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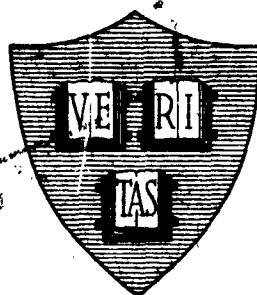
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Contract Nonr-1866 (32)

NR 371-016

A STUDY OF THE SLOT TRANSMISSION-LINE
AND SLOT ANTENNA

Part 1. Some Investigation of the Slot Transmission-Line



By

Robert W. Burton

January 10, 1963

Technical Report No. 397

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

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Abstract

A series of related experiments on the slot transmission-line and their results are described. The three major phases of investigation are (a) a conducting image plane as a termination for a slot transmission-line, (b) a practical design of a matched load, (c) the effect of a bend-out-of-the-plane on the transmission characteristics of the slot transmission-line.


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A STUDY OF THE SLOT TRANSMISSION-LINE AND SLOT ANTENNAS

Part 1. Some Investigations of the Slot Transmission-Line

by

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Division of Engineering and Applied Physics

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1.1 Introduction

In 1959 G. Owyang demonstrated the slot transmission-line in experiments and supported his experimental evidence with a rigorous theory [1]. The slot transmission-line was fabricated by cutting two long slots in a large ground plane and employing the slots for transmission of energy much as one employs wires in normal transmission-line application. As is pointed out by Owyang, the transition from two-strip transmission-line theory to two-slot transmission-line theory in the plane is straightforward. A direct analogy between an electric strip and magnetic strip line may be drawn in all cases; and, in a plane the link between the magnetic strip and slot line is made by application of Babinet's principle. It is the purpose of this first study to investigate experimentally the effects encountered when a slot-transmission-line is employed out of the plane and to attempt to offer some direction in which a theory may be constructed.

Three phases of experiment are incorporated in this investigation:

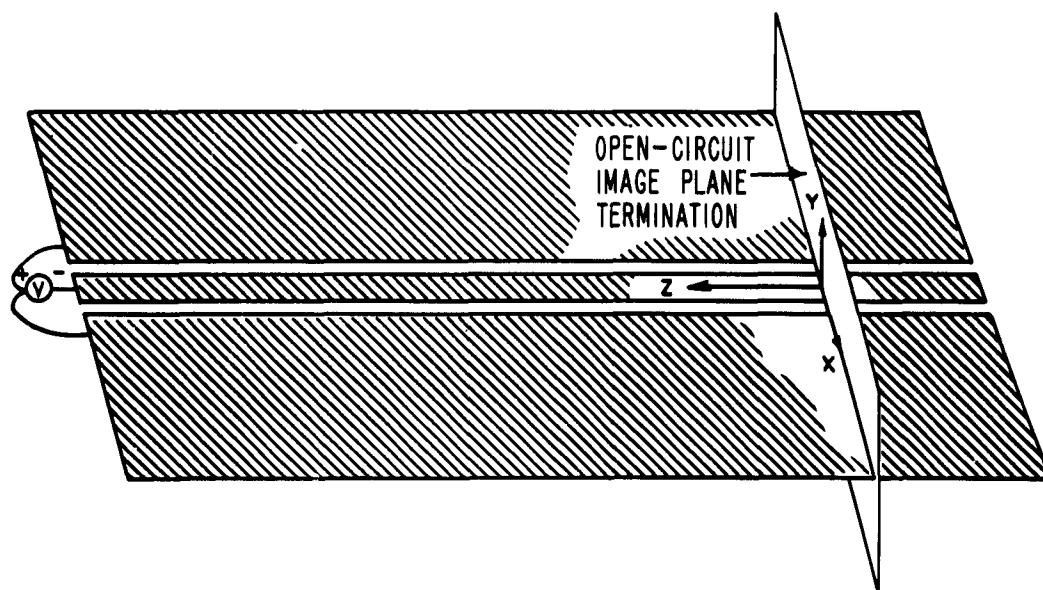
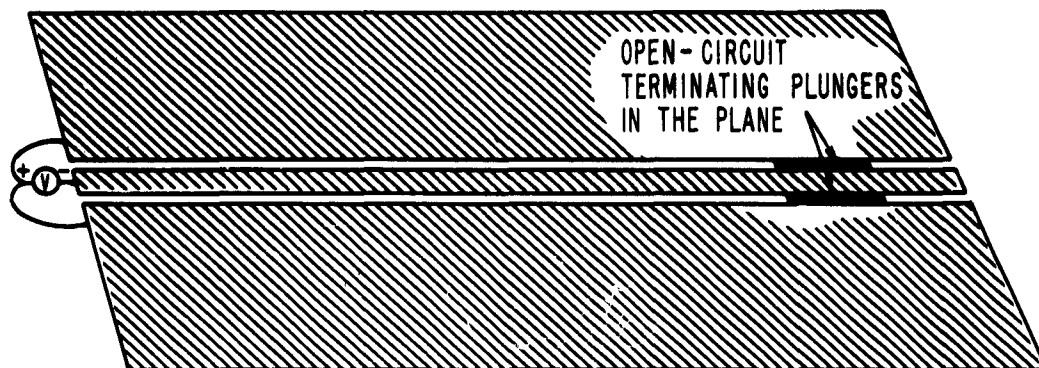
- (a) the effect of a conventional conducting image plane as a termination.

- (b) a practical design of a matched load.
- (c) the effects of a bend-out-of-the-plane on transmission characteristics.

1.2 The Conducting Image Plane as a Termination for the Slot Transmission-Line

In ordinary transmission-line theory it is possible to study the behavior and characteristics of the short-circuited line without end effects if the short circuit is an image plane. No corresponding freedom is possible in the case of the open-circuited termination. As noted by Owyang, the slot transmission-line in the plane is the dual of the two-strip transmission-line, by which is meant that all impedances of the one become corresponding admittances of the other. Therefore, in the case of two slots terminated in a conducting image plane (an open slot line) one may expect a method of analyzing the corresponding open-circuited ordinary transmission-line without end effects; and, indeed, that is the case (Fig. 1.1). The slot transmission-line terminated with metal plungers in the plane has a 0.03λ inductive shift (i. e., towards the termination) of minimums, whereas there is no shift in the case of its termination in a conducting image plane. It is interesting to note the duality between slot and ordinary transmission-lines. On the one hand, the open-circuited ordinary transmission-line is known to have a capacitive shift, and we see here, on the other hand, that the open-circuited slot line has an inductive shift.

