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Analysis of Radiation From Aperture Antenna by Geometrical Theory of Diffraction

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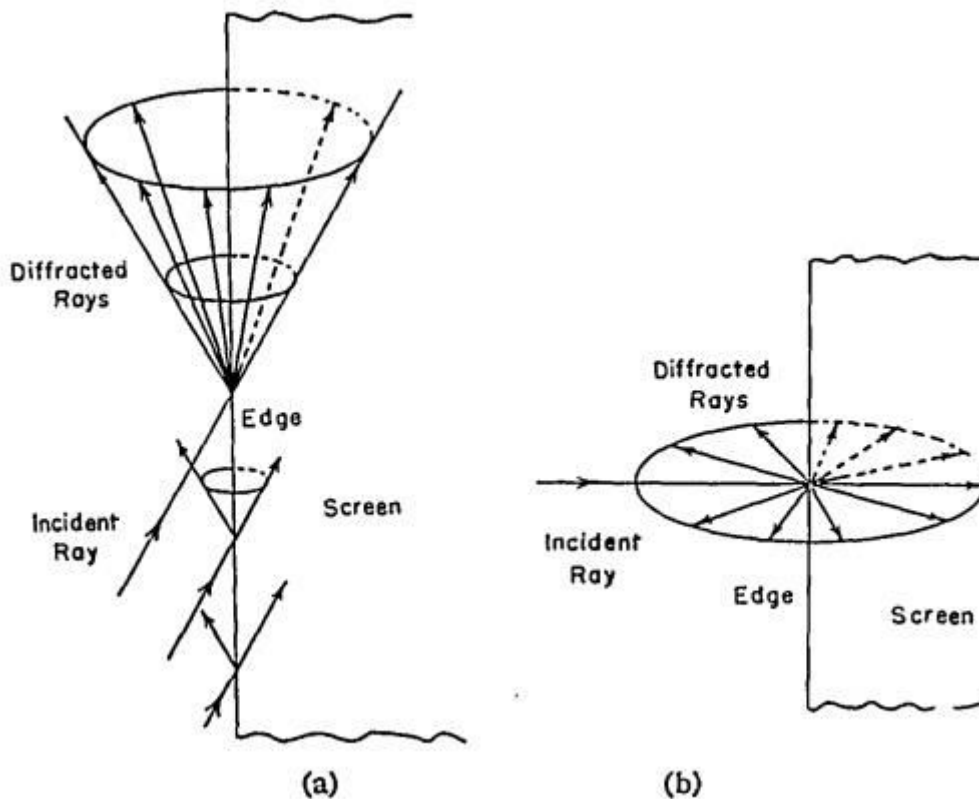
ABSTRACT: The technique that can be applied to the calculation of aperture antenna radiation patterns is the equivalence principle followed by physical optics. The equivalence principle is based on replacing the physical antenna aperture with a virtual antenna aperture consisting of an ensemble of Huygen's sources, each of which is a source of spherical wavelets. The total pattern is taken as a construction of these Huygen's secondary waves. A Fourier transform relation exists between the amplitude distribution of these sources, and the radiation pattern in angle space. For most aperture antenna problems, these classical techniques are adequate and give reasonably accurate results. However, more modern analysis techniques such as method of moments (MOM), finite element method (FRM), and the finite difference time domain (FDTD) method are also discussed.

These are more robust and accurate, but the complexity and large amount of computer resources required must be traded off with the accuracy desired. The geometrical theory of diffraction is an extension of geometrical optics which accounts for diffraction. It introduces diffracted rays in addition to the usual rays of geometrical optics. These rays are produced by incident rays which hit edges, corners, or vertices of boundary surfaces, or which graze such surfaces. Various laws of diffraction, analogous to the laws of reflection and refraction, are employed to characterize the diffracted rays. A modified form of Fermat's principle, equivalent to these laws, can also be used.

