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Experimental study of angular and frequency spectra of laser pulse diffraction on a planar periodic nanostructure of gold V antennas

M.V. Balabas, E.A. Efremova, A.Yu. Ivanov, A.I. Kantserov, I.R. Krylov, E.B. Pelyukhova, Yu.V. Petrov, U.V. Prokhorova, R.V. Silaev, O.Yu. Tret'yak, A.A. Shimko

Abstract. **Irradiation of a planar structure made of periodically spaced gold V antennas by a femtosecond pulsed laser has revealed several anomalously reflected and refracted waves, interpreted as diffraction maxima. Compression of the pulse spectrum in scattered light is observed. The degree of compression and wave polarisation are found to be determined by the scattering direction.**

Keywords: *metamaterial, nanoantennas, femtosecond pulse, planar optics, diffraction grating, left-handed media.*

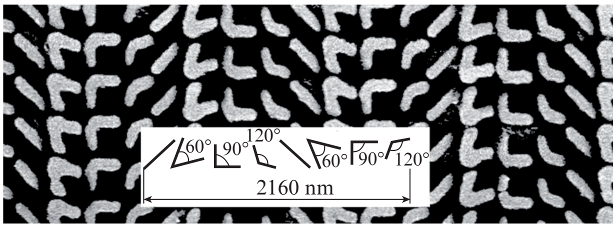

Figure 1. Geometry of a sample (square with a side of 500 μm). The structure period along the horizontal axis (Γ = 2160 nm) contains eight antenna columns.

1. Introduction

Currently, large-scale studies aimed at developing planar nanostructures (which could potentially replace such classical optical tools as lenses, prisms, phase plates and axicons) are underway. An example of promising products in this field is phase-gradient surfaces [1, 2]. They are planar structures consisting of objects (meta-atoms) with a size several times smaller than the light wavelength. Phase-gradient surfaces are used to form metamaterials with a negative refractive index [3, 4], to control the shape of the light wave phase surface [5–7] and the wavefront shape [8] and to perform coherent control of the directions of reflected and refracted beams [9]. These structures make up a potential element base for designing nanoscale optical logic gates. In this context, it is of interest to investigate in detail the specific features of interaction of short light pulses with planar structures. In this paper, we report the results of studying the scattering of pulsed radiation by a periodic phase-gradient structure composed of gold V-shaped nanoantennas. The geometry of this structure and its electron microscopy image are presented in Fig. 1.

A natural approach to the description of the interaction of this structure with a light wave is to consider an anisotropic blazed grating [7, 10, 11]. At the same time, it was shown in [3, 4] that the main features – anomalous directions of reflected and refracted waves – can be described by the generalised Snell law. To this end, the modified Fermat principle was used in [3, 4]; this approach takes into account the phase change by π/4, introduced by successive subwavelength-scale elements. This action of a planar structure is equivalent to that of an optical wedge. It is convenient to use this approach to consider the response of arrays with complex geometry [3]; however, it neglects the occurrence of additional reflected and refracted beams, which can adequately be described in terms of wave optics.

2. Directions and polarisation of diffraction maxima

The V-antenna array analysed in this study has the same geometry and characteristic sizes as that investigated in [4]; it is designed to yield an optical response in the near-IR range (1100–1500 nm). The radiation source was a femtosecond laser complex based on a Mira Optima 900-D laser and a Mira OPO optical parametric converter (Coherent).

The experiment revealed two anomalously refracted and two anomalously reflected beams for the structure with a period of 2160 nm and three beams in refraction and reflection for the structure with a period of 2520 nm. The directions and polarisations of beams for the former case are shown in Fig. 2. The beam directions correspond to the interaction of light with a diffraction grating. The rotation of the polarisation plane of diffracted waves is characteristic of anisotropic diffraction gratings [12, 13].

