Tailored metamaterials for Extremely High-Resolution Imaging and Sensing (TEHRIS)

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ABSTRACT
The TEHRIS project focuses on the development of an innovative super-resolution imaging system based on a Hyperbolic Metamaterial (HMM) lens. The proposed device, constituted of alternating layers of metal and dielectric, works as a so-called "perfect lens" and its operational wavelength can be tuned along the whole visible range by modifying the refractive index of the layers during the deposition process. The HMM-based super-resolution system studied in the context of TEHRIS, promises to have a significant impact on a variety of fields, ranging from high-resolution imaging of biological samples to the sensing of low molecular weight molecules and quantum optics.

Keywords: perfect lens; hyperbolic metamaterials; tuneable device.

1. INTRODUCTION

Hyperbolic Metamaterials (HMMs) are extremely anisotropic nanostructures created artificially, whose optical response can be tailored to meet the requirements of new-generation photonic technologies. Due to the hyperbolic dispersion, HMMs support high wavevector modes (high-k modes), confined within the structure. The most common HMM configuration consists in alternated metal/dielectric layers, whose thickness is much smaller than the wavelength. The light confinement and manipulation possibilities offered by such a configuration are especially promising in bio-chemical sensing, spontaneous emission enhancement and optical sub-wavelength resolution imaging. The latter is the scenario in which HMM technology expresses its greater potential, with the development of the so-called "perfect lenses". HMMs, indeed, allow to overcome the diffraction limit by several orders of magnitude, enabling the imaging and investigation of both organic and inorganic materials – whether these are soft or hard, and independently on their solid or liquid form – with a resolution that is mainly limited by their unit cell thickness. However, HMM perfect lenses suffer a lack of tunability that severely hinders their design flexibility and, therefore, their application range.

The HMM architecture investigated in the framework of TEHRIS overcomes this limitation by modifying the refractive index of the dielectric layers directly during the deposition process. Following this technique, we designed a system that provides an imaging resolution down to approximately 50 nm, which is knowingly unachievable with conventional optical systems. Based on subwavelength light interactions, this method is accurate and completely non-invasive.

- We designed, fabricated and characterized chip-sized meta-lenses with operating wavelength in the whole visible range.
- Proof-of-concept confocal experiments demonstrated the possibility to obtain hyper-resolution imaging.
- Moreover, a new graphene based HMM meta-lens allowing to reach resolution down to $\lambda/500$ has been numerically investigated.

The possibility of selecting the operational wavelength of an HMM lens using only two materials represents a significant step forward towards the rapid commercialization of high-resolution imaging systems working in the visible range, making the core of TEHRIS project ready for a future application step.

2. STATE OF THE ART

Classic optical imaging techniques, like polarized and confocal microscopy, are diffraction limited. One alternative is the so-called Scanning Near Optical Microscopy (SNOM). This technique is based on the excitation and detection of evanescent waves arising in the near field region of the object to be imaged. The resolution achievable with this technique can be enhanced to reach the nanometre scale, however, dedicated expensive setups with delicate tools, such as nano-metric hollow tips, have to be used.

In the last decades, HMM lenses have emerged as a new compact and cheap approach for encompassing diffraction limited imaging systems [1]. To this aim, it is necessary to design an HMM in which the real parallel dielectric permittivity ($\varepsilon_{||}$) is equal to zero and the real perpendicular dielectric permittivity ($\varepsilon_{\perp}$) tends to infinity ($\pm\infty$), at the same wavelength. This wavelength is usually called "epsilon near zero and pole" (ε_{NZP}) and constitutes the spectral transition point between two extremely anisotropic propagation regimes. At the ε_{NZP} wavelength, a "*canalization*" effect takes place and the near-field radiation travels within the HMM in a straight line. In this regime, the phenomenon of "*super collimation*" of light within the HMM [2] can be observed. To overcome the typical lack of design flexibility that affects HMMs, in ref. [3] a three materials system, in which the operating wavelength can be selected in the visible range by tuning the thickness of the dielectric layers, was theoretically investigated.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The HMM lenses are composed of alternating layers of metals and dielectrics and are fabricated *via* e-beam evaporation. Thanks to the lithography-free fabrication process, the size of the devices is solely limited by the size of the sample holder inside the evaporator chamber (see Fig. 1). Therefore, super-lenses of the size of tens of centimetres can be fabricated at no extra cost nor time. This ensures an easy and straightforward scalability from micro-to-wafer scale. Moreover, they can be sold as stand-alone meta-substrates and exploited as external accessories in standard optical apparatuses.

