INVERSE DESIGN OF QUASIMONOCHROMATIC LIGHT SOURCES IN THE VISIBLE RANGE

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Emission of thermal light from a hot body was considered during long time as broadband and quasi-isotropic. Today we know that various micro and nanostructured materials[1-5] (see also the refs. in [5]) are able to radiate in narrow spectral bands and around specific directions of space. In a recent work[6] we have developed a general method for the ab initio design of multilayered coherent thermal sources. This method consists first in setting the coherence degree that we want to recover and then using only the first principles of optics we search, using a genetic algorithm, for the ad hoc structure of a multilayered medium to satisfy this specification. Here, we report the design of quasi-monochromatic 1-D metallodielectric sources for both polarization states in the visible range.

The type of structures we investigate in this work are one-dimensional plasmonic stacks built by superposing nanolayers of metals with different dielectric materials. All these composites materials are formed from M unit nanolayers of the same total thickness L. The total number of all possible configurations that can be theoretically fabricated with N distinct materials is N^M. For ternary structures made with 50 unit layers there are more than 10^{23} possible configurations. Such a large space S offers immense possibilities to sculpt the radiative properties of nanolayered composites. To explore effectively this vast space of composite materials and identify the structures which possess the desired properties, a rational searching method is needed. To do that we use a genetic algorithm[7] (GA) which is a stochastic global optimisation method based on natural selection rules as in the famous Darwin's theory of evolution. To do that we first define some target radiative properties (for instance the spectral and directional emissivity $\varepsilon_{target}(\lambda,\theta)$ and reflectivity $r_{target}(\lambda,\theta)$) that we want to recover. Then, in order to select the best morphologies in this population, in comparison with these objectives functions, we calculate the radiative properties (transmittivity $t(\lambda,\theta)$, reflectivity $r(\lambda,\theta)$ and emissivity $\varepsilon(\lambda,\theta)$) of each individious of a population (basically a hundred of structures) by using their transfer or scattering matrix. In a mathematical form the optimal morphology $\bar{h}=(\bar{a}_1,.....,\bar{a}_N)$ is the global minimum of the functional $J(h)=\sum_p (\left\|\varepsilon^p_{calc}(\lambda,\theta)-\varepsilon^p_{target}(\lambda,\theta)\right\|+\left\|r^p_{calc}(\lambda,\theta)-r^p_{target}(\lambda,\theta)\right\|)$,

i.e.

$$\bar{h}=\min_S J(h). \qquad (1)$$

The discrete sum operates over both states of polarization TE and TM of the light and the norms are the quadratic ones which are calculated over the spectral and angular ranges $[\lambda_{\min};\lambda_{\max}]$ and $[\theta_{\min};\theta_{\max}]$ where we want to recover the radiative properties. The structure we have inverse designed are multilayered made with silver (Ag), glass (SiO_2) and Indium Antimonide (InSb) layers. Our goal is to control the thermal emission both in frequency and in direction. The target emissivity and reflectivity plotted in Fig. 1 are defined in the spectral range $[\lambda_{\min}=0.6\mu m;\lambda_{\max}=1\,\mu m]$ where Ag supports surface waves also called surface plasmon (SP). These waves are due to collective motion of electrons in Ag. In this spectral range the dielectric permittivities of SiO_2 and InSb are well approximated[5] by the real values $\varepsilon_{SiO_2}=2.13$ and $\varepsilon_{InSb}=15.60$ while the Ag permittivity is complex valued and described by the free-electron/Drude model[5] $\varepsilon_{Ag} = 5{,}62 - \frac{\omega_p^2}{\omega(\omega - i\omega_c)}$, where $\omega_p = 13.69 \times 10^{15} rad.s^{-1}$ is the plasma pulsation and $\omega_c = 2.73 \times 10^{13} rad.s^{-1}$ is the electron collision frequency. The geometric parameters of the studied structure have been set to M=50, and d=20 nm so that $L = d \times M = 1\mu m$. Figure 1 shows that the targets are relatively well recovered for both polarization states with an evolution process of 500 generations only. We also observe that the designed structure is highly disordered and was mostly impossible to predict a posteriori without an inverse approach.

