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PREFACE

The objective of this book is to analyze surface waves in absorbing layers used for the purpose of reducing the radar cross sections (RCS). These waves are originally generated by radars at geometrical or material discontinuities on the target surface. They propagate into absorbing coatings where they are transformed into heat energy. In accordance with the reciprocity principle, they can also turn into radiation when encountering such inhomogeneities in the target surface. Thus, surface waves represent a constitutive part of the complex scattering and absorption process. However, their physical properties have not been studied in detail despite the fact that absorbing coatings have widely been used since the Second World War. They have now been investigated in detail by the authors. We have discovered some new physical phenomena, such as upper frequency cutoff limits, the shifting of these cutoff limits to higher frequencies in material with smaller losses, and the merging of high order modes. These and other new results are presented and analyzed in this book. They are useful for electrical engineers and scientists interested in surface waves phenomena and in microwave absorbing material, as well as in lossy microwave circuits.

ABSTRACT

Surface waves are well investigated in problems related to propagation of elastic, acoustic, radio, and optics waves. But this is not the case with surface waves in microwave absorbing materials. In spite of the fact that radar absorbing coatings have been widely used since the Second World War, the properties of surface waves, which can exist in such materials, have not been studied in detail. Currently available books provide a general description of surface and other types of guided waves and focus mostly on the problems which do not relate directly to surface waves in microwave coatings. Analysis of radar absorbing materials (RAM) in technical books is usually based on the evaluation of the reflection coefficient only. However, surface waves play an important role in the absorption of radar waves. These waves also can provide an appreciable contribution to a fine structure of the scattered field when they transform into radiated waves at edges and material discontinuities. It was the authors' intention to fill in the gap in the existing theory of surface waves by investigating their properties in microwave absorbing materials. In this book, the authors present new results for surface waves in actual absorbing layers.

It has been shown that the traditional notions of the phase velocity and group velocity widely used in the theory of transmission lines are inappropriate for surface waves in absorbing layers. New, more general and appropriate definitions based on a physical view point for the phase velocity and energy velocity have been introduced. Physical phenomena hitherto unknown have been discovered and described. These include the upper frequency cutoff of surface waves, shifting of this cutoff to higher frequencies in materials with lower losses, and merging of high order surface waves / modes. These and other new results are presented and analyzed in this book. They can be of interest to the designers of radar absorbing coatings, microwave transmission lines and microwave devices.

INTRODUCTION

Surface waves represent a special class of guided waves. A distinctive feature of these waves is an exponential decrease of their amplitude in the direction normal to and away from the guiding structure. These waves were first discovered theoretically by Sommerfeld [1, 2] and Zenneck [3]. Sommerfeld investigated surface waves supported by thin imperfect cylindrical conductors. Zenneck studied surface waves near a flat interface between two homogeneous media. Goubau demonstrated experimentally surface waves propagating along metallic wires [4]. Since then, numerous articles were published about surface waves and now they have become a classic subject in the theory of guided waves [5-10, 15-18]. However, in this theory, transmission lines are usually considered without losses. Small losses are treated sometimes by the perturbation technique [18, 20].

As far as we know, properties of surface waves in actual absorbing structures with high losses were not well known. They were investigated by these authors in [21-25]. The results of these investigations, their analysis in detail and some other new results are presented in this book.

The first chapter contains the description of general properties of surface waves in absorbing layers. They include the physical structure of surface waves, the interpretation of them as inhomogeneous plane waves incident on the layer under the complex Brewster angles, and interpretations of dispersion equations as zeroes of the numerator or denominator of the reflection coefficient for the incident plane wave. It is also shown that the conventional notions of the phase and group velocities traditionally used in the theory of guided waves are not applicable in the case of actual absorbing material. Instead, we have introduced new physically reasonable and more general definitions for the phase velocity and the energy velocity.

Chapter 2 contains analysis of numerical results for attenuation and propagation constants of surface waves. It describes new physical phenomena discovered in [21-25] which do not exist in layers without

losses. These are the upper frequency cutoff, the shifting of this cutoff to higher frequencies in layers with lower losses, and the merging of high order modes.