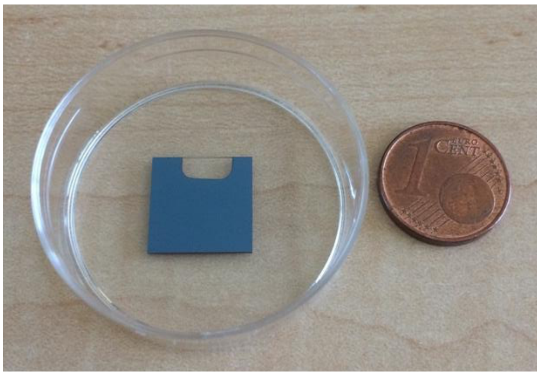


Fig. 1. Chip-sized meta-lens that can be selectively tuned in the whole visible range by controlling the oxidation of the silicon layers during the deposition process.

The main advantage over other HMM lenses arises from the possibility to select the operating wavelength in the whole visible range, by acting directly on the state of oxidation of the two layers during the deposition process. The enhanced resolution demonstrated by the developed device, can bring disruptive improvements not only to the field of optical imaging, but also to quantum information applications due to the coherent propagation of the optical signal, medical imaging diagnostics, and light emitting devices.

4. PROJECT RESULTS

An HMM consisting of 3 metal/dielectric bilayers, has been fabricated. The complex refractive index of the metal and dielectric layers embedded in the HMM have been measured ellipsometrically. Starting from the knowledge of these parameters, a fine theoretical design has been carried out in the framework of the Effective Medium Theory, in order to place the working wavelength at λ=550 nm. Simulations of the far- and near-field properties of the fabricated structures have been performed *via* Scattering Matrix Method and COMSOL Multiphysics platform. Ellipsometric characterization of the fabricated structures allowed us to confirm experimentally the working wavelength of the HMM lens found at λ=550 nm. Proof-of-concept confocal microscopy experiments, carried out *via* Scanning Near Optical Microscopy (SNOM), have been performed to verify the occurrence of the canalization effect in the fabricated HMM lens. As an excitation source, a tunable laser has been focused on the sample through a Zeiss 100x objective confocal with a Leica 60x, used at the bottom for collection. The investigation has been carried out at different wavelengths (400nm, 450nm, 500nm and 570nm), to explore the different propagation regimes around the canalization one. The power of the incident beam has been kept equal for all the used wavelengths. The light spot at the interface between the glass substrate and the bottom metal layer of the HMM (see Fig. 2) has been acquired through a CCD camera. At λ = 400 nm no light was detected, while at λ = 450 nm a very tiny spot was visible. Instead, at λ = 500 nm and λ = 570 nm the spot became clearly visible.

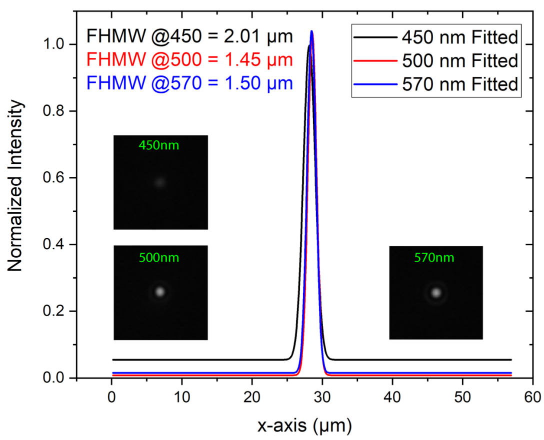


Fig. 2. Hyper-resolution demonstrated in a proof-of-concept confocal experiment.

From the acquired spot, the normalized intensity profiles have been retrieved. The Full Width Half

Maximum (FWHM) has been calculated using a Gaussian fit. The FWHM of the spots at λ = 450 nm was estimated to be equal to 2.01 μm. The FWHM of the recorded light spots at λ = 500 nm and λ = 570 nm were, respectively, estimated equal to 1.45 and 1.5 μm. Both of them are significantly narrower than that at 450 nm, while classic optics would predict the opposite.

