A giant red shift and enhancement of the light confinement in a planar array of dielectric bars

Vyacheslav V Khardikov, Ekaterina O Iarko and Sergey L Prosvirnin

1 Institute of Radio Astronomy of National Academy of Sciences of Ukraine, Kharkiv 61002, Ukraine
2 Karazin Kharkiv National University, Kharkiv 61022, Ukraine

E-mail: khardikov@univer.kharkov.ua, yarkokatya@rian.kharkov.ua and prosvirn@rian.kharkov.ua

Received 29 September 2011, accepted for publication 1 February 2012
Published 23 February 2012
Online at stacks.iop.org/JOpt/14/035103

Abstract
The results of research into resonant phenomena in double-periodic subwavelength planar structures made up of paired dielectric bars are presented. For the first time the existence of high Q-factor trapped mode resonances is revealed in these low-loss entirely dielectric structures. A large red shift of the trapped mode resonance of the structure is observed as compared with the resonant wavelength of the periodic structure with only one dielectric bar per unit cell. This shift of the resonant wavelength is caused by a strong coupling of the electromagnetic fields in the adjacent dielectric bar resonators.

Keywords: trapped mode, Fano resonance, planar dielectric array, germanium periodic structure, light diffraction, infrared wave diffraction

(Some figures may appear in colour only in the online journal)

1. Introduction

Thanks to striking progress in nanotechnology, optically thin layers of materials can be structured with a periodic pattern in order to design planar metamaterials. The planar metamaterials (also known as metafilms) are an impressive modern object, which is driven by certain fascinating facilities such as, e.g. the anomalous reflection and refraction [1], the unusual asymmetric transmission [2, 3], and light reflection that does not change the phase of the incident wave [4].

Typically, a planar metamaterial assigned for visible and near-infrared wavelengths is a plasmonic structure designed on the basis of a periodic array of complex-shaped resonant nanowire metallic particles. The main factor responsible for the spectacular properties of metafilms is some resonant interaction of light with the patterned layer. Moreover, numerous envisioned applications of planar metamaterials do require high Q-factor resonances and a strong confinement of intensive electromagnetic fields. First of all they concern both the projects of gaining or lasing devices such as the spaser [5, 6] and the devices characterized by the bistable reflection and transmission in order to control light with light [7, 8], which could be realized by incorporating some active medium or nonlinear inclusions in periodic structures of resonant metafilms. Another domain, aging a decade, concerns extremely sensitive chemical and biochemical sensors [9].

However, losses are orders of magnitude too large for the envisioned applications. Typically, the Q-factor of the resonances excited in plasmonic structures is small because of high radiation losses and huge energy dissipation inherent to metals in the visible and near-infrared wavelength ranges.

The usual resonance field enhancement inside a planar metamaterial may be greatly increased by involving structures which bear the so-called trapped modes [10, 11]. The excitation of the trapped mode resonances in planar double-periodic structures with broken symmetry was found both theoretically [12–14] and experimentally [15] in microwaves. In particular, those typical peak-and-trough Fano spectral profile resonances can be excited in the periodic array
composed of twice asymmetrically split metal rings. Their specific character arises from some destructive interference of the radiation by the antiphased currents in metallic elements of a subwavelength periodic cell.

In the fully symmetric structure, the coupling of the trapped mode currents can be infinitesimal for a wave incident from free space. Thus, the $Q$-factor of the resonance is limited only by the dissipative losses of the structure. This unique property leads to the analogy between the trapped mode resonance and the metastable energy level in atomic systems, manifesting an electromagnetically induced transparency. Recently, some effective media exhibiting the EIT-like properties and the desired 'light slowing' metamaterials that use the trapped mode plasmonic arrays, have been proposed [16, 17].

Now, the existence conditions and the spectral properties of trapped mode resonances are investigated in detail in the suitably structured planar plasmonic metamaterials developed for the near-IR range [18–20]. The $Q$-factor of the trapped mode resonance essentially exceeds that for the ordinary resonance, but its value is not greater than several tens because of dissipative losses.

Since the intrinsic dissipative losses in plasmonic structures are unavoidable, the idea of their compensation using certain parametric processes and gain media was proposed [21, 22]. Experimental demonstrations of the compensation of the absorption losses in a trapped mode metallic metamaterial by using optically pumped semiconductor quantum dots were presented in [23, 24]. The observed narrowing of the quantum dots photoluminescence spectrum is evidence of the $Q$-factor increase in the pumped structure.

