A combinatorial approach to metamaterials discovery

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Abstract

Some fifteen years ago a paper reporting a combinatorial approach to materials discoveries revolutionized materials research and other disciplines such as chemistry and pharmacology [1]. Here we report on how a combinatorial approach combined with advanced nanofabrication helps to discover photonic metamaterials optimized for prescribed functionalities.

1. Introduction

In this paper we report on a new approach to discovery of electromagnetic metamaterials and their optimization that relies on a parallel synthesis of spatially addressable libraries of materials. A library of regular arrays of split ring meta-molecules with different combinations of size, asymmetry and line width were generated by electron beam lithography on a single glass wafer. The ability to generate and screen combinatorial libraries of metamaterials, when coupled with theory and empirical optical characterization, may significantly increase the rate at which novel optical materials are discovered and optimized and theoretical predictions tested.

In this work we demonstrate the combinatorial approach for photonic metamaterials based on asymmetrically split rings. Such structures are important for a number of applications such as photonic switches, slow light devices, spectral filters and the lasing spaser.

2. Results and Discussion

As illustrated by Fig. 1, combinatorial metamaterial discovery consists of two main steps: (i) the creation of a spatially addressable library of metamaterial samples with systematically varying design parameters and (ii) metamaterial characterization with respect to certain desirable properties. Furthermore, simulations may be used to identify ranges of promising design parameters, thus speeding up the convergence on the optimal metamaterial design.

Here we have created a spatially addressable library of photonic metamaterials that are based on split ring apertures. Using electron beam lithography such aperture arrays with a size of $30 \times 30\ \mu\text{m}^2$ were written in a 30 nm thick gold film supported by a silica substrate. Key design parameters of such structures are the split ring asymmetry and the meta-molecule size, see Fig. 2 (a). As illustrated by Fig. 2 (b), our library contains metamaterials with unit cell sizes s between 400 nm and 500 nm (25 nm steps) and split ring asymmetries t/l between 0.1 and 0.7 (steps of 0.1).

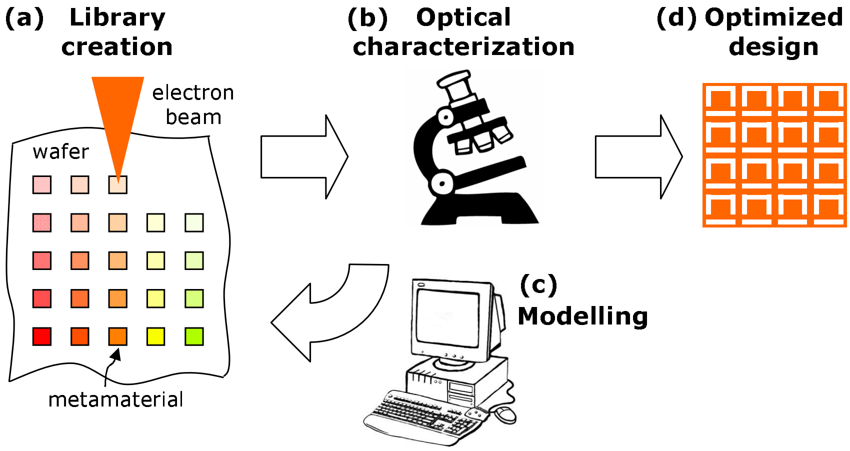

Fig. 1: Combinatorial metamaterial discovery. (a) Metamaterial library creation via electron beam lithography. Several structural parameters of the metamaterial design are varied systematically. (b) Optical characterization, e.g. using a microspectrophotometer. (c) Computer modelling in order to find a promising parameter range for the next metamaterial library. (d) Optimized metamaterial design.

The transmission characteristics of these photonic metamaterials were measured using a microspectrophotometer in the spectral range from 800 to 2000 nm, a typical spectrum is shown by Fig. 2 (c). Asymmetrically split ring metamaterials are known to support narrow (trapped mode) resonances needed for applications including photonic switches, sensors, spectral filters and the lasing spaser. As narrow, high quality factor resonances are desirable for these applications, we define a figure of merit that quantifies the resonance width, $FOM = \lambda_0/\Delta\lambda$, where λ_0 is the wavelength of the trapped mode resonance, while $\Delta\lambda$ is the separation of the neighboring transmission maxima. Transmission through the structures was also simulated using a full three-dimensional Maxwell finite element method solver in the frequency domain.

As illustrated by Fig. 3, both simulations and experiments clearly show that the resonance width strongly depends of the asymmetry of the split ring. Here larger asymmetries lead to narrower resonances, where the resonance width halves as the asymmetry t/l increases from 0.3 ($FOM \sim 1.6$) to 0.7 ($FOM \sim 3.2$).