KEYWORDS: radiation, analysis, aperture, antenna, geometrical, theory, diffraction, wave, physics

I. INTRODUCTION

Diffracted wave fronts are defined, which can be found by a Huygens wavelet construction. There is an associated phase or eikonal function which satisfies the eikonal equation. In addition complex or imaginary rays are introduced. A field is associated with each ray and the total field at a point is the sum of the fields on all rays through the point. The phase of the field on a ray is proportional to the optical length of the ray from some reference point. The amplitude varies in accordance with the principle of conservation of energy in a narrow tube of rays. The initial value of the field on a diffracted ray is determined from the incident field with the aid of an appropriate diffraction coefficient. These diffraction coefficients are determined from certain canonical problems. They all vanish as the wavelength tends to zero. The theory is applied to diffraction by an aperture in a thin screen diffraction by a disk, etc., to illustrate it. Agreement is shown between the predictions of the theory and various other theoretical analyses of some of these problems. Experimental confirmation of the theory is also presented. The mathematical justification of the theory on the basis of electromagnetic theory is described. Finally, the applicability of this theory, or a modification of it, to other branches of physics is explained.



Diffraction theory

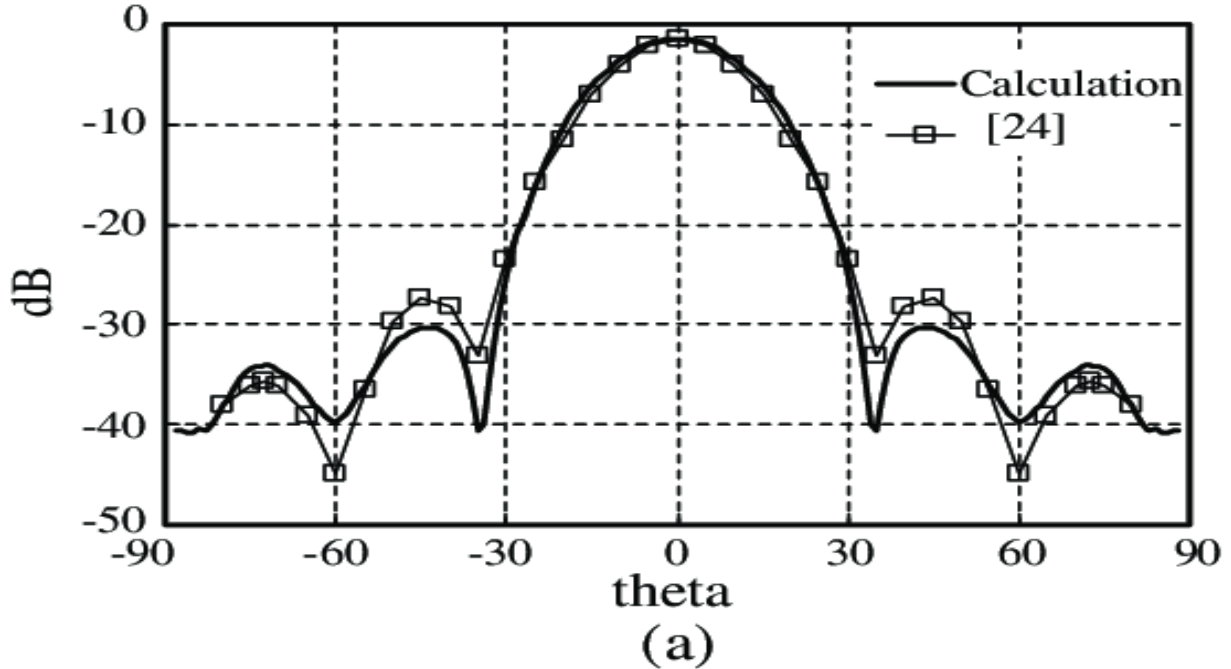
A technique using the hybrid finite element method (FEM)/method of moments (MoM) and geometrical theory of diffraction (GTD) is presented to analyze the radiation characteristics of cavity fed aperture antennas in a finite ground plane. The cavity which excites the aperture is assumed to be fed by a cylindrical transmission line. The electromagnetic (EM) fields inside the cavity are obtained using finite element method (FEM). The EM fields and their normal derivatives required for FEM solution are obtained using:

