Chapter 7

Microwaves

7.1 introduction

Electromagnetic radiation travels at a constant speed in vacuum = 3×10^8 m/s.

λ, m	Radiation
1	radio waves
10^{-1} to 10^{-3}	microwave
10^{-4} to 10^{-5}	infrared
10^{-6}	visible light
10^{-7} to 10^{-8}	ultraviolet
10^{-9} to 10^{-13}	x-ray and gamma radiation
10^{-14}	cosmic rays

Microwaves (unlike light) can penetrate matter (almost all non- metallic materials) and are reflected (scattered) from internal boundaries.

- **no mechanical contact, unlike ultrasonics.**
- **speed is 5 orders of magnitude larger than ultrasonics.**
  - **cannot detect time of arrival as in ultrasonics.**
  - **need to employ continuous wave or frequency modulated signal (no pulse mode).**
  - **rapid inspection is possible.**
- **skin depth in metal is a few mm, totally reflected on surface of metal.**
- **can readily penetrate many non-metals, plastics, ceramics, etc.**

- physical phenomena: based on electromagnetic theory (not covered here in detail)

Source: microwave generator.

Modification: interaction with atoms and molecules (attenuation and thermal effects).

Detector: microwave receiver (antenna, transducer).

Indication: (continuous) wave amplitude, phase shift, frequency of transmitted or reflected signal.

Interpretation: will discuss through examples.

7.1.1 Thickness of Metal Plates

- Metal completely reflects microwaves.
- Both sides of metal plate must be illuminated.
- Amplitude dependence is not generally very strong, except if the plate is near the near field of the antenna (interference of waves). Then, the amplitude becomes a function of the distance between plate and source.
- See schematic of system based on amplitude ($d_1 + d_2 + t$ =constant).
- Can detect up to 25 μm.
- Metal composition or surface condition does not affect the results.

7.2 Phase Measurements

- See schematic of Interferometer system.
- Output:

$$V_{out} = K \sin \frac{\phi_A - \phi_C}{4} \sin \frac{1}{2} \left[\frac{\phi_A + \phi_C}{2} - \phi_B \right] \tag{7.1}$$

- Phase Shifter introduces a phase shift of 90°; so that if ϕ_A leads ϕ_B by 90° and ϕ_C lags ϕ_B by 90°, the output of differential amplifier is zero.

- If thickness changes $(\phi_A - \phi_B + \phi_C - \phi_B)/2$ will no longer be zero.
- The output voltage $\propto$ distance.
- Note: there is sensitivity to both amplitude and phase shift. There are also more advanced systems.

7.3 Surface Cracks in Metals

Monitor refection from surface.

- Since skin depth is very small, a few μm, a crack must break through the surface of the metal.
- As crack opening increases, energy storage within the crack begins to dominate the crack response as frequency increases (very sensitive to crack opening).
- If frequency is very high, wave can propagate within crack and the crack response becomes very sensitive to crack depth.

7.4 Dielectric Plates

Non Metals: Thickness, composition, flaws.

Attenuation

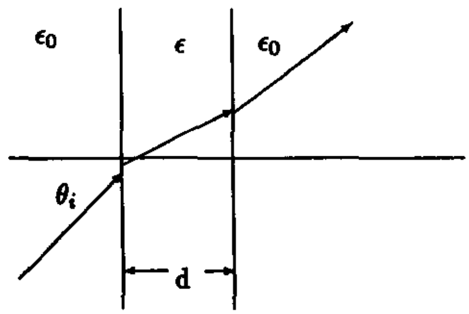
1. interaction with free electrons (composition).
2. interaction with molecular dipoles (composition).
3. scattering from material discontinuity (flaws).
4. beam spreading.

7.4.1 Reflection

See diagram. *Critical Angle:* wave is completely trapped inside; see diagram.

- Standing wave is a wave trapped inside.
- There is always a standing wave, except for the Brewstel angle, if microwave is emitted from high ϵ to low ϵ.

- Position of defect if within the min or max of a standing wave (which depend on frequency) will cause reflection which is related to frequency



disturbance.

$$\rho = \frac{2jR\sin\phi}{\exp(j\phi) - R^2\exp(-j\phi)} \tag{7.2}$$

$$\tau = \frac{1 - R^2}{\exp(j\phi) - R^2\exp(-j\phi)} \tag{7.3}$$

where ρ and τ are respectively, the reflection and attenuation coefficients.

