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2. C. A. Goben, D. L. Begley and M. Davarpanah, "Coupling of Optical Waves Between Thin-Film Waveguides and Glass Fibers," Transactions Missouri Academy of Science, Vol. 8, December 1974.
3. R. J. Bell, C. A. Goben, M. Davarpanah, K. Bhasin, D. L. Begley and A. C. Bauer, "Two-Dimensional Optics with Surface Electromagnetic Waves," Applied Optics, Vol. 14, May 1975.

4. R. J. Bell, M. Davarpanah, C. A. Goben, D. L. Begley, K. Bhasin and R. W. Alexander, Jr., "Measurements of Standing Waves and the Absorption Coefficients of Various Materials with Surface Electromagnetic Waves on Aℓ," Applied Optics, Vol. 14, June 1975.

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PART I

EXCITATION EFFICIENCY OF SURFACE ELECTROMAGNETIC WAVES

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EXCITATION EFFICIENCY OF SURFACE ELECTROMAGNETIC WAVES*

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ABSTRACT

The coupling efficiencies for the excitation of surface electromagnetic waves (SEW) for both the prism and the grating techniques have been studied experimentally in the microwave frequency range. The grating experiments included studies of the SEW coupling efficiencies as functions of the frequency, the angle of incidence, the grating constant, the number of grating bars, and the position of the grating bar at which the maximum radiation field of the antenna was aimed. For the prism coupling technique, the coupling efficiency was studied as functions of the angle of incidence, the aiming point of the transmitting antenna on the prism base, and the height of the prism above the metal strip or the standard railroad rail. The coupling efficiency for the prism coupling technique was found to be about 60 percent, whereas for the grating technique, the coupling efficiency was found to be about 15 percent. The coupling efficiencies for either coupling

technique were found to be different for metal overlaid with thin dielectric materials and uncoated metal surfaces.

INTRODUCTION

This paper is primarily concerned with the coupling efficiencies of surface electromagnetic waves (SEW)[1-4]. The most distinctive property of a surface electromagnetic wave is the nonradiating property as it propagates along an interface. This, in addition to the need of only one conductor as a transmission line, would make surface electromagnetic waves potentially very useful in communications systems[5,6]. SEW have been shown to exhibit geometrical optics phenomena[7], and have also been used for material absorption and spectroscopy studies[8].

Although there are three distinctive forms of surface electromagnetic waves[2], this work is concerned with inhomogeneous plane waves supported by a flat conducting surface[9] (Zenneck Waves)[2]. Metal surfaces of copper and aluminum with and without dielectric overlayers, and uncoated iron (railroad rail), were used as the supporting media for the propagating SEW. The medium above the metal or dielectric overlayer was air.

In infrared and visible wavelength[10] experiments with SEW, it is difficult to control and optimize the parameters associated with each excitation technique, due to the extremely small dimensions required at these wavelengths. In the microwave region, the same parameters must be considered. However, with larger wavelengths (compared to visible or infrared wavelengths) control and optimization of these parameters is more easily accomplished.

Several methods of SEW excitation have been reported[11-17]. In this paper, experimental results of prism[18-22] and grating[10,20,23-27] excitation techniques are considered with emphasis placed on the efficiencies under various conditions.

Although extensive studies have been made for the prism and grating excitation techniques in integrated optics[28-37], the mode of propagation there is that of a guided wave in the film overlayer on a substrate and not as a surface wave. In these SEW studies, it is not necessary for the overlayer to be present, and the metal surface used to support the SEW is extremely absorbing in contrast to the transparent substrates used in integrated optics.

SURFACE ELECTROMAGNETIC WAVE EXCITATION TECHNIQUES

It is well known that for the excitation of a SEW

$$k_x > \frac{\omega}{c} \tag{1}$$

where k_x is the SEW propagation vector in the direction of propagation, ω is the SEW angular frequency, and c is the speed of light in free space. However, for any practical purpose, k_x in the microwave region and for uncoated metal or for very thin dielectric coated conducting surfaces can be approximated[38] by $\frac{\omega}{c}$. The prism and grating coupling techniques for SEW excitation will now be considered subject to this approximation.

A. Prism Coupling Technique

An electromagnetic wave can be totally reflected at any dielectric medium boundary if $\varepsilon_d > 1$, where ε_d is the relative dielectric constant of the dielectric medium with respect to vacuum. The condition for total internal reflection is

$$\sin\theta_i > \frac{1}{\sqrt{\varepsilon_d}} \qquad (2)$$

where θ_i is the angle of incidence with respect to the normal. Under this condition, there is an evanescent wave propagating along the surface. The propagation vector of this evanescent wave is[20]

$$k_x = \sqrt{\varepsilon_d}\,(\omega/c)\,\sin\theta_i\ . \qquad (3)$$

At the critical angle, $\sin\theta_i = 1/\sqrt{\varepsilon_d}$; therefore, the propagation vector of the wave at the prism base from Eq. (3) becomes

$$k_x = \frac{\omega}{c}\ . \qquad (4)$$

If a metal surface, coated or uncoated, is brought under a dielectric prism maintaining a small air gap (of the order of a wavelength) between the base of the prism and the conducting surface, a SEW can be excited on the conducting surface. Fig. 1(a) illustrates the principle of the prism coupling technique[19,20] where θ_c is the critical angle for the prism. In order to couple surface electromagnetic waves onto coated or uncoated metal surfaces and to de-couple at the receiving point, right angle prisms are used, as shown in Fig. 1(b). The prism coupling technique has the following advantages:

1. the surface of the conductor (coated or uncoated) is not physically contacted, and
2. the coupling efficiency is relatively high (60%).

B. Grating Coupling Technique

Referring to Fig. 2, for excitation of a SEW by the grating coupler, the components k_x of the wave vectors tangential to the surface are[20]:

$$k_x = (\omega/c) \sin \alpha + m \frac{2\pi}{d} \qquad m = 0, \pm 1, \pm 2, \ldots \qquad (5)$$

where

α = the angle of incidence,

m = mode order, and

d = grating constant.

For excitation of surface electromagnetic waves in the microwave region where we may take $k_x = \omega/c$, Eq. (5) yields

$$\sin \alpha = 1 - m \frac{\lambda}{d} \tag{6}$$

where λ is the wavelength of the surface electromagnetic wave. Therefore, in order to excite a surface electromagnetic wave with the grating coupler, the angle of incidence α must satisfy Eq. (6).

EXPERIMENTAL RESULTS

We report here the results of the following experiments:

<u>Experiment 1</u>. Grating coupling efficiency as functions of the frequency, the angle of incidence, the grating constant, the number of grating bars, and the position of the grating bar at which the center of the antenna was aimed.

<u>Experiment 2</u>. Prism coupling efficiency as functions of the angle of incidence, the aiming point of the transmitting antenna on the prism base, and the height of the gap between the prism base and the metal strip or the standard railroad rail.

The coupling efficiency is defined as (see Appendix III, Ref. 38):

$$\text{Coupling Efficiency} = \frac{\text{(power carried by the SEW)}}{\text{(power transmitted through the prism or grating coupling aperture)}} \ . \quad (7)$$

These experiments were performed on aluminum and copper both with and without dielectric overlayers. The prism coupling efficiency was examined as a function of the gap between the prism base and the metallic surfaces for both aluminum strip and standard railroad (iron). Low loss polystyrene and special paper were used as dielectric overlayer materials. The paper has a relative dielectric constant equal to 2.70 and loss factor of 0.056 at 9 GHz. Polystyrene has a relative dielectric constant of 2.55 and a loss factor of 0.00033 at 9 GHz.

A. Experiment 1 - Grating Coupling Efficiency

The experimental arrangement is shown in Fig. 3. The transmitting and receiving antennas were identical with a deflector diameter of 18 inches (45.72 cm). The antennas are linearly polarized with 3dB beam width of 6° at 10 GHz. The metal conductor strip was 1 foot (30.48 cm) in width. The transmitting and receiving gratings were of identical design. Each grating was laid on the surface and was composed of seven iron (but could be made of any metal[17]) bars with diameters of 1.27 cm spaced 7.4 cm apart. Microwave energy absorbers with an aluminum plated shield (1 m x 2 m) were used to prevent direct coupling of electromagnetic energy between the antennas. A gap of 12 cm (4 wavelengths) was left between the shields and the 30.48 cm wide metallic strip on which the SEW propagated. The distance between transmitting and receiving gratings was 3 meters for this part of the experiment. Angles of incidence α and β (defined in Fig. 3 which shows the experimental arrangement) were fixed to 36.5° for both coated and uncoated metal surfaces. The frequency was swept with the sweep oscillator. At the receiving point, the propagating surface electromagnetic waves were detected and monitored on an oscilloscope. Plots of the coupling efficiency vs frequency for uncoated and coated copper surfaces are shown in Fig. 4. The maximum efficiencies in these cases are for a frequency of 10 GHz (λ = 3.0 cm) and thus are in agreement with Eq. (6) (α = 36.5°, d = 7.4 cm, m = 1). The full width at half maximum (FWHM) is experimentally seen to be about 0.34 GHz. This may be attributed in part to non-uniformaties in the grating bars and construction of the grating. The results for coupling efficiency vs frequency for uncoated and coated aluminum surfaces are similar to those obtained for uncoated and coated copper surfaces, except that the maximum efficiency for aluminum is slightly smaller. This is attributed to the fact that the conductivity of aluminum is less than the conductivity of copper. It should be noted from Fig. 4 that the results for the uncoated metal surface and dielectric coated metal surface are not the same. The reason for the difference for the thin dielectric coated metal surface is that the propagation vector, k_x, is not as well approximated by ω/c as it is in the case of the uncoated metal surface[38].

For measurements of the grating coupling efficiency as a function of the angle of incidence, the apparatus is again as shown in Fig. 3. However, in this case, the frequency was fixed at 10 GHz and the efficiency was measured for various angles of incidence, β, at the receiving antenna. The angle of incidence, α, at the transmitting antenna was fixed in this experiment ($\alpha = 36.5°$). Thus, the efficiency here is actually the reception efficiency. For any practical arrangement, however, the reception efficiency is also the coupling efficiency. The results of grating coupling efficiencies vs the angle of incidence for uncoated and coated copper surfaces are shown in Fig. 5. These data show that the maximum grating efficiencies are at an angle of incidence (36.5°) predicted by Eq. (6), indicating good agreement between theory and experiment. An error of 3 degrees deviation from the angle for maximum coupling efficiency of 36.5° for the dielectric coated conducting surface and 1.8 degrees deviation for the uncoated conducting surface reduced the efficiency by a factor of two. Note that the addition of the dielectric overlayer thus effectively expands the FWHM from 3.6° to 6°. The results for coupling efficiencies vs angle of incidence for uncoated and coated aluminum surfaces are similar to those results obtained for uncoated and coated copper surfaces, except that the maximum efficiency for aluminum is slightly smaller (the conductivity of aluminum is less than that of copper).

The grating coupling efficiency was measured as a function of the number of grating bars at a frequency of 3.98 GHz (λ = 7.54 cm) and at a grating spacing of 14 cm which required an angle of incidence of 27.5 degrees (see Eq. (6)). It was found that the efficiency not only varied for different numbers of grating bars but also depended upon at which bar in a given array the center of the maximum radiation field of the antenna was aimed. Here again, the reception efficiency was measured. The distance between the receiving antenna and the grating bar array was fixed at 2.7 m. Fig. 6 shows plots of the relative coupling efficiency vs the number of the grating bar at which the center (the maximum radiation field) of the antenna was aimed, counting bars from the front to the back (defined in Fig. 3) for arrays of two to six bars. Curve 6 is for the case for which 6 grating bars were used, and the efficiencies were measured when the receiving antenna was aimed first at grating bar number one (the one which picks up the SEW first); second, at grating bar number two, and so on to grating bar number 6. Curve 5 is for the case in which 5 grating bars were used, and the efficiencies were measured with the receiving antenna aimed first at grating bar number one, second at grating bar number two, and so on to grating bar number 5. It should be noted that it is possible to excite a SEW with as few as two grating bars and that the efficiency is about one-third that of the maximum for the most efficient arrangement of five bars.

Using the two grating bar configuration, the coupling efficiency vs grating constant (d) was measured at a frequency of 3.98 GHz (λ = 7.54 cm) and β = 27.5° on an uncoated aluminum strip. Fig. 7 is a plot of the grating coupling efficiency vs the grating constant, d. The peak efficiency occurs when d = 14 cm and shows excellent agreement between experiment and theory (Eq. (6)). It is noted that when d = 14 cm, the efficiency is found to be the same for the antenna focussed on either of the two grating bars. Fig. 7 illustrates that an error of 5% in the grating constant may reduce the coupling efficiency by a large factor.

B. Experiment 2 - Prism Coupling Efficiency

The experimental set-up for this part is the same as shown in Fig. 3, except that two small right angle prisms replaced the receiving grating. One of the prism angles was chosen so that an electromagnetic beam normally incident on the prism face struck the prism base at the critical angle. These prisms were made of soft polyethylene with relative dielectric constant of 2.25. The prisms were of identical construction with dimensions illustrated in the insert of Fig. 8. Both prisms were used as the reception aperture (see Appendix III, Ref. 38) at the receiving point due to their relatively small individual size compared to the width of the metallic conductor strip (30.48 cm).

The prism coupling efficiencies were measured as a function of the angle of incidence β of the receiving antenna with the frequency fixed at 10 GHz (λ = 3 cm). The angle of incidence, α, for the transmission grating was fixed at 36.5° for both coated and uncoated metal surfaces, the gap between the base of the prism and the metal surfaces was fixed at 3.1 cm (λ/d was approximately equal to one). The results of prism coupling efficiencies vs the angle of incidence β (internal to the prism) for uncoated and coated copper surfaces are shown in Fig. 8. As shown in Fig. 8, the maximum coupling efficiencies occur when the angle of incidence, β (determined internally at the prism base), is 41.8° which is the critical angle for the soft polyethylene prism used. The data in Fig. 8 also show that the efficiencies are equal for both uncoated and coated dielectric surfaces except in the vicinity of the critical angle. Notice that an error of about three degrees deviation from the critical angle for uncoated or dielectric coated metal surfaces results in a reduction of the coupling efficiency by a factor of two from the maximum value at the critical angle.

The results for coupling efficiency vs the angle of incidence for uncoated and coated aluminum surfaces are similar to those obtained for uncoated and coated copper surfaces except that the maximum efficiency for uncoated aluminum is less than that for uncoated copper (40% vs 60%) (attributed to the lower conductivity of aluminum).

The peak coupling efficiency of the prism technique was examined at a frequency of 8.445 GHz (λ = 3.55 cm) by sliding a microwave horn to various positions on the back of the soft polyethylene prism (see Fig. 9). This was accomplished by placing the prism on a styrofoam (ε_R = 1.06) slab 1.50 cm thick (used as an air gap since it is transparent at microwave frequencies), putting an aluminum shield on the front of the prism 3.5 cm up from the prism corner, and sliding the horn over the back prism face. It was found that the peak coupling efficiency occurs when the distance between the target point of the center line of the horn antenna and the corner of the prism was 3.50 cm (about one wavelength) as illustrated in Fig. 9.

The prism coupling efficiencies as a function of the (gap height)/(wavelength) for the soft polyethylene prism were measured for a frequency of 8.445 GHz (λ = 3.55 cm) and are plotted in Fig. 10 for two conditions. Condition one is for the gap height between the prism base and the standard railroad rail, and condition two is for the gap height between the prism base and the planar aluminum strip. The dimensions of the railroad rail are given in the insert of Fig. 10. The aluminum strip was 30.48 cm wide. Note that the peaks in the curves are displaced by a half-integer wavelength for both conditions. The largest efficiencies of the several maxima are found to occur at one wavelength gap height above the plane aluminum strip and at one-half wavelength gap height above the railroad rail. These very important results have implications for on-going work[6,38-44] in the areas of high-speed and/or mass-transit systems for rail guided vehicles (see also Bibliography, Ref. 38). An application of these coupling techniques for SEW on rails is under further investigation and a paper will be forthcoming.

CONCLUSIONS

The coupling efficiencies for SEW excitation for both the prism and grating techniques have been measured. The grating experiments included studies of the SEW coupling efficiency as functions of the frequency, the angle of incidence, the grating constant, the number of grating bars, and the position of the grating bar at which the center of the maximum radiation field of the antenna was aimed. For the prism SEW coupling technique, the coupling efficiency was studied as functions of the angle of incidence, the aiming point of the transmitting antenna on the prism base, and the height of the prism above the aluminum strip or the standard railroad rail.

It was found that the grating coupling efficiency is sharply dependent on the grating constant, the frequency, and the angle of incidence. This has strong possible applications for guidance systems. For practical applications, it is useful to note that two grating bars are sufficient to excite a SEW and that the efficiencies are equal for the center of the antenna aimed at either bar. The coupling efficiency for a particular grating bar array is a function of which bar in the array the antenna is focussed upon for grating arrays of three or more bars.

For the prism coupling technique, the efficiency is 60% vs about 15% for the grating excitation technique. The effective pick-up point for the SEW is about one wavelength back of the prism edge. The coupling efficiency is strongly dependent on the angle of incidence and is also dependent on the gap height, with maximum peak efficiency occurring near (gap height)/$\lambda \approx 1$ for the aluminum strip and (gap height)/$\lambda \approx 1/2$ for a standard railroad rail indicating a clear shape dependence.

These results for both the prism and the grating coupling techniques can be used to control and optimize the same parameters in infrared and visible wavelength experiments with SEW and integrated optics.

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FIGURE CAPTIONS

Fig. 1. (a) Prism coupling technique principle showing critical angle (θ_c), (b) coupling in and out of surface electromagnetic waves by prism couplers.

Fig. 2. Grating coupling technique principle showing the angle of incidence (α) and the grating spacing (d). Mode order 1 is shown coupled as a SEW ($\theta_1 = 90°$).

Fig. 3. Experimental arrangement used for experiment 1, grating coupling efficiency. Each grating is composed of 7 bars with a diameter of 1.27 cm and spaced 7.4 cm apart. The metallic conductor strip is aluminum or copper 30.48 cm wide. The distance between transmitting and receiving gratings is 3 m. Transmitting and receiving antennas are identical with a deflector diameter of 45.72 cm. Shields are made of microwave absorbing materials on (1m x 2m) aluminum plates with a gap of 12 cm above the metal strip.

Fig. 4. Grating coupling efficiency vs frequency on uncoated and dielectric coated copper strips 30.48 cm wide. The grating is composed of 7 iron bars with a diameter of 1.27 cm and spaced 7.4 cm apart. The angle of incidence (β) is fixed at 36.5°. The dielectric materials is 1 mm thick layers of a

special paper with relative dielectric constant of 2.7 and loss factor of 0.056.

Fig. 5. Grating coupling efficiency vs angle of incidence on uncoated and dielectric coated copper strips 30.48 cm wide. The grating is composed of 7 bars with a diameter of 1.27 cm and spaced 7.4 cm apart. The frequency was 10 GHz. The dielectric material is 1 mm thick of special paper with a relative dielectric constant of 2.7 and a loss factor of 0.056.

Fig. 6. Relative grating coupling efficiency vs the number of the grating bar at which the center of the antenna was aimed, counting from the front to the back bar (defined in Fig. 3). Curve 6, e.g., is for the arrangement of six grating bars; aiming the center of the antenna at various grating bars from the front bar (bar 1) thru the back bar (bar 6).

Fig. 7. Grating coupling efficiency vs grating constant for two bars on uncoated aluminum strip. The grating bars are 1.27 cm in diameter. The frequency was fixed at 3.98 GHz (λ = 7.54 cm), the reception angle (β) was at 27.5° and the metallic strip is 30.48 cm wide.

Fig. 8. Prism coupling efficiency vs angle of incidence on uncoated and dielectric coated copper strip 30.48 cm wide at a frequency of 10 GHz. The

dielectric material is 1 mm thick of special paper with relative dielectric constant of 2.7 and loss factor of 0.056. The prism made of soft polyethylene ($\varepsilon_R = 2.25$) is shown in the insert.

Fig. 9. Prism used in experimental determination of efficiency showing placement of microwave horn to pick up the maximum signal. The prism is made of soft polyethylene ($\varepsilon_R = 2.25$). The styrofoam ($\varepsilon_R = 1.06$) at the base of prism used as the air gap.

Fig. 10. Prism coupling efficiency vs (gap height)/(wavelength) for a soft polyethylene ($\varepsilon_R = 2.25$) prism. Symbol O represents gap height between the prism base and the standard railroad rail. Symbol Δ represents gap height between the prism base and the plane aluminum strip 30.48 cm wide.

