Metasurfaces with interwoven conductor patterns on dielectric substrates

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Abstract

The properties of metasurfaces comprised of interwoven conductor patterns on dielectric substrates have been examined. The significant reduction of the fundamental resonance frequency f_r and expanded fractional bandwidths (FBWs) offered by the intertwined spirals and Brigid's crosses extended beyond a single unit cell has been achieved with the aid of thin dielectric substrates. A qualitative model has been proposed and proved to adequately predict the main properties of entwined spiral arrays on dielectric substrates.

1. Introduction

A single layer of electrically small scatterers arranged into two-dimensional periodic arrays are usually referred to as metasurfaces or metafilms. This type of planar metamaterials attracts increasing interest owing to the ease of fabrication and the intricate properties appealing for potential applications. For example, metasurfaces allow effective control of polarization, frequency selectivity and multiband operation while deployed on conformal surfaces. They can also be used in ultra-thin absorbers of substantially sub-wavelength thickness [1], [2].

One of the critical prerequisites for numerous applications of metasurfaces is the sub-wavelength size of both the array unit cell and its constituent elements. The latter requirement is essential for angular invariance of the array response and suppression of the higher order diffraction effects. However, miniaturization of the unit cells with closely spaced resonant elements normally entails degradation of the array performance and prohibitively narrows the fractional bandwidth (FBW). The recently proposed concept of interleaving the conductor patterns into adjacent unit cells of the doubly periodic arrays, where the constituent elements extend beyond a single unit cell, has enabled the high performance of metasurfaces with the unit cell size smaller than 1/30 of wavelength [3]-[5].

The free-standing intertwined quadrifilar spirals and modified Brigid's crosses (Fig. 1), used as proof-of-concept structures, have demonstrated the stable angular response and low cross-polarisation in the broad FBWs [5], [6]. The detailed analysis of the main mechanisms enabling their sub-wavelength response has revealed that interweaving conductor patterns provides concurrent control of both the equivalent capacitance and inductance of the unit cell. This suggests that dielectric substrate which is necessary to support the conductor pattern in the actual metasurface, should noticeably influence the array performance due to the two effects: (i) angular and frequency dependences of the reflectance from a dielectric layer and (ii) variation of the unit cell capacitance by the substrate permittivity.

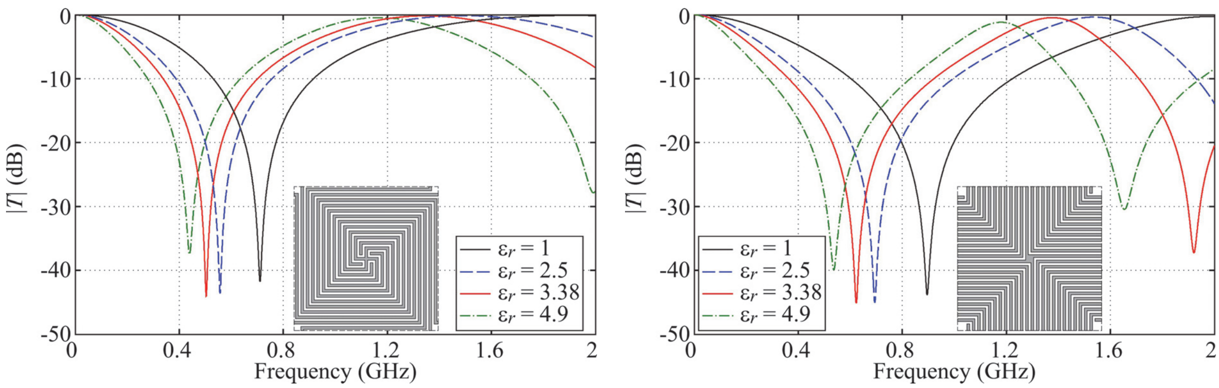
In this work, the effects of dielectric substrate and conductor thickness on the properties of intertwined spiral and modified Brigid's cross arrays have been examined, and it is shown that the characteristics of their fundamental resonances can be estimated with the aid of the effective permittivity determined in the quasi-static approximation. The accuracy and limitations of the model are evaluated.

2. Electromagnetic response of intertwined spiral arrays on dielectric substrates

The intertwining scheme for the doubly periodic arrays of quadrifilar spirals and Brigit's crosses proposed in [5], [6] consists in extending each strip from a reference unit cell into the gap between the strips of the adjacent unit cells. Thus, four additional conductors are counter-wound inside the basic reference spiral in the interwoven layout shown in insert of Fig. 1(a). This causes the increase of the equivalent capacitance and reduction of the equivalent inductance due to the distributed coupling between the arms of the reference spiral and the arms extended from the adjacent unit cells. Such qualitative interpretation of the nature of the array response indicates that dielectric substrate should further increase the unit cell capacitance and facilitate further decrease of f_r.

