Physics Letters A 376 (2012) 1396–1400

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Experimental investigation of photonic band gap in one-dimensional photonic crystals with metamaterials

Yihang Chen [a,b,*], Xinggang Wang [b], Zehui Yong [a], Yunjuan Zhang [a], Zefeng Chen [b], Lianxing He [a], P.F. Lee [a], Helen L.W. Chan [a], Chi Wah Leung [a], Yu Wang [a]

[a] *Department of Applied Physics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China*
[b] *Laboratory of Quantum Information Technology, School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou, China*

ARTICLE INFO

Article history:
Received 18 July 2011
Received in revised form 21 January 2012
Accepted 28 January 2012
Available online 1 February 2012
Communicated by R. Wu

Keywords:
Electromagnetic optics
Photonic crystal
Metamaterials

ABSTRACT

Composite right/left-handed transmission lines with lumped element series capacitors and shunt inductors are used to experimentally realize the one-dimensional photonic crystals composed of single-negative metamaterials. The simulated and experimental results show that a special photonic band gap corresponding to zero-effective-phase (zero-φ_{eff}) may appear in the microwave regime. In contrast to the Bragg gap, by changing the length ratio of the two component materials, the width and depth of the zero-φ_{eff} gap can be conveniently adjusted while keeping the center frequency constant. Furthermore, the zero-φ_{eff} gap vanishes when both the phase-matching and impedance-matching conditions are satisfied simultaneously. These transmission line structures provide a good way for realizing microwave devices based on the zero-φ_{eff} gap.

1. Introduction

The interaction of electromagnetic (EM) wave with matter is determined by the electric permittivity ε and magnetic permeability μ, which are two intrinsic material parameters that describe the response of charges and currents to an applied EM field. Both ε and μ of all transparent natural materials are positive, resulting in a positive index of refraction. However, if the sign and magnitude of the index could be tuned at will, the flow of EM wave could be controlled in unconventional ways [1,2].

In recent years, metamaterials have attracted considerable attention for their ability to precisely control the dispersion and propagation of EM wave. Metamaterials have artificial EM properties that are defined by their sub-wavelength structure rather than their chemical composition. Through variation of the constituent elements and dimensions, metamaterials allow for adjustability of ε and μ that can span between positive, negative, and near-zero values, leading to many interesting applications such as sub-diffraction-limited superlenses [3–5] and cloaking at specific EM wavelength ranges [1,6,7]. Metamaterials that exhibit simultaneously negative ε and μ are called double-negative (DNG) materials. Similarly, the metamaterials with either negative ε or negative μ are referred to as single-negative (SNG) materials. There are two kinds of SNG metamaterials: ε-negative (ENG) material and μ-negative (MNG) material. Since both ε and μ of metamaterials depend on frequency, the characteristics of DNG or SNG can only be realized within a certain frequency range.

Over the last two decades, another kind of artificial materials, photonic crystal, has been the intriguing subject of great attention due to their unique EM properties and potential applications [8,9]. Conventional photonic crystals have periodically modulated dielectric functions and thus possess the photonic band gap as a result of Bragg scattering. As such, the frequency of the Bragg gap is proportional to the lattice constant while randomness generally destroys the band gap [10]. Recently, it was shown that stacking alternating layers of ENG and MNG materials may lead to a special type of photonic band gap, known as the zero-effective-phase (zero-φ_{eff}) gap [11]. Comparing to conventional Bragg gap, the zero-φ_{eff} gap can be insensitive to incident angle and thickness fluctuations [12,13]. It has been theoretically pointed out that the zero-φ_{eff} gap possesses many unique properties which may lead to important applications, such as omnidirectional and multi-channel filters and broadband wave plates [14–17].

In this Letter, we experimentally investigate the properties of the zero-φ_{eff} gap in one-dimensional (1D) photonic crystals comprising SNG materials. The SNG materials were fabricated using composite right/left-handed transmission line by periodically loading lumped-element series capacitors (C) and shunt inductors (L). Experimental results show that, as the length ratio between the ENG and MNG materials varies, the width and depth of the zero-

---

* Corresponding author at: Department of Applied Physics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China.
E-mail addresses: eon.chen@yahoo.com.cn (Y. Chen), apywang@inet.polyu.edu.hk (Y. Wang).

