Bistable Characteristics of an Ultrathin Metal-Dielectric Metasurface with a Nonlinear Element in Wood's Anomalies

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Abstract

We propose and report on the design of a 1-D thin metallo-dielectric grating with Kerr type nonlinear element. In this paper, resonant lattice modes were observed while varying the frequency parameter to study the unique electromagnetic modes generated by Wood’s anomalies. These mode resonances give rise to the enhancement of local field and nonlinear processes on Kerr type nonlinear element. The bistable transmission of the wave through the bar grating with nonlinear element was obtained.

1 Introduction

Periodic structures with a sub-wavelength periodicity can be determined as a metasurface [1-3] and represents a topical area in nanophotonics. It is well known that various kinds of grating resonance are used in electromagnetic devices to improve and manifest the properties of natural materials which depended on the presence of an electromagnetic field. For example, the use of resonance at a defect mode in the grating can be presented as a concentrator of electromagnetic energy [4] for the manifestation of nonlinear behavior of dielectric permittivity [5]. Recently, it was revealed the resonance at the Wood's anomalies provides sufficient enhancement of the Faraday rotation [6, 7].The exhaustive interpretation of those resonances has been given in the review [8] the authors showed that those structural resonances appear near the Rayleigh anomalies, regardless of the material from which the grating was made, and hide in the points of Rayleigh anomalies under certain conditions.

2 Problem Statement and Solution

We study the bistable transmit of the plane electromagnetic wave through a ultrathin metal-dielectric grating at normal incidence. The grating consists of perfectly electric conducting (PEC) bars (Figure 1). The incident wave is polarized linearly in the x-direction. The slits between the bars are filled with three dielectric layers of the same thickness Δ. The first and the third layers in the every slit of the grating are made of silica (SiO$_2$) with the permittivity $\varepsilon_1 = \varepsilon_3 = 2.1$ [9]. The second layer is made of a Kerr-type nonlinear dielectric gallium arsenide (GaAs) with the permittivity ε_s depends on the electric field in the second layer E_{in}^s, as

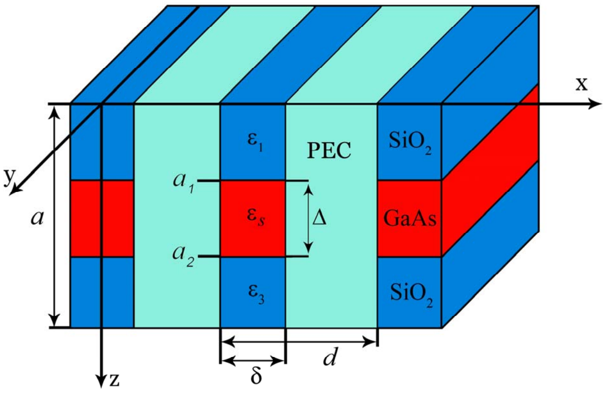

Figure 1. PEC bars grating with a nonlinear element in dielectric filling of its slits. Three periods of an infinitely periodic structure is presented.

$$\varepsilon_s\left(E_{in}^s(z)\right) = \varepsilon_{sl} + \varepsilon_{sn}\left|E_{in}^s(z)\right|^2 , \qquad (1)$$

where the dielectric constant is $\varepsilon_{sl} = 11.0$, the nonlinear coefficient is $\varepsilon_{sn} = 1.3*10^{-3}\, cm^2/kW$.

The goal of the problem is to obtain the bistable resonance for the transmission of the metasurface in the Wood’s anomalies super quality resonance conditions.

We assume the grating period d is smaller than the wavelength of incident wave, which is selected $\lambda = 1.240\,\mu m$. We consider the ultrathin grating with the thickness $a = 0.24d$ (the layer thickness $\Delta = 0.08d$) and the narrow slits with the width $\delta = 0.2d$ which are much smaller than the wavelength of the incident wave. The grating with such geometry belongs to the class of metasurfaces.