With the conducting plate as the image termination on the slot transmission-line the current distribution on the vertical plate was



OPEN-CIRCUIT TERMINATIONS OF SLOT TRANSMISSION-LINE
FIG. 1.1

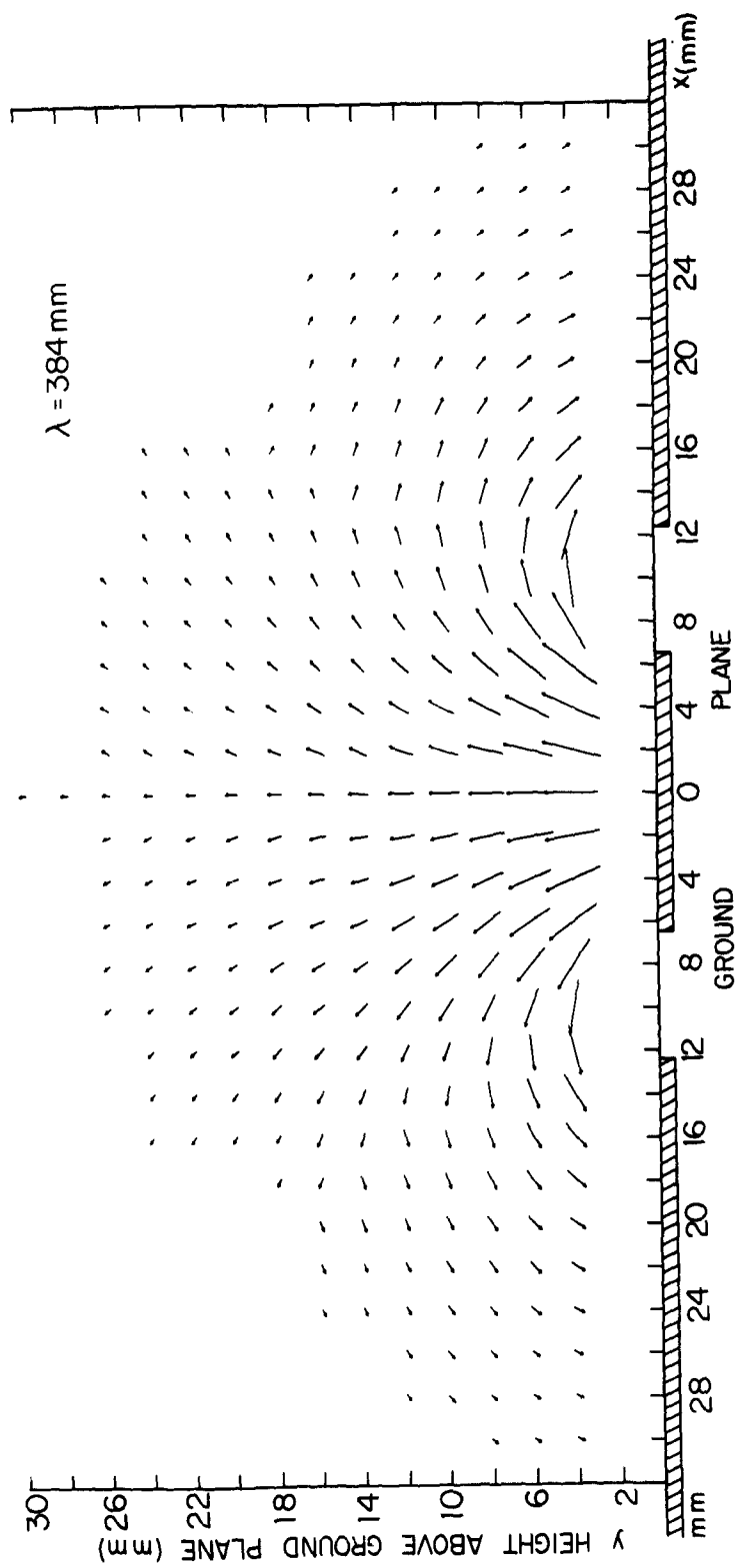
measured as shown in Fig. 1.2. The space vector of current, $J(x, y)$, was determined by orienting a surface type probe of the type in Fig. 1.3 to detect first the x-component then the y-component of $J(x, y)$ in each position. For interest, Fig. 1.4 compares the function $J(0, y)$ and $1/y$ - the $1/y$ variation being the correct theoretical function for cylindrical wires, whereas the slots are of square cross section.

1.3 A Practical Design for a Matched Load for a Slot Transmission-Line

A matched load was built for the slot transmission-line by applying successive coats of Aquadag (colloidal graphite in water) on a styrofoam termination block (Fig. 1.5). A minimum voltage standing-wave ratio of 1.12 was obtained by this method using an impregnated styrofoam block with 69 ohms dc resistance.

1.4 Effects on Transmission Characteristics with a Bend-out-of-the-Plane

The original purpose for designing the matched load for the slot transmission-line was its use in studying effects of bends-out-of-the-plane on transmission characteristics. The horizontal section of line was to be driven, and a tilting section terminated in a matched load could be positioned at angles 0° to 90° out-of-the-plane. The original attempt to measure junction characteristics by observing changes in VSWR in the horizontal line as a function of angle proved futile in that no detectable



PLOT OF NORMALIZED SPACE VECTOR OF CURRENT DENSITY $J(x,y)$ AS A FUNCTION OF POSITION ON THE VERTICAL CONDUCTING IMAGE PLANE

