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The effect of ZnS thin film's electrical conductivity on electromagnetic wave propagated through it

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Abstract

The effect of electrical conductivity on an electromagnetic wave propagating through ZnS thin film is analyzed using electromagnetic wave equation with relevant boundary condition. The solution of this equation enabled us to obtain a parameter known as the skin depth that relates to the conductivity of the thin film. This was found to give rise to exponential damping for all wavelengths between the optical, UV and Near-infrared region during the propagation. The penetration of the field into the thin film medium was seen to decrease in the analysis. The effect of skin depth on the reflection and transmission coefficient of the propagated waves through the thin film was also analyzed.

Keywords
Conductivity, skin-depth, electromagnetic-wave, propagation, penetration depth, thin film, impedance, reflectance, transmittance

1.0 Introduction

The theory propagation of electromagnetic wave on material surface has gone a long way in the understanding of the optical properties of the materials and with much insight on the behaviour of the propagated wave. Electromagnetic wave being an oscillation of electric and magnetic field in mutual perpendicular directions, transporting energy as it propagates through the material had revealed the nature of the some materials [1]. This is because the instantaneous rate of energy flow associated with the EM wave depends on the nature of the material. An understanding of the interactions between the electromagnetic field and the particles of the material that provides quantitative information on the characters and behaviour of the given material as studied [2, 8, 9]. A lot of researchers have studied this concept in different ways, for instance, the analysis of the scalar wave behaviour on the rough surface materials [6, 7]. The propagation of EM field through flat surface has been extended to multiple scattering theories developed by [4]. Multi-Layer conduction structure interacting with a plane EM wave which had earlier been seen to be possible only within the microwave and infrared region as studied by [11], has been extended to the optical region.

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A study of EM Wave incident normally on the surface in the *z*-direction of a bulk conductor measured from a given boundary surface, as studied by Watson and Keller [8], indicated a fall in the field penetration. It is known that as the wave propagates through the conducting material, it interacts with the particles of the material which reduces the strength of the propagated field that offers effective impedance to the propagating field. In accordance with EM wave problem based on the wave propagation over a conductive surface as already studied [2, 5]. The mechanism of energy transport through a medium involving absorption when EM wave impinges upon atoms of the materials was also considered earlier by [3,7]

The analysis of wave propagation in a two dimensional and 3-dimensional photonic crystals in a spectral region of EM wave, and an account of EM wave around multilayer had been examined by [12] and [13] including modeled conductor by [14] Werner and Linda [15] have depicted the field behaviour and penetration characteristics inside the conductor and photonic crystal respectively.

Though many had worked on wave propagation through conducting materials of various types, we intend to look at the analysis of a ZnS thin film, a nanofilm with a real conductive value. To this end, EM wave within uv, visible and near infrared (NIR) was propagated through the thin film [4]. And the analysis was based on the use of general wave equation with the assumption that the film is not magnetic in nature. On this note, we considered a plane wave normal to the thin film and obtained the expression for the skin depth parameter as a factor to determine the depth of wave penetration into the thin film. Our analysis was extended to the reflection and transmission coefficients of the propagated wave.

2.0 Theoretical procedure

The complete system of equations that describe the propagation of EM waves in a conducting surface medium is enshrined in the Maxwell equation [15, 116].

As a result, we start here with general wave equation which is the tool to be used for the analysis in this work. Wave equation is second-order linear partial differential equation that describes the propagation of wave in various medium. The equation is given below as

$$\left[\nabla^2 - {}^{1}\!/\!{}_{c^2}\frac{\partial^2}{\partial t^2}\right]E = 0 \qquad (2.1)$$

for electric field

According to [10]

$$\left[\nabla^2 - {}^{1}\!/\!{}_{c^2}\frac{\partial^2}{\partial t^2}\right]B = 0 \qquad (2.2)$$

for magnetic field which is generally presented in the form

$$\nabla^2\psi(r) = \mu\sigma\frac{\partial\psi(r)}{\partial t} + \mu\varepsilon\frac{\partial^2\psi(r)}{\partial^2 t} \qquad (2.3)$$

