Surface Wave Diffraction by a Finite Metal Grating and Numerical Model for Design of Leaky-Wave Antennas

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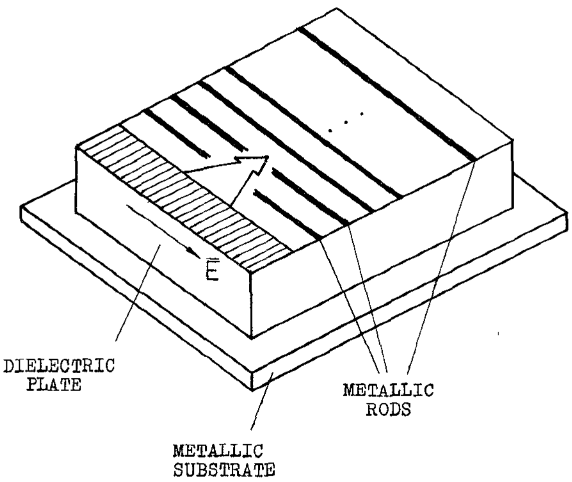
Abstract—**The electrodynamic problem of surface wave diffraction by a finite grating made of thin metal rods and placed on the dielectric plate is studied. Green's function of a dielectric slab situated on a metal substrate is used for mathematics. The system of algebraic linear equations in unknown complex amplitudes of currents in the rods is obtained in a particular case of normal incidence of the traveling wave upon the grating. The effective algorithm for numerical investigation of all diffraction characteristics of the structure is also elaborated. An example of the diffraction model application for design of a leaky-wave antenna in millimeter waveband is presented.**

I. Introduction

It is well known that periodical structures based on surface wave transmission lines can be successfully employed in microwave integrated circuits to fabricate leaky-wave antennas, filters and other devices [1]. In this letter, we have considered the finite periodical metal-dielectric structure working in a leaky-wave regime. Considerable attention has already been paid to a phenomenon of radiation in open waveguide structures with periodical inhomogeneities [2]. In theoretical works the method of investigation consists in computing of the leaky mode complex propagation constant in an infinite open periodical waveguide (see [3]–[6]). The real and imaginary parts of the calculated propagation constant enable to estimate direction of the main beam and half power beam width. In this case the problem of efficiency of radiator excitation by the surface wave and the problem of end effects remains unsettled. So we have considered the problem of modeling of dielectric plate surface wave diffraction by the finite grating made of thin metal rods and elaborated the algorithm for its numerical solution. The suggested diffraction method has been applied for the investigation and design of leaky-wave antennas in millimeter waveband.

II. The Model and Method of Analysis

The model shown in Fig. 1 is used to solve the diffraction problem. The dielectric plate with thickness $2a$ and relative permittivity of ϵ is situated on the metal substrate. A grating consisting of N thin metal rods with period l is placed on the surface of the dielectric plate. For analysis simplification the



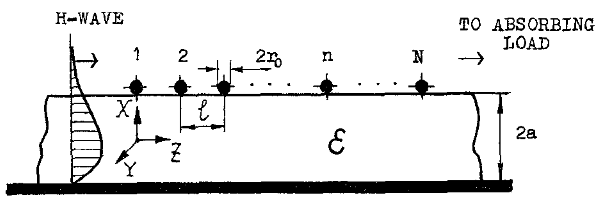


Fig. 1. Normal incidence of surface H-wave upon a finite grating of thin metal rods.

shape of the grating elements has been chosen to be a circular cylinder with small radius r_0 ($r_0 \ll \lambda$ where λ is a free-space wavelength), but it is not a strong limitation. We assume the transmitted power completely absorbs in a load and in the beginning the thermal losses in the structure are neglected.

