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TUESDAY 24TH SEPTEMBER 16:10 – 17:50

	E04	E05	E06
	EuMC09 Integrated Non-reciprocal Devices and Circuits for System Applications Chair: Ke Wu[1] Co-Chair: Tân-Phu Vuong[2] [1]Polytechnique Montreal, [2]IMEP-LAHC Grenoble	**EuMC10** Advanced Filter Synthesis and Design Methodologies Chair: Eric Rius[1] Co-Chair: Michael Höft[2] [1]Université de Brest, [2]Christian-Albrechts-Universität zu Kiel	**EuMC11** Innovative and 3D Printed Passive Components and Filters Chair: Simone Bastioli[1] Co-Chair: Giuseppe Macchiarella[2] [1]RS Microwave Company Inc, [2]Politecnico di Milano
16:10 – 16:30	**EuMC09-1** Operational Aggregation of Dual-Mode Circulator and Dual-Polarization Antenna with Built-in Tunable Self-Interference Cancellation for Full-Duplex Amir Afshani[1], Ke Wu[2] [1]Ecole Polytechnique de Montreal, [2]Polytechnique Univrsity	**EuMC10-1** Improved Section Extraction Technique for Fully-Canonical Cascade Synthesis of Filters Matteo Oldoni[1], Stefano Tamiazzo[2], Giuseppe Macchiarella[1], Gian Guido Gentili[1], Steven Caicedo Mejillones[3] [1]Politecnico di Milano, [2]COMMSCOPE, [3]SIAE Microelettronica S.p.A.	**EuMC11-1** K-Band Waveguide Terminator Suitable for Additive Manufacturing Technology and its Applications Yu Ushijima[1], Hidenori Yukawa[1], Toru Takahashi[1], Naofumi Yoneda[1] [1]Mitsubishi Electric Corporation
16:30 – 16:50	**EuMC09-2** A Reconfigurable Multiband Filtering Isolator Using Multimode Time-Modulated Resonators yuhang ning[1], Zhihua Wei[1], Pei-Ling Chi[2], Tao Yang[1] [1]University of Electronic Science and Technology of China, Chengdu, China, [2]National Yang Ming Chiao Tung University	**EuMC10-2** Direct Synthesis of Wideband Reactive Bandstop Filter using the Coupling Matrix Mario Faura[1], Carlos Caballero[1], Jordi Verdú[1], Pedro de Paco[1] [1]Universitat Autònoma de Barcelona	**EuMC11-2** Fully 3D-Printed Filter Based on Helical Resonators with Elliptical Line Cross-Section Paolo Vallerotonda[1], Luca Pelliccia[1] [1]RF Microtech s.r.l
16:50 – 17:10	**EuMC09-3** Multi-Functional Filtering Power Divider with Tunable Center Frequency and Isolator Functionality Girdhari Chaudhary[1], Palaystint Thorng[1], Phanam Pech[1], Yongchae Jeong[1] [1]Jeonbuk National University, South Korea	**EuMC10-3** An alternative Design Approach for the Design of Wideband Band-pass Filters Based on Cascaded Building Blocks Photos Vryonides[1], Adnan Nadeem[1], Symeon Nikolaou[1], Dimitra Psychogiou[2] [1]Frederick Research Center, Cyprus , Dept. of Electrical and Computer Engineering and Informatics, Frederick University, Cyprus, [2]School of Engineering, University College Cork, Cork, T12 K8AF, Ireland , Tyndall National Institute, Cork, T12 R5CP, Ireland	**EuMC11-3** A Compact Low Passive Intermodulation Band-pass Filter using Folded Groove Gap Waveguide xiang chen[1] [1]China Academy of Space Technology(Xi'an)
17:10 – 17:30	**EuMC09-4** SMD Compatible Ku-Band LTCC Circulators Norbert Parker-Soues[1], Camilla Kärnfelt[2], Richard Lebourgeois[3], Vincent Laur[4], Laurent Roussel[5] [1]Lab-STICC-Université de Bretagne Occidentale, [2]Lab-STICC, IMT-Atlantique, Brest, France, [3]Thales Research and Technology France, 91767 Palaiseau, France, [4]Univ Brest, Lab-STICC, CNRS, UMR 6285, [5]THALES LAS, Elancourt, France	**EuMC10-4** Miniaturized Ka-Band Metasurface Filter With Wide Out-of-Band Rejection up to the 5th Harmonic Arash Arsanjani[1], Arezoo Abdi[1], Ziad Hatab[1], Ahmad Bader Alothman Alterkawi[2], Michael Ernst Gadringer[1], Wolfgang Bösch[1] [1]Graz University of Technology, [2]AT&S AG	**EuMC11-4** Design of Double-Ridge-Waveguide Twists for Ultra-Wideband Application Peng Liu[1], Jia-Lin Li[2], Zhipeng Li[3], Wen-Jie Li[3] [1]Institute of Electronic Engineering of CAEP/School of Resources and Environment, UESTC, [2]School of Resources and Environment, UESTC, [3]Institute of Electronic Engineering of CAEP
17:30 – 17:50	**EuMC09-5** Planar Isolator Based on Field Displacement in Ferrite Substrate Sokha Khim[1], Jehison Leon-Valdes[1], Hervé Parvery[2], Laure Huitema[1], Thierry Monédière[1] [1]University of Limoges/CNRS, XLIM UMR7252, [2]CISTEME, FR		**EuMC11-5** Wideband Double-Ridge Waveguide-Coaxial Adaptor Gian Marco Zampa[1], Marco Farina[1], Lino Russo[2], Giandomenico Amendola[3], Oilid Bouzekri[4], Antonio Morini[1] [1]Università Politecnica delle Marche, [2]ST4I Srl, [3]Università della Calabria, [4]ESA-ESTEC