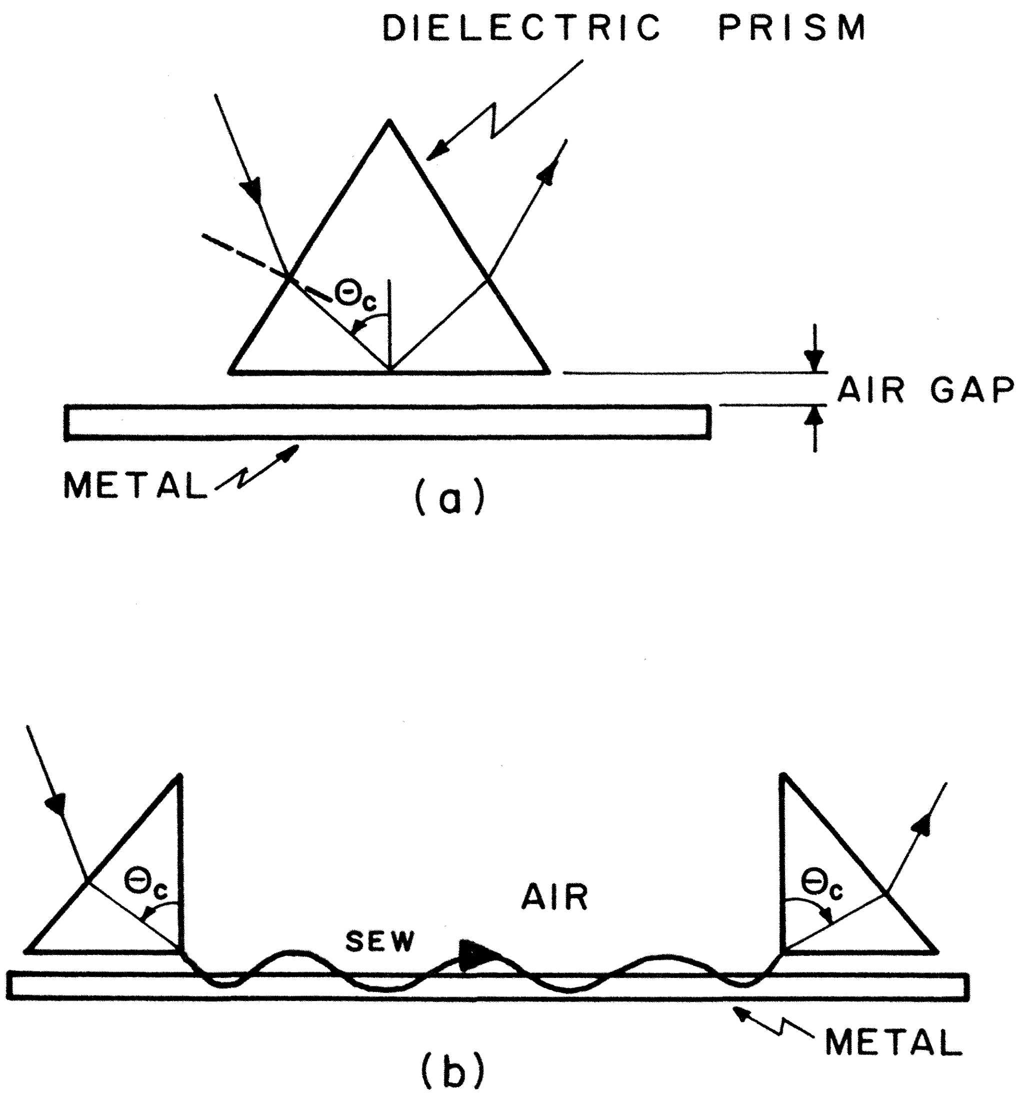


Figure 1

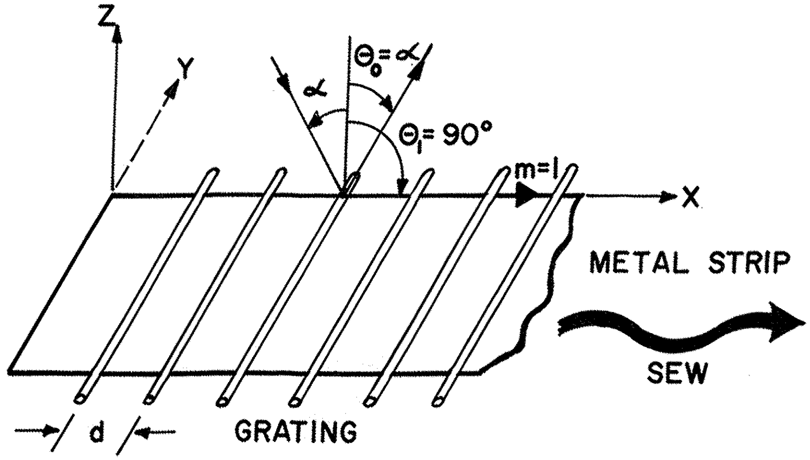

Z
Y
α
$\Theta_0 = \alpha$
$\Theta_1 = 90°$
m=1
X
METAL STRIP
SEW
d
GRATING

Figure 2

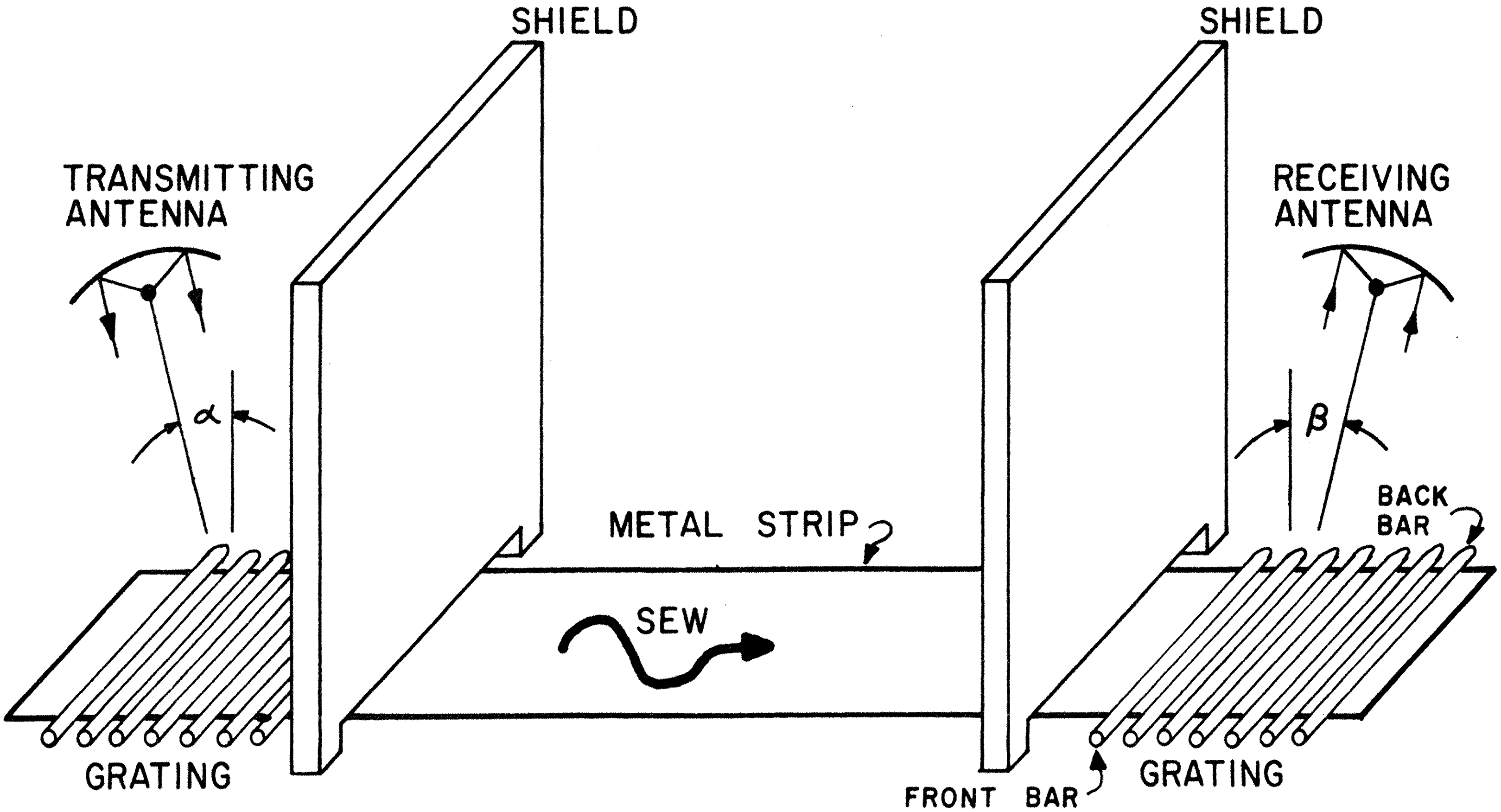

SHIELD
SHIELD
TRANSMITTING ANTENNA
RECEIVING ANTENNA
α
β
METAL STRIP
BACK BAR
SEW
GRATING
FRONT BAR
GRATING

Figure 3

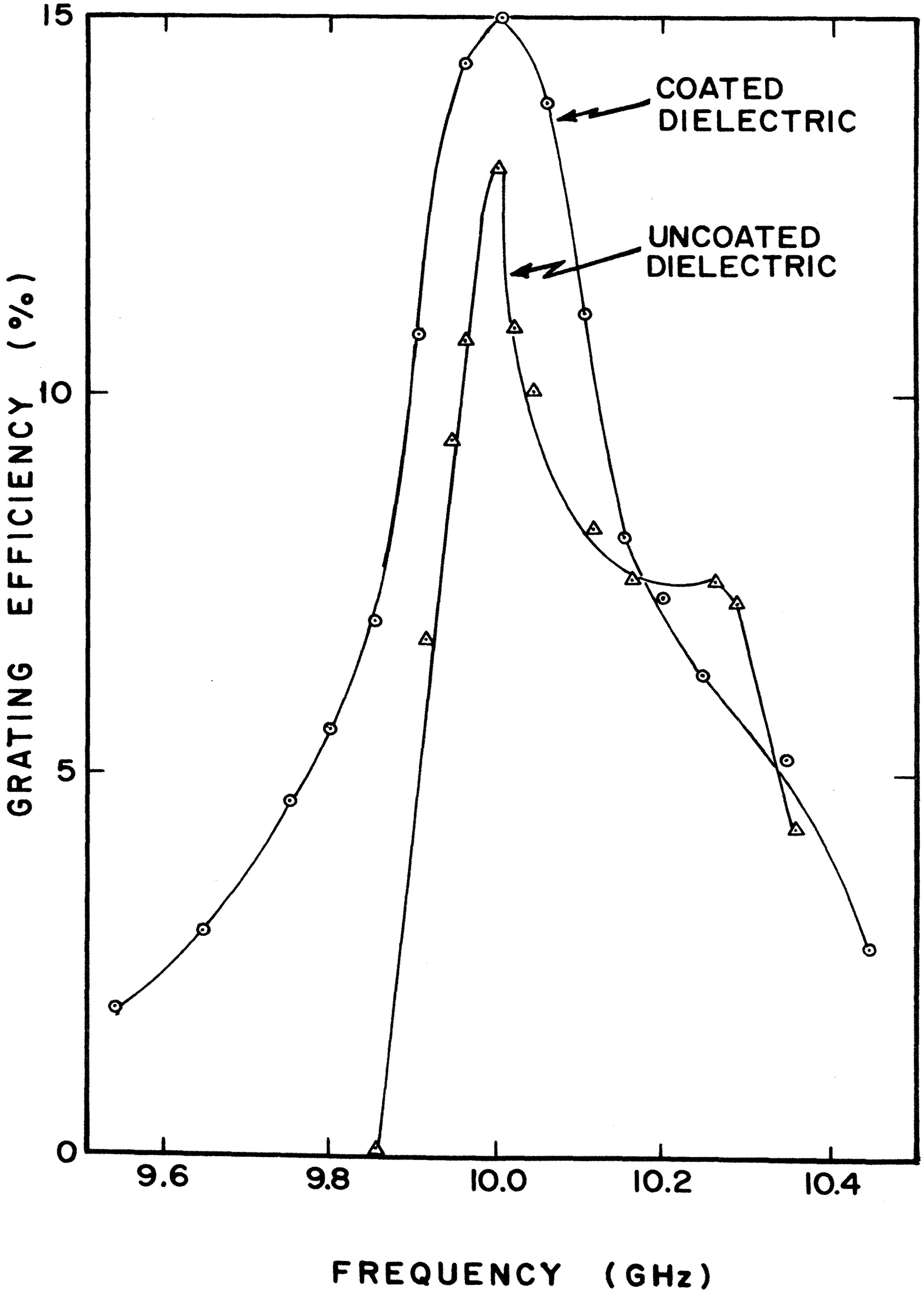
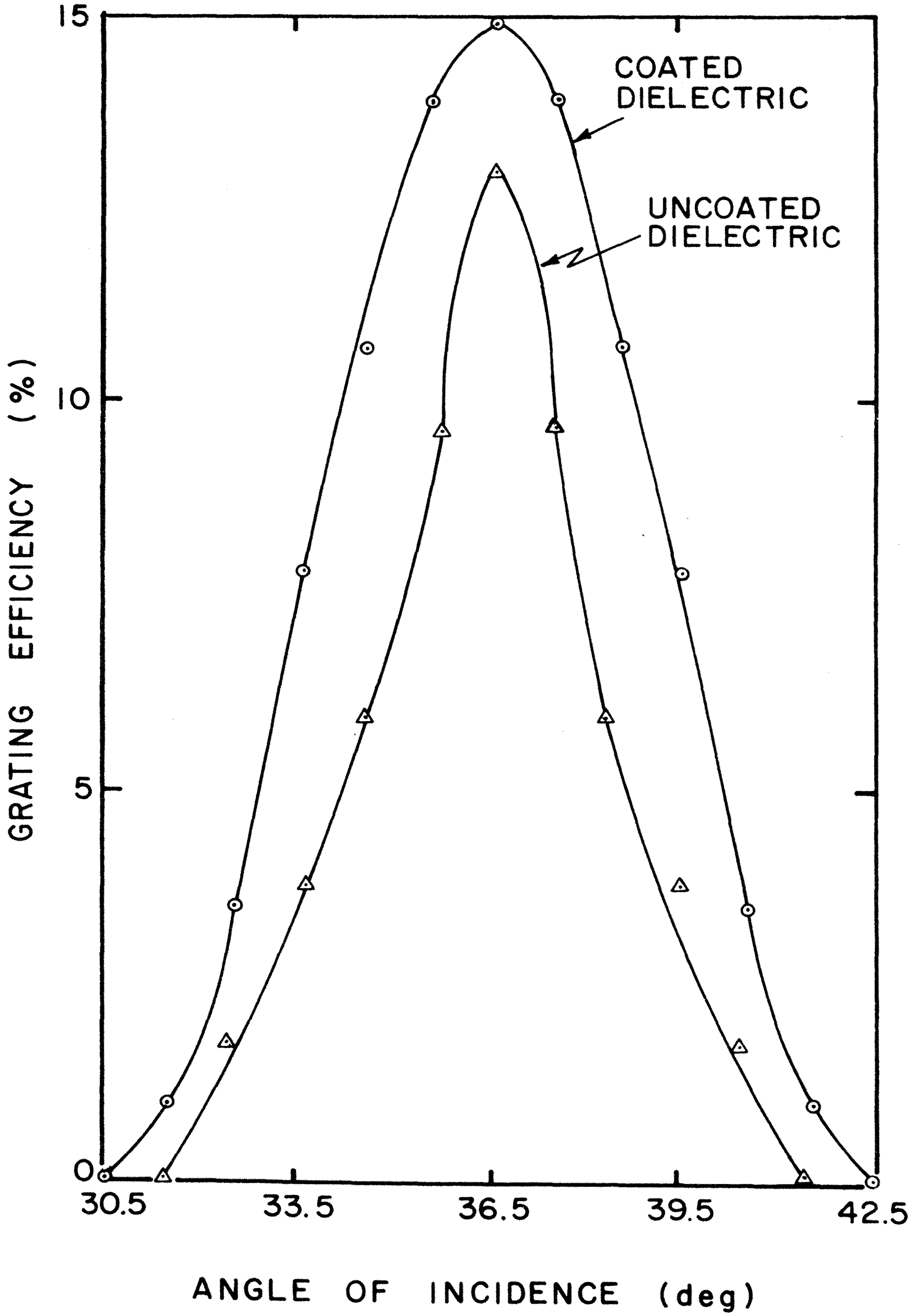

15
10
5
0
GRATING EFFICIENCY (%)
COATED DIELECTRIC
UNCOATED DIELECTRIC
9.6
9.8
10.0
10.2
10.4
FREQUENCY (GHz)

Figure 4



15
10
5
0
30.5
33.5
36.5
39.5
42.5
COATED DIELECTRIC
UNCOATED DIELECTRIC
GRATING EFFICIENCY (%)
ANGLE OF INCIDENCE (deg)

Figure 5

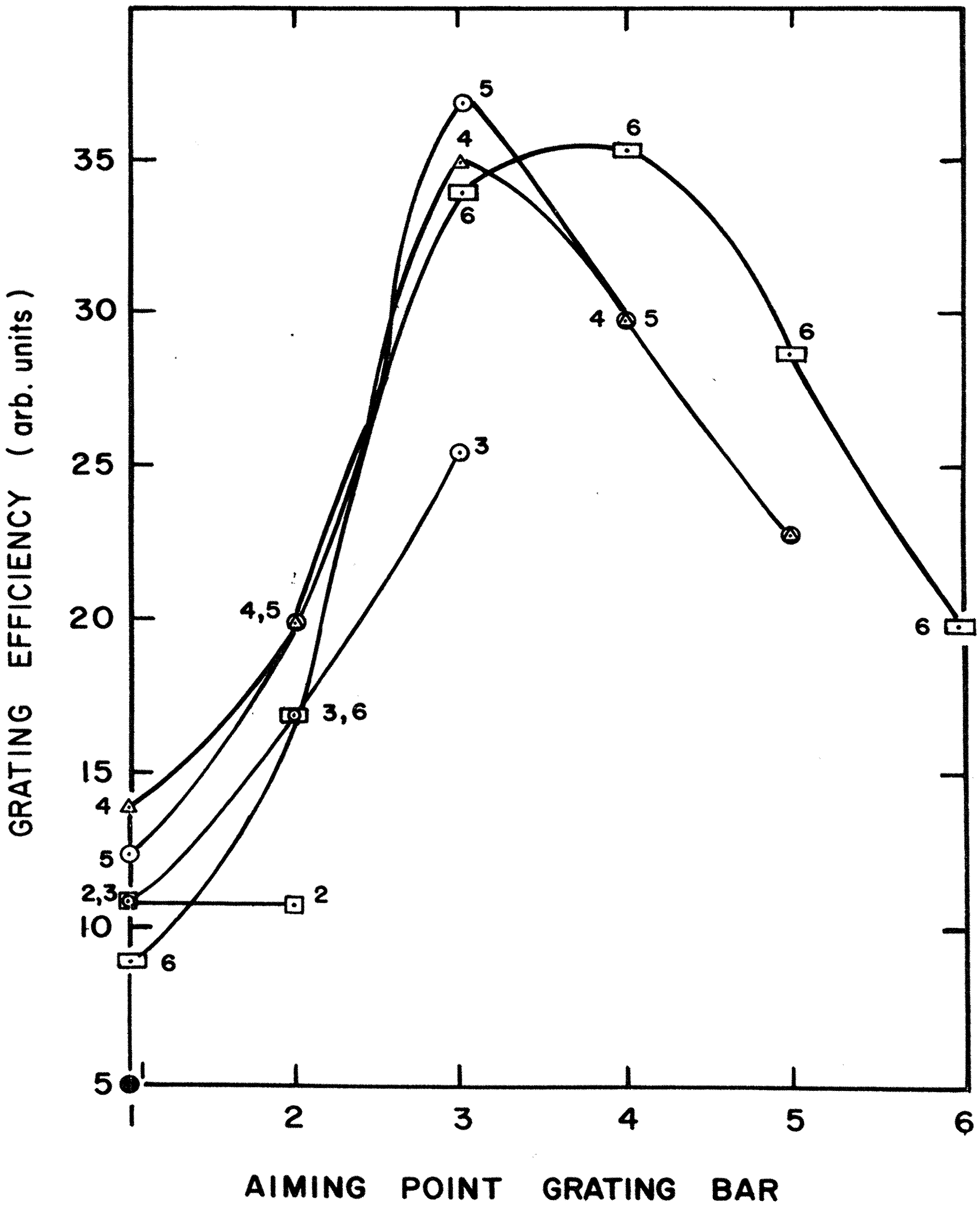

GRATING EFFICIENCY (arb. units)
AIMING POINT GRATING BAR
35
30
25
20
15
10
5
1
2
3
4
5
6
4,5
3,6
2,3
2
4 5
3

Figure 6

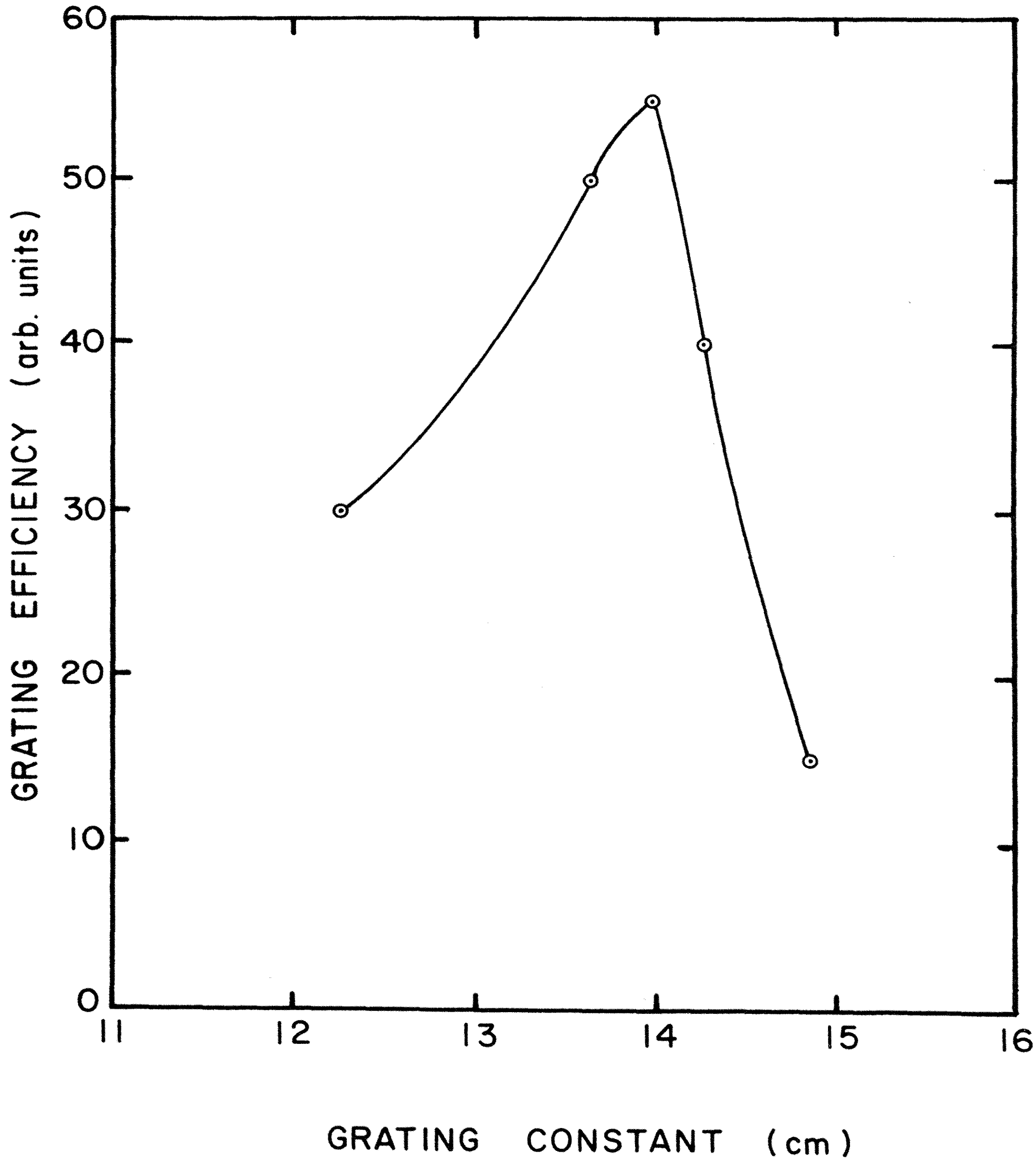

60
50
40
30
20
10
0
GRATING EFFICIENCY (arb. units)
11
12
13
14
15
16
GRATING CONSTANT (cm)

Figure 7

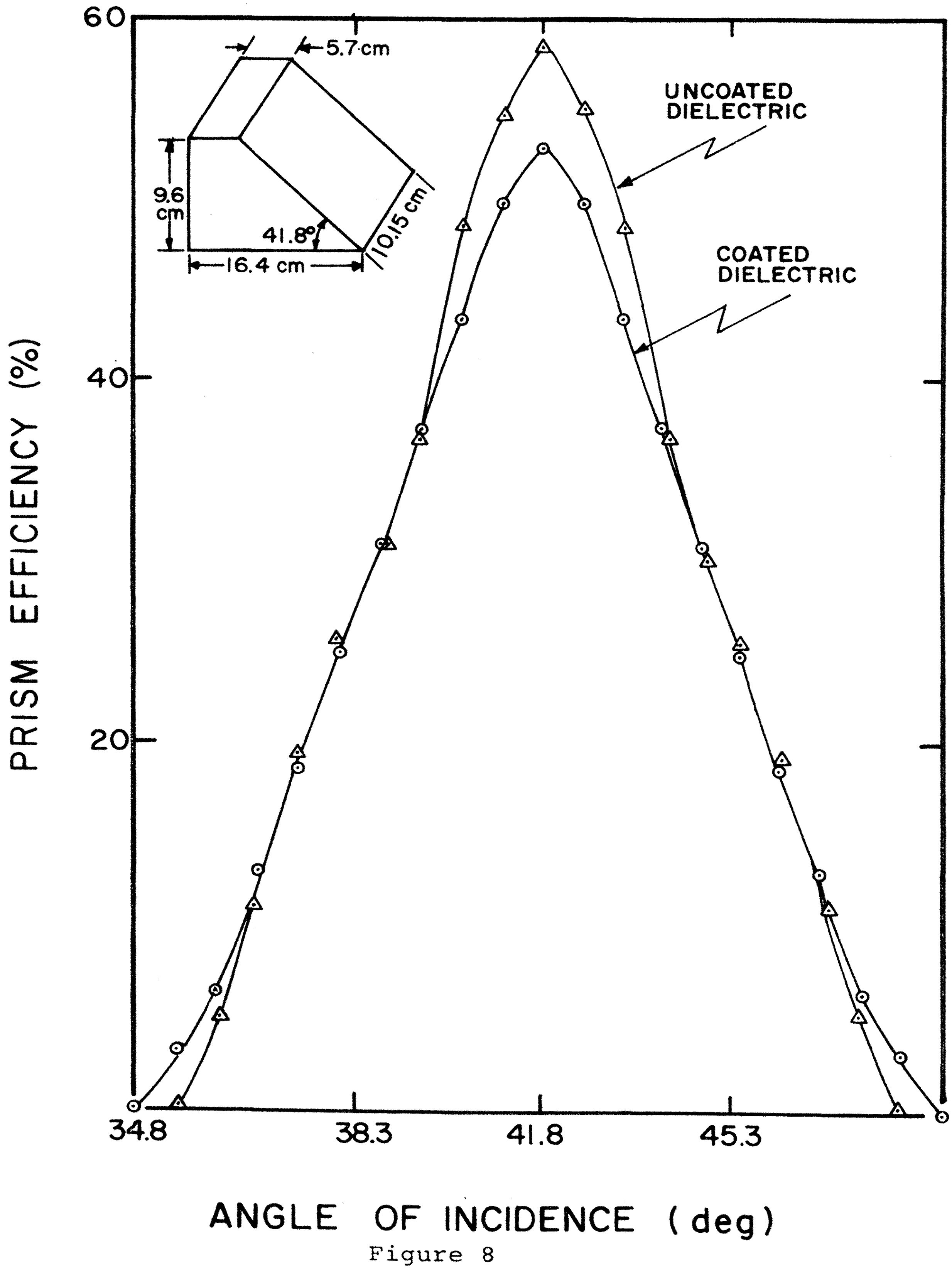

60
40
20
PRISM EFFICIENCY (%)
34.8
38.3
41.8
45.3
ANGLE OF INCIDENCE (deg)
UNCOATED
DIELECTRIC
COATED
DIELECTRIC
5.7 cm
9.6
cm
41.8°
10.15 cm
16.4 cm