FIG. 1.2



SURFACE TYPE PROBE FOR MEASURING RECTANGULAR COMPONENTS OF $J(x,y)$

FIG. I.3

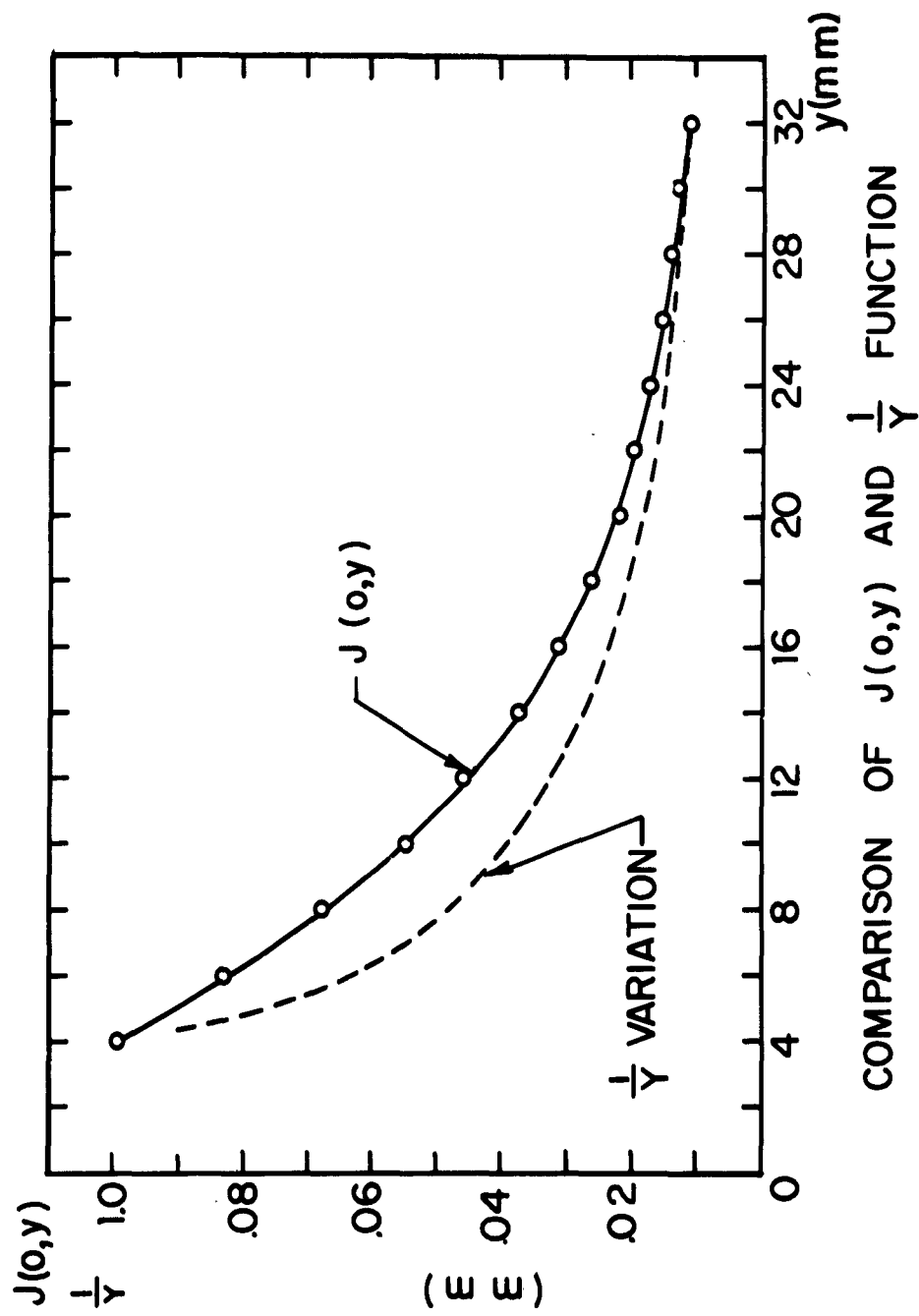
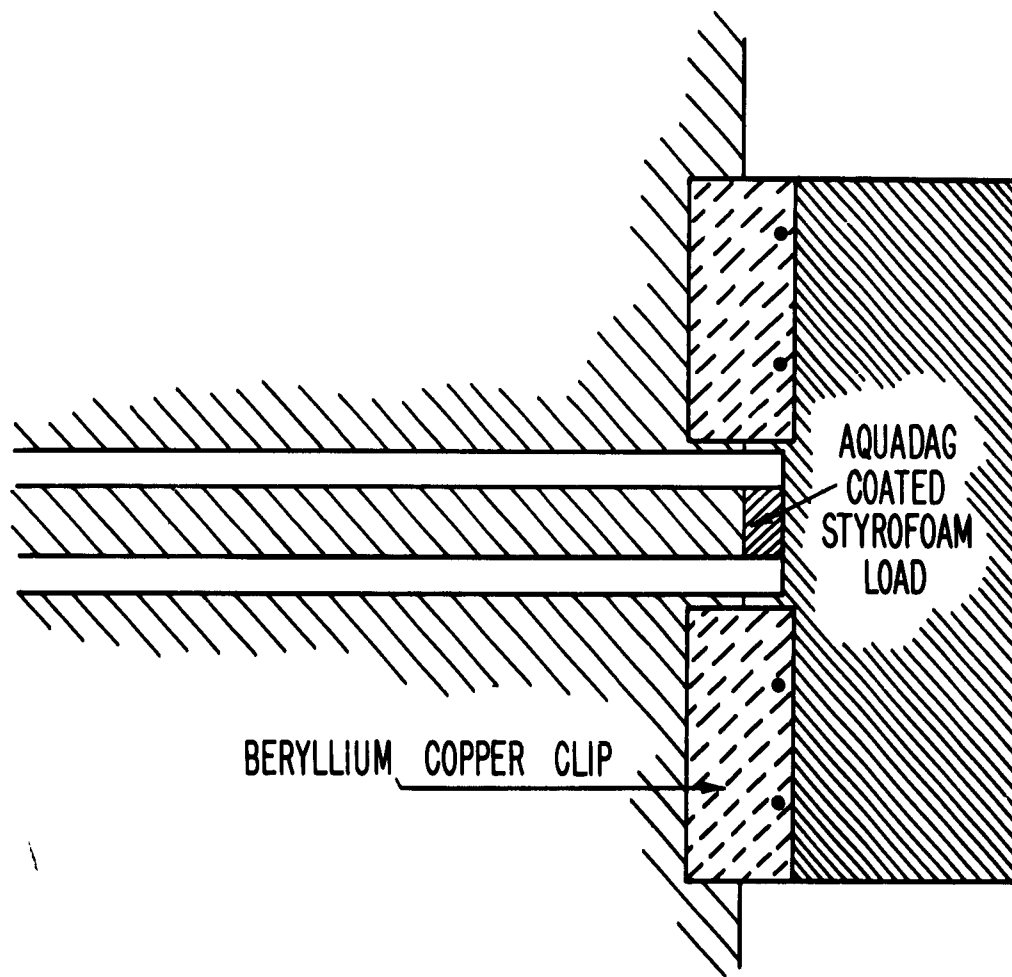


