PROCEEDINGS OF SPIE

Metamaterials IX

Allan D. Boardman
Nigel P. Johnson
Kevin F. MacDonald
Ekmel Özbay
Editors

14–17 April 2014
Brussels, Belgium

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Nigel P. Johnson, University of Glasgow (United Kingdom)

Introduction

The ninth Metamaterials Conference hosted by SPIE in Europe enjoyed strong international audiences and fruitful discussions right through the end of the conference. During informal discussions with the session Chairs, we agreed that the quality of the presentations had increased from an already previously high threshold.

Active Metamaterials featured in three of the sessions with new sessions on Dielectric and Hyperbolic Metamaterials. Two sessions on fabrication included Nanofabrication and Self-Assembled Metamaterials. Sensors, Nonlinear Plasmonics and Metamaterials, Terahertz Metamaterials, Polarisation Control and Transformation Optics, completed the programme of nine sessions.

The venue, in the heart of Brussels, no doubt contributed to this very enjoyable conference. The Chairs of the meeting would like to thank all contributors to the conference, the SPIE team, and the programme committee.

Allan D. Boardman
Nigel P. Johnson
Kevin F. MacDonald
Ekmel Özbay

Contents

Tailoring of the circular dichroism produced by Au covered self ordered dielectric nanospheres.

A. Belardini[1], A. Benedetti[1,*], M. Centini[1], C. Sibilia[1], D. Comoretto[2], F. Buatier de Mongeot[2]

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ABSTRACT

Here we show the way to easily tune and engineer the optical response of hybrid structures composed by self ordered dielectric nanospheres partially covered by anisotropic plasmonic structures. The overall structure is a hybrid plasmonic-photonics nanostructure acting as a meta-surface witch morphology allows efficient and versatile light manipulation both for linear polarized and circular polarized fields in the visible and near infrared frequencies.

Keywords: artificial chirality, self assembled gold nanoantennas, plasmonic resonances, 2D Bragg grating.

INTRODUCTION

In recent years, nanotechnology has become one of the most explored, and promising research sectors [1,2]. It actually refers to an entire world of scientific fields whose common task is to reach the highest order of integration for electronic [3,4], mechanic [5,6] and electromagnetic (e.m.) [7,8] devices. Nano-scale fabrication allows the manipulation of the light signal toward the optical range, by using linear [9-12] and non-linear optical materials [13-15].

Unfortunately, the realization of large areas nano-structured devices operating in the visible range, requires state of art technologies and high fabrication costs. For this reason, self-assembly techniques are extremely appealing [16,17]. They allow the development of highly structured, large area samples without the need of slow and expensive serial operations.

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Self-assembly techniques has been widely used to produce meta-surface composed by nano-resonators as efficient filters in the microwave (MW) [18,19], THz [20,21], infrared (IR) [22] and optical [23] regime. In [24] a technique to develop golden nano-resonators grown on top of a layer of polystyrene (PS) nano-spheres on a glass substrate is described. This technique is promising because is easily controllable and shows high levels of accuracy for the realized samples. Furthermore, the shape acquired by the nano-resonators, acting as antennas, allows to make their ensemble to act as anisotropic optical filters with controllable resonant frequencies. We have reported second harmonic generation (SHG) measurements showing a dichroic behavior both for linearly and circularly polarized waves [25-27]. Dichroism is the ability of a material to better absorb a radiation with a particular polarization orientation. Circular dichroism (CD) is the particular ability of a material to make waves presenting opposite sense of circular polarization be absorbed by different amounts. This character is generally achieved by the use of elements with chiral shape, i.e. elements which do not superpose with their mirror image with respect to a reference direction [28]. Chirality by itself doesn't necessary implicate CD, for example transparent chiral molecules like glucose or chiral crystals like $Bi_{12}SiO_{20}$ [29] show optical activity, but very few circular dichroism, that is a phenomenon related to absorption processes. This feature can be artificially obtained in meta-materials, by engineering the elementary cell of a periodic structure (in this case we have intrinsic (true) chirality) [30,31], or by the particular alignment of a material with no real intrinsic chirality, placed with an orientation such that it breaks the symmetry of the system. In this latter case we have extrinsic (induced) chirality [32-34].