Figure 8

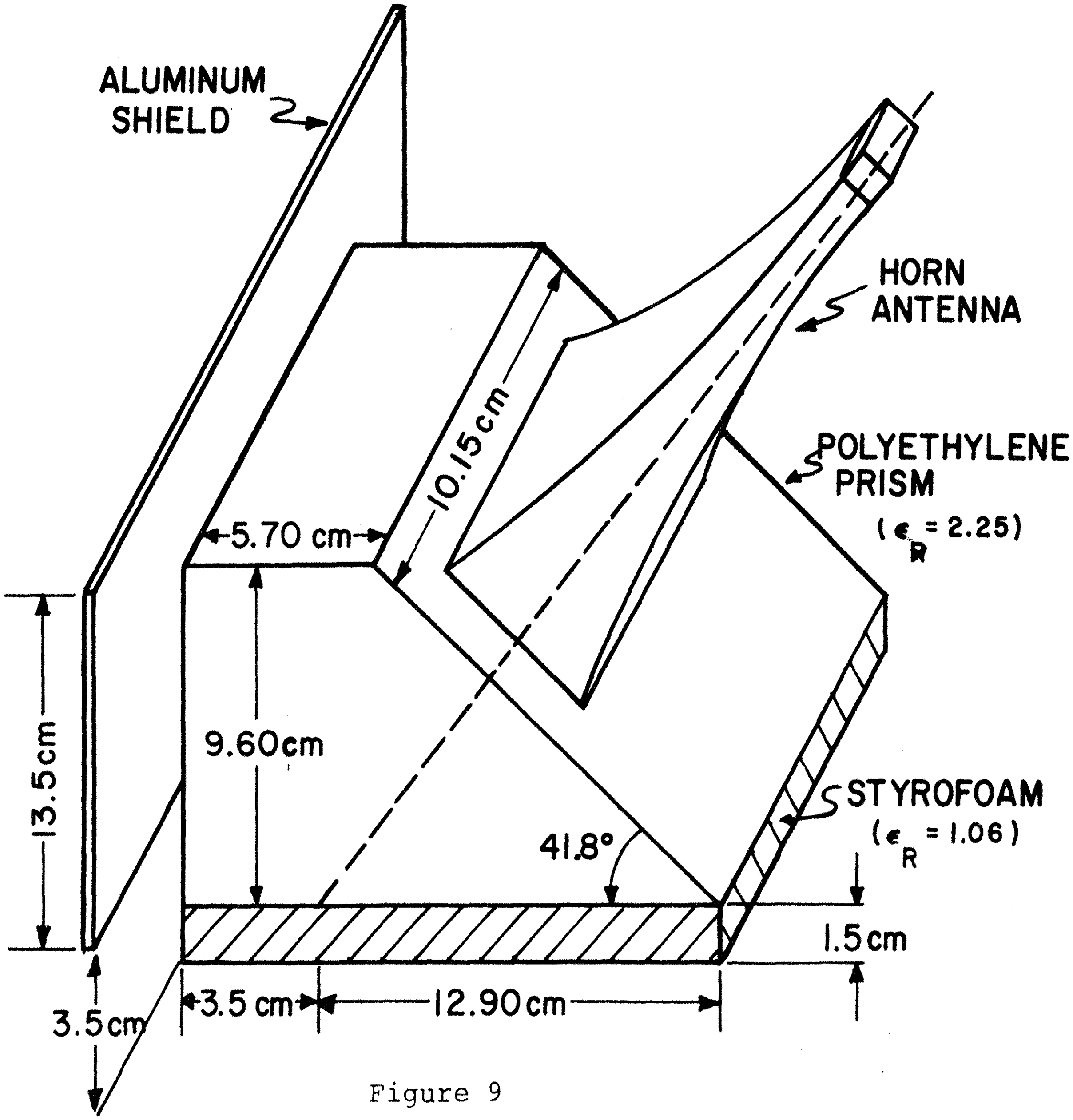

ALUMINUM SHIELD
HORN ANTENNA
10.15 cm
5.70 cm
POLYETHYLENE PRISM
(ϵ_R = 2.25)
13.5 cm
9.60 cm
STYROFOAM
(ϵ_R = 1.06)
41.8°
1.5 cm
3.5 cm
12.90 cm
3.5 cm

Figure 9

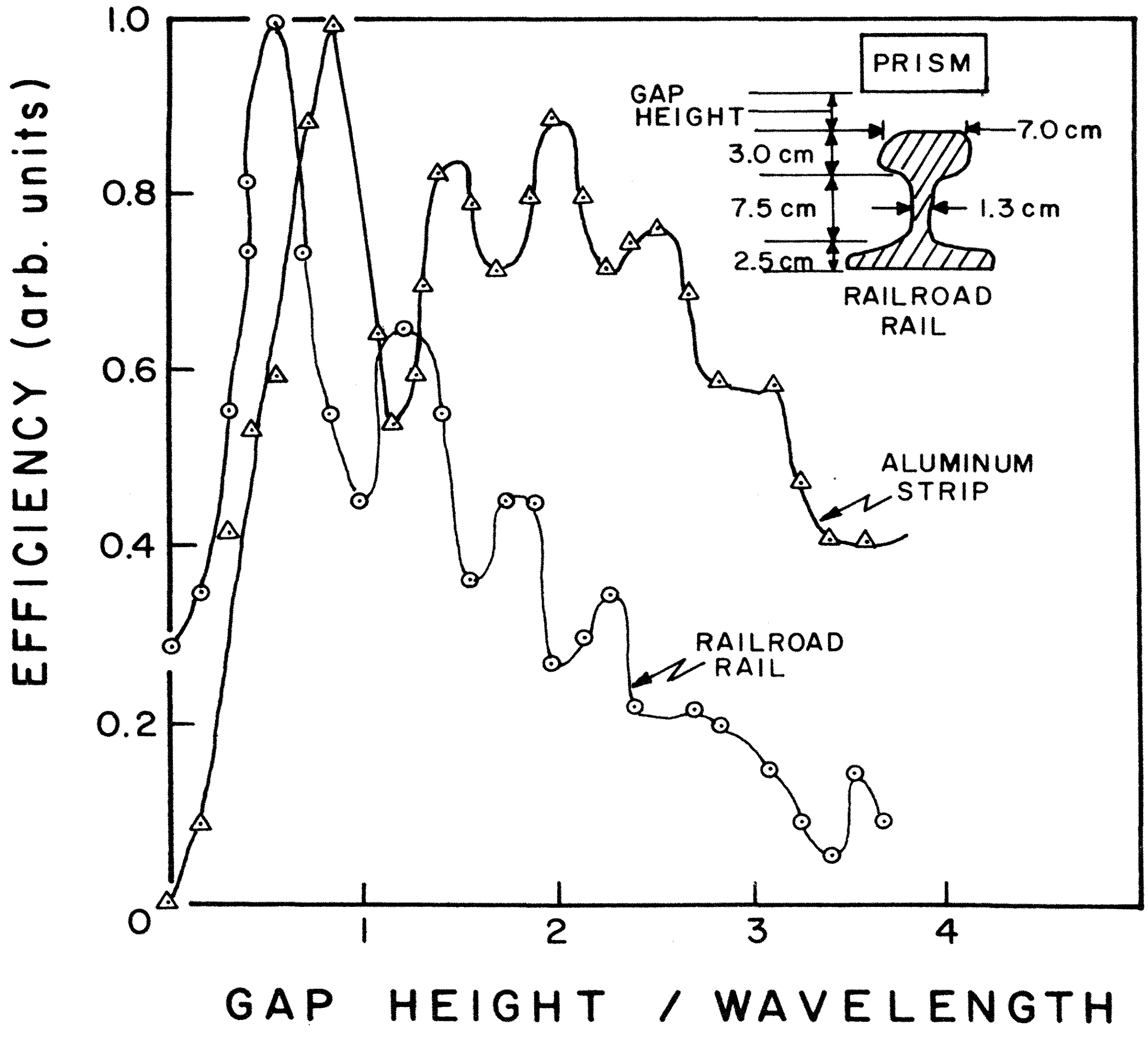

1.0
0.8
0.6
0.4
0.2
0
EFFICIENCY (arb. units)
1
2
3
4
GAP HEIGHT / WAVELENGTH
PRISM
GAP HEIGHT
3.0 cm
7.5 cm
2.5 cm
7.0 cm
1.3 cm
RAILROAD RAIL
ALUMINUM STRIP
RAILROAD RAIL

Figure 10

PART II

MEASUREMENTS OF SURFACE ELECTROMAGNETIC WAVE COUPLING EFFICIENCIES FOR SEVERAL EXCITATION TECHNIQUES

Manuscript has been submitted to IEEE Transactions on Microwave Theory and Techniques

MEASUREMENTS OF SURFACE ELECTROMAGNETIC WAVE COUPLING EFFICIENCIES FOR SEVERAL EXCITATION TECHNIQUES*

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ABSTRACT

The excitation efficiencies for coupling surface electromagnetic waves onto aluminum at microwave frequencies were studied experimentally for several different techniques. The peak efficiencies found were: for the standard rectangular waveguide, 92%; for the horn antenna, 73%; for the right angle prism gapped one vacuum wavelength above the metal, 60%; for the hump of 10 wavelength radius of curvature, 35%; for the thin grating strips on polystyrene coated metal, 30%; for the grating bars gapped one-half wavelength above the metal, 26%; and, for the valley of 10 wavelength radius, 12%. In addition to measuring peak efficiencies, the efficiencies were measured as functions of the gap heights, the angular orientations, the different diffraction modes, the shapes and the materials of the grating bars. Dielectric grating bars were found to be very inefficient compared with solid or

hollow metallic bars, or thin metallic strips. The distance between the target point of the center line of the microwave horn antenna and the corner of the prism was found to be about one wavelength for maximum prism coupling efficiency.

INTRODUCTION

In infrared and visible wavelength[1] experiments with surface electromagnetic waves (SEW), one is often plagued with a lack of knowledge concerning the excitation efficiencies of the SEW using various techniques. There are several parameters in each excitation technique, and each parameter should be optimized and controlled. Since control of shape and spacing cannot be so easily maintained in the near infrared and visible wavelength regions, a microwave frequency ($f = 8.445 \times 10^9$ Hz, $\lambda = 3.55$ cm) was used for this study of coupling efficiencies. We report the measurement of the efficiencies for excitation of SEW on metals using the following techniques: (1) the prism[2-7], (2) the grating[1,4,7-11], (3) the standard waveguide[12], (4) the horn antenna[13-16], (5) the hump[17-19] and (6) the valley or depression[17-19].

Though extensive studies have been made for the prism and the grating excitation techniques in integrated optics[20-29], these SEW studies are necessary because of the different experimental configurations and the ability to control and optimize parameters at the longer wavelength. In integrated optics, the prism or grating produces a guided wave in a transparent overlayer on a transparent substrate. In SEW studies, there is not necessarily an overlayer, and the metal is extremely absorbing in contrast to the transparent substrates of integrated optics.

In previous papers[7,30,31], we reported preliminary experiments using the prism and the grating coupling techniques at microwave frequencies. The reader is referred to one of those papers[7,30,31] for many of the details of the experimental arrangements which are not included in this paper but which are similar for all coupling techniques.

The coupling efficiency is defined as[15,32] the ratio of the power carried by the SEW to the power transmitted through the coupling aperture. The coupling aperture referred to can be that of the prism, the grating, the standard waveguide, the horn antenna, the hump, or the valley. The dependence of the coupling aperture on the SEW excitation technique is discussed in detail in Appendix III of Ref. 32. This work expands the previous work[7,30,31] on prism and grating coupling techniques and explores additional coupling techniques for launching SEW wave on planar surfaces (Zenneck waves[15,33]) using coherent microwave sources.

EXPERIMENTS

In order to facilitate presentation of the data, the results for each excitation technique will be presented and discussed separately.

A. The Prism Excitation Technique

A right angle prism was aligned with the base parallel to the metal onto which excitation of the SEW was desired and the coupling efficiencies were measured. These measurements were made near the light line of the metal-air SEW dispersion curve $k_x = \frac{\omega}{c}$, with a soft polyethylene (ε_R=2.25) prism, where k_x is the propagation vector of the SEW in the direction of propagation, ω is the SEW angular frequency, and c is the speed of light in free space. The coupling efficiencies were measured as a function of the height of the prism base above the metal, i.e., the gap height (g). The data[7] in Fig. 1 show that the efficiency peaks occur for gap heights at multiples of the half-integer wavelength and that the grand maximum is at one wavelength gap height above a plane aluminum strip 30.48 cm wide. The shape of the metal below the prism makes some difference, as the efficiencies for exciting SEW on a standard railroad rail differ from excitation efficiencies vs gap height on plane metal sheets. The grand maximum for the rail was found[7] to occur at a one-half wavelength gap height above the rail with repeated peaks every half-integer wavelength. The cross section of the rail is indicated in the insert in Fig. 1.

The coupling efficiency was studied as a function of the distance (d) between the target point of the center line of the microwave horn antenna and the corner of the prism. The mouth of the microwave horn antenna (7.5 x 5.5 cm) was taped to the back of the polyethylene prism as shown in the insert of Fig. 2. Strong oscillations occur in the coupling efficiency (curve A, Fig. 2) with the main peak coming at a distance approximately equal to the vacuum wavelength (λ) of the source radiation. However, the spacing of the peaks is not simple [$(16n + 11)\lambda/10$, n an integer] and is not fully understood. The efficiency measurements were repeated with a polystyrene ($\varepsilon_R = 2.55$) sheet 1.6 mm thick placed on the metal strip. The results of the dielectric overlayer (curve B, Fig. 2) are not strongly different from the results with no overlayer (curve A, Fig. 2).

The stray radiation emanating from the vertical face of the prism was examined. The insert in Fig. 3 shows the experimental lay-out. Polar plots of the relative radiation intensity levels are shown in Fig. 3 for the case of a bare prism (curve A, Fig. 3) and for the case in which the front and top faces of the prism were shielded with metal sheets (curve B, Fig. 3). These measurements were made at a gap height (g) of 1.4 cm, but the angular variation is not dependent on the gap height. The magnitude, of course, does depend on gap height, as one would expect from Fig. 1.

To couple a SEW by the prism coupling technique at microwave frequencies, the angle of incidence at the base of the prism must be equal to the critical angle[7]. Therefore, by Snell's Law, in addition to the SEW, there should be appreciable radiation at very small forward angles parallel to the surface. Fig. 3 shows experimentally the existence of this radiation at small forward angles from the horizontal. In prism-to-prism SEW measurements, one must take care not to have direct radiation pick-up between the two prisms. This direct radiation can be eliminated by the construction of a hump, with a very large radius of curvature, between the two prisms, i.e., one may use over-the-horizon techniques since the SEW will follow the contour[33] while the radiative component will not.

In these experiments, the maximum coupling efficiency for the prism excitation technique was found to be 60%.

B. The Grating Excitation Technique

A grating made of seven 1.27 cm diameter iron bars with 5.4 cm grating constant was constructed and the efficiencies as functions of the gap heights of the grating above the metal were studied with various thicknesses of polystyrene on the metal. Curve A, Fig. 4, is for the bare metal; curve B, Fig. 4, is for the metal covered with 1.6 mm polystyrene; curve C, Fig. 4, is for the metal covered with 4.8 mm of polystyrene. As with the prism excitation technique, there are strong peaks at gap heights of multiples of the half-integer wavelength. It is also quite striking that the efficiency is very low when the grating is flush with the metal. The gap height dependence of the peaks appears to follow an $n\lambda/2$ formula, n an integer.

Studies of the efficiency vs the number of grating bars and the grating constant appear in another publication[7]. The efficiencies for various shapes and materials of the grating bars were studied here. The results are tabulated in Table I. Dielectric grating bars, masonite ($\varepsilon_R = 2.43$), were very inefficient in initiating a SEW compared with metal rods and strips. The maximum SEW coupling efficiency of 30% was obtained for thin metal strips (width 1.27 cm, height 0.036 cm) placed directly on the 1.60 mm polystyrene overlayer above the metal. Cylindrical metal bars (iron or aluminum) 1.27 cm in diameter produced a 26% maximum SEW coupling efficiency. The results are identical for hollow and solid grating bars. Right angle aluminum strips turned on edge (1.27 cm along a side) produced 22% maximum SEW coupling efficiency.

Measurements of the de-coupling efficiencies vs the angular distribution of radiation as measured from the normal were studied. A polar plot of the efficiencies is presented in Fig. 5. The angles for the various mode orders are determined from[7]

$$\sin \theta_m = 1 - \frac{m\lambda}{d} \tag{1}$$

where θ_m is the angle of incidence for the mode, m is the mode order, λ is the wavelength (3.55 cm), and d is the grating constant (5.4 cm center to center). The angles and corresponding mode order calculated from Eq. (1) are illustrated in Fig. 5 along with the experimental results. The theory and experiment show good agreement. The zeroth, 1st, and 2nd order modes are comparable in SEW coupling efficiency, and the 3rd order mode is about twice as efficient as the zeroth, 1st or 2nd order modes. Fig. 5 shows clearly that high order modes can be used to excite SEW efficiently.

C. The Rectangular Waveguide Excitation Technique

This is a technique which has been previously[12] used to excite SEW. A standard rectangular waveguide is laid parallel to the metal strip. The SEW are coupled to the metal strip at the interface of the waveguide and metal strip. If the waveguide is partially filled with dielectric, the coupling efficiency will increase. A maximum coupling efficiency of 92% was achieved using this technique.

D. The Horn Antenna Excitation Technique

This is a technique which has been previously[13-16] used to excite SEW. A rectangular horn is laid on a metallic surface. The SEW are excited in the base of the horn and progress out the inside of the base onto the large metal strip. With the TM polarization of the SEW the long edge of the 7.5 x 5.5 cm rectangular microwave horn was flat against the metal strip. A maximum excitation efficiency of 73% was obtained using this technique.

E. The Hump and Valley Excitation Techniques

A hump of metal with a height of 37 cm and the curvature cross-section as shown in the insert in Fig. 6 was constructed. The coupling efficiencies were measured as the SEW was excited with the hump by aiming a horn antenna at it at various angles. The peak efficiency of about 35% was realized when the horn was aimed vertically at the hump's center of curvature. Finding the optimum hump parameters could be quite tedious. However, for specific applications special efforts could be worthwhile since these experiments show a peak coupling efficiency of 35% for this simple geometry.

A SEW was excited on the surface of the aluminum using a grating coupler and parabolic dish antenna. The SEW propagated down the metal to the hump located 5.5 meters from the excitation point. Angular distributions of the radiation from the hump were made in the vertical plane parallel to direction of propagation (x-z plane).

Radiation distributions are shown for an uncoated metal hump (curve A, Fig. 6) and for a hump with a 2.29 mm thick overlayer of polyethylene (ϵ_R = 2.25) (curve B, Fig. 6). By reciprocity, the angular distribution obtained indicates the angles and relative efficiencies for excitation of the SEW by the hump. Note that the excitation efficiency without an overcoating (curve A, Fig. 6) is very symmetric for small angles (θ, defined in Fig. 6), whereas with an overlayer, the peak efficiency remains about the same but is not symmetric for small angles (curve B, Fig. 6).

The y-z plane (vertical plane perpendicular to the direction of propagation) radiation distribution for the hump was studied and the full width at half-maximum was found to be about 10° for the bare metal case (curve A, Fig. 7) and 15° for the dielectric coated metal case (curve B, Fig. 7).

The coupling efficiencies were measured as the SEW was excited with the inverted hump (valley or depression) by aiming a horn antenna at it at various angles. This measurement proved to be extremely difficult. However, a peak coupling efficiency of 12% was found when the horn antenna was aimed vertically down on the valley. The valley dimensions were nearly those of the hump just described but, of course, inverted.

CONCLUSIONS

The coupling efficiencies of surface electromagnetic waves on aluminum strips were studied for several excitation techniques operating at a microwave frequency (8.445 GHz). The peak efficiencies found were: standard rectangular waveguide with dielectric, 92%; horn antenna laid on metal, 73%; polyethylene prism at one vacuum wavelength above the metal, 60%; dielectric coated metal hump of about 10 wavelength height, 35%; grating strips on polystyrene coated metal, 30%; and grating bars gapped half a vacuum wavelength above the metal, 26%; and a valley of about 10 wavelength depth, 12%. These are summarized in Table II.

The SEW coupling efficiency curves for both the prism and the grating are strong functions of the height of the gap above the metal, showing peaks at multiples of the half-integer wavelength. The grating technique can be used in several different mode orders with great efficiency. In the infrared frequency range, perhaps the best grating technique to excite SEW on a sample would be to rule or scribe a grating with the desired grating constant on a transparent piece of plastic or glass and gap this grating (ruled side down) above the sample and to shine the exciting radiation through the grating from the unruled side.

The grating coupling efficiency is dependent on the shapes and the materials of the grating bars. Dielectric grating bars are very inefficient compared with metallic strips on a dielectric coated surface or metallic bars. The efficiencies are the same for the hollow or solid grating bars. Using various materials (iron or aluminum) of metallic bars makes no measurable difference in the coupling efficiency.

The right angle prism technique is much used for prism-to-prism SEW studies; however, these studies warn of directly radiated low angle diffracted radiation that must be controlled for reliable measurements. The maximum prism coupling efficiency was found to occur when the distance between the target point of the center line of the horn antenna and the corner of the right angle prism was approximately equal to the vacuum wavelength of the source radiation and the prism is properly gapped above the surfaces.

We have shown that a hump can be used as a very effective means of exciting SEW. The best direction to aim the incident radiation beam is nearly vertically down on the hump. The hump and valley techniques hold promise for future studies since they may lend themselves to theoretical analysis using the work of Barlow and Cullen[33].

The results of these experiments can be used for controlling and optimizing the same parameters in integrated optics and SEW studies at infrared and visible wavelengths.

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TABLE I. GRATING COUPLING EFFICIENCY FOR VARIOUS MATERIALS AND SHAPES OF THE GRATING BARS

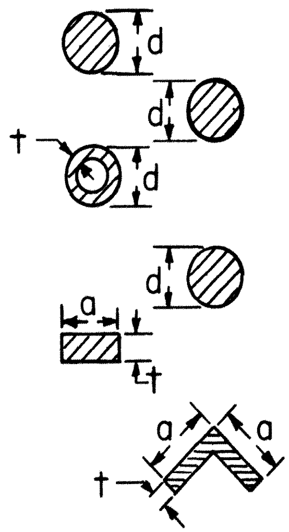
MATERIAL	SHAPE		EFFICIENCY PERCENT	
	CROSS SECTION	DIMENSIONS	WITH 1.60 mm POLYSTYRENE	WITHOUT POLYSTYRENE
Solid Iron Bar		d = 1.27 cm	26	7.5
Solid Al Bar		d = 1.27 cm	26	7.5
Hollow Al Bar		d = 1.27 cm t = 0.89 mm	26	7.5
Masonite Bar		d = 1.27 cm	2.5	1
Al Flat Strip		a = 1.27 cm t = 0.36 mm	30	0
Al Triangle Shape		a = 1.27 cm t = 0.36 mm	16	22

TABLE II. SEW EXCITATION EFFICIENCY FOR VARIOUS COUPLING TECHNIQUES

EXCITATION TECHNIQUE	EFFICIENCY
Rectangular Waveguide	92%
Horn Antenna	73%
Prism	60%
Hump	35%
Grating	30%
Valley	12%

FIGURE CAPTIONS

Fig. 1. Prism coupling efficiency vs (gap height)/(wavelength) for a soft polyethylene ($\varepsilon_R = 2.25$) prism. The circle symbol data represents gap height between the prism base and the standard railroad rail. The triangle symbol data represents gap height between the prism base and the plane aluminum strip 30.48 cm wide (from Davarpanah, Goben and Bell - Ref. 7).

