Multi-band Metamaterials with a Distinguished Angular Sensitivity

N. Born,[1] L. M. Schneider,[1] J. C. Balzer,[1] I. Al-Naib,[2] R. Singh,[3] A. Velauthapillai,[1] M. Scheller,[4] J. V. Moloney[4]
and Martin Koch[1]
[1]Faculty of Physics and Material Sciences Center, Philipps-Universität Marburg, Renthof 5, 35032 Marburg, Germany
[2]Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston K7L 3N6, Canada
[3]Center for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore
[4]College of Optical Sciences, University of Arizona, 1630 E University Boulevard, Tucson, AZ 85721, USA

Abstract **– A metasurface with an ultrahigh angular sensitivity to the angle of incidence at a chosen frequency is presented. Strongly interacting metamolecules are arranged such that a novel functionality of a metamaterial structure with multiple Fano resonances arises. Tuning the lattice constant of the structure enables a precise control of the angular response. We experimentally demonstrate equal responses for changes in azimuthal and for altitude angles of incidence. The concept could be used to enhance angle of arrival measurements, to determine the direction of a propagating wave or enhance the sensitivity of detectors by shielding them from scattered or unwanted signals.**

I. INTRODUCTION

METAMATERIALS have inspired numerous studies due to the fact that the electromagnetic characteristics of these artificial structures can provide useful features not found in nature. In contrast to recent studies which focus on properties of metasurfaces at oblique incidence attempt to reach frequency insensitive configurations [1–4], we study and present a metasurface with a very high angular sensitivity at a selected resonance. A multi-band, high *Q* metamolecule [5] has been designed and optimized for this purpose. As a result, we achieve a strong response with respect to the wavevector of an incident wave at only one resonance of the multi-band metamolecule.

II. RESULTS

The proposed structure basically consists of asymmetric Double Split Ring Resonators (aDSR) [6] similar to the unit cells depicted in Fig. 1. To form multiple trapped mode resonances, the resonators on the anti-diagonal of the lattice have a slightly different asymmetry angle (see Fig. 2 (a)).

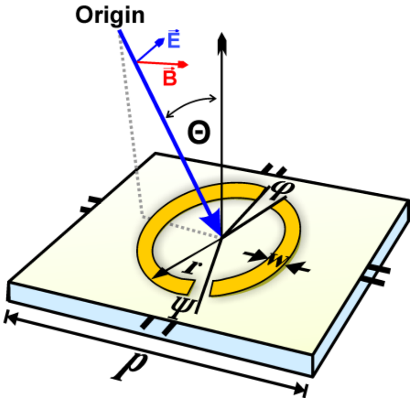

Fig. 1. Scheme of an asymmetric Double Split Ring Resonator at oblique incidence

The geometrical dimensions of the resonators are: $r = 55$ µm, $w = 10$ µm, $\Psi_1 = 11°$, $\Psi_2 = 22°$, $\varphi = 12°$ and a distance from the middle of one resonator to the next neighbor of 160 µm. From this, one can calculate the side length of the primitive cell to be: $p = \sqrt{2 \cdot 160\ \mu m^2} \approx 226\ \mu m$ (see Fig. 2 (b)). A detailed study of the properties and the transmission characteristics at normal incidence can be found in Ref. [7], which would go beyond the scope of this manuscript.

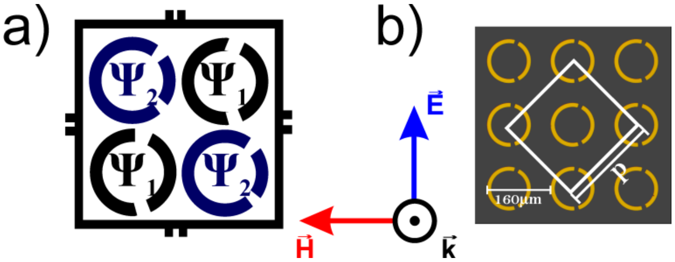

Fig. 2. Schematics of the metamolecule with two different resonators in a chessboard arrangement (a). A photo of a fabricated sample (b) and the primitive cell (white rectangle).