Absorbing layers can support different types of guided waves. Special wave diagrams convenient for classification and analysis of guided waves are suggested in Chapter 3. Transformation of surface waves into other guided waves is investigated. In particular, it is shown that continuous transformation of surface waves into growing and leaky waves is forbidden.

In a single-mode frequency band, thin absorbing layers with appropriate parameters can be considered approximately as a plane with the standard impedance boundary condition. This approach is used in Chapter 3 to analyze the excitation of absorbing layers by an aperture-limited plane wave. An exact analytical solution of this problem is provided and analyzed. Numerical data for the launching efficiency of surface waves are presented.

In this book, we investigate surface waves in a homogeneous absorbing layer placed on a perfectly conducting plane (Fig. 1-1). Though this two-dimensional model is simple, it allows one to study some general properties of surface waves. Some results of this study are also valid for any stratified coatings. It should be noted that all numerical results were performed for an actual commercially available material with constitutive parameters shown in Fig. 1-2.

Such materials are widely used as microwave absorbing coatings. The Debye model-fit (A.1) for these experimental data was developed by Dr. A.D. Varvatsis and is presented in the Appendix. It is consistent with the Kramers-Kronig relations [19] and confirms the validity of experimental data. This material is ceramic in nature and it is embedded with small spherical metallic particles. Such materials are widely used as microwave absorbing coatings. Electromagnetic design and application of radar absorbing materials are presented in the Handbooks [27, 39].

In Fig. 1-1, the thickness of the layer is denoted by the letter a. Its relative permittivity and permeability are ε and μ, respectively. A free space ($\varepsilon = \mu = 1$) is assumed to be above the layer. The wave number in

free space is denoted as $k_0 = \omega\sqrt{\varepsilon_0\mu_0} = 2\pi / \lambda_0$, ω is the angular frequency of harmonic oscillations and λ_0 is the free space wavelength. The time dependence $\exp(-i\omega t)$ is assumed and suppressed below.

CHAPTER ONE

GENERAL PROPERTIES OF SURFACE WAVES

1.1 Basic field equations

The geometry of the problem is shown in Fig. 1-1. Here, ε and μ are the relative permittivity and permeability, respectively. It follows from Maxwell's equations that two types of surface waves can exist in absorbing layers: the transverse magnetic (TM) and transverse electric (TE) waves. In TM-waves, the magnetic vector $\vec{H}$ contains only the *x*-component (H_x), while in TE-waves only the *x*-component (E_x) of the electric vector $\vec{E}$ can exist.

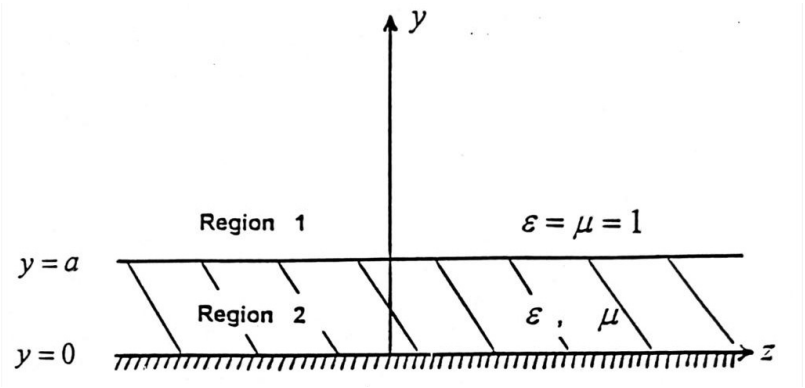

Fig. 1-1. Absorbing layer $(0 \le y \le a)$ backed up by a perfectly conducting plane $(y = 0)$.

