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Radiation from Open Waveguides and Leaky Wave Phenomena

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Abstract

Professor Oliner's work in the area of microwaves and millimeter waves has resulted in important contributions to the theory of open waveguides; to phased array theory; to the recognition and interpretation of new leaky wave phenomena; and, in recent years, to the design and analysis of a class of novel antennas derived from open mm-waveguides. A review of this work will be presented. The first part of the presentation will be concerned with Dr. Oliner's theoretical research, which was often complemented by careful experiments. The subject of the second part will be the applications resulting from this work as exemplified by the new class of open-waveguide leaky-wave antennas.

Introduction

During his long and distinguished career, Professor Oliner has made many important contributions in the areas of microwaves, mm-waves, acousto-electronics and optics. Much of this work has been concerned with the theory of open waveguiding structures for these frequency bands. His research has resulted in the in-depth understanding of the guidance, coupling and radiation properties of these open waveguides and in the discovery of new effects leading to interesting new applications.

Dr. Oliner's work on guided wave phenomena in the strict (non-radiative) sense is the subject of a different paper that will be presented during the same session. The present paper is concerned with the coupling and radiation properties of open waveguides and in particular with his contributions to phased array theory and his work on leaky wave phenomena: their theory, and their utilization in the design of novel antennas and in the explanation of complex scatter, coupling and radiation effects.

Dr. Oliner's contributions are remarkable not only because of their quantity - he has made important contributions to every field in which he has worked - but, in particular, because of their unusual depth and clarity. Several of his achievements are of path-breaking significance and the papers reporting on this research have become classics in their field. For the author of the present paper, this presented a certain problem since he realized immediately that it would not be possible to do justice to Dr. Oliner's achievements within the framework of a short paper. It would be possible only to discuss a few of his major accomplishments and, for the necessary detail, to refer the reader to the cited publications.

In the following an attempt is made to briefly review some of Professor Oliner's most important contributions. Then, during the Special Session at the MTT Symposium in New York, the author plans to concentrate on one of these achievements, the theory and design of a novel class of mm-wave antennas, to demonstrate the way Dr. Oliner has approached this type of problem and to point out the significance, depth and practical usefulness of this research.

Major Contributions

Several of Professor Oliner's major contributions are summarized here in historical order:

1. Radiating Slots

Dr. Oliner derived the well-known closed form expressions for the impedance properties of resonant slots in rectangular waveguide, which are now widely used in the antenna literature. The theoretical expressions he obtained for inclined and displaced series slots are still the best available today, both at and away from resonance [1]. He also provided, for the first time, a method to account for the slot depth (wall thickness); and this technique has been referred to as Oliner's method.

2. Early Leaky-Wave Antennas

In the 1950's there was a great deal of interest in leaky-wave antennas based on rectangular waveguide, such as those sketched in Fig. 1. But the theory of these antennas was not understood until it became clear that a free resonance condition had to be applied leading to a characteristic equation whose improper poles provided the desired leaky wave solutions. Using this concept, Professor Oliner and his associates then developed a systematic method

[2,3] to obtain highly accurate solutions for the structures of interest which included slitted circular waveguide and trough guide (Fig. 2) in addition to the rectangular guide antennas of Fig. 1. The method employs a transverse resonance procedure and expressions derived for the side discontinuities viewed transversely. The results were used very successfully for the design of a variety of antennas, and C. H. Walter in his book, "Traveling Wave Antennas" [4] quotes Dr. Oliner's work more often than that of any other author.

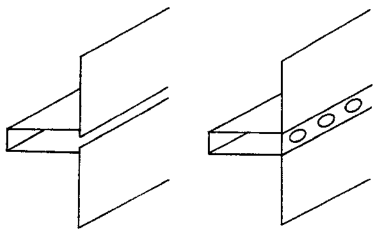

Fig. 1. Leaky-wave antennas based on rectangular waveguide

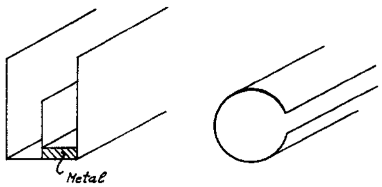

Fig. 2. Leaky-wave antennas based on trough guide and circular waveguide

3. Phased Arrays

Professor Oliner developed a totally new approach to the analysis of phased array antennas [5]. This approach introduced the unit cell concept into phased array theory, in conjunction with the idea of phase-shift walls when the array is scanned. This new concept reduced the whole array, with the scanning function included, to a single waveguide, where the junction with free space involves a transverse discontinuity (containing the slots) between the feedguide and the outside periodic waveguide with phase-shift walls. The antenna analysis is thus reduced to a waveguide problem. In terms of results, the new theory allowed, for the first time, to take all mutual coupling effects accurately into account and to predict the scan performance in both principal planes correctly.

The basic approach, with much additional material, was presented in detail in Vol. II of R.C. Hansen's book, "Microwave Scanning Antennas" [6], and helped to make this book one of the best available on this subject, even today after more than twenty years. Due to Professor Oliner's work and the leadership he provided in this area, the reputation of the Polytechnic Institute in phased arrays became very strong, and this school was asked by DARPA to conduct a four-day symposium on this subject in June 1970. Under Dr. Oliner's chairmanship the symposium became a great success. The Proceedings were published by Artech House under the title, "Phased Array Antennas" [7].

A further important achievement of Dr. Oliner in phased array theory was the explanation of the theoretically very difficult problem of scan blindness which he studied and solved in cooperation with A. Hessel and G. H. Knittel [8, 9].

