Tunable split-ring resonators for nonlinear negative-index metamaterials

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Abstract: We study experimentally the dynamic tunability and self-induced nonlinearity of split-ring resonators incorporating variable capacitance diodes. We demonstrate that the eigenfrequencies of the resonators can be tuned over a wide frequency range, and significantly, we show that the self-induced nonlinear effects observed in the varactor-loaded split-ring resonator structures can appear at relatively low power levels.

OCIS codes: (260.2110) Electromagnetic Theory; (999.9999) Metamaterials.

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1. Introduction

Specially engineered microstructured materials (or metamaterials) that demonstrate many intriguing properties for the propagation of electromagnetic waves such as negative refraction have been discussed widely during recent years (see, e.g., the review paper [1] and references therein). Such materials have been studied theoretically (see, e.g., Refs. [2, 3, 4, 5] to cite a few) and also fabricated experimentally (see, e.g., Refs. [6, 7, 8]). A composite material of this kind is created by a lattice of metallic wires and split-ring resonators (SRRs) with its unique properties associated with the negative real parts of the magnetic permeability and dielectric permittivity. Since the first theoretical paper by Veselago [9], such negative-index metamaterials have also been described as *left-handed materials* (LHMs).

Within the microwave and millimeter frequency ranges, the composite metamaterials containing the SRR systems have been shown to possess macroscopic negative-index (left-handed) properties and thus exhibit peculiarities not found in natural materials. Recent strong experimental efforts have been directed towards the attainment of metamaterials with negative response in the Terahertz [10] and even optical [1, 11] frequency domains.

Since the first extensive studies on negative-index metamaterials, the attention of most researchers has been focused on the passive control and linear properties of these composite structures, where the effective parameters of the structure do not depend on the intensity of the applied field or propagating electromagnetic waves. However, to achieve the full potential of the unique properties of the metamaterials requires the ability to dynamically control the material’s properties in real time through either *direct external tuning* or *nonlinear responses*.

Dynamic control over metamaterials is a nontrivial issue since such materials possess left-handed properties only in some finite frequency range, which is basically determined by the geometry of the structure. The possibility to control the effective parameters of metamaterials using nonlinearity has recently been suggested in Refs. [12, 13] and developed extensively in Refs. [14, 15, 16, 17, 18, 19, 20, 21] where many interesting nonlinear metamaterials effects have been predicted theoretically. The main reason for the expectation of strong nonlinear effects in metamaterials is that the microscopic electric field in the vicinity of the metallic particles forming the left-handed structure can be much higher than the macroscopic electric field carried by the propagating wave. This provides a dynamic yet important physical mechanism for dramatically enhancing nonlinear effects in left-handed materials. Moreover, changing the intensity of the electromagnetic wave not only changes the material parameters, but also allows switching between transparent left-handed states and opaque dielectric states.

In this paper, we make the first step toward the creation and study of fully controlled, tunable nonlinear metamaterial systems through the study of the tunability and self-induced nonlinear

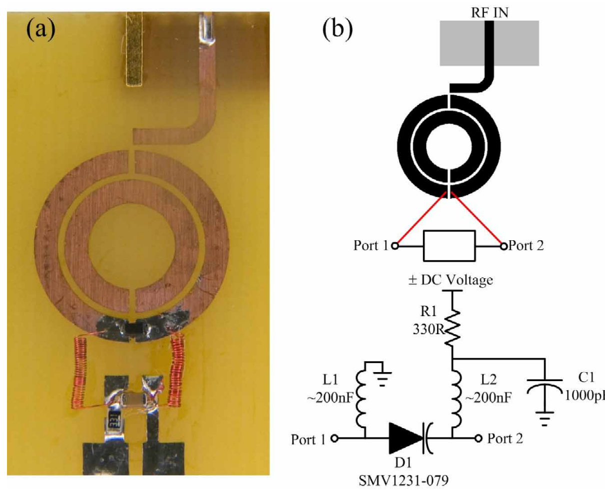

Fig. 1. Experimental structure used to study tunability and nonlinearity of a varactor-loaded split-ring resonator system. (a) Photography showing the fabricated SRR and biasing circuitry used for direct voltage tuning of the resonant frequency. (b) Top: electromagnetic representation of the SRR-diode structure; bottom: schematic of the biasing circuit.

