Study and Optimization of Fishnet Metamaterial Structures

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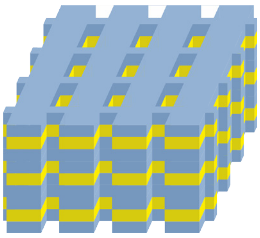
Abstract

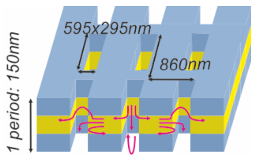
The full-wave numerical simulations of plane-wave excitation of the multilayered nano-fishnets are performed using the in-house made RCWA based software and FDTD MEEP as well as commercial Photon Design tool. The reflection and transmission coefficients are calculated and the material parameters are consequently extracted from the obtained data. Furthermore, the frequency dependence of the effective negative index of refraction is predicted using the semi-analytical approach, describing the wave coupling processes within the fishnet structure, and hence providing more physical insight into these perspective metamaterial structures.

1. Introduction

Metamaterials (MMs) represent the class of artificially-made structures consisting of thin layers, periodically arranged sub-wavelength cells, and / or their combinations. Due to interactions on the scale of few wavelengths, such structures can be designed and engineered to exhibit macroscopic properties, often being fundamentally different from those of the conventional materials. Indeed, under specific conditions, effective negative permittivity and permeability can be achieved by controlling the resonance behaviour with the support of excitations of surface plasmon polaritons (SPP). Basic understanding of MMs, today generally consisting of subwavelength arrangements of non-uniform multilayers, periodic arrangement of plasmonic “nanoparticles” and / or nanostructures, suspended in a background host-medium, is often supported with the concept of homogenization, substituting the light propagation in such complexly structured materials with the interaction through a homogeneous layer with equivalent effective optical properties. However, in view of potential applications of these MM materials, in a variety of areas ranging from sub-wavelength imaging to cloaking, it is also crucial to grasp the underlying physics and hence being able to optimize the optical response and overall performance of such structures.



(a)



(b)

Fig. 1: (a) Example of fishnet metamaterial structure consisting of several MIM layer periods (typically of 150nm thickness), (b) detailed vertical 1 period cut revealing interaction processes inside fishnet structure.

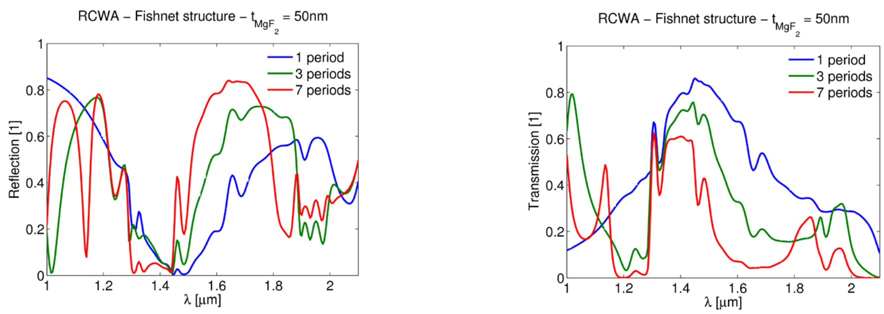
In this contribution, we have focused on theoretical study, both rigorously and semi-analytically, of one specific class of MM structures, called fishnets, consisting of combination of metal and dielectric layers with a periodically arranged sub-wavelength holes drilled in it [1,2]. Fig. 1 reveals such typical fishnet structure under consideration as well as the vertical cut of 1 period where the ongoing elementary processes are also depicted. One of our aims was, in this contribution, indeed, to selectively change fishnet parameters, in order to reveal the interaction processes within the structure and to achieve desired optical effective parameters.