(1) the modal expansion in the feed region and

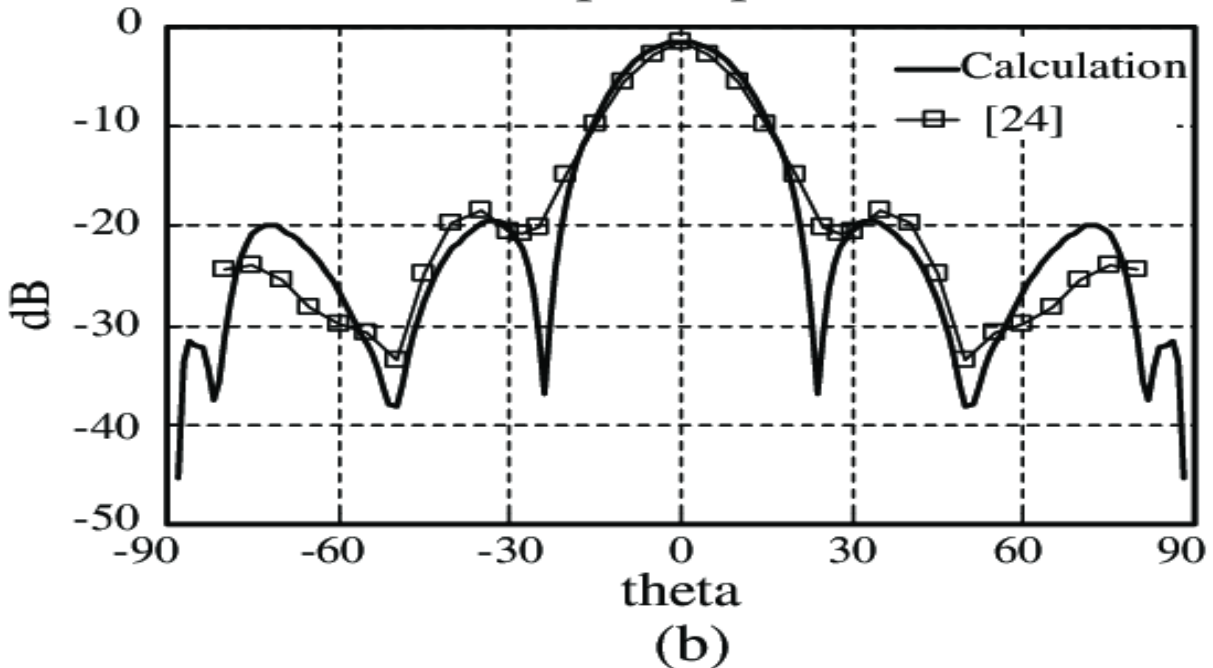
(2) the MoM for the radiating aperture region (assuming an infinite ground plane). The finiteness of the ground plane is taken into account using GTD. The input admittance of open-ended circular, rectangular, and coaxial line radiating into free space through an infinite ground plane are computed and compared with earlier published results. Radiation characteristics of a coaxial cavity-fed circular aperture in a finite rectangular ground plane are verified with experimental results. In another method, physical optics integral representations of the fields are given for the 3-D model of the aperture antenna with specified amplitude excitation law enclosed in a radome. The problem is reduced to finding fields of a plane wave diffracted on the “symmetrized” radome. This model is used for calculations of radiation patterns and for analyses of far-field radiation. Peculiarities of the ray pattern and caustics are analyzed using geometrical optics (geometrical theory of diffraction) method. The contribution of the stationary phase points in the aperture to the far-side radiation has been investigated.