FIG. 1.4



TOP VIEW SLOT TRANSMISSION-LINE WITH MATCHED LOAD

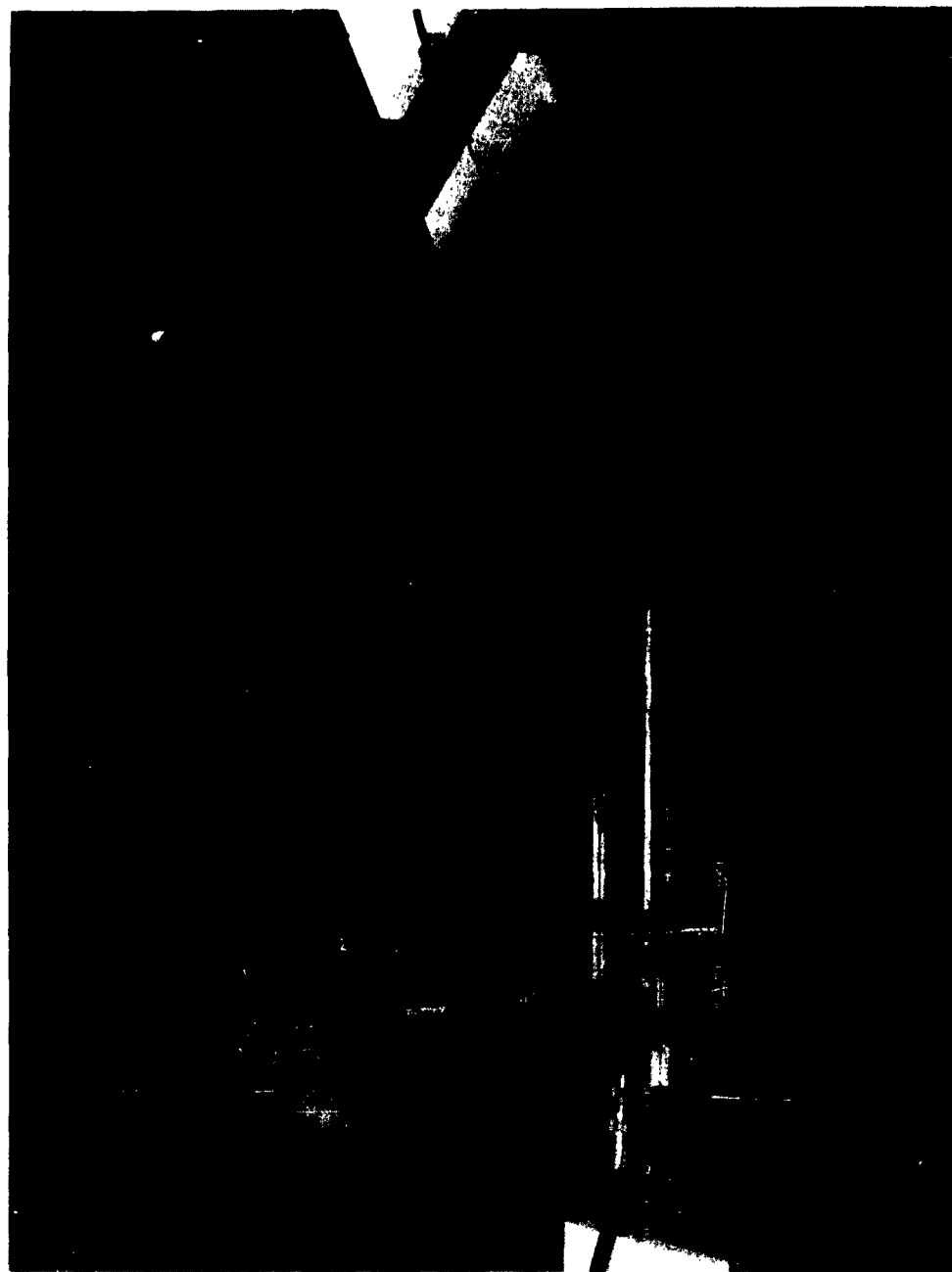
FIG. 1.5

change in VSWR occurred even at a bend of 90° . In addition, the level of VSWR readings on the movable line remained unchanged ruling out any significant radiation. As a result of this coarse experiment, a resonant section of line was constructed to measure junction characteristics directly, and in a more sensitive fashion. [2].

In this phase of the study both an ordinary and a slot resonant section were employed for comparing results. In the case of the ordinary transmission-line a bendable strip of cross section equal to that of the slot was positioned at a distance $d/2$ above an image plane (d is the distance between slots)(Fig. 1.6.). A short-circuiting plate terminated each end of the section of line under consideration. A feed probe on the left was positioned very close to the image plane and loosely coupled to the strip and its mirror image. On the right a loop probe was loosely coupled to detect the H field near the short-circuiting plate.

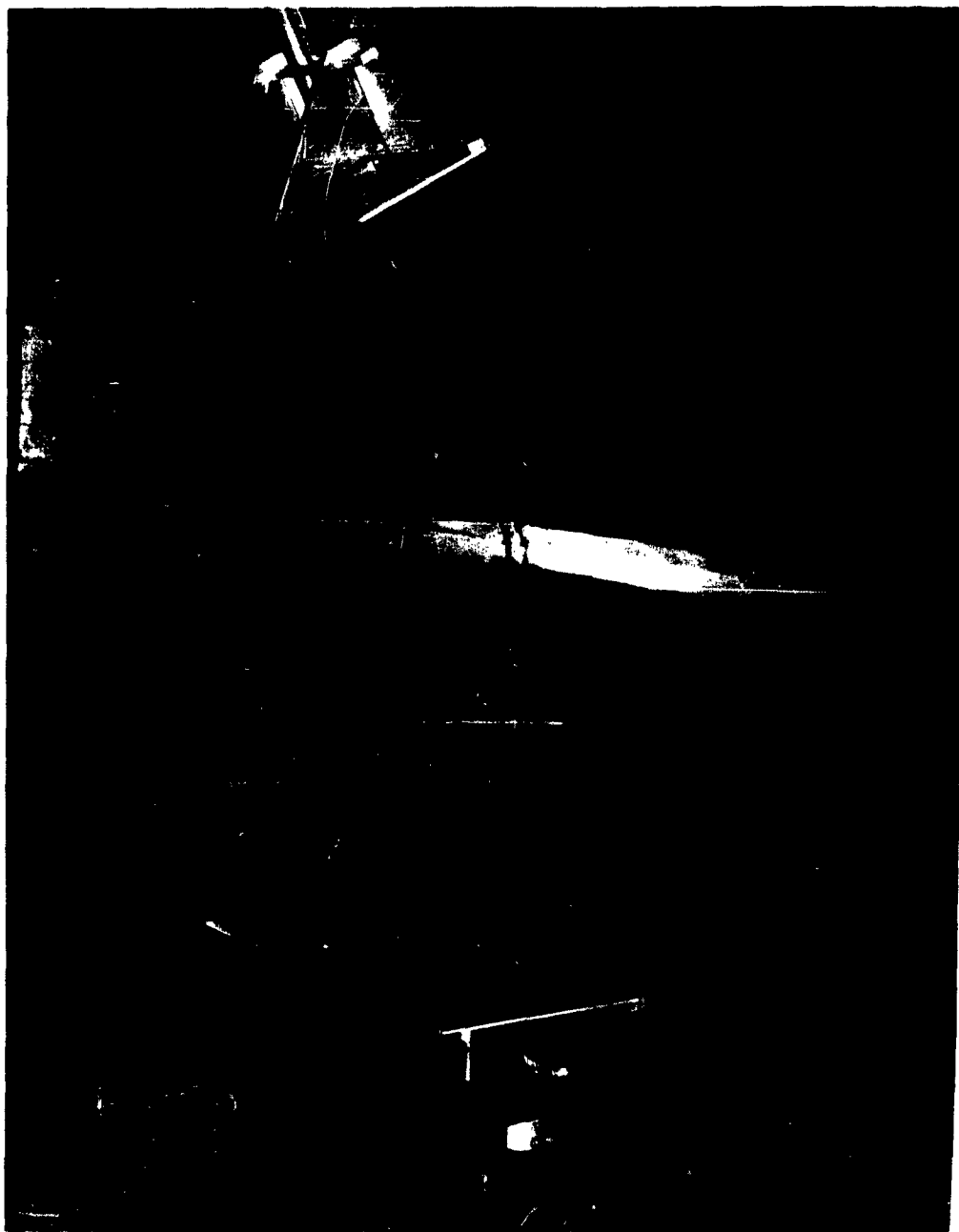
The slot resonant line (Fig. 1.7) was constructed in similar or dual fashion with the one exception that the internal probe system designed by Owyang was used to detect the H field near the terminating plate (Fig. 1.7). In both systems the feed plate was movable.

