Broadband white-light interferometry reveals giant optical activity in metamaterials

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Abstract

We introduce a novel experimental scheme to characterize the transmission characteristics of optical metamaterials in amplitude and phase. The approach reveals all properties of the respective Jones matrix entirely on experimental grounds and was verified to be highly accurate. The presented Jones matrix formalism lifts issues associated with the assignment of effective properties to heterogeneous metamaterials and provides a straightforward, yet accurate description. Thus it is not required to resort on numerical simulations to disclose properties of metamaterials, for which the geometrical details of the considered structures or their material properties are often known with insufficient precision. We show how to discuss the pertinent properties of optical metamaterials once the Jones matrix is determined, and exemplarily present measurements of giant optical activity in a chiral metamaterial. The proposed experimental scheme enables the complex far-field characterization of a very broad class of generally dispersive and/or optically active media.

1. Introduction

The extraordinary optical behaviour of artificial metamaterials is governed by the resonant nature of their constitutive elements. Recent developments in nanostructure technology enabled the fabrication of metamaterials composed of complex three-dimensional nanostructures [1]. This significant progress requires to revise standard theoretical and experimental approaches for the characterization of optical properties of metamaterials. The urgent necessity to find conceptual new means to describe these properties became obvious just recently, particularly in the visible spectral domain. There, the mesoscopic size of the constituting nanostructures is not much smaller than the wavelength of light but only smaller. Due to the resulting strong spatial dispersion inconsistencies and contradictive predictions have been observed by using effective material parameters [2].

Here we advance the conceptual understanding of the far-field properties of optical metamaterials on the basis of an adapted Jones matrix formalism [3]. To tackle this issue we describe in detail an experimental method for the direct quantification of the dispersion relation and the complex Jones matrix of metamaterials [4], [5]. The corresponding setup is based on white-light spectral interferometry and facilitates measurements of complex transmission and reflection coefficients for wavelengths from 600 nm to 1700 nm. To demonstrate the power of the approach, the developed experimental scheme along with the Jones matrix formalism is applied to an optical metamaterial consisting of three-dimensional, chiral nanostructures [1]. Based on the broadband, comprehensive measurements of its Jones matrix, we revealed that the transmission through a single layer structure results in a rotation of the linear polarization state by $3.3\ 10^5$ °/mm at a near-infrared wavelength. This exceeds the optical activity in any natural material by orders of magnitude and exceeds the optical activity previously observed in artificial nanostructured materials in the optical range.

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2. Experimental setup

It was shown in [3] that the transmission of light through any optically active metamaterial can be disclosed by means of an advanced Jones calculus:

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}. \tag{1}$$

Generally, the four coefficients T_{ij} of the Jones matrix are complex-valued. Thus, interferometric measurements are necessary for their full experimental acquisition. For this purpose we built a modified Jamin-Lebedeff-interferometer based on white-light Fourier-transform spectral interferometry in frequency domain (Fig. 1a). To measure the complex functions T_{ij}, we placed an additional polarizer ("X-polarizer") in the sample arm of our interferometer, between the sample and the last birefringent crystal shown in Fig. 1a.

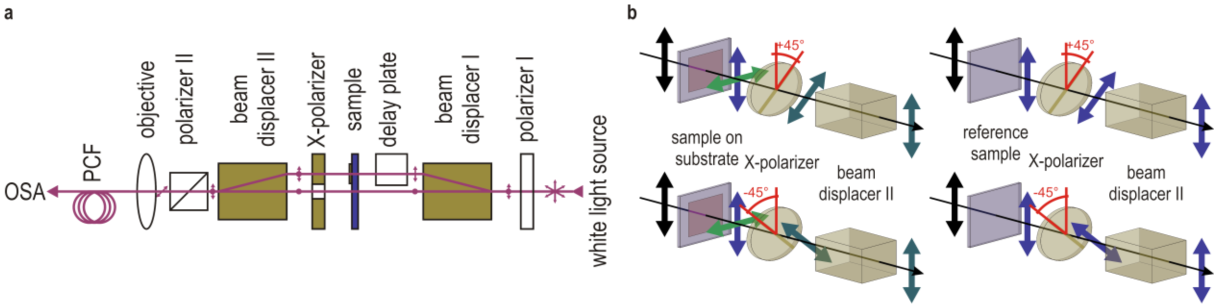

Fig. 1: (a) Sketch of the interferometric setup. (b) Orientation of the X-polarizer during the measurement.