To find the physical origin of these results we have examined the field inside the designed structure when it is submitted to external (normalized) excitations. The result displays in Fig. 2 shows that the intensity of electric field inside the structure becomes locally much larger than 1 at the incidence angles and wavelengths where the emissivity pattern is maximum. This result is due to internal resonant mechanisms. Indeed, if we pay attention on the case where an incident wave of wavelength $\lambda = 0.71\mu m$ impinges the structure under an angle of 20°, we observe that the field at the interface between the Ag layers at $z = 0.3\mu m$, is strongly enhanced by about two orders of magnitude. Such a resonance, exponentially localized on both sides of Ag layers, reveals the presence of surfaces plasmons (SPs) and demonstrates that the incident (propagative) wave is able to couple with them. Thus, the energy of this propagative wave is resonantly transferred to SPs. Therefore, this coupling directly contributes to the strong emission of the structure in the angular lobe centred at 20° . In contrary, for all others angles of incidence at the same frequency and for all angles outside of spectral the range $[0.68\mu m; 0.74\mu m]$ there is no significant enhancement of field in the structure and very few energy is absorbed by the Ag layers. Then, according to the Kirchoff's law, the thermal emission of the structure is very small.

CONCLUSION

It has been demonstrated that by using inverse design one can achieve quasimonochromatic sources in the visible range with metallodielectric structures. This approach should find broad applications to improve the performances of numerous optical technologies such as thermophotovoltaïc energy conversion, infrared spectroscopy or radiative cooling.

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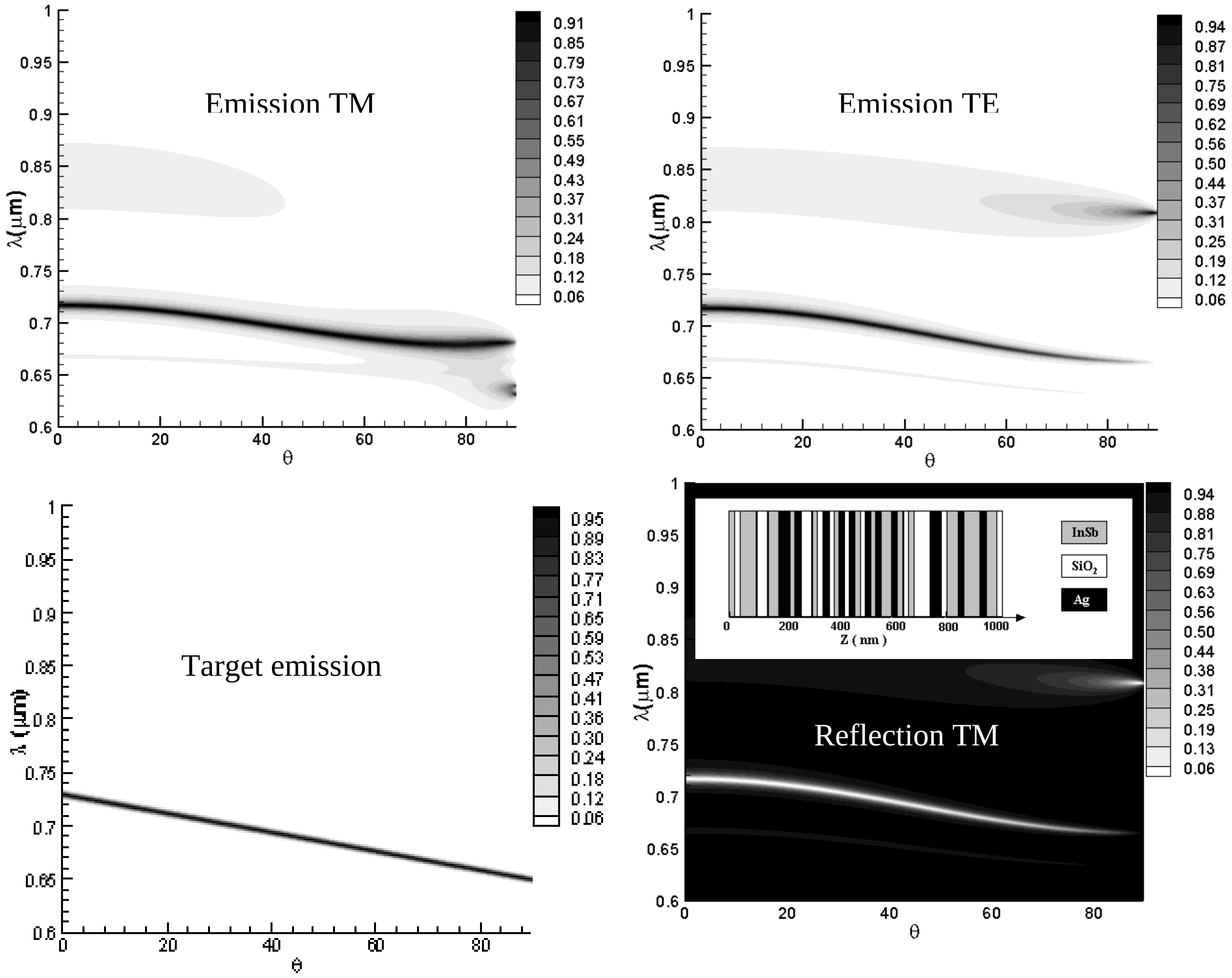