response of a single SRR. The analysis of single SRRs as tunable components of extended composite systems is an extremely important step, and this approach has, for example, been employed to study the effect of disorder in SRR structures [22]. To achieve our goals, we add a variable-capacitance diode (varicap) to the SRR resonant structure. Tunability of the diode capacitance is achieved by varying the width of its specifically doped P-N junction, and associated depletion layer, through the application of a DC bias voltage, or more attractively, through the self-action of the diode with increased applied electromagnetic energy, giving rise to dramatic self-induced nonlinear effects. Changes in the diode capacitance alter the resonant conditions of the SRR producing frequency shifts, which in turn adjust the effective magnetic permeability of left-handed metamaterials. Using this methodology, we experimentally establish a qualitative measure of the tunability of an SRR, and confirm earlier predictions for the *dynamic control* over the properties of SRRs by varying the intensity of the incident electromagnetic signal.

2. Tunable split-ring resonators

Effective control over the resonant conditions of the SRR is achieved by adding the capacitance of the diode in series with the distributed capacitance of the outer ring of the SRR at a point of maxima in the electric currents. This methodology, as well as the motivation, is thus significantly different to previous works by Gil *et al.* [23, 24] that used a varicap to obtain edge coupling *between the two rings* of a uniquely designed SRR structure employed to form a microwave notch filter. Indeed, the series application of the diode provides a simple mechanism for both *tunability* and *nonlinearity* suited to the formation of left-handed metamaterials, particularly with the recent developments in magnetic thin-film and microwave nonlinear materials. The symmetry and simplicity of our system also lends itself to greater integration, allowing the structure to be translated more readily to the THz and optical frequency domains.

To study the potential tunability and nonlinearity of metamaterials we use a single archetype SRR, constructed on fibreglass (FR4, $\varepsilon_r \approx 4.4$) with copper metallization as shown in Fig. 1(a). We use an SRR with an internal ring radius of 2.56mm. Both rings have a linear width of 1.44mm, and the separation between rings as well as the ring slots are 0.32mm. An additional

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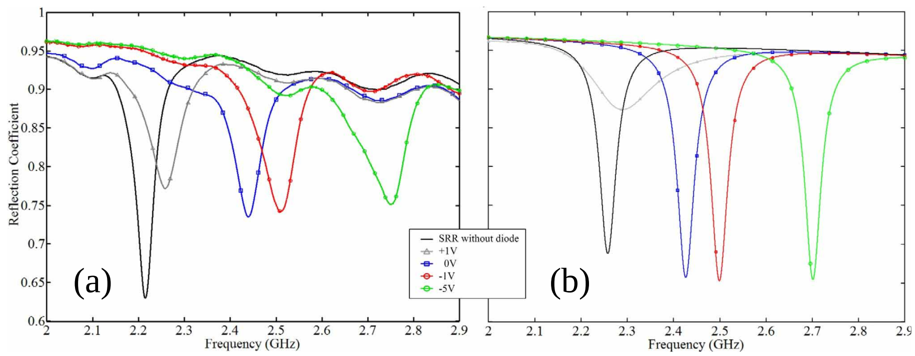

Fig. 2. (a) Experimental and (b) numerical results for the modulus of the reflection coefficient (S_{11}) as a function of frequency for the SRR without the diode circuit, and with the diode circuit under both positive and negative biasing conditions.

gap of 0.4mm is created in the outer SRR ring for mounting of the Skywork's SMV1231-0790 varicap diode. A DC voltage is used to achieve direct tuning of the diode. The parasitic effects of the voltage supply are isolated from the electromagnetic structure of the SRR via a biasing circuit. The simple biasing circuit consist of wire-wound shunt inductors (L1, L2) and de-coupling capacitor (C1), as illustrated in the schematic of Fig. 1(b). In the forward biasing regime a series resistor (R1) is used to limit the forward bias current through the diode and prevent damage; in the reverse bias region this resistor has negligible effect on the circuit's operation. Electromagnetic coupling to the SRR is accomplished with a short trace probe, fabricated on the FR4 substrate with the SRR, (see Fig. 1(a)) that is de-tuned to have a mostly flat response in the SRR's operational bandwidth, allowing the SRR's properties to dominate. The SRR is energized and measured using a 20GHz Rohde and Schwartz vector network analyzer (VNA, model ZVB20), wherein resonant conditions are observed through a reduction in the reflection coefficient (S_{11}) at resonance.