The TM-waves are described by equations

$$H_x = \mathrm{e}^{ik_1(y-a)}\mathrm{e}^{i\beta z},$$

$$E_y = -\frac{\beta}{k_0} Z_0 H_x\,,\ E_z = \frac{k_1}{k_0} Z_0 H_x\,, \tag{1.1}$$

$k_0 = \omega / c = \omega\sqrt{\varepsilon_0 \mu_0}$ in the free space (Region 1), $y \geq a$, and by equations

$$H_x = \frac{\cos(k_2 y)}{\cos(k_2 a)} \mathrm{e}^{i\beta z}\,,$$

$$E_y = -\frac{\beta}{k_0 \varepsilon} Z_0 H_x\,,\ E_z = i\frac{k_2}{k_0 \varepsilon} Z_0 H_x \tan(k_2 y) \tag{1.2}$$

inside the layer (Region 2), $0 \leq y \leq a$. In these equations, $Z_0 = \sqrt{\mu_0 / \varepsilon_0}$ is the impedance of the free space. The complex quantities $k_2 = k_2' + ik_2''$ and $k_1 = k_1' + ik_1''$ are the transverse wave numbers of the wave field inside and outside the layer, respectively. The complex quantity $\beta = \beta' + i\beta''$ is the longitudinal wave number or the propagation constant. These wave numbers are connected by the relations

$$k_1^2 + \beta^2 = k_0^2\,,\ k_2^2 + \beta^2 = k_0^2 \varepsilon\mu \tag{1.3}$$

through the Helmholtz wave equation. It follows that

$$k_2^2 - k_1^2 = k_0^2(\varepsilon\mu - 1)\,. \tag{1.4}$$

The H_x-components from eqs. (1.1) and (1.2) are continuous on top of the layer ($y = a$). The E_z-component satisfies the boundary condition on the perfectly conducting plane ($E_z = 0$ at $y = 0$) and its continuity on top of the layer, $y = a$ leads to a transcendental equation

$$k_1 \varepsilon = ik_2 \tan(k_2 a)\,. \tag{1.5}$$

This transforms into the dispersion equation

$$D^{\mathrm{TM}}(k_0,\beta)=\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\tan\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)+i\varepsilon\sqrt{k_0^2-\beta^2}=0 \quad (1.6)$$

with the substitutions of k_1 and k_2 from eq. (1.3).

The TE-waves are described by similar equations. Their field components above the layer ($y \geq a$) are

$$E_x=\mathrm{e}^{ik_1(y-a)}\mathrm{e}^{i\beta z},$$

$$H_y=\frac{\beta}{k_0}Y_0E_x,\ H_z=-\frac{k_1}{k_0}Y_0E_x, \quad (1.7)$$

and inside the layer ($0 \leq y \leq a$), they are

$$E_x=\frac{\sin(k_2y)}{\sin(k_2a)}\mathrm{e}^{i\beta z},$$

$$H_y=\frac{\beta}{k_0\mu}Y_0E_x,\ H_z=i\frac{k_2}{k_0\mu}Y_0E_x\cot(k_2y), \quad (1.8)$$

where $Y_0=1/Z_0$ is the admittance of free space.

The wave numbers k_1, k_2, β of TE-waves also obey eqs. (1.3) and (1.4). But instead of eq. (1.5) for TM-waves, they satisfy the dispersion equation

$$k_1\mu=-ik_2\cot(k_2a) \quad (1.9)$$

which can be written as

$$D^{\mathrm{TE}}(k_0,\beta)=\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\cot\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)+i\mu\sqrt{k_0^2-\beta^2}=0 \quad (1.10)$$