Fig. 2. Prism coupling efficiency vs d/λ [(The distance of the aiming point of the center line of the 7.5 x 5.5 cm microwave horn antenna from the corner of the prism)/(wavelength)]. The prism is of soft polyethylene ($\varepsilon_R = 2.25$). Curve A is for the uncoated metal strip case and Curve B is for a thin dielectric [1.6 mm thick polystyrene ($\varepsilon_R = 2.55$)] placed above the metal strip 30.48 cm wide.

Fig. 3. Angular distribution of relative radiation intensity from the vertical face of the right-angle prism. Prism is made of soft polyethylene ($\varepsilon_R = 2.25$). Prism gap height is 1.4 cm and $\lambda = 3.55$ cm. Curve A is for the case of a bare prism (no shield), Curve B is for the shielded prism case in which the front and top face of the prism were covered with metal sheets.

Fig. 4. Grating coupling efficiency vs (gap height)/(wavelength) for a grating consisting of seven 1.27 cm diameter iron bars. The grating constant is 5.4 cm and the wavelength is 3.55 cm. Curve A is for the bare metal, Curve B is for the metal covered with a 1.6 mm polystyrene (ε_R = 2.56) overlayer, and Curve C is for the metal covered with a 4.8 mm polystyrene overlayer.

Fig. 5. Angular distribution of relative efficiency from a de-coupling grating. The angles and corresponding mode orders from Eq. (1) are shown here for comparison with experimental results. The grating consists of seven 1.27 cm diameter solid iron bars. The grating constant (d) is 5.4 cm and the wavelength (λ) is 3.55 cm (f = 8.445 GHz).

Fig. 6. x-z Plane (vertical plane parallel to direction of propagation) angular distribution of relative efficiency from a de-coupling hump (x is the direction of propagation). The hump has a height of 37 cm and the curvature cross-section as shown in the insert. Dimension of the hump in y direction is 30.48 cm. Curve A is for an uncoated metal hump and Curve B is for a hump with a 2.29 mm thick overlayer of polyethylene (ε_R = 2.25).

Fig. 7. y-z Plane (vertical plane perpendicular to the direction of propagation) angular distribution of relative efficiency from a de-coupling hump (x is

the direction of propagation). The hump has a height of 37 cm and the curvature cross-section as shown in the insert of Fig. 6. Dimension of the hump in y direction is 30.48 cm. Curve A is for an uncoated metal hump and Curve B is for a hump with a 2.29 mm thick overlayer of polyethylene ($\varepsilon_R = 2.25$).

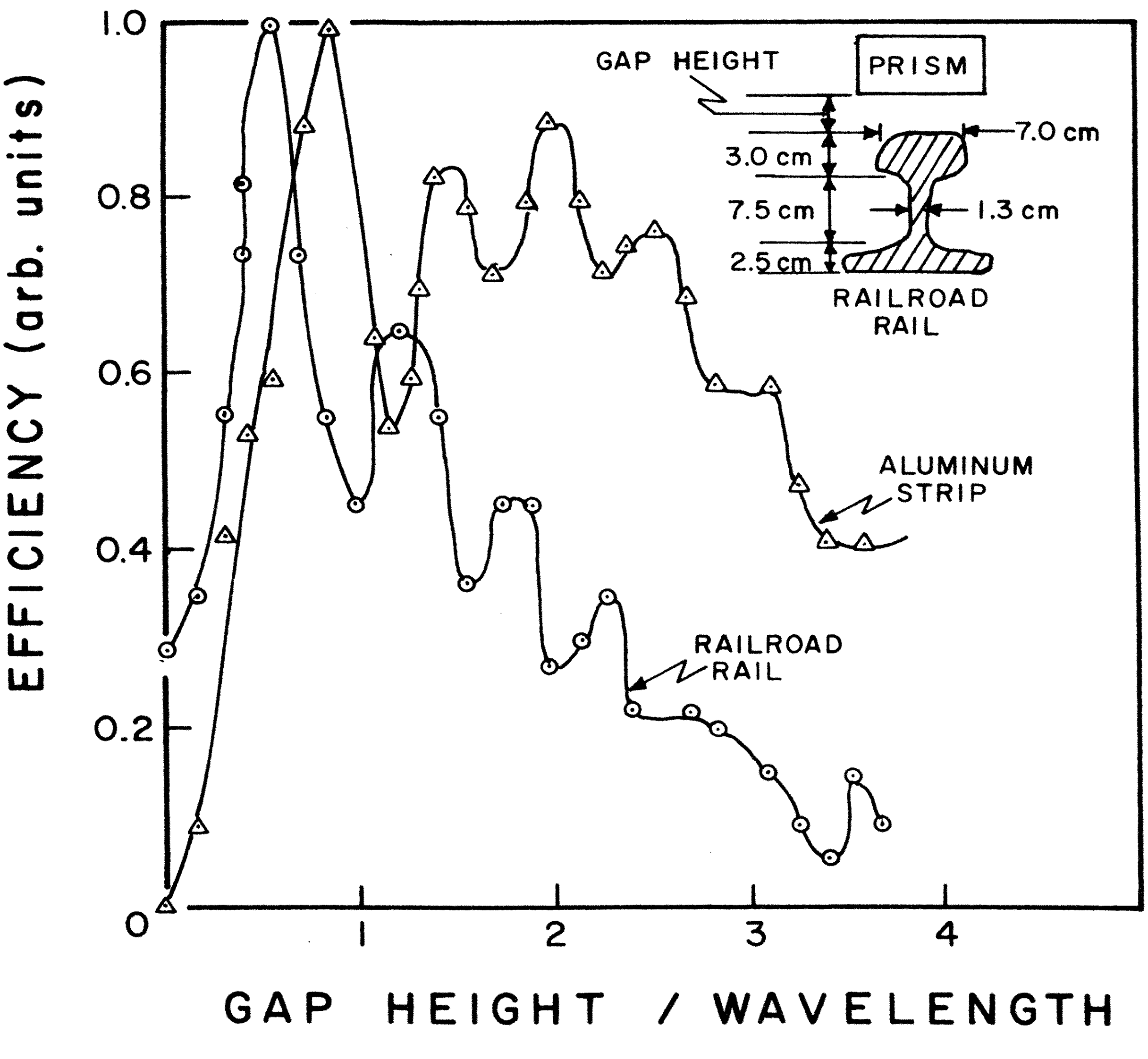

EFFICIENCY (arb. units)
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
GAP HEIGHT / WAVELENGTH
GAP HEIGHT
PRISM
7.0 cm
3.0 cm
7.5 cm
1.3 cm
2.5 cm
RAILROAD RAIL
ALUMINUM STRIP
RAILROAD RAIL

Figure 1

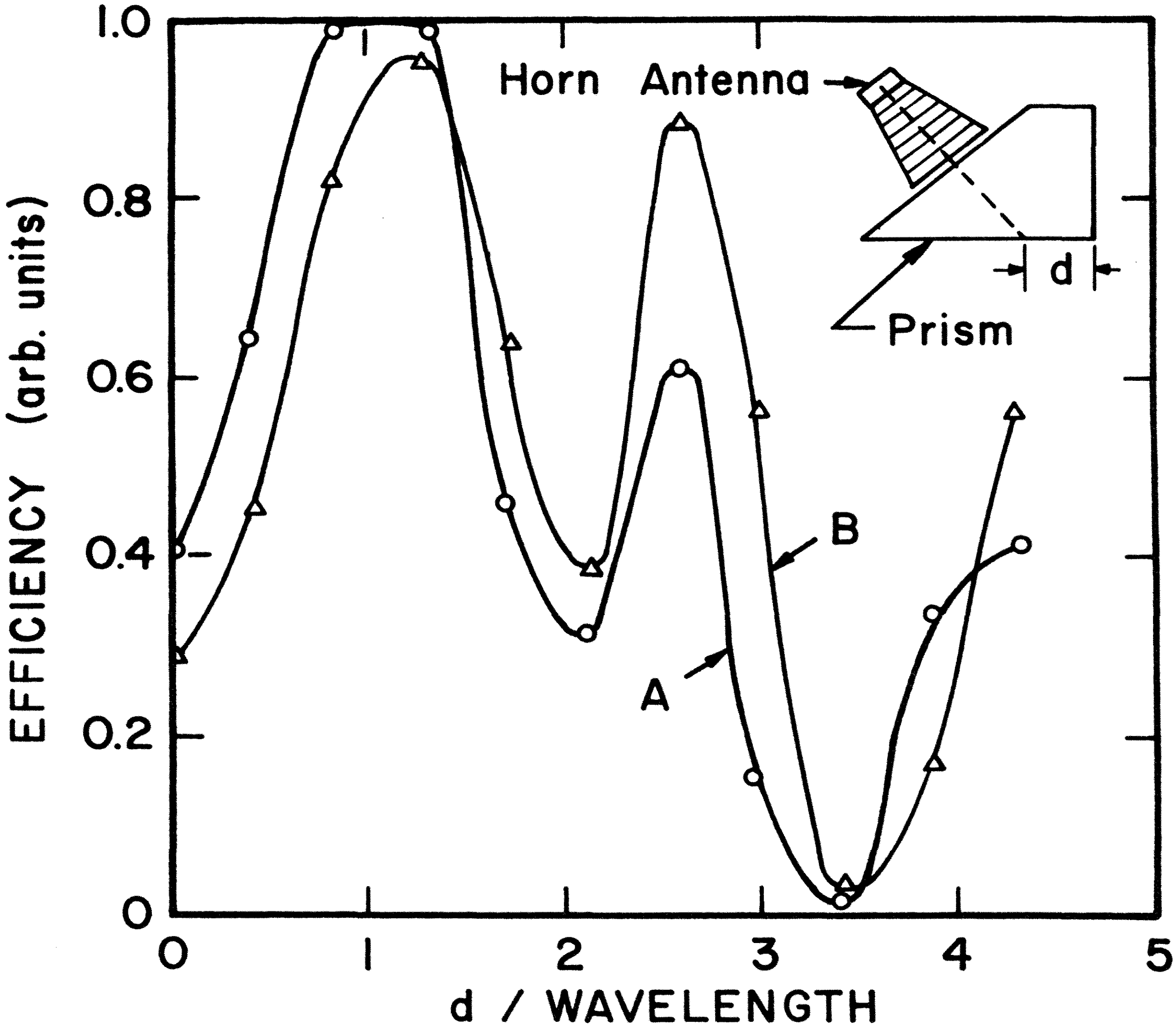

1.0
0.8
0.6
0.4
0.2
0
EFFICIENCY (arb. units)
0
1
2
3
4
5
d / WAVELENGTH
Horn Antenna
Prism
d
A
B

Figure 2

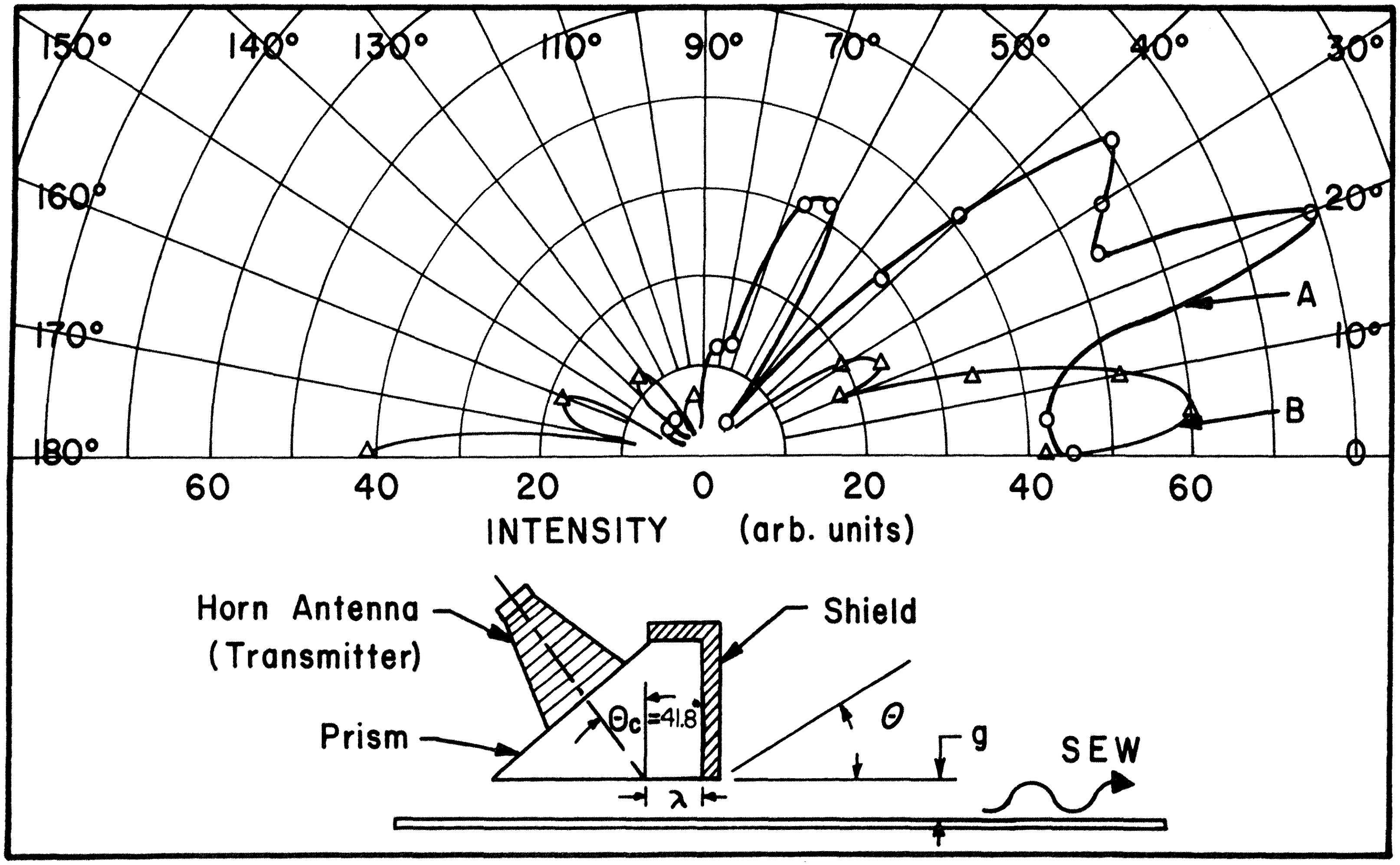

150°
140°
130°
110°
90°
70°
50°
40°
30°
160°
20°
170°
10°
180°
0
A
B
60
40
20
0
20
40
60
INTENSITY (arb. units)
Horn Antenna
(Transmitter)
Shield
Prism
$\Theta_c = 41.8°$
λ
Θ
g
SEW

Figure 3

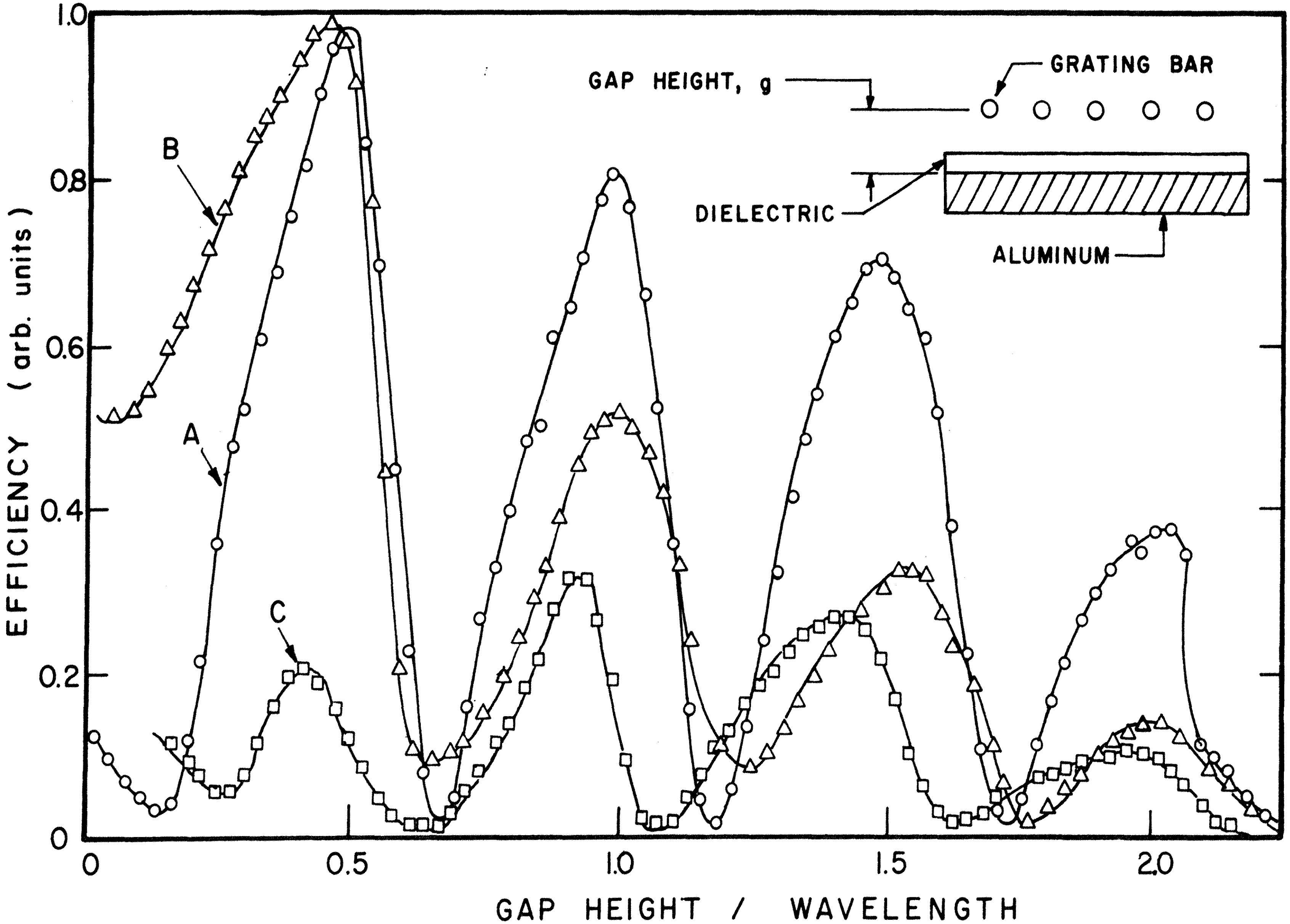

GRATING BAR
GAP HEIGHT, g
DIELECTRIC
ALUMINUM
B
A
C
EFFICIENCY (arb. units)
1.0
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
GAP HEIGHT / WAVELENGTH

Figure 4

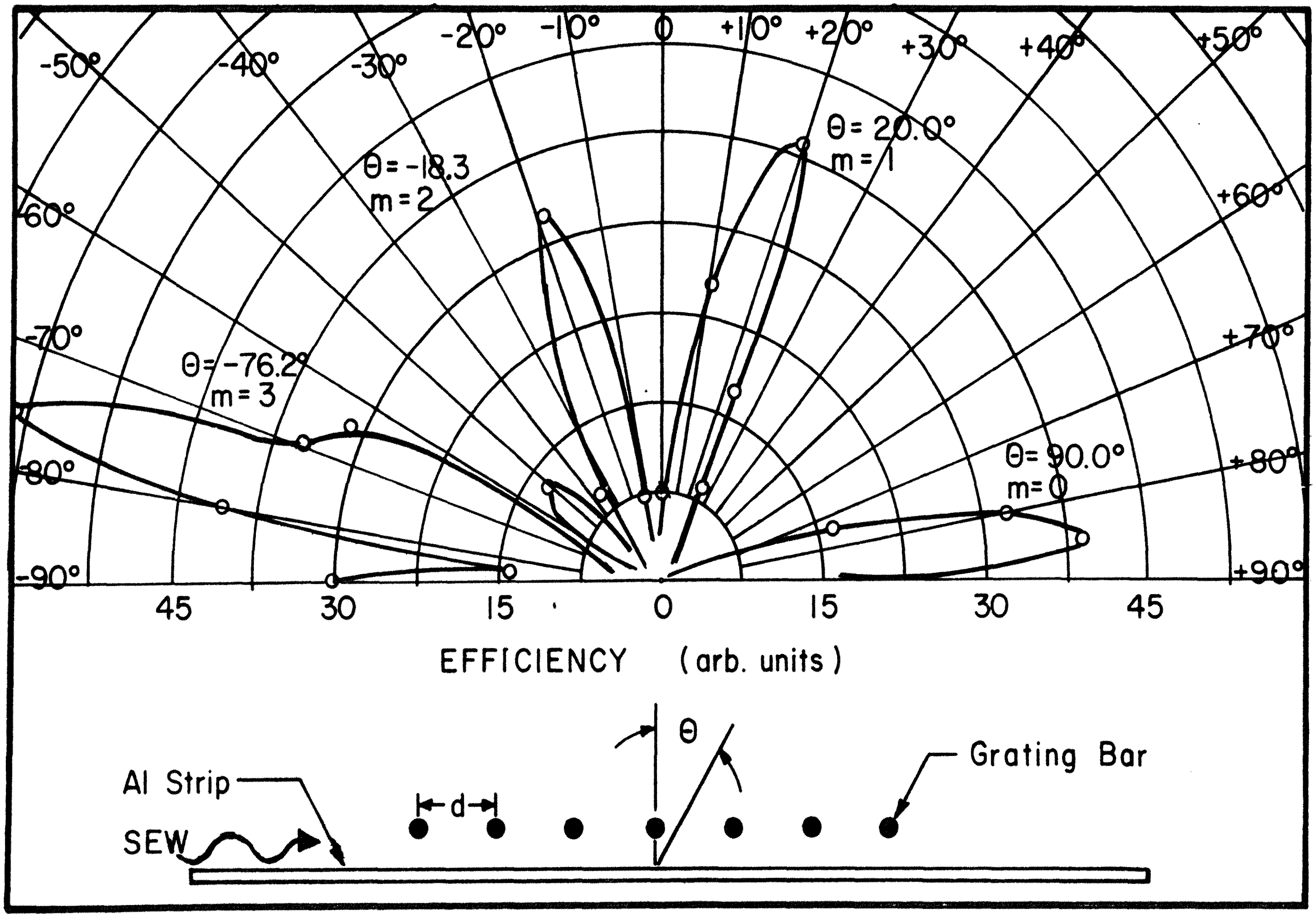

-50°
-40°
-30°
-20°
-10°
0
+10°
+20°
+30°
+40°
+50°
-60°
+60°
-70°
+70°
-80°
+80°
-90°
+90°
θ = 20.0°
m = 1
θ = -18.3
m = 2
θ = -76.2°
m = 3
θ = 90.0°
m = 0
45
30
15
0
15
30
45
EFFICIENCY (arb. units)
θ
Grating Bar
Al Strip
d
SEW