By illuminating an optically active sample with linearly polarized light, the transmitted light becomes, in the general case, elliptically polarized. For two orthogonal polarizations of the illuminating wave $[(E_x, 0)$ and $(0, E_y)]$ the resulting ellipses are:

$$\begin{pmatrix} E_x^1 \\ E_y^1 \end{pmatrix} = \begin{pmatrix} T_{xx}E_x \\ T_{yx}E_x \end{pmatrix}; \begin{pmatrix} E_x^2 \\ E_y^2 \end{pmatrix} = \begin{pmatrix} T_{yy}E_y \\ T_{xy}E_y \end{pmatrix}. \tag{2}$$

The data acquisition comprises two measurements for each illuminating scenario with the X-polarizer rotated to +45° or -45° with respect to the optical axis and relative to the incident polarization on the sample and known reference sample (Fig. 1b). From this data, we can unambiguously access the absolute phase delay of each single coefficient of the Jones matrix. Measurements of the transmittances without phase delay access were done by using only one arm of the interferometer and collecting the intensity signals of sample und reference. The accuracy of the method with respect of an optical phase delay was verified to be 20 mrad and thus better than in previous reports [4].

3. Application to chiral metamaterials

After calibration of the interferometric setup by means of standardized test samples, the method was applied to a chiral metamaterial composed of so-called loop-wire nanostructures [1] shown in Fig. 2a. The excellent agreement between the measured and simulated amplitudes and phases of T_{ij} is demonstrated in Fig. 2b-e. The developed experimental technique disclosed for the first time the full complex transmission response for wavelengths from 600 nm to 1700 nm and allows for unambiguous quantification of, amongst others, circular dichroism (Fig. 2f), circular birefringence (Fig. 2g) and polarization eigenstates of the chiral metamaterial across this broad spectral range. Specifically, the polarization output upon exciting the structure with an arbitrary input can be predicted immediately. It is shown that the fabricated loop-wire metamaterial exhibits giant optical activity for all wavelengths measured. Particularly, we found pure circular birefringence, i.e. a rotation of the polarization azimuth of linearly polarized light exceeding 50° at a wavelength around 1.08 μm. Normalized to the thickness of the metamaterial, this corresponds to a specific rotation of $3.3 \cdot 10^5$ °/mm which is, to the best of our knowledge, larger than that of any linear, passive and reciprocal medium reported to date.

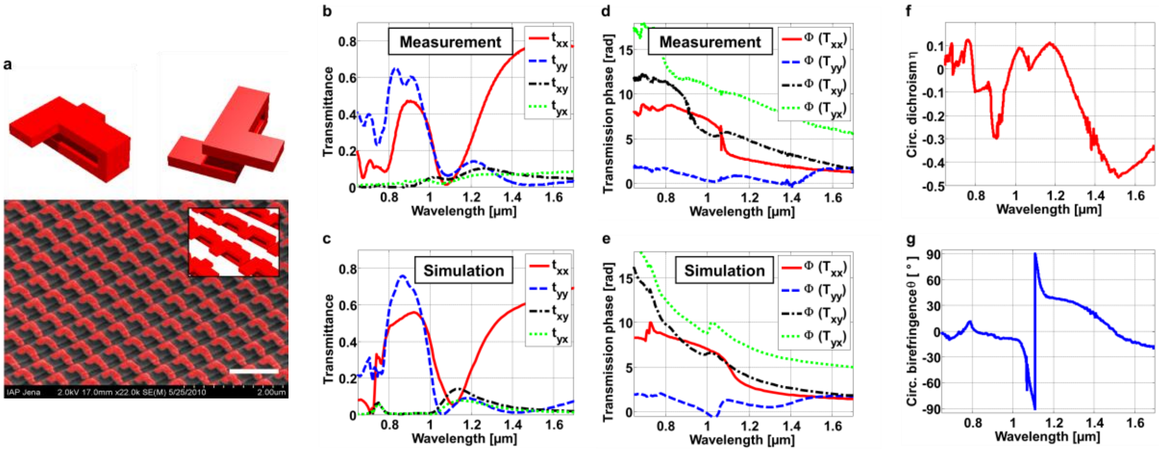

Fig. 2: (a) Two sketches of a single loop-wire metaatom from two different perspectives and a false-colored, tilted view scanning electron microscopy image of the fabricated metaatoms with a periodic lattice of 500 nm in both lateral directions. The scale bar is 1 μm. The inset shows a corresponding sketch of the metaatoms without the supportive dielectric grating structure. (b) Measured and (c) simulated transmittances, (d) measured and (e) simulated transmission phase delays. The different colours indicate the four entries of the Jones matrix. (f) Circular dichroism and (g) circular birefringence extracted from the measured Jones matrix of the loop-wire sample.

4. Conclusion

We presented a novel interferometric scheme which allows for the direct measurement of the complex Jones matrix in the visible and near-infrared spectral domain, applicable not only to optical metamaterials, but rather to a very general class of dispersive media. This approach allows for the quantification of all transmission properties of such complex structural matter by purely experimental means and without resorting to numerical simulations or inaccurate effective media assumptions. The performance of the setup was demonstrated at a chiral metamaterial and reveals its outstanding features, among them, a giant optical activity. Further extensions of the method, e.g. an expansion of the addressable spectral range or an extension to oblique incidence amplitude and phase measurements, are currently on-going and will be discussed in this contribution.

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