OPTICAL BISTABILITY IN PERIODIC NONLINEAR STRUCTURES CONTAINING LEFT HANDED MATERIALS

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ABSTRACT: *We study the transmission properties of a nonlinear periodic structure containing alternating slabs of a nonlinear right-handed material and a linear left-handed material. We find that the transmission associated with the zero-averaged refractive-index gap exhibits a bistable characteristic that is relatively insensitive to incident angles. This is in contrast to the nonlinear behavior of the usual Bragg gap.* © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 528–530, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21037

Key words: *optical bistability; negative refraction; left-handed materials; metamaterials; periodic structures*

1. INTRODUCTION

Negative-index media, first proposed by Veselago [1], have attracted a great deal of theoretical and experimental interest in recent years. The phenomenon of negative refraction was first experimentally demonstrated at microwave frequencies using artificial metamaterials [2] and there are currently attempts to extend this behavior to the optical regime [3–5]. A periodic assembly of alternating positive-index and negative-index materials [6–9] has been found to possess exotic properties. It has been shown that in the mixed type of periodic structure, a new kind of gap results when the average refractive index of the structure becomes zero [10]. This zero-*n* gap has very unusual properties is that it is robust to scaling and disorder [10]. This gap exhibits an omnidirectional feature [11], which makes it of great interest for applications requiring a wide field of view. These properties of the zero-*n* gap are quite different from those of the usual Bragg gap of positive-index structures. It is therefore of interest to investigate whether these novel properties of the zero-*n* gap persist in the presence of nonlinearity in the refractive index. In this paper, we investigate the nonlinear transmission of a positive-negative periodic structure with inherent periodic nonlinearity. We find that the zero-*n* gap exhibits a hysteretic response which is relatively insensitive to input angle, in contrast to the behavior of the Bragg gap [12].

The nonlinear response of positive index Bragg structures was first studied by Winful et al., who showed that intensity-tuning of the transmission bandgap can lead to hysteresis and optical bistability [13]. For mixed positive–negative-index periodic structures, it has been shown that inclusion of a single nonlinear defect layer results in tunable transmission and bistability [14]. That structure, however is essentially a Fabry–Perot resonator with linear distributed-feedback reflectors enclosing a nonlinear lumped element. Here we consider the case where the periodic structure itself is inherently nonlinear. The positive index layers exhibit a Kerr-type nonlinearity while the negative index medium is taken to be linear, although nonlinearity in its electric and magnetic susceptibilities can be easily included.

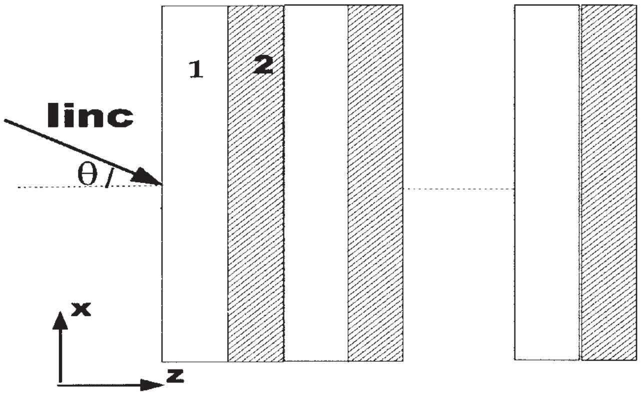

Figure 1 Schematic of the nonlinear periodic structure

2. ANALYSIS

The periodic structure (shown in Fig. 1) consists of N unit cells occupying the region $z = 0, D$, translationally invariant in the x–y plane and bounded on both sides by free space. Each cell is formed of two films, film 1 and film 2, with respective thicknesses d_1 and d_2. Film 1 is a positive-index material with an intensity-dependent permittivity described by

$$\varepsilon_1(\omega, z) = \varepsilon'_{10}(\omega, z) + \varepsilon_{NL}(|E|^2), \tag{1}$$

