Varactor-loaded split ring resonators for tunable notch filters at microwave frequencies

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It is demonstrated that the resonant frequency of split ring resonators (SRRs) can be tuned using varactor diodes. The resulting particles, called a varactor-loaded split ring resonator (VLSRR), is applied to the design of a tunable notch filter at S-band. The device consists on a microstrip transmission line with VLSRRs placed at both sides of the conductor strip. Owing to the proximity of the particles to the line the rings are excited and a transmission notch arises. It is shown that simply using two VLSRRs pairs, rejection levels above 20 dB are achieved in a 0.5 GHz tuning interval centred at 2.85 GHz.

The proposed device is the first tunable notch filter based on SRRs.

Introduction: Split ring resonators (SRRs) have attracted much interest in recent years as key constituent particles for the design of effective media with negative magnetic permeability or left-handed metamaterials (LHM) [1]. Originally proposed by Pendry et al. [2] (see Fig. 1a), SRRs are sub-wavelength resonators (i.e. electrically very small) able to inhibit signal propagation in a narrow band in the vicinity of their resonant frequency, provided the magnetic field is polarised along the axis of the ring. This property has been interpreted as due to the extreme values (highly positive/negative) of the effective permeability below/above that frequency. Alternatively, this frequency selective behaviour can be explained by the induced current loops in the rings at resonance. These current loops are closed through the distributed capacitance between concentric rings; hence, SRRs can be modelled as LC resonant tanks that can be externally driven by a magnetic field and are therefore able to inhibit signal propagation in a certain narrow band if they are properly oriented [3]. Since the equivalent capacitance, \( C \), is given by the edge capacitance between concentric rings, the resonant frequency can be made very small by decreasing ring separation \( d \), i.e. high levels of miniaturisation for such particles can be achieved if the lateral resolution of the layout generation system (typically a drilling machine or standard photo/mask etching techniques) is small.

![Fig. 1 Topologies of circular SRRs and square-shaped VLSRR and relevant dimensions](image1)

Based on these frequency selective properties of SRRs, the authors have designed compact stop band filters in microstrip [4] and coplanar waveguide (CPW) technology [5]. These structures have been optimised to obtain high magnetic coupling between line and rings and hence high rejection levels in the forbidden bands. For the CPW stop band filters, SRRs have been etched in the back substrate side, underneath the slots, while for the microstrip structures, the rings (placed in close proximity to the conductor strip) have been designed with a rectangular-shaped geometry in order to enhance line-ring coupling. Rejection levels above 30 dB have been experimentally obtained in both CPW and microstrip fabricated prototypes, with few SRR stages. It has also been shown that by etching SRRs with slightly different dimensions, gapwidth enhancement is possible [4, 5], with application for instance to the elimination of undesired spurious bands in conventional distributed filters [6, 7]. In this work, the possibility of achieving electronic tuning in SRR-based notch filters has been demonstrated for the first time. To this end, SRRs are loaded with varactor diodes placed between the inner and outer ring. By this means, the diode capacitance is added to the edge capacitance of the particle, and bias control of the resonant frequency is thus possible. These new particles, called by the authors varactor-loaded split ring resonators (VLSRRs), combine tunability with small dimensions, and therefore can be very promising for the design of compact reconfigurable devices at microwave frequencies.

**Varactor-loaded split ring resonators (VLSRRs):** The topology (layout) of the VLSRR (Fig. 1b) is essentially the same as that of the SRRs (a square-shaped geometry has been considered to enhance coupling to the line). However, to connect the diode varactors between the internal and external conductors, the separation between rings, \( d \), is no longer uniform, i.e. in that region where the varactor is placed, this distance is increased. Also, a metal pad is added in the centre of the particle to achieve easy diode biasing. With this configuration, the diode capacitance dominates over the distributed capacitance between rings, and certain electronic control of the resonant frequency of the structure is achieved. Actually, the equivalent capacitance related to electric coupling (edge coupling) between rings in an SRR is given by the series connection of the capacitances corresponding to the left and right halves of the structure [3]. These capacitances are given by \( C_L = C_{left} \cdot p/2 \) and \( C_R = C_{right} \cdot p/2 \), respectively, where \( C_{left}/C_{right} \) is the per-unit length capacitance of the left/right half of the resonator and \( p \) its perimeter. However, for the topology of the VLSRR of Fig. 1b, the right-hand side capacitance is dominated by the varactor. Although this capacitance, \( C_{Var}(V) \), can be made much larger than \( C_L \) due to varactor biasing, an AC ground is added between \( C_L \) and \( C_{Var}(V) \), and significant tuning can be achieved provided \( C_L \) and \( C_{Var}(V) \) are no longer series connected.

