The Excitation of Surface Waveguides and Radiating Slots by Strip-Circuit Transmission Lines*

A. D. FROST,† C. R. McGEOCH,‡ AND C. R. MINGINS†

Summary—**A variety of methods for coupling between a shielded strip-circuit transmission line, operating in the TEM coaxial mode, and a surface waveguide have been investigated. The arrangements include phased dipole arrays, series ground-plane slots and longitudinal slot excited probes. Impedance and matching conditions for each are discussed together with their relative efficiency and bandwidth. In the case of a single radiating slot, measurements on the effective equivalent circuit have been made as a function of the orientation angle of the slot with respect to the axis of the strip-line guide. Slots used ranged in length from 0.3 to 0.6 λ_g, having length /width ratios from 5 to 16.**

Introduction

UNDER THE sponsorship of the Antenna Group of the Air Force Cambridge Research Center, the Research Laboratory of Physical Electronics at Tufts University has undertaken a continuing study of some of the basic properties of strip transmission lines. These studies have been made from both the theoretical and the experimental points of view.[1,2] The work has included investigations into the characteristic impedance, the power handling capabilities, and the losses of various types of lines using both air and solid dielectric. In addition, measurements have been made to establish typical design parameters for such simple line configurations as bends and steps. More recently our attention has turned to a consideration of the problems associated with the integration of strip-line components with existing or proposed microwave system elements. This paper is a report on one phase of this work having application in the field of antennas and radiating structures; that of the coupling of strip line to dielectric-coated conducting sheet waveguides, to surface waves guided by a corrugated ground plane, and to the radiation from slots in strip line.

The investigations reported here were carried out using a so-called balanced strip line with a dual center conductor etched on both sides of a copper-coated teflon glass base material 1/32 inch thick. The lines have an air dielectric and are supported between two parallel ground planes. All lines have a nominal characteristic impedance of 50 ohms and a ground-plane spacing of 0.500 inches. The center conductors have a width of 0.625 inches and are held in position at the lateral edges of the base material by posts which serve also to electrically connect the ground planes at frequent intervals.

Measurements on Radiating Slots

A theoretical expression for the radiation conductance of a narrow transverse slot in one ground plane of a strip-line structure having the configuration shown in Fig. 1 was contained in a paper presented by Dr. Arthur Oliner at the Symposium on Microwave Strip Circuits held at Tufts University, October, 1954.[3] His evaluation gives the normalized conductance of a narrow slot in a thin ground plane with the axis of the slot perpendicular to the principal axis of the strip-line guide. This conductance is expressed as a function of the slot width a',

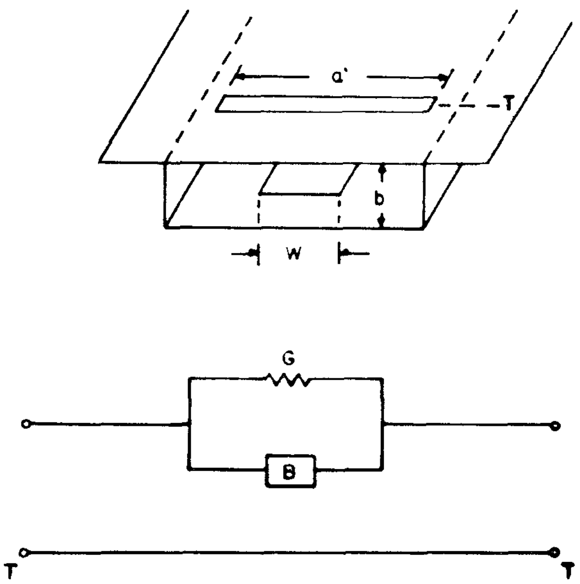

Fig. 1—Transverse slot in equivalent strip-line guide with midplane equivalent circuit representation.

* Manuscript received by the PGMTT, July 16, 1956. Presented before the National Symposium on Microwave Techniques, Philadelphia, Pa., February 2–3, 1956. This work has been performed under Contract No. AF 19(604)-575 with the AF Cambridge Research Ctr., Air Research and Development Command.

† Dept. of Physics, Tufts Univ., Medford, Mass.
‡ Formerly at Dept. of Physics, Tufts Univ., now with Bomac Labs., Beverly, Mass.

[1] A. D. Frost and C. R. Mingins, "Microwave strip circuit research at Tufts College," IRE Trans., vol. MTT-3, pp. 10–12; March, 1955.

