Metal type Effect on Plasmonic Fiber Properties

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Abstract
In this study, the properties of plasmonic fiber have been studied, in which the core is one of the noble metals \((Au,Ag,Cu,Al)\). The modes and the effective refractive index associated with each wavelength were derived using the COMSOL MULTIPHYSICS based on the Finite Element Method. The electrical permittivity was studied using the relationship Lorentz derode to determine the real part for the refractive index and the imaginary part responsible for the attenuation coefficient. Where a frequency range was chosen to hold negative values for the real part. The results show that when drawing the relationship between \((\varepsilon_r)\) or \((\varepsilon_i)\) a function of the wavelength that gold has the highest value and then silver, copper and then aluminum, but in the case of \((n_r)\) or \((n_i)\) we notice that aluminum has the highest elements.

\((n_{eff})\) has also drawn as a function of the wavelength, the four metals, and different of the core radius \((a= 100, 200, 300, 400, 500)\) for the three modes \((LP_{01}, LP_{11}, LP_{21})\) and the metal used. It is observed that increasing the mode index increases the lobes where the mode \((LP_{01})\) is one spot and the mode \((LP_{11})\) is two spot and the mode \((LP_{21})\) is four spot, where the power index increase is the increase in red and yellow color, and this applies to all modes. In other words, by controlling the radius of the core and wavelength, we can balance the ratio of power that propagation forward and backward. The refractive index (neff) has the highest value at small wavelengths and then begins to decrease with increasing wavelength, and has the highest value in the case of gold, then silver, then copper. Then aluminum, which is less than the rest of the elements.

Keywords: Nobel Metals, Plasmonic Fiber, Refractive Index, Permittivity.

1. Introduction
Plasmons are collective oscillations of electron densities that can be generated by a free electron gas interacting with \((EM)\) waves [1]. These special plasmons are then called plasma polaritons. The most prominent material group exhibiting such interactions are metals. Plasmonic vibrations inside a bulk volume of metal possess a special, material-
dependent resonance frequency. This plasma frequency \( \omega_p \) can be calculated with the Drude-Lorentz model and marks the optical frequencies at which a metal changes between transparent or reflective behavior [2].

2. Basic Formalism and Software

To describe light in a waveguide, we solve a wave equation in each region (core and cladding) for both the electric field and the magnetic field. We are interested in traveling plane-wave solutions. As the permittivity of the core are complex functions, so too is the propagation constant \( \beta = \beta' + i\beta'' \) with \( \beta'' \) the attenuation per unit length for a propagating field and \( \beta' \) the propagation wavenumber. Both \( \beta' \) and \( \beta'' \) are real, and \( \beta'' > 0 \). A negative value for \( \beta'' \) implies the material is active (exhibits gain) whereas negative \( \beta' \) corresponds to fields propagating in the negative x-direction. The permittivity of the metal must be complex-valued and are denoted \( \varepsilon = \varepsilon' + i\varepsilon'' \), where \( \varepsilon' \) is the real part which is negative and \( \varepsilon'' \) is the imaginary part. The expressions for \( \varepsilon \) are determined by how models are constructed [3].

The obvious difference between the optical responses of metals and dielectrics enables them to be fundamental elements for designing plasmonic devices. In plasmonic optics, metals are incorporated into nanostructures for the emerging characteristics of the SPPs and other light matter interactions. Both bound electrons and free ones contribute to the optical properties of a general metallic medium. Therefore, the resembling complex dielectric permittivity contains both the Drude component for the intraband effect and the Lorentz term for the interband transition in the form of the Drude–Lorentz model [4]

\[
\varepsilon_r(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega} + \sum_i \frac{f_i \omega_i^2}{\omega_i^2 - \omega^2 - i\gamma_i \omega} \ldots \ldots \ldots (1)
\]

It is noteworthy that, within noble metals, there are usually multiple interband transitions due to the various band structures of bound electrons. Optimal values of typical metals for the Drude–Lorentz model are listed in table (1). These metals have been frequently used in optoelectronic devices.

A surface Plasmon polariton (SPP) wave is a guided wave along the interface of a metal film or a metal substrate and a surrounding dielectric material [5]. This type of wave is formed by the coupling of an electromagnetic wave to oscillating free electrons at the surface
of a conductor. Typically, the material property of a nonmagnetic metallic film that enables the existence of a SPP wave is characterized by a permittivity in Eq.(1) and permeability $\mu_o$. 

At optical frequencies, i.e. $w^2 + \gamma^2 < w_p^2$ for most metal, making the real part of $(\varepsilon_r)$ a negative value. This negative real part of permittivity of the metal and the positive real part of the surrounding dielectric are crucial in allowing the existence of the ($SPP$) wave at the interface [6].