Multi-Functional Filtering Power Divider with Tunable Center Frequency and Isolator Functionality

Girdhari Chaudhary[#], Palaystint Thorng[$], Phanam Pech[$], Yongchae Jeong[#$]
[#]JIANT-IT Human Resource Development Center, Jeonbuk National University, South Korea
[$]Division of Electronic Engineering, Jeonbuk National University, South Korea
girdharic@jbnu.ac.kr, ycjeong@jbnu.ac.kr

***Abstract* —This paper introduces novel co-design approach of multi-functional power divider with tunable center frequency and non-reciprocal behavior ($|S_{21}| = |S_{31}| \approx 1/\sqrt{2}$ and $|S_{12}| = |S_{13}| \approx 0$) by employing spatio-temporal modulation technique. The nonreciprocal response is achieved by modulating its constituent resonators with progressive phase shift a sinusoidal signal. Through parametric numerical simulations, this paper establishes empirical relationships between modulation parameters and design specifications of the proposed non-reciprocal filtering power divider. To validate the proposed method, a non-reciprocal filtering power divider with tunable center was designed and fabricated. Measurement results demonstrate the effectiveness of the proposed approach, showing that passband center frequency is tuned from 1.67 GHz to 1.96 GHz while maintaining forward transmission insertion loss less than 4.8 dB and reverse isolation higher than 20 dB within passband.**

***Keywords*— Isolator, multi-functional filtering power divider, non-reciprocal, time-modulated resonators, varactor diode.**

I. INTRODUCTION

The demand for multi-functional microwave/millimeter wave circuits is escalating, driven by the need for RF front ends that accommodate the emerging wireless applications. Power dividers/combiners are key components for wireless communication systems; however, conventional power divider/combiners are reciprocal ($|S_{21}| = |S_{12}|$ and $|S_{31}| = |S_{13}|$) in nature. To address this limitation, integrating functions of tunable bandpass filter, power divider and isolator into single circuit is one emerging approach to facilitate the development of multi-functional miniaturized RF front-end chains for next generation wireless networks. Non-reciprocal components (such as circulator and isolator) play crucial roles in communication systems, radar, and instrumentation systems by mitigating self-interference between transmitting and receiving signals in full duplex (FD) systems and safeguarding RF front-ends from unwanted reflections [1]. However, conventional non-reciprocal components are mainly designed using ferrite magnetic material [2], which is bulky, expensive, and not compatible with integrated circuit (IC) design.

Spatio-temporal modulation (STM) has been demonstrated as an alternative effective approach to achieve non-magnetic non-reciprocity. Non-magnetic non-reciprocal bandpass filter that allows transmission of signal in only direction ($|S_{21}| \neq |S_{12}|$) have been demonstrated either in the lumped-element or microstrip-type configurations by STM technique [3], [4], [5].