0375-9601/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.physleta.2012.01.044

φ_{eff} gap changes significantly while the central frequency remains invariant. The experimental results are in accordance with the numerical simulations.

2. The model of the SNG materials

Up to now, there are two main approaches to form SNG or DNG metamaterials have been reported: resonant structures made of arrays of wires and split-ring resonators [18–20] and non-resonant transmission line (TL) structures made of lumped elements [21–24]. The TL approach towards metamaterial with left-handed and right-handed attributes, known as composite right/left-handed transmission line (CRLH TL), presents the advantage of lower losses over a broader bandwidth. SNG material can be realized in the frequency range between the right-handed passband and left-handed passband of the CRLH TL. The CRLH TL is fabricated by the repetition of the TL unit cell, which consist of a host transmission line with lumped elements of series capacitors C and shunt inductors L [21,22]. When the average lattice constant l_i is much smaller than the guided wavelength λ_g, the structure exhibits a macroscopic behavior which can be rigorously characterized in terms of the constitutive parameters ε and μ. In practice, $l_i < \lambda_g/4$ can be considered as the sufficient condition for the validity of homogeneous approximation [24]. In our experiment, 50Ω TL was used to fabricate CRLH TL which has FR-4 substrates with thickness $h = 1.6$ mm and relative permittivity $\varepsilon_{sub} = 4.75$. The thickness of copper strip on the FR-4 substrate was $t = 0.018$ mm. The width of the copper strip was $w = 2.945$ mm corresponding to the characteristic impedance of $Z_0 = 50\ \Omega$.

For a one-dimensional CRLH TL, the constitutive parameters can be obtained by mapping the telegrapher's equations to Maxwell equations [21], the effective relative permittivity and permeability are given by the following approximate expressions:

$$\varepsilon_i \approx \left(C_0 - 1/\omega^2 L_i l_i\right)/(\varepsilon_0 p), \qquad \mu_i \approx p\left(L_0 - 1/\omega^2 C_i l_i\right)/\mu_0, \quad (1)$$

where p is a structure constant which given by $p = \sqrt{\mu_0/(\varepsilon_0\varepsilon_{re})}/Z_0$ [24], C_0 and L_0 represent the distributed capacitance and inductance of the host TL, and i represents the type of the CRLH TLs. The effective relative dielectric constant ε_{re} of the microstrip line can be obtained as [25]

$$\varepsilon_{re} = \frac{\varepsilon_{sub}+1}{2} + \frac{\varepsilon_{sub}-1}{2}\left(1+\frac{12h}{w}\right)^{-1/2} - \frac{\varepsilon_{sub}-1}{4.6}\frac{t/h}{\sqrt{w/h}}. \quad (2)$$

For the microstrip lines considered here, the effective relative dielectric constant $\varepsilon_{re} \approx 3.556$. Then it can be obtained that $p = 3.99$, $C_0 = \sqrt{\varepsilon_{re}\varepsilon_0\mu_0}/Z_0 \approx 128$ pF/m, and $L_0 = Z_0^2 \times C_0 \approx 320$ nH/m.

Two types of CRLH TLs with 12 TL units were designed and fabricated to realize the SNG materials. TL1 unit possesses a unit length of $l_1 = 7.2$ mm and loaded lumped elements $C_1 = 5.1$ pF and $L_1 = 5.6$ nH, and TL2 unit has a unit length of $l_2 = 8.4$ mm and loaded lumped elements $C_2 = 2$ pF and $L_2 = 8$ nH, respectively. For the frequency of the guided wave $f_g < 1/4l_i\sqrt{\varepsilon_0\mu_0} \approx 8.9$ GHz, both TL1 and TL2 can be regarded as homogeneous media described by effective permittivities and permeabilities.