3. Results and Discussion

The results include four types of (plasmonic fiber) where noble metals ($Au, Ag, Cu, Al$) were used to calculate electrical permittivity ($\varepsilon$) and for each element the equation (1) and the values in the table (1) were used and the coefficient of Refraction is calculated from $n = \sqrt{\varepsilon}$ considering that the material is not magnetic ($\mu = 1$). After that, in order to calculate the modes, a COMSOL program was used.

COMSOL MULTIPHYSICS (4.5) is a commercial application which depending on the Finite Element Method ($FEM$) [7]. This software includes many physical models and a design window using Computer Aided Draw ($CAD$) for structured design, mesh generator, internal matrix assembler, various numerical solvers for matrices, and several post-processing features [8].

($FEM$) is a method to solve differential or partial equations numerically involve depending on dividing the physical systems, such as structures, solid or fluid continua, into small sub regions or elements [9]. Each element is an essentially simple unit, the behavior of which can be readily analyzed. The complexities of the overall systems are accommodated by using large numbers of elements, rather than by resorting to the sophisticated mathematics required by many analytical solutions. One of the main attractions of finite element methods is the ease with which they can be applied to problems involving geometrically complicated systems. The price that must be paid for flexibility and simplicity of individual elements is in the amount of numerical computation required. Very large sets of simultaneous algebraic equations have to be solved, and this can only be done economically with the aid of digital computers [10].
Table(1): parameter values for the Drude-Lorentz model [11].

| Parameters | Ag  | Au  | Cu  | Al  |
|------------|-----|-----|-----|-----|
| $f_0$      | 0.845 | 0.760 | 0.575 | 0.523 |
| $\gamma_d$ | 0.048 | 0.053 | 0.030 | 0.047 |
| $f_1$      | 0.065 | 0.024 | 0.061 | 0.227 |
| $\gamma_1$ (eV) | 3.886 | 0.241 | 0.378 | 0.333 |
| $\omega_1$ (eV) | 0.816 | 0.415 | 0.291 | 0.162 |
| $f_2$      | 0.124 | 0.010 | 0.104 | 0.050 |
| $\gamma_2$ | 0.452 | 0.345 | 1.056 | 0.312 |
| $\omega_2$ | 4.481 | 0.830 | 2.957 | 1.544 |
| $f_3$      | 0.011 | 0.071 | 0.723 | 0.166 |
| $\gamma_3$ | 0.065 | 0.870 | 3.213 | 1.351 |
| $\omega_3$ | 8.185 | 2.969 | 5.300 | 1.808 |
| $f_4$      | 0.840 | 0.601 | 0.638 | 0.030 |
| $\gamma_4$ | 0.916 | 2.494 | 4.305 | 3.382 |
| $\omega_4$ | 9.083 | 4.304 | 11.18 | 3.473 |
| $f_5$      | 5.646 | 4.384 | —    | —    |
| $\Gamma_5$ | 2.419 | 2.214 | —    | —    |
| $\omega_5$ | 20.29 | 13.32 | —    | —    |

3.1 Permittivity of Nobel Metals

Figure (1) represents the relationship between ($\varepsilon_r, \varepsilon_i$) with the wavelength of the elements (Au, Ag, Cu, Al) is drawn. The plasmonic property is related to ($\varepsilon_r$), and we see from the figure that gold has the highest value, followed by silver, copper, and aluminum. In general, we see that ($\varepsilon_r$) decreases with increasing wavelength, and that the aluminum component is far away from its properties by other properties. We know that the attenuation factor correlates with the imaginary section ($\varepsilon_i$) and we see from the figure ($\varepsilon_i$ as a function to $\lambda$), the most valuable metal is aluminum and the least copper is in gold and silver are identical in the values of ($\lambda < 0.5$) but at the values of ($\lambda > 0.5$) we notice the superiority Gold on the elements, then copper, then silver, and finally aluminum, we see here a difference in this behavior. Figure (2) represents the relationship ($n_r, n_i$) with the wavelength of the elements (Au, Ag, Cu, Al). When drawing ($n_r$ as a function to $\lambda$), we see that the elements (Au, Ag) are of great value at the small ($\lambda$) Very unlike copper, aluminum exceeded silver and then gold. As the wavelength increases, we notice that all elements (Au, Ag, Cu, Al) will have an approximate minimum value of $m\mu$ ($\lambda=0.5$) and then start to increase again. With the continuation of the increase ($\lambda$), aluminum will outperform other elements, and this leads to a difference in the visual characteristics of the models used. Concerning the imaginary part ($n_i$ as a function of $\lambda$), it is clear that aluminum is the highest component of all values ($\lambda$),
followed by copper, noting that gold is higher than silver at (\( \lambda < 0.5 \)), and they agree roughly at the values of (0.5 < \( \lambda < 1 \)). The values of \( m\mu (\lambda > 1) \) are silver and copper agree, then gold.