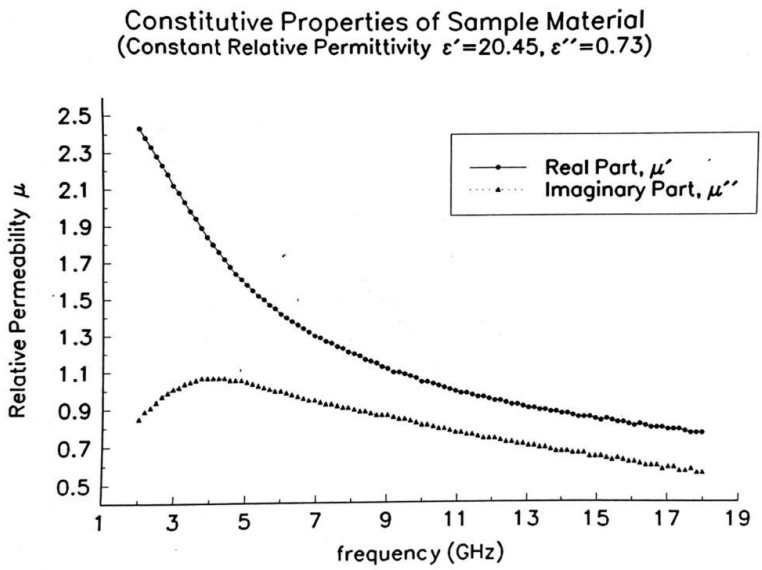

Fig. 1-2. Constitutive properties of sample material (constant relative permittivity: $\varepsilon' = 20.45$, $\varepsilon'' = 0.73$).

All numerical data presented in this book were obtained with the solutions of dispersion equations (1.6) and (1.10) using the Muller's method [28]. Constitutive parameters of a sample material are shown in Fig. 1-2.

For surface waves, the imaginary part of the transverse wave number k_1 is always positive thus ensuring an exponential decay of the field in the direction away from the layer. One should note that a tight connection exists between the dispersion equations (1.6), (1.10), and the reflection coefficients of plane waves incident on the layer. This connection is demonstrated in the next section.

1.2 Dispersion equations as zeroes or poles of reflection coefficients

First, consider the reflection of the TM plane wave

$$H_x^{\text{inc}} = \mathrm{e}^{ik_0(z\cos\theta - y\sin\theta)} \tag{1.11}$$

from the homogeneous absorbing layer (Fig. 1-3). This is a classic problem considered in handbooks on Electromagnetics. We present here only the final expression for the reflected wave

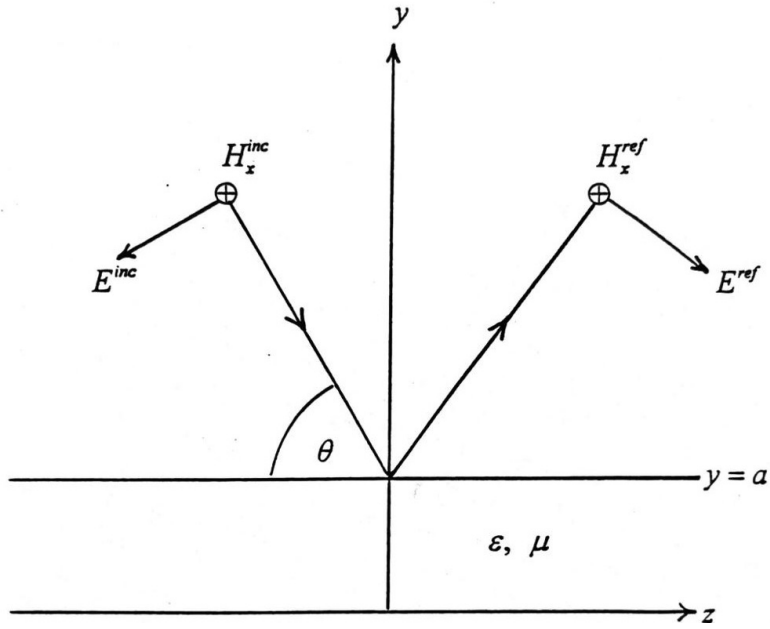

Fig. 1-3. Reflection of the plane wave by the layer.