A 3D Finite Element Methods (FEM) based model has been used to investigate the behaviour of the HMM device on top of which a letter "T", made of PMMA, was placed as the object to be resolved at the bottom. The width and length of the arm of the "T" are 50 nm and 200 nm, respectively, while the thickness of the letter is 50 nm. Fig. 3 reports the electric field intensity 20 nm below the glass/bottom-metal interface, revealing that the letter "T" is observable and perfectly resolved at the output.

At the left bottom corner of Fig. 3, the simulated electric field modulus of the acronym of the project, "tehris", at the same distance from the glass/bottom-metal interface is reported, revealing the ultra-high resolution reached in case of a more complex structure placed on the top of the HMM lens, demonstrating a resolution of about λ/500.

On top of the fabricated HMM lens, nanostructures with different shape and dimension have been lithographed using Electron Beam Lithography (EBL) (see Fig. 4, reporting SEM images of a series of patterns designed on the HMM lens).

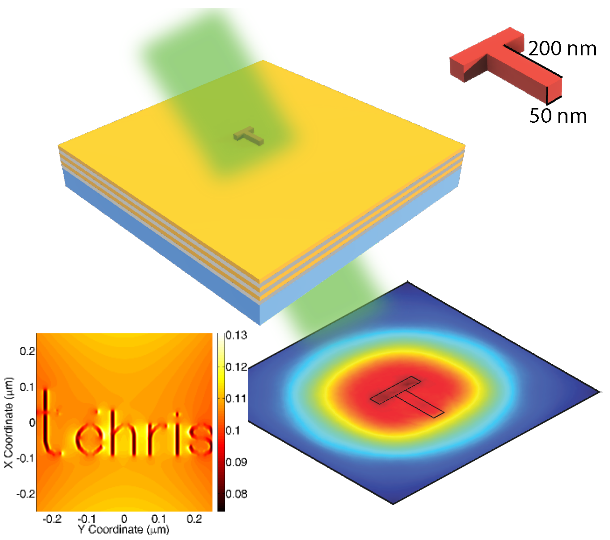


Fig. 3. (top left) 3D schematic view of the developed HMM lens where the yellow and gray parts represent respectively dielectric and metal layers. The inset (top right) reports the dimension of the nanostructure (letter "T") fabricated on top of it. (bottom right) Numerical electromagnetic field at the interface glass-metal of the letter "T" and (bottom left) of the entire acronym of our project.

Confocal microscopy images of the Hyper-Resolution reached with the proposed device (examples reported in Fig. 4), at different operating wavelengths and in a wide range of the visible band, have not been acquired yet due to the limited condition of operation our laboratories were subjected to due to the pandemic period.