Two reference frequency responses are taken for the SRR: without the diode and gap, and with the diode structure at zero bias voltage, as shown in Fig. 2 (a). An initial resonance located at 2.22GHz for the SRR is shifted to 2.44GHz with the diode structure. This increase in resonant frequency is a result of the zero-bias junction capacitance (C_{J0}) caused by the intrinsic depletion layer of the diode. As the diode's capacitance is added in series to the distributed capacitance of the SRR, it causes the total capacitance to decrease and the resonance frequency to increase. Application of a negative biasing voltage to the diode results in an increase of the depletion layer and a subsequent decrease in the diode's capacitance pushing the resonant frequency higher. Conversely, a positive biasing voltage increases the diode's capacitance and decreases the SRR's resonant frequency. However, due to the current-voltage relationship of the diode it can only be forward biased to a maximum voltage of 1.2 volts.

For a negative bias voltage of -10 volts (not shown) the resonant frequency can be shifted to 2.9GHz, whereas for a positive voltage of 1 volt the resonant frequency decreases to 2.27GHz. For this particular varicap diode and SRR structure there is a tuning bandwidth of 0.63GHz, equivalent to a tuning range of approximately 26%.

We note here that this tuning range has not been optimized. Further increases to this range could be achieved through improved materials and impurity doping of the diode, bringing about an increase capacitance ratio, in addition to greater integration of the diode with the SRR structure. Indeed, Fig. 2 (a) shows the quality factor of the SRR's resonance is decreased with the inclusion of the diode structure, resulting from the inherent series resistance of the diode, and

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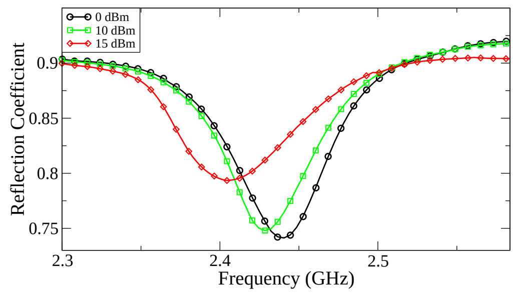

Fig. 3. Experimentally measured modulus of the SRR reflection coefficient (S_{11}) as a function of frequency and applied input power from the vector network analyzer. Power levels at the diode are significantly lower due to input coupling (see text).

packaging and mounting parasitics; all of which can be reduced through greater integration and more advanced fabrication techniques.

3. Numerical simulations

To determine the optimal placement of the varicap diode, we employ numerical simulations. We use a finite element method based electromagnetic simulator in conjunction with a detailed SPICE model of the varactor diode and bias circuit. S-parameters were extracted from the SPICE model and included within the S-parameter calculations of the SRR as a generic two-port device. Results of our numerical simulations generated in this manner are presented in Fig. 2(b) for several biased and unbiased conditions.

By comparing these results with the experimental curves, we observe a good qualitative agreement between the measured and simulated resonant frequency locations. However, the numerical results do not reflect the voltage and frequency dependent changes in the quality factors of the resonances. We believe that changes in the measured quality factors of the resonances occur due to changes in the parasitic series resistance of the diode and, to a lesser extent, changes in the impedance mismatch of the diode and the SRR structure. While the impedance mismatch effect is modeled numerically, the variable series resistance is not, resulting in the quality factor discrepancy. Greater accuracy of the simulated results requires more knowledge of the diode's fabrication, which is not available for the diode used in our experiment.

