Plasmonics in Optical Communications: Optimization of Coupling Efficiency

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***Abstract*—Modern optical communications technology requires miniaturization of the end equipment to micro- and even nanoscale. At this scale, interaction of light with this equipment becomes difficult due to diffraction limit. This problem can be solved by the use of plasmonics, which confines light into subwavelength dimension and, additionally, create a strong field enhancement. One of the major plasmonic problems for our application is the efficiency of coupling of light into a metal-dielectric interface, which is mainly determined by the properties of a metal. In this paper, we presenting the results of our search for an optimal (ideal) metal whose properties provide the best coupling efficiency at 1550nm — the main transmission wavelength in optical communications.**

Keywords- Optical communications; plasmonics; coupling efficiency

I. INTRODUCTION

The volume of global telecommunications traffic keeps increasing at the exponential rate and to carry this traffic, the optical networks, which deliver the vast majority of it, exponentially increase its transmission capacity. One of the major technological means to achieve this increase is wavelength-division multiplexing (WDM), in which many transmitters and receivers are used to send and receive many signals over a single optical fiber. Modern WDM technology, however, requires such density of packaging of all components that these components must be in micro- and even nanoscale. Working with light at this scale becomes problematic due to the diffraction limit, the problem that can be overcome by the use of plasmonics.

Plasmonics [1],[2] is about coupling of photons to free electron oscillations at the interface between the thin film of a conductor and a dielectric. This coupling creates two-dimensional electromagnetic waves called surface plasmon polaritons (SPPs) that propagate along this interface. The result is confinement of light into subwavelength dimension, which enables breaking the diffraction limit and creating a strong field enhancement.

Plasmonics has the potential to combine the best properties of both electronic and photonic worlds; in addition, plasmonics allows for reducing light manipulation from three to two dimensions. All these features might lead to creation of integrated photonic circuits, in which optical communications is in dire need.

From the optical-communications standpoint, the most important feature of plasmonics is that the SPPs can be seen as a new optical carrier of information that allows signal manipulation at the scale below diffraction limit. This is why application of plasmonics in optical communications has attracted a significant interest of a research community [3]–[5]. One of the main problems of application of plasmonics in optical communications is the efficiency of coupling of light into a metal because of tremendous loss that light experiences in a metal film. Clearly, the coupling efficiency shapes the total efficiency of any plasmonic device. The coupling efficiency is determined by the properties of the metal; for visible light, which is mostly used in current research, the best coupling has been achieved with silver and gold due to their beneficial permittivity in this range of wavelengths. Optical communications, however, operates in infrared segment of the spectrum, and the range of wavelengths around 1550nm is most widely used. There are no experimental or theoretical results indicating which metal could provide the optimum coupling in this range. In this work, we present the results of our search for an optimal material providing the best possible coupling efficiency at 1550nm.

The rest of this paper is organized as follows: In Section II, we evaluate the coupling efficiency of the metals mostly used in plasmonics and find their optimal thickness; in Section III, we apply Occam inversion method to find the most efficient optimal material; in Section IV, we present the summary and directions of the future work.

II. COUPLING EFFICIENCY AND OPTIMAL THICKNESS OF AL, CU, PB, AU, AND AG

In this section, we investigate plasmonic properties of Al, Cu, Pb, Au and Ag, the metals mostly used in experimental research. Some of their properties have been studied for visible light; we, however, need to know these properties at the main transmission wavelength of optical communications, λ = 1550nm.

Figure 1 illustrates how light is coupled at the metal-dielectric interface; to optimize this process, we need to achieve the maximum penetration of light from the outside (not shown) material into a metal and obtain the maximum energy of the filed penetrated into a dielectric. Penetration of light into the metal is evaluated by reflection and transmission coefficients; the latter determines the strength of a resonance field, the field penetrated into a dielectric. This strength is crucial because it determines the length the excited light can propagate within the dielectric, which in turn determines the efficiency of the whole plasmonic process in our application.

