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Study of the Relative Permittivity Response of Metal Nanoantenna at Optical Frequency

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Abstract: In this paper the relative permittivity response of some nanometals such as Gold (Au), Silver(Ag), Copper(Cu), Aluminum (Al) and Nickel(Ni) are investigated at optical frequencies. The permittivity response is necessary because the optical response of the metal nanoantenna highly depends on the permittivity of the metals. The surface plasma response largely depends on the permittivity response at optical frequency. This relative permittivity response also playsan important role in the design process of a nanoantenna. This paper represents the permittivity response at the frequency range of 20-300 THz (the wavelength range of 3-15 μm)..
Keywords: Nanoantenna, Relative permittivity, Surface Plasmon resonance,Optical frequency, Nanometal.

I. Introduction

In nanotechnology and antenna science, the antennas at optical frequency have opened up new area of research. Optical antennas and nanoscale metals have the ability to support plasmon resonances that interact with optical fields. The optical antennas can efficiently manipulate light by means of their optical properties such as concentration, absorption and radiation of light at nanoscale.The optical properties of a nanoantennadependson its size, geometry and material[1]. At optical frequencies under specific conditions, metals like gold, silver etc. can show electromagnetic resonances, when being excited by an incident light. These electromagnetic resonances are called surface plasmon resonances[2].In nanoantennas their dispersive permittivity allows for shrinking their size because using dielectric substrates with high permittivity reduces the size of antenna.The dispersive permittivity at optical frequencies should be taken into account as animportant parameter in design and characterization of nanoantennas. The surface plasmon resonance depends on the dispersive permittivity.The optical properties of most metal structures aresignificantly affected by the existence of surface plasmon resonances[3]. In the resonant characteristics of nano antennathe frequency dependent complex permittivity of plasmonic materials is one of the most critical parameters. This work shows the relative permittivity responses of Gold (Au), Silver(Ag), Copper(Cu), Aluminum (Al) and Nickel(Ni) at optical frequency.

II. Method

Over the past decade, intense effort has been made to observe the plasmonics of metallic nanoparticles. The optical properties of nanoantennas have been understood [14,15] . But the dielectric functions of metals at optical frequency have not been studied.The dielectric function, $\mathcal{E}(\omega)$, is determined by experimental methods or theoretical models like the Drude model, the Lorentz model, the Drude-Lorentz model, the Debye-Lorentz model etc. [1]. The Drude-Lorentz model is considered because it deals with both the bound and free electron. But the Drude model does not consider the bound electron caused by harmonic oscillator. So it is not applicable for all metals [11]. The prediction of the optical properties of a nanoparticle system depends on its frequency dependent dielectric function and its surrounding medium characteristics. It considers both the free electron contributions and harmonic oscillations caused by bound electrons[7].In this work, the complex permittivity of the used metal nanoparticles is described by the Drude-Lorentz model. In metals, due to the existence of both free electrons and bound electrons, anomalous optical properties during light scattering and absorption are observed. Due to this, their dispersive permittivity which determines their resonance characteristics at optical frequencies becomes important.The Drude-Lorentz model is a more precise method to describe the dispersion of different metal nanoparticles compared to the two other methods. Therefore, in this work, the Drude-Lorentz model that considers both free electrons contribution and bound electrons contribution is used as an efficient and precise model to describe the dielectric functions of metals. In order to investigate the frequency dependent radiation characteristics of the interested nanoantenna system, the dispersion of the plasmonic material (the frequency dependent dielectric function limits their conductivity) must be taken into account. So it is required to describe the frequency dependent complex permittivity of the interested metals at optical frequencies by means of a precise model like the classical Drude-Lorentz model[7].In Drude-Lorentz model, with the contribution of free electrons and harmonic oscillators the dielectric function can be defined as the following equation

$$\varepsilon(\omega) = \varepsilon_\infty - \underbrace{\frac{\omega_p^2}{\omega^2 + i\omega\gamma fe}}_{\text{Free Electron}} + \underbrace{\sum_{j=1}^{j} \frac{\omega_{pj}^2}{\omega_j^2 - \omega^2 - i\omega\gamma j}}_{\text{Harmonic Oscillator}} \qquad (1)$$

Where, $\varepsilon\infty$ is the relative permittivity at infinite frequency. Plasma frequency is ωp. The bound electrons in a metal nanoparticle contribute to harmonic oscillators and the dielectric function $\varepsilon\infty$ reflects both free electron contributions along with harmonic oscillator behavior. The Drude model contains only the free electoncontribution, no harmonic oscillation is considered here. If the second part of equation (1) is removed it becomes the drude formula.