Figure 5

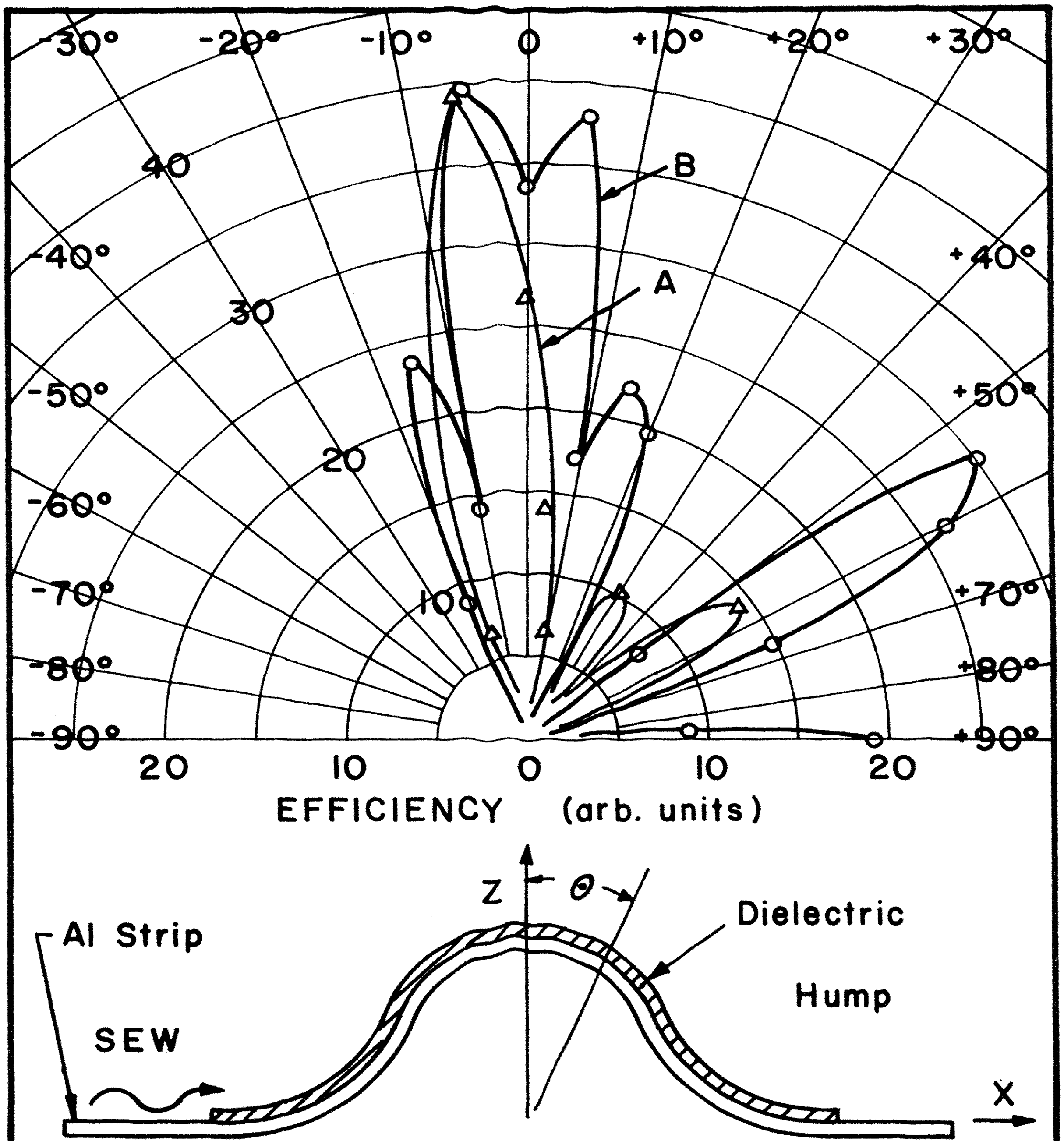

-30°
-20°
-10°
0
+10°
+20°
+30°
40
30
20
10
B
A
-40°
-50°
-60°
-70°
-80°
-90°
+40°
+50°
+70°
+80°
+90°
20
10
0
10
20
EFFICIENCY (arb. units)
Z
θ
Al Strip
SEW
Dielectric
Hump
X

Figure 6

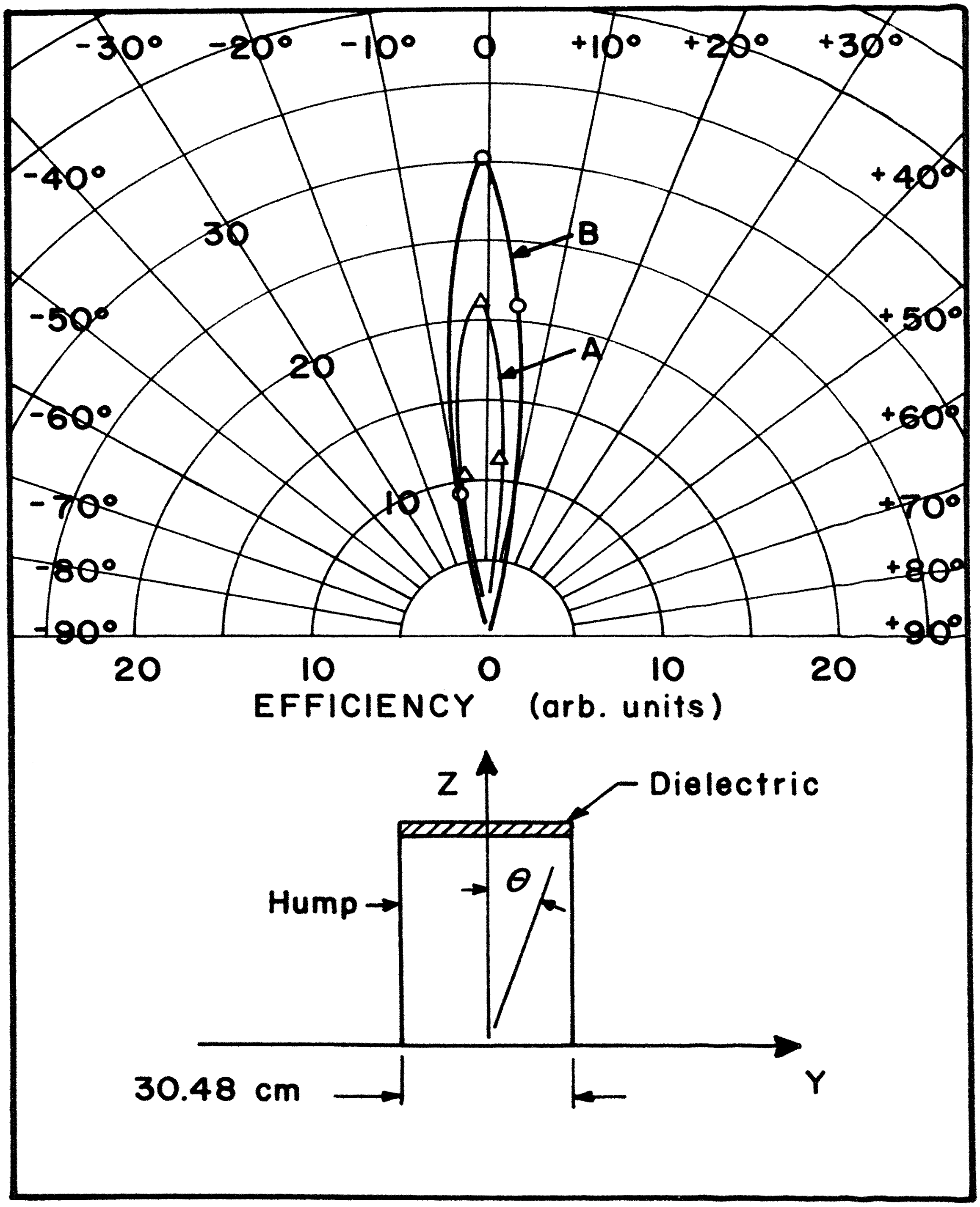

-30°
-20°
-10°
0
+10°
+20°
+30°
-40°
+40°
-50°
+50°
-60°
+60°
-70°
+70°
-80°
+80°
-90°
+90°
30
20
10
B
A
20
10
0
10
20
EFFICIENCY (arb. units)
Z
Dielectric
Hump
θ
30.48 cm
Y

Figure 7

APPENDIX I. SURFACE ELECTROMAGNETIC WAVE FIELDS

In the solution of any electromagnetic problem, the fundamental relations that must be satisfied are the Maxwell's Equations[1]:

$$\nabla \times \overline{H} = \frac{\partial \overline{D}}{\partial t} + \overline{J}$$

$$\nabla \times \overline{E} = - \frac{\partial \overline{B}}{\partial t}$$

$$\nabla . \overline{D} = \rho \qquad (1)$$

$$\nabla . \overline{B} = 0,$$

where the super bar means vector quantity; E is the electric field intensity; D is the electric flux density; H is the magnetic field intensity; B is the magnetic flux density; J is the current density; and ρ is the volume charge density. In addition, there are three relations that concern the characteristics of the medium in which the fields exist. These are, for a homogeneous and isotropic medium,

$$\overline{D} = \varepsilon\overline{E}$$

$$\overline{B} = \mu\overline{H} \qquad (2)$$

$$\overline{J} = \sigma\overline{E},$$

where ε, μ and σ are the permittivity, permeability, and conductivity of the medium. A homogeneous medium is one for which the quantities ε, μ and σ are constant throughout the medium. The medium is isotropic if ε is a scalar constant, so that $\overline{D}$ and $\overline{E}$ have everywhere the same direction.

Consideration is given here to the solution of Maxwell's equations for surface electromagnetic waves (SEW), which are guided along a flat surface (Zenneck Wave)[2,3]. It is assumed that the conducting surface is in the x-y plane and that there is no variation in the y direction ($\partial/\partial y = 0$). It is also assumed that the surface wave is a transverse magnetic wave (TM) propagated in the +x direction. Therefore, only three field components E_x, E_z and H_y are needed in each media to fully describe the wave.

For a transverse magnetic wave, Maxwell's equations in a homogeneous medium are reduced to

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = - \mu \frac{\partial H_y}{\partial t}$$

$$- \frac{\partial H_y}{\partial z} = \sigma E_x + \varepsilon \frac{\partial E_x}{\partial t} \qquad (3)$$

$$\frac{\partial H_y}{\partial x} = \sigma E_z + \varepsilon \frac{\partial E_z}{\partial t} .$$

Using the factor of $e^{j\omega t}$ for time variation, Eq. (3) becomes

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega\mu H_y$$

$$-\frac{\partial H_y}{\partial z} = \sigma\ E_x + j\omega\varepsilon E_x \qquad (4)$$

$$\frac{\partial H_y}{\partial x} = \sigma\ E_z + j\omega\varepsilon E_z$$

or, after factoring,

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\ j\omega\mu H_y$$

$$-\frac{\partial H_y}{\partial z} = j\omega(\varepsilon + \frac{\sigma}{j\omega})\ E_x \qquad (5)$$

$$\frac{\partial H_y}{\partial x} = j\omega(\varepsilon + \frac{\sigma}{j\omega})\ E_z.$$

Letting

$$\varepsilon_{eff} = \varepsilon + \frac{\sigma}{j\omega} = \varepsilon - j\ \frac{\sigma}{\omega} \qquad (6)$$

Eq. (5) becomes

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = - j\omega\mu H_y$$

$$- \frac{\partial H_y}{\partial z} = j\omega\varepsilon_{eff}E_x \qquad (7)$$

$$\frac{\partial H_y}{\partial x} = j\omega\varepsilon_{eff}E_z.$$

For a propagated wave, the variation in the direction of propagation should be represented by $e^{-jk_x x}$, where k_x is the propagation vector in the x direction. Therefore Eq. (7) becomes

$$\frac{\partial E_x}{\partial z} + jk_x E_z = -j\omega\mu H_y$$

$$- \frac{\partial H_y}{\partial z} = j\omega\varepsilon_{eff}E_x \qquad (8)$$

$$- jk_x H_y = j\omega\varepsilon_{eff}E_z.$$

Eq. (8) is solved for two cases, uncoated conducting surface and dielectric coated conducting surface, as follows.

A. Uncoated Conducting Surface

Referring to Fig. 1 for an uncoated conducting surface, there are two media to consider. Air is represented by Region 1 and the metallic conductor by Region 2. Therefore, Eq. (8) for air (index 1) and the metallic conductor

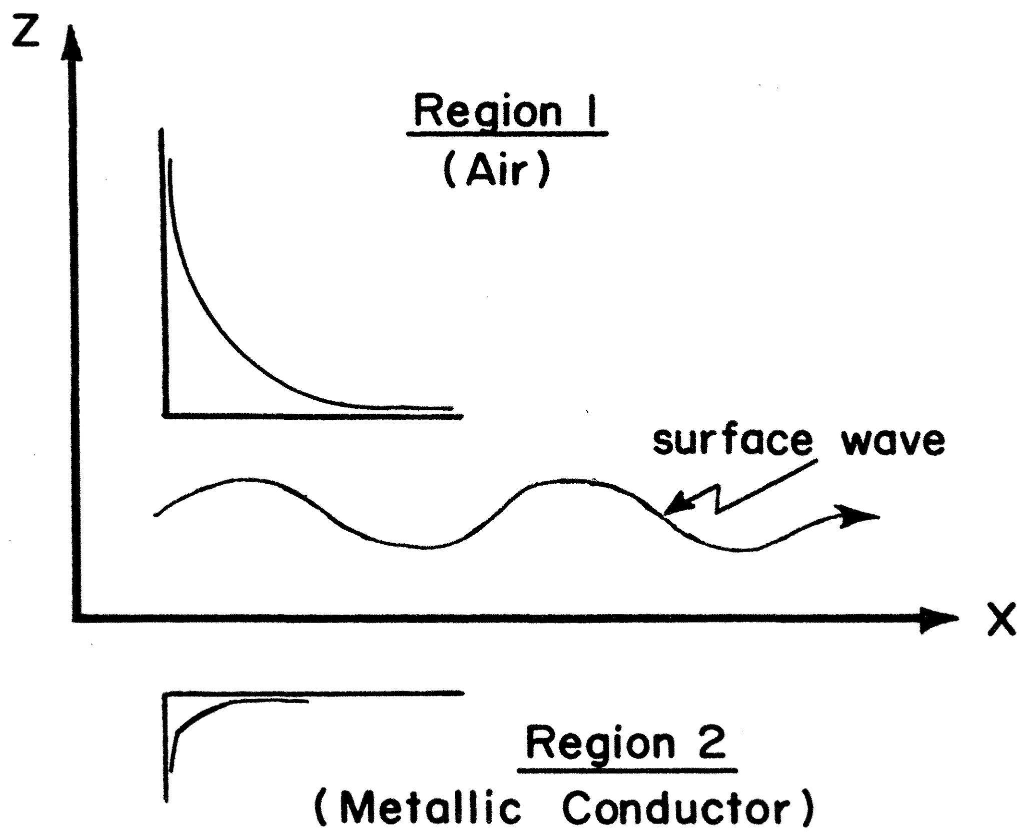


Fig. 1. Surface Electromagnetic Wave is Guided Along A Metallic Plane

(index 2) can be rewritten as

$$\frac{\partial E_x^{(1)}}{\partial z} + jk_{x_1} E_z^{(1)} = - j\omega\mu_1 H_y^{(1)}$$

$$- \frac{\partial H_y^{(1)}}{\partial z} = j\omega\varepsilon_{1eff} E_x^{(1)} \qquad (9)$$

$$- jk_{x_1} H_y^{(1)} = j\omega\varepsilon_{1eff} E_z^{(1)},$$

$$\frac{\partial E_x^{(2)}}{\partial z} + jk_{x_2} E_z^{(2)} = - j\omega\mu_2 H_y^{(2)}$$

$$- \frac{\partial H_y^{(2)}}{\partial z} = j\omega\varepsilon_{2eff} E_x^{(2)} \qquad (10)$$

$$- jk_{x_2} H_y^{(2)} = j\omega\varepsilon_{2eff} E_z^{(2)}.$$

Eliminating $E_x^{(1)}$ and $E_y^{(1)}$ in Eq. (9) results in

$$\frac{\partial^2 H_y^{(1)}}{\partial z^2} = (k_{x_1}{}^2 - \omega^2 \mu_1 \varepsilon_{1eff}) H_y^{(1)} \qquad (11)$$

where

$$\varepsilon_{1eff} = \varepsilon_1 - j \frac{\sigma_1}{\omega} \qquad (12)$$

ε_1, μ_1, and σ_1 are the permittivity, permeability, and conductivity of air, respectively. Since $\sigma_1 = 0$

$$\varepsilon_{1eff} = \varepsilon_1 . \tag{13}$$

For air, $\mu_1 \simeq \mu_0$, so that

$$\mu_1 \varepsilon_1 \simeq \mu_0 \varepsilon_0 \frac{\varepsilon_1}{\varepsilon_0} = \frac{\varepsilon_1/\varepsilon_0}{c^2} = \frac{\varepsilon_{1R}}{c^2} \tag{14}$$

where ε_0 and μ_0 are the permittivity and permeability of free space, ε_{1R} is the relative dielectric constant of air, and c is the speed of light in free space. Substituting Eqs. (13) and (14) into Eq. (11) yields

$$\frac{\partial^2 H_y^{(1)}}{\partial z^2} = (k_{x_1}^{\;2} - \frac{\omega^2 \varepsilon_{1R}}{c^2}) \; H_y^{(1)} \tag{15}$$

which has a solution in the positive z direction

$$H_y^{(1)} = A_1 \; e^{-k_{z_1} z}$$

where A_1 is a constant, and

$$k_{z_1}^{\;2} = k_{x_1}^{\;2} - \frac{\omega^2 \varepsilon_{1R}}{c^2} , \tag{17}$$

where k_{z_1} is the propagation vector in the + z direction (in the air). Eliminating $E_x^{(2)}$ and $E_z^{(2)}$ in Eq. (10) results in

$$\frac{\partial^2 H_y^{(2)}}{\partial z^2} = (k_{x_2}^{\ 2} - \omega^2 \mu_2 \varepsilon_{2eff})\ H_y^{(2)} \tag{18}$$

where

$$\varepsilon_{2eff} = \varepsilon_2 - j\,\frac{\sigma_2}{\omega} \tag{19}$$

and ε_2, μ_2, and σ_2 are the permittivity, permeability, and conductivity of the metal. Eq. (18) has a solution in the negative z direction (in the metallic conductor) as follows

$$H_y^{(2)} = A_2\ e^{k_{z_2} z} \tag{20}$$

where A_2 is a constant and

$$k_{z_2}^{\ 2} = k_{x_2}^{\ 2} - \omega^2 \mu_2 \varepsilon_{2eff} \tag{21}$$

where k_{z_2} is the propagation vector in the -z direction (in the metal). Showing, in addition, the variation in the +x direction, Eqs. (16) and (20) become

$$H_y^{(1)} = A_1\ e^{-k_{z_1} z}\ e^{-jk_{x_1} x} \tag{22}$$

$$H_y^{(2)} = A_2\ e^{k_{z_2} z}\ e^{-jk_{x_2} x}\ . \tag{23}$$

Eqs. (22) and (23) must be equal at the surface (z = 0) because H_y is continuous across the boundary. Equating Eqs. (22) and (23) when z is equal to zero results in

$$A_1 e^{-jk_{x_1} x} = A_2 e^{-jk_{x_2} x} . \tag{24}$$

Therefore,

$$A_1 = A_2 = A = \text{constant} \tag{25}$$

and

$$k_{x_1} = k_{x_2} = k_x . \tag{26}$$

Substituting Eqs. (25) and (26) into Eqs. (22) and (23) yields

$$H_y^{(1)} = Ae^{-k_{z_1} z} e^{-jk_x x} \tag{27}$$

$$H_y^{(2)} = e^{k_{z_2} z} e^{-jk_x x} . \tag{28}$$

Combining Eqs. (9), (13), (26), and (27) and considering time variation yields[1,3-6] for air (z > 0)

$$H_y^{(1)} = Ae^{-k_{z_1} z} e^{-j(k_x x - \omega t)}$$

$$E_x^{(1)} = \frac{Ak_{z_1}}{j\omega\varepsilon_1} e^{-k_{z_1} z} e^{-j(k_x x - \omega t)} \tag{29}$$

$$E_z^{(1)} = - \frac{Ak_x}{\omega\varepsilon_1} e^{-k_{z_1} z} e^{-j(k_x x - \omega t)}$$

Combining Eqs. (10), (26), and (28) and considering time variation yields[1,3-6] for the metallic conductor (z < 0)

$$H_y^{(2)} = Ae^{k_{z_2} z} e^{-j(k_x x - \omega t)}$$

$$E_x^{(2)} = -\frac{Ak_{z_2}}{j\omega\varepsilon_{2eff}} e^{k_{z_2} z} e^{-j(k_x x - \omega t)} \tag{30}$$

$$E_y^{(2)} = -\frac{Ak_x}{\omega\varepsilon_{2eff}} e^{k_{z_2} z} e^{-j(k_x x - \omega t)} .$$

At z equal to zero the expressions for E_x for the air and the metallic conductor regions must be equal (requirement of continuity). Therefore,

$$E_x^{(1)} \Big|_{z=0} = E_x^{(2)} \Big|_{z=0} \tag{31}$$

from which

$$\frac{k_{z_1}}{\varepsilon_1} = -\frac{k_{z_2}}{\varepsilon_{2eff}} . \tag{32}$$

Squaring Eq. (32) yields

$$\frac{k_{z_1}^2}{\varepsilon_1^2} = \frac{k_{z_2}^2}{\varepsilon_{2eff}^2} . \tag{33}$$

Substituting Eqs. (17), (21) and (26) into Eq. (33) results in

$$k_x^2 - \frac{\omega^2 \varepsilon_{1R}}{c^2} = \left(\frac{\varepsilon_1}{\varepsilon_{2eff}}\right) \quad (k_x^2 - \omega^2 \mu_2 \varepsilon_{2eff}) \tag{34}$$

or

$$k_x^2 = \frac{1 - c^2 \mu_2 \varepsilon_0 \dfrac{\varepsilon_1}{(\varepsilon_{2eff})}}{1 - \left(\dfrac{\varepsilon_1}{\varepsilon_{2eff}}\right)^2} \frac{\omega^2}{c^2} \varepsilon_{1R} \; . \tag{35}$$

For a nonferrous metallic conductor μ_2 is approximately equal to μ_0. Therefore,

$$\mu_2 \varepsilon_0 \simeq \mu_0 \varepsilon_0 = \frac{1}{c^2} \; . \tag{36}$$

Substituting Eq. (36) into Eq. (35) yields the dispersion relation

$$k_x = \frac{\omega}{c} \sqrt{\frac{\varepsilon_{2eff}(\varepsilon_1/\varepsilon_0)}{\varepsilon_{2eff} + \varepsilon_1}} \; . \tag{37}$$

For metallic conductors in the microwave region, to a good approximation,

$$\frac{\sigma_2}{\omega} >> |\varepsilon_2| . \tag{38}$$

Therefore, Eq. (19) becomes

$$\varepsilon_{2eff} = - j \frac{\sigma_2}{\omega} \; . \tag{39}$$

Substituting Eq. (39) into Eq. (37) and noting that $\frac{\sigma_2}{\omega} >> \varepsilon_1$ and that $\varepsilon_1 \simeq \varepsilon_0$, the real part of the propagation vector in the x direction (k_x) will be much greater than its imaginary part. Therefore, the propagation vector in the x-direction in microwave frequencies is approximately

$$k_x \simeq \frac{\omega}{c}, \tag{40}$$

which is purely real. Therefore the attenuation of the wave in the x-direction is negligible.

Substituting Eqs. (26) and (37) into Eq. (17) yields

$$k_{z_1} = \frac{\omega}{c} \frac{\varepsilon_1}{\varepsilon_0} \sqrt{\frac{-\varepsilon_0}{\varepsilon_{2eff} + \varepsilon_1}} \tag{41}$$

which is the propagation vector in the +z (air) direction. Substituting Eq. (39) into Eq. (41) and noting that $\frac{\sigma_2}{\omega} >> \varepsilon_1$ and $\varepsilon_1 \simeq \varepsilon_0$, the real and imaginary parts of k_{z_1} will be approximately equal. Therefore the propagating wave in the +z (air) direction will be attenuated.

Substituting Eq. (41) into Eq. (32) yields

$$k_{z_2} = -\frac{\omega}{c} \frac{\varepsilon_{2eff}}{\varepsilon_0} \sqrt{\frac{-\varepsilon_0}{\varepsilon_{2eff} + \varepsilon_1}} \tag{42}$$

which is the propagation vector in the -z (metallic conductor) direction. Substituting Eq. (39) into Eq. (42) and noting that $\frac{\sigma_2}{\omega} >> \varepsilon_1$ and $\varepsilon_1 \simeq \varepsilon_0$, the real and imaginary parts of k_{z_2} will be approximately equal.

Therefore, the propagating wave in the -z (metallic conductor) direction will be attenuated. It should be noted that since the real part of k_{z_2} is much larger than the real part of k_{z_1}, the wave is attenuating in the metallic conductor region much faster than the air region.

