Non-Bragg gap solitons and absorption effects in Kerr-metamaterial periodic and Fibonacci heterostructures

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Abstract — A detailed study of non-Bragg gap solitons in one-dimensional Kerr-metamaterial periodic and Fibonacci heterostructures is performed. The transmission coefficient is numerically obtained by considering the loss effects in the metamaterial slabs. A switching from states of no transparency in the linear regime to high-transparency states in the nonlinear regime is observed for both zero-order and plasmon-polariton gaps. The spatial localization of the non-Bragg gap solitons are also examined and the symmetry properties of the soliton waves are briefly discussed.

The experimental realization of metamaterials, or left-handed materials (LHMs), has opened up interesting possibilities in the study of 1D plasmonic heterostructures. In this respect, both periodic and quasiperiodic structures, made up of bilayers AB composed of materials with positive (RHM) and negative (LHM) indices of refraction, have been the subject of both experimental and theoretical investigations. A study [1] on alternate stacks of nonlinear-Kerr/metamaterial have revealed the existence of a \( n = 0 \) gap soliton: one finds a soliton-mediated transparency switching, from a state of no transparency in the linear regime to total transparency in the nonlinear regime. Moreover, recent investigations on 1D RHMLHM heterostructures have shown that, for oblique electromagnetic incidence, longitudinal bulk-like plasmon polaritons (PPs) may be excited, with the non-Bragg PP gap showing up in the corresponding transmission spectra [2]. Recently, multi stability, transmission switching and soliton formation have been reported on Kerr-metamaterial superlattices at the band edge of the PP gap [3].

Here we are concerned with a heterostructured system composed by the building blocks A (of width \( a \)) and B (of width \( b \)), which are arranged according to a Fibonacci sequence. Layers A (or AA) are characterized by a constant magnetic permeability \( \mu_A \) and an electric permittivity given by \( \epsilon_A = \epsilon_0 + \alpha |E(z)|^2 \), where \( E = E(z) \) is the electric-field amplitude of the electromagnetic field within the heterostructure. Slabs B represent the metamaterial whose frequency-dependent electric permittivity and magnetic permeability are given by \( \epsilon_B = f_\epsilon + \frac{F_\epsilon}{\beta_A - \nu^2 - i \nu \gamma} \) and \( \mu_B = f_\mu + \frac{F_\mu}{\beta_A - \nu^2 - i \nu \gamma} \), respectively. In the above expressions [1, 3], we have set \( f_\epsilon = 1.6 \), \( F_\epsilon = 40 \text{ GHz}^2 \), \( \beta_\epsilon = 0.81 \text{ GHz}^2 \), \( f_\mu = 1.0 \), \( F_\mu = 25 \text{ GHz}^2 \), \( \beta_\mu = 0.814 \text{ GHz}^2 \), \( \nu \) is the linear frequency and \( \gamma \) is a phenomenological damping parameter which accounts for absorption/loss effects in the slabs B, both expressed in GHz. Without loss of generality we have focused on the study of transversal-electric (TE) electromagnetic modes in the heterostructure.

We begin by studying the transmission coefficient as a function of the nonlinearity, at the particular frequency \( \nu = 3.0557 \text{ GHz} \) where the transmission coefficient is negligible in the linear regime. For the Fibonacci generations \( S_{12} \), the transmission-switching phenomena and multi stability is shown to occur and, in Fig. 1, the gap solitons corresponding to the first three points of maximum transmission for the \( S_{12} \) generation are illustrated. For the lowest nonlinearity resonant value where transmission is maximum a one-soliton distribution is clearly shown; the next lowest defocusing value associated to the second maximum or the second resonant point, gives rise to a two-soliton distribution, whereas defocusing corresponding to the third resonant point clearly excites a three-soliton profile and so on. Note that, even in the presence of absorption, results indicate that the
Figure 1: $\langle n \rangle = 0$ gap soliton for normal incidence corresponding to the first, second, and third local maxima [panels (a), (b), and (c), respectively] of the transmission as a function of the defocusing nonlinearity power in the $S_{12}$ Fibonacci heterostructure with $a = b = 10$ mm at $\nu = 3.0557$ GHz. Solid and dashed lines correspond to phenomenological loss/absorption parameters $\gamma = 0$ and $\gamma = 10^{-3}$ GHz, respectively.

$S_{12}$ heterostructure system has been efficiently tuned so that the first three points of maximum transmission lead to one, two and three-soliton solutions, respectively.

We also performed a similar study for frequency values in the vicinity of the magnetic PP gap, for oblique incidence with $\theta = \pi/24$, in the TE configuration. The splitting of the PP modes in the vicinity of the plasmon frequency affects the way in which the transmission-switching occurs, and multiple maximum-transmission peaks with different heights are originated when the transmission coefficient is plotted as a function of the defocusing nonlinearity power. The magnetic PP gap solitons exhibit, in some cases, a strong localization around the inversion center of the entire system, whereas in other cases they localize around the inversion centers corresponding to Fibonacci sequences of lower order which are contained in the heterostructure. The localization properties of the PP gap solitons are a clear manifestation of the quasiperiodicity on the electromagnetic modes in Kerr-metamaterial Fibonacci heterostructures. Finally, we would like to point out that, in all cases studied in the present work, the transparency-switching phenomenon is still observable at low levels of loss/absorption in the heterostructure.

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