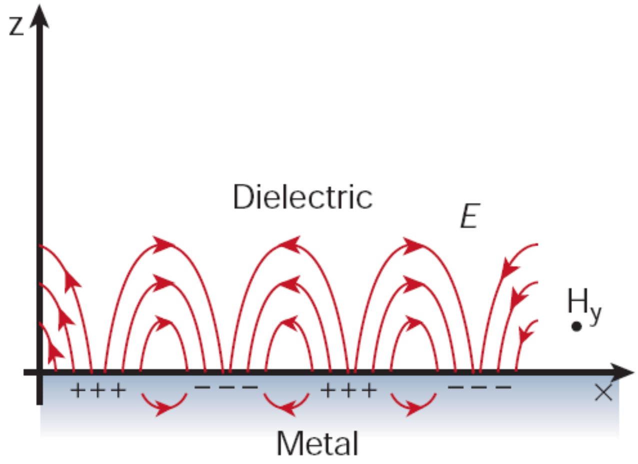

Figure 1. Coupling of light in plasmonics: Electron charges and excited electric waves. (Reprinted with permission [6])

In this section, we consider the setup composed from three media: glass-metal-air. The refractive indexes of glass and air are given by $n_g = 1.5$ and $n_a = 1$, respectively. For this setup we determine the coupling efficiency by finding the reflection and transmission coefficients for arbitrary thickness of each metal. Analysis of these results leads us to the necessity of search of optimal thickness of a metal, which we do as follows.

The Drude model [7] defines dielectric function of free electron plasma and the electric permittivity, ε, of a metal to the optical response as

$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\omega_\tau} \tag{1}$$

where ω_p is the plasma, ω is the incident, and ω_τ is the damping frequencies and ε_∞ is the high-frequency dielectric constant. Using the values of plasma frequency and damping factor from the study conducted by Ordel [7], we calculate the electric permittivity of each metal at λ = 1550nm; the results are shown in Table I.

Using Maxwell's equations and appropriate boundary conditions for our setup, one can derive the formulas (Equations 2, 3 and 4 [2]) that allow for evaluation of reflection and transmission of each metal as a function of incident angle.

TABLE I. ELECTRIC PERMITIVITY OF ALUMINUM, COPPER, LEAD, GOLD AND SILVER

Material	**Permittivity at 1550nm**
Al	-335.83+33.779i
Cu	-96.6111 + 4.2061i
Pb	-91.3055 + 2.0746i
Au	-125.14+4.2232i
Ag	-125.22+2.8367i

$$R_{gm} = \frac{\varepsilon_m k_g(\theta_g) - \varepsilon_g k_m(\theta_g)}{\varepsilon_m k_g(\theta_g) + \varepsilon_g k_m(\theta_g)} \tag{2}$$

$$R_{ma} = \frac{\varepsilon_a k_m(\theta_g) - \varepsilon_m k_a(\theta_g)}{\varepsilon_a k_m(\theta_g) + \varepsilon_m k_a(\theta_g)} \tag{3}$$

$$R_{gma} = \frac{R_{gm} + R_{ma}\exp(i2k_m d_m)}{1 + R_{gm}R_{ma}\exp(i\,2k_m d_m)}, \tag{4}$$

where $\varepsilon_g, \varepsilon_{m,}\varepsilon_a$ are the electric permittivity's of glass, metal and air, respectively; $k_g, k_{m,}k_a$ are the wave numbers of glass, metal, and air; d_m is the metal thickness. We have taken electric permittivity of each metal from Table 1 and perform simulations.

Plots in Figure 2 present the results of our calculations of reflection and transmission coefficients of all mentioned metals at arbitrary 55nm thickness for each of them. Our results show that the thickness of a metal is the second major factor determining the coupling efficiency. We investigated this factor for each material; the samples of such a search for gold are shown in Figures 3 and 4. This example shows that the minimum reflection and the maximum transmission for gold are achieved at 35nm.

