

TUNING OF MATERIAL OPTICAL PROPERTIES BY MODIFICATION OF INTERLAYER THICKNESS

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Abstract

Optical properties of quasi one-dimensional binary thin films made of interchanging Ag and Ni layers are investigated in this work. For this purpose we applied the so called matrix method implementing Maxwell equations for electromagnetic waves propagation thru 11 layers of Silver and Nickel thin layers (20nm and 30nm respectively) separated by one Ni layer with variable thickness. Study showed that by changing only one middle layer dimensions it is possible to tune optical properties in wide range, both by the means of transmission intensity band minimum location and depth. This approach will result in simplification of manufacturing process.

Keywords: thin layers; matrix method; optical properties; electromagnetic wave transmission; periodic systems;

Introduction

Thin layer optical materials are becoming increasingly popular because of their excellent properties while also having well known relatively simple manufacturing process such as magnetron or electrodeposition methods. Those kinds of materials are widely utilized in optical filters [1-5], photonic crystals [6-12], quasicrystals [13-20] and many others. Despite the relative ease of the production process, it is much more resource consuming to vary the properties of material by changing multiple layers thickness than by changing only one chosen layer. Such approach can significantly reduce manufacturing costs and also contribute to decreasing the time needed for material preparation.

There are several known methods used to simulate electromagnetic wave propagation thru various materials, among others two are commonly used, namely FDTD (finite difference time domain) [21-23] and FDFD (finite difference frequency domain) [24]. Both of mentioned methods have their advantages and disadvantages. Unfortunately, both are time and resource consuming because of used FFT algorithms. In this work we used the so-called matrix method, which has the advantage of being algorithmically less complex, giving comparatively precise results. The formal equations of matrix method will be presented under simulation section.

In this work we have chosen to use two common materials for sample preparations: Ag and Ni. The use of those elements in particular was dictated by the long history of employing Ag with deposition methods and the availability of Ni. Furthermore, optical properties of those

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elements, specifically a major difference in refractive index, makes them especially interesting when discussing their mutual relations in one optical system.

The main purpose of this paper is to investigate influence of middle layer thickness (VTL) on the transmission properties of quasi one-dimensional multi layer binary system.

Simulations

Matrix method theoretical background

The transmission of the multilayer structure is calculated from the following equation:

$$T = \frac{n_{out} \cos \Theta_{out}}{n_{in} \cos \Theta_{in}} \left| \frac{1}{X_{11}} \right|^2 \tag{1}$$

where: n_{in} , n_{out} – are respectively the refractive index of the electromagnetic wave (EMW) directed on the multilayer structure and one that is leaving, Θ_{in} – incident electromagnetic wave angle with respect to the superlattice, Θ_{out} – the angle at which EMW leaves multilayer, X_{11} – the first word of the characteristic matrix diagonal X for superlattice described by the relation:

$$X = \frac{1}{t_{in,j+1}} \begin{bmatrix} 1 & r_{in,j+1} \\ r_{in,j+1} & 1 \end{bmatrix} \cdot \left[\prod_{j=1}^J \begin{bmatrix} e^{id_j n_j \frac{2f}{\lambda} \cos \Theta_j} & 0 \\ 0 & e^{-id_j n_j \frac{2f}{\lambda} \cos \Theta_j} \end{bmatrix} \frac{1}{t_{j,j+1}} \begin{bmatrix} 1 & r_{j,j+1} \\ r_{j,j+1} & 1 \end{bmatrix} \right] \tag{2}$$

where: n_j – refractive index of the layer j , d_j – thickness of the layer j , Θ_j – angle of falling of EMW for the layer j determined from Snell's law, λ - the wavelength of incident wave. Depending on the type of polarization t and r determine the amplitude of Fresnel ratios respectively for transmittance and reflectance. For the polarization P, it is defined as:

$$t_{j,j+1} = \frac{2n_j \cos \Theta_j}{n_j \cos \Theta_{j+1} + n_{j+1} \cos \Theta_j}, \tag{3}$$

$$r_{j,j+1} = \frac{n_j \cos \Theta_{j+1} - n_{j+1} \cos \Theta_j}{n_j \cos \Theta_{j+1} + n_{j+1} \cos \Theta_j}$$

Simulation details

The quasi one-dimensional multilayer structure (a structure in which only one of the dimensions is finite and the others tend to infinity) was formed with an alternate stacking of two types of thin films, and is presented on fig. 1.