Based on the parameters given above, the effective material parameters can be written as

$$\varepsilon_1 = 3.57\text{–}6.92 \times 10^{20}/\omega^2,$$
$$\mu_1 = 1.03\text{–}8.75 \times 10^{19}/\omega^2, \quad (3)$$

for TL1, and

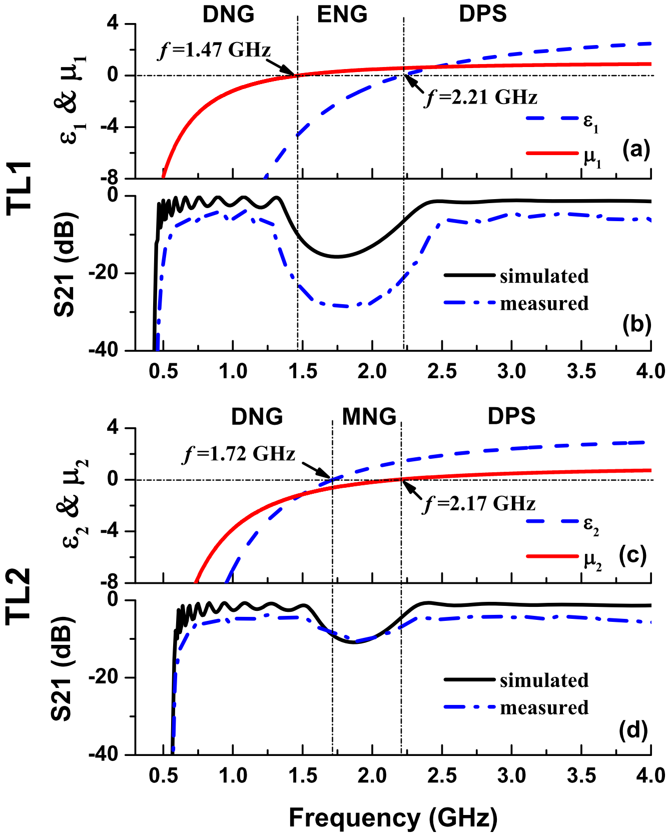

Fig. 1. The calculated effective permittivity (ε_i) and permeability (μ_i) for the CRLH TL1 (a) and TL2 (c). The simulated and measured transmittance of TL1 (b) and TL2 (d) with 12 TL units, respectively.

$$\varepsilon_2 = 3.57\text{–}4.15 \times 10^{20}/\omega^2,$$
$$\mu_2 = 1.03\text{–}1.91 \times 10^{20}/\omega^2, \quad (4)$$

for TL2. The calculated relative permittivity ε_1 and permeability μ_1 of TL1 according to Eq. (3) are presented in Fig. 1(a). The simulated (by Advanced Design System (ADS)) and measured (by Agilent 8720ES S-parameter Network Analyzer) S_{21} parameters for TL1 containing 12 units are shown in Fig. 1(b). It is seen that both ε_1 and μ_1 are positive in the higher frequency range, and a corresponding right-handed passband exist in Fig. 1(b). On the other hand, both ε_1 and μ_1 are negative in the lower frequency range and a corresponding left-handed passband can be observed. In the frequency range 1.47–2.21 GHz, $\varepsilon_1 < 0$ and $\mu_1 > 0$, TL1 is equivalent to an ENG material, a stopband appears since the wave number $k = 2\pi\sqrt{\varepsilon_1\mu_1}/\lambda_g$ is imaginary. As shown in Fig. 1(b), the measured result agrees with the simulations although inevitable losses led to a reduced transmittance. There is a cutoff frequency for the CRLH TL given by [21]

$$f_i = \frac{1}{4\pi\sqrt{L_i C_i}}. \quad (5)$$

It can be calculated from Eq. (5) that $f_1 \approx 0.47$ GHz for TL1, and the propagation of EM wave will be prohibited when the frequency is lower than this cutoff frequency.

Similarly, ε_2 and μ_2 as functions of frequency, and the simulated and measured results for TL2 with 12 units are shown in Fig. 1(c) and (d), respectively. It can be seen that, between the two passbands, a stopband corresponding to $\varepsilon_2 > 0$ and $\mu_2 < 0$ appears in the frequency range 1.72–2.17 GHz. It means that TL2 can be equivalent to a MNG material in the corresponding range of