Based on the results of our search, we calculated the reflection and transmission coefficients for each metal at their appropriate optimal thickness. Figure 5 show the coupling efficiency of 70% for aluminum at 20nm thickness, 100% for copper at 40nm thickness, 95% for lead at 48nm thickness, 95% for gold at 34nm thickness, and 80% for silver at 32nm thickness.

Comparison of the intensity of the field penetrated into a dielectric (see Figure 5, transmission) shows that the strength of a penetrated field varies significantly for each metal; for example, silver exhibits the strongest resonance field, 375 a.u., at slightly less than 80% coupling (Figure 5, reflection), whereas lead exhibits 100% of coupling, but its resonance field is only 25 a.u. strong. Therefore, when searching a metal, which provides the best coupling, we need to consider its reflection and transmission coefficients at its optimal thickness. Only combination of all three parameters provides the optimal coupling efficiency evaluated by reflection, transmission, and the strength of resonance (penetrated) field.

The summary of these results are presented in Table II.

TABLE II. STRENGTH OF A PENETRATED FIELD FOR ALUMINUM, COPPER, LEAD, GOLD AND SILVER

Material	**Thickness**	**Field Strength**	**Coupling**
Al	20nm	20a.u.	70%
Cu	40nm	55a.u.	100%
Pb	48nm	60a.u.	95%
Au	34nm	120a.u	95%
Ag	32nm	375a.u.	80%

III. OCCAM INVERSION AND IDEAL (DESIRED) MATERIAL

In this section, we describe our search of electric permittivity of an ideal material that has high coupling ratio and generates strong resonances on its surface due to the incident radiation at 1550nm. We consider the setup composed from three media, as in the previous section, but instead of the metal we place an ideal material. Using Occam inversion technique [8] and Maxwell's equation with appropriate boundary conditions, we can calculate electric permittivity of a material that generates high resonances on its surface and satisfies above criteria: 100% coupling and long range propagation of excited field.

Occam inversion algorithm, (5), searches for optimal electric permittivity by employing angular scattering, R_{gma}, (4). The algorithm minimizes the difference between the modeled, R_{gma}, and a desired scattering pattern. With each iteration, the obtained solution, ε^{k+1}, is closer to the optimal permittivity; the process stops when the difference between the obtained and previous solutions becomes less than 10^{-9}. Desired scattering pattern exhibits 100% coupling at a given metal thickness. For these calculations we use least-squares method and assume 65nm metal thickness.

$$\varepsilon^{k+1} = [J(\varepsilon^k)^T J(\varepsilon^k) + \alpha^2 L^T L]^{-1} J(\varepsilon^k)^T R. \qquad (5)$$

Here $J(\varepsilon^k)$ is the Jacobian of $G(\varepsilon^k)$, L - laplacian operator, α is the regularization parameter, and R is the desired reflection pattern. Using initial estimation ε^0, which can be arbitrarily chosen, we found the following ideal permittivity

$$\varepsilon_{ideal} = -121.677 + 0.5243019\mathrm{i}\ . \qquad (6)$$

It is worth mentioning that choosing the initial estimation, ε^0, closer to the perfect value will essentially reduce the number of iterations and minimize the simulation process.

Reflection and transmission patterns of an ideal material at thickness 65nm and that of Ag and Pb at their optimal thicknesses plotted in Figure 6. Ag and Pb are chosen as control metals to contrast reflected and transmitted patterns of the optimal material; Ag has highest transmitted patterns at optimal thickness and Pb requires larger thickness for optimal coupling.