H-plane pattern



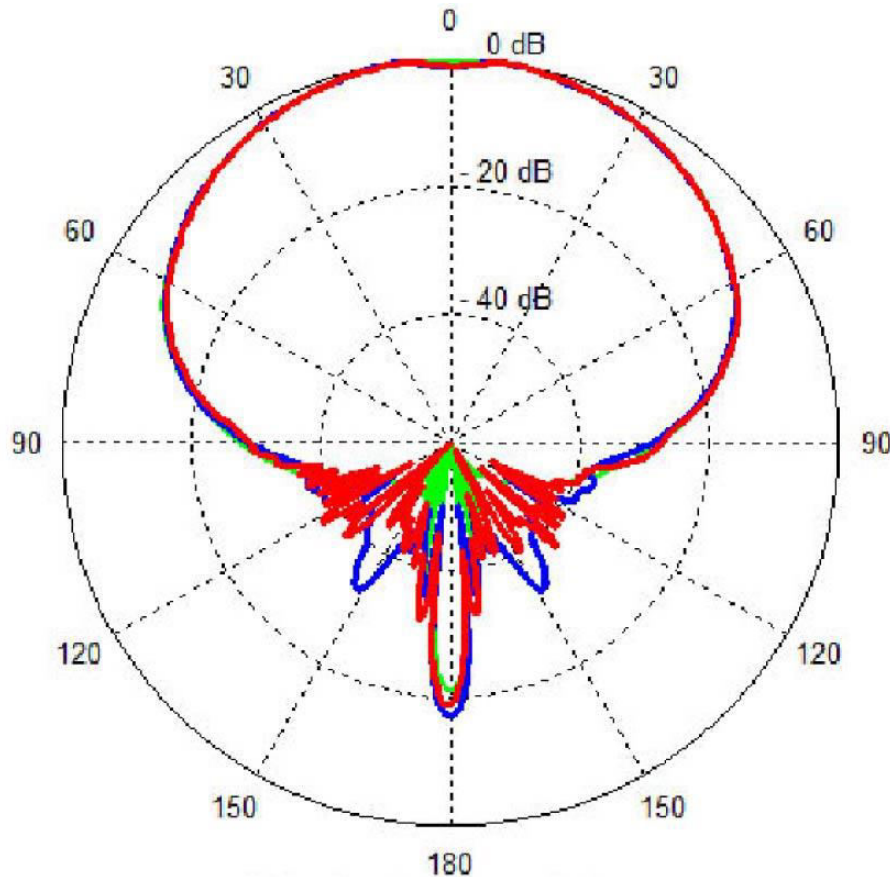
E-plane pattern



Radiation pattern

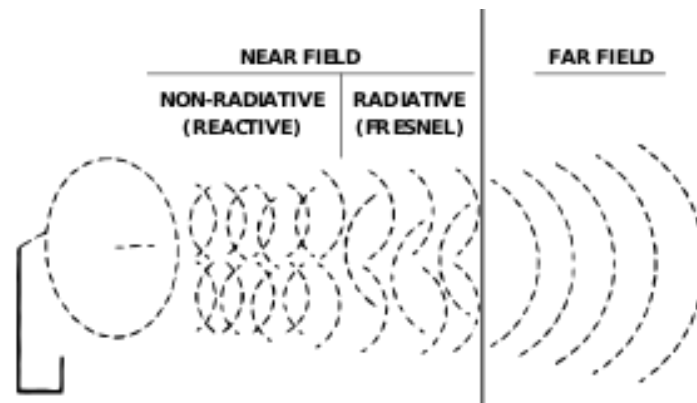
Cavity-backed aperture antennas are very popular in aerospace applications because of their conformal nature. The cavities can also have various types of microstrip antennas residing in them. Hybrid techniques have recently become attractive for the numerical analysis of these types of problems. The combined finite element method and method of moments (FEM and MoM) techniques, in particular, have been used to analyze various cavity-backed antenna systems. The FEM has a relatively simple formulation and is attractive for complex penetrable structures. Also, it results in sparse, banded matrices that can be effectively stored and solved. However, the FEM when used alone does not

incorporate the Sommerfield radiation condition and hence requires discretization to extend far from the source region so that the radiation condition can be imposed. Recent efforts have concentrated on the use of absorbing boundary conditions to reduce the discretization region .



