DUAL-POLARIZED FREQUENCY-TUNABLE COMPOSITE LEFT-HANDED SLAB

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Abstract—A dual-polarized frequency-tunable composite left-handed slab (CLS) is proposed. The CLS consists of periodic split-ring resonators (SRRs) along with thin wires. Two orthogonal SRR/wire arrays are utilized for dual-polarization purposes. Polarization-selectivity and frequency-tuning are achieved by means of on/off switches placed between the rings of the SRR. By opening all of the switches for one array and closing them for the other, the left-handed behavior can be switched on and off, respectively. Frequency-tuning performance is then achieved by turning on/off the switches in the former array. Transmission characteristics of the composite structure are predicted using a fast periodic array simulator based on the hybrid finite element-boundary integral (FE-BI) method in conjunction with the fast spectral domain algorithm (FSDA). Numerical results demonstrate dual-polarization and frequency-tuning performance of the proposed switching configuration.

1. INTRODUCTION

Left-handed metamaterials (LHMs) have recently drawn a great deal of attention due to their unique electromagnetic features not commonly found in nature [1, 2]. Unlike right-handed media, LHMs possess both permittivity negative ($\varepsilon$-negative: ENG) and permeability negative ($\mu$-negative: MNG) characteristics within a frequency band, and thus yield a negative index of refraction. As a result, the direction of phase velocity becomes anti-parallel to the direction of the Poynting vector in such media. This phenomenon, also called the reversed Snell’s law, was first examined theoretically by Veselago [3]. In particular, LHMs provide for a transmission pass-band where simultaneous ENG and MNG behavior is observed [4]. The wave is evanescent in either
an ENG or an MNG medium through which no transmission occurs. However, due to the negative index of refraction, the wave is a propagating one in an LHM, to allow for transmission.

An array of thin wires and an array of split-ring resonators (SRRs) show ENG and MNG behavior, respectively [5,6]. By placing these two structures together, an LHM with ENG/MNG characteristics can be obtained within a frequency range [4]. In this paper, we propose a novel dual-polarized frequency-tunable left-handed (LH) slab composed of SRRs and thin wires as displayed in Fig. 1. The dual-polarization and frequency-tuning of the composite left-handed slab (CLS) is accomplished by means of simple on/off switches placed between the rings of the SRR ($S_1$, $S_2$, and $S_3$). In practice, micro-electro-mechanical systems (MEMS) switches would be the preferred choice due to their compact, low-loss and high-isolation features [7]. We note that a metamaterial consisting of a three-dimensional array of tunable stacked split ring resonators [8] has been introduced recently. In [8], the resonance behavior of the structure is controlled by means of auxiliary lumped elements (capacitor and inductor) inserted between the split of each ring, providing miniaturization of the structure at some degree.

In this paper, we present simulation results to demonstrate dual-polarization and frequency-tuning performance of the proposed CLS design. Transmission characteristics of the CLS are predicted using a fast infinite array simulator [9]. This well-validated analysis tool employs the hybrid finite element-boundary integral (FE-BI) method [10] in conjunction with the fast spectral domain algorithm (FSDA) [11]. The adaptability of the hybrid method along with the speed-up advantage of the FSDA serves as a very efficient analysis tool while designing structures that are complex in geometry and incorporate a variety of materials [12,13].

2. PROPOSED CLS DESIGN

The in-plane configuration of the wire/SRR structure (Fig. 1) was originally introduced by Bayindir et al. [14] where transmission characteristics for a singly-polarized LH array were examined. Here we consider a slab of similar configuration with an additional orthogonal array for dual-polarization purposes (Fig. 1). The $y$-elongated SRR/wire array is utilized for transverse-electric polarization (TE-pol) and the $x$-directed array for transverse-magnetic polarization (TM-pol). For each case, the corresponding magnetic field vector should be orthogonal to the plane of the respective SRR/wire array to realize resonance behavior of the LHM, i.e., the expected ENG/MNG
phenomenon [15]. By closing all of the switches (Fig. 1) for one array and leaving them open for the other, the LH behavior can be switched off and on, respectively. Frequency-tuning performance is then achieved by turning on/off the switches in the latter array.

