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Perspectives on Guided Wave Phenomena

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Abstract

This talk summarizes the work carried out by Professor A. A. Oliner on guided waves throughout his long productive career. As repeatedly pointed out by Prof. Oliner, physically correct guided wave phenomena in certain structures may be hard to find due to hidden factors; ignorance of them will lead to incorrect judgement and unexpected results. This paper reviews several such examples that demonstrate the need for such investigations. Discussion will include applications to contemporary problems.

Introduction

This paper is an attempt to highlight the contributions by Professor Oliner in the area of guided waves. His publication activities started in the late 1940's and the number of publications at the last count exceeds 170. His work on guided waves include acoustic waves, optical waves as well as microwaves and millimeter-waves. He has made major contributions in every area he has worked. Many of these are still used and referenced. This is an attempt to highlight his contributions in the area of guided waves. This topic includes analysis and understanding of wave phenomena in various guided wave structures as well as those generated by a discontinuity. Here, "guided wave structures" means more than a guide, such as a stripline, but includes such structures as an open periodic structure along which a wave can be guided. The wave guided along these guided wave structures may be purely bound or leaky. The topic of the leakage, primarily used for the production of antennas, will be left for a companion talk in this session. Nevertheless, leakage phenomena associated with the guided wave needs to be taken into account for complete understanding.

Dr. Oliner's contributions on guided waves can be classified into five categories. (1) Equivalent circuits for discontinuities in striplines, (2) Various wave types along the interfaces and plasma layer, (3) Open periodic structures, (4) Guidance and leakage properties of open dielectric waveguides, and (5) Leakage effects in microwave integrated circuits. In this paper, the essence of each topic will be described. Items (4) and (5) will be explained in somewhat more detail as they have immediate applications to comtemporary applications in microwave integrated circuits, which are of interest to the majority of the audience.

Equivalent Circuits for Stripline Discontinuities

Today, an extensive effort is being expended for development of microwave integrated circuits. During the 1950's a similar effort existed in connection with striplines. Dr. Oliner was involved with this research and the first to point out that the stripline discontinuity has a reactive component[1] which is well known today. In addition to the expressions for the network elements, the paper was the first place in which the magnetic model was used to introduce an equivalent waveguide for a stripline. Prof. Oliner received the Microwave Prize in 1967 for this paper, which was published in 1955. The concept of an equivalent waveguide model was later used by Prof. Wolff within the framework of microstrip line discontinuity analysis.[2] This is a perfect example of Dr. Oliner's work having a contemporary application. In the case of the microstrip version, the waveguide model provides an "intermediate" solution, which is not completely the full-wave type as it neglects radiation and does not correctly incorporate higher order mode effects, but is superior to the quasi-static solution. It is interesting to point out that such an intermediate solution is not easily available for other planar transmission lines such as finline and slot line.

Various Wave Types along the Interface and Plasma Layer

Inspired by a great interest in the effect of plasma layer on the reentry vehicle, Dr. Oliner, along with Dr. Tamir, carried out an extensive study of waves associated with a plasma layer. Backward waves were first discovered,[3] and subsequently complex spectral waves[4] also, in an isotropic medium. The complex wave transferred no net power since the power circulated from the air to the plasma and always occurs in pairs. This wave has been investigated by Omar and Schuenemann in finlines[5] and by Clarricoates and Slinn in metal waveguides partially filled with dielectrics.[6] Another discovery is that of nonspectral leaky waves.[7] All of this work has been systematically combined in a pair of papers which received the Institution Premium from IEE.[8]

Open Periodic Structures

The surface wave and leaky wave associated with a periodic structure have been difficult problems for rigorous characterization. Dr. Oliner, along with Dr. Hessel, used a sinusoidally modulated suface to obtain the rigorous solution for the first time.[9] This study was later extended to investigate an anomalous scattering phenomena called Wood's anomaly in a grating structure. This study was conducted rigorously by use of the guided wave approach.[10] Further studies have resulted in characterizations of the mode-coupling phenomena in the so-called stop-band regions.[11]