CD is conceptually similar to its linear counterpart, and they are usually described by the use of similar parameters. Linear dichroism (LD) is present in this class of metasurface too, and we will provide a brief description of this behavior in the same structures.

In this paper we investigate the transmission properties of a generic configuration of self-assembled nano-antennas on the PS spheres' layer through the use of numerical calculations based on a finite difference time domain (FDTD) method. By modeling the elements involved in the simulations, we are able to predict resonant effects and spectral behaviors which makes this class of optical filters promising for compact size light manipulators, either for circularly of linear polarized plane waves.

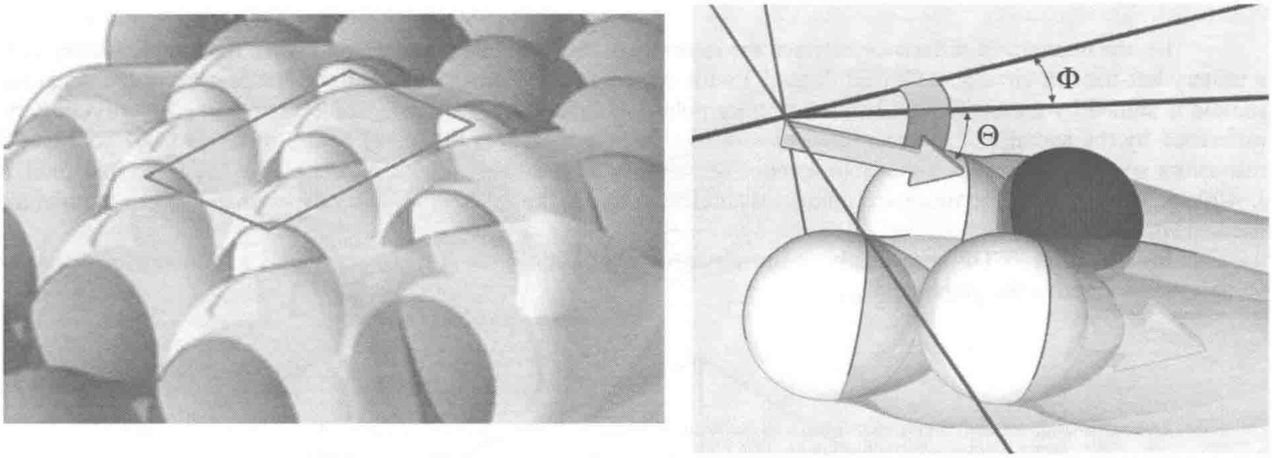
In section 1, a brief description of the numerical modeling is presented, focusing on the beam and shadows projections at the base of process to determine the shapes of the metal nano particles on top of the PS spheres. In section 2, we analyze the numerical results and evaluate the dichroic factor and the anisotropic nature for each configuration according to the relative transmission spectra. Finally, in section 3, the main conclusions are drawn.

1. NUMERICAL MODELING

The meta-material is composed of a regular array of plasmonic nanocrescents produced by grazing evaporating gold upon a self-ordered disposition of polystyrene nanospheres under hexagonal arrangements. The overall structure is a hybrid plasmonic-photonics nanostructure (HPPN) which can be considered a meta-surface for its contained size along the orthogonal direction to the deposition plane. Due to the morphology of the gold nano-elements the overall structure presents several e.m. properties in both linear and circular polarized light [35] as experimentally verified in ref.26 by using second harmonic generation (SHG) technique.

To investigate the several properties of the meta-surface in linear regime, we made a transposition of the experimental fabrication process into a numerical counterpart by the use of primitives elements as spheres and cylinders, as suggested by figure 1a.

