ELECTROMAGNETICS OF NANOFLAT LAYERED TRANSPARENT METALS

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Abstract: The electromagnetic properties of one-dimensional nanostructured transparent metals are analysed at radio frequency up to 1.2 GHz and in the optical range. The material sample is realized by the dual ion-beam sputtering technique. The measured shielding effectiveness at radio frequency is higher than 40 dB and the measured optical transmittance reaches the maximum of 70% between 500 nm and 550 nm.

INTRODUCTION

Transparent metals are one-dimensional (1D) photonic band gap (PBG) structures constituted by alternating layers of conducting (e.g. metal) and non-conducting (e.g. dielectric or semiconductor) materials [1]. Depending on the transmission characteristics in the visible range, i.e. resonant or broad band flat transmittance spectrum, transparent metals can have either periodic or semi-periodic or non-periodic structure [2]-[4].

The scope of this paper is to describe the electromagnetic (EM) properties of semi-periodic transparent metals made of alternating layers of silver (Ag), titanium dioxide (TiO2) and titanium (Ti). The nano-layered coating is deposited by dual ion beam sputtering (DIBS) as described in [5]. The 1D-PBG is expected to have shielding effectiveness (SE) higher than 40 dB at radio frequency up to 1.2 GHz, and maximum optical transmittance higher than 70%.

The aging test is performed in order to assess the stability of the EM properties of the coating after exposure to damp environment.

TiO2 – Ti – Ag TRANSPARENT METAL

Titanium dioxide (TiO2) is a good candidate material for dielectric layers in transparent metals, due to its high refractive index and low absorption in the visible range. Actually, higher maximum transmittance and colour neutrality can be achieved theoretically if the refractive index of the dielectric is higher [6]. Furthermore, titanium dioxide has recently been shown to possess self cleaning catalytic properties, which can be transferred to the multi-layer coating if the top layer is made of this material, increasing the multi-functionality of the EM shield and its utility in the building and automotive field especially. A critical issue in Ag/TiO2 multi-layer coatings realized by conventional radio frequency sputtering technique is the silver oxidation and agglomeration, due to the oxygen diffusion favoured by the heat and ions bombardment from the plasma [7], [8]. The use of blocking layers is necessary in that case.

To this scope, interlayers of titanium (Ti) are deposited on both sides of the silver layers. The structure of the resulting coating, which is constituted by 17 layers, is: (TiO2/Ti/Ag/Ti/TiO2). The thickness of the TiO2 films is 32 nm, of the Ag layers is 17 nm, of the Ti interlayers 1 nm. The total metal content is 68 nm. The overall thickness of the coating is 332 nm.

Shielding effectiveness at radio frequency. The shielding effectiveness of an infinite screen against an incident TEM plane wave is defined by:

\[
SE = 20 \log_{10} \left( \frac{E'(P)}{E''(P)} \right)
\]

in which \(E'(P)\) and \(E''(P)\) are the electric fields in a point \(P\) without and with the shield. If the shield is multilayered, the previous relation can be expressed in terms of the coefficients of the total transmission matrix \([\Phi_{\text{tot}}]\) of the structure, according to the following expression [9]:

\[
SE = 20 \log_{10} \left( 0.5 \left[ \Phi_{\text{tot}}(1,1) + \Phi_{\text{tot}}(2,2) + \eta_\phi \Phi_{\text{tot}}(2,1) + \eta_\phi^* \Phi_{\text{tot}}(1,2) \right] \right)
\]

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in which \( \eta_0 \) is the free space wave impedance. For the TiO\(_2\) – Ti – Ag transparent metal described above, matrix \([\Phi_{\text{tot}}]\) assume the following expression:

\[
[\Phi_{\text{tot}}] = [\Phi_{\text{TiO2}}][\Phi_{\text{Ti}}][\Phi_{\text{Ag}}][\Phi_{\text{TiO2}}]^4
\]

(3)

in which \([\Phi_{\text{TiO2}}], [\Phi_{\text{Ti}}], [\Phi_{\text{Ag}}]\) are the transmission matrices of the TiO\(_2\)-, Ti-, Ag-layers, having thickness of 32 nm, 1 nm, and 17 nm respectively.