while film 2 is a negative-index or left-handed material. Its relative permittivity and permeability variations are taken to be of the following forms, respectively:

$$\varepsilon_2(f) = 1.6 + \frac{40}{0.81 - f^2 - ifL}, \tag{2}$$

$$\mu_2(f) = 1 + \frac{25}{0.814 - f^2 - ifL}, \tag{3}$$

where f is the frequency in GHz and L represents the effect of loss. The implicit assumption in this formulation is that the negative-index layer permits the use of an effective index for the frequency range of interest, which may not be a valid approximation in all cases. Also, we ignore any nonlinearities in the negative-index layer, as done in [15].

In an approach similar to [16], we solve for TE-polarized fields of the form

$$E(x, z) = E(z)e^{ik_0(\beta x - ct)}, \tag{4}$$

where $k_0 = \omega/c$, $\beta = \sin\theta$, and θ is the angle which the incident wave vector makes with the z axis. The spatial evolution of the electric field is governed by

$$\frac{d^2E}{d\zeta^2} + p^2E + \mu_i\varepsilon_{iNL}(|E|^2) = 0, \quad (i = 1, 2), \tag{5}$$

where $p^2 = \mu_i\varepsilon'_i(\omega, z) - \beta^2$, and $\zeta = k_0 z$. The solutions for the most general case have to be obtained by numerical integration of Eq. (5). To obtain the transmission of the structure, we specify the E-field and its derivative at the output face and successively integrate Eq. (5) all the way to the input end. At the interfaces between two films, we apply the following boundary conditions:

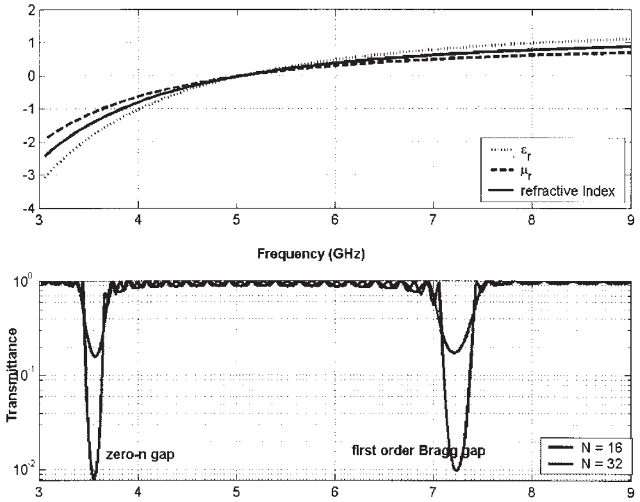

Figure 2 Material parameters of the negative layer and the transmittance of the structure as a function of frequency at normal incidence ($N = 16$, 32)

$$E_i = E_j,$$

$$\mu_j \frac{dE}{d\zeta_i} = \mu_i \frac{dE}{d\zeta_j}.$$

In the linear films, we use the following transmission matrix to propagate the fields:

$$\begin{bmatrix} \cos(p_i k d_i) & -(1/p_i)\sin(p_i k d_i) \\ p_i \sin(p_i k d_i) & \cos(p_i k d_i) \end{bmatrix}. \tag{6}$$

Here, the subscript refers to the film number in the unit cell. If the film is a negative-index type, then a negative value of p is used.

The procedure outlined above has been implemented using MATLAB. The numerical integration was handled by a standard Runge–Kutta solver. Our structure has $d_1 = d_2 = 10$ mm. Film 1 is a positive index material with $\epsilon' = 2$, $\mu = 1$. The positive layer exhibits a Kerr-type nonlinearity modeled by γI. The dispersion relations and the linear transmission spectrum (for $N = 16$, 32) are shown in Figure 2. The zero-n gap occurs at a frequency at which the following condition is satisfied:

$$\sqrt{\varepsilon_1(f)}\ \sqrt{\mu_1(f)}\ d_1 = \sqrt{\varepsilon_2(f)}\ \sqrt{\mu_2(f)}\ d_2.$$

For the parameters used here, the zero-n gap occurs at 3.55 GHz. This gap for an infinite structure is expected to show omnidirectionality. However, in a finite structure, the gap center does vary slightly with the incident angle and the number of layers. This can be attributed to the fact that in a finite structure the end reflections influence the overall transmission.