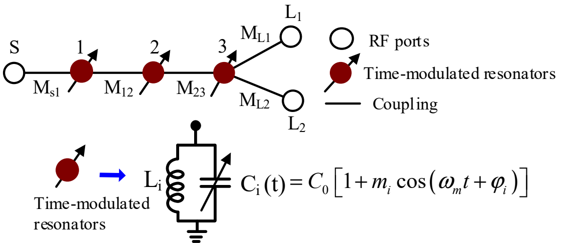


Fig. 1. Coupling diagram of proposed multi-functional non-reciprocal power divider with tunable frequency and isolator functionality.

In recent years, STM concept has been extended to design non-reciprocal power divider ($|S_{21}| \neq |S_{12}|$ and $|S_{31}| \neq |S_{13}|$) by employing combination of static and time-modulated resonators [6]. However, in this structure, tunability of passband frequency is not feasible. In [7], a non-reciprocal power divider with tunable frequency is presented. Nevertheless, this structure requires a large number of time-modulated resonators, thereby increasing the complexity of modulation signal circuit.

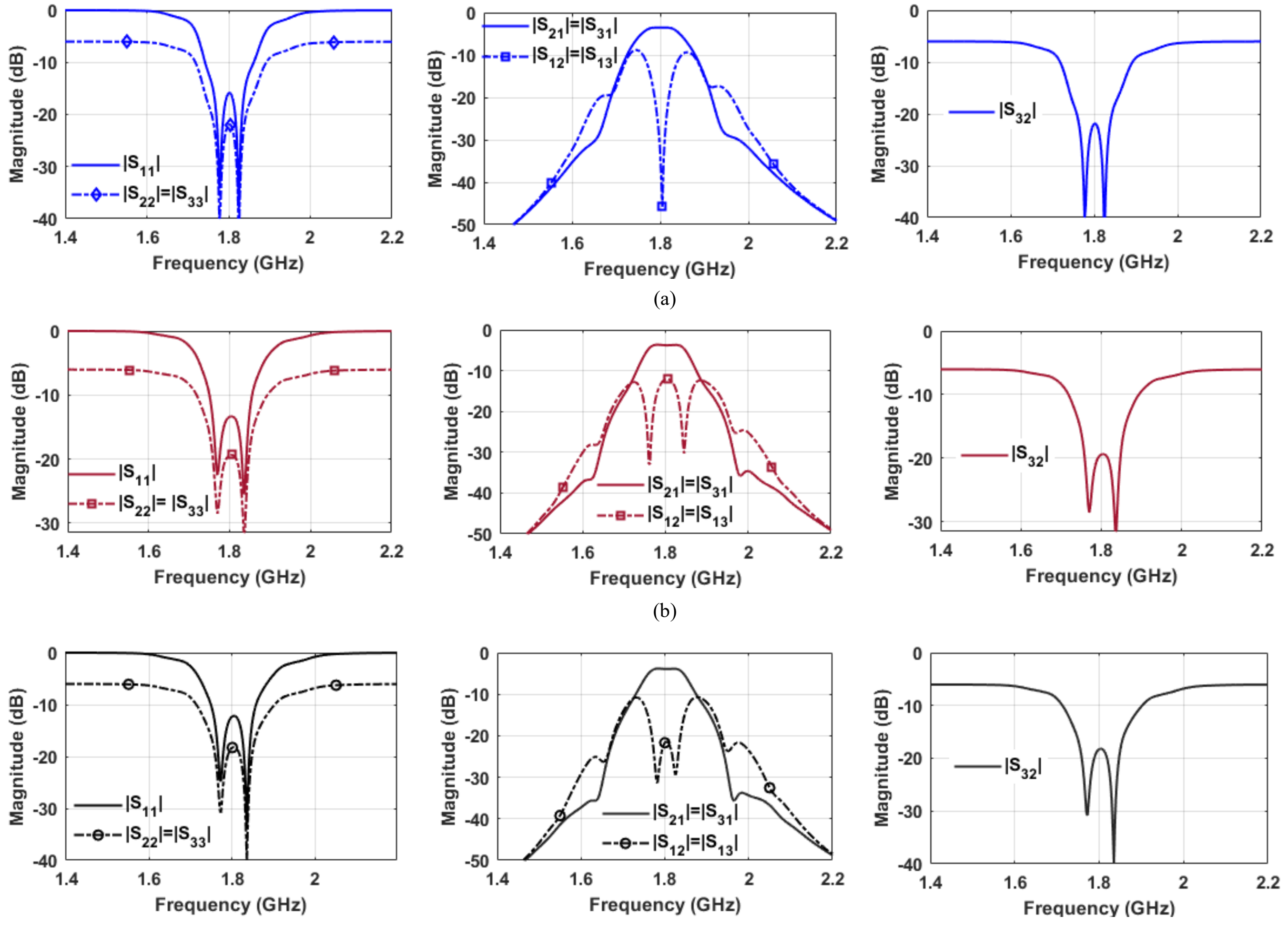
This paper presents novel approach to realize multi-functional non-reciprocal filtering power divider with tunable frequency and isolator functionalities, utilizing only three time-modulated resonators. For proof-of-concept, a microstrip line non-reciprocal power divider is designed and fabricated. Non-reciprocity is achieved by employing progressive phase shift sinusoidal modulation to varactor diode through bias transmission line (TL).