If we choose the circuits of Fig. 1.8 as possible equivalent transfer circuits for the bend, we may determine L_T , L_T^* , C_T and C_T^* much as King and Tomyasu did for the ordinary transmission-line.[3].The neglect of radiation seems appropriate from the results discussed earlier. We may, for example, detect L_T by positioning the short-circuiting plates $\frac{\lambda}{2}$



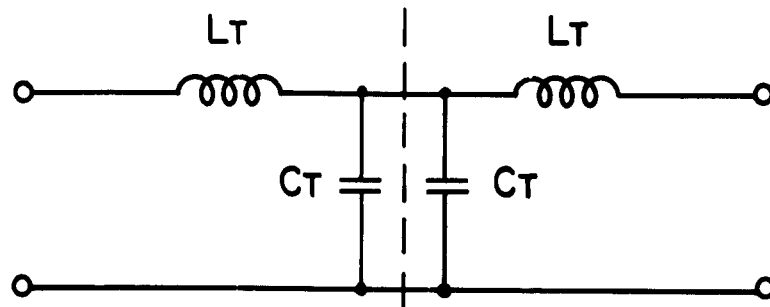
RESONANT SECTION OF ORDINARY STRIP TRANSMISSION - LINE

FIG. 1.6

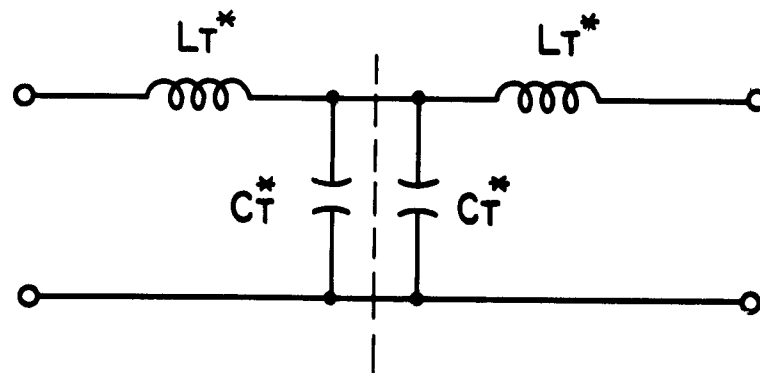


RESONANT SECTION OF SLOT TRANSMISSION-LINE

FIG. 1.7



AN EQUIVALENT TRANSFER CIRCUIT FOR ORDINARY
TRANSMISSION-LINE AT THE BEND



AN EQUIVALENT TRANSFER CIRCUIT FOR SLOT
TRANSMISSION-LINE AT THE BEND

FIG. 1.8

on either side of the bend. In that case, a current maximum and charge minimum will be maintained at the bend, emphasizing the effects of L_T and neglecting those of C_T .

In the experiment it is convenient to measure the distance Δz by which the plate terminations are moved closer together or further apart to achieve a new resonance at a bend angle of θ . This differential distance moved from the original position at $\theta = 0$ is conveniently the normalized L_T/l_0 , C_T/c_0 , L_T^*/l_0^* and C_T^*/c_0^* depending on the case in study.

As a theoretical illustration [4] consider the ordinary line with short circuits positioned $\frac{\lambda}{2}$ on either side of the bend effecting a current maximum and charge minimum at the bend in Fig. 1.9a. The normalized impedance Z_{IN}/z_0 looking either right or left is

$$Z_{IN} = j \tan \beta z \quad (1-1)$$

Z termination = 0.

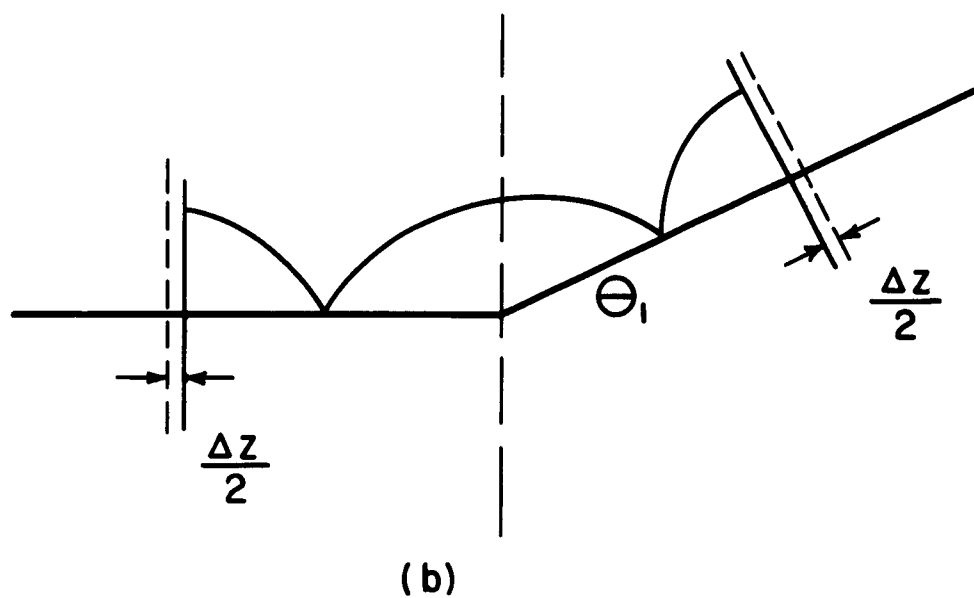
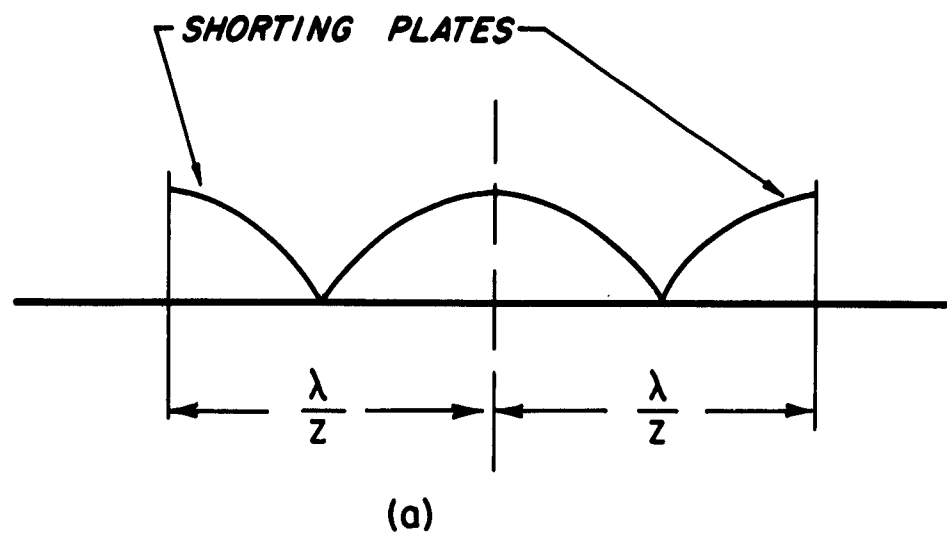
Now in Fig. 1.9b when θ is changed to θ_1 , a new resonance is obtained, say, by moving each image plane toward the bend $\frac{\Delta z}{2}$. The input impedance considering the lengths of line involved into either side is