The metal antennas upon each polystyrene (PS) sphere has been modeled by the application of etching regions which emulate the shadows, produced by the PS spheres, projected by the metal vapor flux during the deposition process [24]. These etching regions assume an orientation as a function of two angles, which are indicated in figure 1b. The shadows areas determine the shape of the metal particle upon the PS spheres' layer, thus they strongly affect the optical properties of the entire sample, by controlling the resonant response of each particle which behaves as an antenna.



(a) *(b)*

Figure 1. (a), schematic view of the geometrical technique used to model the metal nano-antennas (yellow) grown upon the PS spheres (violet), which follow a periodic hexagonal distribution on a glass substrate. The modeling is provided by the interaction of the metal vapor flux against the PS spheres. It projects a shaded region (transparent) outside which the metal deposition is possible. In red is indicated the in-plane periodic elementary cell used in the calculation, the 4 sides are set with periodic boundary conditions (PBC). The vertical confinement for the elementary cell is set with perfect matching layers (PML). In (b) are shown the two angles formed by the metal flux direction used in realistic deposition environment with respect the PS spheres arrangement.

The radius of the spheres is set to 250nm, meanwhile the metal layer has been set to 10nm in thickness in order to be lie in the experimental ranges of the samples used in ref.26. Furthermore, in order to provide the right spacing between nano-antennas, the shaded region has been described adopting spheres and cylinders with augmented radii with respect to the PS spheres' radius. Indeed, a certain shrinking effect is expected during the solidification process of the pseudo-liquid metal on the spheres, thus the resonator will be smaller in size than the free region exposed to the metal vapor flux. We took into account this effect by adding a further shadow enlargement, whose value has been chosen after a speculative investigation of the previous experimental samples [26].

Adopting a rectangle-based geometry for all the stages of our numerical simulations (see the region limited by red rectangle in fig.1a), we used periodic boundary conditions (PBC) to emulate the infinite extension along the two horizontal directions of the meta-surface. All the simulations have been performed under Lumerical FDTD Solutions. We delimited the entire system along the vertical direction by placing two opposite absorbing boundary layers, one in the background region laying on the top and the other in the region filled by the substrate glass below the meta-surface. The transmission spectra have been always evaluated for normally impinging plane waves. The final spectra have been evaluated by multiplying the results of the simulations with the theoretical glass-to-air transmission coefficient to take into account the final transmittance in air to avoid the spurious multiple coherent reflections at substrate interfaces which are only a numerical artifact. In order to overcome possible errors due to the unfit of the rectangular shape of the numeric voxels with respect to the nano-antenna's shape we adopted a sufficiently dense mesh (about 1.2nm) for the FDTD processing.

2. RESULTS AND ANALYSIS

In order to give an esteem of the CD of the meta-surface, we will consider the case of gold (Au) [36] as the compounding metal for the resonators. We afterwards defined a dimensionless parameter that indicates the effectiveness of the CD, the transmittance circular dichroic factor (TCDF) as:

$$TCDF(\Phi,\Theta) = 2 \cdot \frac{I_L(\Phi,\Theta) - I_R(\Phi,\Theta)}{I_L(\Phi,\Theta) + I_R(\Phi,\Theta)} \quad , \qquad (1)$$

i.e. the normalized difference between the intensity of the light that is transmitted when the sample is shined by a unitary left-handed circular polarized light (I_L) with respect to the intensity of the light that is transmitted when the sample is shined by a unitary right-handed circular polarized light (I_R). The normalization is obtained by dividing the difference by the average of the two intensities. In ref. 26, we measured the chiral nature of few sets of gold-on-PS resonators and we detected a noticeable amount of chirality at λ=800nm by the means of the SH generated field at λ=400nm. We think that the measured circular dichroism is due to the intrinsic chirality experienced by the beam at the fundamental frequency.

Investigating TCDF specifically at the wavelength of 800nm for Au, we registered a bidimensional grid of values, summarized in the graphs of fig.2.