Figure 3 shows dependences of the positions of angular diffraction maxima of a grating with a period Γ = 2160 nm for different angles of incidence α_0 of light with a wavelength λ = 1300 nm, calculated from the diffraction-grating formulas

$$\begin{aligned} \beta_b &= \alpha_0 + \arcsin(\lambda/\Gamma - \sin\alpha_0), \\ \beta_{b'} &= \alpha_0 + \arcsin(2\lambda/\Gamma - \sin\alpha_0). \end{aligned} \tag{1}$$

The circles in Fig. 3 correspond to experimentally observed propagation directions of anomalous beams. The vertical line indicates the angle of incidence specified in this experiment:

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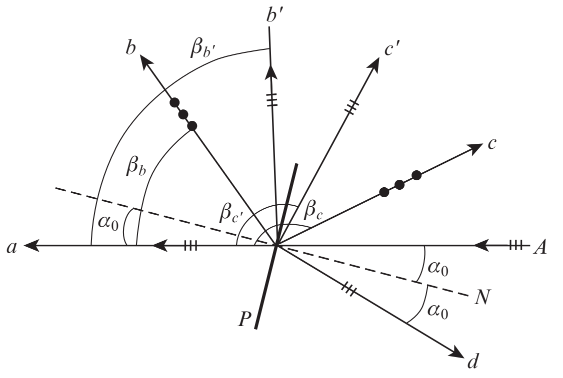

Figure 2. Directions and polarisations of beams (N is the normal to the sample P): (A) incident beam; (a) beam passed through the sample without changing direction; (d) beam specularly reflected from the silicon substrate of the nanostructure; (b, c) anomalously refracted and anomalously reflected beams, respectively; (b', c') anomalously refracted and anomalously reflected beams in the second diffraction order; α_0 is the angle of incidence of light; b, b' and c, c' are the deviation angles of transmitted and reflected light (in the first and second diffraction orders, respectively).

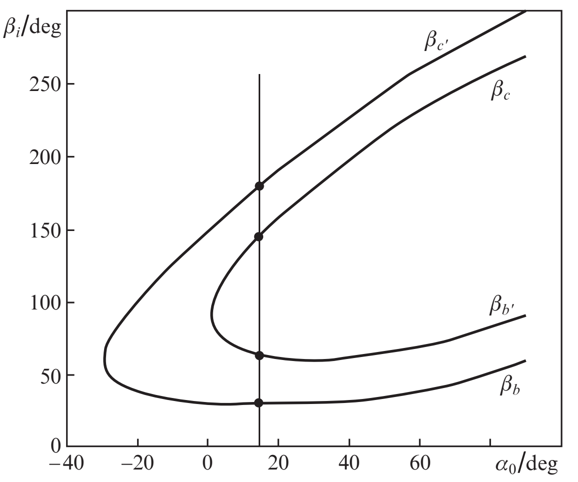

Figure 3. Theoretical (solid line) and experimental (circles) values of the beam deviation angle by the nanostructure with a period Γ = 2160 nm as a function of the angle of incidence of light with a wavelength λ = 1300 nm.

$\alpha_0 = 14.5°$. One can see that the directions in which anomalously reflected and refracted beams are observed ($\beta_b = 35.0°$, $\beta_{b'} = 86.0°$, $\beta_{c'} = 122.2°$ and $\beta_c = 173.7°$) are in agreement with the calculated values (35.1°, 86.9°, 122.1° and 173.9°). The same agreement between the experimental and calculated data was observed in experiments with other angles of incidence of light, other light wavelengths and different grating periods.

Optimal conditions for observing anomalously refracted and reflected beams in the first diffraction order, in correspondence with the results of [3, 4], are implemented when the polarisation of the incident light beam is either parallel or perpendicular to the nanostructure columns (see Fig. 1). In both cases, the polarisation of the anomalously refracted and reflected beams observed by us in the first diffraction order is orthogonal to the polarisation of the incident beam; this is also in correspondence with the results of the aforementioned studies. In our experiment, the power of the anomalously refracted and reflected beams was about 1% of the incident light power. In the second diffraction order, the polarisation coincided with the incident beam polarisation. The power directed to the second diffraction order was approximately half of that observed in the first order.

In the proposed optical scheme (Fig. 2), with the aforementioned values of experimental parameters, the beams in other diffraction orders (except for those shown in the figure), in correspondence with formulas (1), have no allowed directions. The nanostructure under consideration, being a blazed grating, suppresses negative diffraction orders. To verify experimentally their absence, we changed the incident beam direction so as to make the angle of incidence change its sign. Negative orders in formulas (1) correspond to the change in the sign of all values. Beams in negative diffraction orders were not experimentally observed. With allowance for the visualizer sensitivity, we can state that the power of these beams is at least an order of magnitude lower than for the corresponding beams in positive orders. These observations experimentally confirm that the nanostructure under study is an analogue of a blazed grating.