Radiation pattern of aperture antennas

Unfortunately, the accuracy of these approximate boundary conditions depends on specific problem geometry, leading to results of unpredictable accuracy. The method of moments (MoM), on the other hand, incorporates the Sommerfield radiation condition through the use of the appropriate Green's function. As a result, the domain discretization can be kept to a minimum. However, this method has the disadvantage of being difficult to implement for complex penetrable structures. This method also results in full matrices whose treatment requires excessive storage, limiting its application to small-scale devices. To eliminate the disadvantages of both methods, several authors have proposed a combined approach for radiation and scattering problems. For a comprehensive list of references on hybrid FEM/MoM techniques. The modeling of the coaxial feed here is accomplished by replacing the feed probe by a constant filament of current with a delta-gap generator. The feed modeling in here is expected to give good results for shallow cavities, but deep cavities require rigorous feed modeling. In this paper a combined FEM/MoM approach is used to predict characteristics of cavity-backed antennas . Various feed lines such as a rectangular waveguide, a circular waveguide, and a coaxial line are considered. Using the modal expansions of fields in the feed, the input admittance of cavity-backed antennas is calculated accurately. In most antenna-pattern measurements, the infinite ground plane is simulated by a relatively large finite ground plane. Although this simulation does not appreciably affect the input admittance measurements, diffractions from the edges of the ground plane modify the radiation pattern considerably.