II. DESIGN THEORY

Fig. 1 depicts the coupling diagram of the proposed multi-functional non-reciprocal filtering power divider with tunable center frequency. The proposed non-reciprocal filtering power divider consists of RF input port (S), three modulated resonators, power dividing non-resonating nodes, and two output ports (L_1 and L_2). To achieve a nonreciprocal response, the capacitor of each resonator undergoes modulation with a progressive phase shift sinusoidal signal [4] as follows:

$$C(t) = C_0\left[1 + m\cos\{\omega_m t + \varphi_i\}\right],\ \varphi_i = (i-1)\Delta\varphi,\ i = 1,2,3 \qquad (1)$$

where $\omega_m = 2\pi f_m$, $\Delta\varphi$, and m are angular modulation frequency, phase shift, and the modulation index, respectively. Likewise, C_0 is the nominal capacitance. In absence of modulation signal (i.e. static state), the circuit operates as reciprocal filtering power divider where input signal at port 1 is divided into port 2 and 3 (*i.e.* $|S_{21}| = |S_{12}| = 1/\sqrt{2}$ and $|S_{31}| = |S_{13}| = 1/\sqrt{2}$).



(a)

(b)

(c)

Fig. 2. Numerically calculated S-parameters of the proposed non-reciprocal filtering power divider with f_0 = 1.8 GHz, BW_{static}= 100 MHz : (a) f_m = 0.8× BW_{static}, $m = 1.44 \times BW_{static}/f_0$, $\Delta\varphi = 65^o$, (b) $f_m = 1.10 \times BW_{static}$, $m = 1.65 \times BW_{static}/f_0$, $\Delta\varphi = 65^o$ and (c) $f_m = BW_{static}$, $m = 1.8 \times BW_{static}/f_0$, $\Delta\varphi = 70^o$. Coupling matrix is given as: M_{s1} = 1.04, M_{12} = 0.9298, M_{23} = 0.8944, $M_{L1} = M_{L2}$ = 0.7071.

When a modulation signal is applied, the time-modulated resonator generates intermodulation (IM) products due to mixing of RF and modulation signals, which allow transmission with different distinct transmission phases. For simplicity, considering only two nonlinear harmonics, the spectral admittance matrix of time-modulated resonator [7] is given in (2).

$$\lambda_i = \begin{bmatrix} \Omega_{-2} & \frac{x_{-2}m}{2\omega_0\Delta}e^{-j\varphi_i} & 0 & 0 & 0 \\ \frac{x_{-1}m}{2\omega_0\Delta}e^{j\varphi_i} & \Omega_{-1} & \frac{x_{-1}m}{2\omega_0\Delta}e^{-j\varphi_i} & 0 & 0 \\ 0 & \frac{x_0 m}{2\omega_0\Delta}e^{j\varphi_i} & \Omega_0 & \frac{x_0 m}{2\omega_0\Delta}e^{-j\varphi_i} & 0 \\ 0 & 0 & \frac{x_{+1}m}{2\omega_0\Delta}e^{j\varphi_i} & \Omega_{+1} & \frac{x_{+1}m}{2\omega_0\Delta}e^{-j\varphi_i} \\ 0 & 0 & 0 & \frac{x_{+2}m}{2\omega_0\Delta}e^{j\varphi_i} & \Omega_{+2} \end{bmatrix} \tag{2}$$

where

$$\Omega_n = \frac{\omega_0}{\Delta}\left(\frac{x_n}{\omega_0} - \frac{\omega_0}{x_n}\right), \tag{3a}$$

$$x_n = \omega + n\omega_m,\ n = -2,-1,0,1,2 \tag{3b}$$

Similarly, $\Delta = BW_{static}$ and ω_0 are the bandwidth and the center angular frequency of filtering power divider as static state (without modulation).