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With a renewed interest in dielectric waveguides during the late 1970's and early 1980's, Dr. Oliner in collaboration with Dr. Peng initiated an effort to seek accurate solutions for TE and TM mode coupling at a step in a grooved dielectric grating. In the k-β diagram, every stop band becomes four stop bands, anisotropy is introduced, the leakage at higher frequencies occurs at skew angles, and strong cross-polarization effects arise. The findings have been reported in a number of recent publications.[12,13]

Guidance and Leakage Properties of Open Dielectric Waveguides

In connection with extensive works by many researchers on dielectric waveguide structures during the late 1970's, new dielectric waveguides have been invented and more rigorous analyses have been introduced for existing and new structures. Dr. Oliner's group has provided a major contribution in this regard. In this paper, their contribution will be illustrated by an example.

The problem selected as an example is the analysis of an inverted strip dielectric (ISD) waveguide.[14] This choice was made because it is one of the most familiar to the author and it contains many essential features characteristic to Dr. Oliner's work. Fig.1 shows a cross section of the ISD. When this waveguide was conceived, it was expected that the wave was guided. This was because, in the vertical direction the wave is concentrated in the guiding layer, which has the highest permittivity, and in the horizontal direction the effective dielectric constant in the central region (Region I) is larger than the two outside regions (Region II).

This waveguide has been analyzed by the "effective dielectric constant" (EDC) method. In this approach, both Regions I and II are considered to be a portion of a respective planar slab waveguide of infinite width. It is then assumed that only one mode of interest is found in each region by the transverse resonance analysis applied in the vertical direction. This process results in the dispersion characteristics of each mode. The effective dielectric constant is defined as that of a hypothetical medium in which the phase velocity of a plane wave is identical to that of the surface wave mode analyzed as above. Regions I and II are now replaced with these hypothetical media and the transverse resonance condition is then applied in the horizontal direction. The solution to this equation is assumed to provide the phase constant of the guided mode of the original structure. Note that the geometrical discontinuity between Regions I and II are neglected. In many cases, a surprisingly accurate result can be obtained from this simple approach. In the case of ISD, the propagation constant and the field distributions computed by this method have even been verified by experiments.

Hidden Phenomena

It was not until the group led by Dr. Oliner started looking at the ISD problem that the EDC solution was found to be incapable of predicting the subtle, but important, physical phenomena of leakage and resonance associated with its guided mode.[15] It has been pointed out that the EDC method is actually the one mode approximation of the mode matching technique. Since each modal field in each constituent region (I or II) can be represented by an appropriate transmission line, the EDC method can be modeled by the cascaded transmission line. In the mode matching analysis, each constituent region is represented by more than one mode, or equivalent transmission lines, as shown in Fig.2. The discontinuity between the regions is represented by a box (transformer) as shown. By application of the mode matching method, a more accurate solution would result. However, the improved analysis method itself does not guarantee discovery of the new phenomena.

In most circumstances, at least two surface waves, one TE and one TM, are supported in each constituent region. Once this fact is recognized, it is readily seen that leakage and resonance could occur due to the TE-TM mode coupling at the discontinuity. The ISD is usually excited in a TM-like fashion, or in the E^y mode. If the TM transmission line in the outside region is below cutoff, the mode is guided under the EDC approximation. However, if TE modes are considered, the situation is different. For instance, if the TE line in the outside region excited by the mode coupling at the discontinuity is above cutoff, there is a leakage of the wave due to the power carried away from the central region by this mode. The resonance phenomena can be explained by way of the TE mode excited in the inside region (I).[16,17]

Lessons Learned

Once the equivalent circuit is created that includes at least two constituent modes in each region, it is not difficult to understand that the leakage and resonance phenomena are nothing magical, but very physical. However, the author has learned a valuable lesson. It is important to understand the physical phenomena as much as possible before some analytical or numerical methods are introduced. In many cases, if the model is far from the physical reality, the theoretical results will be poor. Unfortunately, in the case of the ISD the real part of the propagation constant is not strongly affected by the leakage and resonance phenomena as in many ISD configurations. Therefore, unless these new physical phenomena are anticipated and looked for by careful complex arithmetic, they may never be found. In fact, even the experimental investigation might not reveal these phenomena. Even though the loss of the guided power was found, there are many discontinuities such as a waveguide launcher appearing in the experimental setups and, hence, the loss can be attributed to these elements. Careful experimental verifications have of course been conducted once theoretical predictions were available.[18]

