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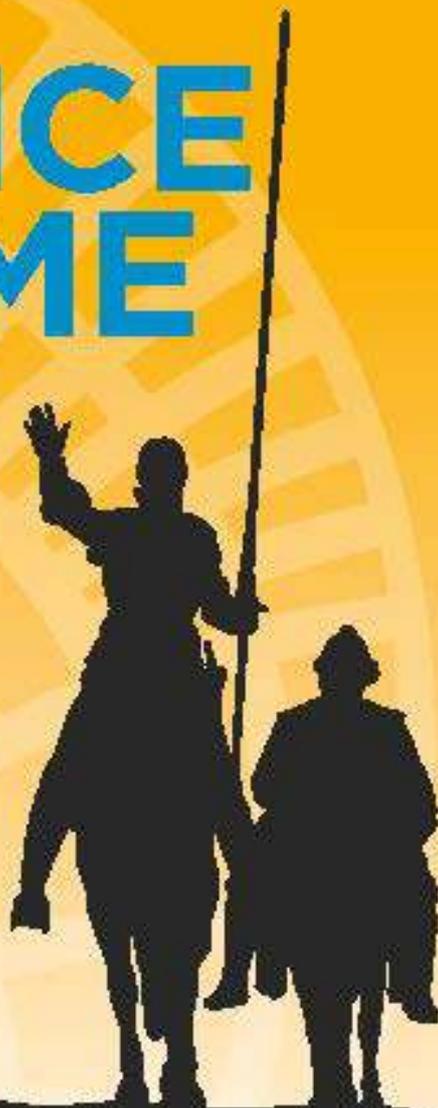www.eumweek.com

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	N101 + N102	**N105**	**N109 + N110**	**N115**
	EuMC01 **Power Amplifier Architectures for High Efficiency and Linearity** Chair: Georg Fischer[1] Co-Chair: Paolo Colantonio[2] [1]FAU Erlangen-Nuremberg, [2]University of Roma tor Vergata	**EuMC02** **Measurement Systems** Chair: Ilona Rolfes[1] Co-Chair: Bianca Will[2] [1]Ruhr-University Bochum, [2]FH Südwestfalen	**EuMC03** **Couplers and Dividers** Chair: Anthony Ghiotto[1] Co-Chair: Roberto Sorrentino[2] [1] University of Bordeaux, Bordeaux INP, UMR CNRS 5218, IMS Laboratory, [2]RF Microtech Srl	**EuMC04** **Metamaterials and Periodic Structures** Chair: Ferran Martín[1] Co-Chair: Dmitry Kholodnyak[2] [1]Universitat Autonoma de Barcelona, [2]St. Petersburg Electrotechnical University "LETI"