B. Dielectric Coated Conducting Surface (Grounded Dielectric Slab)

Referring to Fig. 2, for a dielectric coated conducting surface, there are three media to consider. Air is represented by Region 1, dielectric by Region 2, and metal by Region 3. The thickness of the dielectric film is ℓ. Therefore, Eq. (8) for air (index 1), dielectric (index 2), and metallic conductor (index 3) can be rewritten. For air ($z > \ell$)

$$\frac{\partial E_x^{(1)}}{\partial z} + j\, k_{x_1}\, E_z^{(1)} = -j\omega\mu_1 H_y^{(1)}$$

$$-\frac{\partial H_y^{(1)}}{\partial z} = j\omega\varepsilon_{1eff} E_x^{(1)} \tag{43}$$

$$-\, j\, k_{x_1}\, H_y^{(1)} = j\omega\varepsilon_{1eff} E_z^{(1)}.$$

For the dielectric ($\ell > z > 0$)

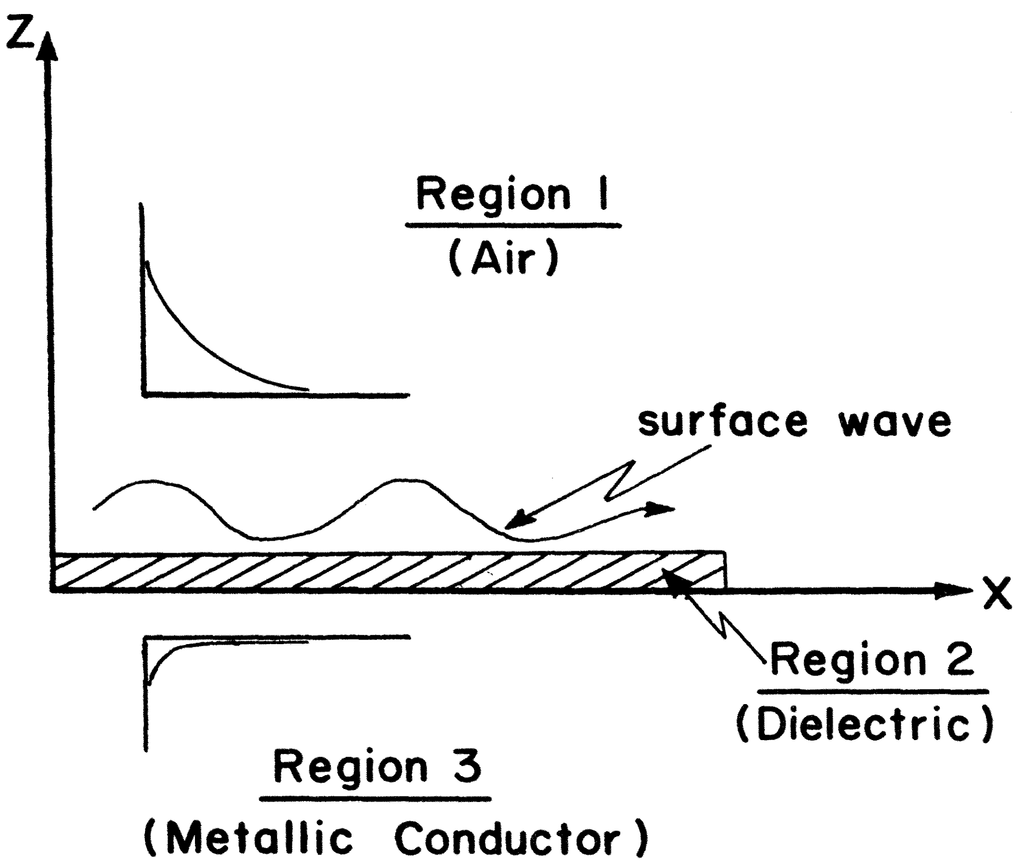


Fig. 2. Surface Electromagnetic Wave is Guided Along A Dielectric Coated Metallic Conducting Plane

$$\frac{\partial E_x^{(2)}}{\partial z} + j\, k_{x_2}\, E_z^{(2)} = -j\omega\mu_2 H_y^{(2)}$$

$$- \frac{\partial H_y^{(2)}}{\partial z} = j\omega\varepsilon_{2eff} E_x^{(2)} \tag{44}$$

$$- j\, k_{x_2} H_y^{(2)} = j\omega\varepsilon_{2eff} E_z^{(2)} .$$

For the metallic conductor (z < 0)

$$\frac{\partial E_x^{(3)}}{\partial z} + j\, k_{x_3} E_z^{(3)} = j\omega\mu_3 H_y^{(3)}$$

$$- \frac{\partial H_y^{(3)}}{\partial z} = j\omega\varepsilon_{3eff} E_x^{(3)} \tag{45}$$

$$- j\, k_{x_3} H_y^{(3)} = j\omega\varepsilon_{3eff} E_z^{(3)} .$$

Eliminating $E_x^{(1)}$ and $E_y^{(1)}$ in Eq. (43) yields

$$\frac{\partial^2 H_y^{(1)}}{\partial z^2} = (k_{x_1}^{\ 2} - \omega^2 \mu_1 \varepsilon_{1eff})\ H_y \tag{46}$$

where

$$\varepsilon_{1eff} = \varepsilon_1 - j\, \frac{\sigma_1}{\omega} \tag{47}$$

and ε_1, μ_1, and σ_1 are the dielectric constant, permeability and conductivity of air, respectively. Since σ_1 is equal to zero, therefore from Eq. (47)

$$\varepsilon_{1eff} = \varepsilon_1. \tag{48}$$

For air $\mu_1 \simeq \mu_0$ so that

$$\mu_1\varepsilon_1 \simeq \mu_0\varepsilon_0 \frac{\varepsilon_1}{\varepsilon_0} = \frac{\varepsilon_1/\varepsilon_0}{c^2} = \frac{\varepsilon_{1R}}{c^2} . \tag{49}$$

ε_0 and μ_0 are the dielectric constant and permeability of free space. ε_{1R} is the relative dielectric constant of air. c is the speed of light in free space. Substituting Eqs. (48) and (49) into Eq. (46) yields

$$\frac{\partial^2 H_y^{(1)}}{\partial z^2} = (k_{x_1}^{\ 2} - \frac{\omega^2}{c^2} \varepsilon_{1R}) H_y \tag{50}$$

which has a solution in the positive z direction ($z > \ell$) as follows.

$$H_y^{(1)} = A_1 e^{-k_{z_1}(z-\ell)} \tag{51}$$

where A_1 is a constant, and

$$k_{z_1}^{\ 2} = k_{x_1}^{\ 2} - \frac{\omega^2}{c^2} \varepsilon_{1R} \tag{52}$$

where k_{z_1} is the propagation vector in Region 1 (air).

Eliminating $E_x^{(2)}$ and $E_y^{(2)}$ in Eq. (44) results in

$$\frac{\partial^2 H_y^{(2)}}{\partial z^2} = (k_{x_2}^{\ 2} - \omega^2 \mu_2 \varepsilon_{2eff}) \ H_y^{(2)} \qquad (53)$$

where

$$\varepsilon_{2ff} = \varepsilon_2 - j \frac{\sigma_2}{\omega} \ . \qquad (54)$$

ε_2, μ_2, and σ_2 are the permittivity, permeability, and conductivity of the dielectric, respectively. Noting that there is a standing wave within the dielectric film, Eq. (53) has a solution in Region 2 (dielectric) as follows

$$H_y^{(2)} = A_2' \cosh (k_{z_2} z) + A_2'' \text{Sinh} (k_{z_2} z) \qquad (55)$$

where A_2' and A_2'' are constants, and

$$k_{z_2}^{\ 2} = k_{x_2}^{\ 2} - \omega^2 \mu_2 \varepsilon_{2eff} \ , \qquad (56)$$

where k_{z_2} is the propagation vector in Region 2 (dielectric).

Eliminating $E_x^{(3)}$ and $E_y^{(3)}$ in Eq. (45) yields

$$\frac{\partial^2 H_y^{(3)}}{\partial z^2} = (k_{x_3}^{\ 2} - \omega^2 \mu_3 \varepsilon_{3eff}) \ H_y^{(3)} \qquad (57)$$

where

$$\varepsilon_{3eff} = \varepsilon_3 - j\,\frac{\sigma_3}{\omega} \tag{58}$$

where ε_3, μ_3, and σ_3 are the permittivity, permeability, and conductivity of the metal, respectively. Eq. (57) has a solution in the negative z direction (metallic conductor) as follows

$$H_y^{(3)} = A_3\, e^{k_{z_3} z} \tag{59}$$

where A_3 is a constant, and

$$k_{z_3}^{\ 2} = k_{x_3}^{\ 2} - \omega^2 \mu_3 \varepsilon_{3eff} \tag{60}$$

where k_{z_3} is the propagation vector in the -z direction (metallic conductor). Showing the variation in the x direction, in addition, Eqs. (51), (55), and (59) become

$$H_y^{(1)} = A_1\, e^{-k_{z_1}(z-\ell)}\, e^{-jk_{x_1} x} \tag{61}$$

$$H_y^{(2)} = [A_2' \cosh (k_{z_2} z) + A_2'' \sinh (k_{z_2} z)] e^{-jk_{x_2} x} \tag{62}$$

$$H_y^{(3)} = A_3\, e^{k_{z_3} z}\, e^{-jk_{x_3} x} . \tag{63}$$

H_y must be continuous at the boundaries; therefore

$$H_y^{(1)} \Big|_{z=\ell} = H_y^{(2)} \Big|_{z=\ell} \tag{64}$$

$$H_y^{(2)} \Big|_{z=0} = H_y^{(3)} \Big|_{z=0} \tag{65}$$

or,

$$A_1 e^{-jk_{x_1}x} = [A_2' \cosh (k_{z_2} \ell) + A_2'' \sinh (k_{z_2} \ell)] e^{-jk_{x_2}x} \quad (66)$$

$$A_2' e^{-jk_{x_2}x} = A_3 e^{-jk_{x_3}x} . \quad (67)$$

From Eqs. (66) and (67), it is seen that

$$k_{x_1} = k_{x_2} = k_{x_3} = k_x. \quad (68)$$

Therefore, substituting Eq. (68) in Eqs. (66) and (67) results in

$$A_1 = A_2' \cosh (k_{z_2} \ell) + A_2'' \sinh (k_{z_2} \ell) \quad (69)$$

$$A_2' = A_3. \quad (70)$$

Combining Eqs. (43), (48), (61) and (68) and considering the time variation yields[3,4,7] for air ($z > \ell$)

$$H_y^{(1)} = A_1 e^{-k_{z_1}(z-\ell)} e^{-j(k_x x - \omega t)}$$

$$E_x^{(1)} = \frac{A_1 k_{z_1}}{j\omega\varepsilon_1} e^{-k_{z_1}(z-\ell)} e^{-j(k_x x - \omega t)} \quad (71)$$

$$E_z^{(1)} = - \frac{A_1 k_x}{\omega\varepsilon_1} e^{-k_{z_1}(z-\ell)} e^{-j(k_x x - \omega t)}$$

Combining Eqs. (44), (62), and (68) and considering time variation yields[3,4,7] for the dielectric ($\ell < z < 0$)

$$H_y^{(2)} = [A_2' \cosh (k_{z_2} z) + A_2'' \sinh (K_{z_2} z)]\ e^{-j(k_x x - \omega t)}$$

$$E_x^{(2)} = - \frac{k_{z_2}}{j\omega\varepsilon_{2eff}} [A_2' \sinh (k_{z_2} z)$$

$$+ A_2'' \cosh (k_{z_2} z)]\ e^{-j(k_x x - \omega t)} \tag{72}$$

$$E_z^{(2)} = - \frac{k_x}{\omega\varepsilon_{2eff}} [A_2' \cosh (k_{z_2} z)$$

$$+ A_2'' \sinh (k_{z_2} z)]\ e^{-j(k_x s - \omega t)} .$$

Combining Eqs. (45), (63), and (68) and considering time variation yields[3,4,7] for the metallic conductor ($z < 0$)

$$H_y^{(3)} = A_3\ e^{k_{z_3} z}\ e^{-j(k_x x - \omega t)}$$

$$E_x^{(3)} = \frac{A_3 k_{z_3}}{j\omega\varepsilon_{3eff}}\ e^{k_{z_3} z}\ e^{-j(k_x x - \omega t)} \tag{73}$$

$$E_z^{(3)} = - \frac{A_3 k_x}{\omega\varepsilon_{3eff}}\ e^{k_{z_3} z}\ e^{-j(k_x x - \omega t)} .$$

At the boundaries, the expressions for E_x must be equal. Therefore

$$E_x^{(1)} \Big|_{z=\ell} = E_x^{(2)} \Big|_{z=\ell} \tag{74}$$

$$E_x^{(2)} \Big|_{z=0} = E_x^{(3)} \Big|_{z=0} \tag{75}$$

or,

$$\frac{A_1 k_{z_1}}{\varepsilon_1} = - \frac{k_{z_2}}{\varepsilon_{2eff}} [A_2' \sinh (k_{z_2} \ell) + A_2'' \cosh (k_{z_2} \ell)] \tag{76}$$

$$\frac{-A_2'' k_{z_2}}{\varepsilon_{2eff}} = \frac{A_3 k_{z_3}}{\varepsilon_{3eff}} . \tag{77}$$

Substituting Eqs. (70) and (77) into Eqs. (69) and (76) results in

$$A_1 = A_3 \cosh (k_{z_2} \ell) - A_3 \frac{k_{z_3}}{k_{z_2}} \frac{\varepsilon_{2eff}}{\varepsilon_{3eff}} \sinh (k_{z_2} \ell) \tag{78}$$

and

$$\frac{A_1 k_{z_1}}{\varepsilon_1} = - \frac{k_{z_2}}{\varepsilon_{2eff}} [A_3 \sinh (k_{z_2} \ell) - A_3 \frac{k_{z_3}}{k_{z_2}} \frac{\varepsilon_{2eff}}{\varepsilon_{3eff}} \cosh (k_{z_2} \ell)] . \tag{79}$$

Dividing Eq. (78) by Eq. (79) yields

$$\frac{\varepsilon_1}{k_{z_1}} = -\frac{\varepsilon_{2eff}}{k_{z_2}} \frac{\cosh(k_{z_2}\ell) - \frac{k_{z_3}}{k_{z_2}}\frac{\varepsilon_{2eff}}{\varepsilon_{3eff}}\sinh(k_{z_2}\ell)}{\sinh(k_{z_2}\ell) - \frac{k_{z_3}}{k_{z_2}}\frac{\varepsilon_{2eff}}{\varepsilon_{3eff}}\cosh(k_{z_2}\ell)} \tag{80}$$

or

$$\tanh\,(k_{z_2}\ell) = \frac{1 - \frac{k_{z_3}}{k_{z_1}}\frac{\varepsilon_1}{\varepsilon_{3eff}}}{\frac{k_{z_3}}{k_{z_2}}\frac{\varepsilon_{2eff}}{\varepsilon_{3eff}}\frac{k_{z_2}}{k_{z_1}}\frac{\varepsilon_1}{\varepsilon_{2eff}}}\,. \tag{81}$$

In order to solve Eq. (81) for k_{z_1}, it is assumed that $\ell << \lambda$, where λ is the SEW wavelength ($\lambda = \frac{2\pi c}{\omega}$). Therefore,

$$k_{z_1}\ell << 1 \tag{82}$$

and

$$\tanh\,(k_{z_2}\ell) \simeq k_{z_2}\,\ell. \tag{83}$$

Substituting Eqs. (82) and (83) into Eq. (81) yields

$$k_{z_1} = \frac{k_{z_3}\,\varepsilon_1}{\varepsilon_{3eff}} - k_{z_2}^{\;2}\,\frac{\varepsilon_1\ell}{\varepsilon_{2eff}}\,. \tag{84}$$

Now, since the surface electromagnetic wave propagates in the air and the dielectric (very close to the metal surface) it is also assumed that

$$k_x = k_{x_1} = k_{x_2} = k_{x_3} \simeq \frac{\omega}{c} \; . \qquad (85)$$

Substituting Eq. (85) into Eqs. (56) and (60) and letting $\mu_3 = \mu_2 = \mu_0$ results in

$$k_{z_2} = \frac{\omega}{c}\sqrt{1 - \frac{\varepsilon_{2eff}}{\varepsilon_0}} \qquad (86)$$

and

$$k_{z_3} = \frac{\omega}{c}\sqrt{1 - \frac{\varepsilon_{3eff}}{\varepsilon_0}} \; . \qquad (87)$$

Since, for any metal at microwave frequency range, $\left|\frac{\varepsilon_{3eff}}{\varepsilon_0}\right| > > 1$, Eq. (87) can be rewritten as

$$k_{z_3} = \frac{\omega}{c}\sqrt{- \frac{\varepsilon_{3eff}}{\varepsilon_0}} \; . \qquad (88)$$

Substituting Eqs. (86) and (88) in Eq. (84) and using $\varepsilon_1 \simeq \varepsilon_0$)

$$k_{z_1} = \frac{\omega}{c}\sqrt{- \frac{\varepsilon_0}{\varepsilon_{3eff}} + \frac{\omega^2}{c^2}\left(\frac{\varepsilon_{2eff} - \varepsilon_1}{\varepsilon_1}\right)} \qquad (89)$$

where

$$\varepsilon_{3eff} = \varepsilon_3 - j \frac{\sigma_3}{\omega}. \tag{90}$$

For metallic conductors in the microwave region to a good approximation

$$\frac{\sigma_3}{\omega} >> \left|\varepsilon_3\right|. \tag{91}$$

Therefore, Eq. (90) becomes

$$\varepsilon_{3eff} \simeq - j \frac{\sigma_3}{\omega} . \tag{92}$$

Substituting Eq. (92) into Eq. (89) yields

$$k_{z_1} = \frac{\omega^2}{c^2} [(\frac{\varepsilon_{2eff} - \varepsilon_1}{\varepsilon_{2eff}}) \ell + \frac{1}{\sqrt{j\sigma_3\omega\mu_0}}] \tag{93}$$

or

$$k_{z_1} = \frac{\omega^2}{c^2} [(\frac{\varepsilon_{2eff} - \varepsilon_1}{\varepsilon_{2eff}}) \ell + \frac{\delta}{2} (1 - j)] \tag{94}$$

where

$$\delta = \text{skin depth of the metallic conductor} = \sqrt{2/\sigma_3\omega\mu_0}. \tag{95}$$

k_{z_1} is the propagation vector in the +z (air) direction. Substituting Eq. (94) into Eq. (52) yields

$$k_x = \frac{\omega}{c} \sqrt{1 + \frac{\omega^2}{c^2} [(\frac{\varepsilon_{2eff} - \varepsilon_1}{\varepsilon_{2eff}}) \ell + \frac{\delta}{2} (1-j)]^2}, \qquad (96)$$

which is the propagation vector in the +x direction. The skin depth of the metallic conductor, in the microwave region, is much less than the wavelength. Therefore, for a low loss coated dielectric material, k_x is approximately a pure real number and the attenuation of the wave in the + x direction is negligible.

C. Numerical Calculations

A number of numerical calculations have been obtained to illustrate the behavior of the SEW field components in different circumstances. In these calculations, aluminum is used for a conducting medium which has conductivity, σ (= 3.72×10^7 mho), and skin depth, δ (= 8.97×10^{-4} mm). Frequency is assumed to be 8.445 GHz (λ = 3.55 cm). For free space, the permittivity is ε_0 (= 8.854×10^{-12} farad/m) and the permeability is μ_0 (= $4\pi \times 10^{-7}$ henry/m).

1. Uncoated Conducting Surface

The propagation vectors k_x, $k_{z\,(air)} = k_{z_1}$ and $k_{z\,(metal)} = k_{z_2}$ have been calculated from Eqs. (37), (41) and (42), respectively, and the results are shown in Table I. The fields fall to 1/e of its surface value at a height

$$h_{air} = \frac{1}{Re\ (k_{z_1})} \tag{97}$$

$$h_{metal} = \frac{1}{Re\ (k_{z_2})} \ . \tag{98}$$

Both h_{air} and h_{metal} are calculated from Eqs. (97) and (98), respectively, and the results are shown in Table AI-1.

2. Dielectric Coated Conducting Surface

These calculations are based on a dielectric material (polystyrene) whose relative dielectric constant is 2.55 and loss factor of 0.00033 at 8.445 GHz. The propagation vectors k_x, $k_{z(air)} = k_{z_1}$ and $k_{z(metal)} = k_{z_3}$ have been calculated from Eqs. (96), (94), and (60), respectively, and the results are shown in Table I. The fields fall to 1/e of their surface value at a height

$$h_{air} = \frac{1}{Re\ (k_{z_1})} \tag{99}$$

$$h_{metal} = \frac{1}{Re\ (k_{z_3})} \ . \tag{100}$$

h_{air} and h_{metal} are calculated from Eqs. (99) and (100), respectively, and are shown in Table I.

From Table I, it is seen that the k_x for uncoated and dielectric coated conducting surfaces are almost the same and they can be approximated to $\frac{\omega}{c}$ (= 176.87 m^{-1}). The field in the +z direction falls to 1/e of its surface value at 71.43 m for uncoated conducting surface. However, using a dielectric material only 1.6 mm thick results in a reduction of this height to only 3.28 cm and, therefore, implies that the field decays in the +z direction (in air) much more rapidly for the dielectric coated conducting surface.