[2] R. L. Pease and C. R. Mingins, "A universal approximate formula for characteristic impedance of strip transmission lines with rectangular inner conductors," IRE Trans., vol. MTT-3, pp. 144–148; March, 1955.

[3] A. A. Oliner, "Equivalent circuits for discontinuities in balanced strip transmission lines,. IRE Trans., vol. MTT-3, pp. 134–143; March, 1955.

the wavelength, and a parameter related to the width of the center conductor.

The test fixture which was designed to permit measurement of such slot radiation effects and of the properties of other stripline components is shown in Fig. 2.

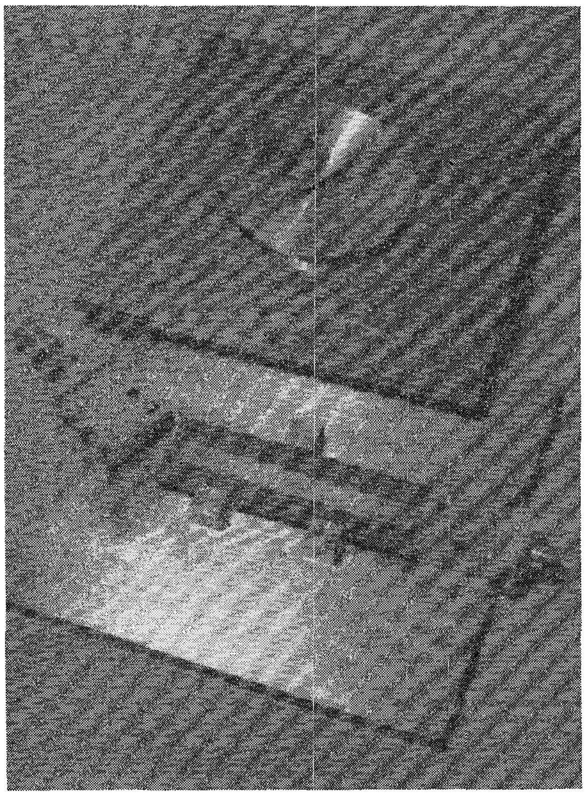

Fig. 2—Test fixture for slot radiation measurements.

The section is fitted with a circular removable center section which can be rotated for other measurements discussed in a later section of this paper. The strip line is joined at one end to a slotted line and at the other to a coaxial moving short using simple strip line to type N connector transitions such as those described by Fubini[4] and Fromm.[5] With a matched load at the terminal end of the system and a blank cover in place, the test section gave an over-all vswr of 1.1 in the operation range from 8 to 11 cm while with the movable short in position the vswr was under all conditions greater than 36 db.

Measurements of the input reflection coefficient of the test system as a function of the position of the moving short were taken for a number of slots ranging in length from 0.2 to 0.6 of a wavelength at orientations from 0° to 90°. In each case an approximate series conductance term introduced by the slot, as compared with the conditions with the blank in place, was determined.

The results for some of the measurements are shown in Fig. 3 together with the theoretical curve of normalized slot conductance as a function of slot length in wavelengths. The points shown represent slots which differ both in length and in length/width ratio. The posts which join the ground planes and incidentally serve to support the center conductor must have a lateral spacing measured at right angles to the axis of the strip line that is less than a half wavelength to insure dominant TEM mode operation. It is therefore not possible to excite a 90° slot which is a half wave long in the manner pictured in Fig. 1, in which it is presumed that the wave field in the guide is effective for the entire width. The use of additional grounding posts which has been made in some cases would not correspond to this situation. The possibility suggests itself, however, that operation of a slot rotated away from the 90° position could be substituted in some cases, providing sufficient line-to-slot coupling was achieved. In this way a slot of resonant length could be accommodated within the practical limits of a strip-line system. while maintaining the post spacing requisite for mode suppression.