Time				
08:30 – 08:50	**EuMC01-1** **A High-Efficiency GaN Transistor Module With Thick-Film BST-Based Tunable Matching Network** Sebastian Preis[1], Alex Wiens[2], Enrico Lia[3], Wolfgang Heinrich[1], Rolf Jakoby[2], Holger Maune[2], Olof Bengtsson[1] [1]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, [2]Technische Universitaet Darmstadt, [3]European Space Agency	**EuMC02-1** **Impact of On-Silicon De-Embedding Test Structures and RF Probes Design in the Sub-THz Range** Chandan Yadav[1], Marina Deng[1], Sebastien Fregonese[1], Magali De Matos[1], Bernard Plano[1], Thomas Zimmer[1] [1]University of Bordeaux, IMS laboratory	**EuMC03-1** **Compact Tunable Wilkinson Power Divider With Simple Structure** Xiaolong Wang[1,2], Zhewang Ma[1], Masataka Ohira[1], Chun-Ping Chen[3], Tetsuo Anada[3] [1]Saitama University, [2]Jilin University, [3]Kanagawa University	**EuMC04-1** **Three-Dimensional Frequency Selective Surface With Multiple Transmission Zeros for Wide Stopband** Jianping Zhu[1], Zhengyong Yu[1], Wanchun Tang[2] [1]Nanjing University of Science and Technology, [2]Nanjing Normal University
08:50 – 09:10	**EuMC01-2** **Dynamic Load Modulated Low-Voltage GaN PA Using Novel Low-Loss GaN Varactors** Raul Amirpour[1], Sebastian Krause[1], Rüdiger Quay[1] [1]Fraunhofer Institute for Applied Solid State Physics IAF	**EuMC02-2** **On-Wafer Broadband Microwave Measurement of High impedance Devices - CPW Test Structures with Integrated Metallic Nano-Resistances** Khadim Daffe[1], Faisal Mubarak[2], Vincenzo Mascolo[3], H. Votsi[3], Nick Ridler[4], Isabelle Roch[1], Gilles Dambrine[1], Kamel Haddad[1] [1]Univ. Lille - IEMN, [2]VSL, [3]Advanced Technology Institute, University of Surrey, [4]NPL	**EuMC03-2** **Liquid Crystal Based Tunable Reflection-Type Power Divider** Matthias Nickel[1], Mario Mueh[1], Roland Reese[1], Ersin Polat[1], Matthias Jost[1], Rolf Jakoby[1], Holger Maune[1] [1]TU Darmstadt	**EuMC04-2** **Theoretical Minimum of Phase Shift Error of Switchable-channel Phase Shifters on Left-handed and Right-handed Transmission Lines** Dmitry Kholodnyak[1] [1]St. Petersburg Electrotechnical University "LETI"
09:10 – 09:30	**EuMC01-3** **Band-limited Digital Predistortion with Band-switching Feedback Architecture for 5G mmWave Power Amplifiers** Soubhik Deb[1], Tanio Masaaki[1], Shinichi Hori[1], Noriaki Tawa[1], Yasushi Wada[1], Kazuaki Kunihiro[1] [1]NEC Corporation	**EuMC02-3** **A Unified, Wave-Based Calibration framework for Vector Network Analyzers** Yves Rolain[1], Indy Magnus[1], Gerd Vandersteen[1] [1]vUB	**EuMC03-3** **High Performance 3dB Coupler (Hybrid) with Broadband Flat Amplitude Characteristics** Uwe Rosenberg[1], Petronilo Martin-Iglesias[2] [1]Mician Global Engineering GbR, [2]ESA / ESTEC	**EuMC04-3** **Slow-Wave Artificial Transmission Lines Based on Stepped Impedance Shunt Stub (SISS) Loading: Analysis and Stopband Bandwidth Enhancement** Jan Coromina[1], Jordi Selga[1], Paris Vélez[1], Jordi Bonache[1], Ferran Martín[1] [1]Universitat Autònoma de Barcelona
09:30 – 09:50	**EuMC01-4** **Novel DC-Biasing Circuits with Arbitrary Harmonic-Control Capability for Compact High-Efficiency Power Amplifiers** Shinichi Tanaka[1], Tomoya Oda[1], Kento Saiki[1] [1]Shibaura Institute of Technology	**EuMC02-4** **Nonlinear Three-Port Characterization of a Class-G Supply Modulated RF Power Amplifier using a Nonlinear Vector Network Analyzer** Felice Francesco Tafuri[1,2], Troels Studsgaard Nielsen[2], Nikolai Wolff[3], Ole Kiel Jensen[1], Jan Hvolgaard Mikkelsen[1], Olof Bengtsson[3] [1]Aalborg University, [2]Keysight Technologies, [3]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik	**EuMC03-4** **Design of a SIW Based Hybrid Ring Coupler with Arbitrary Power Splitting Ratio Using Gaussian Process Regression** Karthik Thothathri Chandrasekaran[1,2], Arokiaswami Alphones[1], Muhammad Faeyz Karim[1] [1]Nanyang Technological University	**EuMC04-4** **A Microfluidic-based Reflective-type 1-bit Terahertz Digital Metamaterial** Fangjing Hu[1], Peiyi Song[1], Huafeng Liu[1], Liangcheng Tu[1] [1]Huazhong University of Science and Technology
09:50 – 10:10	**EuMC01-5** **Practical Load Compensation Networks in Chireix Outphasing Amplifiers Using Offset Transmission Lines** Aleksander Bogusz[1], Jonathan Lees[1], Roberto Quaglia[1], Gavin Watkins[2], Steve Cripps[1] [1]Cardiff University, [2]Toshiba Research Europe Ltd.	**EuMC02-5** **On Wafer Millimetre Wave Power Detection Using a PN Junction Diode in BiCMOS 55 nm for In-Situ Large Signal Characterization** Joao Carlos Azevedo Goncalves[1], Issa Alaji[2], Daniel Gloria[1], Vincent Gidel[1], Frederic Gianesello[1], Sylvie Lepilliet[2], Guillaume Ducournau[2], François Danneville[2], Christophe Gaquiere[2] [1]STMicroelectronics, [2]IEMN	**EuMC03-5** **Arbitrary Terminated Coupler With Tunable Negative and Positive Group Delay Responses** Girdhari Chaudhary[1], Phanam Pech[1], Phirun Kim[1], Yongchae Jeong[1] [1]Chonbuk National University	**EuMC04-5** **Practical Design of a Band-Pass Filter Using EBG SIW technology** David López Navarro[1], Ángela Coves Soler[1], Enrique Bronchalo[1], Germán Torregrosa-Penalva[1], Maurizio Bozzi[2] [1]Universidad Miguel Hernández de Elche (UMH), [2]University of Pavia