$$Z_{IN} = j \tan \left\{ \frac{2\pi}{\lambda} \left(\frac{\lambda}{2} - \frac{\Delta z}{2} \right) \right\} \quad (1-2)$$

given a change of impedance of

$$Z_{IN} = -j \tan \frac{\pi \Delta z}{\lambda} \approx -j \frac{\pi \Delta z}{\lambda} \quad (1-3)$$

Since we have achieved resonance in this position ($Z_{IN} = 0$), the bend must have introduced an impedance of $+j \frac{\pi \Delta z}{\lambda}$. Since, in this case, the



RESONANT SECTION OF ORDINARY TRANSMISSION-
LINE IN BENDING EXPERIMENT

FIG. 1.9

equivalent transfer circuit is essentially inductive

$$\frac{\omega L_T}{Z_c} = \frac{\pi \Delta z}{\lambda} \quad (1-4)$$

or

$$\frac{L_T}{l_0} = \frac{\Delta z}{2} \text{ cm.} \quad (1-5)$$

Similarly, in the case of the slot transmission-line with opens positioned at $\frac{\lambda}{2}$

$$Z_{IN}^* = \frac{1}{j \tan \beta z} \quad (1-6)$$

Z^* termination = ∞

which is $\theta = 0$ and $z = \frac{\lambda}{2}$ gives $Z_{IN}^* = \infty$. When θ is changed to θ_1 , a new resonance is obtained by moving the image planes towards the bend a distance $\frac{\Delta z}{2}$ each. The new input impedance Z_{IN}^* considering transmission-line length is now

$$Z_{IN}^* = \frac{1}{j \tan \left\{ \frac{2\pi}{\lambda} \left(\frac{\lambda}{2} - \frac{\Delta z}{2} \right) \right\}} \quad (1-7)$$

giving a change of impedance of

$$Z_{IN}^*_{CHANGE} = \frac{1}{j \tan \frac{\pi \Delta z}{\lambda}} \approx \frac{1}{-j \frac{\pi \Delta z}{\lambda}} \quad (1-8)$$

In order to achieve resonance ($Z_{IN}^* = \infty$ in this case) the impedance $\frac{1}{j \frac{\pi \Delta z}{\lambda}}$ was introduced by the bend. Since the circuit is primarily capacitive, $\frac{C_T^*}{c_0}$ may be determined as follows

$$\frac{\frac{1}{j\omega C_T^*}}{Z_c^*} = \frac{1}{\frac{j\pi \Delta z}{\lambda}} \quad (1-9)$$

and

$$\frac{C_T^*}{c_0} = \frac{\Delta z}{2} \text{ cm.} \quad (1-10)$$

As a practical matter in the experiment, it was not suitable to move both image planes since the maximum total distance moved was less than 0.5 cm. Consequently, only the feed plate was moved and corresponding slight error was introduced. The magnitude of this error is obviously small, since even in the maximum shift of 0.5 cm, the ratio at the bend was still 40 dB.

For interest, Fig. 1.10 displays an experimental resonance curve for the slot line. In this experiment $\theta = 0$ and the feed plate was moved. The internal probe positioned near the fixed plate detected a signal proportional to the square of the current along the outer edge of one slot. The major results of this phase of experimental work are presented in Figs. 1.11 and 1.12. The theoretical curves were accomplished by applying the approximate theory of Tomiyasu and King to a transmission-line with a square cross section. In all instances the differential distances moved to achieve resonance are corrected for the increase in mean length from 0 to $\frac{\pi a}{4}$ (a is the slot or strip thickness) as the transmission-line was bent from 0° to 90° .

