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PLANAR SPIRAL RESONATORS FOR COMPACT ANTENNA APPLICATIONS

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Abstract

Planar spiral resonators on the conductor backed substrates are examined in the view of metamaterial, compact antenna and System-in-Package applications. A single layer spiral and stacked tightly coupled spiral resonator pairs on the conductor backed substrates have been investigated. It is shown that rotation of the spirals with respect to each other in a pair results in decrease of the resonance frequencies. This feature provides a means for tuning of metamaterial and antenna magnetic response.

1 Introduction

Design of the artificial electromagnetic media with the engineered dielectric and magnetic response represents one of the priority areas in metamaterial research. The antenna applications of metamaterials are ubiquitous and include small antennas, artificial magnetic conductors (AMC), frequency selective absorbers and spatial-frequency discriminators to mention a few. All these applications involve strong magnetic interaction of electromagnetic field with the radiating elements and medium. Therefore artificial magnetism created in metamaterials provides a means for implementation of novel types of the antenna applications. Periodic arrays of tightly coupled split ring resonators (SRRs) have been used first to emulating strong magnetic response of an artificial medium illuminated by the plane waves of certain polarisation and angles of incidence. Experimental demonstration of the negative refraction phenomenon inspired extensive research in the new types of metamaterials scaleable to various frequency ranges. In particular, metamaterials composed of tightly coupled pairs of nano rods were suggested in [1] for optical frequencies as alternative to SRR. These pairs arranged in the periodic arrays form the current loops resonating in the transmission line mode and create magnetic moment lattices. While the SRRs and coupled rods have demonstrated feasibility of generating magnetic response of the artificial medium, other arrangements of the constituent particles have been proposed for microwave frequencies in [2]. These particles exploit the same principle of tight coupling between the conducting wires or stripes in each pair that gives rise to two types of resonances, associated with their electric and magnetic properties. By varying the particle and lattice geometry, the individual resonances can be tailored to provide the required collective response of the array which is often described in terms of permittivity and permeability of effective medium when the size and separation of the constituent particles are small as compared with the wavelength.

The magnetic response of artificial medium is one of the prime characteristics required for design of the high impedance surfaces and small antennas. Therefore printed coupled stripes and planar spirals which intrinsically possess inductive properties are good candidates for practical realisation of both AMC and compact radiating elements. The square spiral resonators were used in [3] to build a reflector for compact antenna system based on a finite AMC comprising 20x31 spirals operated at 2.68GHz. A double-spiral resonator (DSR) structure was proposed in [4] to realise negative effective permeability at the low frequency. The resonant frequency achieved with the DSR was three times lower than that of the conventional SRR with the same footprint. Further size reduction of the spiral resonators used in AMC surface was demonstrated in [5]. A truly tremendous miniaturisation of the spiral resonator to the order of $\lambda/170$ has been reported in [6]. The printed spiral resonators have also been used to design frequency selective surfaces and compact microstrip filters [7] and diplexers [8]. Being compatible with the printed circuit board technology, the planar spiral resonant elements can

provide the low cost solutions for miniaturised antennas integrated with microwave circuits of the RF front end in System-In-Package, wireless communication, airborne and spaceborne applications.

The main objective of this work is to explore the tightly coupled stacked spiral resonators on the conductor backed substrates which can be used as miniature antennas and elements of the AMC surfaces.

2 Single-Layer Spiral Resonator

The spiral resonators on thin conductor backed substrates were analysed first for compact antenna applications. The effect of geometry on the resonance frequencies and radiation efficiency was examined using Agilent ADS Momentum. The simulation results showed that the resonance frequency decreased with the number of turns. However the saturation effect was observed, i.e. little change in the simulated characteristics occurred when the number of turns exceeded eight. This observation appeared to be consistent with the observations in [6].

Based on the simulation results, a resonator prototype with eight turns was built on Taconic RF-35 substrate of thickness 30 mils and dielectric constant of 3.5. The spiral radiator was designed with the following dimensions: stripe width $W=0.25$ mm, gap $S=0.3$ mm and inner turn size $L_{in}=1.1$ mm. The complete antenna shown in Fig. 1 was fabricated by using an LPKF ProtoMat C60 milling machine. The measured return loss of the prototype antenna is presented in Fig. 2 and demonstrates good agreement with the simulated data for the substrate permittivity of 3.2. Some discrepancy between the simulated and measured characteristics is likely caused by excessive cutting into the substrate material between the spiral turns, thus reducing the effective permittivity of the substrate.