**Design of VLSRR notch filter in microstrip technology:** The designed device consists of a 50 Ω microstrip line with two VLSRR pairs placed at both sides of the line (Fig. 2). The substrate is the commercial Rogers RO3010 (dielectric constant \( \varepsilon_r = 10.2 \), thickness \( h = 1.27 \) mm). With these substrate parameters, the width of the conductor strip (obtained by means of the Agilent LineCalc transmission line calculator) has been found to be \( W = 1.17 \) mm. With regard to VLSRR dimensions, these have been estimated to provide a resonant frequency in the vicinity of 3 GHz. Specifically, ring strip widths are \( c = 0.2 \) mm, while the separation between rings has been set to \( d = 0.2 \) mm, except at the right edge of the structure, where this dimension has been increased to provide sufficient space for the varactors. To enhance the coupling between line and rings, their separation has been minimised as much as possible (0.2 mm). Finally, the length and width of the VLSRRs is 6.2 and 2.8 mm, respectively, and the distance between adjacent particles 2 mm. To electronically control the position of the filter notch, BB833-Infineon Technologies silicon tuning diodes have been used as nonlinear capacitances. These devices exhibit a high capacitance ratio, which is of interest to achieve a wide tuning range, i.e., device capacitance is 9 and 0.75 pF at 1 and 28 V reverse bias, respectively. This capacitance range dominates over the edge capacitance of the rings and is therefore adequate for our purposes. Diode biasing is very simple provided the rings are electrically isolated from the line and neither DC blocks nor inductor chokes are required, i.e. reverse bias is directly applied between the polarisation pad of the VLSRRs and ground (back substrate side).

**Results:** The simulated (using the Agilent Momentum commercial software) and measured (by means of the Agilent 8720ET vector network analyser) frequency responses of the structure without the presence of the varactors are depicted in Fig. 3. A peaked notch at
3.5 GHz is visible with a rejection level (measured) above 60 dB. Since diode varactors are absent, current loops do not flow to the inner metalisation (bias pad and smaller ring), and this resonance is that corresponding to a single ring with an aperture (dynamic resonance). However, if the varactors are added, the whole current flows through the varactors, the frequency response of the device is decreased, and it can be bias controlled. Fig. 4 exhibits the measured frequency responses (transmission coefficient) that have been experimentally obtained under different bias conditions. As expected, the resonant frequency of VLSRRs is tuned and accordingly the position of the notches. At low polarisation levels, the contribution of the varactors to the whole capacitance is greater and, therefore, the effects of losses (manifested through the diode and source series resistance) increase. This explains rejection reduction when bias is decreased. Nevertheless, a wide tuning range has been obtained, with rejection levels above 20 dB between 2.6 and 3.1 GHz. The results of this work open the possibility not only to tune gap position, but also to electronically enhance the gap width by merely adding more VLSRRs with independent bias control.

**Fig. 3** Simulated (dashed lines) and measured (solid lines) frequency responses for structure of Fig. 3 without presence of diode varactors

**Fig. 4** Measured transmission coefficients (insertion loss) for VLSRR notch filter obtained under different bias conditions

**Conclusion:** It has been demonstrated that frequency tuning in microstrip notch filters is possible using VLSRRs (a new particle introduced by the authors) coupled to the line. The fabricated prototype (a two-stage device) is very small and exhibits high rejection levels (above 20 dB) in a 0.5 GHz tuning range centred at 2.85 GHz. This is the first time that frequency tuning based on the use of split ring resonators is demonstrated. Owing to the small dimensions and tunability of VLSRRs, it is believed that these particles can become key elements in microwave engineering.

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