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Characteristics of a Single I-shaped Slitted Zeroth-Order Resonance Mushroom Antenna based on Metamaterials

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Abstract: The broadband design of a metamaterials-based zeroth-order resonance (ZOR) mushroom antenna with an I-shaped slit is presented and experimentally studied. The presented metamaterials-based antenna uses a unit cell based on a composite right/left handed (CRLH) transmission line and can provide a ZOR frequency. By designing the I-shaped slot resonance frequency adjacently to the ZOR frequency, the presented antenna can achieve a 10-dB bandwidth enhancement of roughly 7 times with respect to a conventional rectangular-shaped mushroom structure.

Keywords: Metamaterials, Slit, Mushroom, Antenna, Zeroth-order.

1 Introduction

Metamaterials (MTMs) with simultaneously negative permittivity (ε) and permeability (μ) have recently received considerable attention in the scientific and engineering communities [Veselago (1968); Smith, Padilla, Vier, Nemat-Nasser and Schultz (2000)]. MTMs have some extraordinary properties compared to conventional right-handed materials, such as negative refraction, backward waves, and anti-parallel phase/group velocities, and have been widely studied on this basis for application to perfect superlenses [Liu, Fang, Yen, and Zhang (2003)], spatial filters [Schurig and Smith (2003)], beam shaping [Shadrivov, Zharov and Kivshar (2003)], sensors [Qing amd Chen (2004); Taya, Shabat and khalil (2009)], and antennas [Lee, Lee, Woo and Kim (2012)].

Microstrip patch antennas have been used in many applications due to their inherent capabilities, such as low cost, low weight, and low profile. Unfortunately, patch antennas have the limitations of narrow bandwidth, low efficiency, and low gain. To overcome these disadvantages, a lot of methods are developed such as high impedance surface, photonic bandgap, and MTM.

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Especially, by using the novel characteristics of MTM, the performances of antennas have been extensively discussed and studied [Alu, Bilotti, Engheta and Vegni (2007); Chen, Wu, Ran, Grzegorczyk and Kong (2006)]. On the other hand, some researchers have described MTMs as effective homogeneous structures that can be modeled by transmission lines (TLs) of composite right/left-hand (CRLH) structures under the condition that the average cell size be smaller than the guided wavelength [Eleftheriades, Iyer and Kremer (2002)].

A general CRLH TL unit-cell consists of a series capacitance and a shunt inductance, as well as a series inductance and a shunt capacitance. A typical microstrip CRLH TL unit cell was introduced by Caloz et al. in 2004 [Caloz, Sanada and Itoh (2004)], and it has the structure of inter-digital capacitors and stub inductors shorted to the ground plane by vias [Lai, and Itoh and Caloz (2004)]. Because the CRLH TL has anti-parallel phase velocity and group velocity, the infinite-wavelength propagation can be obtained at a certain frequency, which is referred to as the zeroth-order resonator (ZOR) frequency. The ZOR having a zero propagation constant (β=0, $\omega \neq$0) has been used to design ZOR antennas smaller than a conventional patch antenna having a half wavelength width. As a two-dimensional CRLH structure, a mushroom structure with a square-shaped top patch was presented by Itoh [Lai, Itoh and Caloz (2004); Sievenpiper, Zhang, Broas, Alexopolous and Yablonovitch (1999)].

The two-dimensional CRLH can be physically realized by using the Sievenpier mushroom structure as shown in Fig. 1 [Lai and Itoh (2005)].

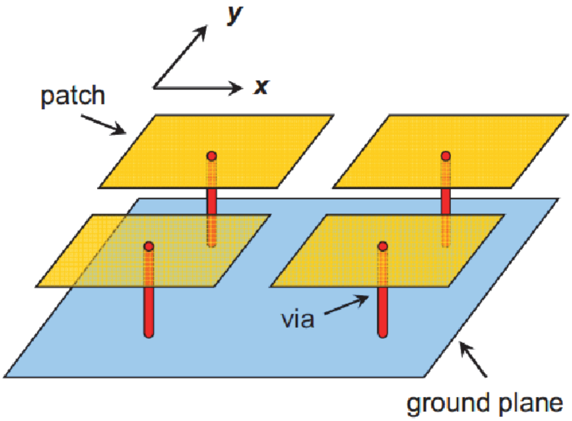

Figure 1: Microstrip realization of two-dimensional CRLH metamaterial based on the Sievenpiper higher-impedance surface.