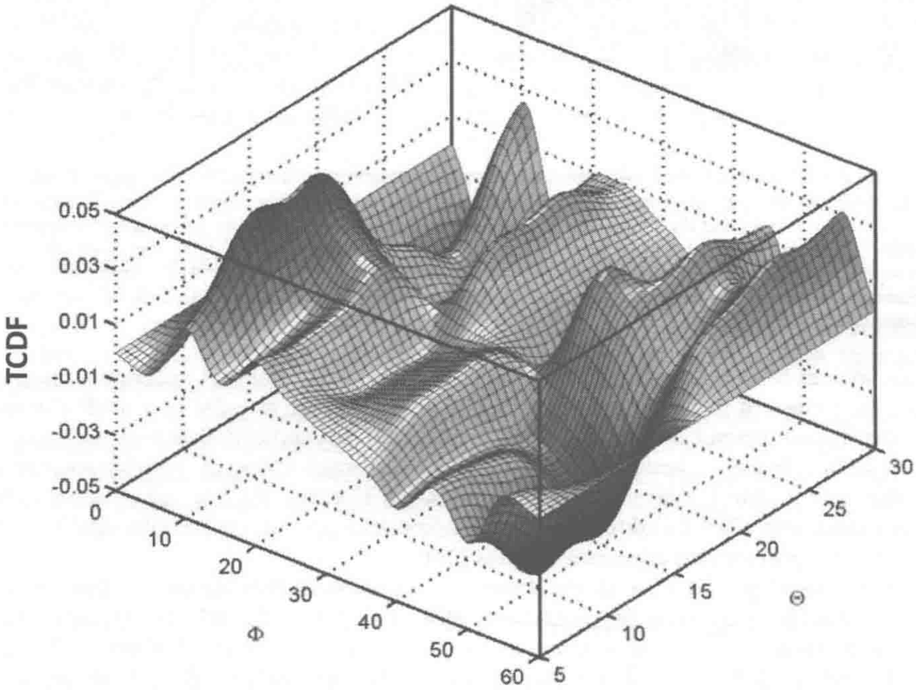


Figure 2: map for Au resonators over PS spheres as a function of Φ and Θ at λ=800nm.

We considered different values of Φ , from 0° to 60°, after which the TCDF profile is repeated periodically because of the regular shape of the elementary cell in the hexagonal lattice. This is the explanation even for the odd profile of the CDF for the range (0°-30°) with respect to the range (30°-60°). For Θ a maximum value of 30° has been set because it is very close to the lower limit for the inclination given by geometric reasoning: if we try to set the shadow radius equal to the PS sphere's radius, the maximum allowed Θ before the substrate beneath the PS layer is directly enlighten by the optical rays, for $\Phi=0$ and $\Phi=30$ respectively, is given by:

$$\max\{\Theta\}_{\Phi=0} = \frac{180}{\pi}\arctan\left(\frac{\sqrt{2}}{2}\right), \quad \max\{\Theta\}_{\Phi=30} = \frac{180}{\pi}\arctan\left(\frac{\sqrt{2\sqrt{3}-3}}{\sqrt{4-3\sqrt{3}}}\right) \quad , \qquad (2)$$

which are approximately equal to 35.3° and 40.9°, respectively. For Au resonators we reported a TCDF peak approximately of 0.04 belonging to the configuration associated with the angular couple (Φ,Θ)=(10°,14°). The difference in the transmittance due to left-handed and right-handed polarization light is due to different field localization (different resonances) for the single resonator according to the sign of the circular polarization as depicted in figure 3. In the following, we will refer to configurations that presents the largest value of TCDF as Au-(10°,14°).