An important condition for the manifestation of the nonlinear properties of the GaAS is a strong inner field at resonance conditions. Therefore, it is necessary to obtain a high-Q frequency dependence under the unit amplitude of the incident field (linear case). Dependences of the transmission coefficients $|T|$ on the normalized frequency κ of the grating with the second layer permittivity

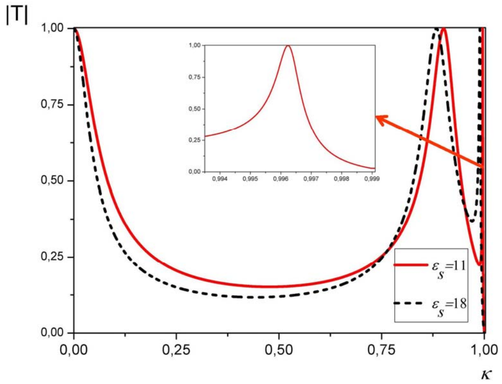

Figure 2. Transmittance spectrum of the metasurface with the second layer permittivity $\varepsilon_{sl} = 11.0$ (red solid line) and $\varepsilon_{sl} = 18.0$ (black short dash line).

$\varepsilon_{sl} = 11.0$ (red solid line) and $\varepsilon_{sl} = 18.0$ (black short dash line) demonstrated in Figure 2. The normalized frequency is determined by $\kappa = \frac{d}{\lambda}$. The transmittance resonance with quality factor $\mathrm{Q} = 682.37$ obtained at the resonance frequency $\kappa_r = 0.99627$ (Figure 2 red solid line). It corresponded to Wood's anomaly. The normalized frequency is determined by $\kappa = \frac{d}{\lambda}$. The quality factor is determined as the ratio of the resonant frequency to the width of the resonance at half power. When the permittivity of the second layer increases, the resonances of the grating shift to long wavelengths area.

Figure 3 shows the dependences of the magnitude of the inner electric field $|E_{in}|$ versus z/d along the grating thickness into the slits with the second layer permittivity $\varepsilon_{sl} = 11.0$ at the resonance frequency $\kappa_r = 0.99627$. The red short dash line points at the inner electric field distribution in the second layer. The maximum value of the inner electric field $E_{\max} = 8.198$.

In the nonlinear case, when the amplitude of the incident field is much larger than unity, the permittivity ε_s of GaAs depends on the inhomogeneous distribution of the electric field along the z-axis in the second layer. We neglect the inhomogeneity of the electric field in the ultrathin periodic structure and take the value of the inner electric field at the point 0.5Δ as an average inner electric field $\overline{\left|E_{in}^s\right|^2}$. Then, expression (1) has the form:

$$\varepsilon_s\left(E_{in}^s\right) = \varepsilon_{sl} + \varepsilon_{sn}\overline{\left|E_{in}^s\right|^2} \qquad (2).$$

Dependence of the average inner electric field $\overline{\left|E_{in}^s\right|^2}$ in the second layer with the permittivity $\varepsilon_{sl} = 11.0$ on the frequency κ of the grating was demonstrated in Figure 4.

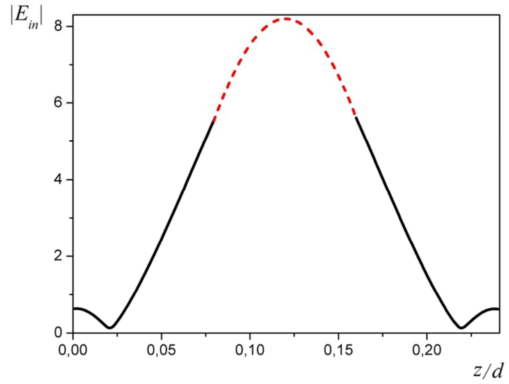

Figure 3. Module of the inner electric field E_{in} versus z/d of the grating with nonlinear layer at resonance frequency.

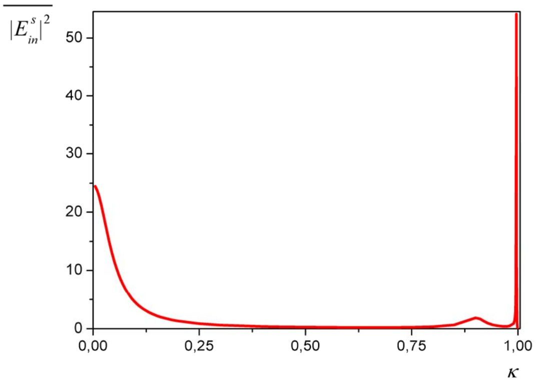

Figure 4. Dependence of the average inner electric field in the second layer with $\varepsilon_{sl} = 11.0$ on the frequency.