4. Nonlinear split-ring resonators

Tunability of the SRR via an applied voltage is a valuable mechanism; however the integration of the biasing network and delivery of voltage sources, albeit possible, requires careful design to prevent these components affecting the composite performance of a LHM. Furthermore, the ability to change the properties of a LHM in response to the power of the applied signal leads to important effects such as dynamic control of the material's opaqueness and the switching between left- and right-handed material responses. To study these self-induced nonlinear effects we zero bias the diode and sweep the applied power from the vector network analyzer from 0dBm to 17dBm. The power levels at the diode are, however, substantially lower due to the significant losses at the input coupling probe.

As previously described theoretically in Ref. [12], the nonlinear properties of the SRR with nonlinear capacitance gives rise to eigenfrequency shifts as the intensity of the applied electromagnetic wave is varied. This occurs due to the intense, localized currents within the SRR decreasing the diodes depletion layer and subsequently changing its capacitance, which in turn, changes the effective capacitance of the whole SRR, and thus its resonant frequency. Such non-

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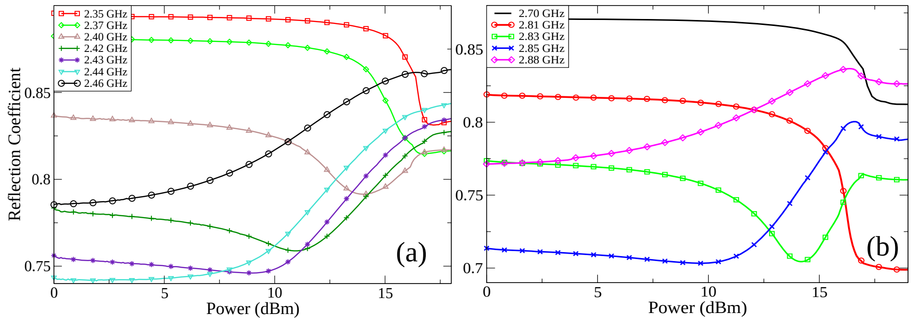

Fig. 4. Experimentally measured modulus of the reflection coefficient (S_{11}) as a function of the output power of vector network analyzer; (a) at several frequencies for zero voltage bias , and (b) -7 V (reverse) bias voltage. Power levels at the diode are significantly lower due to input coupling (see details in the text).

linear frequency shifts are explicitly observed in our measurements. Figure 3 shows the measured reflection coefficients for different vector network analyzer output power levels, under zero DC biasing conditions. The key observation is that the resonance shifts to lower frequencies as we increase the power. We also observe a decrease in the quality factor of the nonlinear SRR at higher power levels, which may be due to the increased series resistance of the varicap diode.

The self-induced nonlinear response of the SRR-diode structure is illustrated in Fig. 4(a), where the dependence of the reflection coefficient on the applied signal is observed for the zero-biased condition. The demonstrated reflection coefficient dependence provides switching between high and low reflection states, corresponding to high and low currents in the SRR and thus the magnetic momenta. Control over the nonlinear response can be achieved with static biasing of the diode as illustrated in Fig. 4(b), where a fixed reverse bias voltage of -7 volts has been applied. Negative biasing results in an enhanced response whereas positive biasing causes a reduced response arising from the increased series resistance and diminished quality factor. As the nonlinear effects are observed near the linear SRR resonance, the frequency range where the SRR is strongly nonlinear shifts as the bias voltage changes.

5. Conclusions

We have demonstrated experimentally both the direct real-time tunability and self-induced nonlinear response of a varactor-loaded split-ring resonator structure; a key element for the creation of a nonlinear, negative-index metamaterial. The structure we have used is based on a typical SRR design, and employs a commercially available varactor diode placed at a maximum of the SRR's current and in series with its distributed capacitance. Through the application of a positive and negative biasing voltage, we have observed more than half a GHz frequency tuning range; a tuning range equivalent to 26% of the zero-biased frequency. Using a zero-bias diode, with and without an external biasing circuit and voltage supply, we have demonstrated the ability of this structure to switch between high and low reflection states associated with a power-dependent frequency shift. These results suggest that negative-index metamaterials constructed with SRRs and varactor diodes can exhibit large tunability and nonlinearity, enabling many unique and novel metamaterial properties not available within nature. We believe our results will encourage the future design of nonlinear, negative-index metamaterials within the microwave and optical frequency domains.

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