3. BISTABLE TRANSMISSION

The intensity-dependent refractive index makes it possible to tune the properties of the periodic structure, resulting in optical switching, hysteresis, and bistability. Figure 3 shows the intensity-dependent transmission for an input signal tuned inside the 1st-order Bragg gap. At this frequency, both media in the periodic structure have a positive refractive index. For an input at normal incidence, the transmission displays a large bistable region as the incident intensity is varied. The bistable response is, however, very sensitive to the incident angle. For the same input frequency, bistability is strongly degraded at an angle of 5° and disappears completely at an incident angle of 10°. This sensitivity to incident angles is in marked contrast to the nonlinear behavior of the zero-n gap. Figure 4 shows the bistable response of the structure for an input frequency tuned inside the zero-n gap. Bistability persists for input angles as large as 45°. In contrast, for detuning near the zero-gap center (f near 3.55 GHz), the hysteresis curves (Figs. 4 and 5) for a wider range of incidence angles are seen to follow each other closely. Bistability persists for angles as large as 45°. This is the result of the omnidirectionality feature that is present in the linear response of the zero-n gap. Because of the asymmetric nature of the dispersion about the center frequency of this gap, the detailed nature of the nonlinear transmission curves depend on whether the input is detuned slightly to the left or to the right of the gap center. Figure 5 shows the bistability curves for an input frequency slightly to the right of the zero-n gap center. The intensity required for bistability is somewhat higher in this case, but the transmission

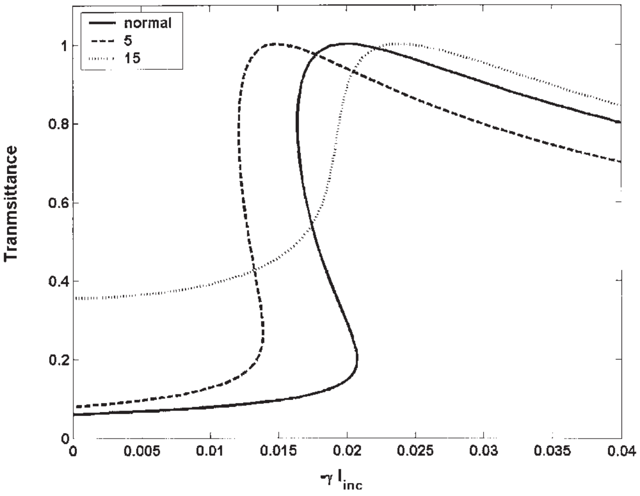

Figure 3 Hysteresis behavior of transmittance as a function of a defocusing γI_{inc} for detuning near the 1st-order Bragg gap ($f = 7.15$ GHz, $N = 32$) for incident angles $\theta = 0°$, 5° (note that for $\theta = 15°$, hysteresis is not observed)

