Flexible metamaterials at visible frequencies and applications

A. Di Falco[1], Y. Zhao[2], A. Alù[2]

[1]School of Physics and Astronomy, University of St Andrews
North Haugh, KY16 9SS, St Andrews, Fife, UK
Fax: + 44–1334463104; email: adf10@st-andrews.ac.uk
[2]Department of Electrical and Computer Engineering, The University of Texas at Austin
1 University Station, C0803, Austin, Texas, USA
Fax: + 1-5124716598; email: alu@mail.utexas.edu

Abstract

We discuss our recent results regarding the realization and characterization of metamaterials on flexible substrates at visible wavelengths (Metaflex). We outline the fabrication procedure and show the electromagnetic response for different plasmonic structures. We also report on the verification of Fano resonances on Metaflex, which yields to ultra-narrow spectral features in flexible plasmonic surfaces, and on the realization of a flexible metamaterial with response independent on polarization and angle of incidence.

1. Introduction

Possibly the most attractive feature of metamaterials (MMs) is the possibility to design at will their electromagnetic response by tailoring the distribution of their smallest constituents [1]. For example, transformation optics applies naturally to MMs technology, because controlling the topology of the meta-atoms allows the manipulation of light with unprecedented accuracy [2]. While most of the practical realizations of MMs are made on flat and rigid substrates, as required by classic lithographic techniques, recently researchers have started to develop approaches to fabricate MMs in flexible substrates [3-5]. Flexible and supple substrates naturally implement and conform to complex geometries and, most remarkably, flexible MMs could be used to tune their topology, hence their electro-magnetic response [3], according to changing environmental conditions or specific requirements. Here we report on the design, fabrication and characterization of flexible MMs at visible frequencies (Metaflex) [6]. We first discuss briefly the fabrication procedure and then focus on three specific meta-atoms and patterns, each yielding a unique and specific optical response of Metaflex.

2. Metaflex

To fabricate the membranes, we spin a lift-off sacrificial layer on a silicon carrier wafer followed by a SU8 polymer (Microchem) layer of the desired thickness. After UV exposure and baking to complete the polymer cross-linking, we deposit a layer of gold (typically from 10 nm to 40 nm thick) by electron beam evaporation. The nanopatterns are typically written on a further layer of SU8, now used as mask, with a modified LEO/Raith Elphy Electron Beam Lithography system, with an accuracy of 2 nm. After 2 minutes of post-exposure curing at 100C and development for 45 s in EC, the patterns are transferred on gold with dry etching, using an Ar assisted RIE process. Finally, the membranes are chemically released and mounted on a sample holder for characterization. Membranes with thickness down to few microns can easily be manipulated, as shown in Fig. 1.
The inset in the same figure shows an SEM picture (bottom) of a fishnet structure, with period of 1μm and wires width of ~100 nm on a 4 μm thick membrane. The experimental transmission curve at normal incidence for this metasurface, for two orthogonal polarizations aligned along the wires, is shown in the top inset of fig. 1. The characteristic dip at 620 nm demonstrates how this geometry could yield a flexible bulk negative index material in the visible region, by stacking several layers of Metaflex. The alignment accuracy requirements and the behaviour of the resulting 3D material under stress and

distortion are currently under investigation, and go beyond the scope of this paper. While, as discussed, our patterned membranes could be used to fabricate flexible 3D MMs in the visible, a single layer of Metaflex offers novel physical mechanisms, which will be addressed in the following sections.

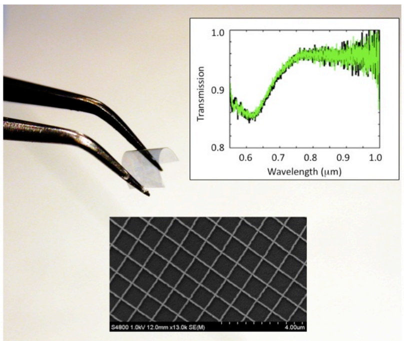


Fig. 1: A metaflex sample held with tweezers. The bottom inset shows a SEM picture of a fishnet structure, the top inset shows its transmission curves for orthogonal polarizations, aligned along the wires.

3. Fano Resonance

In Fig. 2 we show an SEM picture of a one-dimensional grating (gold thickness 40nm) on a Metaflex membrane with thickness 1 μm. The numerical transmission map for different wavelengths and duty cycle is shown the inset. The reduced thickness of the membrane induces Fabry-Perot resonances, which interact with the gold grating, producing narrow spectral features due to Fano-resonances [7]. Remarkably, as the duty cycle is varied, it is possible to obtain both high and low transmission narrow features, with maximum and minimum value as high as 100% and 0%, respectively. The possibility to obtain plasmonic resonances with linewidth well below 1 nm, and weakly affected by the typically detrimental losses, could be efficiently used for a new class of sensing and integrated optical devices. The system behaviour has been characterized numerically and experimentally for all the relevant geometrical parameters [8]. Additionally, the one-dimensional grating could be designed to be insensitive to the angle of incidence [9], thus granting a response independent on the curvature of the membranes (under minimum pattern deformation due to stretching and bending). While this mechanism, currently under investigation, is predicted to be polarization dependent [10], it is possible to design Metaflex meta-atoms that support resonances in the visible range, independently from the angle of incidence and polarization of light, as discussed in the next section.