3 Paired Spiral Resonators

Stacked tightly coupled spiral resonator pairs on the conductor backed substrate have been simulated using CST Microwave Studio. The resonator arrangement shown in inset of Fig. 3 comprises a pair of four turn spirals with the stripe width $W=0.25$ mm and gap $S=0.3$ mm. All conductors have thickness $T_c=17.5$ μ m and the thickness of both dielectric layers is $T_s=0.75$ mm. The largest side of each spiral is $L_{out}=5.2$ mm long and the outermost turn is offset from the substrate edge for $G=0.4$ mm. The discrete port source connected between the upper spiral and ground plane feeds the top spiral, while the lower spiral acts as a passive (floating) reactance. The simulated Return Loss (S11) in Fig.3 shows that the lowest resonance occurs at frequency $F = 1.41$ GHz. This implies that the resonator side has the size of $\sim \lambda/24$ where λ is wavelength in free space.

Fig. 1. Miniature spiral resonator antenna on conductor backed substrate.

Fig. 2. Measured (red) & simulated (blue) S11 for the antenna demonstrator in Fig.1.

Fig. 3. Return Loss (S_{11}) of the stacked pair of spiral resonator with parallel stripes.

Parameters: $W = 0.25 \text{ mm}$, $S = 0.3 \text{ mm}$, $L_{in} = 1.1 \text{ mm}$, $L_{out} = 5.2 \text{ mm}$, $G = 0.4 \text{ mm}$, $T_s = 0.75 \text{ mm}$, $T_c = 17.5 \mu\text{m}$

The radiation pattern at the resonance frequency of 1.41 GHz is displayed in Fig. 4. It shows that the stacked pair of coupled spirals over ground plane radiates nearly omni-directionally at low elevation angles, while a null occurs in the boresight direction. Analysis of the field and current distributions has revealed that once the source feeds the top spiral, the high current is induced on the lower spiral which acts as an anisotropic impedance patch. The higher order resonances marked in Fig. 3 exhibit completely different radiation patterns with the radiation maximum in boresight. Also it is interesting to note that in contrast to a single spiral which primarily radiates circular polarised fields, the field radiated by the stacked pair of the spirals has nearly linear polarisation.

To achieve the necessary magnetic response in the stacked pairs of planar spirals at low frequencies, tight controllable coupling between the two spirals is required. The coupling level could be adjusted by varying the separation between the two spirals. However in practice this approach is limited by the available substrate heights. Alternatively, the coupling can be adjusted by varying mutual orientation of the spirals rotated about their centres as shown in inset of Fig. 5. The simulation results in Fig. 5 illustrate this effect. In particular, at an angle of 45° between the stripes (green curve), the lowest order resonance at 1.41 GHz is suppressed while the resonance frequencies of the higher orders decrease in the arrangement of the spirals rotated for 45° as compared with the case of the aligned spirals with parallel stripes.

Fig. 4. Radiation pattern of the stacked pair of spiral resonators of Fig. 3 at $F=1.41 \text{ GHz}$.

Fig. 5. Return Loss (S11) of the stacked pairs of spiral resonators with the parallel stripes (blue) and the spirals offset for 45° (green). The structure parameters are the same as in Fig.3.

4 Conclusions

Planar spiral resonators on the conductor backed substrates have been examined in the view of their applications as constituent particles of metamaterials, compact antennas and reactive components of the System-in-Package devices. Good agreement between the simulation and measurement results for a single layer spiral resonator is achieved. Stacked tightly coupled spiral resonator pairs on the conductor backed substrate have been investigated using CST Microwave Studio. It is shown that at low frequencies the stacked spiral resonator pairs exhibit omni-directional radiation pattern with boresight null while for higher order resonances the maximum is reached at boresight. It is demonstrated that variation of mutual orientation of the spirals by rotating them with respect to each other within a pair results in decrease of the resonance frequencies. This feature provides an alternative means for fine tuning of metamaterial magnetic response and spiral antenna characteristics.

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