Arbitrary Terminated Coupler With Tunable Negative and Positive Group Delay Responses

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Abstract — This paper presents a design of arbitrarily terminated coupler with tunable negative group delay (NGD) response and power division ratio. The proposed coupler provides tunable NGD through port 3 and 1 whereas positive group delay (PGD) through port 2 and 1. The analytical analysis shows that the power division ratio and NGD are controlled by a junction resistance of parasitic compensated PIN diode. Perfect matching and infinite isolation are obtained at the center frequency (f_0). The proposed coupler is validated by fabricating circuit at f_0 = 2.14 GHz. Measurement results are well agreed with simulated and predicted results. The experimental results show that NGD is varied from -0.2 to -1.3 ns with NGD fractional bandwidth (bandwidth of GD < 0) of 21.14 % to 15.88%.

Keywords — Arbitrarily terminated coupler, parasitic compensated PIN diode, positive group delay, tunable wideband negative group delay.

I. INTRODUCTION

Power dividers are basic building components of microwave circuits and systems and have been extensively studied over the past decades [1]-[2]. Because the group delay (GD) can influences the performances of RF/electronic circuits and systems, understanding GD effect of power divider in RF/electronics systems has become critical for communication systems. A RF predistortion method is one of the low-cost linearization techniques [3]. To improve the linearity, the GDs, magnitudes, and phases of two path signals should be matched in the predistorter. Therefore, the research that can demonstrate power divider/combiner with the negative group delay (NGD) will be beneficial in such systems to compensate the positive group delay (PGD) and help to enhance linearity performance as well as elimination of additional GD element and attenuator circuits. In [4]-[7], power dividers with NGD are presented, however, these works are limited to fixed termination impedance, NGD, and narrow NGD bandwidth.

This paper demonstrates a design of novel coupler with four independently arbitrary terminated impedances, tunable NGD and unequal power division ratio. Both analytical and experimental results have been provided. The proposed coupler offers several functions including impedance transformation capability of four termination impedances, tunable NGD and PGD with wide bandwidth and high level of matchings.
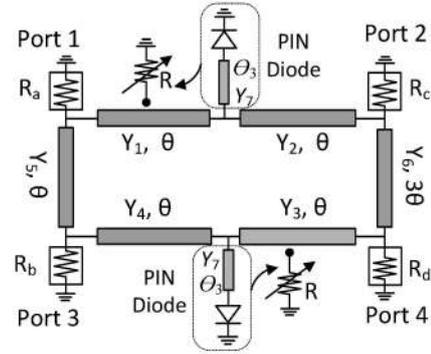

Fig. 1 Proposed structure of arbitrarily terminated coupler with tunable negative group delay response.