The geometry of the proposed CLS configuration for $N_z = 2$ is displayed in Fig. 1. The structure is presumed to be infinite-periodic in the $x$-$y$ plane and finite-periodic along the direction of wave propagation ($\mathbf{k} = -k\hat{z}$) with $N_z$ denoting the number of SRR cells along $z$. The dimensions of a unit cell containing orthogonal SRR/wire sections are $D_x = D_y = 6.9$ mm. Zero-thickness metallic SRR/wire segments with a width of $w = 0.9$ mm are supported by a substrate of $\varepsilon_r = 3.0$ with a thickness $t = 0.6$ mm. The dimensions of outer and inner rings of each square SRR are $L_1 = 5.7$ and $L_2 = 3.3$, respectively, with split gaps of $g = 0.3$, all in mm. Also, the switches $S_1$, $S_2$, and $S_3$ are modeled by simply placing metallic pads between the SRR rings as shown in Fig. 1. We remark that those optimized design parameters were obtained by means of extensive parametric studies carried out using the full-wave simulator [16].

**Figure 1.** Dual-polarized frequency-tunable CLS configuration.
We note that the FE-BI simulator employs a structured mesh consisting of prismatic finite elements. An element size of $dx = dy = 0.3 \text{mm}$ was used for the triangular surface grid while modeling a periodic unit cell of the CLS configuration. The corresponding unit cell yielded almost 65000 FE-BI unknowns, 2000 of them being BI unknowns located at the top and bottom apertures of the structure. The simulations were carried out on a Pentium IV PC with a 3.2 GHz processor and the required computer time (using a total number of 49 Floquet modes) was 5 minutes for each frequency point on the average.

2.1. True Left-handed Behavior

We first consider a singly-polarized CLS (only TM array is present and all switches are open; see Fig. 1) to demonstrate the true LH behavior [17] of the design. The predicted transmission data for $N_z = 5$ are displayed in Fig. 2 for various array configurations, namely, CLS (SRR/wire), SRR-only (SRR), wire-only (wire), closed-SRR (CSRR: splits of the rings are closed), and CCLS (closed-SRR/wire). As shown in Fig. 2, the wire array has a cut-off frequency around 11.2 GHz below which no transmission occurs, corresponding to effective permittivity ($\varepsilon_{\text{eff}} < 0$). The SRR array, on the other hand, exhibits two band-gaps, one from 5.3–6.0 GHz and the other above 9.5 GHz, where transmission is not allowed. The latter band-gap is also observed for the CSRR array, but not the former. The band-gap present for both the SRR and the CSRR may be due to negative $\varepsilon_{\text{eff}}$ or exclusively to the periodicity [17]. On the other hand, the band-gap occurring at lower frequencies (5.3–6.0 GHz) is due to magnetic resonance induced by the splits of the SRR and corresponds to effective permeability ($\mu_{\text{eff}} < 0$) [17]. In fact, as seen in Fig. 2, this is the band in which a transmission peak is observed around 5.8 GHz for the CLS (but not for the CCLS) due to the LH behavior.

In addition, we examined variation of the transmission spectra for different values of $N_z$ (the number of unit cells along the propagation direction). As shown in the inset of Fig. 2, the transmission peak tends to disappear as $N_z$ decreases [14]. In a practical realization, the choice of $N_z = 5$ (at least) would be preferable to observe a distinct transmission peak profile.