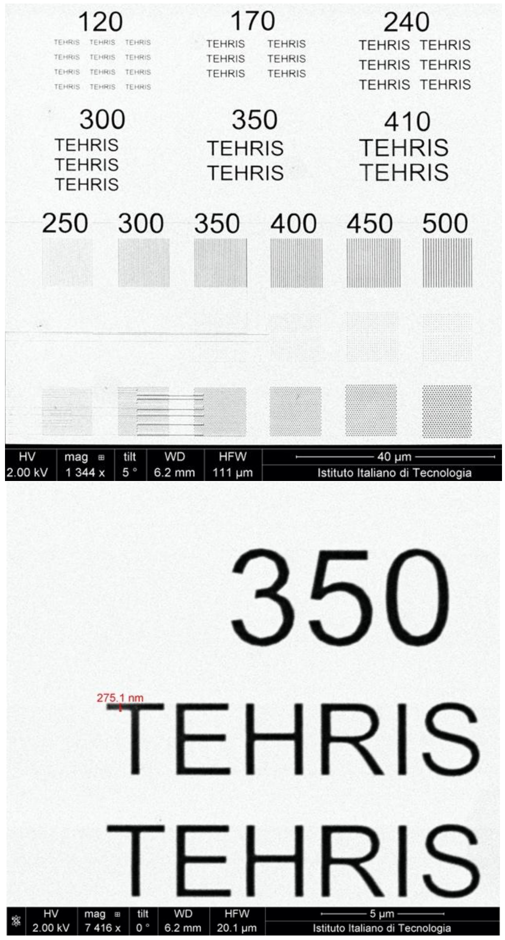


Fig. 4. (top) SEM image of a series of patterns designed on the HMM lens by EBL technique, including 1D gratings of different periods and arrays of pillars in a hexagonal configuration. (Bottom) Particular of the center area of the top SEM image, showing the minimum size obtained on the letter "T" of the project acronym.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The lithography-free deposition process used to fabricate the HMM lenses can be easily scaled and thus straightforwardly adapted from micro- to wafer-scale technologies at no extra cost nor time. The realization of a device at a specific working wavelength, however, requires precise control of the thickness of each layer and of the deposition parameters in order to ensure the desired optical properties of the materials in terms of dielectric constant. Up to now, a TRL between 3 and 4 has already been reached.

5.2. Project Synergies and Outreach

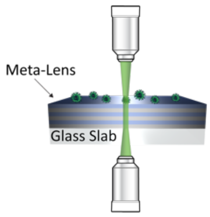
To implement the proposed device on classic optical systems and reach a TRL 5-7, the TEHRIS's team would interface with companies specialized in thin film deposition processes for metals and dielectrics. For integration in imaging systems, the following step aims to collaborate with companies specialized in the production of high-quality objectives and confocal apparatuses interested in achieving optical imaging below the diffraction limit. In order to obtain ready-to-market, reliable systems, companies specialized in bio-imaging and sensing in the visible regime are essential. In this view, the TEHRIS team will coordinate the interplay of all the companies.

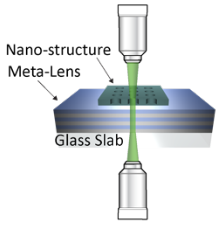
The results obtained during the project will be considered for patent applications and, in a second moment, they will be published in high-impact open access peer-reviewed international journals and presented at international conferences for a rapid dissemination.

5.3. Technology application and demonstration cases

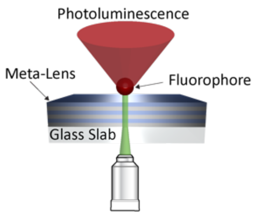
The proposed lenses will find application, for example, in:

- bio-imaging of bacteria and viruses with a resolution down to 50 nm.
- bio-sensing of low-molecular weight molecules with high sensitivity (> 10000 nm/RIU).
- morphological imaging of nano-scale features in metallic and dielectric systems and nano-architectures.
- low-cost and scalable devices to engineer the spontaneous emission dynamics of fluorophores towards single photon sources and quantum optics





Many of these applications, but not limited to them, find a concrete place in some of the areas of Scientific Research, Industry and Societal Challenges proposed by the European Commission as priorities, like Health, Food Security.



5.4. Technology commercialization

For a commercialization of the technology developed during the TEHRIS project, it will be necessary to collaborate with companies specialized in thin film technology and in high-quality objectives and confocal apparatuses.

Other opportunities to reach out to venture capitalists and investors will be guaranteed by the Start-up Incubator "TechNEST" of the University of Calabria and technology transfer office of the project's partners.

5.5. Envisioned risks

The main risk could be related to the difficulty in uniformly depositing thin film on high-quality substrates and, in a second phase, directly on objective lenses. Another risk is related to the fact that the HMM lens should be very close to the object to be resolved for reaching high resolution.

5.6. Liaison with Student Teams and Socio-Economic Study

One of the persons working on TEHRIS project will be in charge of facilitating the collaboration with students of scientific and economic disciplines. Moreover, public seminars and TV interviews will be organized for a public audience without competence in this specific field. The members of the University of Calabria will collaborate with their colleagues specialized in economic and humanistic disciplines to investigate the societal and economic impact of the project.

6. ACKNOWLEDGEMENT

The authors thank the "Area della Ricerca di Roma 2", Tor Vergata, for the access to the ICT Services (ARToV-CNR) for the use of the COMSOL Multiphysics Platform and Origin Lab, and the Infrastructure \Beyond-Nano" (PONa3-00362) of CNR-Nanotec for the access to research instruments.

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222

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