Fig. 1. Schematic of presented multilayer system. VTL - variable thickness layer.

As the material A silver was used, while as material B thin nickel film was used respectively. Silver layers thickness was set to 20 nm and nickel thickness was set to 30 nm. Both materials were placed directly adjacent to each other in such a way, that they formed a periodic structure with 11 elements in total. The middle layer's (also made using nickel) thickness was then varied from 10 nm up to 100 nm with the 5 nm step. The simulation included the extinction coefficient for both materials. Key parameters for used materials are shown in table 1.

Table 1. Some key parameters of used elements

Element name	Refractive index n	Extinction coefficient $[10^{-6}]$	Thickness [nm]
Silver - A	0.1501	3.4727	20
Nickel - B	1.9077	3.4656	30

Results and Discussion

Figure 2 presents EMW wave transmission graphs for selected VTL thickness with incident wave angle $= /4$. The minimal thickness (when VTL is 10 nm) of the whole structure is $d_{min}=260$ nm while maximal thickness of the whole structure is $d_{max}=350$ nm.

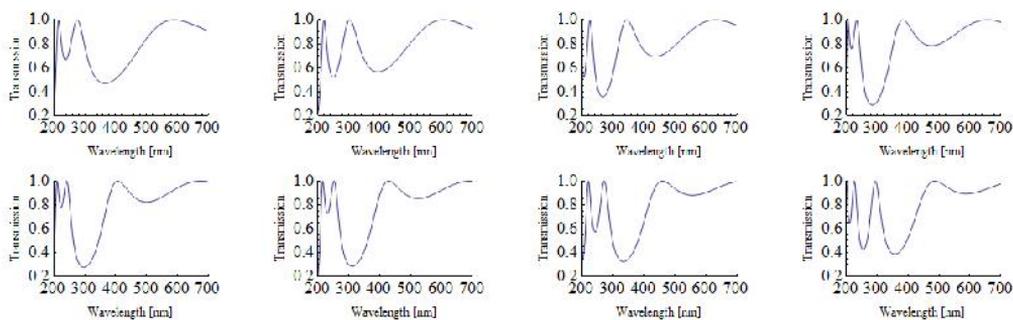


Fig. 2. Transmission vs. EMW wavelength for structure with (from upper left) VTL=10, VTL=20, VTL=35, VTL=50, VTL=60, VTL=70, VTL=85, VTL=100 nm.

As can be seen by analysis of figure 2, increasing the middle layer's thickness has two visible effects on the transmission of EMW. First effect is connected with shifting of created bands toward higher wavelength direction. This effect is especially visible when a band with a minimum located at about 380 nm is considered through increasing VTL. At the same time, depth of this band decreases significantly, disappearing almost completely at VTL=100 nm. Another effect that could be observed is the creation of bands. This is visible in particular when

observing left side (near 200 nm EMW wavelength) of transmission graphs. It seems, that as the VTL layer thickness increase, more bands are created.

The shift creation and spontaneous diminishing of bands effects are well visible when transmission graphs are superimposed onto one graph, what can be seen on figure 3.

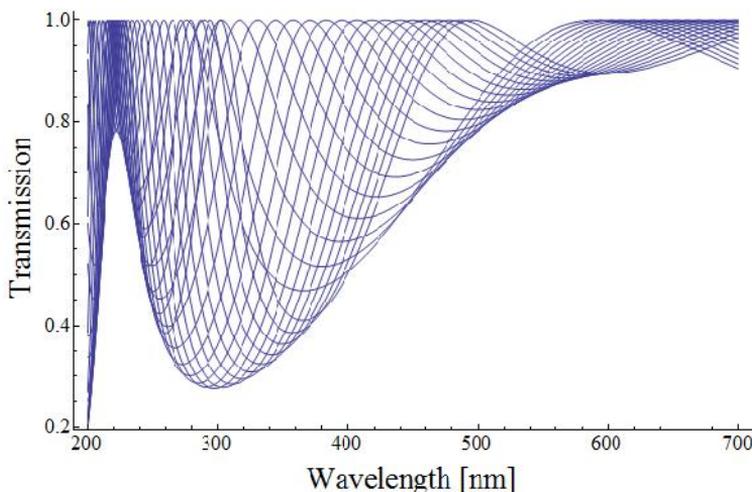


Fig. 3. Superposed transmission graphs for transmission of EMW for whole range of middle layer thickness.