Figure 1. (a) Emission of the designed structure, (b) target emission and (c) reflection in polarization TM (the result in polarization TE is analog). The inset in (c) is the morphology of the inverse designed source.

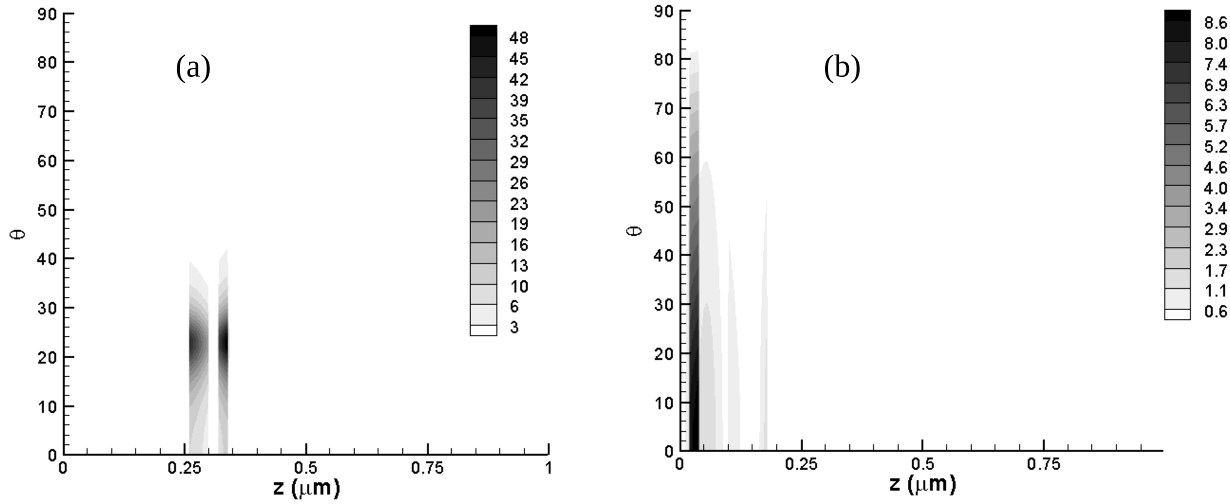

Figure 2. Modulus of the electric field (polarization TM) inside the inverse designed metallodielectric structure when it is highlighted by an incoming field of unit magnitude. Wavelengths of excitation are $\lambda = 0.71 \mu m$ (a) and $\lambda = 0.9 \mu m$ (b).