Wide defect in a Resonantly Absorbing Bragg Grating as a nonlinear microresonator for polaritons

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The nonlinear polariton transmission, reflection and trapping by a defect in the resonantly absorbing Bragg grating (RABG) is demonstrated in numerical simulation. It is shown that the wide defect under some conditions could effectively serve as microresonator for polaritonic wave storage. The three types of the defect such as microcavity, groove and stripe are considered. Capture the electromagnetic field inside the microcavity (with no resonant nanoparticles) placed in the RABG is observed, as well as stuck of trapped polarization modes to the defect edges for the groove (defect span with reduced density of nanoparticles) and for the stripe with relatively increased density. Strong radiation reflection and adhered propagation of the polarization mode along the first edge of the stripe with high density of resonant atoms is exhibited by numerical computation.

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In last years the interest to the intermediate between electronics and photonics has arisen. The new terms polaritonics and plasmonics attract attention of scientists and engineers. The interest of polaritonics is in interaction of light with the microstructured matter. Due to the prominent progress that has occurred last years in fabrication of novel materials with engineered internal structure (photonic bandgap fibers, carbon nanotubes, nanowires), there is the demand for an analysis of the phenomena that can arise due to specific properties of artificial materials.

The substantial achievements in fabrication of periodic structures in different materials attract interest to metallic periodic structures such as metallic combs, periodic array of indentations [1], two-dimensional hole lattices [2] and one-dimensional groove arrays [3] machined into flat interfaces, conducting wire tailored with a periodic array of radial grooves [4] and even 'superstructures of nanowires and nanoparticles connected by molecular springs' [5]. The objects of interest are waves resulting from the photon interaction with plasmonic oscillations in metal [6]. The theory of surface plasmons polaritons on structured surfaces as well as recent advances in experimental studies are reported [7]. The relevant method for preparation the dielectric structure with periodic thin films containing metallic nanoparticles or molecules could be e-beam deposition or layer-by-layer adsorption technique [8] which allows creation of nanometer-scale multilayered films.

The nonlinear periodic structure that is referred to as resonantly absorbing Bragg grating (RABG) has been proposed and investigated in [9, 10, 11]. The RABG consists of linear homogeneous dielectric medium containing thin film array of resonant two-level atoms. The results of the theory are summarized in [12]. The model developed in [13, 14, 15] describes the ultrashort (comparing to the relaxation time) pulse which is propagates through the regular Bragg grating evolved from films of metallic nanoparticles. Nonlinear plasmonic oscillations are governed by the cubic Duffing equation. Solitary electromagnetic waves coupled with media polarization, i.e., polaritonic solitary waves, were found. The robustness of these polaritonic gap solitons (PGSs) was demonstrated by numerical simulation.

Optical soliton scattering on defects in lattices is attractive problem of nonlinear optics. The paper [16] is devoted to trapping of light in a nonuniform resonant structure by the defect which is created as a result of the inversion of the atoms population. Depending on strength of the defect the pulse either can pass through it with low radiation or to localize in the defect. Action of the second pulse could lead to depinning of the initial pulse or to trapping both of them in the defect. Trapping Bragg solitons by a pair of localized defects has been also demonstrated [17]. Thus, it would be very natural to consider interaction of the PGSs with different types of the RABG defects, such as the absence of the resonant atom layers in the grating or oppositely the conglutination of several films. The influence of all these effects arising in the process of artificial media fabrication can be crucial in material guiding properties.

A homogeneous span between two distributed Bragg mirrors is the effective laser microresonator in integrated optics [18, 19] and nano-optics [20, 21, 22]. During last years the persistent interest for optical properties of these structures is subsists. The review of the nonlinear properties of semiconductor microcavities can be found in [23]. The quantum well that is grown inside the
Bragg-mirror microcavity appears as the defect in regular periodic structure. So, the array of quantum wells in Bragg-mirror microcavity is tantamount to wide defect in regular grating. A similar statement is true also for the resonantly absorbing Bragg grating.

In this paper we will consider the three types of microresonator, which will be referred as microcavity, groove and stripe. Specification of these terms will be done below. We perform numerical simulation of the coupled solitary waves which are interact resonantly with media consisting of dielectric layers alternating with thin films with metallic nanoparticles (or quantum dots, nanoagregates with nonlinear dielectric properties) [13]. Due to Bragg resonance condition a weak electromagnetic pulse can not propagate in the RABG, whereas the moving polaritonic gap soliton that has been found in [13] is able to reach for inner defect.