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\gamma fe} \qquad (2)$$

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The Drude-Lorentz model is simulated with the MATLAB simulator to observe the permittivity response of the metals. The values used for the simulation are taken from the references [12-13]. The important values are listed below.

Metal	ωp	ω	γ
Au	176.7083026	0~260.659	1.037~43.326
Ag	76.3169221	0~67.96	0.939~47.337
Cu	211.932549	0~218.781	0.587~84.245
Al	293.1440058	0~67.963	0.93~66.182
Ni	311.5388901	0~119.155	0.939~123.128

III. RESULTS

The observation is donewithin the frequency range of 20-300 THz (The wavelength range of 3 to 15 μm). The relative permitivity responses at 20-300 THz (the wavelength range of 3-15 μm) are obseved from the MATLAB simulated curves. The combined permittivity response curve is given below.

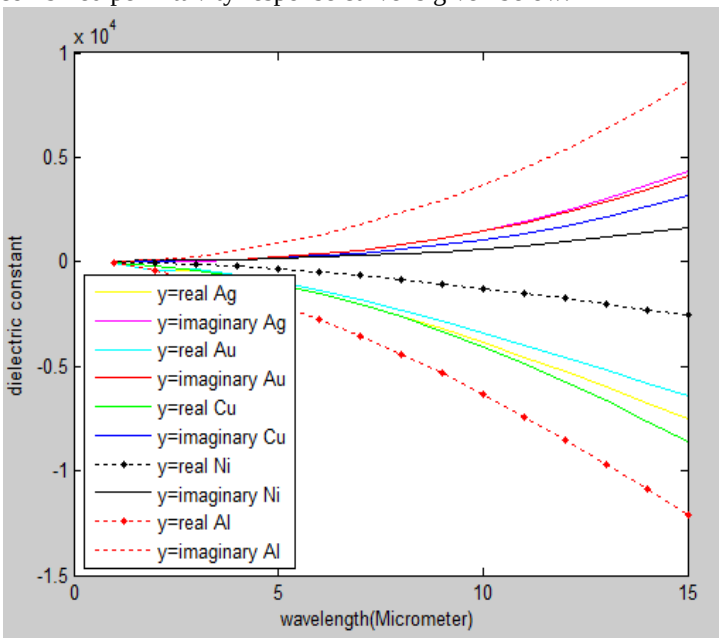

Figure 3.1: The dielectric functions for gold (Au), silver (Ag), copper (Cu), aluminium (Al) and nickel(Ni) at optical frequencies.

Figure 3.1 shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the metal dielectric function is negative due to free electron contributions.). Inter-band transition happens when the bound electrons in deeper bands are likely to be promoted into the conduction band. This phenomenon compared to free electrons contributions, plays a dominant role in changing the sign of the real part of $\mathcal{E}(\omega)$ to negative as shifting to high frequencies close to the resonance frequency. It should also be mentioned that, at the resonance frequency of a plasmonic structure, the imaginary part of the metal complex permittivity plays a dominant role in its absorption loss compared to other parameters such as the size and shape of the optical antenna [1].

The individual graphs of each metal is given below(with both the real and imaginary curves)

Figure 3.2 shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the Gold dielectric function is negative due to free electron contributions. The imaginary part gives positive response. The real part of gold shows large dispersion then other metals