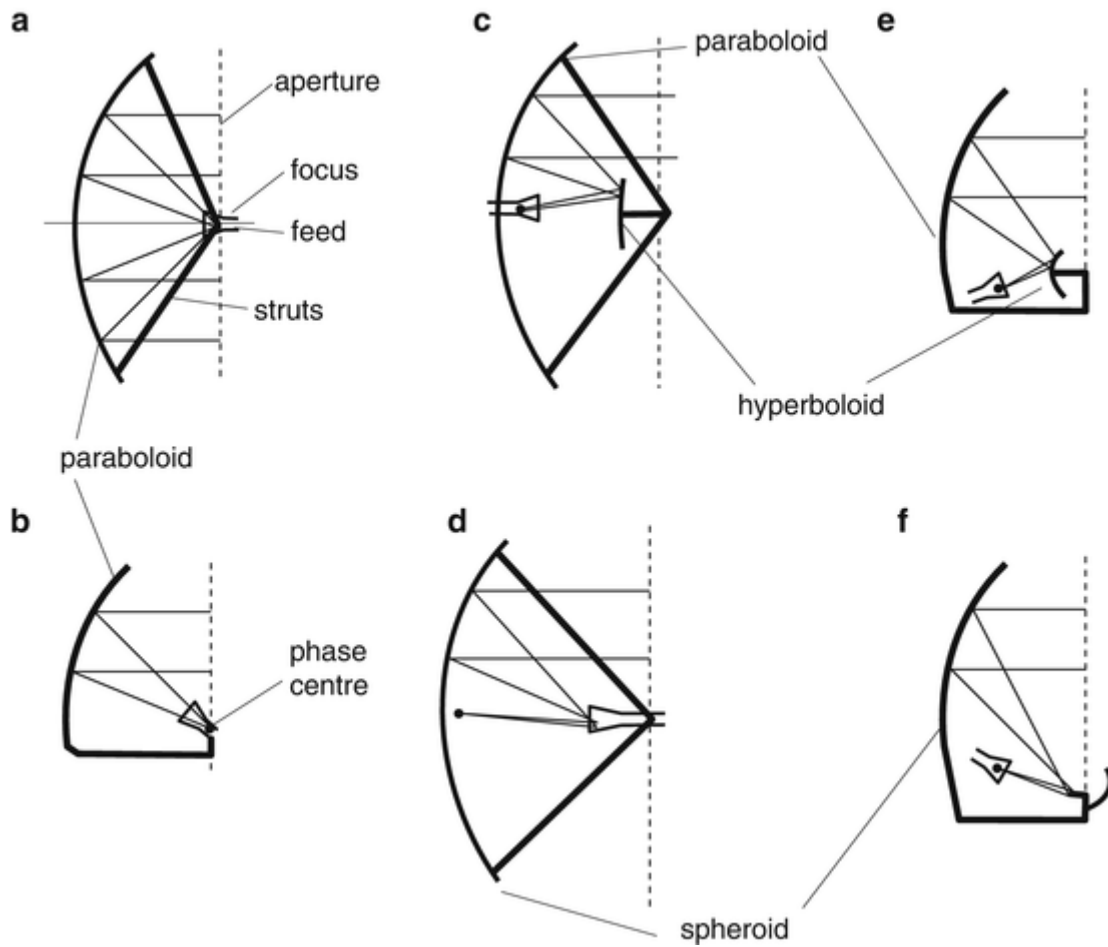


Near and far field

In the past, the geometrical theory of diffraction (GTD) was successfully applied to predict the changes in the radiation pattern of the aperture antennas caused by a finite ground plane. The technique 2 described here predicts the changes in the radiation patterns of cavity-backed aperture antennas with finite ground planes. The body of this paper is organized in the following manner. The article presents the theory for cavity-backed apertures in infinite ground planes. The paper compares the numerical results calculated using the present analysis with the available results in the literature. The input admittance calculations for an open rectangular waveguide, a circular waveguide, and a coaxial line are presented and compared with the results available in the literature. To verify the validity of the GTD technique used in combination with the FEM/MoM technique, the radiation patterns of a coaxial cavity with finite ground plane are calculated and compared with experimental results measured at the Langley Low-Frequency Antenna Test Facility. Numerical data for input return loss of such a coaxial cavity are also computed and compared with experimental data. Section 4 presents concluding remarks. For completeness, an appendix includes expressions for modal expansions of electric fields of input-feed-line structures.

II. OBSERVATIONS

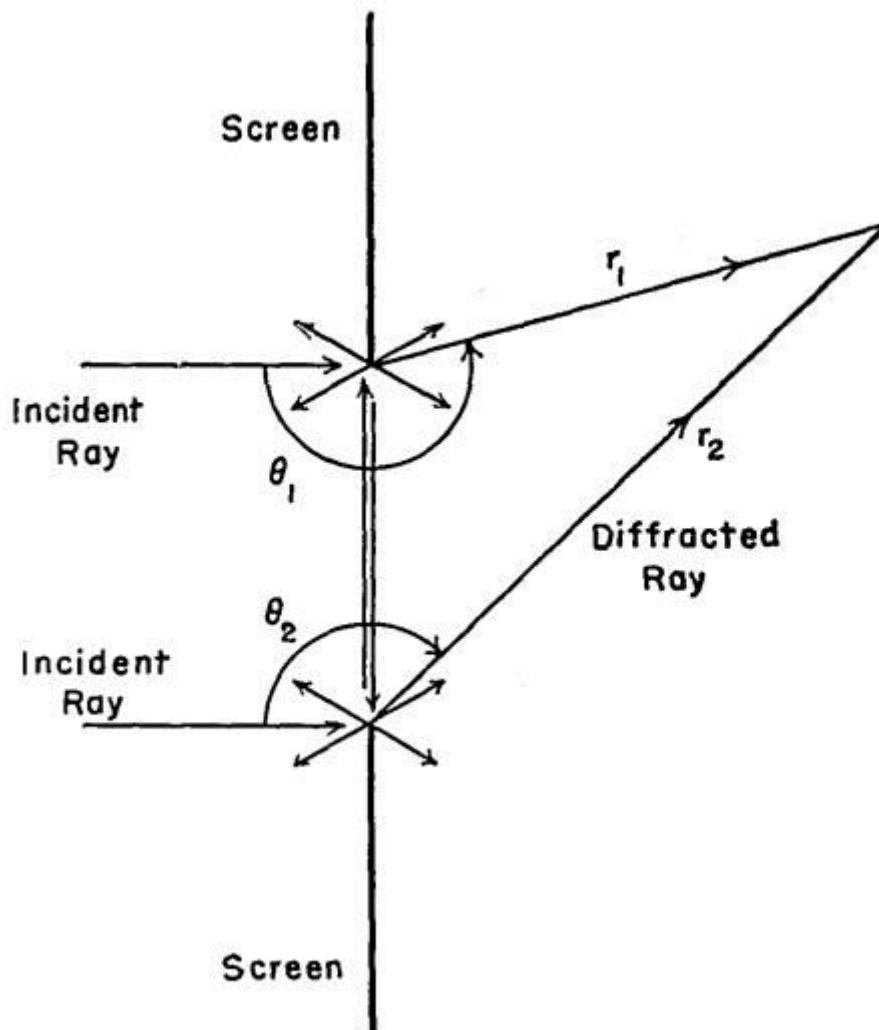
A circular aperture in an infinite ground plane and excited by a circular waveguide is considered as a second example. The circular waveguide of length L from the aperture is considered as a circular cavity for FEM discretization. The dominant TE₁₁ mode is considered to be incident at the plane $z = -L$. The input admittance is computed as a function of the radius of the waveguide and along with the numerical data given by Bailey and Swift. Very good agreement is seen between the results computed using the present technique. Radiation characteristics of cavity backed aperture antennas in finite ground plane are presented using a hybrid FEM/MoM technique and GTD. Various numerical examples are considered to demonstrate the flexibility and validity of the method. Very good agreement is seen between the numerical data obtained using the present method and the data available in the literature. The successful application of the GTD method in conjunction with FEM-MoM is demonstrated for calculating the radiation patterns of a coaxial cavity with finite ground plane. Since FEM is used for cavity region this method is applicable to arbitrarily shaped cavities with complex and anisotropic materials. By proper modelling, the present method can be used to analyze microstrip antenna arrays residing in a cavity with finite ground plane. This method can also be easily extended to a finite circular ground plane without much effort.