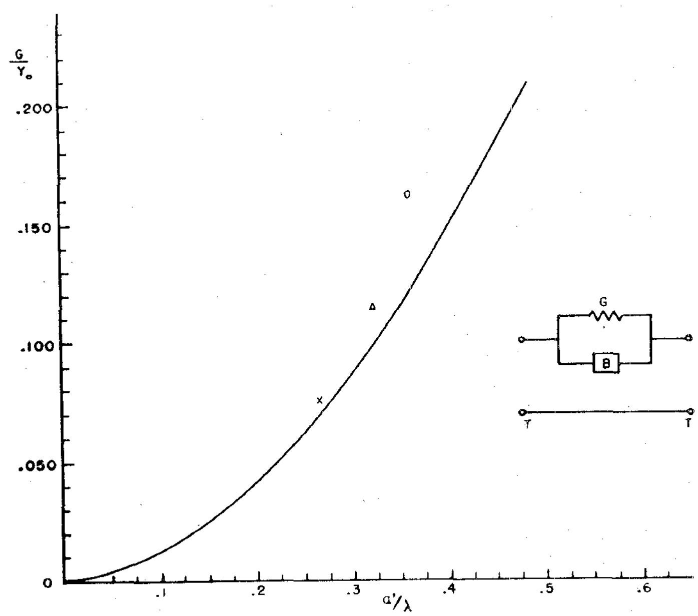

Fig. 3—Normalized slot conductance as a function of slot length. Measured values for finite width slots are shown.

A theoretical expression in integral form for the variation in slot conductance as a function of slot orientation angle has also been derived by Dr. Oliner but has not yet been evaluated. This derivation assumes, as does the previous one for the 90° slot, a thin ground plane and symmetrical orientation of slot and line.

Analysis of a range of measured values of slot conductance component as a function of rotation gives the

[4] E. G. Fubini, "Stripline radiators," IRE Trans., vol. MTT-3, pp. 149–156; March, 1955.

[5] W. E. Fromm, "Characteristics and some applications of stripline components," IRE Trans., vol. MTT-3, pp. 13–20; March, 1955.

data shown in Fig. 4. Relative conductance as compared to the value in the transverse or 90° position is plotted as a function of rotation angle. As was the case in the previous curve, these curves are for slots which differ both in length and length/width ratio. For shorter lines, those having a length a little more than twice the width of the center conductor, the variation in conductance is slow at small angles. In general most of the change takes place between 30° and 60°. Measurements on slots closer to resonant length than these confirm the sharp rise in conductance shown for angles less than 30°.

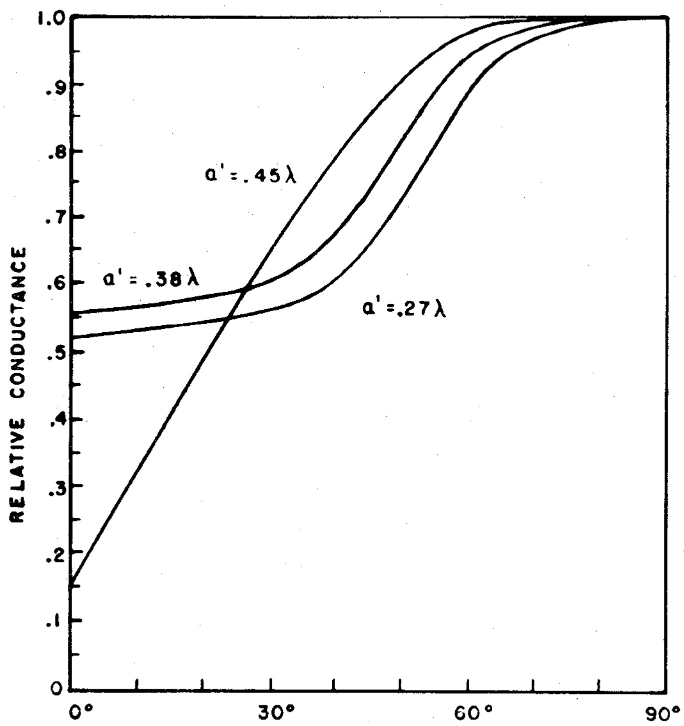

Fig. 4—Measured values of slot conductance as a function of slot orientation.

Excitation of Surface Waves from Strip Line

Studies have also been conducted on the coupling of strip line to surface waveguides of the kind provided by a grounded dielectric sheet and by a plane corrugated surface.

In the case of the dielectric waveguide three coupling techniques suitable for thick sheets have been explored. These include a single radiating dipole, multiple probes acting through a thick slot, and a phased array of dipoles.

In all cases the dielectric sheet used was a slab of polystyrene 1 inch thick as shown in Fig. 5.

Coupling by a single dipole was achieved with a probe passed through a $\frac{3}{8}$ inch hole in a thick ground plane, using a polystyrene bushing for support. The radiating probe was oriented within the slab so as to be symmetrically located between the long sides at a point approximately $\frac{3}{4}$ of a wavelength from one end. A cross-sectional view of the dielectric block, probe, and associated strip line is shown in Fig. 6. This view is at right angles to the axis of the strip line. With such a geometry the incident wave will be involved in a variety of mode transformations, some of which will radiate from the dielectric block in competition with the desired surface wave mode of present interest. A measure of the overall effectiveness of a radiating or mode conversion element can, within limits, be expressed in terms of the change in effective conductance as compared to some standard such as a dipole over an extended ground plane.