The model of the polaritonic wave propagating in the resonantly absorbing Bragg grating is considered following to [14]. The width of the resonant film is about hundred of nanometers and it is negligible small comparing to the dielectric layer separating two thin films of resonant inclusions. According to slowly varying envelope approximation, pulse width includes about hundred of grating double periods and varies slowly on one period. Considering microresonator as the defect in the RABG, we assume that this defect consists of several hundreds of layers containing resonant nanoparticles so the slowly varying envelope approximation is still valid. The normalized form of the model equations is

\[ i \left( \frac{\partial}{\partial \zeta} + \frac{\partial}{\partial \tau} \right) e_1 + \delta e_1 = -\gamma(\zeta) p \\
\left( \frac{\partial}{\partial \zeta} - \frac{\partial}{\partial \tau} \right) e_2 - \delta e_2 = \gamma(\zeta) p \\
\frac{\partial p}{\partial \tau} + \Delta p + \mu |p|^2 p = - (e_1 + e_2). \tag{1} \]

The dimensionless variables \( e_{1,2} \) are slowly varying envelopes of the electromagnetic field components, which are propagate in forward and backward directions, and \( p \) is the slowly varying envelope of the polarization, which is determined by the array of thin films containing resonant nanoparticles. Here \( \Delta = 2 \sqrt{\varepsilon} (\omega_d - \omega_0) / \omega_p \) is the detuning of a nanoparticle’s resonance frequency from the field’s carrier frequency \( \omega_0 \), \( \omega_p \) is the plasma frequency, \( \omega_d \) is the frequency of dimensional quantization of nanoparticles, \( \delta = 2(\varepsilon / \omega_p) \Delta q_0 \) with \( \Delta q_0 = q_0 - 2 \pi / a, q_0 = \omega_0 / \sqrt{\epsilon} / c \) is wave vector in the media, and \( \varepsilon \) is permittivity, \( \mu \) is a dimensionless coefficient of anharmonicity. Normalized spatial and time variables denote as \( \zeta \) and \( \tau \), respectively. Total field acting on resonant atoms is the sum of \( e_1 \) and \( e_2 \) [13].

The defects in RABG are described by the indicator function \( \gamma(\zeta) \). The regular RABG is produced from thin layers with equal concentration of nanoparticles. For this reason we put \( \gamma(\zeta) = 1 \) in the regular grating. Here we consider the lattice defect as span with alternative nanoparticles concentration (see Fig. 1). When coordinate \( \zeta \) belongs to defect region the function \( \gamma(\zeta) \) is not equal unit. If the density of nanoparticles in layer at point \( \zeta \) is more (less) comparing with the density of particles in regular part of the grating, then \( \gamma(\zeta) > 1(\gamma(\zeta) < 1) \). In other words, the indicator function is equal to ratio of nanoparticle density in the defect layer per nanoparticle density of regular layers. The region with \( \gamma(\zeta) < 1 \) will be termed the groove defect. The region where \( \gamma(\zeta) > 1 \) will be denoted as the stripe. The solitary wave solution (i.e., the polaritonic gap soliton) corresponding to regular RABG has been found and discussed in [13]. It reads as

\[ e_1(\eta) = -0.5 (1 + \alpha) f_s(\eta) \exp \{ i \delta r \}, \]

\[ e_2(\eta) = -0.5 (1 - \alpha) f_s(\eta) \exp \{ i \delta r \}, \]

\[ p(\eta) = q(\eta) \exp \{ i \delta r \}. \tag{2} \]

where \( \eta = r \alpha \zeta, \beta = 2(\alpha^2 - 1), \alpha > 1 \) is a free parameter defining the solitary wave group velocity. Auxiliary functions \( f_s = u \exp \{ i \varphi \} \) and \( q = r \exp \{ i \psi \} \) are defined through the following amplitudes

\[ u^2(\eta) = 4 \sqrt{\beta} \cosh^{-1} \left[ 2 \sqrt{\beta} (\eta - \eta_0) \right], \]

\[ r^2(\eta) = 4 \beta \cosh^{-1} \left[ 2 \sqrt{\beta} (\eta - \eta_0) \right]. \tag{3} \]

and phases

\[ \varphi(\eta) = \varphi_0 \pm \arctan \tanh \left[ \sqrt{\beta} (\eta - \eta_0) \right], \]

\[ \psi(\eta) = \psi_0 \pm 3 \arctan \tanh \left[ \sqrt{\beta} (\eta - \eta_0) \right]. \tag{4} \]

Initial phases are set in such way that \( \varphi_0 - \psi_0 = \pi / 2 \), at \( \eta \to -\infty \). In (3) and (4) parameter \( \eta_0 \) is an integration constant that indicates the initial pulse position.

The nonlinear polaritonic wave [2] propagates through the ideal RABG without radiation loss or change of the initial shape. It should be noted that passing the RABG is not allowed for linear waves due to the band gap. For this reason we used the solution [2] as the initial configuration for our numerical simulation of the solitary wave propagation through the microresonator span in RABG. (Fig. 1).

In all following figures, which are illustrate results of numerical simulations, the wide defect is represented by

![Distribution of nanoparticles density](image)

FIG. 1: Distribution of nanoparticles density in (a) RABG microcavity \( \gamma(\zeta) = 0 \), (b) RABG wide groove defect \( \gamma(\zeta) < 1 \) and (c) RABG wide stripe defect \( \gamma(\zeta) > 1 \).
the span with width=10 (normalized spatial units $\zeta$) with the indicator function $\gamma(10 < \zeta < 20) \neq 1$. Left part of these pictures illustrates evolution of total electromagnetic field $(e_1 + e_2)$, and right part is represents evolution of polarization component $p$.