Let a plane H-wave with nonzero and y-independent components H_x, H_z and E_y incidents perpendicularly upon the grating from the left side $z < 0$. The unperturbed propagation constant is $\gamma = kU$ where k is the free-space wavenumber ($k = 2\pi/\lambda$) and U is the phase retardation factor. Using the Green's function for the dielectric plate situated on the metal substrate and satisfying the boundary condition for the E_y component of the field on the cylinders' surfaces we obtain the N Kirchhoff equations:

$$I_m Z_o + \sum_{n=1}^{N}{}' I_n Z_{|m-n|} + E_0 e^{-i\gamma l(m-1)} = 0, \qquad m = 1, 2, \cdots, N, \quad (1)$$

Manuscript received May 10, 1991.
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IEEE Log Number 9102911.

1051-8207/91/1000-0282$01.00

where I_n is an unknown complex amplitude of the current in the nth rod, Z_o is a rod's own impedance, $Z_{|m-n|}$ is a reciprocal impedance of the nth and mth elements. In the free term the value of E_0 depends on the amplitude of the incident surface wave. The prime indicates that $n = m$ are to be omitted when summing. The solution of (1) enables to determine the main diffraction characteristics of the structure: a reflection coefficient R, transmission coefficient T, radiation pattern $\psi(\varphi)$ (φ is an angle between the z axis and radiation direction) and radiation power P_{rad}. As the thermal losses are neglected, the following equality clearly takes place:

$$1 - |R|^2 - |T|^2 = \int_0^{\pi} |\psi(\varphi)|^2 \, d\varphi. \tag{2}$$

The equality (2) can be used for the verification of final results.

The main difficulty in finding of the solution of (1) is a calculation of the matrix coefficients $Z_{|m-n|}$. For this purpose it is necessary to accomplish numerical integration of the highly complicated functions having a pole type singularities in the integration contour. The residue at the pole describes the interaction between the grating elements through the surface wave field. The numerical integration also enables to take into account interaction between elements through total waves spectrum. Besides when the index $|m - n|$ is large enough the appearance of fast oscillations in the integrand must be taken into consideration. However, we have succeeded in overcoming the difficulties and computing the coefficients $Z_{|m-n|}$ quite effectively even in the case of the large number N (in practice N can reach several tens).

III. Results

An example of application of numerical model to a design of the radiator is shown in Fig. 2 in the case when a number of rods N in the structure must be determined. The other parameters are the following: an operating frequency $f = 60$ GHz ($\lambda = 5$ mm), $\epsilon = 9.8$, $2a = 1$ mm, $r_0 = 0.02\lambda$, $l = 0.3657\lambda$. The value of $\gamma = 2.461k$ and the value of a phase shift between neighboring rods $\gamma l = 1.8\pi$ correspond to the parameters. The example obviously demonstrates rereflection phenomenon caused by a finite length of the grating. As N increases the reflection coefficient nonmonotonically reaches some value that is determined by the surface wave reflection by the semi-infinite grating while the transmission coefficient reaches zero. But even for the large N the reflection by the right end of the grating has still an influence on the diffraction characteristics. The current amplitude distribution along the grating and radiation pattern having an oscillatory behavior are shown in Figs. 3 and 4 for $N = 60$. The physical explanation of such behavior is the following. The excited leaky wave of the periodical metal-dielectric structure that travels along the positive z-direction partly reflects from the right end and travels in the opposite direction. On the whole 96.7% of incident power is radiated, 1.3% is reflected and 2.0% is nonradiated and absorbs in the load. The difference between the right and left sides of the equality (2) is about 10^{-6}, which confirms the correctness of the obtained results.