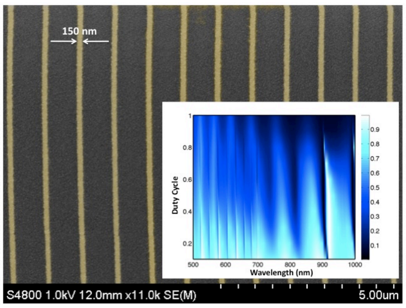
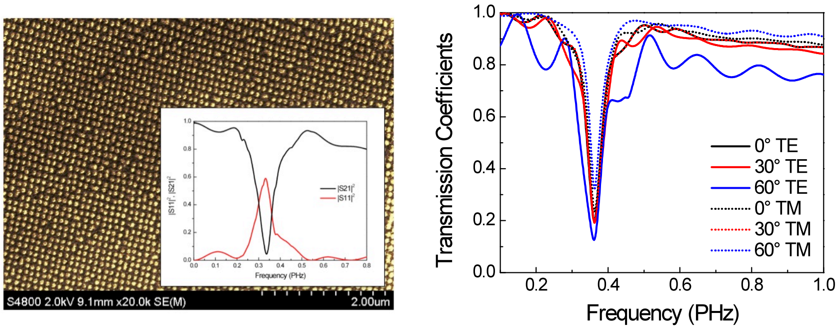


Fig. 2: SEM picture of a one-dimensional grating (period 1 μm and wires width 150 nm). The inset shows the calculated transmission vs wavelength for different duty cycles.

4. All angle reflectors

In the framework of frequency-selective surfaces (FSS), it is well established that a single patterned layer of metal could support resonances independently on the angle of incidence and polarization: this occurs when the metallic features are arranged with a period well below the wavelength of light [11]. We have fabricated a Metaflex sample with meta-atom made of gold disks of thickness 30 nm, period

100 nm and diameter ranging from 60 nm to 80 nm (see fig. 3 for a SEM picture of a typical sample). The inset of fig. 3 (a) shows the calculated reflection (red) and transmission (black) curves for this system, fabricated on membrane of thickness 4μm. Fig. 3 (b) shows the full wave numerical simulation results of the polarization and angle independence of the optical resonance for such structure. It is seen how the position of the resonance dip is unchanged with varying the incidence angle from normal incidence to 60°, and similar results are obtained for both transverse electric and transverse magnetic polarized inputs, indicating the polarization independence of the structure. We have also experimentally confirmed these findings (the experimental data are not shown here) [12]. We predict that similar independence of the transmission spectra may be obtained upon arbitrarily bending the metasurface.



(a) **(b)**

Fig. 3 (a) SEM picture of a Metaflex composed of gold disks (period 100 nm, diameter 70 nm). The inset shows the calculated reflection (red) and transmission (black) vs frequency. (b) Simulated transmission spectra for different incidence angles.

4. Conclusions

We have presented our progress on the fabrication and characterization of flexible metamaterials at visible frequencies. We have shown that Metaflex offer all the peculiar properties of MMs, while supporting novel physical mechanisms, unique to a supple and deformable membrane MM.

References

[1] C. M. Soukoulis, S. Linden, M. Wegener, Negative refractive index at optical wavelengths, *Science,* vol. 315, p. 47, 2007.

[2] U. Leonhardt and T. G. Philbin, *Geometry and Light: the Science of Invisibility*, Mineola, NY: Dover, 2010.

[3] I. M. Pryce, K. Aydin, Y. A. Kelaita, R. M. Briggs, and H. A. Atwater, Highly Strained Compliant Optical Metamaterials with Large Frequency Tunability, Nano Lett., vol. 10, p. 4222, 2010.

[4] H. Tao, A. C. Strikwerda, K. Fan, W. J. Padilla, X. Zhang and R. D. Averitt, Reconfigurable Terahertz Metamaterials, Phys. Rev. Lett., vol. 103, p. 147401, 2009.

[5] N. Gibbons, J. J. Baumberg, C. L. Bower, M. Kolle, and U. Steiner, Scalable Cylindrical Metallodielectric Metamaterials. Adv. Mater., vol. 21, pp. 3933, 2009.

[6] A. Di Falco, M. Ploschner and T. F. Krauss, Flexible metamaterials at visible wavelengths, New Journal of Physics, vol.12, p. 113006, 2010.

[7] U. Fano, The theory of anomalous diffraction gratings and of quasi-stationary waves on metallic surfaces (Sommerfeld's waves), J. Opt. Soc. Am., vol. 31 p. 213S, 1941.

[8] A. Christ, S. G. Tikhodeev, N. A. Gippius, J. Kuhl, and H. Giessen, Waveguide-Plasmon Polaritons: Strong Coupling of Photonic and Electronic Resonances in a Metallic Photonic Crystal Slab, Phys. Rev. Lett., vol. 91, p. 183901, 2003.

[9] A. Di Falco *et al.*, Fano-assisted resonances in flexible metamaterials, in preparation.

[10] F. J. Garcia-Vidal and L. Martin-Moreno, Transmission and focusing of light in one-dimensional periodically nanostructured metals, Phys. Rev. B, vol. 66, p. 155412, 2002.

[11] J. A. Gordon, *et al.*, A physical explanation of angle-independent reflection and transmission properties of metafilms/metasurfaces, IEEE Antennas Wireless Propagat. Lett., vol. 8, pp. 1127-1130, 2009.

[12] A. Di Falco, Y. Zhao, A. Alu, All angle reflector in flexible metamaterials, in preparation.