The phase difference (*i.e.* $\varphi_i = (i-1)\Delta, i = 1,2,3$) is the key mechanism that enables non-reciprocal response. When RF signal at operating frequency ω_0 is applied to input port (S), IM products are generated at $\omega_0 \pm k\omega_m$ (where $k = \cdots, -2, -1, 0, +1, +2, \cdots$) with distinct phase delays, resulting from interaction of RF and modulation signals through time-modulated resonators [7]. After traveling through subsequent time-modulated resonator, the existing IM products undergo a second and third time mixing with modulation signal. The power divider can be designed in such a way that the powers of IM products can be added in phase during forward propagation at output ports (L_1 and L_2), while the powers of IM products at input port (S) can be added 180° out of phase during reverse propagation. With appropriate selection of modulation parameters, the powers of IM products can be constructively (0° in phase) combined at the RF carrier frequency, resulting minimum transmission loss (*i.e.* $|S_{21}| = |S_{31}| \approx 1/\sqrt{2}$). Conversely, the powers of IM products

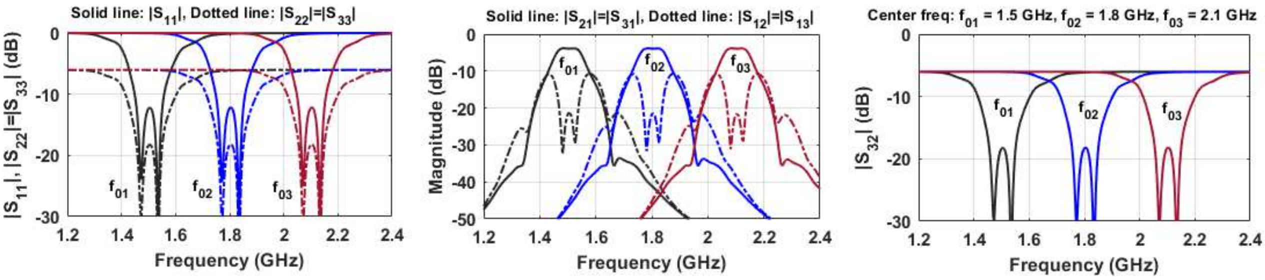
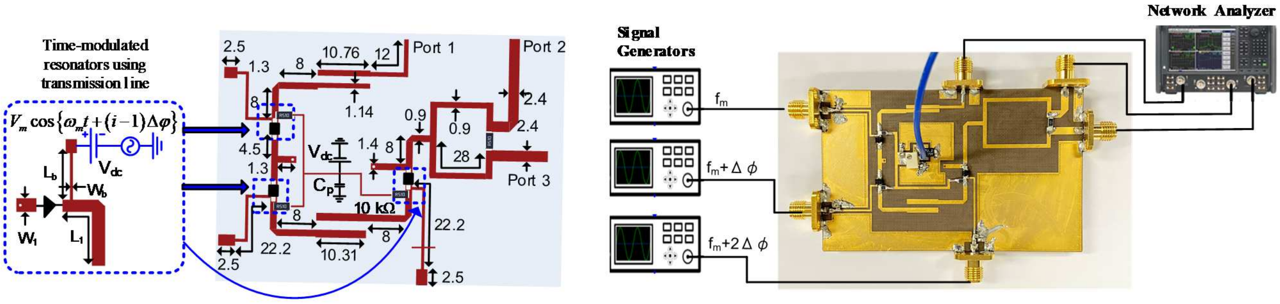


Fig. 3. Numerically calculated S-parameters of the proposed non-reciprocal power divider with tunable passband frequency and BW_{static} = 100 MHz. Modulation parameters : $f_m = BW_{static} = 100$ MHz, $m = 1.8 \times BW_{static}/f_{0i}$, $\Delta\varphi = 65^o$. Coupling matrix : M_{s1} = 1.04, M_{12} = 0.9298, M_{23} = 0.8944, $M_{L1} = M_{L2}$ = 0.7071 and $f_{0i} = f_{01}$ = 1.5 GHz, f_{02} = 1.8 GHz, and f_{03} = 2.10 GHz.



