 [3]. He derived an expression for the resonant conductance of the edge slot for slot length corresponding to the first resonance. In order to simplify the formulation, Stevenson assumed that the slot resonates at half the free space wavelength and left unsaid the part of slot on the broad wall of the waveguide.

The wrapped part of the slot was tried to be incorporated in the formulation of impedance properties of the edge slot several decades later by Das *et al.* in [4]. They used the method of plane wave spectrum to calculate the external power of the slot in an infinite ground plane. Their calculations concluded that the resonant length was 0.4625 lambda. This result was not quite in agreement with the experimental data reported in [1]. By applying the variational formula, Hsu and Chen added the internal reactive power to the external power [5],[6]. Their analysis could improve the Stevenson's formulation, but the assumption of the electric field distribution along the slot still produced large discrepancies with the measurement data.

Criticizing the assumption of previous investigations, moment method was brought to calculate the electric field distribution along the slot from which the network equivalent parameter was derived. Lakhani *et al.* in [7] developed the moment method coupled with internal Green's function and half space Green's function, respectively for expressing the radiated field inside and outside the waveguide. He also mentioned the effect of the waveguide wall thickness, but it was just implied in the calculation of the slot length instead of the field distribution. A similar technique had been also presented by Jan *et al.* [8]. They accounted the external broad wall part of the edge slot by introducing the 90° wedge Green's function to approximate the scattering effect in the external corner. This analysis was criticized by Jan and Hsu themselves due to its computation time. Then, they applied this Green's function with variational method and got a comparable result with less computation time. Prakash *et al.* [9] also claimed that the 90° Green's function was complicated in its calculations. Then they tried to avoid its usage by employing hybrid MoM/FDTD. The calculation of the admittance properties based on the electric field distribution resulted from those above methods was better than the previous analyses that directly derived the admittance. It also had another advantage since the other antenna parameter, such as radiation pattern, directivity, etc., can be derived from the electric field distribution. However, the negligence of wall thickness still yielded a significant disagreement with the experimental measurements.

The effect of wall thickness that was omitted in the preceding analyses was accounted for by Kraut *et al.* in [10] using the finite difference time domain method. This method was simpler because it did not need the knowledge of Green's function, but it needed a large number of memories and computer resources. Therefore, Kraut could not list the detail of the network parameters of the slot due to his computer resource limitation.

In 1996, Jan and his colleagues proposed a more flexible finite element analysis considering the wall thickness in the analysis of the edge slot [11]. The formulation began with the variational equation which was derived from the variational reaction theory. The fields on the inner and outer surfaces of the slot were expressed with the internal and external Green's function as those used in [8] and solved by the method of moments. This method could improve the numerical prediction of the edge slot, although it still had some errors from the measurement data about 0.6 to 1.7 percents for resonant length and 3.3 to 8.5 percents for the normalized conductance. These errors were probably caused by the nature of the finite element method that was usually slowly convergent for the domain that contained some sharp edge on the corners of the waveguide wall.

The latest investigation on the single edge slot regarding the wall thickness was developed using a combination of the finite difference and moment methods. A coupled magnetic field integral equation which was formulated at the slot aperture was solved by the moment method with the Galerkin's approach and the entire domain sinusoidal basis function. The external scattered fields were computed by using the finite difference time domain (FDTD) method. This gave better result than FEM and could avoid the use of rigorous external Green's function, but at less numerical efficiency because it needed a lot of computer memories and relatively longer calculation time especially during the FDM calculations.

An edge slot also have been investigated in terms of antenna array. The mutual impedance properties were calculated by using various methods such as the moment method [12], [13], and [14]. However, the characteristic of the array has to be deduced from the characteristic of a single slot, so the growth of research always follows the single edge slot.

Considering that the finite element method coupled with the moment method is naturally more flexible and efficient to analyze the edge slot, although its accuracy in the Jan's work is less than FDTD [15] due to the ignorance of the corner effect in the domain of analysis. Therefore, this research proposes to apply the combined finite element and moment methods to analyze the edge slot antenna and contributes to invoke a singular shape function to improve the accuracy and numerical convergency of the applied method regarding the singularity of fields in the region around the corners. The network parameters are calculated for verifying the calculation result to the measurement data and other methods. In addition, the radiation characteristic of the edge slot antenna is investigated to provide the required information for practical design.

1.3 Objectives of the Research

The objectives of the research are:

1. Applying the Finite Element Method and the Moment Method to calculate the electric field distribution along the edge slot with finite waveguide wall thickness

2. Employing the singular element shape function to improve the accuracy of FEM analysis regarding the existence of field singularity at slot corners

3. Verifying the analysis by calculating the network equivalence parameters of the edge slot based on the resulted electric field distribution and comparing with the

previous analysis and published measurement data

4. Investigating the radiation pattern of an edge slot.

1.4 Chapter Organization

This report consists of five chapters. The first chapter presents the introduction of this research, including background, motivation of research, research objectives, and report structure. Afterward, the second chapter discusses the mathematical derivations used in the edge slot analysis. It elucidates the formulation of the variational equation and its solution by using the combined finite element and moment methods. Some integrals on the analysis can be evaluated analytically and others are derived by using the Gauss quadrature integral approximation. The next subsection conducts the calculation of the antenna radiating parameters derived from the electric field distribution resulting from the analysis.

Chapter three contains one of the contributions of the research that is the application of the singular element shape function on the analysis starting with explanations of singular element shape function and its characteristics. The singular element is the one that has been published by Akin in [16]. The application of this shape function in the analysis causes some integral unsoluble analytically because of its quadratic form . Thus, the integral approximation must be employed. It uses the Gauss quadrature to solve this problem.

Chapter four deals with the numerical example on which the analysis is applied. The improvement due to application of the singular element is evaluated by analyzing the resulting electric field distribution and the admittance properties. The results are validated by comparing to the measurement data and the numerical result of other methods that are taken from the published paper. Radiation pattern and other antenna parameters are also presented.

Finally, chapter five summarizes the findings of the research and discusses some recommendations for future works.