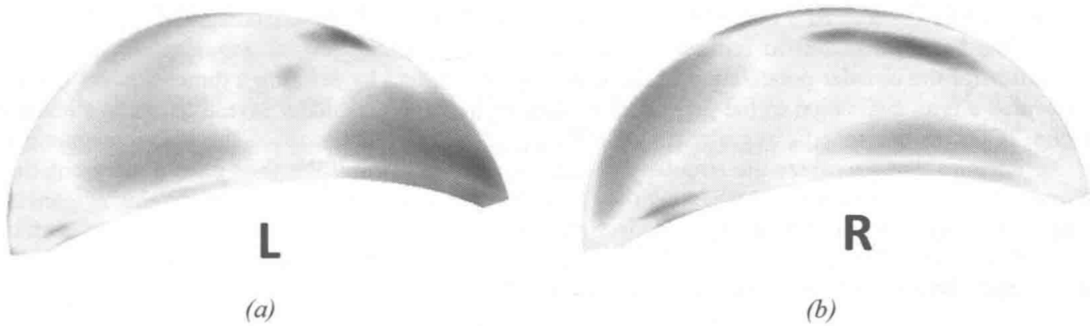


Figure 3. Logaritmic profile of intensity (with respect to the maximum value) of the electromagnetic field localisation for the Au-(10°,14°) configuration, for (a) left-handed circular polarised light and (b) right-handed circular polarised light.

In order to investigate the role of the plasmonic response of the metal nanoparticle we spectrally investigate the TCDF among the wavelength range of 400-800nm thus containing the plasma frequency of the gold.

We report our main results in fig. 4 for Φ ranging from 0° to 30° with a step of 5°, and Θ fixed to 20°. Each angular configuration provides the nano-resonators with a different shape and consequently with different dichroic response.

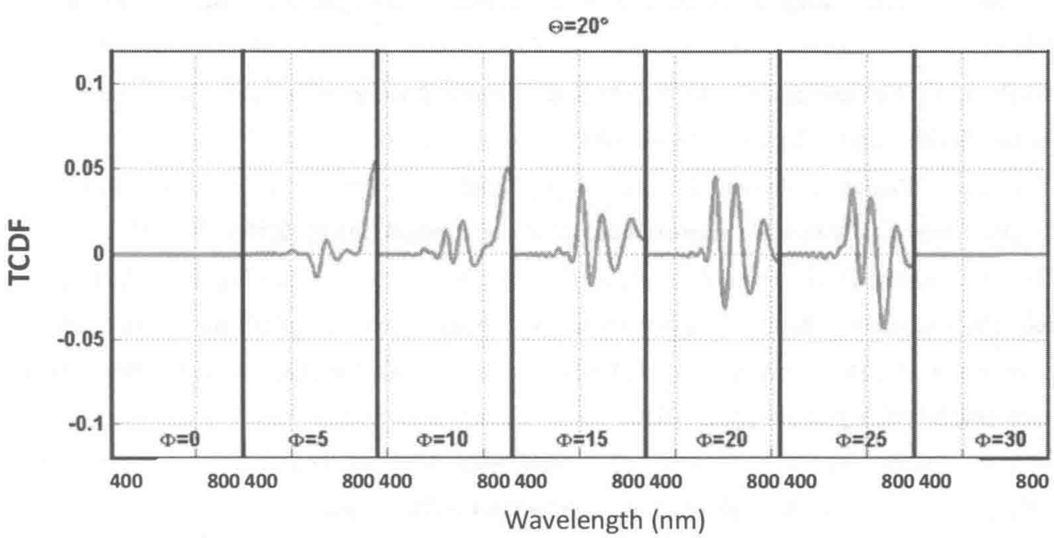


Figure 4. TCDFs for several angular values of the metal vapor flux as a function of the wavelength (400nm-800nm range).

It is very interesting to see in figure 4 that for a given geometrical shape of the single nanoantennas (i.e. once the Θ and Φ angles are determined) the circular dichroism is present only when plasmonic resonances are excited (the TCDF arise only for wavelength larger that the plasma frequency of the gold). For the case of Φ=0° or Φ=30° the shape of the antennas are symmetric so the TCDF is zero so the whole sample behaves like an achiral medium.