$$H_x^{\text{ref}} = \rho_h(\theta)\, \mathrm{e}^{ik_0(z\cos\theta + y\sin\theta)}\, \mathrm{e}^{-i2k_0 a\sin\theta} \tag{1.12}$$

where the reflection coefficient $\rho_h(\theta)$ is given by

$$\rho_h(\theta) = \frac{\varepsilon\sin\theta + i\sqrt{\varepsilon\mu - \cos^2\theta}\,\tan\left(k_0 a\sqrt{\varepsilon\mu - \cos^2\theta}\right)}{\varepsilon\sin\theta - i\sqrt{\varepsilon\mu - \cos^2\theta}\,\tan\left(k_0 a\sqrt{\varepsilon\mu - \cos^2\theta}\right)}. \tag{1.13}$$

By setting $\cos\theta = \beta / k_0$ and $\sin\theta = -\sqrt{1-(\beta/k_0)^2} = -k_1/k_0$ with complex β determined by eq. (l.6), the incident plane wave given by eq. (1.11) transforms into eq. (1.1) for the surface wave. Here the angle θ can be recognized as the complement of the Brewster angle γ_B defined in the next section. The reflection coefficient changes into

$$\rho_h = \frac{i\varepsilon\sqrt{k_0^2-\beta^2} + \sqrt{k_0^2\varepsilon\mu-\beta^2}\,\tan\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}{i\varepsilon\sqrt{k_0^2-\beta^2} - \sqrt{k_0^2\varepsilon\mu-\beta^2}\,\tan\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}. \qquad (1.14)$$

The numerator of this expression is exactly the left-hand side of the dispersion equation (1.6) and, therefore, it is equal to zero. This confirms the observations [5, 29], that the surface wave can be interpreted as an inhomogeneous plane wave incident on the guiding structure under the complex Brewster angle without reflection.

We also can transform the reflected wave (1.12) into the surface wave (1.1) by setting $\cos\theta = \beta / k_0$ and $\sin\theta = \sqrt{1-(\beta/k_0)^2} = k_1/k_0$.

In this case, the reflection coefficient changes to

$$\rho_h = \frac{i\varepsilon\sqrt{k_0^2-\beta^2} - \sqrt{k_0^2\varepsilon\mu-\beta^2}\,\tan\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}{i\varepsilon\sqrt{k_0^2-\beta^2} + \sqrt{k_0^2\varepsilon\mu-\beta^2}\,\tan\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}. \qquad (1.15)$$

The denominator of this expression equals zero due to the dispersion equation (1.6). This pole of the reflection coefficient can be interpreted as the existence of the reflected wave (i.e. surface wave) in the absence of the incident wave.

Now let us consider the reflection of TE plane wave

$$E_x^{\text{inc}} = \mathrm{e}^{ik_0(z\cos\theta - y\sin\theta)} \qquad (1.16)$$

from the same layer. The reflected wave is determined as

$$E_x^{\text{ref}} = \rho_e(\theta)\,\mathrm{e}^{ik_0(z\cos\theta + y\sin\theta)}\,\mathrm{e}^{-i2k_0 a\sin\theta} \qquad (1.17)$$

with the reflection coefficient

$$\rho_e(\theta)=\frac{\mu\sin\theta-i\sqrt{\varepsilon\mu-\cos^2\theta}\,\cot\left(k_0a\sqrt{\varepsilon\mu-\cos^2\theta}\right)}{\mu\sin\theta+i\sqrt{\varepsilon\mu-\cos^2\theta}\,\cot\left(k_0a\sqrt{\varepsilon\mu-\cos^2\theta}\right)}. \qquad (1.18)$$

By setting $\cos\theta=\beta/k_0$ and $\sin\theta=-\sqrt{1-(\beta/k_0)^2}=-k_1/k_0$ with complex β determined by eq. (1.10), the incident plane wave (1.16) transforms into eq. (1.7) for the surface wave and the reflection coefficient changes into

$$\rho_e=\frac{i\mu\sqrt{k_0^2-\beta^2}-\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\cot\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}{i\mu\sqrt{k_0^2-\beta^2}+\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\cot\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}. \qquad (1.19)$$

The numerator of this coefficient equals zero due to the dispersion equation (1.10). This means that the surface wave can be interpreted as the inhomogeneous plane wave incident on the layer under a complex Brewster angle. Again, the reflected wave (1.17) also can be considered as the surface wave by setting $\cos\theta=\beta/k_0$ and $\sin\theta=\sqrt{1-(\beta/k_0)^2}=k_1/k_0$.