The optimal material shows the maximum coupling (0% reflection), but very weak penetrated field, about ten times smaller than that of silver. Thus, there is a need to optimize the thickness of this metal. The results of this search are presented in Figures 7 and 8, where we plot all reflection and transmission coefficients of above mentioned metals at 55nm thickness (Figure 7) and at 35nm thickness (Figure 8). One can clearly see that at 55nm an optimal material has about 85% of coupling efficiency but the strength of penetrated field is only 160 a.u., whereas at 35nm this material exhibits almost 7000 a.u. of the resonance field at the expense of coupling, which is reduced to 30%. Thus, these two processes contradict each other. Recalling that for ideal material we need 100% of coupling (0% of reflection) and the highest energy of penetrated field (e.g., 10,000 a.u.) to provide the longest propagation of the excited field in a dielectric, we come to the conclusion that required optimization is not an easy task.

IV. SUMMARY AND CONCLUSION

We can summarize the results presented in this paper as follows:

1. We have found out the reflection coefficients, the strengths of resonance fields and optimal thickness of a set of natural metals widely used in plasmonics. To our knowledge, we did this the first time at λ = 1550nm, the main transmission wavelength in optical communications. The importance of these results cannot be overestimated they have determined the fundamental limitations imposed on the application of these metals in plasmonic devices in optical communications.
2. We have searched for the desired (optimal) material, which could provide the optimal coupling efficiency. We have determined its desired characteristics+, such as electric permittivity, reflection coefficient and the strength of a resonance field; we have proven that this material could achieve the increase of the strength of its field by an order of magnitude at 1550nm , as compared with Ag and Pb.

Our results lead us to the following directions of the future work:

1. Considering the characteristics of the desired (optimal) material, we note that the real part of its electric permittivity is close to that of silver and gold, but its imaginary part is tenfold less than the proper parts of these natural metals. It means that such a desired (optimal) material does not exist in nature and we need to artificially create a material with the required electric permittivity. This is one direction of the future work.
2. Our simulations have shown that the requirements of simultaneously maximizing both the coupling and the strength of penetrated field contradict each other. Therefore, we need to either optimize the properties of the desired material or find the different approach

to satisfy these mutually contradictory requirements. This work would be the other direction of our future research.

3. We will need to find out how our desired (optimal) material would work not only at a single 1550nm wavelength, but also in both C- and L-bands used in modern DWDM optical transmission networks.

ACKNOWLEDGMENT

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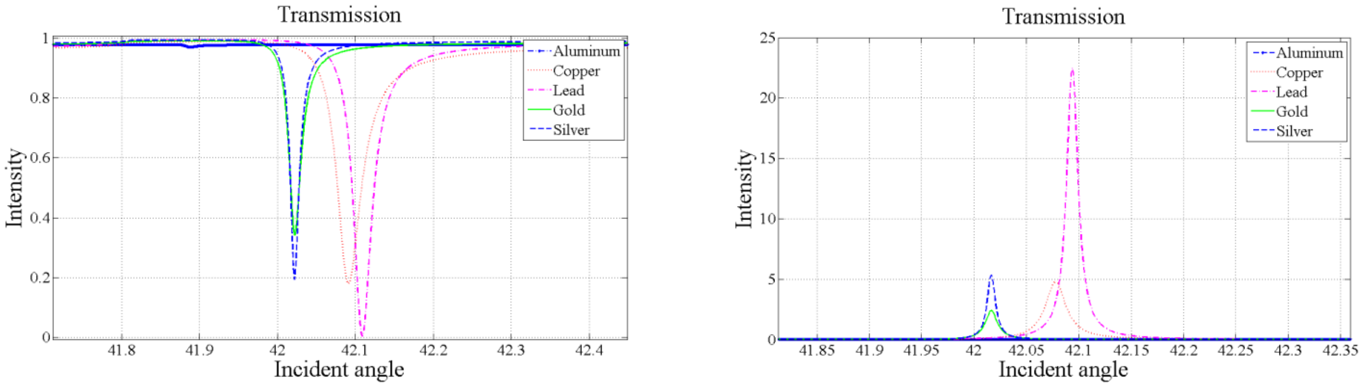

Figure 2. Reflection and transmission patterns of aluminum, copper, lead, gold and silver at equal thicknesses of 55nm.

