Optical Multiplexing using Transparency Window of Good Conductors.

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Abstract

Thin metal films are excellent reflectors and extremely opaque at microwave and mm-wave frequencies. Bulk metalΓ howeverΓ becomes partly transparent at optical frequencies due to the shape of the Lorentz-Drude permittivity function at that frequency regime. We explore this property for designing optical filters composed of a finite number of periodically placed thin metal filmsΓ supported by conventional dielectrics. The resulting filters exhibit comb-filter multiplexing characteristics similar to Bragg reflectors at frequencies higher than 10^{14} HzΓbutΓunlike Bragg reflectorsΓare completely opaque to any smaller frequencies.

Introduction

It is well known that good conductors are excellent reflectors and extremely poor transmitters of electromagnetic radiation for frequencies up to mm-waves. It is perhaps less well-known that good conductors become transparent in a region around the free-electron plasma frequency[1]Γgiven by $\omega_p^2 = \mathcal{N}e^2/m\epsilon_0$Γwhere $\mathcal{N}$ is the free-electron density in the metal and m the electron effective mass. The plasma frequency falls in general in the optical regime for all good conductorsΓ and the corresponding relative complex permittivity of the metal can be obtained from the Lorentz harmonic oscillator model by setting the oscillator restoring force to zeroΓi.e.Γ$\omega_0 = 0$:

$$\epsilon_c = 1 - \frac{\omega_p^2}{\omega(\omega - j\gamma)} \ . \tag{1}$$

Eq. (1) is valid all the way down to DC. The permittivity parametersΓ for all good conductorsΓ are in the ranges $7eV < h\omega_p/2\pi < 15\ eV$Γ $005\ eV < h\gamma/2\pi < 0.13\ eV$ and result from fits to somewhat model-dependentΓ low-energy reflectivity data[1]. For the rest of this paper we will choose the representative values

$$\omega_p = 10^{16}\ Hz, \quad \gamma = 10^{-2}\omega_p \ , \tag{2}$$

giving a DC conductivity $\sigma = \omega_p^2\epsilon_0/\gamma \simeq \mathcal{O}(10^7\ S/m)$.

It has been recently observed[2] that one could use the transparency window of normal metals to construct metallo-dielectric periodic arrays with tunable transmission characteristicsΓwhere the transmission through the periodic structure is enhancedΓrelative to its single-film valueΓmuch like in a Fabry-Perot resonator. The authors in [2] present various predictions of the transmittivity of these structuresΓ for normal plane-wave incidenceΓ a fixed number of unit cells and fixed values of dielectric thickness in the unit cellΓ but do not provide a systematic investigation of the parameter-space for the filter performance in terms of its scaling variables.

In this paperΓwe follow-up on the work of ref. [2] in two important ways: FirstΓwe provide a closed analytical formula for the transmission and the reflection through an arbitrary number N of unit cells comprizing the filterΓat an arbitrary angle of incidence and for bothΓTE and TM polarizations. SecondlyΓ we systematically evaluate the filter performance and multiplexing properties as a function of the physical parameters of the filterΓnamely material thicknessesΓ polarization and incident angleΓ and$N$.

The Filter Design equations

We will denote with $\{d_c,\ d_d\}$ the thicknesses of the conducting film and dielectric slab in the filter's unit cell and our filter will contain an arbitrary number N of such unit cells.

We find the reflection coefficient for p-polarized plane-wave incidence at angle θ ($p = 1 \rightarrow$ TEΓ$p = 2 \rightarrow$ TM) to be[3]

$$\Gamma^p_N(\theta) = \frac{2f_{21}\left[(1+\zeta)^N - (1-\zeta)^N\right]}{(f_{11}-f_{22})\left[(1+\zeta)^N - (1-\zeta)^N\right] + \zeta(f_{11}+f_{22})\left[(1+\zeta)^N + (1-\zeta)^N\right]}\ , \tag{3}$$

where

$$\zeta = \frac{f_{11}-f_{22}}{f_{11}+f_{22}}\sqrt{1+\frac{4f_{12}f_{21}}{(f_{11}-f_{22})^2}}\ . \tag{4}$$

The matrix elements f_{ij} are obtained from the transmission matrix through one unit cell of the filter:

$$\mathbf{f} = \begin{pmatrix} 1-\Gamma^{1;p}_{a,c}\Gamma^{1;p}_{a,d} & -(\Gamma^{1;p}_{a,d}+\Gamma^{1;p}_{a,c}Z^p_{a,d}) \\ \Gamma^{1;p}_{a,c}+\Gamma^{1;p}_{a,d}Z^p_{a,c} & -\Gamma^{1;p}_{a,c}\Gamma^{1;p}_{a,d}+Z^p_{a,c}Z^p_{a,d} \end{pmatrix}\ , \tag{5}$$

where the functions $\Gamma^{1;p}_{a,j}$ are the reflection coefficients of 1 slab of material $j \in$ {conductor $\equiv c$, dielectric $\equiv d$} for p-polarized plane-wave oblique incidence from air

$$\Gamma^{1;p}_{a,j} = \Gamma^p_{a,j}\left(\frac{1-e^{-2\gamma_j d_j}}{1-(\Gamma^p_{a,j})^2 e^{-2\gamma_j d_j}}\right)\ , \tag{6}$$

and $Z^p_{a,j}$ are closely related (but irreducible) functions

$$Z^p_{a,j} = \frac{-(\Gamma^p_{a,j})^2 + e^{-2\gamma_j d_j}}{1-(\Gamma^p_{a,j})^2 e^{-2\gamma_j d_j}}\ . \tag{7}$$

