Infrared radiation manipulation in polar metamaterials

In recent years, much effort has been expended upon managing and tuning the radiative properties of structures and material surfaces in the infrared (IR) wavelength range (3–12 micron) for several applications, such as thermal radiation control as well as IR sensing [1].

Polar materials are particularly suitable for this purpose, i.e. those materials where it is possible to excite the collective oscillations of the lattice ions, just like the collective modes of electrons in metals.

The polarization waves of the crystal lattice are called surface polaritons, similarly to the surface plasmons excitable in the ultraviolet and visible in metals. Since the oscillation frequencies of the crystalline lattice ions are typically lower, compared to the plasma frequencies, they fall in the infrared wavelength range. As a consequence, polar materials along with derived phononic structures offer the possibility of manipulating and amplificating IR emissivity by the excitation of such surface modes.

Depending on the direction of vibration of the lattice cores, the polarization wave will assume longitudinal or transverse wave characteristics, respectively. However in bulk polar media the longitudinal polariton can be excited only at angles other than zero and with a polarization of the electric field in the incidence plane (i.e. in TM polarization).

We have recently developed a numerical/theoretical model to design metamaterials composed by a polar matrix and air inclusions. Combining homogenization techniques with the transfer matrix method for birefringent-layered materials, we modelledan effective medium layer where different inclusions' content, shape and orientation can be taken into account. The use of depolarization factors defined along the three main axes [2] allows to treat inclusions as oriented ellipsoids.

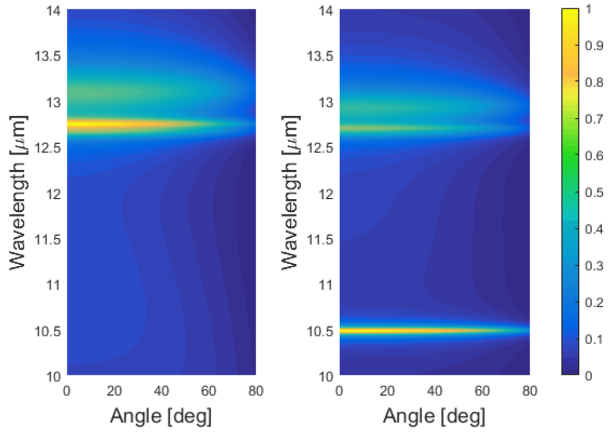

Figure 1 Emissivity spectra calculated for TE polarized fields as functions of wavelength and incidence angle for (a) a single SiC layer and (b) a SiC layer with 20% oriented air inclusions. SiC thickness is 1 micron, onto a Si substrate.

The resulting dielectric constant display very different features in the directions of the three main axes making possible the tuning of spectral emissivity curves. One of the most intriguing feature of such nanostructured media is the random spatial alternation of inclusions and matrix, which offers the possibility to excite the longitudinal polaritons even at normal incidence and for the TE polarization (Figure 1).

We have shown how anisotropic ellipsoids can be arranged, choosing both shape and orientation, so that the resulting spectral emissivity could match the emissivity peaks of hazardous chemicals for different polarizations of the emitted light. As an example, we designed a metamaterial-based device that matches the emissivity lines of two explosives, such as XRD (cyclotrimethylenetrinitramine) and TNT (trinitrotoluene), providing a double check in polarization that could increase accuracy of chemical sensors [3].

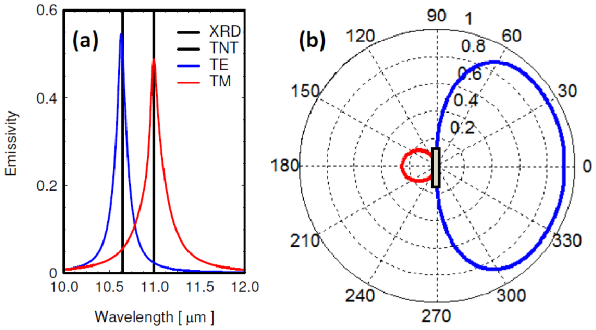

Figure 2. (a) Spectral emissivity calculated for a system composed by oriented SiC inclusions into air matrix [3]. (b) polar plot of emissivity curve calculated at 10.48 micron, for a SiC layer 4 microns thick with graded air porosity [4].

Many configurations can be considered by applying the same model in order to get also spatial modulation of infrared emissivity. We investigated a multilayer structure where the inclusions content is varying along matrix thickness to obtain strongly asymmetric emissivity features. Optimization of the porosity degree along the matrix thickness was performed in order to maximize the contrast between forward and backward infrared emission, in single SiC layer only few microns thick [4].

Furthermore, changing the shape of inclusions cross section opens the way to very unusual features of the resulting effective medium. The typical ellipsoid of the refractive indices can be shaped as an uniaxial or even biaxial hyperboloid, in correspondence of negative values of the dielectric constant along one or two directions.

Taming and tuning the strength and the position of the phonon resonance in polar materials allows the design of versatile optical elements as basic elements for further developments of infrared filters, thermal diodes and thermal logic gates.

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