Design of Optical Metamaterials

S. Maisch, P. Schau, K. Frenner, H. Schweizer, and W. Osten

Institut fuer Technische Optik (ITO), Universitaet Stuttgart
Pfaffenwaldring 9, D-70569 Stuttgart, Germany

mailto:itomaisc@ito.uni-stuttgart.de

Materials with simultaneous negative magnetic permeability and electric permittivity are able to transmit electromagnetic waves without exponential damping. These materials gained attention because they can be used for sub-wavelength resolution imaging. We performed a geometric optimization of metamaterials using rigorous coupled wave analysis (RCWA) simulation.

Introduction

After the theoretical prediction of *V. Veselago*[1] in 1976, materials with simultaneously negative magnetic permeability $\mu < 0$ and electric permittivity $\varepsilon < 0$ being able to transmit electromagnetic waves without exponential damping, *J. Pendry*[2] showed these systems bending light in the “wrong direction”, namely showing a negative index of refraction $n < 0$. These materials are commonly referred to as “metamaterials”.

Today, there is much interest in these materials, as they are capable of sub-wavelength optical imaging,[3, 4] by directly manipulating the electromagnetic near field.

In this work, we performed rigorous coupled wave analysis (RCWA)[5-9] simulations of split-ring resonator (SRR) and meander metamaterials with the aim to geometrically optimize the structures for deep and broad resonances and lowering the absorption.

Optical Metamaterials

There is a wide variety of nanometer-sized periodic structures that act as metamaterials in the optical wavelength range. In our work, split-ring resonators (SRRs)[10, 11], and meander surfaces (Fig. 1) were examined.

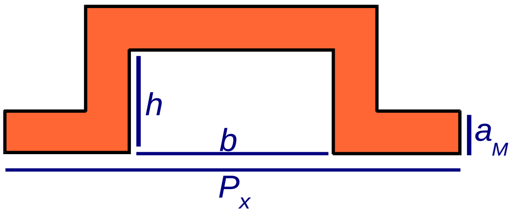

Fig. 1 *Cross section of one unit cell of size P_x of the one-dimensional meander structures used. The geometric parameters b, h (height of dielectric), and a_M (thickness of metal layer) are defined herewith.*

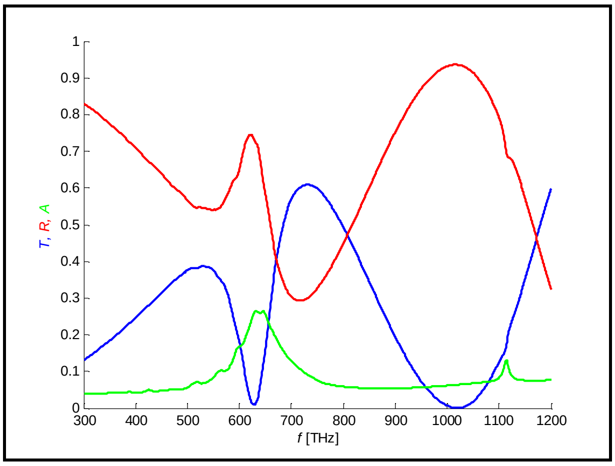

Fig. 2 *Transmission (T, blue), reflection (R, red), and absorption (A, green) spectra of the meander structure at normal incidence.*

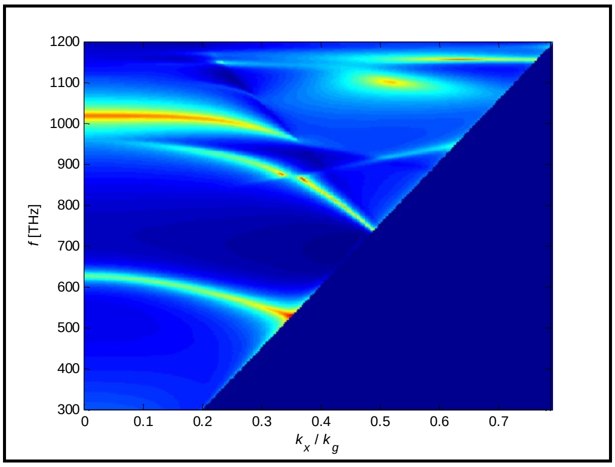

Fig. 3 *Dispersion plot of the meander structure. The color function is chosen according to -ln(T) showing the absorption bands of the plasmons. The normalized expression k_x / k_g represents the transversal photon momentum.*

As the experimental realization of these structures is a complex procedure, it is very important to have access to optimized geometries before manufacturing them by nanofabrication methods. Therefore, we have established a method for simulating the behavior of metamaterials in the electromagnetic field of the light wave.

An RCWA simulation gives the transmission, reflection and absorption spectra, which can be used to retrieve the index of refraction, and to calculate the dispersion diagram of the plasmonic system. Here the fact is used that RCWA allows for the simulation of light incident at any angle. This makes it possible to vary the transversal component of the photon linear momentum. RCWA requiring a periodic structure for its input makes it convenient for this problem and superior to other Maxwell solvers, because metamaterials are inherently periodic in two or three dimensions. Convergence is achieved easily, because in the case of sub-λ structures, only the zeroth diffraction order is propagating.

The simulated spectra are in very good accordance to experimental measurements, which were done using large area meander surfaces on glass slides, relatively easily available from laser interference patterning of photo resist.

Fig. 2 and Fig. 3 show the spectra and dispersion plot of a meander with arbitrarily chosen geometric parameters ($P_x = 200$ nm, $b = 80$ nm, $h = 50$ nm, $a_M = 20$ nm).

From this starting point, we have established an optimization procedure of the nanostructure geometry to achieve a resonant behavior leading to negative refraction. It simultaneously optimizes the magnitude of the negative refraction and minimizes the loss.

We used a retrieval algorithm[12-14] for the determination of the real and imaginary part of the refractive index n. Fig. 4 shows the result for an optimized structure with geometric parameters different from that of Fig. 2 and 3. It does have a broad and deep region of negative refraction (real part) with simultaneously acceptably low absorption (imaginary part).

Conclusions

Meander structures are promising for the nanofabrication of systems showing negative refraction and being able to image the optical near-field.

We have performed an RCWA simulation of these structures, and optimized them geometrically. Optimized structures show the effect of negative refraction and might be used for various applications of metamaterials like sub-λ imaging, magnification and near-field to far-field transformation.

The next work is the simulation and experimental preparation of far-field propagating devices.

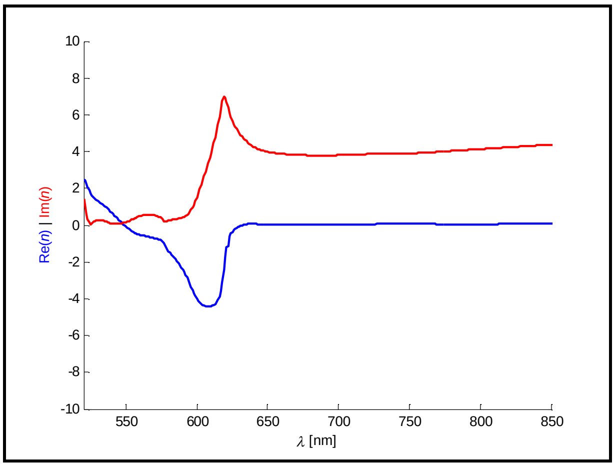

Fig. 4 *Real (blue) and imaginary (red) part of the index of refraction for an optimized meander structure. Its geometric parameters are: $P_x = 400$ nm, $b = 170$ nm, $h = 30$ nm, $a_M = 30$ nm.*

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