$$R = \text{Reflection Ratio} = (Z-1)/(Z+1) \tag{7.4}$$

$$Z = \text{intrinsic impedance of plate}$$

$$Z = \frac{\sqrt{\epsilon/\epsilon_0 - \sin^2\theta_i}}{(\epsilon/\epsilon_0)\cos\theta_i} \quad \text{for // polarization} \tag{7.5}$$

$$Z = \frac{\cos\theta_i}{\sqrt{\epsilon/\epsilon_0 - \sin^2\theta_i}} \quad \text{for} \perp \text{polarization} \tag{7.6}$$

$$\phi = \text{electrical thickness of plate}$$

$$\phi = kd\sqrt{(\epsilon/\epsilon_0 - \sin^2\theta_i)} \tag{7.7}$$

where $k = 2\pi/\lambda$. See graph for ρ and τ vs. ϕ:

- ρ is more sensitive to changes in ϕ than τ.
- At $\phi = \pi/2$ or multiples of $\pi/2$, the slope is zero (poor sensitivity).
- Amplitude is most sensitive to changes in electrical thickness when ϕ is multiples of π (largest slope).

7.5 Flaws

7.5.1 Voids

- Discontinuity of scattered radiation (reduced intensity).
- Amount of scattering increases with ϵ and frequency.
- Size of flaw $\approx \lambda$; small void requires high frequency.

7.5.2 Delamination

- This is essentially a packed-shaped void filled with air (delamination between two adhesively bonded dielectric materials).
- $R < 0.3$, $\rho = 2j \exp(-j\phi) R \sin\phi$.
- If thickness $<< \lambda$, i.e. $\phi << 1$, $\rho \propto \phi$.

7.5.3 Porosity

Large number of small voids distributed in some regions of materials; ϵ causes change in ϕ; same techniques as in delamination.

7.5.4 Inclusions

Energy scattered by inclusions.

- $\lambda >>$ radius of inclusion, a (assumed to be a sphere).
- Above is called Rayleigh region: $\frac{2\pi a}{\lambda} < 0.4$.
- In far field: Prob. of scattering = scattering cross section, σ:

$$\sigma(\text{backscattering}) = \lambda^2 \frac{9}{\pi} \left(\frac{2\pi a}{\lambda}\right)^6 \tag{7.8}$$

$$\sigma(\text{forward scattering}) = \lambda^2 \frac{1}{4\pi} \left(\frac{2\pi a}{\lambda}\right)^6 \tag{7.9}$$

- Backscattering is stronger than forward scattering.

7.5.5 Material Properties

Change in ϵ: moisture content: water has a very high ϵ, very strong absorber of microwave.