Each unit-cell consists of a metallic patch connected to ground with a metallic via. Similar to the one-dimensional CRLH MTM, the mushroom's left-handed (LH) capacitance is attributed to the edge coupling between the top patches and the mushroom's LH inductance is attributed to the inductance on the via connected to the ground. The right-hand (RH) effects are due to the capacitive coupling between patches and due to the inductance on the top patches.

However, ZOR mushroom antennas are implemented on classical microstrip patches having inherently narrow frequency bandwidths, which limit their usage into wide-spread applications. Recently, the addition of U-shaped slots was shown to provide enhanced bandwidth [Lee, Lee, Woo and Kim (2012)]. When cutting a slot or a slit inside a microstrip patch, if the resonance frequencies of the slit and the patch are close to each other, then the inserted slit can produce a wideband frequency bandwidth. In this paper, to extend bandwidth, we implement a metamaterial-based ZOR mushroom antenna with an inserted single I-shaped slit. The length and width of the inserted slit were determined according to the ZOR frequency of the mushroom antenna. The patch of the I-shaped mushroom structure for two unit-cells provided a reduced shunt capacitance and increased the 10-dB bandwidth by about 5 times compared to the Sievenpiper mushroom structure [Sievenpiper, Zhang, Broas, Alexopolous and Yablonovitch (1999)].

2 Antenna design and Experiment

Figure 2 shows the ZOR mushroom antenna consisting of a two-stage periodic array printed on a dielectric substrate. Each mushroom-structured unit-cell is built with an I-shaped top patch and a metal via connecting the top patch to the ground.

The gap between neighboring unit-cells represents the left-handed series capacitance, and the vertical via of the top plate acts as the left-handed shunt inductance in the equivalent circuit model. The right-handed contribution comes from the distributed series inductance and distributed shunt capacitance. The resonant frequency of the slot is determined by the width and length of the slit on the patch. An I-shaped slit was properly designed to have similar resonance frequency with the CRLH TL to widen the bandwidth of the antenna. The structure of the I-shaped-mushroom ZOR antenna had the following dimensions: via diameter (2Rv) of 0.6 mm, distance between the edge and the via (Lv) of 18 mm, gap between patches (Gpa) of 0.5 mm, and height and relative permittivity of the substrate (FR4) of 1.6 mm and 4.4, respectively. The width (W) and the length (L) of the top patch of the rectangular-shaped mushroom are 42 mm and 32 mm, respectively, and for the impedance matching the width (Wtl) and length (Lin) of the feed inset line are 3 mm, 13 mm, respectively. The I-shaped-mushroom ZOR antenna has the following slit structure: slit width (Wsl) of 4 mm, slit length (Lsl) of 28 mm.

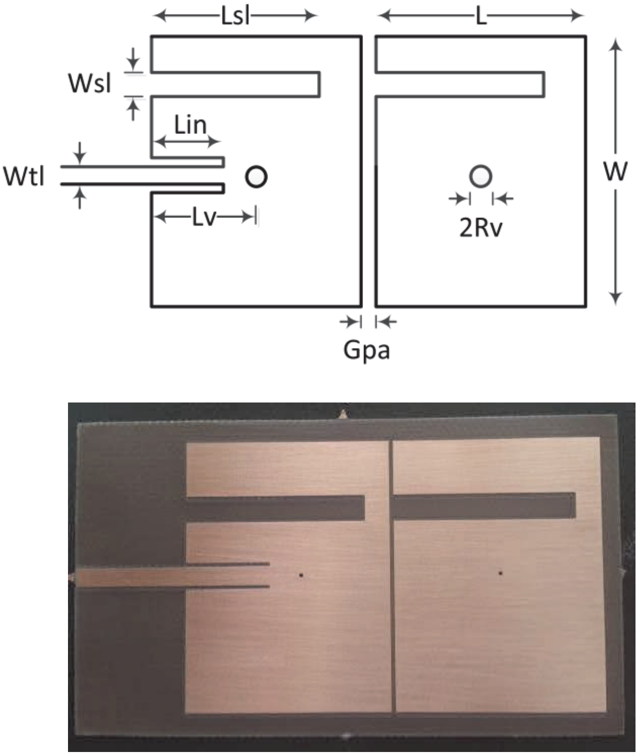

Figure 2: Structure of the presented antenna.