The maximum value $\overline{\left|E_{in}^s\right|^2} = 54.077$ at the Wood's anomaly.

3 Results and Discussion

When the intensity of the incident field increases, it leads to grow the nonlinear layer permittivity of the grating, it results in a shift of the resonance to the long-wavelength region. For calculation of the bistable transmission resonance in the nonlinear case, we chose frequency which is close to resonant frequency from the left side of the resonance. Dependences of the permittivity value ε_s of the nonlinear layer (blue short dash line) and the intensity of the electric field I_{in}^s inside the nonlinear layer of the grating (red solid line) on the incident field intensity I_{inc} at the frequency $\kappa = 0.99450$ were presented in Figure 5. The intensity of the inner (incident) electric field I_{in}^s is determined through the inner (incident) electric field by the expression,

$$I_{in}^s = \frac{\sqrt{\varepsilon_s}\,\overline{\left|E_{in}^s\right|^2}}{240\pi} \qquad (3).$$

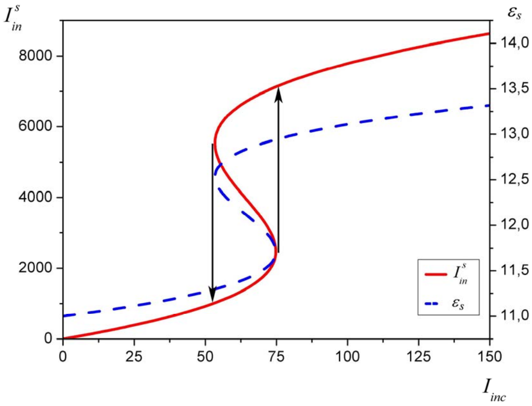

Figure 5. Dependences of the inner field intensity (red solid line) and permittivity value of the nonlinear layer (blue shorted dash line) on the incident field intensity.

Switching the operating regime of the grating occurs at the values of the incident field $I_{inc} = 74.802$ W/cm^2 (forward direction) and intensity $I_{inc} = 53.394$ W/cm^2 (backward direction). When the intensity of the incident field reaches the value $I_{inc} = 74.802$ W/cm^2, the inner intensity in the second layer I_{in}^{s} changes from 2.475 kW/cm^2 to 7.127 kW/cm^2, which corresponds to the change in the second layer permittivity from $\varepsilon_s = 11.709$ to $\varepsilon_s = 12.942$ (forward direction). In the backward direction, the intensity of the electric field inside the nonlinear layer changes from $I_{in}^{s} = 5.525$ to $I_{in}^{s} = 1.018$ kW/cm^2, and the values of the permittivity are $\varepsilon_s = 12.530$ and $\varepsilon_s = 11.297$, respectively.

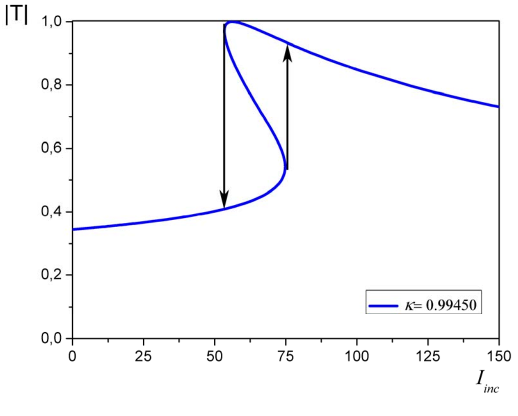

Figure 6. Dependence of the magnitude of the transmission coefficient versus the intensity of the incident field at $\kappa = 0.99450$.

Figure 6 shows dependence of the module of the transmission coefficient on the intensity of the incident field at the frequency $\kappa = 0.99450$. In the forward direction we observed the jump from $|T| = 0.542$ to $|T| = 0.936$. In the backward direction, the jump is observed from $|T| = 0.969$ to $|T| = 0.409$.

4 Conclusions

The bistable operating regime of the ultrathin metal-dielectric metasurface can be obtained with low values of the incident field intensity $I_{inc} = 53.394, 74.802\, W/cm^2$ using a Kerr-nonlinear dielectric element in the Wood's anomalies resonance conditions. Therefore, the metasurface with GaAs-nonlinear element is promising for creating ultra-compact optical devices, which can be controlled by the incident field intensity.

5 References

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