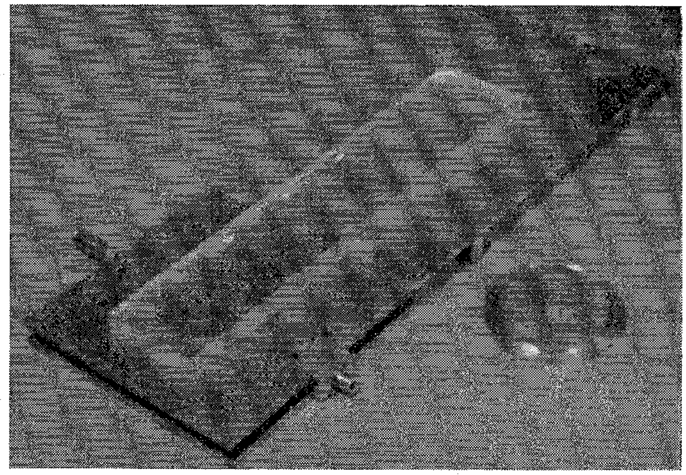

Fig. 5—Dielectric surface wave guide and associated strip-line connectors.

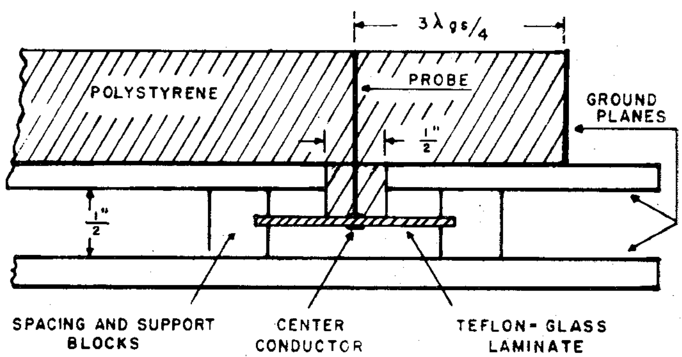

Fig. 6—Sectional view through dielectric guide showing single dipole coupling method.

Since all radiating modes will contribute to this single conductance term, it becomes necessary to isolate or eliminate, insofar as possible, the undesired modes which may be present. With this in mind and in an attempt to eliminate direct radiation from the near edges of the slab, conducting surfaces were provided at the end and for a short distance along the long dimensions of the slab. Since the critical angle for internal reflection is 42° in polystyrene, it was not necessary to continue this shielding for the entire length. The presence of radiation from the extreme end of the slab was evidenced by a significant alteration in the probe input impedance when this end was covered. With the ends and a portion of the lateral sides covered as described above, the dipole admittance was only slightly greater than that introduced by the supporting polystyrene plug alone. The radiation from the extreme end of the slab was essentially due to the desired guided surface wave. By placing a metal barrier 3 inches high and somewhat wider than the slab perpendicular to the ground plane and to the long axis of the slab, it was possible both to provide an impedance matching section and to form a horn launching device. When adjusted for maximum effect the dipole conductance was appreciably increased. Measurements of the wavelength of the surface wave were made by moving a conducting bar along the principal surface of the slab and plotting the perturbation in probe conductance. The value of 7.6 cm, obtained for a free space wavelength of 10.6 cm, is in agreement with the predicted values for a TM wave over a polystyrene layer.[6]

Variation in the length of the dipole gave a maximum effectiveness, in terms of the conductance and measured with the matching radiating section in position, for a dipole length of 1.6 cm at 10.6 cm free space wavelength. This corresponds approximately to a quarter wavelength for a TEM wave in polystyrene. The normalized conductance in this case was 0.8 Y_0 as compared to a value of 0.55 Y_0 for a resonant dipole in air over a conducting ground plane.

A second technique employed for coupling strip line to a dielectric slab line is shown in Fig. 7. Three equispaced probes couple to the dielectric slab through a thick longitudinal slot. The strip-line center conductor has been tapered to adjust for the change in dielectric. To provide support and to preserve symmetry, a second polystyrene block not shown on the figure was positioned below the slot. Because of mutual coupling between the probes, the maximum mode conversion occurs with the probes extending the full thickness of the dielectric. In this case, with optimum end matching, the maximum system conductance was 0.65 Y_0. The variation in conductance with actual probe length was found to be less rapid than for the single probe.