In the experiments [3, 4], a light beam was incident on a nanostructure from the substrate side. In the case of irradiation from the side of the nanostructure, we obtained the same diffraction pattern in reflection and refraction.

3. Spectral compression of light pulses

The use of a pulsed laser as a light source allowed us to investigate the response of the nanoantenna array to a broad-spectrum pulse. We recorded compression of spectrum in diffraction maxima. Its theoretical value is determined by the relative spectral resolution of diffraction grating $\delta\lambda/\lambda = 1/(mN)$ (m is the diffraction order and N is the total number of grating lines). This resolution is obtained if the angle of light collection is smaller than the angular width of the grating diffraction maximum $\delta\alpha = \lambda/(Nd\cos\alpha)$ (d is the grating period and α is the diffraction angle). Using an optical fibre 0.6 mm in diameter, we recorded light deviated by the nanostructure at a distance of 300 mm from the sample; correspondingly, the angle of light collection was 1/500. The nanostructure size was Nd = 500 μm. At a wavelength λ = 1.1 μm, the diffraction maximum angular width $\delta\alpha$ was larger by a factor of 1.5–2 than the angle of collection, i.e., we can assume that light was collected from a small angle. The experimental spectral curves of pulses propagating without a change in the direction and in anomalous-refraction directions of the first and second diffraction orders are presented in Fig. 4, which contains also approximation of the spectra by Gaussians.

As one would expect, the effect of compression of the femtosecond pulse spectrum is enhanced with an increase in the diffraction order. The spectral curves recorded in reflected light behave similarly.

The experimentally found spectral widths of beams a, d, b, b' and c' are, respectively, 17.8, 17.5, 9.8, 6.5 and 8.5 nm.

For comparison, we performed an experiment in which a sample with a nanostructure was replaced by a diffraction grating (with a diaphragm) having an almost linear size. The spectral width of diffraction maxima for this grating turned out to be smaller than for the nanostructure by a factor of about 1.5. This difference may be assumed to be caused by the technological defects of nanostructure preparation (fluctuations of nanoantenna sizes).

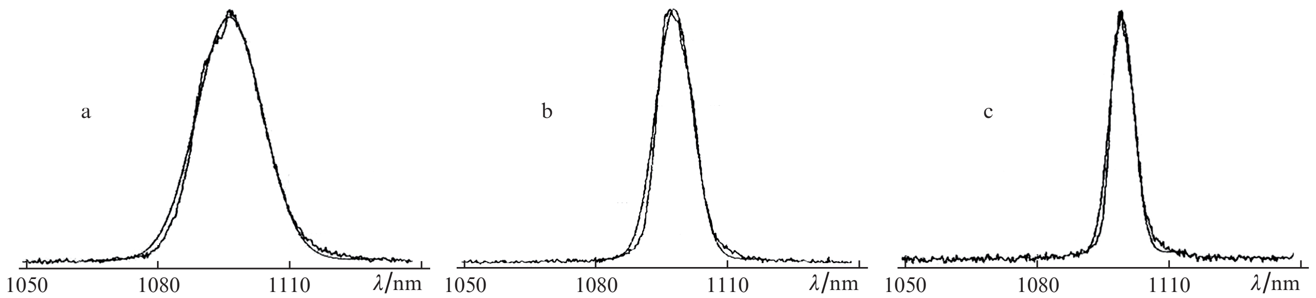

Figure 4. Spectra of light (a) transmitted through the sample in the zero diffraction order and (b, c) anomalously refracted in the (b) first and (c) second diffraction orders.

4. Conclusions

Our experiments demonstrated the presence of anomalously reflected and refracted beams under irradiation of a planar array of V-shaped gold nanoantennas by pulsed broadband light. The beam polarisation was found to be determined by the diffraction order. Compression of the spectrum of femtosecond pulses as a result of interaction of their electromagnetic field with the nanoantenna array was experimentally observed. A dependence of the degree of compression on the diffraction order at small angles of collection was obtained. The observed effects are consistent with the diffraction model of action of a planar phase-gradient periodic structure. The results of our study should be interesting for any application of phase-gradient planar nanostructures as optical elements.

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