Metasurfaces with intertwined conductor patterns

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Abstract

Metasurfaces comprised of interweaved periodic conductor patterns providing highly stable angular reflection and transmittance response with low cross-polarisation are explored. Two layouts of intertwined conductor patterns comprised of quadrifilar spirals and modified Brigid's crosses are examined. Peculiar features enabled by the proposed interweaved array patterns and their potential for applications as metasurfaces are discussed.

1. Introduction

Applications of artificial surfaces composed of periodically patterned conductors have recently expanded far beyond the original realm of spatial microwave and optical filters to the fields of high impedance surfaces and metamaterials. Indeed, the electrically small scatterers arranged into a two-dimensional array at a media interface represent single layer metamaterials, which are usually referred to as metasurfaces or metafilms. This type of metamaterials has recently attracted considerable attention owing to the novel intriguing physical phenomena involved and potential for future applications. For example, metamaterial structures based on strongly coupled layers of frequency selective surfaces (FSSs) with vanishing separation between them have shown the electromagnetic responses resembling the electromagnetic induced transparency in cold gases. Metasurfaces can also be used to implement slow-light effects in compact configurations [1] and designed to create narrow band perfect absorbers that are not limited to a minimum thickness of a quarter-wavelength like conventional materials (e.g., Salisbury screens) [2].

The properties of metasurfaces are determined by the resonant response of their constituent elements and unit cells which can be as large as half a wavelength at the operating frequency. This implies that their characteristics depend on the angle of the incident wave. To achieve tailored reflectance and transmittance properties invariant to the incidence angle, it is necessary to decrease the array unit cell size. The smaller unit cells also defer onset of the higher order diffraction effects.

However, miniaturization of the unit cells with closely spaced resonant elements often entails degradation of the array performance and prohibitively narrows fractional bandwidth (FBW). To alleviate these shortcomings, it has been proposed to extend each array element beyond a single unit cell by intertwining the conductor patterns in adjacent unit cells. This approach leads not only to reducing the unit cell size but also to broadening the array operational bandwidth [3]-[5].

In this work, we explore the resonance properties of metasurfaces comprised of interweaved periodic conductor patterns providing highly stable angular reflection and transmittance response with low cross-polarisation. Two layouts of intertwined conductor patterns comprised of quadrifilar spirals and modified Brigid's crosses are examined. Peculiar features enabled by the proposed interweaved geometries and their potential for applications as metasurfaces are discussed.

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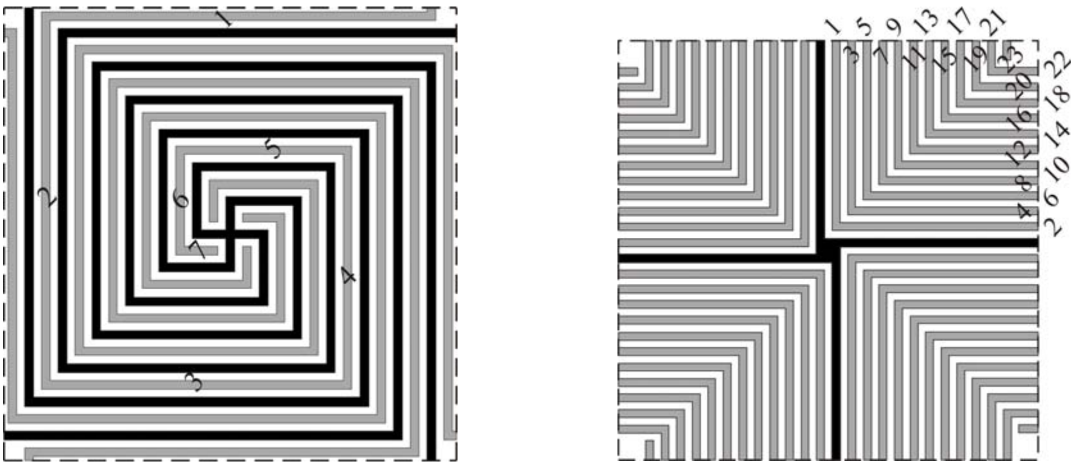
2. Arrays of intertwined conductors

Two different intertwining schemes are applied to doubly periodic arrays of quadrifilar spirals and cross-shaped conductors that are referred to as Brigid's crosses. The unit cell layouts of these intertwined arrays, both with square lattices, are shown in Fig. 1. In the quadrifilar spiral arrays, each conductor spiral arm from a reference unit cell protrudes into the gap between the turns of one of the spirals lying in the adjacent unit cells. In the resulting interweaved spiral layout, four additional conductors (depicted in light grey colour in Fig. 1(a)) are thus counter-wound inside the basic reference spiral [5]. For the Brigid's cross topology the interweaving process consists of adding a straight conductor segment horizontally or vertically at each even or odd step, respectively. This leads to the array configurations where the conductor strips extending from all the eight unit cells surrounding the reference one are co-directionally wound within it.