This equation can be solved using various methods but in this work separation of variable was used. In this case we used ψ just as used in a general case after
transforming equation (2.3) as below

$$[\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}]\psi(r) \qquad (2.4)$$

in three dimensions wave equations.
Solving this equation using Cauchy boundary condition we have

$$\psi(r) = \exp i(k.r - \omega t) \qquad (2.5)$$

The solution to wave equation of (2.4) given as in equation (2.5) where β is the propagation constant of the thin film medium that is considered to be complex and makes the amplitude to decay over distance. Let $\beta = \beta + i\delta$, then

$$(\beta + i\delta)^2 = \beta^2 = \delta^2 + 2i\beta\delta \qquad (2.6)$$

If this is compared with parameters in equation (2.3), then

$$(\beta + i\delta)^2 = \beta^2 - \delta^2 + 2i\beta\delta = \mu\varepsilon\omega^2 + i\mu\sigma\omega \qquad (2.7)$$

$$\beta^2 - \delta^2 = \mu\varepsilon\omega^2 \text{ and } 2i\beta\delta = \mu\sigma\omega \qquad (2.8)$$

This implies that

$$\beta = \left[\frac{\mu\varepsilon\omega^2}{2}\left(1\sqrt{1 + \frac{\sigma^2}{\varepsilon^2\omega^2}}\right)\right]^{1/2} \qquad (2.9)$$

and also

$$\delta = \left[\frac{\mu\varepsilon\omega^2}{2}\left(1 + \sqrt{\frac{\sigma^2}{\varepsilon^2\omega^2}}\right) - 1\right]^{1/2} \qquad (2.10)$$

For a good conductor, σ f f $\varepsilon\omega$ and this implies that $\beta = \delta$. Thus considering equation (2.10)

$$\delta = \sqrt{\frac{\omega\mu\sigma}{2}} \qquad (2.11)$$

When this is inserted into the equation (2.5), it becomes

$$\psi(r) = \exp\delta z \exp i(\omega t - \beta z) \qquad (2.12$$

If *r*, is taken to be along the *z*-direction, δ is a parameter that relate to the skin depth of the thin film [11] as equation {2.11) is in *z*-direction. Where δ is the skin depth of the material thin film according to [11], and β is the wave number such that we have

$$\psi(z) = \exp\left[\sqrt{\frac{\omega\sigma\mu}{2}}\right] z \exp i(\omega t - \beta z) \qquad (2.13)$$

Equation (2.12) is decomposed into real, ψ(z) and imaginary, ϕ(z) parts of the field. Where σ is the conductivity of the thin film and for a non magnetic material, where $\mu = \mu_{0,}$ constant. This assumption enabled us to obtain expression for both reflected wave as

$$R = 1 - \frac{4\pi n\sigma}{\lambda} \qquad (2.14)$$

as it is well known that for a conductor σ << λ , the reflection coefficient approaches a unity. The transmission coefficient, *T* also becomes.

$$T = 1 - R = \frac{4\pi n\sigma}{\lambda} \qquad (2.15)$$

3.0 Result and discussion

The propagation of EM wave through a thin film is affected by the conducting nature of the thin film [5]. Figures 3.1a and 3.1b to Figure 3.6b explained how the conductivity of the thin film, σ gave rise to an exponential damping for uv visible and infrared regions as specified during the propagation. The penetration of the field inside the thin film medium decreases and falls to 1/ δ of the surface value in distance given in equation (2.11).

Since $2\pi/\beta \approx 1/\delta$ defines the attenuation length [1] *d* is the skin depth,

$$d = 1/\delta = \sqrt{\frac{2}{\omega\sigma\mu}}$$

This relation reveals that as σ and ω → ∞, δ→ zero, within the conductor. This then went on to suggest that good conductors are not easily penetrated by electromagnetic field which agree with what Wait presented on his work that electromagnetic wave incident normally on the surface in the *z*-direction of a conducting material has been observed to decrease [2]. For a good conductor, $\sigma << \varepsilon\, \omega$, implying that δ as given in equation 8 has a relation to wavelength as $2\pi/\beta = 1/\delta$ which contributed to the damping of the wave equation as presented in the graphs in figures 3.1 to 3.6. The graphs in figures 3.1a and 3.1b up to figures 3.6a and 3.6b depicted the field pattern for wavelength in visible, UV and near infrared regions as it propagates through the thin film with conductivity σ = 0.039 for both real and complex parts respectively.