Reflector antennas

III. DISCUSSION

In optics, the Fraunhofer diffraction equation is used to model the diffraction of waves when the diffraction pattern is viewed at a long distance from the diffracting object (in the far-field region), and also when it is viewed at the focal plane of an imaging lens.[1][2] In contrast, the diffraction pattern created near the object (in the near field region) is given by the Fresnel diffraction equation. The equation was named in honor of Joseph von Fraunhofer[3] although he was not actually involved in the development of the theory. This article explains where the Fraunhofer equation can be applied, and shows the form of the Fraunhofer diffraction pattern for various apertures. A detailed mathematical treatment of Fraunhofer diffraction is given in Fraunhofer diffraction equation.

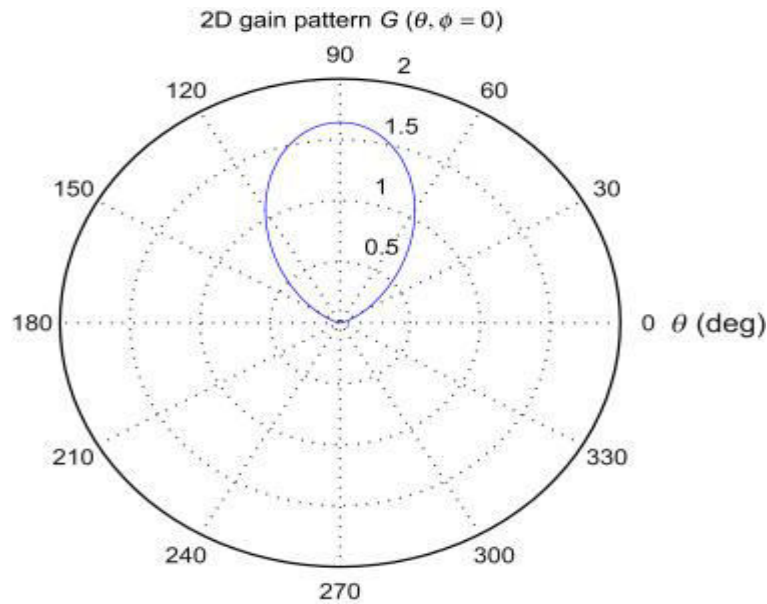


Theory of diffraction

Two powerful techniques for the analysis of aperture antennas are now used. One is based on the convenient Fourier transform relationship between aperture field and far-field radiation pattern. Here this relationship is derived from the plane wave spectrum representation of the aperture fields. In the near field of the aperture, Fourier transforms become Fresnel transforms. Far-field patterns may be predicted from near-field measurements by treating the near field as the aperture plane. In its application this method is basically the Kirchhoff approximation of diffraction theory. It is accurate for the forward fields of large antennas but cannot provide the lateral and back radiation. The other method is based on aperture edge diffraction and called the geometrical theory of diffraction. It is developed from an asymptotic approximation to rigorous diffraction theory. Inherently more accurate and more widely applicable, it is especially useful in the calculation of antenna radiation in the lateral and rear directions. However, at present it fails in some situations where the Kirchhoff method succeeds, for example the axial fields of paraboloidal reflectors. In this sense the two methods are complementary and often both are required in antenna analysis. Application of the two methods to the calculation of the pattern, gain and reflection coefficient of some common antenna types is shown and comparisons are made with experiment.

IV. RESULTS

Radiation from a cavity-backed circular aperture surrounded by concentric corrugations is studied. An electromagnetic boundary-value problem of the cavity-backed circular aperture surrounded by concentric corrugations is solved by using the Green's function, Hankel transform, and mode matching method.

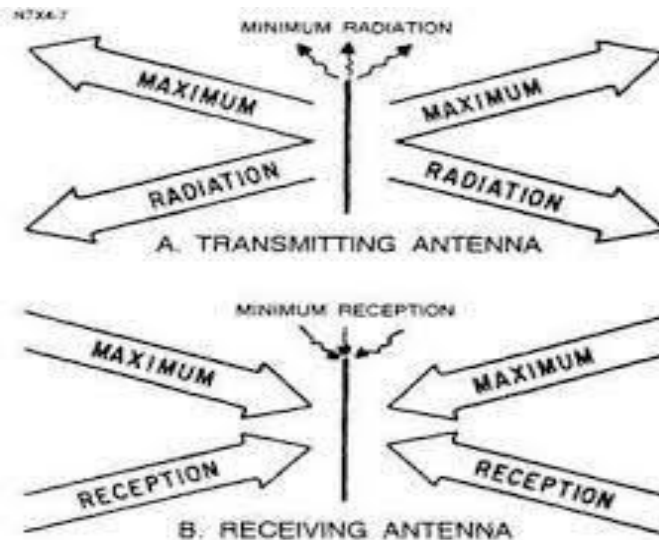


Radiation pattern

The radiated fields are computed in terms of corrugation geometry to illustrate radiation behaviors and measured to validate our computation. The effects of the corrugation geometries on the radiation are discussed. The asymptotic solution of a high-frequency electromagnetic field transmitted through a finite aperture is studied. In applying Keller's geometrical theory of diffraction (GTD), a basic yet unanswered question for an observation point in the lit region is: "Should the geometrical optics field on a direct incident ray be included in the total field solution." By studying a test problem and utilizing the newly developed uniform asymptotic theory (UAT), we have deduced simple and explicit rules for the role of the geometrical optics field and the regions of validity for GTD in a general aperture diffraction. The rules reveal that the success of GTD in treating aperture problems in the literature depends critically on the assumption that both the source and the observation points are infinitely far away from the aperture. Had either point been a finite distance away, Keller's GTD, in general, would fail and UAT must be used.

V. CONCLUSION

We report measurements of photon and neutron radiation levels observed while transmitting a 0.43 MW electron beam through millimeter-sized apertures and during beam-off, but accelerating gradient RF-on, operation.





Antenna and wave propagation

These measurements were conducted at the Free-Electron Laser (FEL) facility of the Jefferson National Accelerator Laboratory (JLab) using a 100 MeV electron beam from an energy-recovery linear accelerator. The beam was directed successively through 6 mm, 4 mm, and 2 mm diameter apertures of length 127 mm in aluminum at a maximum current of 4.3 mA (430 kW beam power). This study was conducted to characterize radiation levels for experiments that need more \hat{A} to operate in this environment, such as the proposed DarkLight Experiment. We find that sustained transmission of a 430 kW continuous-wave (CW) beam through a 2 mm aperture is feasible with manageable beam-related backgrounds. We also find that during beam-off, RF-on operation, multipactoring inside the niobium cavities of the accelerator cryomodules is the primary source of ambient radiation when the machine is tuned for 130 MeV operation. \hat{A} less

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