Field-circuit co-simulation for microwave meta-materials with nonlinear components

Delong Li,[1] Jinfeng Zhu,[1*] Shanshan Wu,[1] Xiaoping Xiong,[1] Yanhui Liu,[1] Qing H. Liu[1,2*]
[1]Department of Electronic Science, Xiamen University, Xiamen 361005, China
[2]Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA
*Email: nanoantenna@hotmail.com (J. Zhu), qhl@xmu.edu.cn (Q. H. Liu)

***Abstract*-We demonstrate an analysis of the metamaterials medium consisting of SRRs (split ring resonators) integrated with nonlinear microwave components based on a circuit and 3D electromagnetic wave co-simulation method. The simulations are performed by using Wavenology EM, which is an efficient multiphysics and multiscale wave simulator. Our investigations show that the resonant frequency of the SRR loaded by a varactor reduces slightly when incident wave power increases, which is consistent with previous experimental research. We propose to connect an adjustable capacitor in parallel with the varactor to tune the resonant frequency. The simulation results indicate the tuning range is from 12.30 to 14.92 GHz, and the resonant frequency and quality factor decrease as the parallel capacitance increases.**

I. INTRODUCTION

Microwave metamaterials are usually periodic arrays of artificial structures which have negative refractive index, and they have diverse potential applications, such as cloaking [1], superlens [2]. A split ring resonator (SRR) is a commonly used array unit that delivers strong magnetic coupling for metamaterials [3, 4]. Recently, the nonlinear metamaterials based on SRRs has attracted surge of interest [5-7], due to the strong local electromagnetic field enhancement in a sub-wavelength unit cell [5, 8]. Da Huang et al. have done the fundamental research about the nonlinear metamaterial consisting of varactor-loaded SRRs, and they have used an analytical method to investigate the power dependent tuning at microwave frequency. However, this method is inconvenient and inefficient, especially for the engineering design of circuit-loaded metamaterials with complex structures. In this paper, the field-circuit problem of SRR-based metamaterials with nonlinear components is co-simulated by using Wavenology EM, which is an efficient multiphysics and multiscale wave simulator software. We propose to make the nonlinear metamaterials intelligent by paralleling an adjustable capacitor without changing the structure geometry of SRRs, and investigate its resonant properties by using the co-simulation method.

II. MODELING AND SIMULATION

A. *Physical model and co-simulation using Wavenology EM*

One of the highlighted features of Wavenology EM is the ability to co-simulate both complex circuits and microwave systems together. It provides a flexible and fast route to solving field-circuit coupling problem. A full wave transient 3D EM solver based on finite difference time domain method and a SPICE module for circuit design are hybridized to simulate microwave response of SRRs loaded by nonlinear components.

The SRR is a single copper square with an outer edge length of 2.2 mm, an inner edge length of 1.8 mm, and a slit width of 0.3 mm, placed on a 0.25 mm thick FR4 (ε = 4.4) substrate. In the modeling work, the SRR is integrated with a circuit module (including an SMV1231-079 varactor) into the gap of the SRR [5], as shown in Fig. 1. The circuit-loaded SRR unit cell is located at the center of the computation domain, and perfect magnetic conductor and perfect electric conductor boundary conditions are used at the top and bottom walls of the simulation region. Two wave ports perpendicular to x axis are used to investigate the plane wave excitation and response. Such a configuration in the co-simulation model can reflect the resonant properties of a microwave nonlinear metacrystal consisting of SRRs with nonlinear microwave components.

B. *Circuit model*

The RLC equivalent circuit model of a varactor-loaded SRR is presented in Fig. 2(a). The varactor is integrated into the capacitive gap of the SRR. We also propose to connect an adjustable capacitor Cp in parallel with the varactor to manipulate resonant properties of the circuit-loaded SRR, as shown in Fig. 2(b).

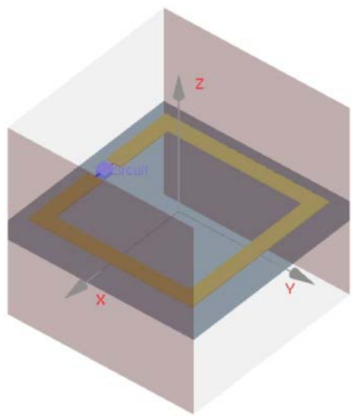

Fig.1 Simulation model of an SRR with a circuit module.

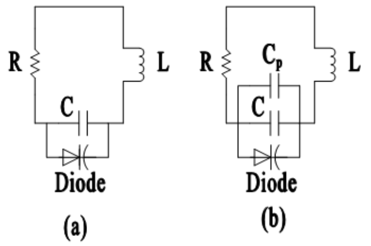

Fig.2. Equivalent circuit: (a) a varactor-loaded SRR, and (b) a varactor-loaded SRR with a parallel capacitor.

III. Results and Discussion

A. Nonlinear response of changing incident wave power

Here, we use the shift of resonant frequency by increasing incident power to characterize the nonlinear response of varactor-loaded SRRs. The varactor has a nonlinear capacitance that varies with the applied voltage as $C(V_D)=C_0(1-V_D/V_P)^{-M}$, where V_D is the bias voltage, C_0 is the zero bias capacitance, V_P is the intrinsic potential, M is the gradient coefficient, and the reverse breakdown voltage is 15V. The nonlinear response of the microwave metacrystal is originated from the performance of the nonlinear capacitance.

