Non-Reciprocal 2nd-Order Bandpass Filter by Using Time-Modulated Microstrip Quarter-Wavelength Resonators

Xiaohu Wu[$#1], Mahmoud Nafe[#2], Xiaoguang Liu[#5],
[#]University of California, Davis, USA
[$]Nanjing University of Information Science & Technology, Nanjing, China
[1]wxhwu@ucdavis.edu, [2]manafe@ucdavis.edu [3]lxgliu@ucdavis.edu

***Abstract*— A microstrip non-reciprocal 2nd-order bandpass filter is presented by using time-modulated resonators. Quarter-wavelength resonators are loaded with varactors to miniaturize the circuit size. The varactors are reverse-biased by dc voltages and then sinusoidal waves are applied to modulate their equivalent capacitance in time-domain. Circuit analysis shows that by properly introducing phase shift between the two modulation waves, non-reciprocal transmission can be generated. To verify the proposed concept, a microstrip 2nd-order non-reciprocal bandpass filter at 1.0 GHz is designed and simulated. Results show low insertion loss in the forward transmission and large attenuation in the backward transmission, leading to 4.7 dB non-reciprocity in the transmission magnitude.**

***Keywords*— bandpass filter, magnet-free, non-reciprocity, spatio-temporal modulation (STM), time-modulated**

I. Introduction

Non-reciprocal devices, i.e., circulators and isolators, play important roles in radio frequency circuits and systems due to their unique and directional signal transmission properties. The non-reciprocal properties can be used to either protect the active chains from reflected signals [1] or enable full-duplex communications [2], [3]. For decades, theses devices have been achieved using ferromagnetic materials, which are bulky, expensive and can not be integrated with other circuit devices [4].

Recently, there has been an arising interest in the exploration of magnet-free non-reciprocal devices. Two main approaches have been reported: one is based on the active devices [5], which intrinsically have non-reciprocal transfer functions, another is based on time-varying technologies [6]–[11]. The first approach shows compact size and compatibility with other circuit blocks, but suffers from poor noise figure and limited power handling. By sequentially switching on and off the transmission line segments in [6], separated transmit and receive channels have been generated to function as a wideband magnet-free circulator. $\pm\pi/2$ phase non-reciprocity is achieved based on staggered commutation and embedded into a ring resonator to realize circulator design in [7]. By mechanically circulating the fluid inside a resonant ring cavity in [8], spatio-temporal modulation (STM) is used to implement angular momentum biasing that breaks reciprocity and develop the magnetic-free acoustic circulator. Latter, by electrically modulating the resonator frequencies of LC resonators, lumped circulators in microwave frequency are presented in [9]–[11].

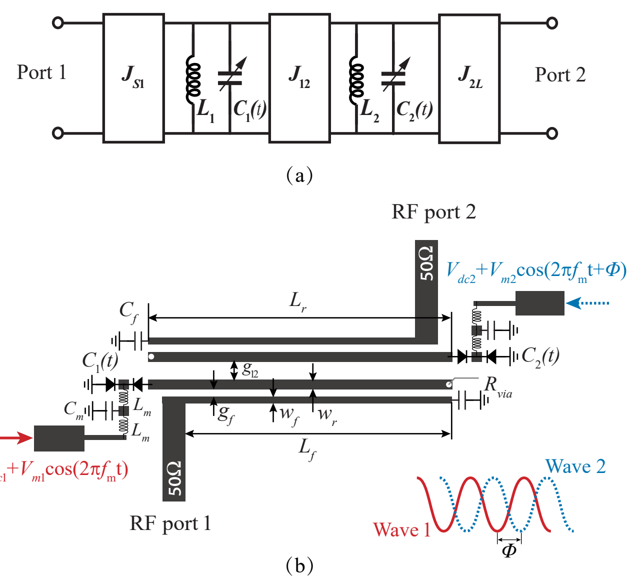


Fig. 1. (a) Ideal circuit model presented in [12]. (b) Layout of the implemented microstrip non-reciprocal 2nd-order filter using time-modulated quarter-wavelength resonators. Time-varying capacitors are implemented by using varactors biased by DC voltages V_{dci} and sinusoidal waves V_{mi}.

Same-frequency non-reciprocity in one-dimensional space is for the first time presented in [12] by modulating the resonant frequencies of the filter networks. Theory and analysis in [12] show that by properly choosing the modulation index, frequency, and incremental phase, there is low insertion loss in the forward transmission $|S_{21}|$ and large attenuation in the backward transmission $|S_{12}|$, which exhibits significant non-reciprocity.

