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# Investigating the Optical Properties of a Novel 3D Self-Assembled Metamaterial made of Carbon Intercalated with Bimetal Nanoparticles

**Muhammad Abdullah Butt,[1,2,3,*] Martin Neugebauer,[1,2] Antonino Calà Lesina,[4,5,6] Lora Ramunno,[4,5,6] Pierre Berini,[4,5,6,7] Alessandro Vaccari,[8] Thomas Bauer,[9] Alina A. Manshina,[10] Peter Banzer,[1,2,6] and Gerd Leuchs[1,2,4,6]**

*[1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany*
*[2]Institute of Optics, Information and Photonics, University Erlangen-Nuremberg, 91058 Erlangen, Germany*
*[3]School of Advanced Optical Technologies, University Erlangen-Nuremberg, 91052 Erlangen, Germany*
*[4]Department of Physics, University of Ottawa, Ottawa, ON K1N 6N5, Canada*
*[5]Centre for Research in Photonics, University of Ottawa, Ottawa, ON K1N 6N5, Canada*
*[6]Max Planck - University of Ottawa Centre for Extreme and Quantum Photonics, Ottawa, K1N 6N5, Canada*
*[7]School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada*
*[8]Centre for Materials and Microsystems, Fondazione Bruno Kessler, 32123 Trento, Italy*
*[9]Department of Quantum Nanoscience, Delft University of Technology, 2628 CJ Delft, Netherlands*
*[10]Institute of Chemistry, St. Petersburg State University, St. Petersburg, Russia*
**muhammad-abdullah.butt@mpl.mpg.de*

**Abstract:** We investigate the optical properties of a self-assembled three-dimensional metamaterial consisting of novel carbon allotrope intercalated with gold-silver alloy nanoparticles. For our experimental study we use a microscopic Müller matrix measurement technique. The metamaterial exhibits strong linear birefringence in the visible spectral range as a direct consequence of the crystal structure of the carbon matrix, holding an immense potential for future applications. 

**OCIS codes:** (160.3918) Metamaterial; (110.0180) Microscopy; (110.5405) Polarimetric imaging

## 1. Introduction

In the last decade, nano-optics has emerged as a scientific field, pushing the boundaries of science and technology. A very important subcategory of this field is the investigation and fabrication of different artificial materials and surfaces, based on layers of structured dielectrics and metals. The reason for the interest in these metamaterials and metasurfaces is the vast variety of applications, such as guiding, shaping and focusing of light beams, the development of ultrathin complex polarizing elements and many more [1, 2].

Here, we now investigate and discuss the optical properties of a novel type of laser-induced, self-assembled three-dimensional metamaterial. It consists of a monoclinic crystalline carbon matrix intercalated with bimetal (gold and silver) nanoparticles [3]. Our detailed experimental study shows that this novel hybrid material exhibits a strong linear optical birefringence, a property which is very useful for variety of different optical applications.

## 2. Measurements and results

For the experimental study, we implemented a microscopic Müller matrix measurement approach based on a far-field polarization analysis. A microscope objective with a numerical aperture (NA) of 0.9 was used to focus polarized light onto the micrometer-sized flake-like structures (see Fig. 1a for an SEM micrograph) fabricated with a laser-induced growth technique [3].

For the measurements, the flakes are displaced step by step with respect to the focused beam [4], which is smaller than the lateral dimensions of the flake itself, allowing for a distinction between edge effects the optical properties of the flake material itself. A second microscope objective with an NA of 1.3 was used to record the angular spectrum of the transmitted light. With the help of two liquid crystal retarders in combination with an analyzer, six different output polarization states were measured, which are used for calculating the Stokes vector of the transmitted light beam. Repeating the measurement for different input polarization states allows for the reconstruction of the Müller matrix of the metamaterial under study. Optical properties such as, attenuation, diattenuation and birefringence can be extracted from the Müller matrix. The measurements were performed for different wavelengths ranging from 400 nm to 700 nm, using a supercontinuum light source together with an acousto-optical tunable filter. The measurement results indicate a linear increase in attenuation (A) with decreasing wavelengths (e.g. $A = 0.19$ for a wavelength of 700 nm; $A = 0.78$ for a wavelength of 460 nm; see Fig. 1b). Most importantly, the investigated structure shows a strong optical birefringence on the order of $\Delta n = 0.1$ at a wavelength of 460 nm (see Fig. 1c). Also, the optical birefringence is observed to increase with smaller wavelengths. Our experimental findings are in very good agreement with the theoretical results.

The theoretical analysis is based on a model containing sheets of a graphene-like material and Au-Ag alloy (1:1) nanoparticles [5]. The nanoparticles are intercalated between sheets following a face-centered cubic arrangement [6]. The susceptibility of graphene is stretched to match the carbon material optical response. The model is simulated by the finite-difference time-domain (FDTD) method on a high-performance computing platform (SOSCIP) [7]. The simulation reproduces the absorptance peak at ~450 nm due to the alloy nanoparticles, the decreasing absorptance with increasing wavelength, and the absorptance at long wavelengths due to the carbon material only. The birefringence is explained using the Clausius-Mossotti theory [8], for a monoclinic (non cubic) lattice.

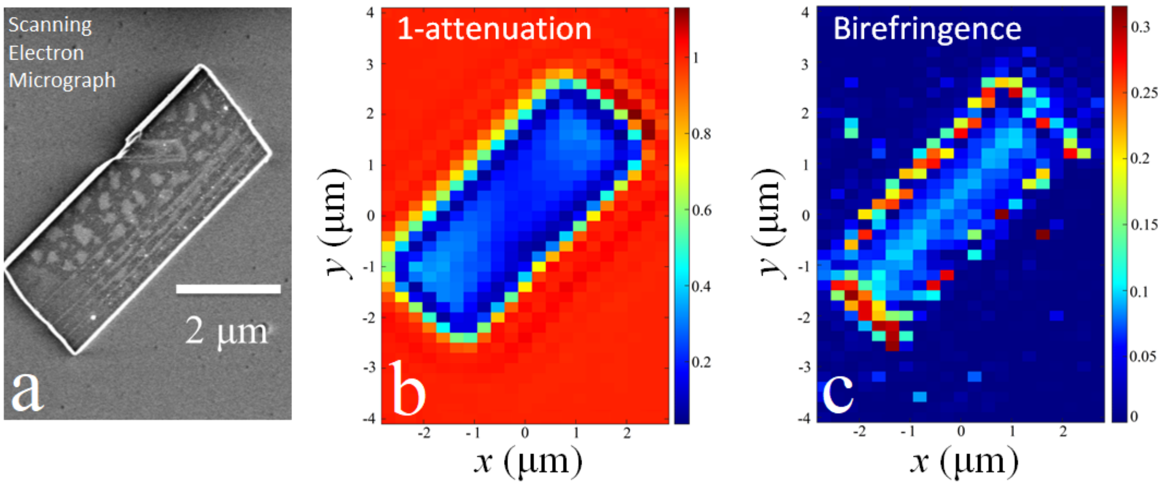


Fig. 1: Scans of the carbon flake structure at a wavelength of 460 nm. (a) SEM image of the investigated carbon flake. (b) 2-D experimental transmission scan result. (c) Optical birefringence deduced from the experimental Müller matrix analysis.

## 3. Conclusion

We present the first experimental and theoretical optical analysis of a novel carbon allotrope intercalated with gold and silver nanoparticles. The material under study shows an extraordinarily high optical birefringence in the visible spectral range, rendering it a promising candidate for the nano-optical toolbox.

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