We consider the microcavity, i.e., wide defect which is not contains resonant nanonarticles, as the first example of microresonator in the RABG. At the front interface of the defect, as Fig. 2 demonstrates, the incident solitary polaritonic wave transforms to the electromagnetic pulse which is propagates in the linear regime until it crosses the second interface of the microcavity. (Inside the defect the pulse velocity coincides with the velocity of linear wave.) Near all energy of the incident electromagnetic pulse transfers to this linear wave. Besides one can see the localized plasmonic mode. It results from excitation of undamped plasmonic oscillations due to polariton scattering on the microcavity edge. Has traversed the cavity, the pulse sheds radiation on the second edge of the defect. Since the reflected pulse has small amplitude (less 0.2 - 0.4 of incident pulse amplitude), it transforms into linear waves which are remain trapped in the cavity as they cannot further propagate in RABG. The left part of Fig. 2 provides an illustration of linear radiation which is trapped by the microcavity. The pulse refracted on the second interface restores plasmonic wave, so nonlinear solitary polaritonic wave arises again although with smaller energy. Part of polaritonic pulse energy lost after passage the cavity is lay out for generation the periodic localized polarization modes that can be seen in the right of the Fig. 2. These bright spots forming a periodic pattern are the consequence of reflection between moving solitary pulse (moving mirror) and the edge of the defect. We observed more pronounced periodic pattern for polarization together with backward and forward waves (in total field they are cancel each other due to interference) for the narrow defect with $\gamma(10 < \zeta < 11) = 0$ (defect width is less then the pulse width).

It is relevant to mention that the characteristic of the refracted pulse passing through microcavity corresponds to light ray passing the dielectric layer according to geometric optics laws.

Considering groove (i.e., region with decreased concentration of resonant nanonarticles) one can see (Fig. 3) that part of incident pulse energy is expended for excitation of the plasmonic oscillations in the groove, hence the total electromagnetic field in the cavity decreases (comparing to the microcavity case). Increase the density of resonant nanonarticles ($\gamma = 0.25$, $\gamma = 0.5$) in the span results in drop of the radiation losses inside the groove-type defect. Linear polaritonic waves, which are trapped inside the groove, remain conspicuous. In case then concentration of nanoparticles in the groove is the half of the regular one, polaritonic wave refraction at the fringes of the groove decreases, and localization of plasmonic modes tends to occur close to the fringes of the groove.

The third type of the microresonator is the stripe of optically denser medium. Provided nanoparticle density in the stripe is not so high ($\gamma = 1.5$), solitary polaritonic wave undergoes small losses of energy on the boundaries, and localization of polarization modes occurs only on the fringes of the stripe (Fig. 4). At $\gamma = 3$ the PGS effectively dissipates with appearance of reflected backward waves. Some part of the incident pulse creates a trapped plasmonic mode and the rest of pulse transfers forward being converted into solitary wave with smaller amplitude. If density of resonant nanoparticles in the defect is high, e.g., $\gamma = 5$, the PGS does not survive, most of
its electromagnetic component reflects backward. Also a high energetic plasmonic mode locking with the fore-part of the stripe is appears. Part of radiation passes through the stripe defect in the RABG. In the case of a narrow stripe of dense material the transmitted pulse intensity is higher and the pulse is more localized comparing with the pulse transmitted though the wide stripe with the same density. Polarization mode is defined only by the lower fringe reflection and it is seems does not change with variation of the stripe width. As follows from [2] and definition of parameter $\eta$, solitary wave velocity is controlled by parameter $\alpha$, i.e., increase of $\alpha$ leads to decrease of PGS’s velocity. Slow solitary wave is more effectively interact with the defects. Systematic simulation have shown that in the case of groove the slower PGS transfers more energy to localized plasmonic oscillations (Fig. 5). If the polariton is very slow, e.g., $\alpha = 5$, it can be trapped effectively by the groove (Fig. 6). Beyond the groove there is virtually no radiation.

In the case of stripe almost all energy of the electromagnetic wave transfers to the reflected pulse and nearly half energy of the polaritonic wave transfers into the localized mode. Transmitted wave is very weak.

In conclusion we have demonstrated that the wide defect in the RABG can be considered as nonlinear microresonator. In particular weak light pulse trapping is shown for the microwave cavity placed into RABG.

Solitary polaritonic wave scattering and transition is studied for groove defects. We observed the capture of both electromagnetic field and localized plasmonic mode in this case. Some part of radiation remain localized in the groove. It is notable that the slow PGS can be completely trapped by the groove-type microresonator.

The near-total reflection resulted in PGS collapse on the stripe-defect is demonstrated in numerical simulation. Generation of localized plasmonic oscillations attends solitary wave scattering on the defect. Stripe-type defect with high density of nanoparticles could serve as the guide for highly intensive polarization mode which propagates along the defect edge.

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FIG. 6: Slow PGS trapping in the groove-type microresonator ($\gamma = 0.1$).