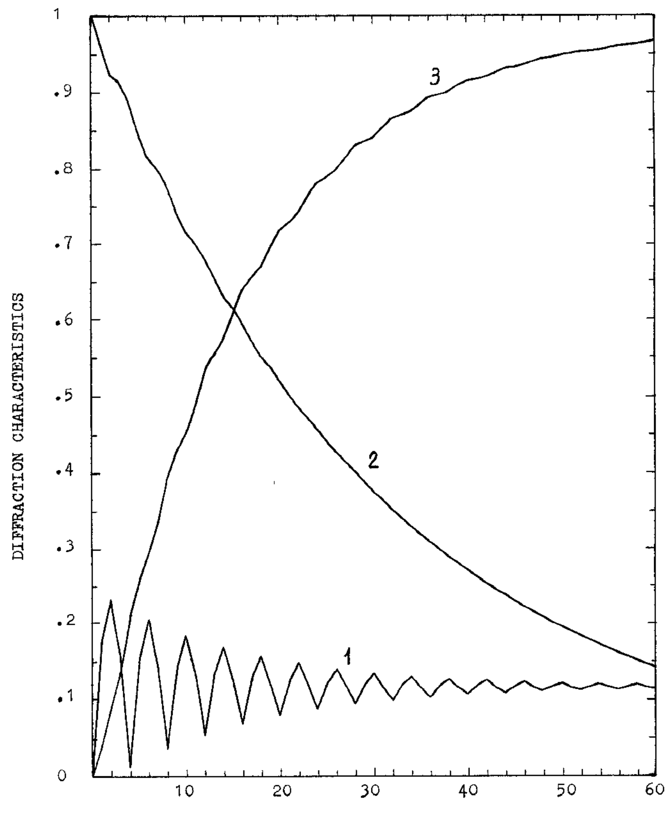

Fig. 2. Diffraction characteristics of the grating depending on the total number of rods: 1—reflection coefficient $|R|$, 2—transmission coefficient $|T|$, 3—radiation power P_{rad}.

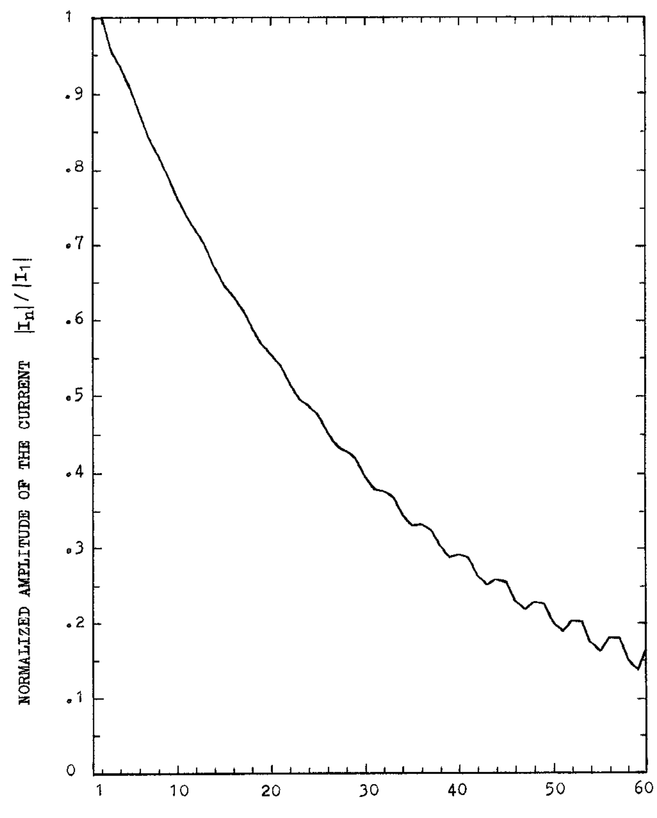

Fig. 3. Normalized distribution of a current modulus along the grating for a value of $N = 60$.