Leakage Effects in Microwave Integrated Circuits

The approach supported by the philosophy of observing the guided wave structure from a physical perspective led Dr. Oliner to focus his attention to different waveguide structures, nonradiative dielectric waveguide (NRD) invented by Yoneyama and Nishida.[19] Once again, by means of a rather simple equivalent circuit type approach supported by physical insight, the basic understanding of the guided mechanism and possible leakage in such a structure or modification has been presented.[20]

Recently, Dr. Oliner investigated the properties of higher order modes in a covered microstrip line and found that they become leaky near and below cutoff, and that the leakage is in the form of a beam at an angle above cutoff and spread out below cutoff. This leakage is in addition to the leakage produced by conversion into suface waves at microstrip discontinuities.[21] This new phenomenon, if overlooked, will cause serious problems in microwave integrated circuits at higher frequencies. The cross-talk and coupling due to these leakage effects can ruin the performance of a complex, high-density microwave and high-speed circuits unless these effects are properly understood and controlled.

Impact of Dr. Oliner's Work on the Contemporary Applications

Through a review of his contributions, the thought process and the approach characteristic of Dr. Oliner are, hopefully, extracted. From this all of us can learn a great deal, particularly as to how one might approach a new problem. As we have seen, the underlying philosophy of Dr. Oliner in attacking a guided wave problem is (1) complete understanding of all essential physical phenomena, (2) derivation of a simple model or an equivalent circuit, and (3) calculations only to the extent necessary for extraction of the phenomena.

Guided wave structures are expected to play an important role in microwave and other high frequency configurations and correct understanding will be indispensable. Perhaps, a number of new waveguide structures will be invented using the approach developed by Dr. Oliner to characterize all essential phenomena associated with the structure. New types of passive devices may be created if these phenomena are well understood.

Another area in which the leakage phenomena described above are important is a complicated integrated structure. Most numerical analysis methods are inadequate or uneconomical to completely characterize these complex structures in which interactions between devices exist in both conspicuous and non-conspicuous ways. However, by reducing these structures to a generic form and extracting only the essential features, basic understanding of wave interactions in such structures may be facilitated. In addition to qualitative understanding of the phenomena, numerical analysts will benefit by being able to devise their numerical algorithms so that these important phenomena are not missed and nonessential points can be bypassed.

In any case, in a world full of numerical procedures, an approach relying on a basic physical understanding should enjoy its importance and will be applied to a number of useful structures and devices.