In order to assess the effect of the substrate permittivity on the properties of intertwined spiral and Brigid's cross arrays, their transmittance and reflectance have been simulated in CST Microwave Studio at normal incidence on the intertwined spiral arrays printed on 0.8-mm-thick substrates with variable permittivity ε_r. As apparent from Fig. 1, the f_r corresponding to min $|T|$ monotonically decreases and FBW grows at higher substrate permittivities. Such behaviour of f_r is consistent with that for FSSs on thin dielectric substrates [7]. However, the simultaneous broadening of FBW is a distinctive feature of the intertwined arrays associated with the enhanced capacitive content in the interleaved conductor layout. It is necessary to note that the substrate permittivity has even stronger effect on the transmission resonance (max $|T|$) than on f_r. However the simulation results show that the separation between the reflection and transmission resonances increases with the number of interleaved folds [5]. Therefore the arrays with intertwined conductor patterns exhibit superior FBW than the conventional FSS. At the same time, variable number of spiral turns and interleaved folds in fully and partially intertwined layouts provide additional degrees of freedom which can be further exploited for shaping resonances and FBW in the multimode operation of the tessellated entwined spiral arrays with dissimilar nested patterns of the unit cells and lattice symmetries [8].

The fundamental resonance frequency $f_r(\varepsilon_r)$ and FBW of the arrays with interwoven conductor patterns on a dielectric substrates can be approximately evaluated with the aid of the effective permittivity ε_r^{eff} for a FSS on a dielectric substrate, combined with the resonance response $f_r(\varepsilon_r{=}1)$ of the respective free-standing array [7]:

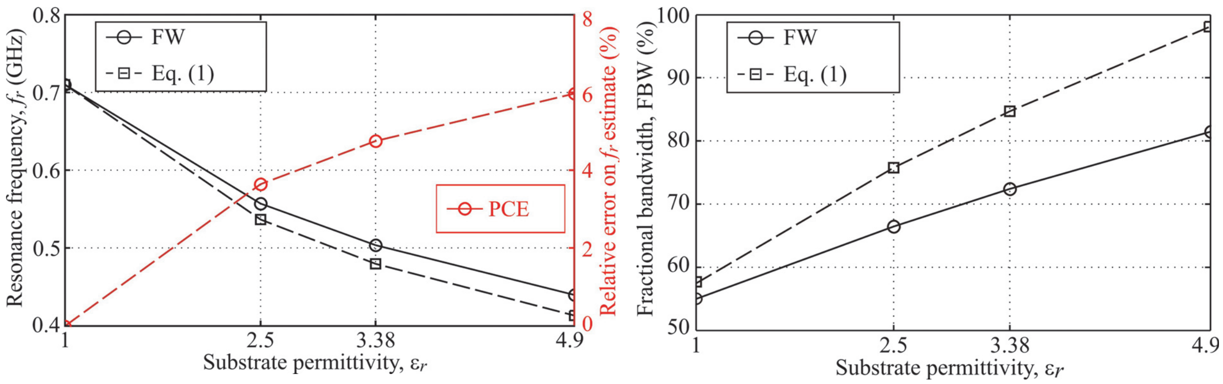


(a) (b)

Fig. 1: Transmittance of the intertwined quadrifilar spiral (a) and Brigit's cross (b) arrays on dielectric substrate with permittivities ε_r = 1, 2.5, 3.38, 4.9. The square unit cells shown in the inserts have size p = 10.8 mm, and the widths of strips (s) and gaps (g) are s=g=0.2 mm, and the conductor thickness is 17.5 µm.

$$f_r(\varepsilon_r) \sim f_r(\varepsilon_r = 1)\left(\varepsilon_r^{eff}\right)^{-1/2}; \quad \varepsilon_r^{eff} = \left(\varepsilon_r + 1\right)/2 \tag{1}$$

The resonance frequencies and FBWs of the intertwined spiral array on dielectric substrates obtained from (1) are presented in Fig. 2 in comparison with the corresponding results of the full-wave (FW) simulations. Accuracy of approximation (1) has been evaluated as percentage error (PCE), defined by $PCE = \left|f_r(\text{FW}) - f_r(\varepsilon_r)\right| / f_r(\text{FW}) \times 100$. It is necessary to note that *PCE* rapidly grows with the substrate permittivity ε_r. Discrepancy between the FW data and (1) can be partly attributed to the effect of the conductor thickness, which somewhat reduces the effective permittivity due to the field crowding in the free-space gaps between the strip walls. However, an extensive numerical analysis has shown that the substrate effect on the response of intertwined spiral arrays involves more complicated interactions, and can only be explained by taking into account the second-order effects of the distributed coupling between the strips, discontinuities at the corner portions and field redistribution in the high permittivity substrates. The role of substrate permittivity becomes even more important for the complementary interwoven arrays where the field duality is not applicable. The detailed account of these phenomena will be provided in the presentation.



(a) (b)

Fig. 2: Resonance frequencies (a) and FBW (b) for the intertwined quadrifilar spiral arrays on dielectric substrates with variable permittivity ε_r = 1, 2.5, 3.38, 4.9. Data from full-wave (FW) simulations in Fig. 1 are compared with the values predicted by (1). Lines provide an eye-guide only.

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