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# Multiple omnidirectional defect modes and nonlinear magnetic-field effects in metamaterial photonic superlattices with a polaritonic defect

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ABSTRACT

We report the existence of multiple omnidirectional defect modes in the zero-$\bar{n}$ gap of photonic stacks, made of alternate layers of conventional dielectric and double-negative metamaterial, with a polaritonic defect layer. In the case of nonlinear magnetic metamaterials, the optical bistability phenomenon leads to switching from negligible to perfect transmission around these defect modes. We hope these findings have potential applications in the design and development of multichannel optical filters, power limiters, optical-diodes and optical-transistors.



Nowadays it is possible to engineer nanostructured materials whose physical properties are defined not only by the constituent materials, but also by the design and geometry of their nanoscale building blocks [1–10]. These synthetic materials, frequently known as metamaterials, are made as an arrangement of artificial structural resonant elements, such as split-ring resonators (SRRs), to demonstrate extraordinary, advantageous, and/or unusual physical properties as, for example, the negative-index of refraction, predicted by Veselago [11] in the sixties. The inclusion of these metamaterials as the constituent slabs of periodic multilayers of two alternate media leads to forbidden frequency ranges, also known as photonic band gaps (PBGs), which are compact and robust against disorder and scale effects [12–17]. In particular, in the case of one-dimensional photonic stacks made of alternate layers of conventional dielectric material and negative-refractive metamaterial, the zero-$\bar{n}$ gap occurs due to a zero-geometrical averaged refractive index [13,16]. Also, it has been shown that, under some specific conditions [17] for each polarization, the zero-$\bar{n}$ gap can be omnidirectional, i.e., independent on the angle of incidence. Moreover, the inclusion of defect layers in metamaterial photonic superlattices leads to the existence of defect modes, inside the zero-$\bar{n}$ gap, which have shown to be of great interest for the development of new optical filters [18]. Additionally, the excitation of multiple defect modes, of particular significance for the design and development of multichannel optical filters [19–22], has been previously theoretically demonstrated only by considering several defects [19,21] or periodicities [20,22], thus being a challenging experimental task.

In the present work, we show that the inclusion of a single polaritonic defect layer at the center of metamaterial/dielectric photonic superlattices leads to the excitation of several defect modes in the zero-$\bar{n}$ gap. This phenomenon is due to the strong

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light-matter interaction in polaritonic materials [23–26] where a fast and strong variation of the corresponding refractive index is observed for frequencies near the transversal phonon branch. As well as, we consider the geometrical condition for the transversal magnetic (TM) omnidirectional zero-$\bar{n}$ gap [17], showing that the corresponding defect modes remain also omnidirectional. Moreover, as it has been previously shown that nonlinear effects on defect modes deserve great attention because their potential applications for frequency multipliers [27], optical-diodes and optical-transistors [28,29], we have considered the nonlinear magnetic metamaterial effects in order to dynamically tune these omnidirectional defect modes by means of the incident magnetic field intensity. Such nonlinear magnetic metamaterials can be fabricated by placing a varactor diode [30,31] or a photosensitive semiconductor [32] within the gap of the SRRs, which allows the SRRs to be tuned by an applied dc voltage or by a high-power signal, as was already shown in experiments [30,31]. Although in the available literature we can found works about the nonlinear phenomena around the defect modes occurring in metamaterial superlattices with a dielectric defect [33–35], the scientific community attention was mainly focused on the nonlinear effects around the edges of the non-Bragg gaps occurring in these systems [36–38]. Thus, there is a lack of attention to the nonlinear optical phenomena in the case of multiple omnidirectional defect modes. Here, we not only shown how to excite several omnidirectional defect modes with the inclusion of a defect layer, but we also study their nonlinear properties, which may have applications in the design and development of multistable omnidirectional filters.

The problem we are concerned here consists in the study of the light propagation properties through one-dimensional metamaterial photonic superlattices with a polaritonic defect layer at the center of the structure. Growth direction is considered along the $z$-axis, where layers A (dielectric), B (metamaterial) and polaritonic (D) have widths $a = 8$ $\mu$m, $b = 6$ $\mu$m, and $l = 12$ $\mu$m, respectively, as depicted in Fig. 1. Within the Maxwell's framework, for TM polarized incident light, we should solve the following differential equation for the magnetic field

$$\frac{d}{dz}\left[\frac{1}{\varepsilon(z)}\frac{d}{dz}H(z)\right] = -\mu(z)\left[\left(\frac{\omega}{c}\right)^2 - \frac{q^2}{n^2(z)}\right]H(z), \tag{1}$$

where $n(z) = \sqrt{\varepsilon(z)}\sqrt{\mu(z)}$ is the $z$ position-dependent refractive index and $q = \omega/cn_A\sin\theta$ is the wave vector along the $x$-axis. A similar equation can be obtained for the $E$ field in the case of transversal electric (TE) polarization. In the linear case, Eq. (1) is solved by means of the widely reported transfer matrix method (TMM) [39]. As it was previously mentioned, we are concerned with the inclusion of a polaritonic defect layer in onedimensional photonic superlattices. The corresponding dielectric constant for polar materials, in the absence of losses, can be written as [23–26].

$$\varepsilon_D(\nu) = \varepsilon_\infty\frac{\nu^2 - \nu_L^2}{\nu^2 - \nu_T^2}, \tag{2}$$

with $\nu_L = 2.55$ THz ($\nu_T = 1.91$ THz) and $\varepsilon_\infty = 3.0$ corresponding to the longitudinal (transversal) phonon frequency and the high frequency limit of the dielectric permittivity for the Cesium-Iodide (Cs-I) compound [23], while magnetic permeability was considered as $\mu_D(\nu) = 1$. Dielectric permittivity and magnetic permeability for dielectric layers were considered as $\varepsilon_A = 6.65$ and $\mu_A = 1.0$, respectively. For metamaterial layers we have taken the effective dielectric permittivity and magnetic permeability as

$$\varepsilon_B(\nu) = 1 + \frac{5^2}{0.9^2 - \nu^2} + \frac{10^2}{11.5^2 - \nu^2}, \tag{3}$$

$$\mu_B(\nu) = 1 + \frac{3^2}{0.902^2 - \nu^2} + \alpha|H|^2. \tag{4}$$

In the linear case, $\alpha = 0$, these responses coincide with the metamaterial proposed in Ref. [13]. Metamaterial unit cells were considered as scaled to work in the far-IR regime, thus $\nu = \omega/2\pi$ is the frequency in THz. As we are limited here to the lower THz regime, ohmic losses are being neglected by having into account previous experimental reports about negative-refractive metamaterials with low-loss levels even for optical frequencies at near and mid-IR regimes [9]. We have

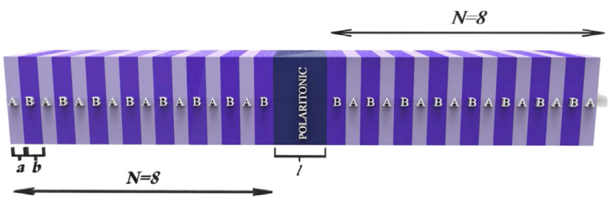


**Fig. 1.** (Color online) Pictorial representation of the system under study, $(AB)^8$ $D(BA)^8$. Building layers are denoted as A (dielectric), B (metamaterial), and polaritonic (D), with slab widths $a$, $b$ and $l$, respectively. Defective superlattice is considered as having 8 unit cells on each side of the defect layer, and $d = a + b$ is the length of the unit cell.