In this case, the reflection coefficient changes into

$$\rho_e=\frac{i\mu\sqrt{k_0^2-\beta^2}+\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\cot\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}{i\mu\sqrt{k_0^2-\beta^2}-\sqrt{k_0^2\varepsilon\mu-\beta^2}\,\cot\left(a\sqrt{k_0^2\varepsilon\mu-\beta^2}\right)}. \qquad (1.20)$$

According to the dispersion equation (1.10), the denominator here equals zero. The infinite reflection coefficient means the existence of the reflected wave (i.e. the surface wave) in the absence of the incident wave. Thus, we see that dispersion equations can be interpreted as zeroes or poles of the reflection coefficients. This property of the reflection coefficients is used sometimes to derive dispersion equations.

1.3 Phase and amplitude fronts of surface waves

Equations (1.1) describe a spatial distribution of the surface wave outside the layer ($y > a$) with a factor

$$e^{i(\phi_p - \phi_a)} \text{ where } \phi_p = \beta' z + k_1' y \,,\ \phi_a = \beta'' z + k_1'' y \,. \tag{1.21}$$

For physically allowed solutions above the lower cutoff frequency, the dispersion equations provide the following values: $\beta' > 0$, $\beta'' \geq 0$, and $k_1' \leq 0$, $k_1'' > 0$. Therefore, the surface wave outside the absorbing layer is an inhomogeneous plane wave incident on the layer without reflection. Due to the losses inside the layer this wave undergoes the exponential attenuation in the *z*-direction and its amplitude decreases exponentially along the normal to the layer (in the *y*-direction).

Setting $\phi_p = const$ and $\phi_a = const$ determines the phase and amplitude fronts, respectively:

$$y_p = z_p \tan\gamma_p + const \,,\ y_a = z_a \tan\gamma_a + const \,, \tag{1.22}$$

where

$$\tan\gamma_p = -\frac{\beta'}{k_1'} \,,\ \tan\gamma_a = -\frac{\beta''}{k_1''} \,. \tag{1.23}$$

According to eq. (1.3), the quantity $k_1^2 + \beta^2$ is purely real. It follows that

$$\beta'\beta'' + k_1' k_1'' = 0 \,, \tag{1.24.1}$$

$$\tan\gamma_a = -\frac{\beta''}{k_1''} = \frac{k_1'}{\beta'} = -\cot\gamma_p \,. \tag{1.24.2}$$

Therefore, $\gamma_a = \frac{\pi}{2} + \gamma_p$, i.e., outside the layer, the phase and amplitude fronts of the surface wave are perpendicular to each other (Fig. 1-4). This is in agreement with the well-known property of inhomogeneous plane

waves propagating in lossless media. The angles γ_p and γ_a are shown in Figs. 1-5 and 1-6 as functions of frequency.

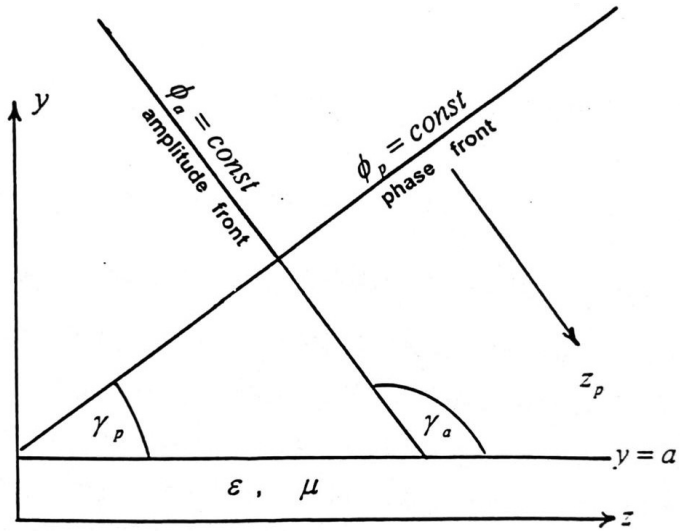

Fig. 1-4. Amplitude and phase fronts of the surface wave above the layer.