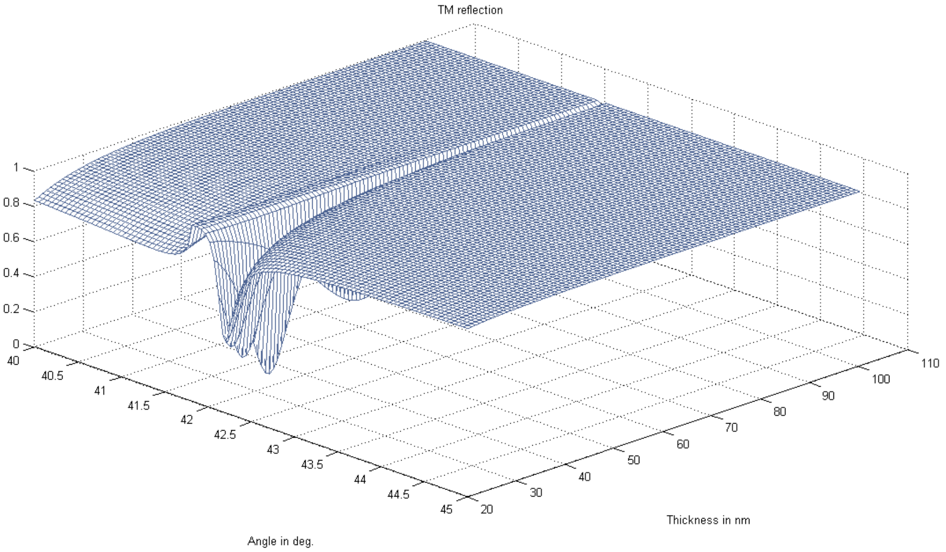

Figure 3. Optimal thickness of gold providing the minimum of reflection.

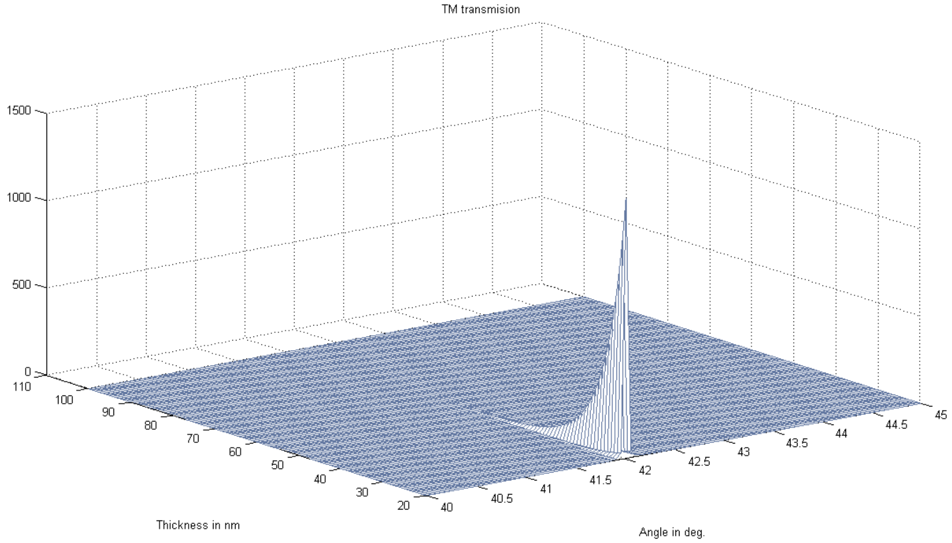

Figure 4. Optimal thickness of gold providing the maximum of transmission.