A mushroom unit-cell consists of a series capacitance and a shunt inductance, as well as a series inductance and a shunt capacitance [Sievenpiper, Zhang, Broas, Alexopolous and Yablonovitch (1999)]. The series capacitance and shunt inductance correspond to a left-handed TL, and the shunt capacitance and series inductance correspond to a right-handed TL due to the parasitic effect caused by the microstrip geometry. Since the physical length of the mushroom unit-cell is much smaller than the quarter of the wavelength, the CRLH TL can be considered as a homogeneous transmission line.

As shown in Fig. 3, a mushroom unit-cell consists of a series capacitance and a shunt inductance, as well as a series inductance and a shunt capacitance. The series capacitance and shunt inductance correspond to a left-handed TL, and the shunt capacitance and series inductance correspond to a right-handed TL due to the parasitic effect caused by the microstrip geometry. Since the physical length of the mushroom unit-cell is much smaller than the quarter of the wavelength, the CRLH

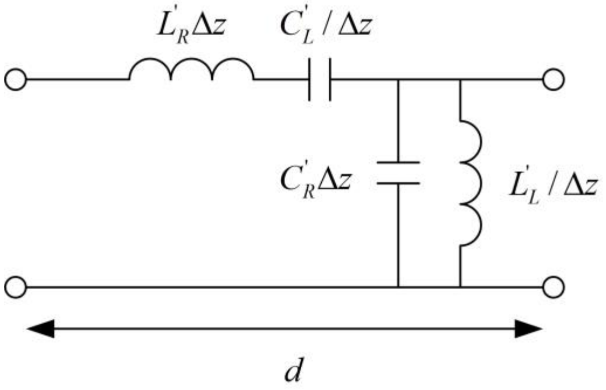

Figure 3: Circuit model of the presented antenna.

TL can be considered as a homogeneous transmission line.

The CRLH TL equivalent model can be derived as a combination of a per-unit-length right-handed series inductance ($L_{R}\prime$), a per-unit-length right-handed shunt capacitance ($C_{R}\prime$), a times-unit-length left-handed shunt inductance ($L_{L}\prime$), and a per-unit-times length left-handed series capacitance ($C_{L}\prime$). According to lossless transmission line theory, the propagation constant of a CRLH TL is given by γ=jβ = $\sqrt{}$(Z$\prime$Y$\prime$), where Z$\prime$ and Y$\prime$ are the per-unit-length impedance and per-unit-length admittance, respectively. Z$\prime$ and Y$\prime$are obtained as

$$\begin{aligned} Z'(\omega) &= \frac{Z(\omega)}{\Delta z} = j\left(\omega L'_R - \frac{1}{\omega C'_L}\right), \\ Y'(\omega) &= \frac{Y(\omega)}{\Delta z} = j\left(\omega C'_R - \frac{1}{\omega L'_L}\right). \end{aligned} \tag{1}$$

The series resonance frequency and shunt resonance frequency are given as ω_{se}=1/$\sqrt{}$($L_{R}\prime$ $C_{L}\prime$), and ω_{sh}=1/$\sqrt{}$($L_{L}\prime$ $C_{R}\prime$), respectively.

If periodic boundary conditions related to Block-Floquet theory are applied to the one-dimensional CRLH TL unit-cell, the dispersion equation is obtained as follows:

$$\cos\beta d = 1 - \frac{1}{2}\left\{\frac{\omega^2}{\omega_{RH}^2} + \frac{\omega_{LH}^2}{\omega^2} - \left(\frac{1}{\omega_{sh}^2} + \frac{1}{\omega_{se}^2}\right)\omega_{LH}^2\right\}, \tag{2}$$

where ω_{RH}=1/$\sqrt{}$($L_R C_R$), ω_{LH}=1/$\sqrt{}$($L_L C_L$), β is the propagation constant, and d is the length of the unit cell. The series resonance frequency and shunt resonance frequency are given as ω_{se}=1/$\sqrt{}$(L_R C_L), and ω_{sh}=1/$\sqrt{}$($L_L C_R$), respectively. For an open-ended CRLH TL, the resonant condition of β_md=mπ must be satisfied, where m=0,±1,±2, … , ±(N-1) is the resonance mode. At the zeroth-order resonance (m=0), the CRLH TL supports a zero propagation constant (β=0), where an infinite wavelength is obtained, and hence the length of the CRLH TL becomes independent of the resonance condition. When a zeroth-order resonance frequency is used for the antenna, it inherits independence of physical size, leading to one degree of freedom in designing an antenna smaller than a conventional patch antenna with a half wavelengthfield distribution.