II. ANALYTICAL ANALYSIS

The schematic of the proposed arbitrary terminated coupler is shown in Fig. 1 which consists of horizontal transmission lines (TLs) with the characteristic admittance of Y_1, Y_2, Y_3, Y_4 and same electrical length θ and vertical TLs with characteristics impedance of Y_5, Y_6 and the electrical length of θ and 3θ respectively. Letting R be the effective resistance of TL terminated with PIN diode terminated where characteristic admittance and the electrical length of TL are Y_7 and θ_3, the Y-parameters of the structure shown in Fig. 1 can be found as (1)

$$Y_{11} = -jY_5 \cot\theta + \frac{Y_1\left(1/R - jY_2\cot\theta + jY_1\tan\theta\right)}{Y_1 + j\left(1/R - jY_2\cot\theta\right)\tan\theta} \quad (1a)$$

$$Y_{22} = -jY_6 \cot 3\theta + \frac{Y_2\left(1/R - jY_1\cot\theta + jY_2\tan\theta\right)}{Y_2 + j\left(1/R - jY_1\cot\theta\right)\tan\theta} \quad (1b)$$

$$Y_{33} = -jY_5 \cot\theta + \frac{Y_4\left(1/R - jY_3\cot\theta + jY_4\tan\theta\right)}{Y_4 + j\left(1/R - jY_3\cot\theta\right)\tan\theta} \quad (1c)$$

$$Y_{44} = -jY_6 \cot 3\theta + \frac{Y_3\left(1/R - jY_4\cot\theta + jY_3\tan\theta\right)}{Y_3 + j\left(1/R - jY_4\cot\theta\right)\tan\theta} \quad (1d)$$

$$Y_{12} = Y_{21} = \frac{Y_1 Y_2 \csc^2\theta}{j\left(Y_1 + Y_2\right)\cot\theta - 1/R} \quad (1e)$$

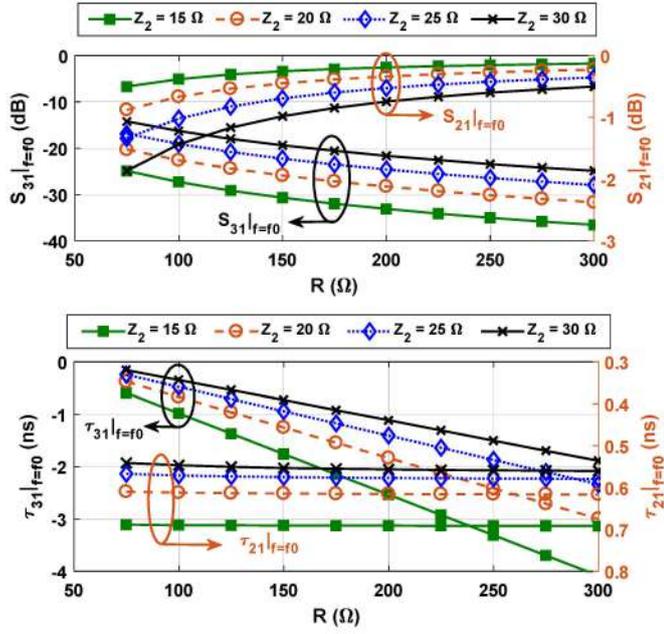$$Y_{13} = Y_{31} = jY_5\csc\theta, \quad Y_{24} = Y_{42} = jY_6\csc 3\theta \quad (1f)$$

Fig. 2. Calculated magnitude and group delay at $f_0 = 2.14$ GHz with $R_a = R_b = R_c = R_d = 50\ \Omega$ and different Z_2 and R.

$$Y_{34} = Y_{43} = \frac{Y_3 Y_4 \csc^2 \theta}{j(Y_3 + Y_4)\cot\theta - 1/R} \tag{1g}$$

Although PIN diode has parasitic components in addition to junction resistance, the parasitic reactive effect can be removed due to TL [8].