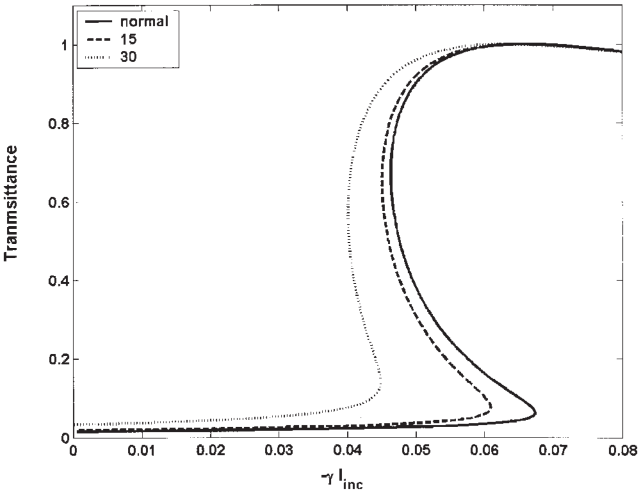

Figure 4 Hysteresis behavior of transmittance as a function of a defocusing γI_{inc} for detuning to the left of the zero-n gap ($f = 3.51$ GHz, $N = 32$) for incident angles $\theta = 0°$, 15°, and 30°

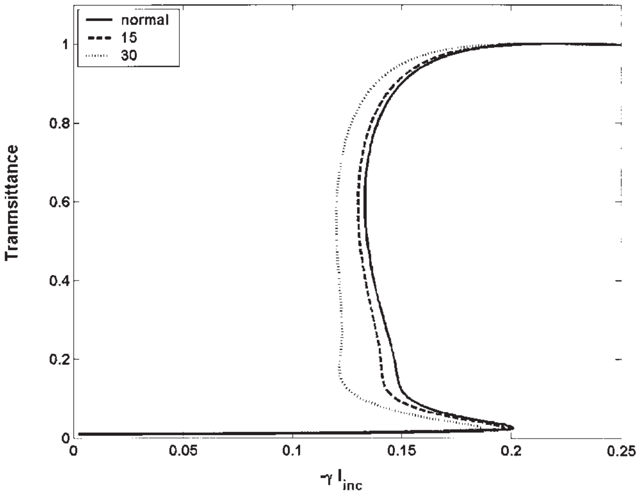

Figure 5 Hysteresis behavior of transmittance as a function of a defocusing γI_{inc} for detuning to the right of the zero-n gap (f = 3.58 GHz, N = 32) for incident angles $\theta = 0°$, 15°, and 30°

curves still follow each other closely as the incident angle is varied.

4. CONCLUSION

In summary, we have studied the nonlinear transmission of a periodic structure containing alternating layers of positive-index and negative-index materials. The gap associated with a zero-average refractive index exhibits a bistable response that is relatively insensitive to input angles, in contrast to the behavior of the usual Bragg gap. This would make possible the operation of all-optical switches that have a wide field of view. The phenomenon of negative refraction is always accompanied by dispersion [1] and, hence, plays a key role in nonlinear gap tuning. By changing the dispersion in the negative-index material, the gap tuning and hysteresis behavior can be controlled.

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A DIELECTRIC RESONATOR ANTENNA WITH ORTHOGONAL CPW FEED AND T-MATCH

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ABSTRACT: *This paper presents a new coplanar waveguide (CPW) orthogonal feed with T-match that is used to excite a dielectric resonator antenna (DRA). It results in a compact and highly efficient radiating element appropriate for active arrays. The simulated and measured results are presented at 5 GHz, which exhibit a large bandwidth.* © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 46: 530–532, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21038

Key words: *dielectric resonator antenna; orthogonal feed; active integrated source*

1. INTRODUCTION

An active antenna can be realized by combining elementary sources and active circuits in a planar array. In such a combination, an active circuit can be associated with each radiating element in order to control its magnitude and/or its phase. It should be integrated as close as possible to the radiating source in order to efficiently compensate for losses in the feeding network. Moreover, the resultant active source must be sufficiently compact so that a reduced interelement spacing will be achieved. Orthogonal feeding provides an attractive solution for this kind of problem, especially when combined with aperture coupling [1]. Vertical microstrip lines have been used to feed the DRA [2, 3], leading to compact radiating structures with large bandwidths. In [4], we proposed an original DRA with orthogonal feeding that uses a vertical slot line emerging in the middle of a horizontal aperture. This DRA was demonstrated to improve cross-polarization, but it requires a lossy slot line/CPW transition and involves a cumbersome slot-line stub.