Fortunately, the use of plasmonic structures is not a single possible way to develop the thin planar metamaterials to ensure a strong enhancement of the confined resonant field. One evident way to produce low-dissipative structures, with similar electromagnetic properties is to use entirely dielectric elements in designing the double-periodic structures maintaining the trapped mode resonances. It was shown recently, by simulation, that the microwave left-handed media may be constructed on the basis of cubic high dielectric resonators [25] or dielectric rings and rods put together [26] instead of the classical split-ring metallic resonators.

This paper is aimed at investigating in the family of the high-$Q$ trapped mode planar metamaterials the new and highly desirable low-loss structures made up of entirely dielectric elements.

The resonances in the plasmonic and dielectric structures have a considerably different nature. A plasmon–polariton excitation propagating along metallic surfaces replicates their shape. Therefore, the complex-shaped metallic elements can be used to provide a resonant interaction light with a periodic structure in a deeply subwavelength range. On the contrary, complications of the shape of dielectric elements do not involve a substantial increase of the resonant wavelength, as in the case of metallic elements.

The paper studies the excitation conditions and the main properties of the near-infrared trapped mode resonance in a low-loss subwavelength planar array with the unit cell that includes a pair of resonant dielectric bars.

2. The problem statement and the method of solution

Let us consider a dielectric bar of square cross section as a constituent element of the entirely dielectric array. Thus the problem of light diffraction by a double-periodic planar array of dielectric bars placed on a substrate with thickness $L$ is under investigation (see figure 1). The unit cell of the array includes a pair of dielectric bars which are different in length but identical in cross section and material. The longer bar length is $h_1$ and the shorter $h_2$. The sizes of the square periodic cell are $d_x = d_y = 975$ nm. The minimal distance between the longer and the shorter bars of the pair is 195 nm for all of the two-element dielectric arrays studied below. The periodic cell is symmetric relative to the line drawn through the cell center parallel to the $y$-axis. The normal incidence of a linearly $x$-polarized plane wave is considered. The resonant response of the array is studied in the near-infrared wavelength range from 1000 to 3000 nm. The substrate material is assumed to be synthetic fused silica. Its refractive index is approximately 1.44 in the wavelength range under consideration [27].

In order to provide a resonant light reflection without forming the diffraction orders, the dielectric bars are chosen to have a resonant wavelength larger than the unit cell size. The size of the dielectric bar cross section is restricted by the following condition $l^2 < \lambda/2$ where $\varepsilon$ is the bar relative permittivity and $l$ is the cross-section size; this eliminates the transverse interference resonances inside bars.

The bar permittivity value is substantially limited by the properties of dielectric materials suitable for the dielectric array manufacture. The usual dielectrics extensively used in microchip technologies have permittivities not exceeding 4. However, some semiconductors can be used as materials for the array elements. The use of semiconductors is promising because they have transparency windows in the visible and near-infrared wavelength ranges. The permittivity of well-known suitable semiconductors has a value from 11 to 18.
and their dielectric loss tangent does not exceed $10^{-3}$ within the transparency windows. For example, the germanium transparency window extends from 1600 to 2000 nm and its refractive index varies from 4.07 to 4.23 over this window [28].

Taking into account everything mentioned above, the size of the square cross section of dielectric bars is chosen to be $l = 195$ nm.

To solve the diffraction problem, the numerical method proposed in [29] is used. This method is based on both the mapped PSTD method [30] and the transfer matrix theory. For simplicity the dispersion of dielectrics is not taken into account in this paper. The relevancy of such an approach is due to two reasons. First, the dispersion of the chosen materials is very weak in the wavelength range considered. Next this, dispersion has no effect on the properties of the trapped mode resonances. However, the constituents dispersion may be taken into account in the context of the method used.

3. The trapped mode resonances in the arrays of dielectric bars

Let us assume that silica fills up all the half space $z > 0$ below the array to simplify the analysis by excluding the interference resonances in the substrate. As known, and shown by simulation in [29], the finite thickness of the substrate results in the interference fringes along the wavelength dependences of the reflection and transmission coefficients. In the actual structures approximately 0.5 mm thick, these interference resonances are destroyed because of local inhomogeneity of the substrate.