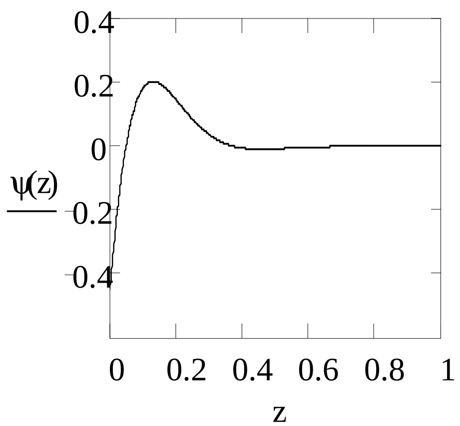

Figure 3.1a: Graph of the real part of the field ψ(z) against thickness for λ=0-5μm and σ =0.039

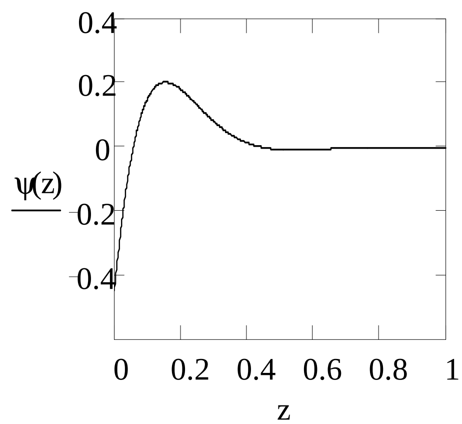

Figure 3.2a: Graph of the real part of the field ψ(z) against thickness for λ=0-7μm and σ = 0.039

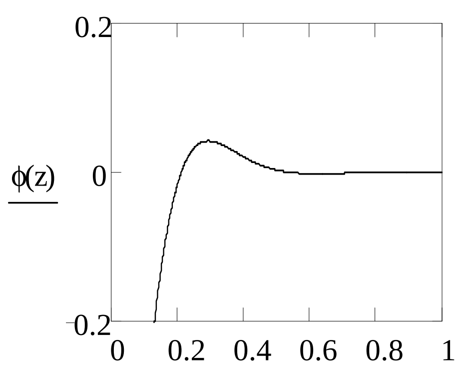

Figure 3.1b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=0-5μm and σ = 0.039

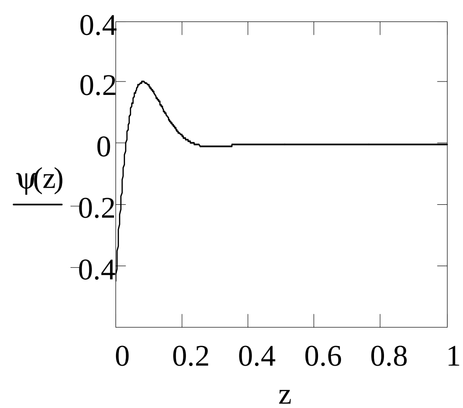

Figure 3..2b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=0-7μm and σ = 0.039

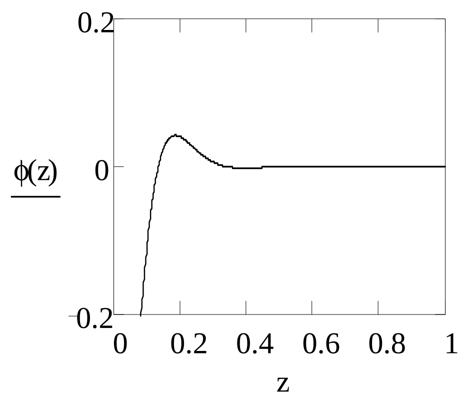

Figure 3.3a: Graph of the real part of the field ψ(z) against thickness for λ=0-2μm and σ = 0.039

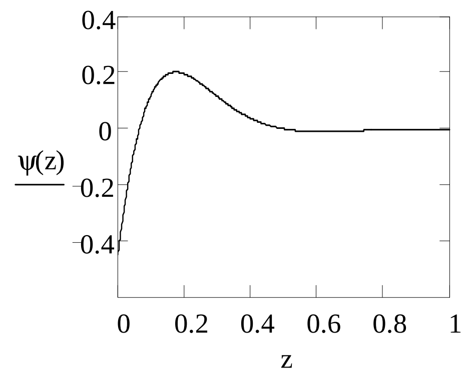

Figure 3.4b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=0-3μm and σ = 0.039