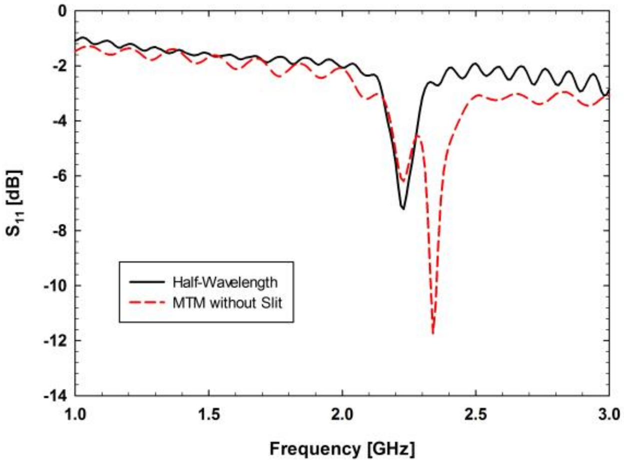

Figure 4: S_{11} parameters.

Figure 4 shows the S_{11} parameters of a conventional rectangular-shaped RH microstrip patch antenna without a slit and of the MTM mushroom antenna without a slit on the top plate. A network analyzer (Agilent, PNA-X N5247A) was used to measure the return losses, which can show that the resonance frequency of the RH microstrip antenna without a slit was 2.17 GHz and the shunt resonance frequency (ω_{sh}) of the presented MTM mushroom antenna without a slit was 2.34 GHz.

Figure 5 shows the S_{11} parameters of the ZOR antennas with and without an I-shaped slit on the top plate. A network analyzer (Agilent, PNA-X N5247A) was used to measure the return losses, the S_{11} parameters, which can show the frequency bandwidth.

The presented microstrip antenna is a rectangular patch on top of a substrate material with relative dielectric constant (ε_r) of thickness t $<< \lambda$.

When the length is approximately a half wavelength in terms of the wavelength in the dielectric, the patch becomes resonant and is called a half-wavelength rectan-

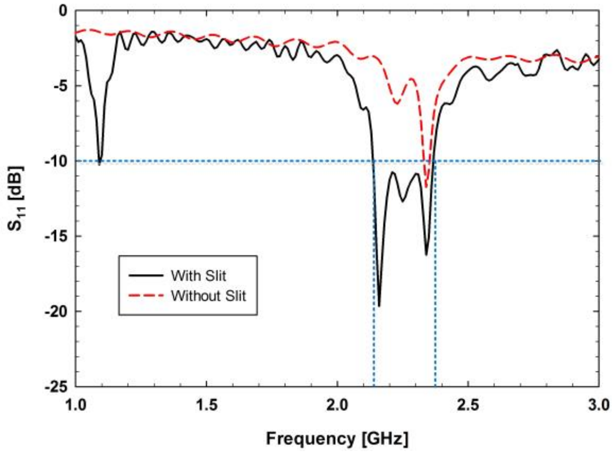

Figure 5: S_{11} parameters.

gular patch antenna.

For a half-wavelength patch antenna, its width is

$$L = \frac{1}{2}\frac{1}{f_r\sqrt{\mu_0\varepsilon_0}} \tag{3}$$

For an efficient radiator, a practical width that leads to good radiation efficiencies is

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{4}$$

where f_r is the operating frequency in terms of the patch dimension; μ_0 and ε_0 are permeability and permittivity of free space, respectively.

Due to the fringing fields along the radiating edges of the antenna there is a line extension associated with the patch, which is given by the formula [Hammerstad (1975)],

$$L_{eff} = L + 2\Delta L \tag{5}$$

The normalized extension of the length is

$$\frac{\Delta L}{h} = 0.412\left(\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right)\left(\frac{\frac{W}{h}+0.264}{\frac{W}{h}+0.813}\right) \tag{6}$$

The effective dielectric constant, ε_{eff}, due to the fringing fields is

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r + 1}{2}\left(1 + \frac{10h}{W}\right)^{-\frac{1}{2}} \tag{7}$$

The resonance frequency of the microstrip antenna can be estimated by using the formula

$$f_r = \frac{1}{2\sqrt{\mu_0 \varepsilon_0}\,(L + 2\Delta L)\,\sqrt{\varepsilon_{eff}}} \tag{8}$$

The resonant frequency is designed to 2.17 GHz for a 1.6-mm-thick substrate with ε_r=4.4, and preceeding formulas yield the width of the patch (W) of 42 mm and the length of the patch (L) of width of 32 mm.