We first discuss the co-simulation result of the model shown in Fig. 2(a). It is observed that the amplitude of incident excitation voltage is 0.05V, but voltage amplitudes of more than 0.15V at P and N nodes of the varactor are generated, as shown in Fig. 3. This simulation result demonstrates that the strong electric filed enhancement at the gap of the SRR, which excites the nonlinear response in the varactor-loaded SRR. Fig. 4 shows that the resonant frequency of S21 decreases slightly as the incident power V_i increases, which demonstrates the nonlinear properties of the investigated microwave metacrystal, and the simulation result is consistent with previous research work in Ref. [5] and [7].

B. Effects of tunable circuit

Next, we discuss the proposed model shown in Fig. 2(b). An adjustable capacitor in parallel with the varactor can be used to tune the resonant response in the RLC circuit [9], and therefore make the unit cell intelligent and flexible for research of nonlinear metamaterials. As shown in Fig. 5, the incident voltage amplitude is set to 0.01V, and the transmission properties are tuned obviously as the value of C_p

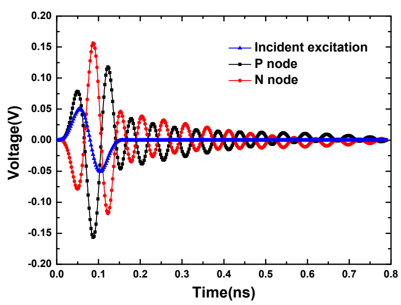

Fig.3. Incident wave excitation and voltages at P and N nodes of the varactor, for the model shown in Fig. 2(a).

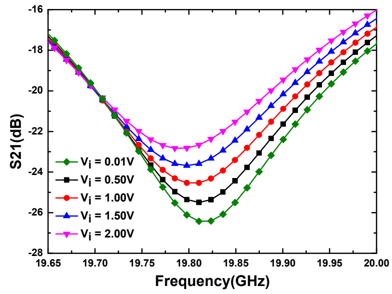

Fig.4. S21 of incident voltage amplitudes from 0.01V to 2.00V, for the model shown in Fig. 2 (a).

Changes from 0.05pF to 0.10pF [10]. The result in Fig. 5 indicates that the quality factor and resonant frequency decrease as the parallel capacitance increase. As C_p increase from 0.05pF to 0.10pF, the quality factor is gradually reduced, but the resonant frequency is shifted from 14.92GHz to 12.30GHz, which is a broad tunable range for microwave metamaterials.

IV. Conclusion

We have demonstrated the tunability, strong local field enhancement, and adjustability of circuit-loaded SRRs by using field-circuit co-simulation. The co-simulation result for microwave metameterials with nonlinear circuit components is in agreement with previous research analysis. Without changing the physical geometry of the SRR unit cell, the permeability of the nonlinear metacrystal is adjustable through manipulating the nonlinear circuit. In future work, the co-simulation approach for tunable circuit-loaded SRRs will be experimentally verified by S-parameter measurement using a vector network analyzer and applied in the design of nonlinear metamaterials.

Acknowledgment

Jinfeng Zhu acknowledges the support from the Institute of Electromagnetics and Acoustics at Xiamen University. The authors thank Dr. Bo Zhao from Wave Computation Technologies, Inc. for technical support and helpful discussions.

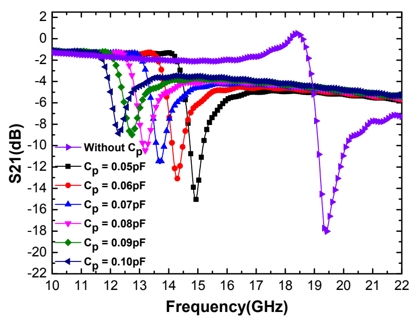

Fig.5 S21 of controlling C_p, for the model shown in Fig. 2(b).

References

[1] W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, "Optical cloaking with metamaterials," *Nature photonics,* vol. 1, no. 4, pp. 224-227, 2007.

[2] X. Rao, and C. Ong, "Subwavelength imaging by a left-handed material superlens," *Physical Review E,* vol. 68, no. 6, pp. 067601, 2003.

[3] D. Smith, D. Vier, T. Koschny, and C. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical Review E,* vol. 71, no. 3, pp. 036617, 2005.

[4] D. Huang, E. Poutrina, H. Zheng, and D. R. Smith, "Design and experimental characterization of nonlinear metamaterials," *JOSA B,* vol. 28, no. 12, pp. 2925-2930, 2011.

[5] D. Huang, E. Poutrina, and D. R. Smith, "Analysis of the power dependent tuning of a varactor-loaded metamaterial at microwave frequencies," *Applied Physics Letters,* vol. 96, no. 10, pp. 104104-104104-3, 2010.

[6] E. Poutrina, D. Huang, and D. R. Smith, "Analysis of nonlinear electromagnetic metamaterials," *New Journal of Physics,* vol. 12, no. 9, pp. 093010, 2010.

[7] B. Wang, J. Zhou, T. Koschny, and C. M. Soukoulis, "Nonlinear properties of split-ring resonators," *arXiv preprint arXiv:0809.4045*, 2008.

[8] J. Pendry, A. Holden, D. Robbins, and W. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 47, no. 11, pp. 2075-2084, 1999.

[9] I. V. Shadrivov, S. K. Morrison, and Y. S. Kivshar, "Tunable split-ring resonators for nonlinear negative-index metamaterials," *arXiv preprint physics/0608044*, 2006.

[10] M. Gorkunov, and M. Lapine, "Tuning of a nonlinear metamaterial band gap by an external magnetic field," *Physical Review B,* vol. 70, no. 23, pp. 235109, 2004.