Effective material parameters ($\varepsilon_{\text{eff}}, \mu_{\text{eff}}$) for the CLS design ($N_z = 5$) were also retrieved from the simulated data to confirm the expected ENG/MNG behavior over the transmission pass-band [18]. By considering transmission ($T$) through a homogeneous dielectric slab with a finite thickness ($d$) [19], the frequency ($f$) dependent effective parameters $\varepsilon_{\text{eff}}$ and $\mu_{\text{eff}}$ [5,6] were extracted from the transmission data by means of a nonlinear curve-fitting algorithm.
Figure 2. Transmission characteristics for the singly-polarized CLS with $N_z = 5$ (only TM array is present and all switches are open; see Fig. 1). Also displayed are the characteristics for the CLS with closed SRRs (CCLS), the SRR-only (SRR), the closed-SRR (CSRR), and the wire-only (Wire) structures. Inset: the CLS transmission spectra for different values of $N_z$.

The corresponding formulae used in the retrieval process are given in equations (1)–(5) where $c_0$ is the speed of light in vacuum ($\approx 3 \times 10^8$ m/s). The computed effective parameters are displayed in Fig. 3 for the CLS design. As seen, the real parts of $\varepsilon_{\text{eff}}$ and $\mu_{\text{eff}}$, and in turn the real part of refractive index ($n$) all yield negative values within the frequency range (5.76–5.88 GHz) where the transmission pass-band occurs (see Fig. 2), as expected.

$$\varepsilon_{\text{eff}}(f) = 1 - \frac{f_{ep}^2}{f^2 - j\Gamma_{ep} f}$$  \hspace{1cm} (1)

$$\mu_{\text{eff}}(f) = 1 - \frac{f_{mp}^2}{f^2 - f_{m0}^2 - j\Gamma_{mp} f}$$  \hspace{1cm} (2)

$$n(f) = \sqrt{\varepsilon_{\text{eff}}(f) \cdot \mu_{\text{eff}}(f)}$$  \hspace{1cm} (3)
\[ T = \frac{4}{(1 - Z)(1 - Z^{-1})e^{-\gamma d} + (1 + Z)(1 + Z^{-1})e^{\gamma d}} \]  
\[ Z = \sqrt{\mu_{\text{eff}}(f)/\varepsilon_{\text{eff}}(f)}, \quad \gamma = j(2\pi f)n(f)/c_0 \]  

**Figure 3.** Real parts of the effective material parameters \((\varepsilon_{\text{eff}}, \mu_{\text{eff}})\) for the CLS design considered in Fig. 2 and the corresponding index of refraction \((n)\).

### 2.2. Frequency-tuning Performance

Having shown the true left-handed behavior of the CLS, we now demonstrate frequency-tuning performance of the proposed dual-polarized CLS (DCLS) design with \(N_z = 5\) at normal incidence. For this, we consider the configuration for the TM-pol operation where both TE and TM arrays are present and the switches \(S_1, S_2,\) and \(S_3\) in the former array are closed (on). The frequency-tuning is then achieved by means of those switches in the latter array (Fig. 1). Fig. 4 displays the simulation results corresponding to different switching states. As seen, the transmission pass-band occurs around 5.4 GHz when all of those switches are in off-state. On the other hand, when each switch is closed one at a time, the pass-band shifts downwards to a respective frequency. In Fig. 4, we also display the singly-polarized
The frequency tuning performance relies on the placement of switches with respect to the split locations and the resulting coupling mechanism between the splits of the ring resonators. As shown in Fig. 4, the switch placed equidistant from each of the splits ($S_2$) provides for operation around 4.25 GHz whereas the switch closer to the split of the outer ring ($S_1$) and the switch closer to the split of the inner ring ($S_3$) provide for operation at a lower band (around 3.9 GHz) and at a higher band (around 4.7 GHz), respectively. Hence, a multi-frequency operation is accomplished over the band of 3.5–6.0 GHz. In addition, as seen in Fig. 4, the switching states of $S_1$-on/$S_2$-off/$S_3$-
Figure 5. Index of refraction \((n)\) characteristics for different switching states considered in Fig. 4.

on and \(S_1\)-off/\(S_2\)-off/\(S_3\)-on provide the same transmission spectra. Apparently, the switch closer to the outer ring (\(S_1\)) does not contribute to the coupling mechanism between the splits for the former case. Note that all other switching states result in transmission levels well below \(-60\,\text{dB}\) over the frequency band of interest as can be seen in Fig. 4. This is because those states effectively close down the coupling path between the splits and switch off the magnetic resonance. Note that similar frequency-tuning performance can be obtained for the TE-pol operation (at normal incidence) by closing the switches in the TM array and switching \(\text{on/} \text{off}\) those in the TE array.