The S-parameters of the proposed coupler can be determined by using conversion relation between Y-parameter to S-parameter as (2) [9].

$$S = -\sqrt{y}\left[Y + y\right]^{-1}\left[Y - y\right]\left[\sqrt{y}\right]^{-1}, \tag{2}$$

where y is diagonal matrix of port termination admittances. For all-port matchings ($S_{11} = S_{22} = S_{33} = S_{44} = 0$) and infinite isolation between port 1 and 4 ($S_{41} = 0$) with $\theta = \pi/2$ at center frequency f_0, the characteristics admittances of TLs are derived as (3)

$$Y_1 = \sqrt{\frac{R_c}{R_a}}Y_2,\ \ Y_3 = \sqrt{\frac{R_c}{R_d}}Y_2,\ \ Y_4 = \sqrt{\frac{R_c}{R_b}}Y_2 \tag{3a}$$

$$Y_5 = \frac{1}{\sqrt{R_a R_b}},\ Y_6 = \frac{1}{\sqrt{R_c R_d}} \tag{3b}$$

where $Z_1 = 1/Y_1$, $Z_2 = 1/Y_2$, $Z_3 = 1/Y_4$, $Z_5 = 1/Y_5$, and $Z_6 = 1/Y_6$ are characteristic impedances of TLs. Similarly, R_a, R_b, R_c and R_d are port termination impedances of coupler, Subsequently, the magnitudes of transmission coefficients at f_0 are determined as (4).

$$S_{21}\big|_{f=f_0} = S_{34}\big|_{f=f_0} = \frac{R_c R Y_2^2}{R_c R Y_2^2 + 1} \tag{4a}$$

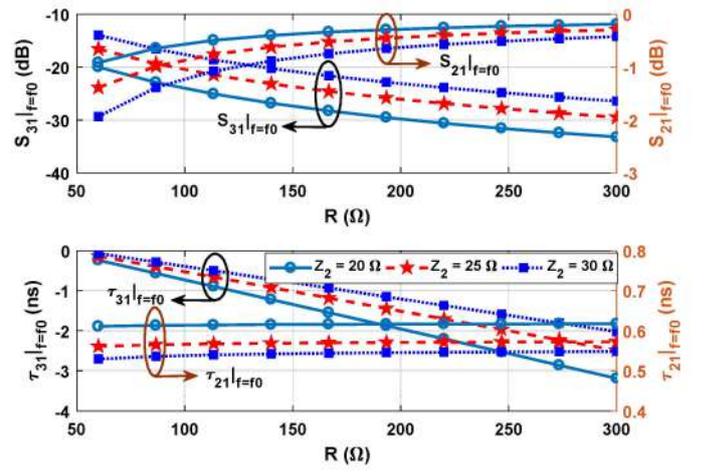$$S_{31}\big|_{f=f_0} = S_{42}\big|_{f=f_0} = \frac{j}{R_c R Y_2^2 + 1} \tag{4b}$$

Fig. 3. Calculated magnitude and group delay at $f_0 = 2.14$ GHz with $R_a = 50\ \Omega$, $R_b = 55\ \Omega$, $R_c = 65\ \Omega$, $R_d = 65\ \Omega$ and different Z_2 and R.
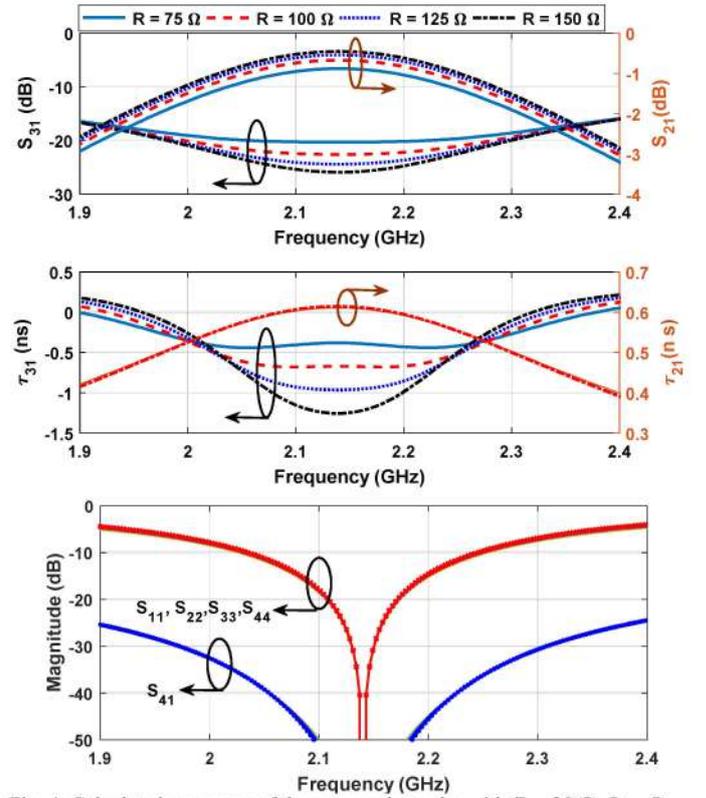