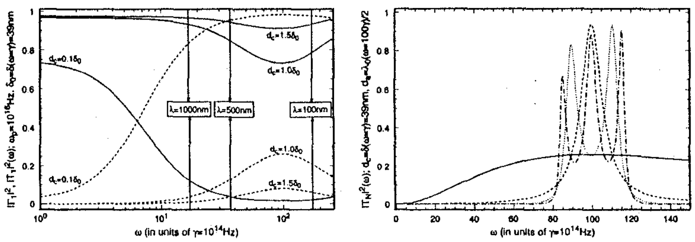

Figure 1: Left: Reflectivity (solid) and Transmittivity (dashed) of a single metal filmΓ versus ωΓ for various film thicknesses parametrized in terms of conductor skin depth δ_0 (evaluated at $\omega = \gamma$); Right: Transmittivity for fixed unit cell thicknessesΓ as a function of N and ω. N=1 (solid)Γ 2 (dashed)Β (dotted)Γ4 (dot-dashed).

In these equations appear the intrinsic (bulk) reflection coefficients of the materialsΓ $\Gamma^p_{a,j}$Γ andpropagation constantsΓγ_jΓfor the above excitation:

$$\Gamma^{p=1}_{a,j} = \frac{(\eta_j/\cos\theta_j) - (1/\cos\theta)}{(\eta_j/\cos\theta_j) + (1/\cos\theta)},\ \Gamma^{p=2}_{a,j} = \frac{\eta_j\cos\theta_j - \cos\theta}{\eta_j\cos\theta_j + \cos\theta},\ \gamma_j = jk_0\cos\theta_j/\eta_j\ , \quad (8)$$

where η_j are the relative wave impedances

$$\eta_c = \frac{1}{\sqrt{\epsilon_c}}\ ,\ \eta_d = \frac{1}{\sqrt{\epsilon_d}\sqrt{1 - j\alpha}}\ , \quad (9)$$

and $\epsilon_c, \epsilon_d, \alpha$ are the conductor permittivity given by Eq. (1)Γthe real part of the permittivity and the loss tangent of the dielectricΓ respectivelyΓand

$$\cos\theta_j = \sqrt{1 - \eta_j^2\sin^2\theta}\ . \quad (10)$$

The transmission coefficient through the filterΓ$T^p_N(\theta)$Γis similarly calculated:

$$T^p_N(\theta) = \Gamma^p_N(\theta)\times\left(\frac{f_{11} + f_{22}}{f_{21}}\right)\zeta\left(\frac{2\Gamma^{1;p}_{a,c}\Gamma^{1;p}_{a,d}e^{-\gamma_c d_c}e^{-\gamma_d d_d}}{\Gamma^p_{a,c}\Gamma^p_{a,d}(f_{11} + f_{22})(1+\zeta)}\right)^N\left[1 - \left(\frac{1-\zeta}{1+\zeta}\right)^N\right]^{-1}. \quad (11)$$

A sample of results

Due to space limitationsΓ we will only present results for normal incidence and air-suspended metallic films.

In Fig. 1 we show the energy reflection and transmission of a single metal film for various film thicknesses. We observe that a single film becomes completely opaque at frequencies $\omega < \gamma$Γeven when the thickness is much smaller than the

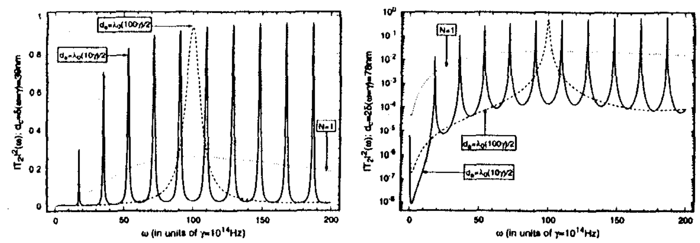

Figure 2: Multiplexing at optical frequenciesΓfor different air (dielectric) thicknesses d_a. Left: For film thickness δ_0; Right: For film thickness $2\delta_0$.

skin depth at these smaller frequencies. For microwave frequenciesΓ the skin depth of good conductors is of the order of micronsΓ a full 2-3 orders of magnitude larger than the thicknesses shown here. We also show the basic filter response as a function of N. We observe that 2 unit cells provide the cleanest filter response.

In Fig. 2 we show the optical multiplexing properties of the filter. Notice that the periodicity of the responce is controlled by the air (dielectric) thicknessΓ which we normalize as a half-wavelength at an arbitrary frequency $(\lambda_0(\omega)/2)$. The response is that of a comb filter with peaks modulated according to the transmittivity of the single metal film. In the passbandsΓhoweverΓthe transmittivity greatly overshoots the values of its single-film counterpart. In particularΓ for$d_c = 2\delta_0$Γ the single-film transmittivity is less than 2%Γbut the mere addition of one more unit cell provides transmittivities of 60% in the optical. FinallyΓ the filter is completely opaque for any $\omega < \gamma$. As the air (dielectric) thickness increasesΓthe passbands can be as densely distributed as desired with corresponding decrease of their bandwidth.

References

[1] See C. Bohren and D. HuffmanΓ*Absorption and Scattering of Light by Small Particles*ΓJohn Wiley & SonsΓInc.ΓNew YorkΓ1983Γpp. 251-267 and references therein.

[2] M. Scalora et al.Γ"TransparentΓMetallo-DielectricΓOne-DimensionalΓPhotonic band gap Structures"Γ(Sept. 15Γ1997)Γto be published in Jour. App. Phys.

[3] These formulas are generalizations of the ones for normal incidence derived in H. ContopanagosΓN. Alexopoulos and E. YablonovitchΓ"High-Q Radio Frequency Structures using One-Dimensionally Periodic Metallic Films"Γ(June 6Γ 1997)Γ to bepublished in IEEE Trans. MTT.