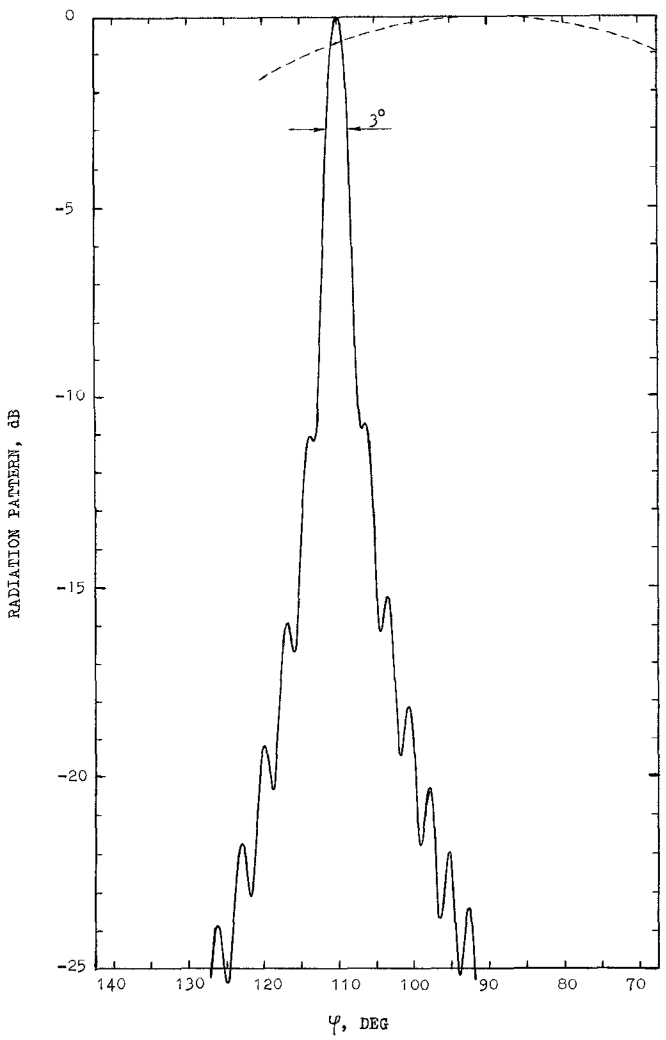

Fig. 4. Fragment of a radiation pattern in the neighborhood of the main beam for a value of $N = 60$. Broken line is a radiation pattern of the alone element ($N = 1$).

If a nonzero imaginary part of the permittivity Im $\epsilon = 10^{-4}\epsilon$ and finite metal conductivity (copper) are taken into account the thermal losses in the different parts of the structure must be estimated. Under present conditions the losses are approximately distributed in the following proportion: 1.9% in the dielectric plate, 1.6% in the metal substrate and 0.3% in the rods.

IV. Conclusion

Thus the numerical model of the surface wave diffraction by a finite grating formed by thin metal rods is elaborated. The example of study of the leaky-wave antenna in millimeter waveband is presented. The results of the work confirm that the investigation of diffraction phenomena can serve as a basis for a choice of antenna parameters in a real design situation. It should also be noted that the suggested approach can be applied to a wider class of the structures including antennas with nonperiodical gratings and Bragg diffraction filters.

References

[1] T. Itoh, "Application of gratings in a dielectric waveguide for leaky-wave antennas and band-reject filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1134-1138, Dec. 1977.
[2] A. A. Oliner, "Resent developments in millimeter-wave antennas," *Alta Freq.*, vol. 58, pp. 491-505, Sept.-Dec. 1989.
[3] M. Guglielmi and A. A. Oliner, "A practical theory for dielectric image guide leaky-wave antennas loaded by periodic metal strips," presented at *Proc. 17th European Microwave Conf.*, Rome Italy, Sept. 7-11, 1987, pp. 549-554.
[4] R. Mittra and R. Kastner, "A spectral domain approach for computing the radiation characteristics of a leaky-wave antenna for millimeter waves," *IEEE Trans. Antennas Propagat.*, vol. AP-28, pp. 652-654, July 1981.
[5] M. Ghomi, H. Baudrand, and C. Cavalli, "New approach for computing radiation pattern of dielectric leaky-wave antenna," *Electron. Lett.*, vol. 25, no. 5, pp. 345-346, Mar. 1989.
[6] M. Matsumoto, "Analysis of leakage properties of periodic dielectric image guides," *Electron. Lett.*, vol. 25, no. 23, pp. 1568-1569, Nov. 1989.