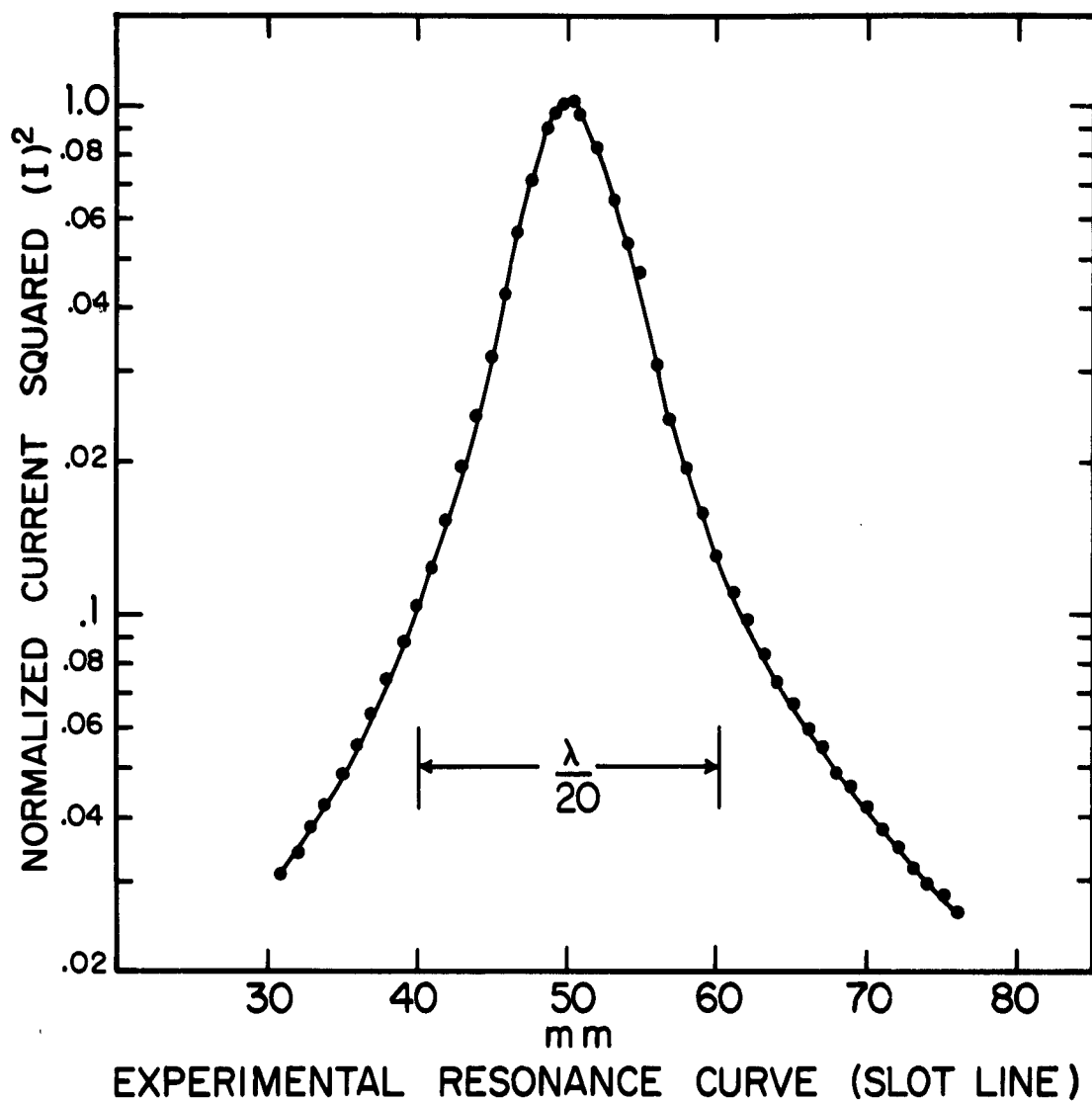
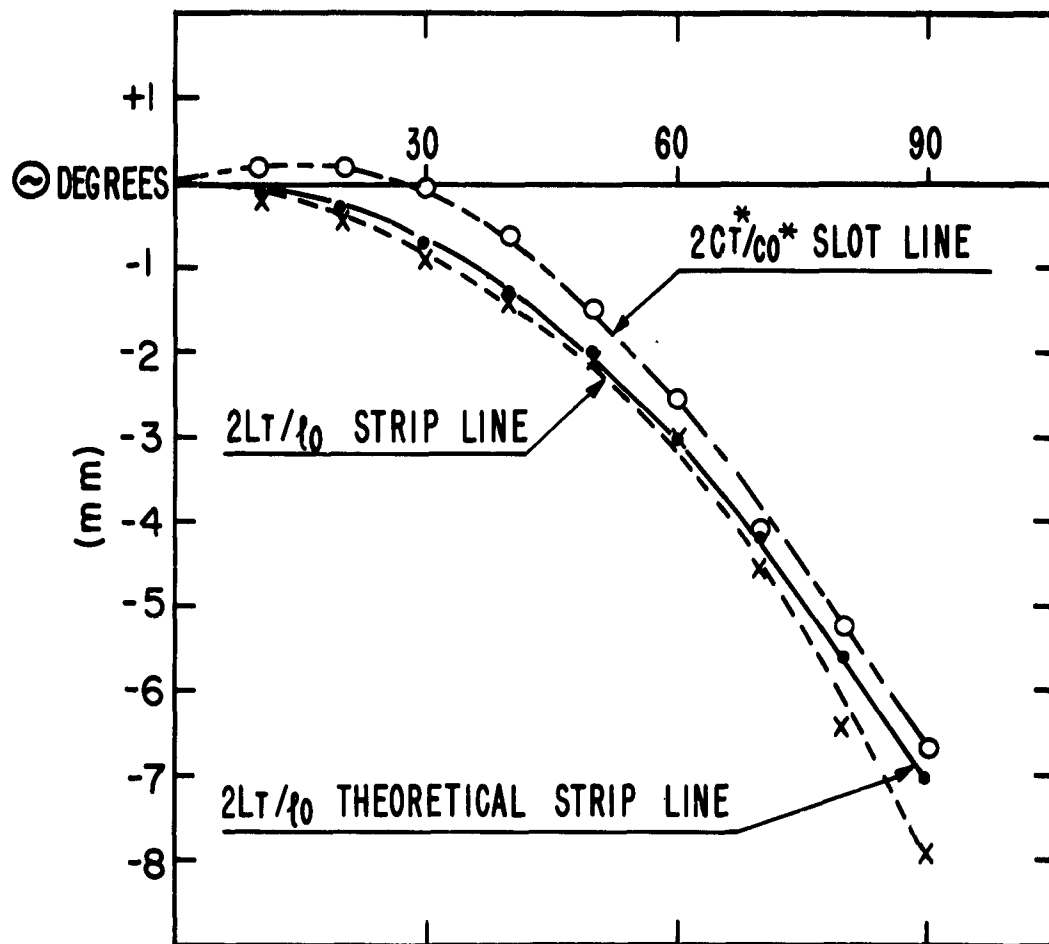
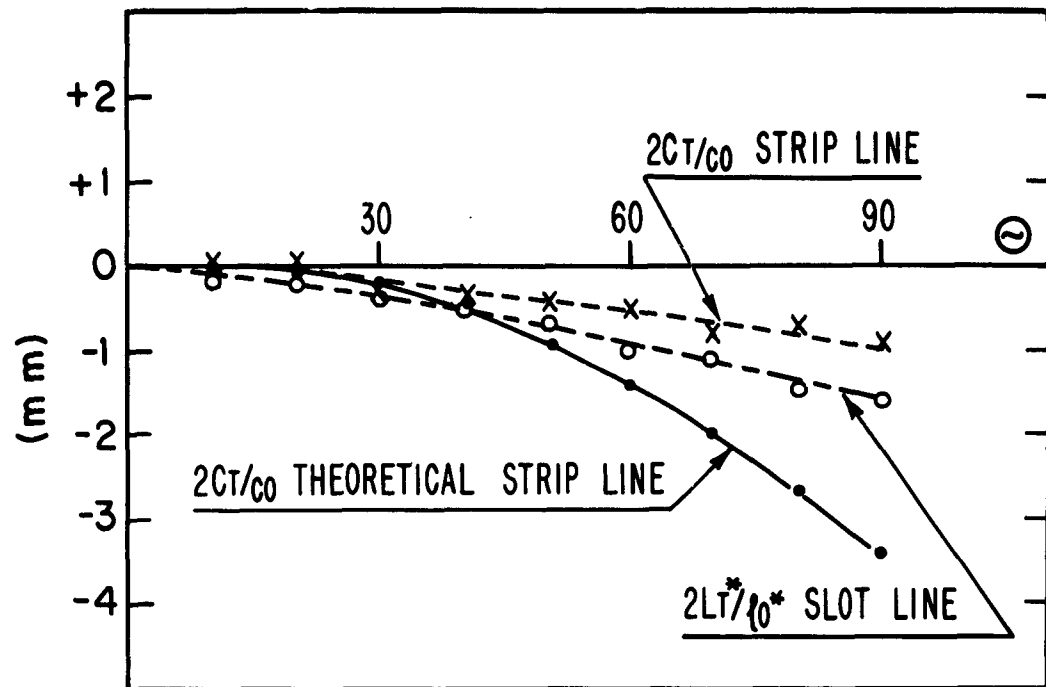