To produce a wideband frequency bandwidth, we cut a slit inside a microstrip patch to put close the resonance frequencies of the slit (2.16 GHz) and the patch (2.17 GHz). Since the I-shaped slit makes the longer path of the current on the top patch, the increased path extension makes the resonance frequency lower than that of a top patch without a slit. The increased path length by the slit is calculated to 2 mm to scale the resonant frequency of the slit to 2.16 GHz. The resonance mode of the I-shaped slit was shown to operate at 2.16 GHz, and the series resonance frequency (ω_{se}) and shunt resonance frequency (ω_{sh}) corresponded to 2.25 GHz and 2.34 GHz, respectively.

The 10-dB bandwidth of the I-shaped mushroom ZOR antennae is 220 MHz which is between 2.15 GHz and 2.37 GHz. The 10-dB bandwidth was enhanced by approximately 7 times as large as that (30 MHz) of a conventional rectangular mushroom antenna without a slit.

The measured radiation patterns of the I-shaped top plates are plotted in Fig. 6 on the E and H planes at 2.22 GHz. Main lobe magnitude is 2.5 dBi and 3dB angular width is 130 degree, which is wider that of a conventional rectangular antenna without the slit. When there is a inserted slit, it is observed that the surface current path is changed and hence the H plane is also tilted from the broadside direction (0 degree).

Figure 7 shows the simulated radiation pattern of a rectangular-shaped top plate on the E plane at 2.22 GHz. Main lobe magnitude is 6.6 dBi and 3dB angular width is 86.8 degree.

3 Conclusion

In this paper, we present a metamaterial-based ZOR mushroom antenna based on CRLH TL unit-cell implemented by using a single I-shaped mushroom structure.

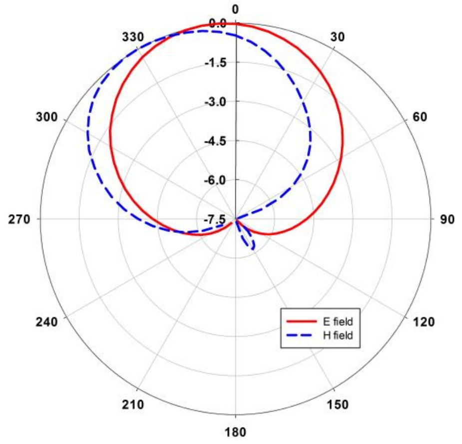

Figure 6: Measured radiation pattern of the presented antenna.

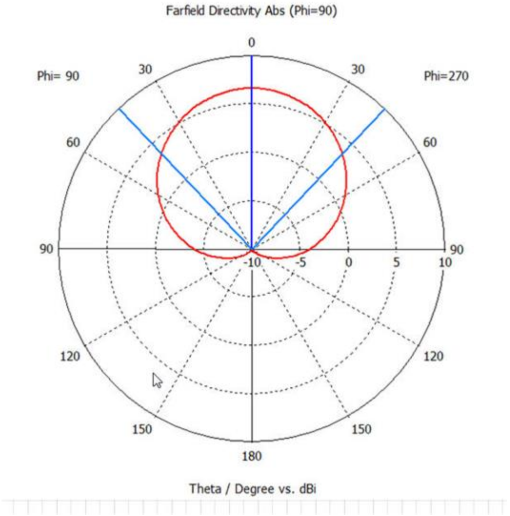

Figure 7: Simulated E-plane radiation pattern of a conventional rectangular mushroom antenna.

The single I-shaped slit was designed to place its resonance frequency (2.16 GHz) near to the series resonant frequency (2.25 GHz) in order to widen the small bandwidth of the ZOR mushroom antenna. The patch of the I-shaped mushroom structure achieved 220 MHz of 10-dB bandwidth representing an enhancement of about 7 times compared to that of a rectangular-mushroom structure without the slit.

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