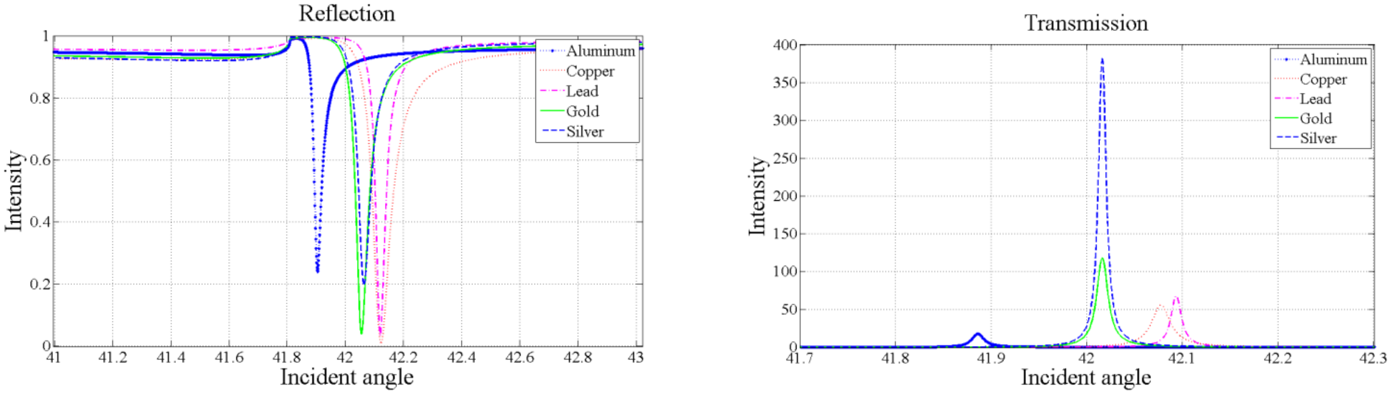

Figure 5. Reflection and transmission patterns of aluminum at thickness of 20nm, copper at thickness of 40nm, lead at thickness of 48nm, gold at thickness of 34nm, and silver at thickness of 32nm.

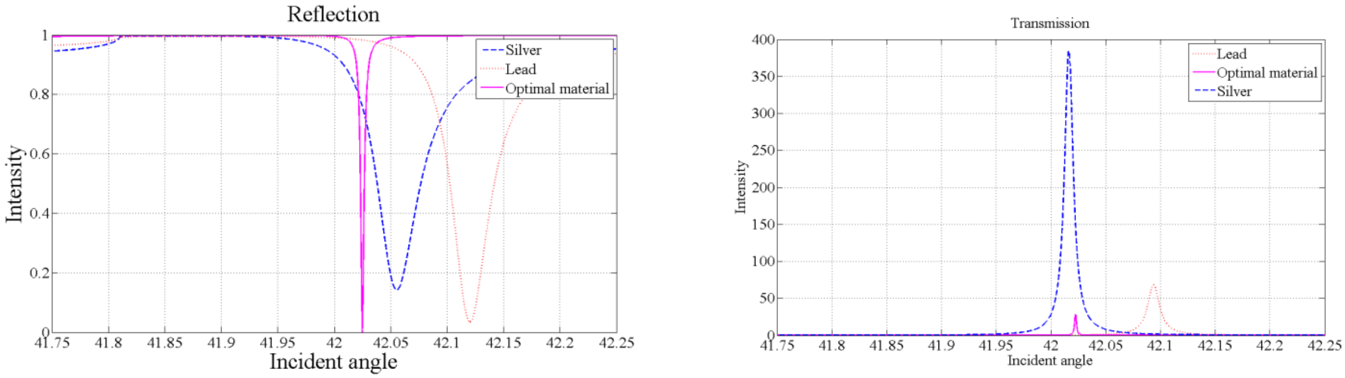

Figure 6. Reflection and transmission patterns of lead at thickness of 48nm, silver at thickness of 34nm and optimal material at thickness of 65nm.