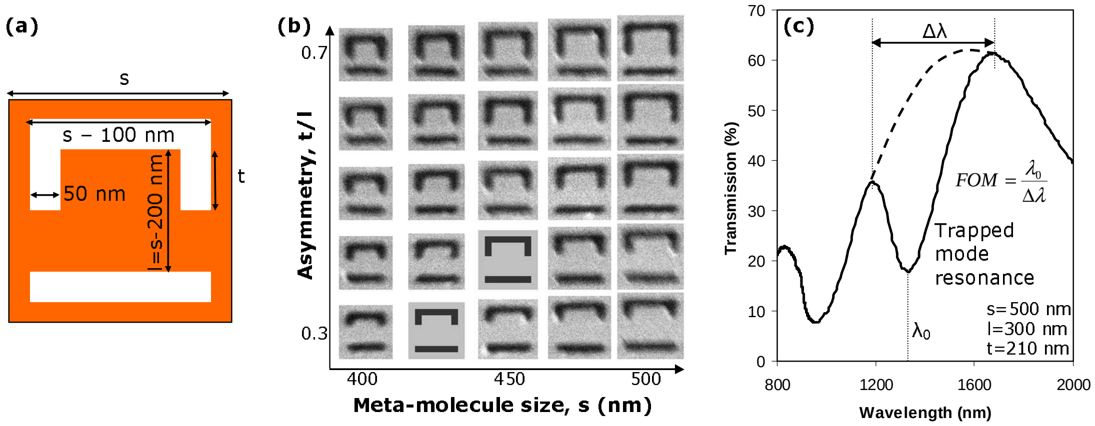

Fig. 2: (a) Schematic of the metamaterial unit cell. (b) The metamaterial library, where each array is represented by its unit cell. (c) Typical transmission spectrum of an asymmetrically split ring metamaterial. The figure of merit, FOM, quantifies the width of the trapped mode resonance. The typical spectrum of a symmetrically split ring metamaterial is indicated by a dashed line.

It should be noted that for smaller asymmetries no trapped mode resonance can be identified. For larger asymmetries, simulations indicate even narrower resonances, however, due to the very small splitting of the ring such structures are very difficult to manufacture. Remarkably, the dependence of the resonance width on the split ring asymmetry is exactly opposite to microwave metamaterials of this type, for which narrow trapped mode resonances arise from small asymmetries. This behavior can be explained by the fact that trapped modes at microwave frequencies are governed by scattering losses, while in photonic metamaterials they are governed by absorption losses.

Intriguingly, the figure of merit also depends on the size of the metamaterial unit cell. While increasing losses in metals at shorter wavelengths should generally lead to relative resonance broadening for smaller structures, here we see exactly the opposite behavior. Smaller split rings of the same asymmetry have a higher figure of merit. This counter-intuitive behavior may be explained by the plasmonic properties of gold.

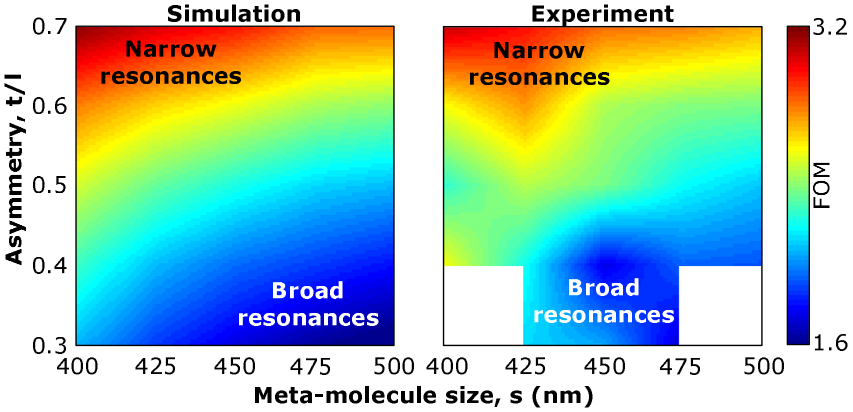

Fig. 3: Combinatorial optimization of photonic metamaterials for switching and sensing applications. The narrowest resonances [high figure of merit (FOM)] are achieved for split ring apertures of high asymmetry t/l and small size s.

4. Conclusion

In summary we introduce a combinatorial approach to the design of metamaterials. We apply this technique arrays of asymmetrically split ring apertures, which show narrow trapped mode resonances and could form the basis of a huge range of applications. Here the split ring design showing the best performance (narrowest resonance) has a large asymmetry of $t/l = 0.7$ and a unit cell size of $s = 400$ nm.

The resonant properties of split ring nanostructures also depend on the gap position and the width of the nano-slits. At the conference we will present a comprehensive combinatorial study taking also these design parameters and the resonance depth into account. Thus we will provide the complete recipe for manufacturing planar photonic metamaterials with high quality factor resonances for applications from sensing, switches and electromagnetically induced transparency to possibly even a lasing spaser.

References

[1] X.-D. Xiang, X. Sun, G. Briceño, Y. Lou, K.-A. Wang, H. Chang, W. G. Wallace-Freedman, S.-W. Chen and P. G. Schultz, A Combinatorial Approach to Materials Discovery, *Science,* vol. 268, p. 1738, 1995.