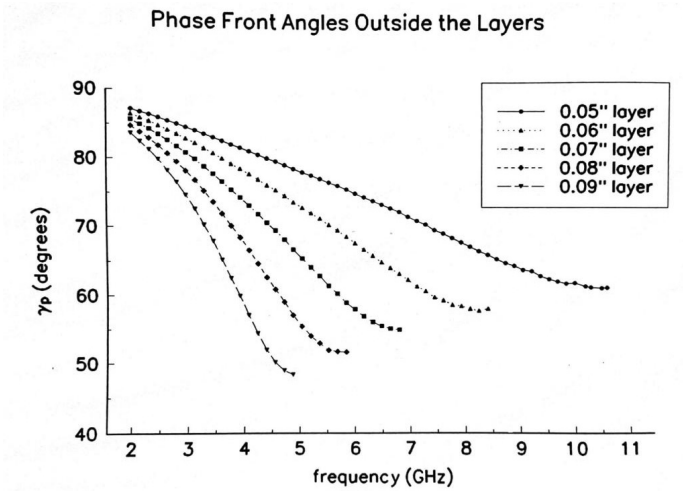

Fig. 1-5. Phase front angles of TM-waves outside the layers.

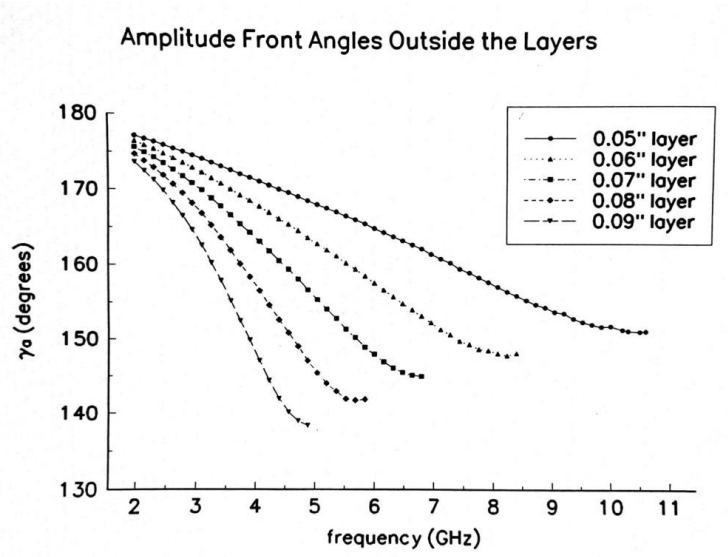

Fig. 1-6. Amplitude front angles of TM-waves outside the layers.

It is interesting to note a close connection between the angle γ_p and the complex Brewster angle $\gamma_B = \gamma_B' + i\gamma_B''$. The latter is introduced by the relation

$$e^{i(\beta z + k_1 y)} = e^{ik_0(z\sin\gamma_B - y\cos\gamma_B)} \tag{1.25}$$

where

$$\sin\gamma_B = \beta / k_0\,,\ \cos\gamma_B = -k_1 / k_0\,. \tag{1.26}$$

From these equations it follows that $\sin\gamma_B'\cosh\gamma_B'' = \beta' / k_0$, $\cos\gamma_B'\sinh\gamma_B'' = \beta'' / k_0$, $\cos\gamma_B'\cosh\gamma_B'' = -k_1' / k_0$, $\sin\gamma_B'\sinh\gamma_B'' = k_1'' / k_0$, and

$$\tan\gamma_B' = -\beta' / k_1' = k_1'' / \beta''\,, \tag{1.27}$$