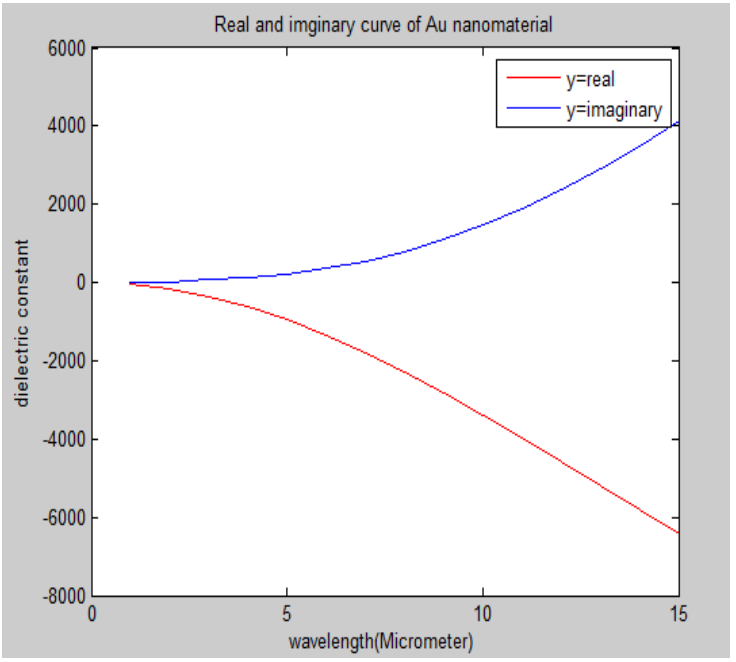

Figure 3.2: The dielectric functions for Gold at optical frequencies

Figure 3.3 shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the metal dielectric function is negative due to free electron contributions. The response of imaginary part is positive.

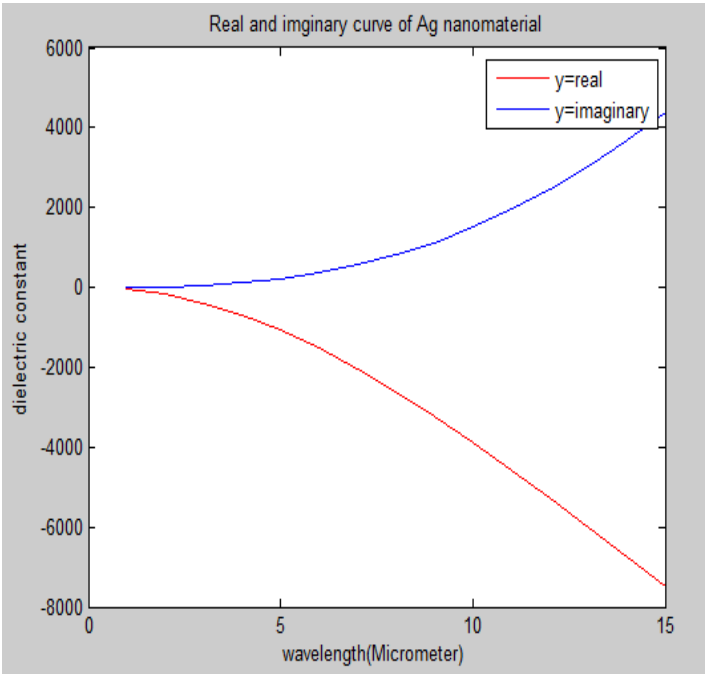

Figure 3.3: The dielectric functions for Silver at optical frequencies

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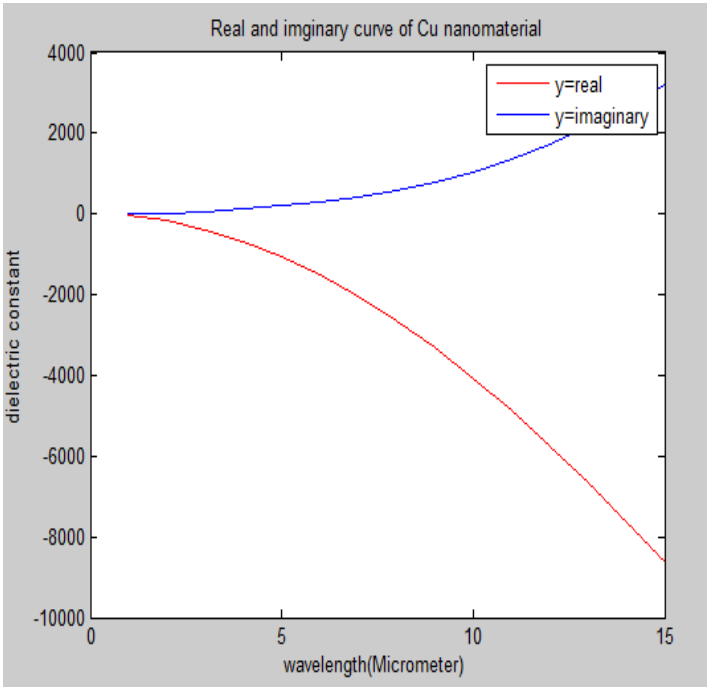

Figure 3.4: The dielectric functions for Copper at optical frequencies.