2. Rigorous numerical and semi-analytical modeling of fishnets

In order to model the optical properties of the fishnet MM structure, we have used both our in-house implemented (2D periodic) RCWA method [3,4], as well as FDTD based MEPP and commercial Photon Design [5] tools. Additionally, FDTD tool has been also used to obtain scattering coefficients necessary for the semi-analytical model. Our semi-analytical approximate approach, inspired with [6-10], was based on the field interaction and energy tracking throughout the fishnet mesh. In this model, light propagation and scattering processes are described via coupled-mode approach, involving propagation of the fundamental Bloch modes through the structural holes, as well as their scattering into the SPP mode propagating along the metal-insulator-metal structural boundaries. Indeed, such procedure allows one to separate the effective material parameters of the whole structure.

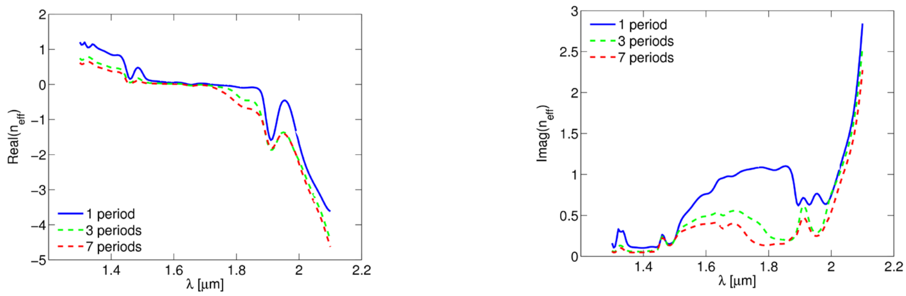
3. Results

Spectral dependencies of the power transmissions (T) and reflections (R) presented here (Fig. 2) were calculated by our RCWA method; for 1, 3 and 7 MIM period arrangements. Further-more, from these data, the extraction of the effective MM parameters was performed. For this purpose, several effective MM parameters retrieval methods [11-13] were implemented and applied to extract the effective permittivities and permeabilities, from the calculated complex reflection and transmission characteristics, at particular thickness of a homogenized structure with equivalent properties. As an example, the resulting frequency dependencies of the real and imaginary parts of the effective refrac-tion indices are summed up in Fig. 3.



(a) (b)

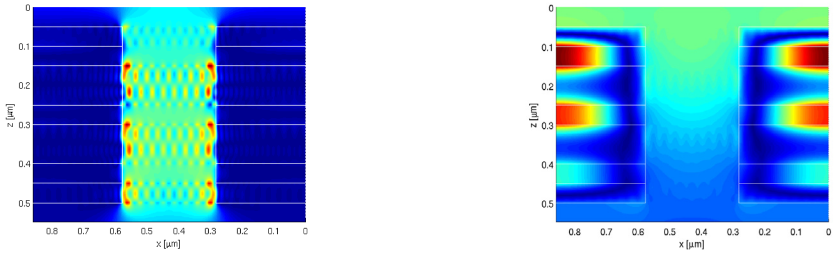
Fig. 2: Reflection (a) and transmission (b) intensity spectra of the fishnet structure, with the dependence on the number of MIM periods as the parameter.



(a) (b)

Fig. 3: Spectral dependences of the real (a) and imaginary (b) parts of the effective refractive index of fishnet structures under consideration, with the dependence on the number of MIM periods as the parameter.

Additionally, as another supporting example, Fig. 4 shows field profiles at wavelength λ=1.78µm, corresponding to the minimum in the transmission spectra for 3 MIM period structure which is needed to identify the principal mode carrying the energy and its degree of localization. Scattering at the intersection of the two sub-wavelength channels excites the plasmon polariton of the MIM structure which propagates in the *x*-direction and recovers the energy back to the Bloch mode at the neighbouring period, resulting in the decrease of the imaginary part of the refractive index (see green curve in Fig. 3).



(a) (b)

Fig. 4: Demonstration of the calculated field profiles within 3 MIM period fishnet structure: (a) absolute value of the E_x and (b) H_y fields (@λ=1.78μm).

4. Conclusion

To conclude, by combining the exact numerical modelling and insight from approximate models, we have been able to reveal in detail, the physics behind the light interaction with fishnet MMs structures. Also, by performing parametric studies of several fishnet configurations, we have optimized the geometrical structural parameters, and thus the performance of these configurations.

Acknowledgement

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