The samples were fabricated by standard photolithography techniques on a fused silica substrate. Measurements were performed in a THz-TDS setup with photoconductive antennas as detector and emitter [8]. The samples were mounted on a thick fused silica block to exclude Fabry-Pérot echoes from the signal pulse that arises from the reflection on the back side of the substrate. Simulations were performed with the commercial Software *CST Microwave Studio* in the frequency domain solver with unit cell boundary conditions.

Fig. 3 shows the measured and simulated transmission characteristics of the metamolecule. Additionally, the angle of incidence is varied for the azimuthal angle and for the altitude angle.

In the transmission spectrum of this metamolecule at an angle of incidence of 0°, different Fano-like resonances emerge [7] as shown in Fig. 3. The two sharp resonances at the lowest frequencies ($f_1 = 0.472$ THz and $f_2 = 0.517$ THz) are interpreted to be the two trapped modes of the different resonators with $\Psi_1 = 11°$ and $\Psi_2 = 22°$, respectively. The resonance at $f_3 = 0.661$ THz is a collective excitation of the strongly interacting currents on the metaatoms, which form a Fano-like mode similar to the former mentioned trapped modes – but this time with opposing currents in the neighboring resonators [5].

Furthermore, the measurements reveal the modified transmission through the metasurface by changing incidence angle Θ (Fig. 3). Ref [9] gives a detailed discussion about this characteristics and the reasons, using the example of a comparable metamolecule.

In the presented multi-band metamolecule, the size of the primitive cell p is very close to the effective wavelength v_{f3} of the resonance frequency f_3. At this resonance, we expect v_{f3} to be at $c/(n \cdot f_3) = c/(1.96 \cdot 0.661THz) \approx 231\ \mu m$, were n is the refractive index of the substrate and c is the speed of light in vacuum. This value is slightly larger than $p \approx 226$ µm. Hence, the resonance f_3 is very sensitive to the angle of incidence radiation. For all other resonances the sensitivity to the angle is rather negligible in the discussed range of the incidence angle, since the former mentioned criterion for the size of p in respect to the resonance frequency is not fulfilled.

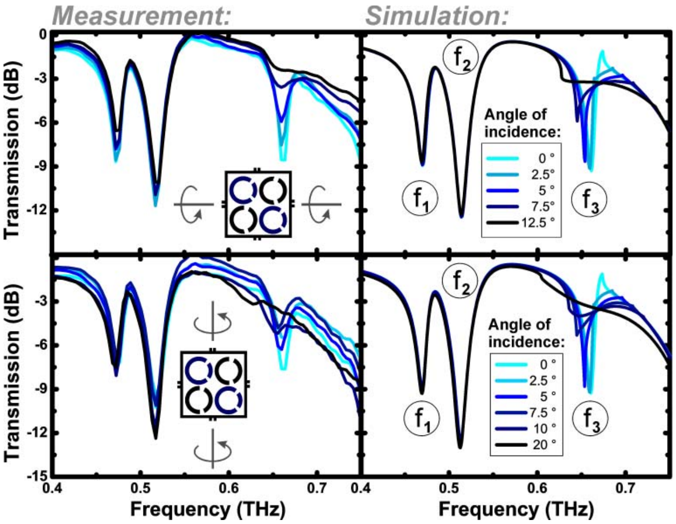

Fig. 3. Measured (left) and simulated (right) transmission characteristics of the metamolecule at different incidence angles for rotations around the altitude (top) and around the azimuthal angles (bottom).

As a result, a very strong response of the resonance f_3 is observed with respect to changes of the incidence angle Θ, while the resonances f_1 and f_2 remain almost unaffected. This is a remarkable finding, since the angular effect already takes place for very small changes. Furthermore, we have experimentally achieved a similar behavior to the angle of incidence for the azimuthal angle and for the altitude angle. Additional simulations (not shown here) show that complementary metamaterials based on the Babinet principle [10], [11] can also be realized. They could exhibit sharp pass-bands that can be used to achieve a pronounced tunnel vision. Moreover, this concept could be easily applied for polarization independent metamolecules [12].

III. CONCLUSION

In conclusion, we presented a general concept to design metasurfaces with a pronounced sensitivity to the angle of incidence. We proof our concept with an experimental characterization of a metamolecule, which shows a significant angular sensitivity for both azimuthal and for the altitude angles of incidence.

Our concept may find application in future techniques to determine the direction of a propagating wave or enhance the sensitivity of detectors by shielding them from scattered or unwanted signals.

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