In this paper, the concept is extended to distributed non-reciprocal circuit design. By temporally modulating the resonant frequencies of the microstrip quarter-wavelength resonators, microstrip non-reciprocal bandpass filter is presented and designed. The designed forward transmission has an insertion loss of 1.8 dB and backward transmission is attenuated to 6.5 dB, showing a transmission non-reciprocity of 4.7 dB.

II. Circuit analysis

Fig. 1 (a) showss the circuit topology of the 2nd-order non-reciprocal filter network. The circuit consists of time-invariant inverters (J_{S1} and J_{2L}), time-invariant

This file is a preprint of the manuscript accepted by IEEE ICMMT 2019, Guangzhou, China.

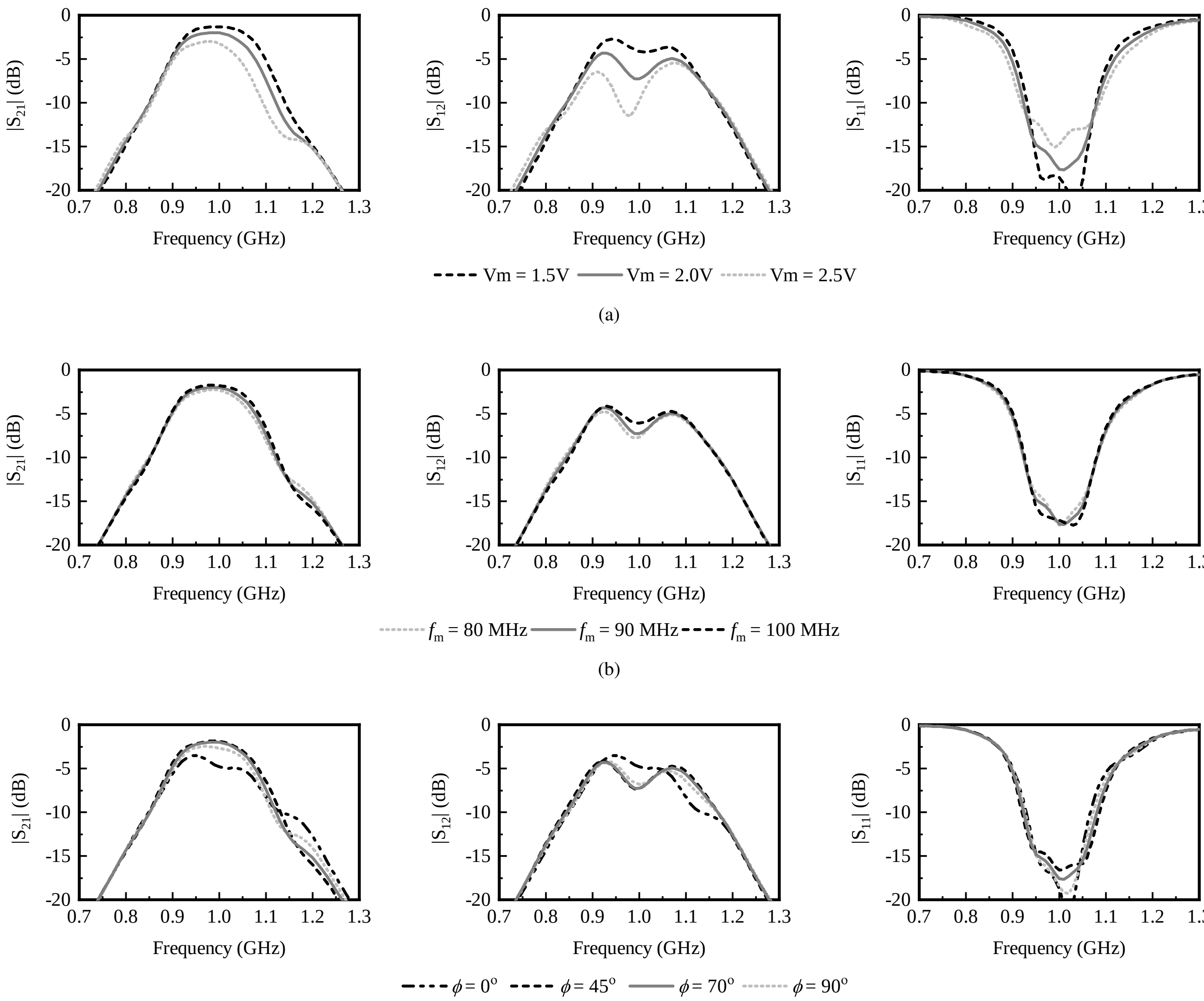
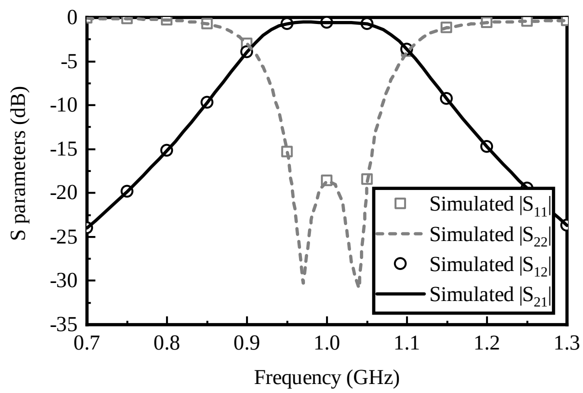