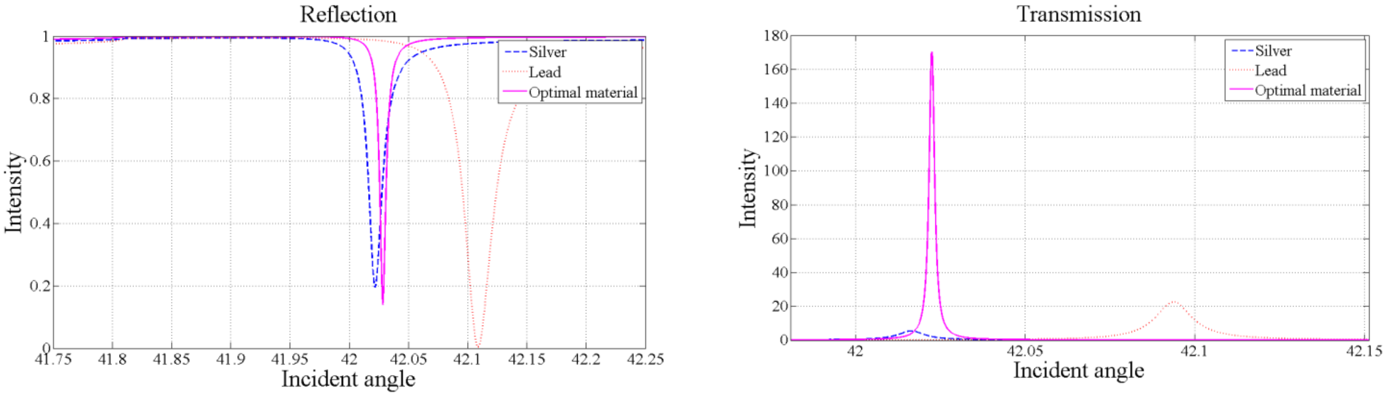

Figure 7. Reflection and transmission patterns of silver, lead, and optimal material at thicknesses of 55nm.

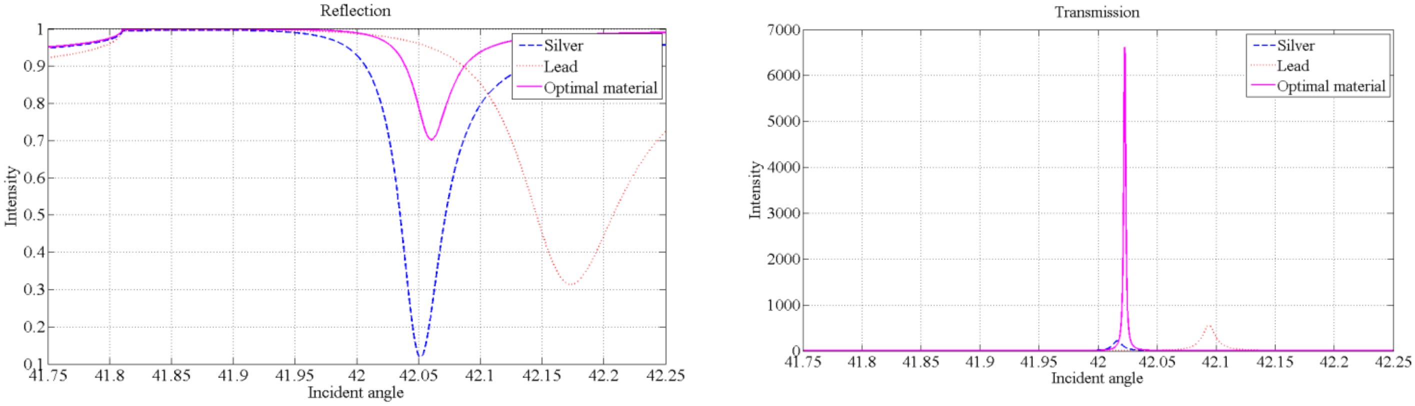

Figure 8. Reflection and transmission patterns of silver, lead, and optimal material at thicknesses of 35nm.