Figure 3 reveals also another effect which is related to crossing the wavelength "border" located near 300 nm. When incident light wavelength exceeds 300 nm, it can be seen that the depth of the widest band is decreasing for the whole range of VTL thicknesses.

In order to determine the character of relationship between layer thickness and band shifting property we plotted position in respect to layer thickness of wide band minimum located at 300 nm in figure 4.

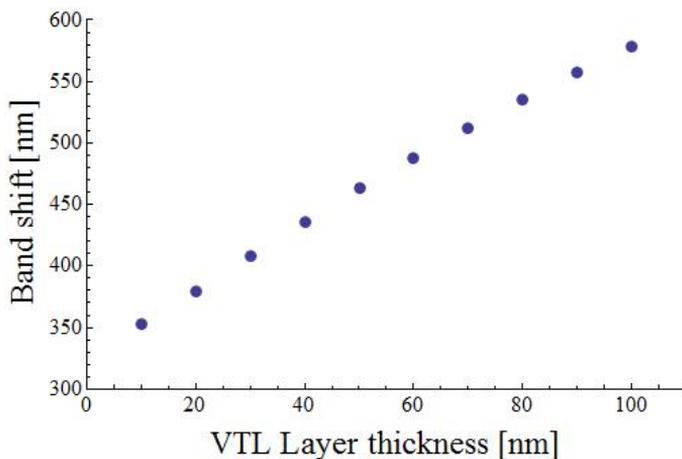


Fig. 4. Wide band located at 300 nm minimum position shift in respect to VTL layer thickness.

As can be seen, the relationship between shift in position of band shows nearly linear character relative to VTL layer thickness. In the next figure (fig. 5) the same band minimum depth (or transmission depth) is presented in respect to middle layer thickness.

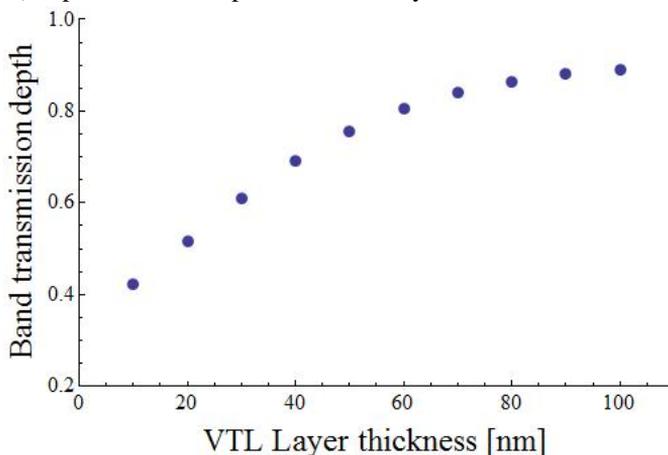


Fig. 5. Wide band located at 300 nm minimum depth in respect to VTL layer thickness.

According to fig. 5, it can be seen that relative depth character of band gap is more complex than it's shift. The general tendency is band shallowing with the increase of VTL layer thickness.

Conclusions

In this study, we examined the influence of increasing one (middle) layer's thickness and its influence on electromagnetic wave transmission through quasi one-dimensional multilayer system made of alternating silver and nickel thin layers. Based on the study it can be concluded that the matrix method is useful for the study of photonic properties of multilayer structures.

It has been found that the presence of the photonic band gap depends strongly on the thickness of superlattice middle layer.

Also it was shown, that the increase of VTL thickness causes three major effects, namely: creation of new bands, shifting of those bands in direction of higher wavelengths and diminishing of bands that crossed band edge located near 300 nm. Those effects are obviously connected with the reflection of EMW at the borders between neighbouring layers, as well as through the creation of standing waves inside VTL layer. Also, the longer wavelength of incident EMW, the greater it's transmission through studied structure. This limits the usefulness of such system to devices operating in visible up to ultraviolet light range.

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