3.1. The resonant properties of the arrays composed of metallic bars

For further comparison between the resonant properties of plasmonic and entirely dielectric planar metamaterials, and to begin with, let us briefly mention the reflection wavelength dependences of the arrays of gold bars. The square unit cell of the structure considered has $d_x = d_y = 500$ nm. The longer and shorter bar lengths are 450 nm and 400 nm respectively. The minimal distance between the longer and the shorter bars is 100 nm. The array is placed on the silica semi-infinite substrate. Since metals have a strong inherent dispersion in the near-infrared range, the gold dispersion has been taken into account by using the complex-pole model and the method of additional differential equations (see, for example [20]).

The wavelength dependence of the reflection coefficient magnitude of this structure is shown in figure 2 (line 1). Another two lines present the wavelength dependences of the reflection coefficient magnitudes of the arrays with a single gold bar in the periodic cell. Line 2 corresponds to the array which consists of the longer bars from the two-element array and line 3 to the array of the shorter ones.

The trapped mode resonance is marked by I in figure 2. It has the typical trough-and-peak Fano spectral profile [31]. As is well known [20, 19], this resonance results from the excitation of the antiphased plasmon–polaritons in the adjacent metallic bars. One important point is that the trapped mode resonance of the two-element periodic structure is excited in the wavelength band restricted by the wavelengths of the reflection resonances of the one-element arrays or in a wavelength close to this band. This is easily seen from the spectral dependences in figure 2 and presented in [19].

3.2. Identification of the reflection resonances of a subwavelength dielectric array

First of all, in order to identify the kind of resonances, we consider the normal reflection by arrays which are assumed to be made of a hypothetical lossless dielectric with the large refractive index of 5.5. Such a special choice of the refractive index enables us to observe at least two reflection resonances of one-element arrays of dielectric bars in the subwavelength range. The wavelength dependences of the reflection coefficients’ magnitudes are shown in figure 3 for both the array of paired dielectric bars (line 1) and the one-element arrays. Lines 2 and 3 correspond to the array of the longer and the shorter dielectric bars, respectively. There are two reflection resonances of the one-element arrays in the considered wavelength range. As revealed by the numerical analysis of the electric field distributions along the periodic cell of arrays, they are the ordinary resonances of dielectric bars. These resonances are excited under the condition that the bar length is approximately equal to $\lambda_d/2$ or $3\lambda_d/2$ where $\lambda_d$ is the wavelength in the dielectric of bars.

If two bars of different length are combined in the periodic cell, some additional reflection resonances are excited (see figure 3, line 1). Particular interest is stimulated by the additional resonance in the long-wave part of the considered range. It is a typical Fano-shape sharp resonance with a specific wavelength dependence of the reflection coefficient rolled over trough to peak.
Figure 3. The wavelength dependences of the reflection coefficients’ magnitudes of the arrays composed of paired dielectric bars ($h_1 = 877$ nm and $h_2 = 780$ nm, line 1) and single dielectric bars 877 nm long (line 2) and 780 nm (line 3). The sizes of the periodic cell and the bar cross section are 975 nm and 195 nm, respectively. The refractive index of the bar dielectric is 5.5.

The electric field distributions within the periodic cell have been plotted and studied for all of the additional resonances, to clarify their nature. One such distribution relating to the plane $z = -l/2$ is shown in figure 4 at the wavelength 2208 nm that corresponds to the additional resonance with the maximum wavelength. As the field has a symmetric distribution, it is presented only within a half of the cell.

One can see that both dielectric bars behave as half-wavelength dielectric resonators, i.e. the maximum of the electric field within the bar is located close to its center and the field decreases to the bar facets (figure 4(b)). The electric field maxima observed outside the bar at its ends result from large enough difference between the permittivities inside and outside the bar. Actually, the normal components of the electric field induction satisfy the continuity condition $E_x^- = \varepsilon E_x^+$, where $E_x^-$ and $E_x^+$ are the electric fields in free space and inside the bar, respectively. Thus the electric field in free space between the bars has the value $\varepsilon$ times greater than the field inside the bars. In our case this coefficient is $\varepsilon = 30.25$. The antiphased field distribution evidences that the studied resonance is a trapped mode one. Notice that the $E_y$ field component has its maximum value of the same order as the maximum of $E_x$ and the maximum of $E_z$ one is then over 100 times less.