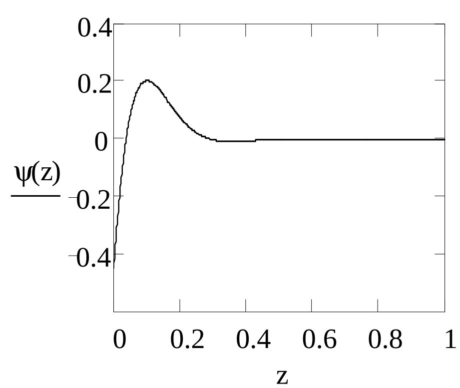

Figure 3.3b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=0-2μm and σ = 0.039

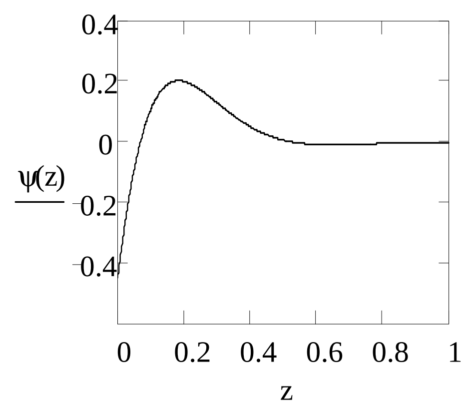

Figure 3.5a: Graph of the real part of the field ψ(z) against thickness for λ=0-9μm and σ = 0.039

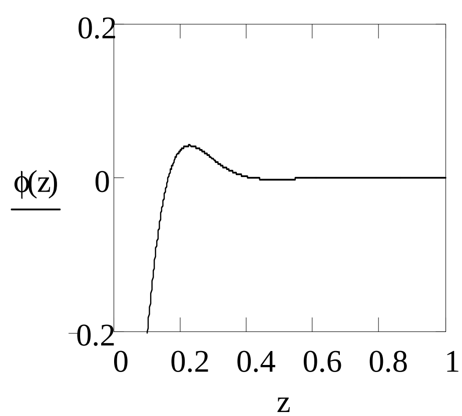

Figure 3.4a: Graph of the real part of the field ψ(z) against thickness for λ=0-3μm and σ = 0.039

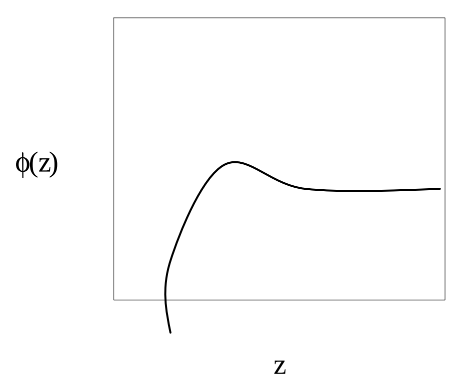

Figure 3.5b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=0-9sμm and σ = 0.039

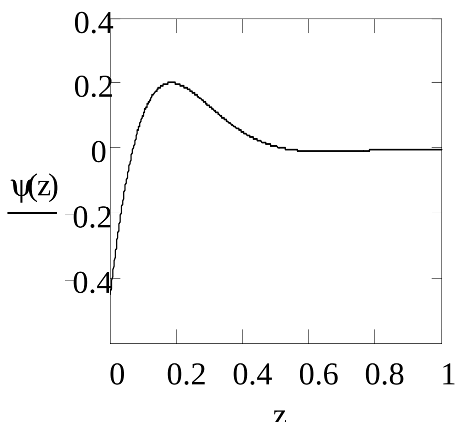

Figure 3.6a: Graph of the real part of the field ψ(z) against thickness for λ=1,6μm and σ = 0.039