Fig. 4. Calculated responses of the proposed coupler with $Z_2 = 20\ \Omega$, $R_a = R_b = R_c = R_d = 50\ \Omega$ and different R.

$$S_{41}\big|_{f=f_0} = S_{42}\big|_{f=f_0} = 0 \tag{4c}$$

The power division ratio (k^2) is simplified as (5) using (4).

$$k = \left|\frac{S_{31}}{S_{21}}\right| = \left|\frac{S_{24}}{S_{34}}\right|_{f=f_0} = \frac{1}{R_c R Y_2^2} = \frac{Z_2^2}{R_c R} \tag{5}$$

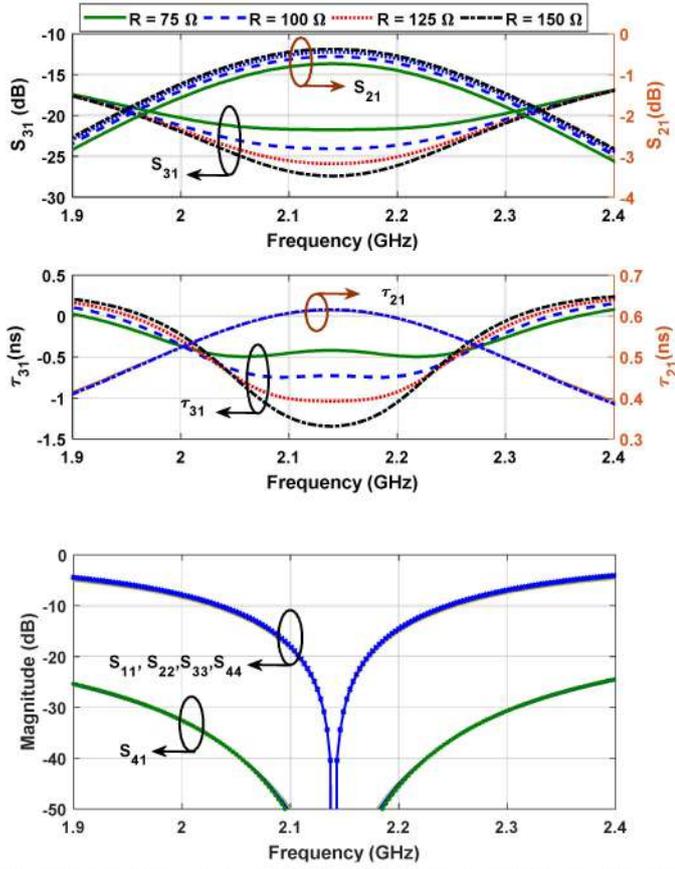Finally, using the phases of S_{21} and S_{31}, the GDs through transmission paths can be determined as (6)

Fig. 5. Calculated response of the proposed structure $Z_2 = 20 \ \Omega$, $R_a = 40 \ \Omega$, $R_b = 55 \ \Omega$, $R_c = 60 \ \Omega$, $R_d = 65 \ \Omega$ and R.

$$\tau_{21} = -\frac{1}{2\pi}\frac{d\angle S_{21}}{df}, \tau_{31} = -\frac{1}{2\pi}\frac{d\angle S_{31}}{df}. \tag{6}$$

For illustration of analytical analysis, Figs. 2 and 3 show the calculated transmission magnitudes and GDs at $f_0 = 2.14$ GHz for different Z_2, R and termination port impedances. As observed from these figures, higher NGD through port 3 and 1 can be obtained by decreasing Z_2 and increasing R. However, low Z_2 increases insertion loss (S_{31}) through port 3 and 1. It is also being noted from these figures that the GDs through port 2 and 1 have small variation. Therefore, the proposed coupler provides tunable the NGD and power division ratio if variable R is implemented with PIN diode.