Besides the enhanced $Q$-factor, the main distinctive feature of the trapped mode resonance of the two-element dielectric array is a great red shift of its wavelength relative to the resonant wavelengths of the corresponding one-element arrays (see figure 3). Thus the coupling between the dielectric bars of the two-element periodic array results in an extremely large increase of the resonant wavelength as opposed to the coupling in the array of metallic bars (see figure 2). This property of the entirely dielectric trapped mode arrays is quite important in view of possible applications.

Figure 4. The distribution of the electric field $x$-component within the periodic cell of the two-element dielectric array in the plane $z = -l/2$. The field distribution is presented for the longest resonant wavelength 2208 nm (see figure 3). Since the electric field values essentially differ inside and outside the bars the field distribution is plotted, for convenience, in the whole of the periodic cell (a), and only inside the bars (b) at different scales.
in the field of infrared metamaterials. First, the ratio of the array pitch to wavelength may be decreased to design more homogeneous metamaterials. Second, the increase of the resonant wavelength results in an enhancement of the confinement of the field intensity due to a decrease of radiation losses. It is equally important to the design of nonlinear and active artificial media. Third, this property of dielectric arrays gives us a way to design double-periodic structures with the trapped mode resonance using materials of relatively small refractive index; for example, made of semiconductors in the wavelength range of their transparency windows.

Finally, research into the field distributions concerning all the rest of the studied resonances over two-element dielectric array (see the spectral dependence in figure 3, line 1) results in the conclusion that they are the ordinary dimensional resonances.

3.3. The trapped mode resonance of a germanium-bar array within the transparency window bandwidth

Now let us study some more realistic array of the germanium bars with the sizes mentioned above. The refractive index of germanium is assumed to be equal to 4.12. Such a value of the germanium refractive index corresponds to the wavelength range from 1850 to 1950 nm. This range is the shaded one in figure 5 where the wavelength dependence of the reflection coefficient of the array is presented. The trapped mode resonance is observed in this range.

Figure 5 illustrates the effect of the array asymmetry as a consequence of the influence of the difference of bar lengths on the wavelength and the $Q$-factor of the trapped mode resonance. It is evident that the trapped mode resonance cannot be excited in a symmetrical structure with equal lengths of both bars by the normally incident plane wave because of the zeroth coupling of the asymmetrical mode of bars and the plane wave in free space and substrate (see line 1 in figure 5). A decrease of the asymmetry degree characterized by the value $h_1/h_2$ results in an increase of the red shift of the trapped mode resonance and a decrease of the wavelength difference between the reflection trough and peak, i.e. in the trapped mode resonance $Q$-factor growth.

To estimate the trapped mode resonance $Q$-factor, consider the expression $Q = \lambda_1 \lambda_2 / (2 \lambda_0 (\lambda_2 - \lambda_1))$, where $\lambda_1$ and $\lambda_2$ are the wavelengths of the trough and peak of the reflection coefficient, respectively, and $\lambda_0$ is the wavelength corresponding to the reflection coefficient value $(|R(\lambda_1)| + |R(\lambda_2)|)/2$. The $Q$-factors of the trapped mode resonances of the germanium bar structures are 203 and 1080 for $h_1 = 975$ nm, $h_2 = 877$ nm, and $h_2 = 838$ nm, respectively (see lines 2 and 3 in figure 5 for comparison). Note that for the structure of the dielectric bars with the refractive index 5.5 (see figure 3, line 1), the $Q$-factor of the trapped mode resonance is 127.

The semiconductors dissipative losses will certainly affect the $Q$-factor of the trapped mode resonance. However, in the transparency window the dielectric loss tangent of germanium does not exceed $10^{-3}$ (this bandwidth is marked as shaded in figure 5). Over this band, one can see only negligible variations of the reflection magnitude and a very small widening of the trapped mode resonance which reveals a decrease of the $Q$-factor (see figure 6) with an increase of the dielectric loss tangent.

The field of high intensity confined in the periodic array under the trapped mode resonance may effectively interact with a substrate of an active or nonlinear material. In the first case, one can observe amplification of the reflected or transmitted light. In the case of a nonlinear substrate, a certain light with light controlling can be achieved in very thin structures.