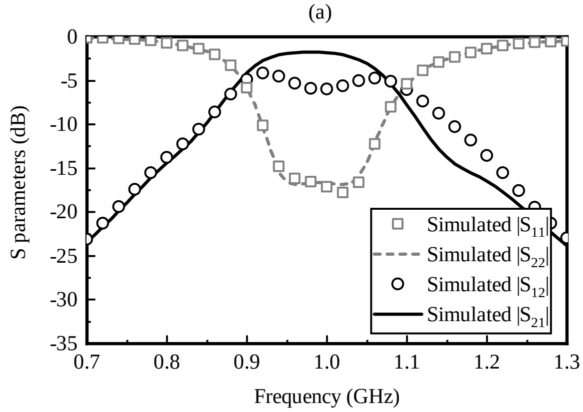
Fig. 2. Filter responses with varied modulation parameters ($g_f = 0.3\,\text{mm}$, $g_{12} = 1.14\,\text{mm}$, $w_f = 0.7\,\text{mm}$, $w_r = 1.0\,\text{mm}$, $L_f = 28.7\,\text{mm}$, $L_r = 32\,\text{mm}$, $R_{via} = 0.25\,\text{mm}$, $L_m = 68\,\text{nH}$, $C_m = 33\,\text{pF}$, and $V_{dc1} = V_{dc2} = 6\,\text{V}$.). (a) Varied sinusoidal wave magnitude V_m ($V_{m1} = V_{m2} = V_m$, $f_m = 90\,\text{MHz}$, and $\phi = 70°$). (b) Varied sinusoidal wave frequency f_m ($V_m = 2\,\text{V}$, $\phi = 70°$). (c) Varied sinusoidal wave phase shift ϕ ($V_m = 2\,\text{V}$, $f_m = 90\,\text{MHz}$).

inductors (L_1 and L_2), and time-varying capacitors ($C_1(t)$ and $C_2(t)$). The time-invariant inductors and time-varying capacitors constitute the parallel resonators, whose distributed implementation is given in Fig. 1 (b). Back-to-back varactors are loaded at the open-ends of the microstrip resonators. Positive dc voltages V_{dc1} and V_{dc2} are used to reverse-bias the varactors. Sinusoidal waves with frequency f_m and magnitude V_{m1}, V_{m2} are applied to modulate the varactor capacitance. According to the analysis in [12], when there is a phase shift ϕ between two modulation waves, non-reciprocity can be generated.

Fig. 2 shows the results of parametric studies of the presented circuit with varied modulation parameters. As seen in Fig. 2 (a), non-reciprocity between forward transmission $|S_{21}|$ and backward transmission $|S_{12}|$ increases as the modulation wave magnitude V_m varies from $1.5V$ to $2.5V$. However, the increased non-reciprocity is at the cost of increased forward transmission insertion loss. When the modulation frequency f_m varies from 80 MHz to 100 MHz, as seen from Fig. 2 (b), larger insertion loss of the forward transmission $|S_{21}|$ as well as larger attenuation of the backward transmission $|S_{12}|$ can be observed. Fig. 2 (c) is the circuit responses under different incremental phase ϕ. When the two modulation waves are in-phase, i.e., $\phi = 0$, forward transmission $|S_{21}|$ is the same with backward transmission $|S_{12}|$, i.e., the circuit is reciprocal. Due to the signal power converted to the inter-modulation frequencies [12], transmissions in both direction shows 5-dB insertion loss at the center frequency of 1.0 GHz. When ϕ is non-zero, e.g., 45°, 70°, and 90° in Fig. 2 (c), non-reciprocal transmission is generated between forward and backward transmissions. For all the studied cases in Fig. 1, good impedance matching can



(a)



(b)

Fig. 3. (a) Simulated reciprocal results without modulation. (b) Simulated non-reciprocal results with modulation.

be observed for all ports.