7.6 Graphs

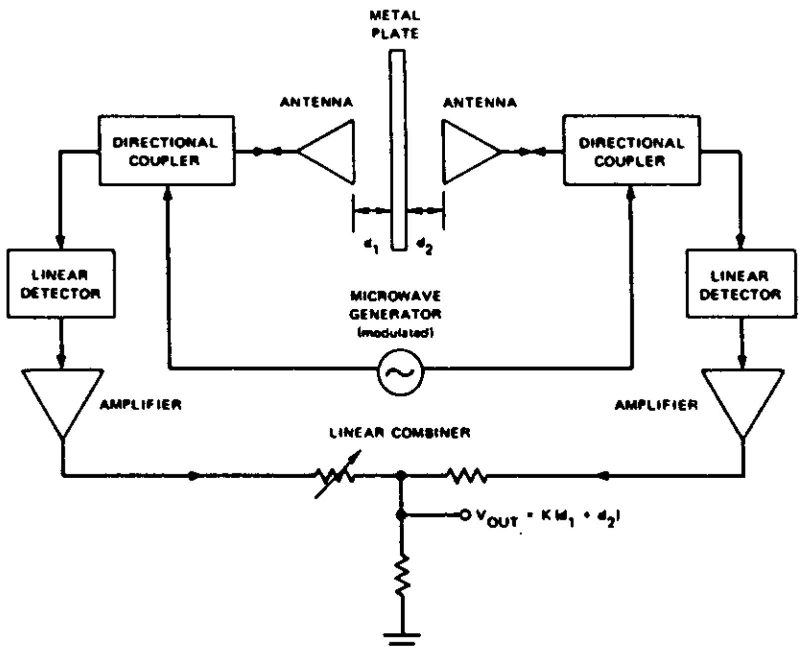


Figure 7.1: Amplitude Method for Thickness Measurement

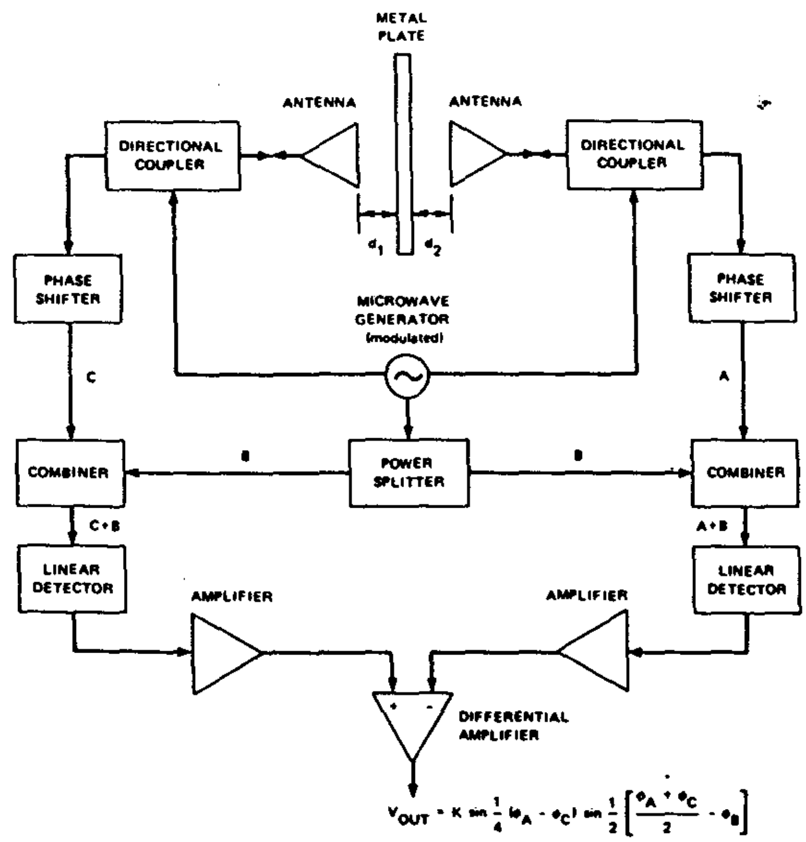


Figure 7.2: Phase-Shift Method for Thickness Measurement

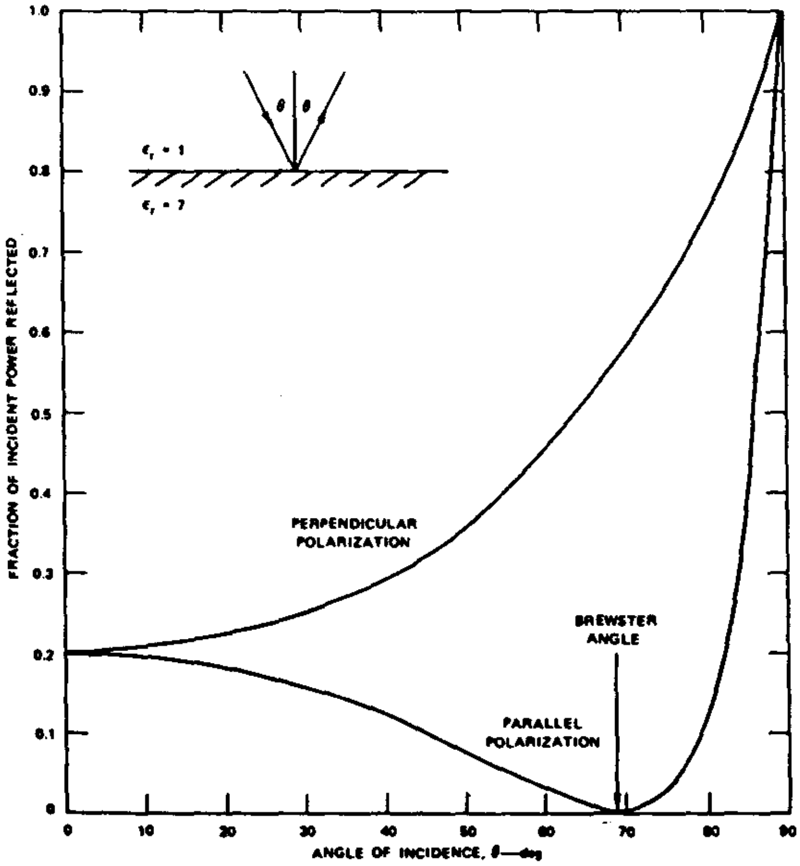


Figure 7.3: Air-to-Dielectric Reflection