FIG. 1.10



PLOT OF $2LT/l_0$ THEORETICAL AND EXPERIMENTAL RESULTS FOR STRIP LINE, $2CT/co^*$ EXPERIMENTAL RESULT FOR SLOTTED LINE AS A FUNCTION OF Θ , ANGLE OF BEND

FIG. 1.11



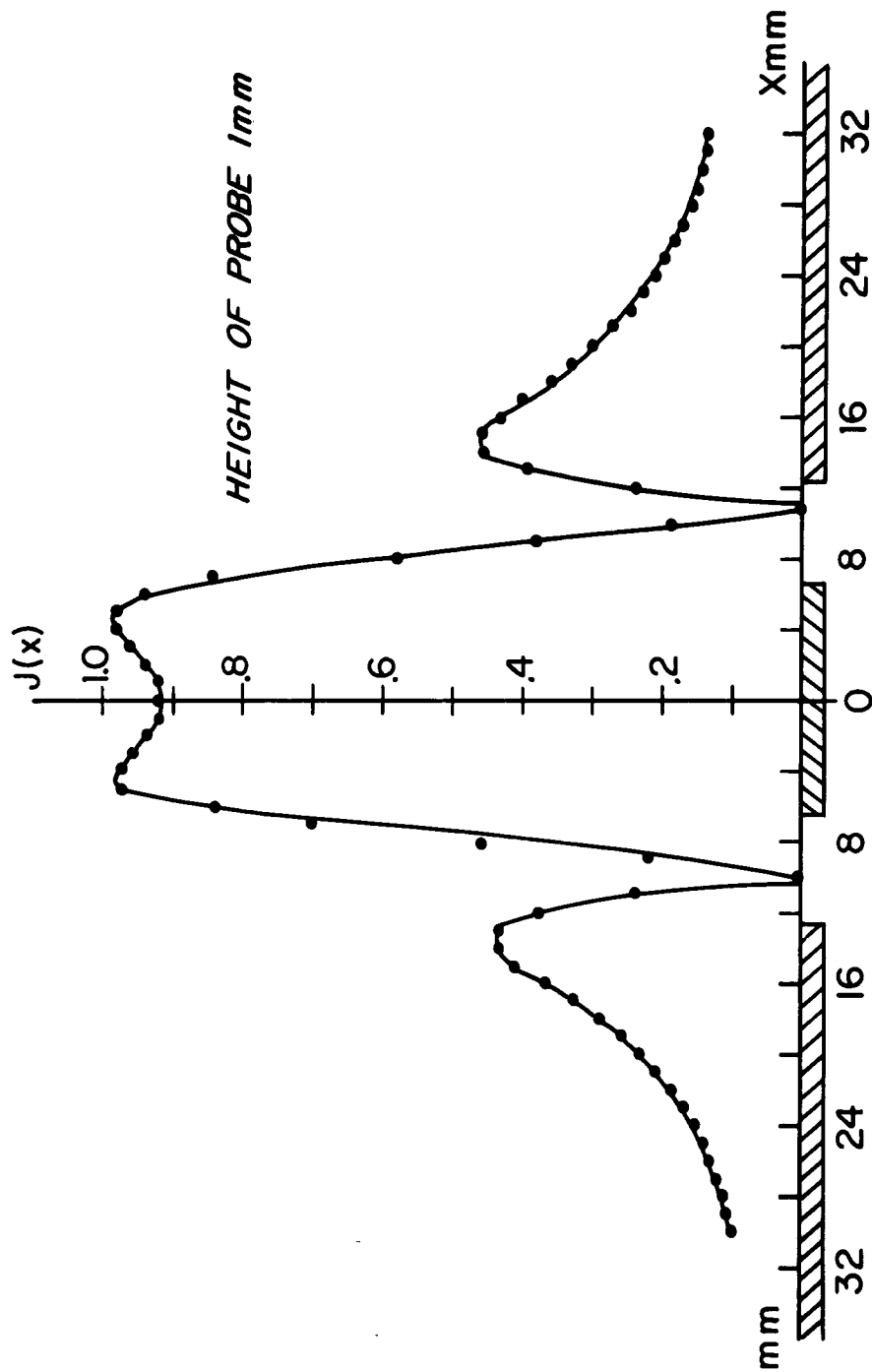
PLOT OF $2CT/c_0$ THEORETICAL AND EXPERIMENTAL RESULTS FOR STRIP LINE AND $2LT/l_0^*$ EXPERIMENTAL RESULT FOR SLOT LINE AS A FUNCTION OF Θ , ANGLE OF BEND

FIG. 1.12

1.5 Conclusion



The results of this experiment to show the effects of bends out-of-the-plane are, on the one hand, somewhat surprising and, on the other, somewhat expected. Babinet's principle offers a method of solving complementary or dual problems but only if the elements are in the plane. Electromagnetic fields resulting from dual sources or elements are synthesized using symmetrical and antisymmetrical fields about a planar surface. No corresponding analogy may be drawn for fields about non-planar configurations.  On the other hand, if the problem is considered as a transmission-line problem, a study in local effects is in order. If we consider Fig. 1.13, a plot of current density $J(x)$ as a function of position measured normal to the slots, we observe that the current outboard of the slots is generally confined to an area in width of about $40 \text{ mm} (\lambda/10)$ on either side of the slots. As a consequence, there is no reason to expect that the slot transmission-line will not behave as its dual does around bends and curves. In fact, with such a confined distribution of current, it may be convenient to consider the slot transmission-line as a hybrid three-wire line with current flowing down the center conductor between the slots and back along the sides outboard of the slots. In addition to this viewpoint, it might be well to consider a four-wire line representation with two streams of current concentrated near the outer edges of the inner conductor flowing down and two return streams flowing back along the outboard edges of the slot.



PLOT OF NORMALIZED CURRENT DENSITY $J(x)$ AS A FUNCTION OF POSITION MEASURED NORMAL TO TRANSMISSION LINE

FIG. 1.13

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