![Fig.(1): real and imaginary parts of Relative permittivity as a function of wavelength for the metals (Au, Ag, Cu, Al).](image1)

![Fig.(2): real and imaginary parts of refractive index as a function of wavelength for the metals (Au, Ag, Cu, Al).](image2)

### 3.2 Plasmonic Fiber Modes

Figures (3) to (5) represent different samples of modes of lower index (\( LP_{01}, LP_{11}, LP_{21} \)) using different values of the radius core and wavelength and metal used. We see from Figure (3) which is related to the gold element at the radius of 500 (nm) and wavelengths (\( \lambda = 1000, 1500, 2000 \)) nm, The increase of the mode index increases the lobes, where the mode (\( LP_{01} \)) is one spot and the mode (\( LP_{11} \)) is two-spot and the mode (\( LP_{21} \)) is four spot. The difference here when using a normal fiber is that the core does not show details...
of the mode and this is why it is used (metal core). It can be seen that the ratio of energy outside (core) increases with increasing (λ). As the energy increase indicator is red and yellow. This applies to all modes. In other words, controlling the radius of the core and the wavelength we can balance the ratio of the power that propagates forward and backward, and even stopping the light can be achieved. From the observation of Figure (4) which concerns (Ag) at (a = 200) nm, the same above observations apply here except that the size of the mode spot decreases with decreases (a). Figure (5) represents a copper element with a wavelength of (1500) nm using different radii, and it shows that the size of the pattern spot increases with (a) and this includes all the ranks of the pattern. Here, we can say that different (a) means different conditions for the type of propagation.

Fig.(3): selected samples of modes for Au at a=500 nm for the wavelengths (λ=1000, 1500, 2000) nm.
Fig. (4): selected samples of modes for 

\( Ag \) at \( a=200 \) nm for the wavelengths \( (\lambda=1000, 1500, 2000) \) nm.

Fig. (5): selected samples of modes for 

\( Cu \) at \( \lambda=1500 \) nm for the radius \( (a=100, 200, 300, 400, 500) \) nm.

3.3 Core Radius Effects

Figures (6) to (8) represent the relationship between \( n_{eff} \) as a function to \( (\lambda) \) for different elements \( (Au, Ag, Cu, Al) \) and different half-diameters \( (a = 100, 200, 300, 400, 500) \) and patterns \( (LP_{01}, LP_{11}, LP_{21}) \) in order. In the three figures, we notice that the refractive index \( (n_{eff}) \) has the highest value at small wavelengths and then begins to decrease with increasing wavelength, as it was observed that \( (n_{eff}) \) in all the values of \( (a) \) and for the two cases \( (LP_{01}) \) and \( (LP_{11}) \) have the highest value in the case Gold, then silver, copper, and
finally aluminum. As for \((LP_{21})\), we notice that \((n_{eff})\) in all \((a)\) values have almost equal values in the case of all four elements.

Figure (6) shows the relationship in the case of pattern \((LP_{01})\), and has the highest value in the case of the radius of the heart nm \((a = 100)\) and then the following \((200)\) then \((300)\) then \((400)\) then \((500)\) which are almost identical. Then, \((n_{eff})\) in \((a = 300)\) corresponds to \((400, 500)\) at the wavelength \((\lambda = 1400)\) in all elements.

As for the form (7) that represents the relationship in the case of pattern \((LP_{11})\), and has the highest value in the case of the radius of the heart nm \((a = 500)\) then \((400)\) then \((300)\) and then \((200)\) and finally \((100)\), and note \((n_{eff})\) in the case of \((a = 300)\) and \((500)\) in the case of the element gold, silver and copper are almost identical at the wavelength \((\lambda = 1000)\) and is identical \((n_{eff})\) in the case of \((a = 300, 400)\) in the case of the aluminum element.

Figure (8), which represents the relationship in the case of mode \((LP_{21})\). And it has the highest value in the case of the radius of the heart nm \((a = 500)\) then \((400)\) then \((300)\) and then \((200)\) and finally \((100)\), and we note the matching \((n_{eff})\) in almost all the values of \((a)\) and gradually in the case \((\lambda < 1600)\) Then they differ a little later and the match remains in the state of \((a = 300, 200)\) approximately, except that \((Al)\) it moves away from them completely from the beginning and increases differently at \((\lambda = 1700)\) nm. It is also noted that \((n_{eff})\) in all values of \((a)\) have almost equal values in the case of all four elements.

