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| Metamaterials for advanced electromagnetic wave control  **Anna C. Tasolamprou**1#\***, Odysseas Tsilipakos**1**, George Perrakis**1**, Charalampos Mavidis**1**, Ioannis Katsantonis**1**, Anna Theodosi**1**, Zacharias Viskadourakis**1**, George Kenanakis**1**, Maria Kafesaki**1,2**, Costas Soukoulis**1**, Eleftherios N. Economou**1,3  1 Institute of Electronic Structure and Laser, Foundation for Research and Technology Hellas, N. Plastira 100, 71110, Heraklion, Crete, Greece  2Department of Materials Science and Technology, University of Crete, Heraklion, 70013, Greece  3Department of Physics, University of Crete, Heraklion, 70013, Greece  # Presenting author: A. C. Tasolamprou, email:atasolam@iesl.forth.gr  \* Corresponding author: A. C. Tasolamprou, email:atasolam@iesl.forth.gr |

abstract

The Photonic-, Phononic-, and Meta-Material (PPM) group of the Institute of Electronic Structure and Laser is in the last 15 years on the forefront of the metamaterials research. Metamaterials are mane-made structures with extraordinary properties (with the term metamaterials to include also photonic crystals and plasmonics - as engineered composite materials and also their two dimensional analogue, metasurfaces). It collectively has been, and continues to be, a prime mover and initiator of the development of one of the main categories of metamaterials, that of left-handed metamaterials (i.e. metamaterials characterized by both negative electrical permittivity and permeability values, and thus negative refractive index). The revolutionary concept of negative refractive index originally prompted objections, based on perceived violations of causality, momentum conservation, and Fermat’s principle.

Metamaterials provide control over the material properties in an atomic level though engineering of their architecture in the elementary units, the meta-atoms. An electromagnetic wave impinging on a metamaterial induces the excitation of local currents whose distribution is defined by the details of the electromagnetic wave, i.e., frequency, incidence angle and polarization, and by the shape, size and constituent materials of the meta-atoms. Given that the size of the meta-atom is subwavelength, the induced local currents produce a far-field response that can be perceived much like a material property. Metamaterials have opened up the path to novel electromagnetic features, negative effective permeability (mu-negative, MNG) and negative refractive index NIMs, usually achievable by combining negative effective permittivity and permeability) artificial chirality, accessing parity-time symmetry, toroidal response, topological photonic states, which are some of the topics that the PPM group focuses on. The original studies in metamaterials led to many fascinating applications pioneered by the PPM group. These indicatively include i) flat optics, i.e., ultrathin electromagnetic sheets for wavefront shaping, steering, focusing, shielding and polarization control ii) HyperSurfaces that merge metasurfaces with embedded electronic control elements and well-defined software programming interfaces and tools. The control elements receive external software commands and alter the metasurface structure, yielding a desired electromagnetic behavior on demand. iii) Metamaterial-based integrated circuits that control the impedance and parasitic effects by independently tuning electric permittivity and magnetic permeability to values impossible to achieve in natural materials, high frequency phase shifters based on reconfigurable metamaterials for contemporary electronics iv) Graphene-based metasurfaces and nanotubes for wave manipulation, ultrafast and nonlinear modulated response in space and time and efficient third harmonic generation in THz, within the framework of 6G technology v) Enhanced molecular chirality detection with using gain-loss resonant materials and enhanced polarization control capabilities via the combination of chirality with PT-symmetry vi) Topological photonic waveguides for unidirectional propagation and backscattering immunity vii) 3D printed metamaterials for microwave components viii) Passive radiative cooling for the temperature control of photovoltaics (PVs) through multiband metasurfaces and ultrathin, flexible coatings, ix) RF energy harvesting for trickIe-charging batteries and powering battery-free devices further enabled though toroidal excitations.