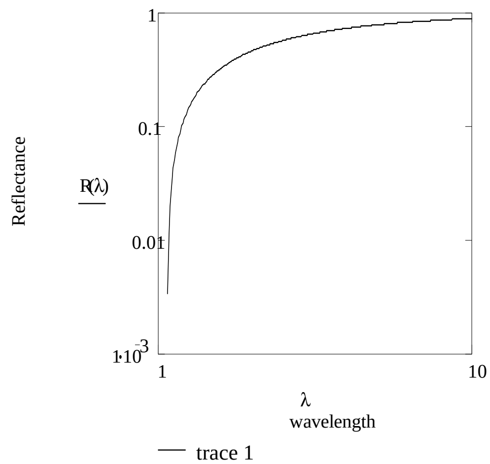

Figure 3.7: Graph of reflectance vs wavelength

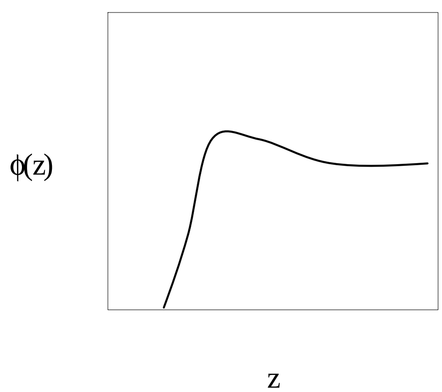

Figure 3.6b: Graph of the imaginary part of the field ϕ(z) against thickness for λ=1.0μm and σ = 0.039

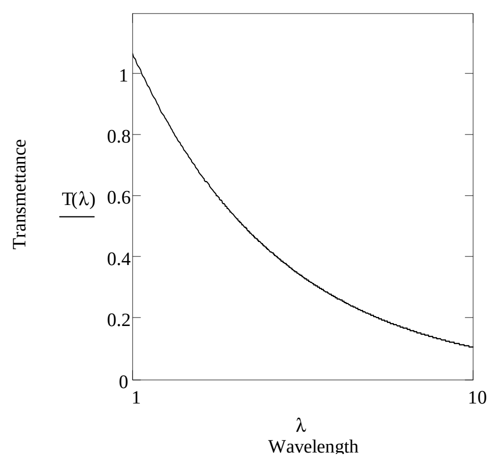

Figure 3.8: Graph of transmittance vs wavelength

The wave patterns appear to look alike with an indication of heavily damped oscillation. The damping behaviour as shown in the graphs for all the chosen region UV, visible and NIR both for the real and complex part are almost the same allowing only half oscillation with maximum amplitude of 0.2 followed by a heavy damping leading to zero oscillation. This result as seen in graphs presented in figure 3.1 to figure 3.6 decreases very sharply as a result of heavy damping of the propagated field through the thin film.

The reflected and transmitted waves are obtained by considering appropriately the correct matching of the boundary conditions that led to equations (2.10) and (2.11) respectively. The graphs of reflectance and transmittance are presented in figure 3.7 and figure 3.8. From figure 3.7, it is seen that the reflectance increases sharply to about 0.15 within UV range, and stabilized at 1.15microns and slightly increased to a unity as the wavelength approached 10 micron. On the other hand, the behaviour of the transmittance depicted exponential decay of the transmittance as the wave length approaches 10 micron. This suggests

that the transmitted wave through the thin film become absorbed at a given depth of penetration inside the material thin film. The computed reflectance and transmittance were seen to agree with the experimental reflectance and transmittance as obtained by [4] The reflectance of the thin film was found to be low within the visible and near infrared region where as the transmittance is high within the same range. From this result it is obvious that the thin film cannot be useful in anti–reflective coating.

4.0 Conclusion

In this work, the effect of conductivity of the ZnS thin film on electromagnetic wave propagation at a given conductivity was analyzed using wave equation as a tool. From the analysis, it was observed that the conductivity, σ introduced a damping for the propagated wave as shown in the graphs. The attenuation of electromagnetic wave is seen to be a function of the skin depth, δ as was observed from the plotted graphs. The penetration of the propagated wave was seen to decrease along the inside medium of the film with distance, δ which is the skin depth. The reflection and transmission co-efficient graphs showed that the reflection and transmission behaviour of wave propagated inside conducting material thin film is just like that of bulk material conductors. This behaviour suggests the fact that electromagnetic wave does not penetrate the conducting material thin film deeper than the skin depth.

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