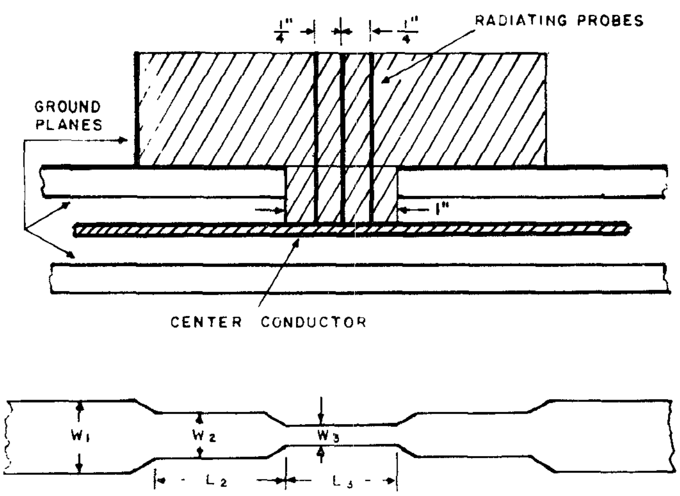

Fig. 7—Sectional view through dielectric guide showing slot-probe coupling method and associated strip-line center conductor.

[6] L. Hatkin, "Analysis of propagating modes in dielectric sheets," Proc. IRE, vol. 42, pp. 1565–1568; October, 1954.

In contrast to this system we have also considered the arrangement shown in Fig. 8.

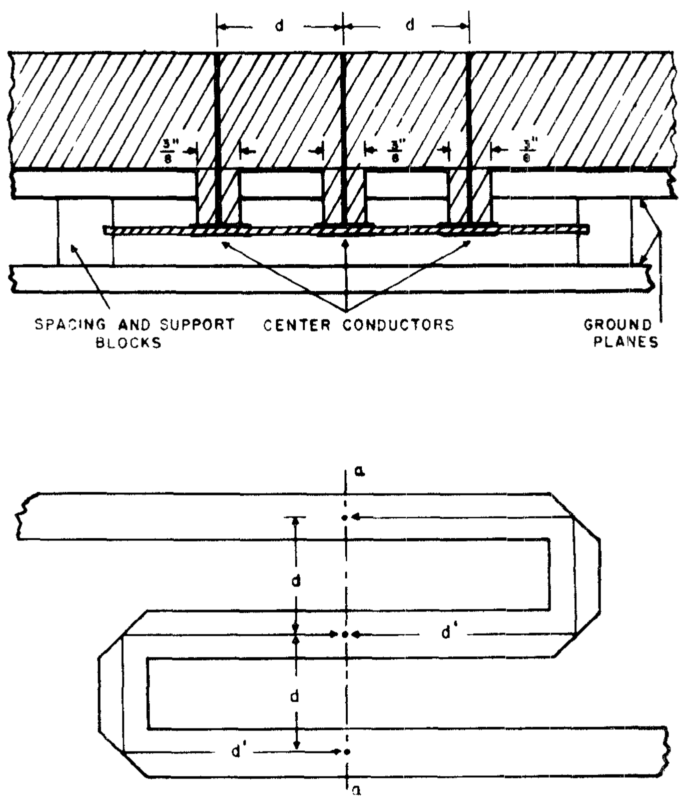

Fig. 8—Sectional view through dielectric guide showing plane dipole array coupling method and associated strip-line center conductor.

This comprises an array of spaced dipoles providing a cumulative end-fire array. Appropriate element phasing is provided by the use of an S-shaped strip line in which the differing phase velocities for waves in polystyrene and in the strip line are matched by an increased path length as shown. In this case the optimum probe length is near that for a single dipole but the change in relative effectiveness with a change in frequency is more rapid.