(a)

(b)

Fig. 4. (a) Microstrip line implementaiton of the proposed non-reciprocal power divider with physical dimensions (b) photogrpah of fabricated non-reciprocal power divider with experimental setup.

are added up destructively (180° out of phase) in the reverse direction to create high isolation (*i.e.* $|S_{12}| = |S_{13}| \approx 0$). The coupling matrix values (M_{S1}, M_{12}, M_{23}, M_{L1} and M_{L2}) can be synthesized with Chebyshev or Butterworth response at static state (without modulation). To improve the isolation ($|S_{23}|$) between the output ports, a 100 Ω resistor needs to be connected.

A. Modulation parameters

Numerical parametric simulations are conducted to determine optimum modulation parameters (f_m, m, $\Delta\varphi$), and results are depicted in Fig. 2 for various modulation frequency and modulation indices. The power divider is designed at center frequency (f_0) of 1.80 GHz and bandwidth of 100 MHz at static state (without modulation). The coupling matrix values are synthesized using the Chebyshev response with an equiripple of 0.043 dB at passband of the static state. As observed from figures, the proposed power divider provides filter response with the low transmission insertion loss (IL) in the forward direction of propagation, while demonstrating isolator functionality in the backward direction. When the modulation frequency f_m is less than BW_{static}, high reverse isolation (IX) with a single null can be achieved at center frequency as shown in Fig. 2(a). Conversely, when f_m exceeds $\mathrm{BW_{static}}$, reverse IX with wider bandwidth and two nulls can be achieved in the backward direction of propagation as shown in Fig. 2(b), however, reverse IX at f_0 is only 12 dB. When f_m is nearly equal to BW_{static}, the power divider can provide low transmission IL (IL < 0.6 dB) and high reverse IX (IX > 22 dB at f_0) with two nulls in the backward direction of propagation as shown in Fig. 2(c). Given the lossless nature of circuit, the IL in forward direction mainly arises from power conversion to IM products, which is not entirely converted to back to the fundamental frequency. Based on these results, it can be inferred that forward transmission IL < 0.6 dB (excluding inherent 3 dB power division), input return loss (RL) > 12 dB, and IX ($|S_{12}| = |S_{13}|$) > 22.2 dB within the passband can be achieved if modulation parameters are selected as follows:

$$f_m = BW_{static}, \quad m = \frac{1.8 \times BW_{static}}{f_0}, \quad 65^o \le \Delta\varphi \le 70^o \tag{4}$$

B. Frequency Tunability

The frequency tunable response of non-reciprocal power divider can be obtained by adjusting resonant frequency of time-modulated resonators. Fig. 3 demonstrated the numerically calculated frequency response of non-reciprocal power divider, showing its frequency tunable characteristics. The modulation parameters are selected using (4). As observed from the figure, frequency of non-reciprocal power divider can be tuned continuously from 1.5 GHz to 2.1 GHz while maintaining forward IL < 0.6 dB (excluding 3 dB power division), input RL > 12 dB and reverse IX > 22 dB within the passband.

III. EXPERIMENTAL RESULTS

To experimentally validate the proposed structure, a non-reciprocal filtering power divider with equal power division ratio was designed and fabricated on a Taconic substrate with a dielectric constant of 2.2 and a thickness of 0.787 mm. The objective was to achieve revers IX > 20 dB and low transmission loss while continuously tuning frequency from