4. Leaky-Wave Interpretations of Interesting Physical Phenomena

Leaky waves are an advanced and very useful concept, but they have been viewed sometimes with suspicion since they are not proper modes of the (open) guiding structures where they occur and since they do not satisfy the radiation condition at infinity. But they are exact solutions of Maxwell's equations, and in the space range of interest, energy leakage and coupling phenomena can often be explained in a very clear and concise manner by the use of this concept while a representation in terms of proper modes would lead to a mathematically complicated formulation which is difficult to interpret in physical terms. Dr. Oliner was one of the first to fully understand the usefulness (and limitations) of leaky modes. He has utilized these modes in the analysis of a number of different physical phenomena, and in doing so he has clarified and explained this rather powerful concept. These applications include the analysis of radiation from slots on a reentry vehicle when it is covered by a plasma sheath [10]; a new interpretation of the Wood's anomalies on optical gratings [11]; the explanation of blindness in phased arrays [8,9]; and a new theory of Čerenkov and Smith-Purcell radiation [12]. Out of each of these appli- cations there emerged a new theory that not only provided a novel approach but also yielded new results that had not been obtained using more conventional methods. For example, the new interpretation of the Wood's anomalies had a broad impact far beyond the explanation of these anomalies themselves, and the new theory of Čerenkov radiation provided a more complete analysis in addition to permitting a simpler physical "microwave" way of understanding this radiation.

5. New Leaky-Wave Antennas for the Millimeter Wave Region

In recent years, Professor Oliner has suggested and studied an interesting group of new mm-wave antennas. These radiating structures are derived from open mm-waveguides and may be described as uniform waveguide leaky-wave antennas or, more simply, as "antennas that are really waveguides." The antennas are novel with no microwave heritage. A main advantage is their simple structure which overcomes fabrication difficulties due to the short wavelength in the mm-wave region. Despite their structural simplicity, the antennas provide a high degree of design versatility.

The new antennas are based on low-loss waveguides, in particular NRD (non-radiative dielectric) guide and groove guide. Methods to induce radiation include the introduction of asymmetry, the foreshortening of (metal) walls, and the utilization of higher, leaky modes. The latter method has also been used for the design of a traveling wave antenna based on microstrip. All of these antennas, which operate as leaky- wave antennas but, apart from this common feature, show significant differences in their structure and performance, have been analyzed in detail by Dr. Oliner and his coworkers and can be regarded as well understood by now. Systematic design information useful for engineers is available. The analysis of the microstrip traveling wave antenna, furthermore, has resolved an interesting controversial question concerning the guidance and leakage properties of the higher modes on microstrip and has resulted in an antenna of substantially improved performance over an earlier version suggested by a different group.

The antennas may be used singly, as "line sources," or in arrays, in a parallel arrangement, providing highly directive beams that can be scanned by frequency variation in one principal plane and by phasing in the second plane. In addition, the antennas are directly compatible with the waveguides from which they are derived and useful for integrated designs; and most of these antennas are suitable for conformal and flush-mounted installation. Figure 3 shows an array of line sources of this type. The metal ridges separating the (closely spaced) element antennas are important for achieving the excellent scan performance of these arrays which, when appropriately designed, can be scanned over a relatively wide angular range with little beam degradation, negligible cross polarization, no blind spots and no grating lobes.

A detailed review on these new leaky-wave antennas, which contains much of the available information, will appear in the millimeter wave antenna chapter of a new Handbook on Antenna Theory and Design edited by Y. T. Lo and S. W. Lee [13]. The handbook is scheduled for publication in 1988.

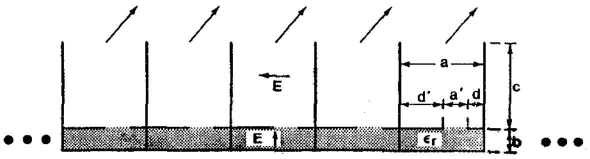

Fig. 3 Cross-section view of linear array of novel leaky-wave line sources. The line sources in this case are printed circuit versions of offset-groove-guide leaky-wave antennas. These element antennas are fed from one end, and the array can be scanned in the longitudinal plane by frequency variation and in the cross-section plane by phasing.

Presentation

The presentation during the Special Session at the MTT Symposium will be concerned primarily with the last subject discussed above, i.e. with the class of new leaky wave antennas derived from open mm-waveguides. It is hoped that by presenting one of Dr. Oliner's major contributions in some detail, his method of approach will become more apparent. It is characterized by first achieving a completely clear, in-depth understanding of all the physical phenomena involved, which is then used to devise a method of analysis that is tailored to the problem, conceptually transparent (e.g. taking the form of a network representation) and, as a consequence, produces highly accurate results often in an unexpectedly simple analytical form despite the complexity of the problem. These formulas are then used to determine the performance of the antennas precisely and with careful attention to detail, leading to a full characterization of these devices and to design guidelines useful for engineering applications.

EM theory is sometimes viewed as a "mature science." This author is ready to accept this term provided it is understood in the sense that the simpler problems have been solved and the new problems awaiting solution are of a much more difficult nature requiring the development of advanced analytical and numerical methods. What is needed now, even more than before, are conceptual clarity and in-depth understanding and, based on this, the development of solution methods that are adapted to the problem at hand and can be carried through to a large extent analytically. Only in this way the physical implications of the problem can be fully understood; and experience shows that such methods usually result in well converging numerical techniques. This author feels that Dr. Oliner has mastered this difficult art in a way which is setting standards, and that there is a great deal to be learned from his approach for everyone working in the area of electromagnetic research.

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