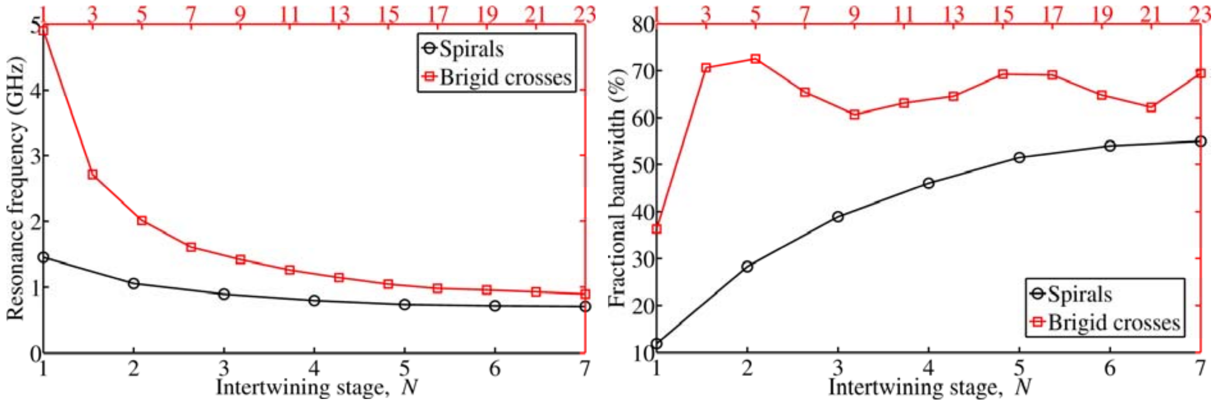
(a) (b)

Fig. 1: Topologies of the unit cells of intertwined (a) quadrifilar spiral and (b) Brigid's cross arrays. Highlighted in black are the original conductor patterns whereas successive intertwined conductors extending from adjacent unit cells are depicted in grey and numbered correspondingly to the interleaving stage.

3. Electromagnetic response of interweaved arrays

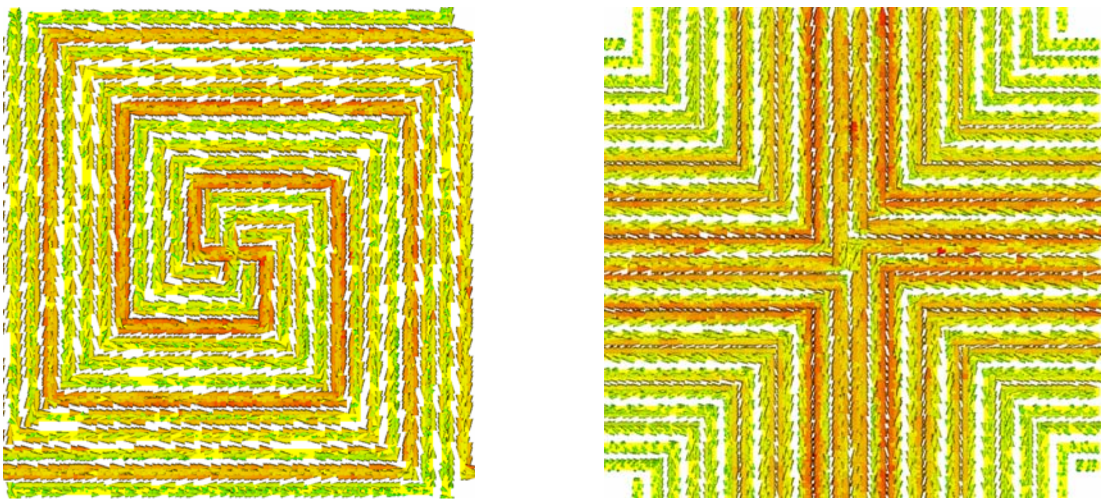
Both interweaved spiral and Brigid's cross arrays provide efficient concurrent control of both the equivalent capacitance and inductance in the unit cell. As a result, these patterns enable significant reduction of the unit cell electrical size along with broadening FBW at ever lower resonance frequencies. The resonance frequencies (f_r) and the FBWs of the interweaved spiral and Brigid's cross arrays at variable stages of their interleaving (N) are compared in Fig. 2. The periodicity of both square lattices is p = 10.8 mm and strip conductors and gaps have the same width 0.2 mm. As apparent, for both arrays f_r decreases monotonically and FBW grows with increasing N. However, while FBW of the Brigid's cross array rapidly reaches its maximum after a few interleaving steps, and then tends to oscillate about it, FBW of entwined spirals steadily increases with N. Finally, at full interweaving, the spiral array features the lowest resonance frequency but its FBW, though remarkably large, is smaller than the FBW of Brigid's cross array, which, on the other hand, exhibits a slightly higher f_r (lower packaging density λ_r/p, where λ_r is the wavelength at frequency f_r).

The dramatic decrease of λ_r/p in the intertwined arrays is attributed to the large equivalent capacitance, which also provides broader FBW. Such large capacitive content is produced by the intertwined strips that can be inferred by examining the current distributions in the unit cells at their respective resonance frequencies, which are shown in Fig. 3. Indeed, it can be observed that in the entwined spirals (Fig. 3(a)) only a pair of arms carry a non-zero net current, whereas all the other spiral arms, either originating inside or extending from outside of the reference unit cell, have the net current vanishing. This occurs because the currents at the opposite edges of these spiral arms are counter directed, and the respective stripes basically act as a floating ground. Conversely, the large capacitance in the Brigid's cross unit cell results from the strong coupling between adjacent stripes, on which the currents flow in opposite directions, with the exception of the central cross arms (Fig. 3(b)).



(a) (b)

Fig. 2: Resonant frequencies and FBWs at variable interleaving steps for the entwined quadrifilar spiral (a) and Brigid's cross (b) arrays from Fig. 1 (CST simulations)



(a) (b)

Fig. 3: Current distributions in the unit cells of the interweaved spiral (a) and Brigid's cross (b) arrays from Fig.1

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