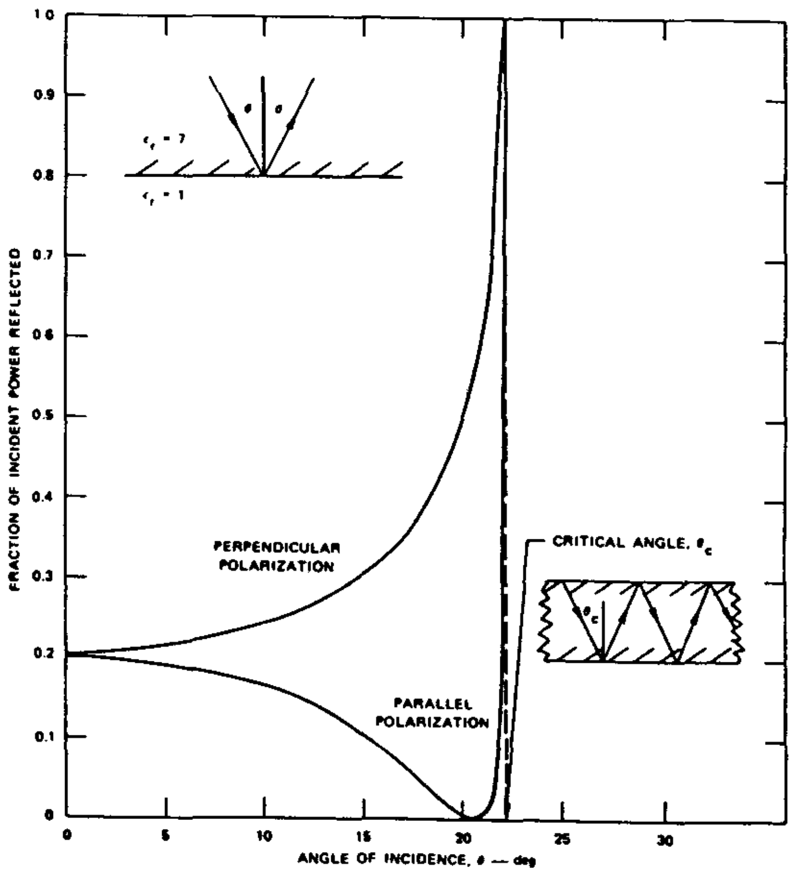


Figure 7.4: Dielectric-to-Air Reflection

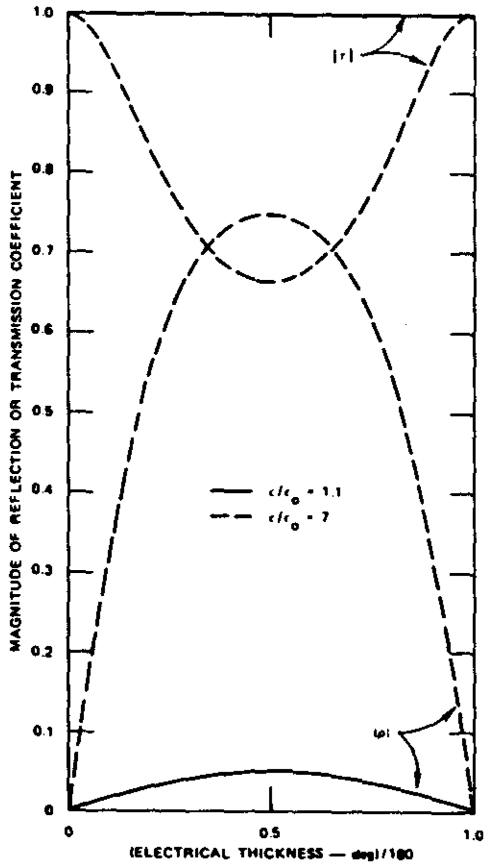


Figure 7.5: Electrical Thickness vs. Reflection and Transmission coefficients

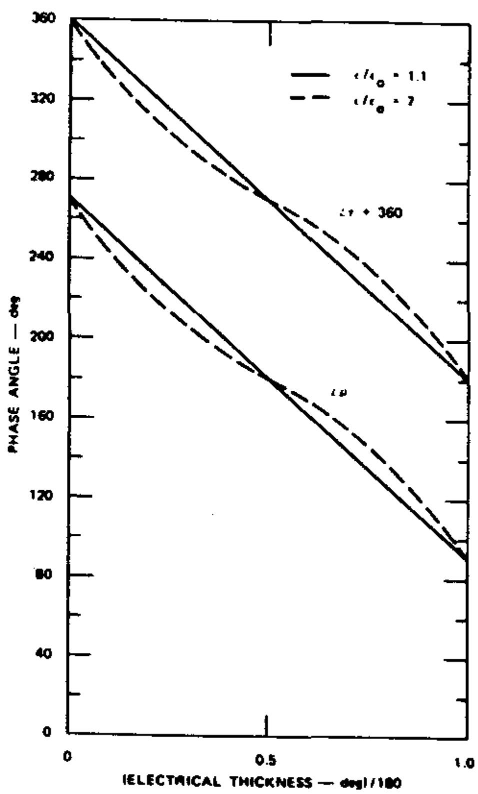


Figure 7.6: Phase-Shift vs. Electrical Thickness