References

1. A. A. Oliner, "Equivalent circuits for discontinuities in balanced strip transmission line", IRE Trans. Microwave Theory and Techniques, Vol. MTT-3, pp. 134-143, March 1955.
2. I. Wolff and N. Knoppik, "Rectangular and circular microstrip disk capacitors and resonators," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-22, pp. 857-864, October 1974.
3. A. A. Oliner and T. Tamir, "Backward waves on isotropic plasma slabs," J. Applied Physics, Vol. 33, pp. 231-233, January 1962.
4. T. Tamir and A. A. Oliner, "The spectrum of electromagnetic waves guided by a plasma layer," Proc. IEEE, Vol. 51, pp. 317-332, February 1963.
5. A. S. Omar and K. Schuenemann, "New type of evanescent modes in fin-lines," 15th European Microwave Conference, pp. 317-322, September 9-13, 1985, Paris, France.
6. P. J. B. Clarricoats and K. R. Slinn, "Complex modes of propagation in dielectric-loaded circular waveguide," Electronics Letters, Vol. 1, pp. 145-146, July 1965.
7. T. Tamir and A. A. Oliner, "The influence of complex waves on the radiation field of a slot-excited plasma layer," IRE Trans. Antennas and Propagation, Vol. AP-10, pp. 55-65, January 1962.
8. T. Tamir and A. A. Oliner, "Guided complex waves - Part I Fields at an interface," Proc. IEE (London), Vol. 110, pp. 310-324, February 1963; "Guided complex waves - Part II Relation to radiation patterns," Proc.IEE (London), Vol. 110, pp. 325-334, February 1963.
9. A. A. Oliner and A. Hessel, "Guided waves on sinusoidally-modulated reactance surfaces," IRE Trans. Antennas and Propagation, Vol. AP-7, pp. S201-S208, December 1959.
10. A. Hessel and A. A. Oliner, "A new theory of Wood's anomalies on optical gratings," Appl. Optics, Vol. 4, pp. 1275-1297, October 1965.
11. A. A. Oliner, "Guided complex waves on slow-wave periodic structures," in Proc. Symp. on Electromagnetic Wave Theroy, pp. 467-476, Pergamon Press, New York, 1965.
12. M. J. Shiau, H. Shigesawa, S. T. Peng and A. A. Oliner, "Mode conversion effects in Bragg reflection from periodic grooves in rectangular dielectric image guide," 1981 IEEE MTT-S International Microwave Symposium, pp. 14-16, June 15-17, 1981, Los Angeles, CA.
13. A. A. Oliner, "New physical effects on open dielectric waveguides due to TE-TM mode coupling," Proc. Seventh Colloquium on Microwave Communication, pp. 390-397, September 6-10, 1982, Budapest, Hungary.
14. T. Itoh, "Inverted strip dielectric waveguide for millimeter-wave integrated circuits," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-24, pp. 821-827, November 1976.
15. A. A. Oliner, S. T. Peng and J. P. Hsu, "New propagation effects for the inverted strip dielectric waveguide," 1978 IEEE MTT-S International Microwave Symposium, pp. 408-410, June 27-29, 1978, Ottawa, Canada.
16. S. T. Peng and A. A. Oliner, "Guidance and leakage properties of a class of open dielectric waveguides: Part I - ---Mathematical formulations," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-29, pp. 843-855, September 1981.
17. A. A. Oliner, S. T. Peng, T. I. Hsu and A. Sanchez: "Guidance and leakage properties of a class of open dielectric waveguides: Part II ----New physical effects," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-29, pp. 855-869, September 1981.
18. H. Shigesawa, M. Tsuji, J. S. Myung, S. T. Peng and A. A. Oliner, "Direct experimental confirmation of new leakage effects on open dielectric strip waveguides, " 1983 IEEE MTT-S International Microwave Symposium, pp. 293-295, May 31- June 3, 1983, Boston, MA.

19. T. Yoneyama and S. Nishida, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits", IEEE Trans. Microwave Theory and Techniques, Vol. MTT-29, pp. 1188-1192, November 1981.

20. A. Sanchez and A. A. Oliner, "Microwave network analysis of a leaky-wave structure in non-radiative dielectric waveguide," 1984 IEEE MTT-S International Microwave Symposium, pp. 118-120, May 30 - June 1, 1984, San Francisco, CA.

21. A. A. Oliner and K. S. Lee, "The nature of the leakage from higher modes on microstrip line," 1986 IEEE MTT-S International Microwave Symposium, pp. 57-60, June 2-4, 1986, Baltimore, MD.

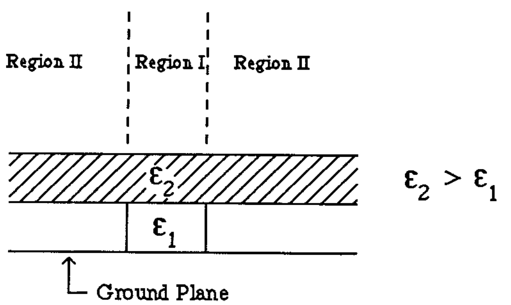

Figure 1 Inverted strip dielectric waveguide and its model by the effective dielectric constant method

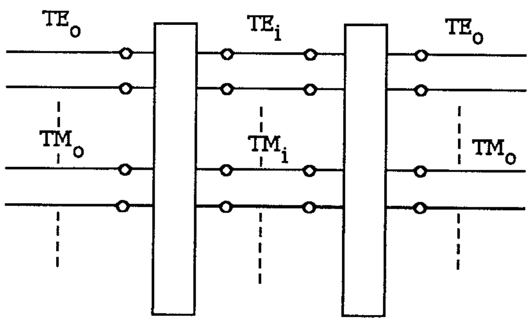

Figure 2 Equivalent circuit including TE and TM transmission line networks