In the radio frequency range, up to ten gigahertz, the electrical conductivity of the Ag film, which is dependent from the film thickness as shown in Table I, is much higher than the conductivity of the TiO\(_2\)- and Ti-films. It results that matrices \([\Phi_{\text{TiO2}}]\) and \([\Phi_{\text{Ti}}]\) are nearly coincident with the diagonal unit matrix. Therefore, (3) is replaced by the following approximated one:

\[
[\Phi'_{\text{tot}}] = [\Phi_{\text{Ag}}]^4 = [\Phi_{\text{Ag}}]
\]

(4)

which is the transmission matrix of a single Ag layer having the thickness of 4*17 nm = 68 nm.

**Optical transmittance.** The optical design of the transparent metal sample is performed by using for calculation a commercial software (TFCalc, Software Spectra Inc.), which applies the standard matrix transfer method. The optical performance of the material sample is strongly governed by its complex refractive index \( \hat{n} = n + jk \), whose real and imaginary parts are defined as functions of the real and imaginary parts of the complex permittivity of the medium \( \hat{\varepsilon} \), according to the following relations:

\[
\text{Re}(\hat{\varepsilon}) = n^2 - k^2, \quad \text{Im}(\hat{\varepsilon}) = 2nk
\]

The dielectric constants of TiO\(_2\) and Ti are derived as function of wavelength from the spectro-photometric measurements of the single layer coatings. The dispersion characteristics of \( n \) and \( k \) for Ag are reported in [10].

The transmission coefficient or transmittance of the structure is defined as the ratio between the transmitted electric field and the incident one.

Table I - Measured electrical conductivity values for silver single layers deposited by DIBS with different thicknesses. The values reported in literature for the bulk specimen is reported for comparison.

<table>
<thead>
<tr>
<th>Thickness [nm]</th>
<th>17</th>
<th>63</th>
<th>400</th>
<th>bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity [S/m]</td>
<td>7.75*10^6</td>
<td>12.8*10^6</td>
<td>15.6*10^6</td>
<td>66.7*10^6</td>
</tr>
</tbody>
</table>

**Experimental characterization of electromagnetic performances.** The measurements of the SE of planar samples of transparent metal are performed by using the coaxial waveguide set-up, according to the ASTM-D4935-89 standard for shielding effectiveness measurement of planar samples from 30 kHz to 1.5 GHz [11]. The SE test is performed by inserting the test specimen between two coaxial transitions, having characteristic impedance of 50 \( \Omega \) and internal diameter of 76.8 mm, and measuring the scattering parameter \( S_{21} \). The effect of the contact impedance between the material sample and the guiding structure is corrected by using as reference the scattering parameter \( S_{21} \) measured when the two coaxial transitions are coupled through the “reference” specimen, which covers only the contact areas of the waveguide with the “test specimen”.

The measured SE frequency spectrum is reported in Fig.1(a) and compared with the SE spectrum of a single layer film of Ag having the thickness of 68 nm. The good agreement between the two curves confirms the validity of the approximation (4). The average SE in the considered frequency range is higher than 40 dB. Specular transmittance and reflectance spectra at normal incidence are recorded in the visible-near infrared range by standard spectro-photometric technique (Lambda 19 Spectrophotometer by Perkin-Elmer). The transmittance is measured before and after exposition of the sample to damp heat test (according to the normative ISO 9211-3:1994(E) for optical coatings), which requires that the sample is stored at 55°C and 95% humidity for 16 h. The measured spectra before and after aging, reported in Fig.1(b), are nearly overlapping, thus demonstrating the stability of the nano-layered coating. The peak value of the optical transmittance reaches 70% between 500 nm and 550 nm.
CONCLUDING REMARKS

Innovative transparent metal made of 17 alternating layers of TiO2, Ti and Ag is realized by dual ion beam sputtering. The EM properties of the nanolayered structure are tested at radio frequency up to 1.2 GHz and in the optical range. It results that the realized 1D-PBG provides the same shielding effectiveness of a single layer film containing the same amount of silver. At the contrary, the transmittance in the visible range reaches the peak value of 70%.

REFERENCES