Figures (9) to (13) represent \((n_{eff})\) as a function of \((\lambda)\) using the three modes \(LP_{01}, LP_{11}, LP_{21}\) and various elements \((Au, Ag, Cu, Al)\) for the radii \((100, 200, 300, 400, 500)\) In order. Figure (9) shows the relationship in the case of the radius core \((a = 500)\) nm, where we notice from the figure in the case of the mode \((LP_{01})\) that the refractive index \((n_{eff})\) has the highest value at small wavelengths and then begins to decrease with increasing wavelength, and has a higher value in the case of the element of gold, then silver, then copper, and aluminum, the least of which is at a wavelength \((\lambda > 1400)\). We note that silver and copper are almost identical. We also notice that \((Al)\) is one less than the rest of the elements. This is the same thing in the case of the mode \((LP_{11})\) and the mode \((LP_{21})\), but in the case of the mode \((LP_{11})\), we note the match of gold, silver, and copper at \((\lambda > 1200)\) and in the case of the mode \((LP_{21})\) then we notice in this case that the refractive index \((n_{eff})\) Gold, silver, and copper are almost identical from the beginning, and \((Al)\) in the three types of patterns remains aloof, and the lowest of them is in the mode state \((LP_{01})\) \((n_{eff})\) has the
highest value of all elements in the case of mode \((LP_{01})\), then the mode follows \((LP_{11})\) and then \((LP_{21})\).

As for Figure (10), the relationship is shown in the case of the radius core of \((a = 400)\) nm, as it is similar to Figure (9). Figure (11) shows the relationship in the case of the radius core \((a = 300)\) nm as it is similar to the figure (9). However, in the case of the mode \((LP_{21})\), the refractive index \((n_{eff})\) \((Au, Ag, Cu)\) is almost identical from the beginning, except that the element \((Al)\) at \((\lambda > 1100)\) corresponds to the rest of the elements. As for Figure (12), it shows the relationship in the case of the radius core \((a = 200)\) nm, where we notice a similar mode to figure (9), but in the case of the mode \((LP_{11})\), the refractive index \((n_{eff})\) \((Au, Ag, Cu)\) are identical from the beginning, \((Al)\) so it will be a little less. Figure (13) shows the relationship at the radius core \((a = 100)\) nm, where we also notice a similar shape to (9), but in the case of the pattern \((LP_{21})\), the refractive index \((n_{eff})\) of all elements is exactly the same from the beginning, and we notice a wavelength. \((\lambda > 1800)\) The deviation of the curves from its primitive path and \((n_{eff})\) of \((Cu)\) is less than one of the elements.

![Fig.(6): \((n_{eff})\) as a function of \(\lambda\) for \((LP_{01})\) mode using different elements and radii.](image)
Fig.(7): \(n_{\text{eff}}\) as a function of \(\lambda\) for \((L_{P11})\) mode using different elements and radii.

Fig.(8): \(n_{\text{eff}}\) as a function of \(\lambda\) for \((L_{P21})\) mode using different elements and radii.
Fig(9): represent \( n_{\text{eff}} \) as a function of \( (\lambda) \) using the three modes \( (LP_{01}, LP_{11}, LP_{21}) \) and various elements \( (Au, Ag, Cu, Al) \) for the radii \((a= 500)\).

Fig(10): represent \( n_{\text{eff}} \) as a function of \( (\lambda) \) using the three modes \( (LP_{01}, LP_{11}, LP_{21}) \) and various elements \( (Au, Ag, Cu, Al) \) for the radii \((a= 400)\).
Fig(11): represent \( \text{n}_{\text{eff}} \) as a function of \( \lambda \) using the three modes \( \text{LP}_{01}, \text{LP}_{11}, \text{LP}_{21} \) and various elements (Au, Ag, Cu, Al) for the radii \( a = 300 \).

Fig(12): represent \( \text{n}_{\text{eff}} \) as a function of \( \lambda \) using the three modes \( \text{LP}_{01}, \text{LP}_{11}, \text{LP}_{21} \) and various elements (Au, Ag, Cu, Al) for the radii \( a = 200 \).
Fig(13): represent \( n_{eff} \) as a function of \( \lambda \) using the three modes \( (LP_{01}, LP_{11}, LP_{21}) \) and various elements \( (Au, Ag, Cu, Al) \) for the radii \( (a=100) \).

4. Conclusions

As a conclusion: the plasmonic property is related to \( (\varepsilon_r) \), and it was noted that gold possesses the highest value and hence silver, copper and aluminum, and that \( (\varepsilon_r) \), decreases with increasing wavelength. The attenuation factor is related to \( (\varepsilon_i) \), and it is noted that aluminum has the highest value and that copper has the lowest value. The true portion of the refractive index of gold and silver has the highest value at small wavelengths, while the imaginary part of aluminum has the highest value. Controlling the radius of the heart and the wavelength, we can balance the ratio of the power that propagates forward and backward, that is, the difference \( (a) \) means different control conditions with the type of propagation.

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