Figure 3.4 shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the metal dielectric function is negative due to free electron contributions. The imaginary part gives positive response.

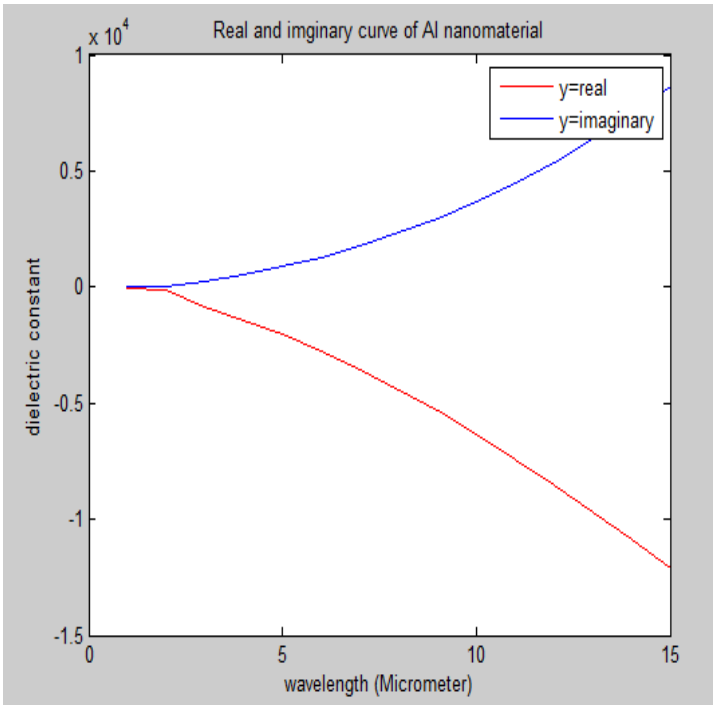

Figure 3.5: The dielectric functions for Aluminium at optical frequencies

Figure 3.5 shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the metal dielectric function is negative due to free electron contributions. The imaginary part gives positive response.

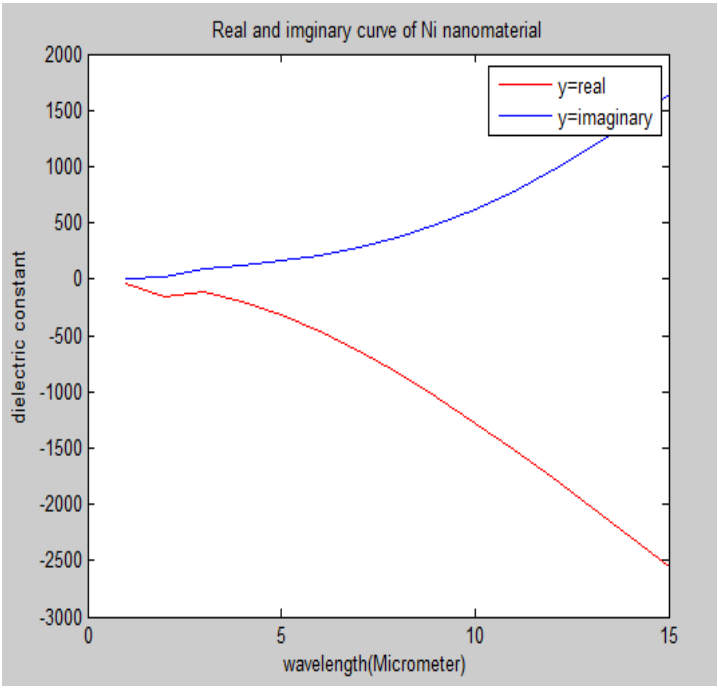

Figure 3.6: The dielectric functions for Nickel at optical frequencies.

Figure 3.6shows the complex permittivities of gold, silver, copper, aluminium and nickel. The real part of the metal dielectric function is negative due to free electron contributions. The imaginary part gives positive response.

IV. Conclusion

The negative part of$\mathcal{E}(\omega)$refers to high frequencies close to the resonance frequency. This work shows the relative permittivity response of metals at optical frequency. The imaginary part of the investigated metals are almost similar. But Gold metal has a larger real part of dielectric function than other metals. Therefore the Gold metal will get the best resonance frequency.

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