The wavelength dependences of the ratio $|E|/|E_0|$ are presented in figure 7. Here $|E|$ is the maximum of the absolute...
value of the electric field in one or another chosen point within the array and $|E_0|$ is the maximum of the absolute value of the incident wave electric field in free space. The wavelength dependences of $|E|/|E_0|$ are shown for four different points. Lines 1 and 2 correspond to the centers of the shorter and the longer dielectric bars, respectively. Near those points the electric field reaches its maximum level inside the bars. Lines 3 and 4 correspond to the center of a gap between two adjacent shorter and longer bars, respectively. It should be noticed that the electric field magnitude reaches its minimum along both the mentioned gaps in these points (see figure 4(a)). The magnitude of electric field enlarges over 28 times in the center of the gap between the bars despite the fact that the electric field has its minimum in these points. The maximum of the electric field magnitude in the array corresponds to the wavelength 1899 nm. This wavelength is approximately equal to the central wavelength of the trapped mode resonance $(\lambda_1 + \lambda_2)/2 = 1898$ nm).

The $Q$-factor increasing results in a rise of the electric field intensity in the structure. For example, the maximal ratio $|E|/|E_0|$ is 2.3 times greater in the case of the germanium array with $h_1 = 877$ nm and $h_2 = 838$ nm than with the array with $h_1 = 877$ nm and $h_2 = 780$ nm.

4. Conclusions

The problem of the normal reflection of the near-infrared radiation by a planar array with a subwavelength square translation cell composed of two dielectric bars of different lengths has been solved. For the first time the existence of the high-$Q$ trapped mode resonance has been found in these low-loss entirely dielectric structures. A coupling between the adjacent bars induces field enhancement in the surrounding media, which can result in phenomena such as luminescence, nonlinear scattering, absorption, and lasing. The spectral response of this novel planar metamaterial closely resembles the EIT phenomenon in atomic systems. In contrast with plasmonic arrays, the trapped mode resonance excited in an entirely dielectric structure demonstrates a giant red shift relative to the wavelength of the ordinary resonance of the array with only one dielectric bar per unit cell. This remarkable property of the dielectric trapped mode arrays enables us to design highly desirable deep-subwavelength low-loss planar metamaterials in the near-infrared range.

Acknowledgment

This work was supported by the Ukrainian State Foundation for Basic Research, Project F40.2/037.

References

[1] Yu N et al 2011 Light propagation with phase discontinuities: generalized laws of reflection and refraction Science 344 333–7
[2] Fedotov V A, Mladyonov P L, Prosvirnin S L, Rogacheva A V, Chen Y and Zeludev N I 2006 Asymmetric propagation of electromagnetic waves through a planar chiral structure Phys. Rev. Lett. 97 167401
[3] Fedotov V A, Schwanecke A S, Zeludev N I, Khardikov V V and Prosvirnin S L 2007 Asymmetric transmission of light and enantiomerically sensitive plasmon resonance in planar chiral nanostructures Nano Lett. 7 1996–9
[4] Schwanecke A S, Fedotov V A, Khardikov V V, Prosvirnin S L, Chen Y and Zeludev N I 2007 Optical magnetic mirrors J. Opt. A: Pure Appl. Opt. 9 L1–2
[5] Bergman D J and Stockman M I 2003 Surface plasmon amplification by stimulated emission of radiation: quantum generation of coherent surface plasmons in nanosystems Phys. Rev. Lett. 90 027402
[6] Zeludev N I, Prosvirnin S L, Papasimakis N and Fedotov V A 2008 Lasing spaser Nature Photon. 2 351–4
[7] Tuz V R, Prosvirnin S L and Kochetova L A 2010 Optical bistability involving planar metamaterials with broken structural symmetry Phys. Rev. B 82 233402
[8] Carretero-Palacios S et al 2010 Optical switching in metal-slit arrays on nonlinear dielectric substrates Opt. Lett. 35 4211–3
[9] Flory F, Escoubas L and Berginc G 2011 Optical properties of nanostructured materials: a review J. Nanophoton. 5 052502
[10] Stockman M I, Falleev S V and Bergman D J 2001 Localization versus delocalization of surface plasmons in nanosystems: can one state have both characteristics? Phys. Rev. Lett. 87 167401
[11] Liu H C and Yariv A 2009 Grating induced transparency (GIT) and the dark mode in optical waveguides Opt. Express 17 11710–8
[12] Prosvirnin S L and Zouhdi S 2001 Multi-layered arrays of conducting strips: switchable photonic band gap structures Int. J. Electron. Commun. (AEÜ) 55 260–5
[13] Prosvirnin S and Zouhdi S 2003 Resonances of closed modes in thin arrays of complex particles Advances in Electromagnetics of Complex Media and Metamaterials ed S Zouhdi et al (The Netherlands: Kluwer Academic) pp 281–90
[14] Blackburn J F and Arnaut L R 2004 High performance split ring FSS for WLAN bands Proc. 27th ESA Antenna Technology Workshop on Innovative Periodic Antennas: Electromagnetic Bandgap, Left-handed Material, Fractal