III. Experimental Validation

The microstrip filter is implemented on a 0.813-mm Rogers 4003C substrate with a relative permittivity of 3.55 and a loss tangent of 0.0029. Skyworks SMV1234 varactors are used in the design. The filter is designed and optimized in Keysight Advanced Design System (ADS) using the harmonic balance (HB) simulator. First, 2nd-order filter without modulation is designed based on the well-known filter design procedures [1]. Second, by applying sinusoidal waves at the modulation ports and fine tuning the modulation wave parameters according to the above analysis, non-reciprocal filter can be designed and realized. The optimized final dimensions of the designed filter are $g_f = 0.3\,\text{mm}$, $g_{12} = 1.14\,\text{mm}$, $w_f = 0.7\,\text{mm}$, $w_r = 1.0\,\text{mm}$, $L_f = 28.7\,\text{mm}$, $L_r = 32\,\text{mm}$, $R_{via} = 0.25\,\text{mm}$. Components: $L_m = 68\,\text{nH}$, and $C_m = 33\,\text{pF}$.

Fig. 3 (a) shows the simulated and measured results when varactors are only reverse-biased by dc voltages of 6.0 V. The responses are reciprocal with the passband located at 1.0 GHz. The simulated insertion loss at the center frequency is 0.65 dB and the 3-dB passband covers a frequency range of 0.91–1.1 GHz. When two sinusoidal waves with frequency 100 MHz and magnitude 2 V are applied at the modulation ports, the capacitance of the varactors is temporally modulated. By introducing modulation phase difference between the two waves ($\phi = 70°$), non-reciprocity can be achieved as seen in Fig. 3 (b). The simulated forward transmission $|S_{21}|$ has an insertion loss of 1.8 dB while the backward transmission $|S_{12}|$ is attenuated to -6.5 dB at 1.0 GHz, showing 4.7 dB non-reciprocity. The reflection at both ports is well bellow -15 dB no matter the modulations waves are applied or not.

IV. Conclusion

In this paper, we report a magnet-free microstrip non-reciprocal bandpass filter by using time-modulated quarter-wavelength resonators. Sinusoidal waves are applied to modulated the reverse-biased varactors to perform as time-varying capacitors. By properly adjusting the modulation parameters, magnitude non-reciprocity can be generated. The presented concept contributes to the development of novel magnet-free non-reciprocal devices.

References

[1] D. M. Pozar, *Microwave Engineering*. Wiley, 2012.

[2] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 375–386.

[3] A. Kord, D. L. Sounas, and A. Al, "Achieving full-duplex communication: Magnetless parametric circulators for full-duplex communication systems," *IEEE Microwave Magazine*, vol. 19, no. 1, pp. 84–90, Jan 2018.

[4] C. K. Seewald and J. R. Bray, "Ferrite-filled antisymmetrically biased rectangular waveguide isolator using magnetostatic surface wave modes," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 6, pp. 1493–1501, June 2010.

[5] J. Chang, J. Kao, Y. Lin, and H. Wang, "Design and analysis of 24-ghz active isolator and quasi-circulator," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 8, pp. 2638–2649, Aug 2015.

[6] M. M. Biedka, R. Zhu, Q. M. Xu, and Y. E. Wang, "Ultra-wide band non-reciprocity through sequentially-switched delay lines," *Scientific Reports*, vol. 7, p. 40014, Jan 2017.

[7] N. Reiskarimian and H. Krishnaswamy, "Magnetic-free non-reciprocity based on staggered commutation," *Nature Communications*, vol. 7, p. 11217, Apr 2016.

[8] R. Fleury, D. L. Sounas, C. F. Sieck, M. R. Haberman, and A. Alù, "Sound isolation and giant linear nonreciprocity in a compact acoustic circulator," *Science*, vol. 343, no. 6170, pp. 516–519, 2014.

[9] N. A. Estep, D. L. Sounas, J. Soric, and A. Al, "Magnetic-free non-reciprocity and isolation based on parametrically modulated coupled-resonator loops," *Nature Physics*, vol. 10, pp. 923–927, Dec 2014.

[10] N. A. Estep, D. L. Sounas, and A. Al, "Magnetless microwave circulators based on spatiotemporally modulated rings of coupled resonators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 2, pp. 502–518, Feb 2016.

[11] A. Kord, D. L. Sounas, and A. Al, "Pseudo-linear time-invariant magnetless circulators based on differential spatiotemporal modulation of resonant junctions," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 6, pp. 2731–2745, June 2018.

[12] X. Wu, X. Liu, M. D. Hickle, D. Peroulis, J. S. Gomez-Diaz, and A. A. Melcon, "Non-reciprocal bandpass filters using time-modulated resonators," *IEEE Transactions on Microwave Theory and Techniques*, vol. Submitted, October 2018.