TABLE I. COMPARISON OF k_x, $k_{z(air}$, $k_{z(metal})$, AND h_{metal} FOR TWO CASES: UNCOATED CONDUCTING SURFACE AND DIELECTRIC COATED CONDUCTING SURFACE

PARAMETER		UNCOATED METAL	DIELECTRIC COATED METAL
k_x	(m^{-1})	176.98	179.60
$k_{z(air)}$	(m^{-1})	0.014(1-j)	30.46
$k_{z(metal)}$	(m^{-1})	$1.1x10^{6}$(1+j)	$1.1x10^{6}$(1+j)
h_{air}	(m)	71.43	$3.28x10^{-2}$
h_{metal}	(m)	$0.91x10^{-6}$	$0.91x10^{-6}$

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APPENDIX II. POWER CARRIED BY SURFACE ELECTROMAGNETIC WAVES

A. Uncoated Conducting Surface

The average power transmitted by surface electromagnetic waves (SEW) per unit length in the y direction above the surface (air) is given by[1]

$$P_x = -\frac{1}{2}\,\mathrm{Re}\left[\int_{z=0}^{z=\infty} E_z^{(1)}\, H_y^{(1)*}\, dz\right] \tag{1}$$

where $E_z^{(1)}$ and $H_y^{(1)}$ are the field components in the air medium-Region 1. $H_y^{(1)*}$ is the complex conjugate of $H_y^{(1)}$. From Eq. (29), Appendix I, it is seen that

$$H_y^{(1)} = A\, e^{-k_{z_1} z}\, e^{-j(k_x x - \omega t)} \tag{2}$$

$$E_z^{(1)} = -\frac{Ak_x}{\omega\varepsilon_1}\, e^{-k_{z_1} z}\, e^{-j(k_x x - \omega t)} . \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1) and letting $k_x \simeq \frac{\omega}{c}$ [Eq. (40) Appendix I], yields

$$P_x = -\frac{1}{2}\int_{z=0}^{\infty} -\frac{A^2 k_x}{\omega\varepsilon_1}\, e^{-2\,\mathrm{Re}\,(k_{z_1}) z}\, dz . \tag{4}$$

Since $\varepsilon_1 \simeq \varepsilon_0$ (ε_0 and ε_1 are the permittivities of free space and air, respectively), Eq. (4) can be rewritten as

$$P_x = -\frac{1}{2}\left[\frac{A^2 k_x}{-2\omega\varepsilon_0[\mathrm{Re}\,(k_{z_1})]}\right] . \tag{5}$$

Noting that $\varepsilon_{2eff} \simeq -j\,\frac{\sigma}{\omega}$, Eq. (41), Appendix I yields

$$\mathrm{Re}(k_{z_1}) = \frac{\omega}{c}\sqrt{\frac{\omega\varepsilon_0}{2\sigma}} , \tag{6}$$

where σ is the conductivity of the metal, and c is the speed of light in free space. Substituting Eq. (6) into Eq. (5) and letting $k_x \simeq \frac{\omega}{c}$ [see Eq. (40), Appendix I], yields

$$P_x = A^2\sqrt{\frac{\sigma}{(2\omega\varepsilon_0)^3}} . \tag{7}$$

Eq. (7) shows the total power propagated in the air region. To find the power propagated by SEW within the height $z = h$, Eq. (1) becomes

$$P_{x_h} = -\frac{1}{2}\,\mathrm{Re}\left[\int_{z=0}^{z=h} E_z^{(1)}\,H_y^{(1)*}\,dz\right] . \tag{8}$$

Substituting Eqs. (2), (3), (6) and (7) into Eq. (8) results in

$$P_{x_h} = P_x\left(1 - e^{-\sqrt{2\omega\varepsilon_0/\sigma}\,\frac{\omega}{c}\,h}\right) . \tag{9}$$

From Eq. (9) it is seen that the height above the surface for 90 percent power concentration is

$$h_{90\%} = 2.3 \ \frac{c}{\omega} \sqrt{\sigma/2\omega\varepsilon_0}. \tag{10}$$

B. Dielectric Coated Conducting Surface

The average power transmitted by the SEW per unit length in the y direction above the surface (air and dielectric regions) is given by[1,2]

$$P_x = P_{x(\text{dielectric})} + P_{x(\text{air})} \tag{11}$$

where

$$P_{x(\text{dielectric})} = -\frac{1}{2} \text{Re} \left[\int_{z=0}^{\ell} (E_z^{(2)} \ H_y^{(2)*}) \ dz \right] \tag{12}$$

and

$$P_{x(\text{air})} = -\frac{1}{2} \text{Re} \left[\int_{z=\ell}^{\infty} (E_z^{(1)} H_y^{(1)*}) \ dz \right] \tag{13}$$

where ℓ is the thickness of the dielectric material, $P_{x(\text{dielectric})}$ is the average power propagated in the dielectric material, and $P_{x(\text{air})}$ is the average power which is propagated in the air. From Eq. (7), Appendix I, it is seen that for air ($z > \ell$)

$$H_y^{(1)} = A_1 \ e^{-k_{z_1}(z-\ell)} \ e^{-j(k_x s - \omega t)} \tag{14}$$

$$E_z^{(1)} = -\frac{A_1 k_x}{\omega\varepsilon_1} \ e^{-k_{z_1}(z-\ell)} \ e^{-j(k_x x - \omega t)} \ . \tag{15}$$

Substituting Eqs. (14) and (15) into Eq. (13) and letting $k_x \simeq \frac{\omega}{c}$ [see Eq. (85), Appendix I], yields

$$P_{x(air)} = \frac{1}{4} \frac{A_1^2}{c\varepsilon_1 [\mathrm{Re}\ (k_{z_1})]} \ . \tag{16}$$

Notice that in Eq. (16) k_{z_1} is [see Eq. (94), Appendix I]

$$k_{z_1} = \frac{\omega^2}{c^2} [(\frac{\varepsilon_{2eff} - \varepsilon_1}{\varepsilon_{2eff}}) \ \ell + \frac{\delta}{2} (1-j)] . \tag{17}$$

To find the power propagated by the SEW in the air between $z=\ell$ and $z=h$, Eq. (13) becomes

$$P_{x(air)_h} = - \frac{1}{2} \mathrm{Re}[\int_{z=\ell}^{h} (E_z^{(1)} H_y^{(1)*}) \ dz] . \tag{18}$$

Substituting Eqs. (14) and (15) into Eq. (18) yields

$$P_{x(air)_h} = P_{x(air)} \ (1 - e^{-2 \ \mathrm{Re}(k_{z_1})(h-\ell)}) . \tag{19}$$

From Eq. (19), it is seen that the height above the metal surface for 90 percent power concentration (only in air) is

$$h_{90\%} = \ell + \frac{2.3}{2 \ \frac{\omega^2}{c^2} \ [(\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2}) \ell + \frac{1}{2} \ \delta]} \tag{20}$$

where δ = skin depth of the metallic conductor = $\sqrt{2/\sigma\omega\mu_0}$, ε_1 and ε_2 are the permittivities of the air, and the dielectric material, respectively. μ_0 is the permeability of the free space and σ is the conductivity of the conducting material.

C. Numerical Calculations

The following numerical calculations have been obtained to show the behavior of the power concentration in different circumstances. In these calculations, aluminum is used for the conducting medium with conductivity σ (= $3.72\text{x}10^7$ mho), and skin depth δ (= $8.97\text{x}10^{-4}$ mm). The frequency is assumed to be 8.445 GH_z (λ = 3.55 cm). For free space the permittivity is ε_0 (= 8.85 $\text{x}10^{-2}$ farads/m) and the permeability is μ_0 (=$4\pi\text{x}10^{-7}$ henry/m). The material which is used as the dielectric (polystyrene) has a relative dielectric constant 2.55 and loss factor 0.00033 at 8.445 GH_z. The $h_{90\%}$ is calculated from Eqs. (10) and (20) for an uncoated and a dielectric coated conducting surface, and found to be 81.77 m for an uncoated metal and $3.94\text{x}10^{-2}$ m for a dielectric coated metal, respectively.

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APPENDIX III. DETERMINATIONS OF POWER TRANSMITTED THROUGH COUPLING APERTURES AND MEASUREMENTS OF COUPLING EFFICIENCIES FOR SEVERAL SEW EXCITATION TECHNIQUES

In this first part consideration is given to the determination of the power transmitted through the coupling apertures and the measurements of the coupling efficiencies for the grating and the prism surface electromagnetic wave (SEW) excitation techniques. Determination and the measurements of these same parameters for the horn antenna, the waveguide, the hump, and the valley SEW excitation techniques are discussed later. It is assumed that the conducting surface is in the x-y plane and the SEW is propagating in the +x direction.

A. Grating and Prism SEW Excitation Techniques

Referring to Fig. 1(a), a linearly polarized antenna with a reflector radius b (= 22.86 cm) is used to transmit electromagnetic energy to a metal surface of 2w wide at an incident angle α with respect to the normal (z direction). It is assumed that the transmitted beam is uniform and parallel. The projection of the beam on the x-y plane is an ellipse as shown in Fig. 1(b). The minor axis of this ellipse in the y direction is b which is the same as the antenna reflector radius. The major axis a, however, is

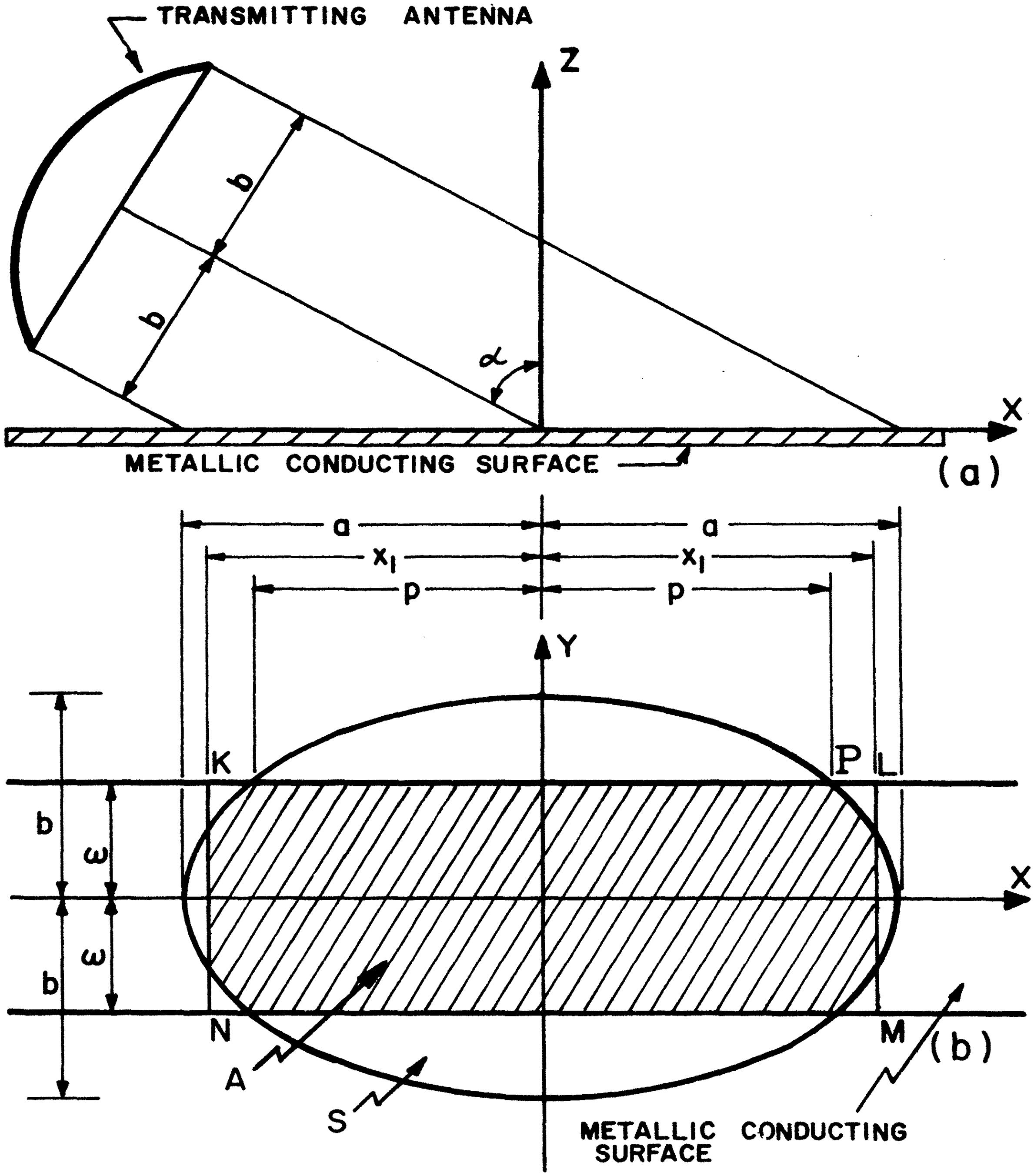

Fig. 1. Arrangement for defining and determining the power transmitted through the coupling apertures for the prism and grating SEW excitation techniques. (a) the projection of the system on the x-z plane and (b) the projection of the beams on the x-y plane.

$$a = \frac{b}{\cos\alpha} . \qquad (1)$$

The area of the ellipse (S), shown in Fig. 1(b), is

$$S = \pi ab. \qquad (2)$$

Substituting Eq. (1) into Eq. (2) yields

$$S = \frac{b^2}{\cos\alpha} . \qquad (3)$$

Fig. 1(b) shows that the maximum coupling aperture area (A_{max}) is the common area of the ellipse and the metal surface. Notice that A_{max} is the maximum area which can be used for exciting a SEW on the metalic surface.

Let B be the area of the coupling aperture parallel to the metalic surface onto which we wish to couple a SEW. An effective coupling aperture area (A_{eff}), now, can be defined as the common area between A_{max} and B. For example if B is the rectangle KLMN [see Fig. 1(b)], the shaded area in Fig. 1(b) is A_{eff}.

The x coordinate of point L, x_1, in Fig. 1(b) is called the effective length of the effective coupling aperture area. We wish now to calculate A_{eff} as a function of the effective length x_1. The equation of the ellipse in Fig. 1(b) is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1. \qquad (4)$$

To find the x coordinate of point P, p, the intersection of line y = w and the ellipse [see Fig. 1(b)], y = w is substituted in Eq. (4). Therefore

$$p = \frac{a}{b}\sqrt{b^2 - w^2}\ . \tag{5}$$

A_{eff} is found for three cases, when x_1 is greater than, equal to, or less than p, as follows.

Case 1: For $x_1 \leq p$

$$A_{eff} = 4wx_1 . \tag{6}$$

Case 2: For $a > x_1 > p$

$$A_{eff} = 4[wp + A_1], \tag{7}$$

where

$$A_1 = \int\int dx\ dy = \int_p^{x_1} dx \int_o^{\frac{b}{a}\sqrt{a^2 - x^2}} dy \tag{8}$$

or, since a > o,

$$A_1 = \frac{b}{2a}\ [x_1\sqrt{a^2 - x_1^2} - p\sqrt{a^2 - p^2}$$

$$+ a^2(\sin^{-1}\frac{x_1}{a} - \sin^{-1}\frac{p}{a})]. \tag{9}$$

Case 3: For $x_1 \geq a$

$$A_{eff} = 4[wp + A_2], \tag{10}$$

where

$$A_2 = \frac{b}{2a}\,[\pi a^2/2 - p\sqrt{a^2-p^2} - a^2 \sin^{-1}\frac{p}{a}]. \qquad (11)$$

The coupling efficiency, η, is defined as[1]

$$\eta = \frac{P_{sew}}{P_{tca}}\ , \qquad (12)$$

where

P_{sew} = Power carried by the surface electromagnetic waves,

P_{tca} = Power transmitted through the coupling aperture.

P_{tca} may be written as

$$P_{tca} = P_t \cdot \frac{A_{eff}}{S} \qquad (13)$$

where P_t is the power transmitted by the antenna. Substituting Eq. (13) in Eq. (12) results in

$$\eta = \frac{S}{A_{eff}}\ \frac{P_{sew}}{P_t}\ . \qquad (14)$$

In order to find the grating and the prism coupling efficiencies from Eq. (14), they are considered separately as follows.

1. Grating Coupling Efficiency

The experimental arrangement is shown in Fig. 2. The transmitting and receiving antennas were of identical parabolic reflector design. The metal strip was 1 foot (30.48 cm) wide. The transmitting and the receiving gratings were of identical design. Each grating was composed of seven iron bars with diameters of 1.27 cm and grating constant of 7.4 cm. Large microwave energy absorbers and aluminum plated shields (1m x 2m) were used to prevent direct coupling of electromagnetic energy between antennas. A gap of 12 cm was left between the shields and the 30.48 cm wide metal strip on which the SEW propagated. The distance between transmitting and receiving gratings was 3 meters and the frequency, f, was fixed at 10 GHz. The SEW wavelength can be found from

$$\lambda = \frac{c}{f} \qquad (15)$$

where c is the speed of light in free space. Angles of incidence α and β (defined in Fig. 2) were fixed at 36.5°.

For the grating, the effective length is

$$x_1 = \frac{(n-1)d}{2} \qquad (16)$$

where

n = number of grating bars

d = grating constant.

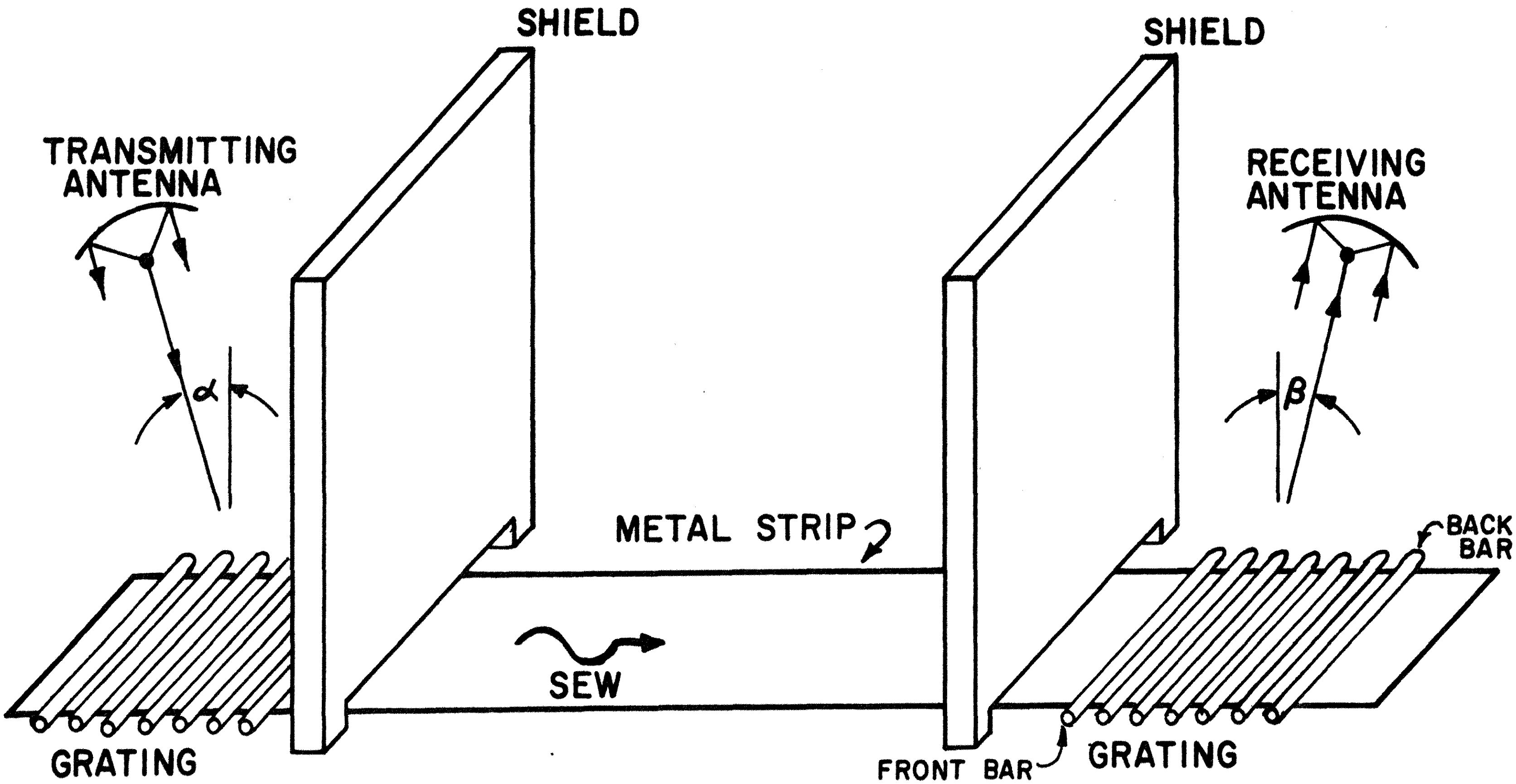

Fig. 2. Experimental arrangement used for the measurement of the coupling efficiency for the grating SEW excitation technique.

The grating constant (the distance between two successive bars) in the microwave frequency range for maximum grating coupling efficiency can be calculated from

$$d = \frac{m\lambda}{1-\sin\alpha} \qquad (17)$$

where

α = angle of incidence

λ = SEW wavelength, and

m = mode order ($m = 0, \pm 1, \pm 2, \ldots$).

To summarize, all known parameters in this experiment are

$\alpha = \beta = 36.5°$

f = 10 GHz

λ = 3 cm

w = 15.24 cm

b = 22.86 cm

a = 28.44 cm

m = 1 (first mode is coupled as SEW)

d = 7.4 cm

n = 7 bars

x_1 = 22.20 cm

p = 21.20 cm [see Eq. (5)].

Since $a > x_1 > p$, A_{eff} from Eq. (7) is

$$A_{eff} = 4[15.24 \times 21.20 + A_1] \qquad (18)$$

where from Eq. (9) A_1 is 16.50 cm^2 .

Therefore,

$$A_{eff} = 1358.38\ cm^2. \tag{19}$$

From Eq. (1), S is

$$S = \pi \times 28.44 \times 22.86 - 2042.47\ cm^2. \tag{20}$$

Substitution of Eqs. (19) and (20) in Eq. (14) results in

$$\eta_{grat}^{(t)} = \frac{P_{sew}^{(t)}}{0.67\ P_t} \tag{21}$$

where $\eta_{grat}^{(t)}$ is the coupling efficiency of the transmitting grating. From Eq. (20), $P_{sew}^{(t)}$ (the SEW power at transmitting grating point) is

$$P_{sew}^{(t)} = 0.67\ \eta_{grat}^{(t)}\ P_t\ . \tag{22}$$

To determine the relationship between $P_{sew}^{(r)}$ (the SEW power at the receiving grating point) and $P_{sew}^{(t)}$, one must consider the power dissipation of the SEW while it is propagating from the transmission grating point to the receiving grating point.

The attenuation constant in nepers per unit distance is expressed by[2]

$$\alpha_{atten} = \frac{\text{Power lost per unit distance}}{\text{Twice the power transmitted}}\ . \tag{23}$$

Since the SEW is a guided wave[2],

$$P_{sew}^{(r)} = P_{sew}^{(t)} \cdot \exp(-2\alpha_{atten}\ x), \tag{24}$$

where x is the distance between the transmitting and the receiving gratings in meters. For x = 3m, Eq. (24) becomes

$$P_{sew}^{(r)} = P_{sew}^{(t)} \cdot \exp\ (-6\alpha_{atten}), \tag{25}$$

or if an attenuation factor (γ) is defined as

$$\gamma = \exp(-6\alpha_{atten}), \tag{26}$$

Eq. (25) becomes

$$P_{sew}^{(r)} = \gamma\ P_{sew}^{(t)}\ . \tag{27}$$

The attenuation constant, α_{atten}, and the attenuation factor, γ, for copper and aluminum, uncoated or coated with some special dielectric were experimentally measured and are tabulated in Table I. The special dielectric has a relative dielectric constant of 2.70 and loss factor of 0.056 at 9 GHz.

TABLE I. THE ATTENUATION CONSTANT α_{atten} AND THE ATTENUATION FACTOR γ FOR COPPER AND ALUMINUM UNCOATED OR COATED WITH SOME SPECIAL DIELECTRIC

Material	α_{atten} neper/m	γ
Uncoated copper	0.21	0.28
Coated copper	0.11	0.52
Uncoated aluminum	0.14	0.43
Coated aluminum	0.08	0.62

Substituting Eq. (22) into Eq. (27) yields

$$P_{sew}^{(r)} = 0.67\ \eta_{grat}^{(t)} \cdot \gamma \cdot P_t . \qquad (28)$$

At the receiving grating, the SEW is decoupled and detected. $\eta_{grat}^{(r)}$ is the grating coupling efficiency for the receiving grating and P_r is the power received by the receiving antenna. Since all of the power decoupled by the receiving grating can be detected by the receiving antenna,

$$\eta_{grat}^{(r)} = \frac{P_r}{P_{sew}^{(r)}} . \qquad (29)$$

Substituting Eq. (29) in Eq. (28) yields

$$P_r = 0.67\ \eta_{grat}^{(t)}\ \eta_{grat}^{(r)}\ \gamma\ P_t . \qquad (30)$$

By the reciprocity theorem, we have

$$\eta_{grat}^{(t)} = \eta_{grat}^{(r)} . \tag{31}$$

Combining Eqs. (30) and (31) results in

$$\eta_{grat}^{(t)} = \eta_{grat}^{(r)} = [\frac{P_r}{0.67 \gamma P_t}]^{1/2} . \tag{32}$$

A maximum coupling efficiency of 30% was experimentally achieved using this method.

2. Prism Coupling Efficiency

The experimental set up for this measurement is the same as shown in Fig. 2 except that two small right angle prisms replaced the receiving grating. One of the prism angles was chosen so that an electromagnetic beam normally incidence on the prism face struck the prism base at the critical angle. The prisms were made of soft polyethylene with a relative dielectric constant of 2.25. The prisms were of identical construction with dimensions illustrated in Fig. 3. Both prisms were used at the receiving point due to their relatively small individual size compared to the width of the metallic conductor strip (30.48).