Figure 7. Wavelength dependences of ratio $|E|/|E_0|$ for some points within a two-element array of germanium bars. The structure sizes are $d_x = d_y = 975$ nm, $l = 195$ nm, $h_1 = 877$ nm, and $h_2 = 780$ nm. The refractive index of germanium is assumed to be 4.12. Lines 1 and 2 correspond to the center of the shorter and the longer bars, respectively. Lines 3 and 4 correspond to the center of air gaps between two adjacent shorter and longer bars, respectively.
[15] Fedotov V A, Rose M, Prosvirnin S L, Papasimakis N and Zheludev N I 2007 Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry Phys. Rev. Lett. 99 147401

[16] Zhang S, Genov D A, Wang Y, Liu M and Zhang X 2008 Plasmon-induced transparency in metamaterials Phys. Rev. Lett. 101 047401

[17] Papasimakis N, Fedotov V A, Zheludev N I and Prosvirnin S L 2008 Metamaterial analog of electromagnetically induced transparency Phys. Rev. Lett. 101 253903

[18] Khardikov V V, Iarko E O and Prosvirnin S L 2010 Trapped-mode resonances in light diffraction by a planar doubly periodic structure with asymmetric metal elements Radio Phys. Radio Astron. 1 221–31

[19] Dong Z G et al 2010 Plasmonically induced transparent magnetic resonance in a metallic metamaterial composed of asymmetric double bars Opt. Express 18 18229–34

[20] Khardikov V V, Iarko E O and Prosvirnin S L 2010 Trapping of light by metal arrays J. Opt. 12 045102

[21] Popov A K and Shalaev V M 2006 Compensating losses in negative-index metamaterials by optical parametric amplification Opt. Lett. 31 2169–71

[22] Gordon J A and Zaiatkowski R W 2007 The design and simulated performance of a coated nano-particle laser Opt. Express 15 2622–53

[23] Plum E, Fedotov V A, Kuo P, Tsai D P and Zheludev N I 2009 Towards the lasing spaser: controlling metamaterial optical response with semiconductor quantum dots Opt. Express. 17 8548–51

[24] Tanaka K, Plum E, Ou J Y, Uchino T and Zheludev N I 2010 Multifold enhancement of quantum dot luminescence in plasmonic metamaterials Phys. Rev. Lett. 105 227403

[25] Kim J and Gopinath A 2007 Simulation of a metamaterial containing cubic high dielectric resonators Phys. Rev. B 76 115126

[26] Jelinek L and Marquès R 2010 Artificial magnetism and left-handed media from dielectric rings and rods J. Phys.: Condens. Matter 22 025902

[27] Malitson I H 1965 Interspecimen comparison of the refractive index of fused silica J. Opt. Soc. Am. 55 1205–8

[28] www.filmetrics.com:80/refractive-index-database/Ge/Germanium

[29] Khardikov V V, Iarko E O and Prosvirnin S L 2008 Using transmission matrix and pseudospectral time-domain method to study of light diffraction on planar periodic structures Radiophys. Radioastron. 13 146–58 (in Russian)

[30] Gao X, Mirotznik M S, Shi S and Prather D W 2004 Applying a mapped pseudospectral time-domain method in simulating diffractive optical elements J. Opt. Soc. Am. A 21 777

[31] Fano U 1961 Effects of configuration interaction on intensities and phase shifts Phys. Rev. 124 1866–78