The properties of periodically corrugated surfaces as waveguides have been presented in the literature by

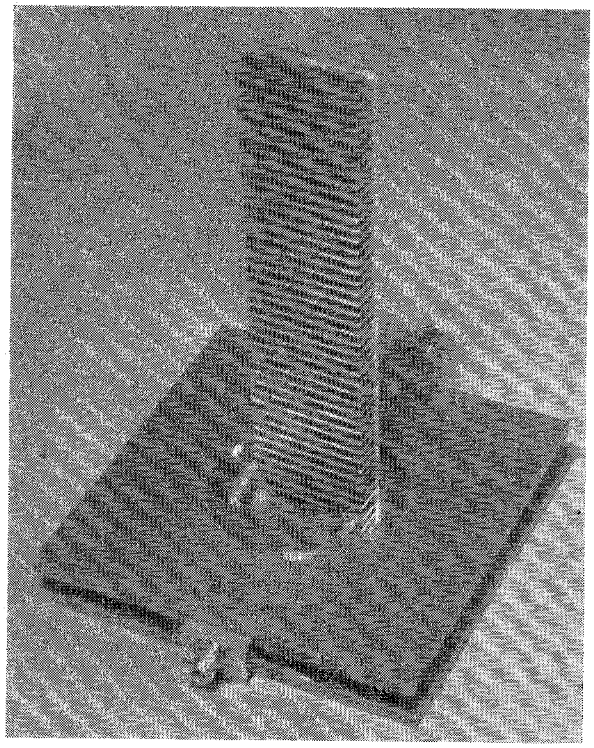

Fig. 9—Corrugated surface guide slot coupled to strip line.

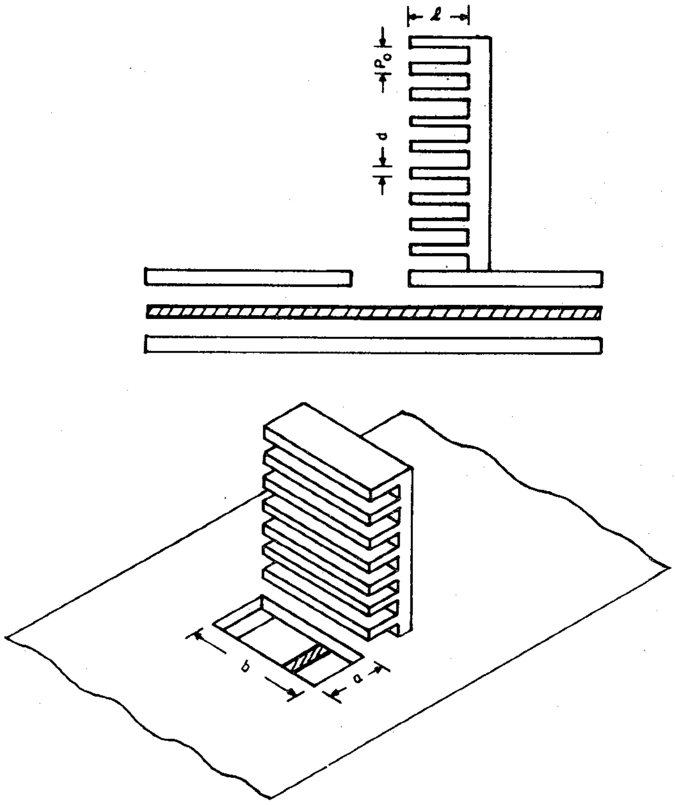

Fig. 10—Sectional and perspective view showing coupling method between corrugated surface guide and strip line.

various writers.[7,8] In the simple form which we have considered, parallel grooves, each less than $\lambda/4$ in length, provide an essentially inductive impedance to an incident wave and tend thereby to bind a progressive wave to the surface. The velocity of propagation is less than that of a free-space wave. The similarity between the TM wave in dielectric sheets and on such surfaces has led us to investigate the possibilities of the excitation of such waves using strip lines.

Of those methods considered, the one most successful to date has been that pictured in Fig. 9. A cross section showing the relationship between the slot, the strip line, and the corrugated guide is whown in Fig. 10.

The surface waveguide consists of a portion of corrugated surface which is slot-coupled to a strip-line as shown. As in the case of the excitation of a surface using a horn, the guided wave is mixed with a direct radiation component from the source, Measurements of the standing wave on the guide surface gave a λ_g or 5.80 cm at a source wavelength λ_0 of 10.6 cm. This is in agreement with the prediction for surface-guided wavelengths for a surface of limited width. Maximum surface wave component was obtained for a slot width of 0.85 cm.

[7] W. Rotman, "A study of single-surface corrugated guides," Proc. IRE, vol. 39, pp. 952–959; August, 1951.
[8] A. S. Dunbar, "Ridge and Corrugated Antenna Studies," Final Rept. on Project 199, Stanford Res. Inst., January 15, 1951.