3. CONCLUSIONS

We studied the transmission properties of meta-surfaces realized by a new self assembling technique based on the deposition of a metal vapor flux upon polystyrene spheres, and we tested different geometries produced by changing the flux deposition parameters. By changing the flux direction it is possible to obtain in a easy and controlled way achiral or chiral asymmetric nano-resonators acting like antennas at the visible and near infrared frequencies. The obtained 2D distributions can be actually considered a homogeneous resonant meta-surface. The electromagnetic field distribution along the structure has been calculated to retrieve the spectroscopic aspect of several geometries. We tested the transmission properties for the circular polarization of the impinging wave, and by defining a dimensionless parameter the TCDF we provided a brief evaluation of the general dichroism in the structures under investigation. We obtained a 2D profile for the TCDF at the specific wavelength of 800nm and we plot the map of the electromagnetic field distribution on the antennas that maximize the circular dichroic response at 800nm. We then gave a representation of the TCDF as a function of the wavelength investigating the role of the plasmonic response of the metallic antennas. We predict that those kind of promising self-assembled and low cost 2D meta-material can be adopted to produce efficient and versatile circular dichroic filters, such as circular polarizers and optical rotators for the visible light and near infrared frequencies and many other types of light manipulations.

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Chirality and polarization-dependent characteristics of dielectric single gyroid metamaterials

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ABSTRACT

Gyroid is a type of three-dimensional chiral structures, which have attracted much research attention recently. A dielectric single gyroid (SG) can be a candidate for providing new means of guiding light because it has been shown to exhibit complete photonic band gaps. Owing to the chiral nature, the SG metamaterials may exhibit circular polarization-dependent properties, leading to new types of polarization-sensitive devices. In this work, we present studies based on finite-difference time-domain (FDTD) method for analyzing the polarization-dependent characteristics of dielectric SG. We show that the operation frequency of SG metamaterials can be advanced from microwave to visible region by varying its material, lattice constant and volume fraction. The corresponding band structures, transmission spectra for right circularly polarized (RCP) light and left circularly polarized (LCP) light, and circular dichroism (CD) indices are examined. According to our analysis, a circular polarization gap is found in the visible region. In particular, the correlation between the volume fraction of dielectric SG and the frequency range of circular polarization band gaps is also investigated. These results are crucial for the design of functional polarization-sensitive devices at the visible wavelength based on dielectric single gyroid metamaterials.

Keywords: metamaterial, circular polarization, chirality, gyroid

1. INTRODUCTION

In recent years, metamaterials have drawn much attention owing to many exotic applications, such as perfect lens[1], invisibility cloaking and broadband optical filter[2]. Initially the experimental realization of metamaterials was mainly implemented in the microwave region. By virtue of the advanced techniques that enable the fabrication of three-dimensional nanostructures, the operation regime can now be brought up to infrared and visible regimes. For example, nanofabrication using bottom-up approaches, such as block copolymer templating, have been demonstrated to make a variety of three-dimensional nanostructures. In this scheme, block copolymers are self-assembled into three-dimensional periodic nanostructures with various morphologies such as sphere, cylinder, gyroid, etc..[3] Among these morphologies, the self-assembled gyrotropic structures are worth exploring for the design of synthetic chiral optical metamaterials, as these gyroid networks comprise of chiral motifs and may exhibit circular polarization-sensitive properties. The dielectric single gyroids (SGs) have been shown to exhibit complete photonic band gaps[4] and circular polarization gaps[5]. They can be promising candidates for providing new means for guiding light or behaving as a polarization filter.

In this work, the numerical calculation based on finite-difference time domain (FDTD) method by LUMERICAL was implemented to perform optical properties computations of dielectric SGs. 2×2×2 unit cells of SGs and the chiral morphology along [100] direction were shown. The band structure and the coupling coefficient ratio of the dielectric SGs were calculated to investigate the properties of modes for circularly polarized waves. From the analysis of band structures and coupling coefficients, photonic polarization band gaps were able to be found. Furthermore, we examined the reflection spectra of the dielectric SGs along [100] direction. The results are consistent with the band structure and coupling coefficient calculations. The polarization properties of the modes can be derived by the aforementioned results.

2. STRUCTURE

The gyroid is a three-dimensional chiral structure. The minimal surface of the gyroid structure can be approximated by the function[6]

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