We also computed index of refraction characteristics for the DCLS design with different switching states by means of the parameter-extraction process discussed earlier. The corresponding data are displayed in Fig. 5. As seen, for each switching-state, the real part of refractive index \((n)\) yields negative values within a specific frequency band where a respective pass-band is observed in transmission spectra as shown in Fig. 4, as expected. Thus, the LH behavior of the structure is dynamically changed by means of the switching configuration.
2.3. Dual-polarization Performance

Finally, we present dual-polarization performance of the proposed DCLS design. For this, we consider the dual-polarized CLS configuration with $N_z = 5$ where both TE-pol and TM-pol arrays are present (Fig. 1). Polarization-selectivity is achieved by means of the switches ($S_1$, $S_2$, and $S_3$). As mentioned above, the true LH behavior is observed when the splits of the SRR are open. Therefore, by closing the splits for one array and opening them for the other, the LH behavior can be turned off and on, respectively. Alternatively, by closing those switches for one of the arrays (leaving those open for the other), the inner and outer rings of the corresponding SRR are shorted-out, and hence the LH behavior can be switched-off for the former (and switched-on for the latter).

The performance analysis was carried out for each polarization one at a time. The simulation results for the TM-pol operation are displayed in Fig. 6 for different angles of incidence ($\theta$). For this case, the switches $S_1$, $S_2$, and $S_3$ in the TM-pol array are opened (off) while those of the TE-pol array are closed (on), leaving the latter inactive. As seen, the transmission spectra shift upwards as $\theta$ increases while the transmission peak-profile tends to disappear with an increase in the transmission bandwidth. This is to be expected since the magnetic field vector of the incident wave is no more orthogonal to the plane of the SRR/wire array towards horizon; thus no magnetic resonance is induced. Moreover, the cross polarization (cross-pol) component of the transmitted wave (TE-pol component in this case) was also computed. The corresponding transmission data are displayed in the inset of Fig. 6. As seen, the cross-pol transmission levels for the DCLS are well below $-20\,\text{dB}$.

For the TE-pol operation, the switches $S_1$, $S_2$, and $S_3$ in the TE-pol array are now opened (off) while those of the TM-pol array are closed (on). As can be seen in Fig. 7, similar yet slighter frequency-shifts in the transmission spectra are observed towards horizon as in the TM-pol case. Likewise, the transmission peak-profile tends to vanish as $\theta$ increases, but in a different manner. In this case, the transmission levels decrease towards horizon and are reduced to around $-6\,\text{dB}$ for $\theta = 60^\circ$. This is mainly because an appreciable amount of the transmitted wave is now contributed to the cross-pol component (TM-pol), as can be observed from the inset of Fig. 7, unlike the TM-pol operation.
Figure 6. TM-pol ($\phi = 0^\circ$) transmission characteristics for the DCLS design (TE-array is switched-off). Inset: the cross-pol (TE) component of the transmitted TM-pol wave.

Figure 7. TE-pol ($\phi = 0^\circ$) transmission characteristics for the DCLS design (TM-array is switched-off). Inset: the cross-pol (TM) component of the transmitted TE-pol wave.
3. CONCLUSION

In this paper, we have introduced a novel switching configuration for multi-frequency operation of a dual-polarized CLS comprised of SRRs and thin wires. The full-wave analysis of the CLS configuration is carried out using an efficient array simulator based on the hybrid FE-BI method. Polarization-selectivity and frequency-tuning are achieved using the switches placed between the rings of the SRR. It has been demonstrated that the LH behavior of the CLS can dynamically be changed by means of the proposed switching configuration. The practical realization of the proposed design is in progress and will be considered in another transaction.

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