The base of each prism as shown in Fig. 3 was 10.15 x 16.4 cm. Therefore, for the two prisms, the effective coupling aperture area is

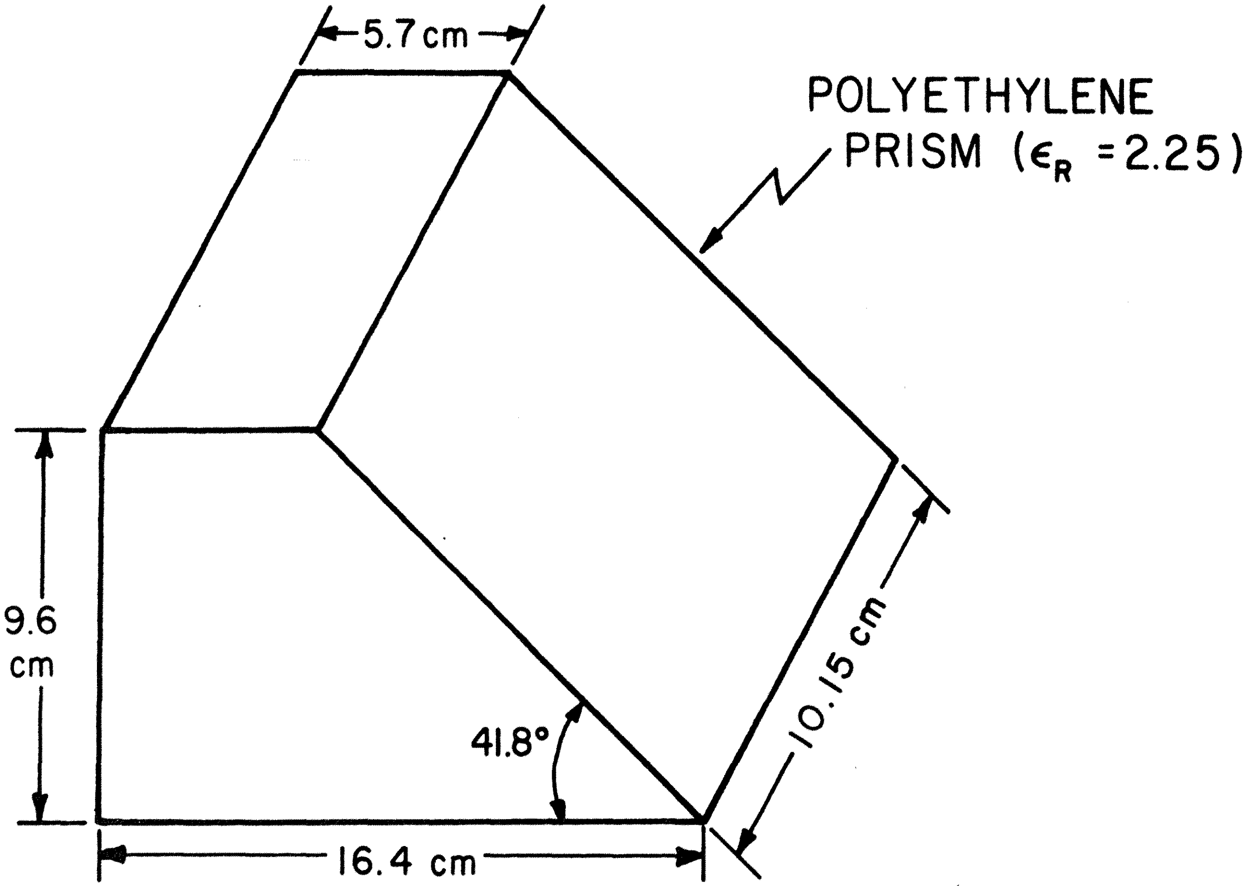

Fig. 3. Prism used in the measurement of the coupling efficiency for the prism SEW excitation technique.

$$A_{eff} = 2 \times 10.15 \times 16.40 = 332.92 \text{ cm}^2 . \qquad (33)$$

Notice that in this experiment the SEW was excited by the grating coupler utilizing exactly the same procedure as illustrated previously. The SEW power at the receiving point can be found from Eq. (28) as

$$P_{sew}^{(r)} = 0.67 \, \eta_{grat}^{(t)} \, \gamma \, P_t . \qquad (34)$$

Since A_{eff} at the receiving point (332.92 cm^2) is 24.51% of A_{eff} at the transmitting point (1358.38 cm^2), only 24.51% of the SEW can be decoupled by the two small prisms. Therefore the prism coupling efficiency at the receiving point is

$$\eta_{prism}^{(r)} = \frac{P_r}{0.245 \, P_{sew}^{(r)}} . \qquad (35)$$

Substituting Eq. (35) into Eq. (34) results in

$$\eta_{prism}^{(r)} = \frac{P_r}{0.245 \times 0.67 \times \eta_{grat}^{(t)} \, \gamma \, P_t} . \qquad (36)$$

By the reciprocity theorem we have

$$\eta_{prism}^{(t)} = \eta_{prism}^{(r)} . \qquad (37)$$

A maximum coupling efficiency of 60% was experimentally achieved using this method.

B. Horn Antenna Coupling Efficiency

Two identical rectangular horn antennas were used in this experiment. The mouth of the horn antenna is 7.5 cm x 5.5 cm. First the transmitting power, $P_{horn}^{(t)}$, is measured by facing the two antennas, one as transmitting and the other one as receiving. The two antennas were laid two meters apart on a block of styrofoam as shown in Fig. 4(a). The relative dielectric constant of styrofoam is 1.06 and therefore it is used as a material very similar to air. The power measured in this case [Fig. 4(a)] is a direct coupling power, $P_{direct\ coup}^{(avg)}$. The average of the measured power of several points across the width of the styrofoam block is $P_{direct\ coup}^{(avg)}$. A 30.48 cm wide aluminum strip and a 1.6 mm thick polystyrene overlayer were laid on the styrofoam block as shown in Fig. 4(b). Polystyrene has a relative dielectric constant of 2.55 and a loss factor of 0.00033 at 9 GHz. The distance between the two antennas was 2 meters. The power measured in this case is $P_r^{(avg)}$. Again $P_r^{(avg)}$ is the average of the measured powers of several points along the cross width of the metal strip. The difference of the last two power measurements is

$$P_r^{(avg)} - P_{direct\ coup}^{(avg)} = P_{sew}^{(avg)} \ \eta_{horn}^{(r)} \qquad (38)$$

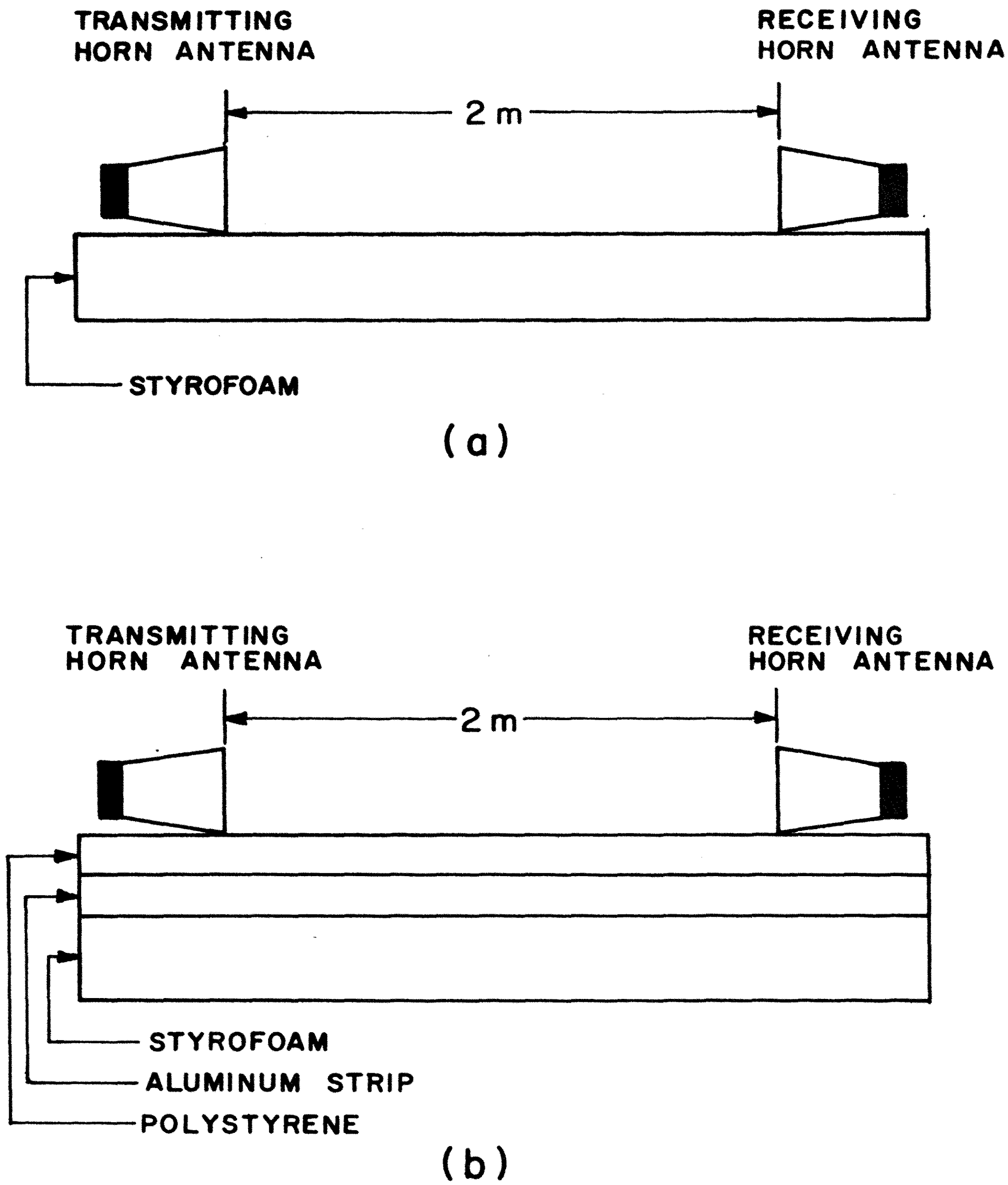

Fig. 4. Arrangement for defining and determining the power transmitted through the coupling aperture and the measurement of the coupling efficiency for the horn antenna SEW excitation technique. (a) The two antennas were laid two meters apart on a block of styrofoam. (b) The two antennas were laid on a 30.48 cm wide aluminum strip with a 1.60 mm thick polystyrene overlayer on a styrofoam block.

where $\eta_{horn}^{(r)}$ is the receiving horn antenna efficiency and $P_{sew}^{(avg)}$ is the average power of the SEW at the receiving point. The SEW power loss is negligible from the transmitter to the receiver for a low loss polystyrene coated metal strip. Therefore, the SEW powers are the same at the transmitting and the receiving points. Considering the fact that the width of the metal strip (30.48 cm) is four times the edge width of the horn antenna (7.5 cm), the SEW receiving power is

$$P_{sew}^{(r)} = 4\ P_{sew}^{(avg)} . \tag{39}$$

Substituting Eq. (38) into Eq. (39) yields

$$P_{sew}^{(r)} = \frac{4}{\eta_{horn}^{(r)}} \left(P_r^{(avg)} - P_{direct\ coup}^{(avg)}\right) . \tag{40}$$

Since the SEW powers are the same at the transmitting and the receiving points

$$P_{sew}^{(t)} = P_{sew}^{(r)} = \frac{4}{\eta_{horn}^{(r)}} \left(P_r^{(avg)} - P_{direct\ coup}^{(avg)}\right) . \tag{41}$$

The horn antenna coupling efficiency is

$$\eta_{horn}^{(t)} = \frac{P_{sew}^{(t)}}{P_{horn}^{(t)}} . \tag{42}$$

Combining Eqs. (41) and (42) yields

$$\eta_{horn}^{(t)} \; \eta_{horn}^{(r)} = \frac{4}{P_{horn}^{(t)}} \left(P_{r}^{(avg)} - P_{direct\ coup}^{(avg)}\right) . \tag{43}$$

By the reciprocity theorem the transmitting and the receiving efficiencies are the same. From Eq. (43) one obtains

$$\eta_{horn}^{(t)} = \eta_{horn}^{(r)} = 2 \sqrt{\frac{P_{r}^{(avg)} - P_{direct\ coup}^{(avg)}}{P_{horn}^{(t)}}} . \tag{44}$$

A maximum coupling efficiency of 73% was experimentally achieved using this technique.

C. Rectangular Waveguide Coupling Efficiency

The experimental set-up for this measurement was the same as that shown in Fig. 4, except that a rectangular waveguide replaced the transmitting horn antenna. To measure the transmitting power of the waveguide, $P_{waveguide}^{(t)}$, the rectangular waveguide (transmitter) and the horn antenna (receiver) were put face to face and the transmitting power was measured at a fixed frequency. The direct coupling power, $P_{direct\ coup}$, was measured following the procedure previously described [horn antenna coupling efficiency - see Fig. 4(a)]. The transmitting horn antenna was replaced by the transmitting waveguide and the power was measured only at one position. There was no need for obtaining an average. A 30.48 cm wide aluminum strip and 1.6 mm thick polystyrene ($\varepsilon_R = 2.55$) overlayer was laid on the styrofoam block as shown in Fig. 4(b). The polystyrene sheet was cut 1.90 cm in width (the interior edge dimension of the waveguide) and was placed between the mouths of the waveguide and the horn antenna. The received power is P_r. The difference between the last two power measurements is

$$P_r - P_{direct\ coup} = P_{sew}^{(r)} \; \eta_{horn}^{(r)} \; . \tag{45}$$

$P_{sew}^{(r)}$ is the same as $P_{sew}^{(t)}$ since the loss for the polystyrene coated metal is negligible between the transmitting and receiving points.

The rectangular waveguide coupling efficiency is given by

$$\eta_{waveguide}^{(t)} = \frac{P_{sew}^{(t)}}{P_{waveguide}^{(t)}} \; . \tag{46}$$

Combining Eqs. (45) and (46) yields

$$\eta_{waveguide}^{(t)} = \frac{P_r - P_{direct\ coup}}{P_{waveguide}^{(t)} \; \eta_{horn}^{(r)}} \; . \tag{47}$$

A maximum coupling efficiency of 92% was experimentally achieved using this technique.

D. Hump Coupling Efficiency

A hump of metal with a height of 37 cm and a cross section curvature as shown in Fig. 5 was constructed. Fig. 5 illustrates that the transmitting horn antenna is at a height such that all of the transmitted electromagnetic energy illuminates the hump. The transmitting power of the horn antenna, $P_{horn}^{(t)}$, is actually the power transmitted to the hump coupling aperture. From Eq. (12)

$$\eta_{hump}^{(t)} = \frac{P_{sew}^{(t)}}{P_{horn}^{(t)}} \tag{48}$$

where $P_{sew}^{(t)}$ is the SEW power at the transmitting point. The metal plated shield was used to prevent the direct coupling of electromagnetic energy between the antennas. The power measured by the receiving horn antenna is $P_r^{(avg)}$. Again, $P_r^{(avg)}$ is the average of the measured powers of several points across the width of the metal strip. The metal strip is four times the width of the edge of the horn antenna. Therefore,

$$P_{horn}^{(r)} = 4\ P_{horn}^{(avg)} \tag{49}$$

since

$$P_{sew}^{(r)} = \frac{P_{horn}^{(r)}}{\eta_{horn}^{(r)}} . \tag{50}$$

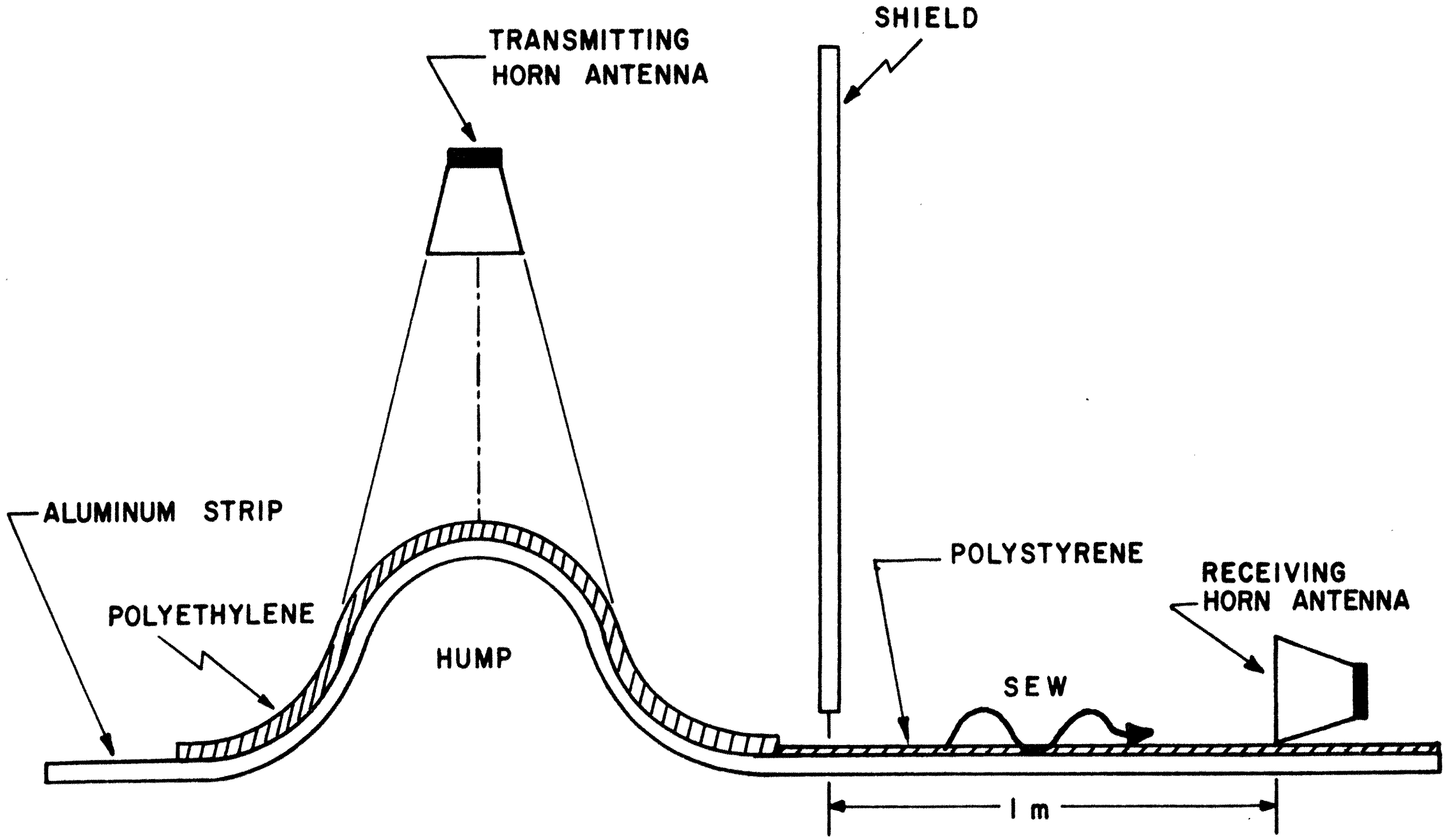

Fig. 5. Arrangement for defining and determining the power transmitted through the coupling aperature and the measurement of the coupling efficiency for the hump SEW excitation technique.

By substituting Eq. (49) in Eq. (50)

$$P_{sew}^{(r)} = \frac{4\ P_{horn}^{(avg)}}{\eta_{horn}^{(r)}} . \tag{51}$$

Again $P_{sew}^{(r)}$ is equal to $P_{sew}^{(t)}$ since the loss for polystyrene coated metal is negligible between the hump and the receiving horn antenna. From Eq. (51)

$$P_{sew}^{(t)} = P_{sew}^{(r)} = \frac{4\ P_{horn}^{(avg)}}{\eta_{horn}^{(r)}} . \tag{52}$$

The efficiency of the hump obtained by combining Eqs. (48) and (52) is

$$\eta_{hump}^{(t)} = \frac{P_{sew}^{(t)}}{P_{horn}^{(t)}} = \frac{4\ P_{horn}^{(avg)}}{P_{horn}^{(t)}\ \eta_{horn}^{(r)}} . \tag{53}$$

Using this technique, a peak coupling efficiency of about 35% was achieved when the transmitting horn antenna was aimed vertically down at the hump's center of curvature and the hump was covered with a 2.29 mm thick overlayer of polyethylene ($\varepsilon_R = 2.25$).

E. Valley Coupling Efficiency

A valley of metal with the dimensions approximately equal to those of the hump just described but inverted was constructed as shown in Fig. 6. Fig. 6 illustrates that the transmitting horn antenna is at a height such that

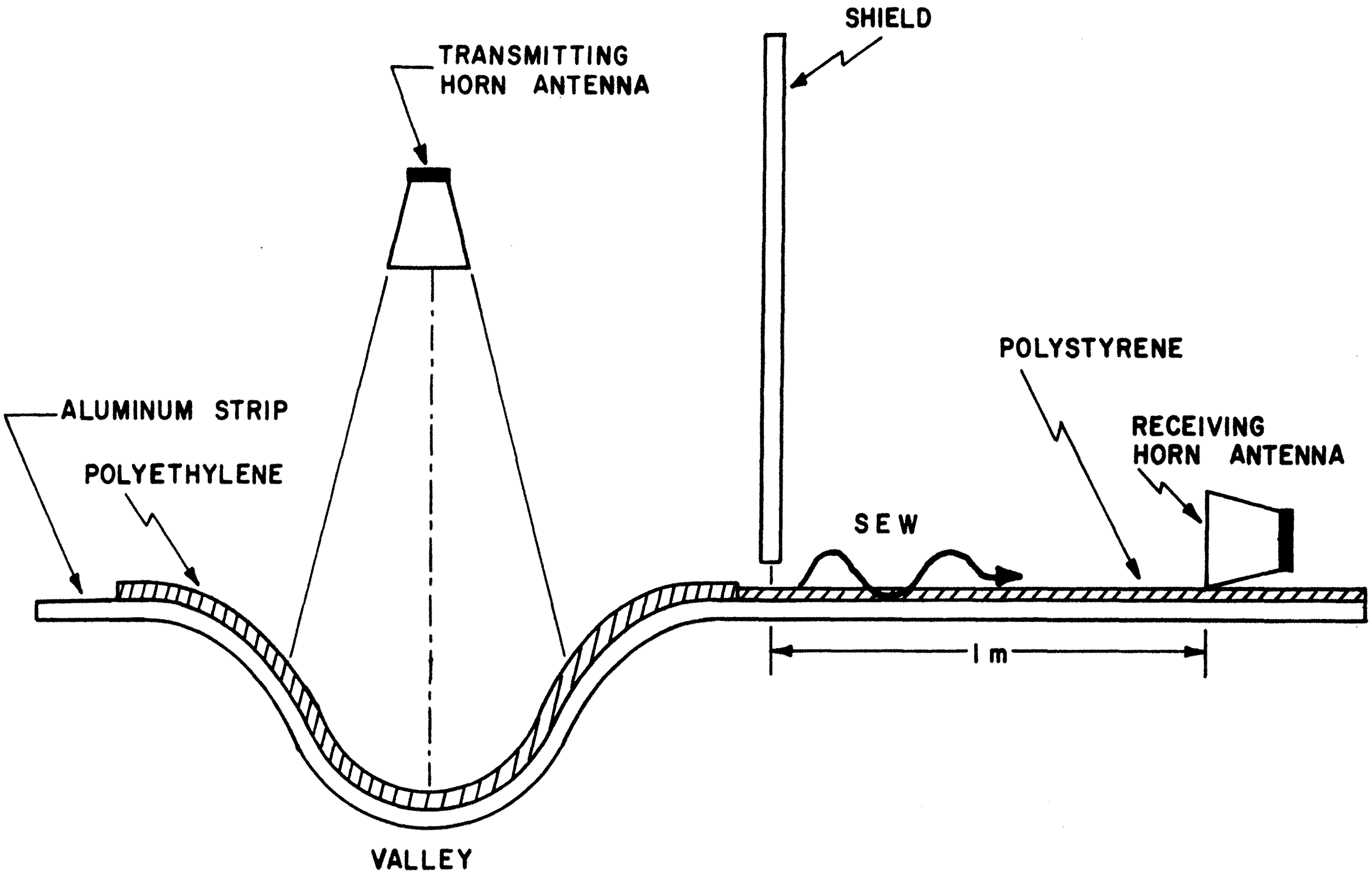

Fig. 6. Arrangement for defining and determining the power transmitted through the coupling aperture and the measurement of the coupling efficiency for the valley SEW excitation technique.

all of the transmitted electromagnetic power illuminates the valley. The transmitted power of the horn antenna, $P^{(t)}_{horn}$, is the power transmitted to the valley coupling aperture. From Eq. (12)

$$\eta^{(t)}_{valley} = \frac{P^{(t)}_{sew}}{P^{(t)}_{horn}} \tag{54}$$

where $P^{(t)}_{sew}$ is measured following the procedure described previously (hump coupling efficiency). Therefore, analogous to Eq. (53),

$$\eta^{(t)}_{valley} = \frac{4\ P^{(avg)}_{horn}}{P^{(t)}_{horn}\ \ \eta^{(r)}_{horn}} \ . \tag{55}$$

A peak coupling efficiency of 12% was measured when the transmitting horn antenna was aimed vertically downward and the valley was covered with a 2.29 mm thick overlayer of polyethelyene ($\varepsilon_R = 2.25$).

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