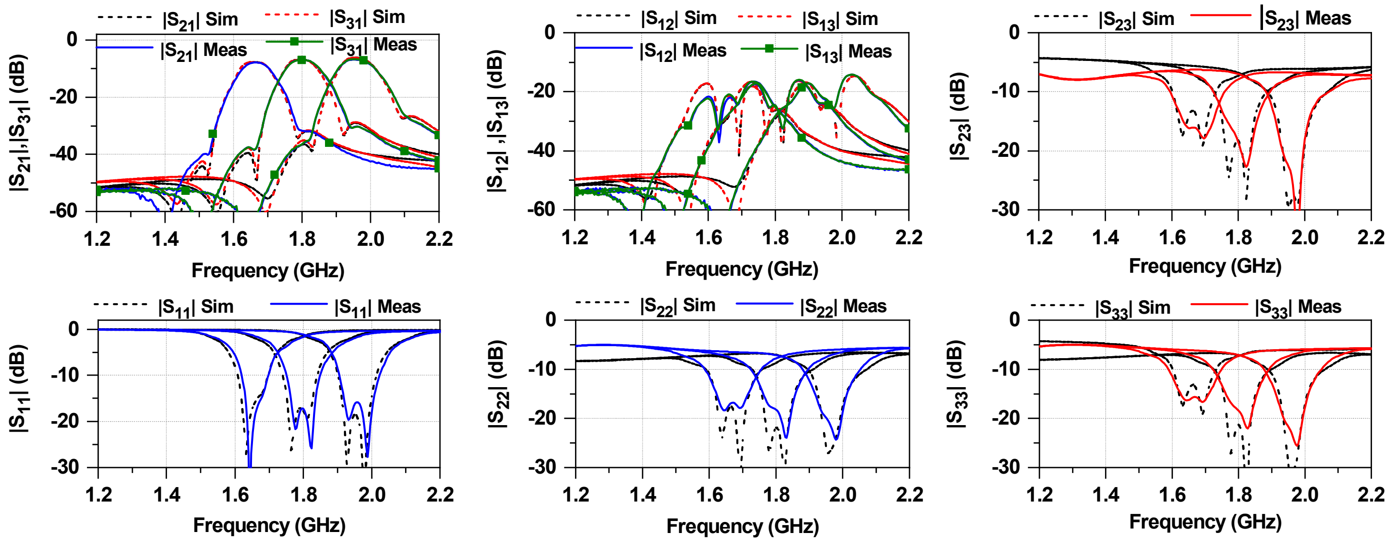


Fig. 5. Simulated and measured results of fabricated multi-functional non-reciprocal power divider with tunable passband frequency and isolator functionality.

1.60 GHz to 2 GHz and desired bandwidth of BW$_{static}$ = 90 MHz.

Fig. 4(a) depicts the microstrip line implementation of the proposed non-reciprocal power divider. The time-modulated resonators are realized using TL terminated with varactor diode SMV1233-076LF from Skyworks. The coupling M_{s1} between input RF port and first resonator is implemented through series TL and coupled line. The coupling M_{12} between resonators 1 and 2 is implemented using short-circuited stub. Likewise, the coupling M_{23} between resonators 2 and 3 is implemented with coupled line. The progressive phase shift sinusoidal modulation signals are applied through bias TL. The coupling between resonator 3 and output ports (L_1 and L_2) is implemented using quarter-wavelength TL. Fig. 4(b) shows the photograph of fabricated non-reciprocal power divider along with measurement setup.

Fig. 5 shows both simulation and measurement results of the proposed non-reciprocal power divider. The non-reciprocal response is achieved by applying f_m = 85 MHz, V_m = 2.4 v and $\Delta\varphi = 65^\circ$. The measurement results are well agreed with simulation results. As depicted in the figure, frequency is continuously tuned from 1.67 GHz to 1.96 GHz by adjusting the bias voltage of varactor diodes. The forward IL varies from 3.90 dB to 5.10 dB (excluding inherent 3 dB power division), while maintaining input RL and output RLs higher than 16 dB and 15.5 dB, respectively, and reverse IX higher than 20 dB within the passband. The isolation between output ports ($|S_{23}|$) is higher than 15.2 dB at f_0. The forward IL degrades when frequency is tuned toward a lower value. As the dc-bias voltage is changed to lower value, parasitic resistance of varactor diode increases. The degradation of IL is mainly due to parasitic series resistance of the varactor diode.

IV. CONCLUSION

In this paper, multi-functional filtering power divider with tunable frequency and isolator functionalities is demonstrated employing time-modulated resonators. The proposed divider integrates functions of tunable bandpass filter, power divider and isolator within single circuit. For experimental validation, microstrip line non-reciprocal power divider is designed and fabricated. The measurement results are well agreed with simulations, affirming the effectiveness of the proposed design approach.

ACKNOWLEDGMENT

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