Figs. 4 and 5 show the calculated magnitudes and GDs of the proposed coupler with $R_a = R_b = R_c = R_d$ and $R_a \neq R_b \neq R_c \neq R_d$, respectively. As seen from these figure, the GD through port 3 and 1 is tuned from -0.3829 to -1.255 ns at $f_0 = 2.14$ GHz when R is varied from 75 to 150 Ω. However, the GDs through port 2 and 1 are almost same. Similarly, the perfect matching and infinite isolation characteristics are obtained at f_0 regardless of R and termination impedances.

As observed from above results, the NGD increases with increasing insertion loss (S_{31}), therefore, trade off occurs between them. Similarly, the NGD bandwidth which is defined as bandwidth when GD < 0, decreases with increasing
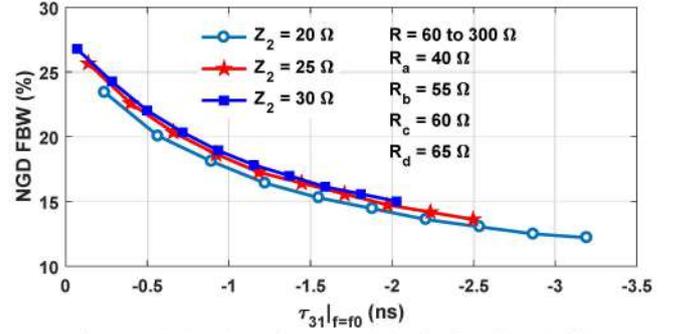

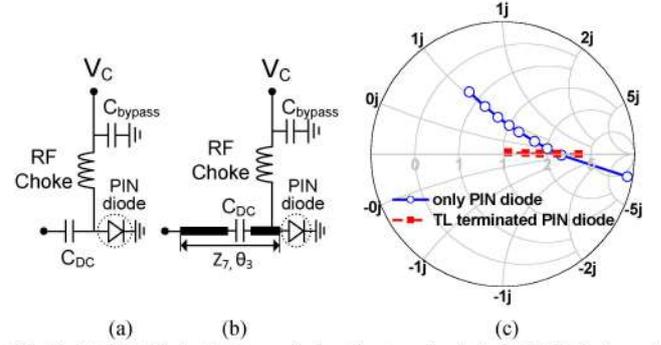Fig. 6. Calculated negative group delay fractional bandwidth.

Fig. 7: (a) PIN diode, (b) transmission line terminated with PIN diode and (c) simulated input impedance at $f_0 = 2.14$ GHz.

NGD. Fig. 6 shows the calculated NGD fractional bandwidth (FBW) using (7).

$$FBW = \frac{f_2 - f_1}{f_0}\times100\% \tag{7}$$

where f_1 and f_2 are lower and upper cut-off frequencies when GD < 0.

III. IMPLEMENTATION AND RESULTS

For experimental demonstration, the prototype circuit is designed and fabricated at $f_0 = 2.4$ GHz using RT/Duroid 5880 substrate with dielectric constant of 2.2 and thickness of 31 mils. The goal of designed circuit is to obtain the GD through port 3 and 1 of -0.2 ns to -1.3 ns at f_0. For simplicity of measurement, the coupler is designed with termination impedances of 50 Ω. The calculated circuits of the demonstrated coupler are given as $Z_1 = Z_2 = Z_3 = Z_4 = 20 \ \Omega$, $Z_5 = Z_6 = 50 \ \Omega$, and $R = 60$ to 155 Ω.

In this work, the variable resistors are implemented with PIN diodes HSMP-4810 from Avago. The current controlled variable resistor of PIN diode can not provide purely resistance at microwave frequencies because of parasitic components as shown in Figs. 7(a) and (c). Therefore, the TL terminated PIN diode as shown in Fig. 7(b) is used to compensate the parasitic components and obtain purely resistive input impedances at f_0.

Fig 7(c) shows the simulated input impedances of PIN diode with and without parasitic compensated where the characteristic impedance, the electrical length of TLs and DC-blocking capacitor are given as $Z_7 = 58 \ \Omega$, $\theta_3 = 78°$ and $C_{dc} = 22$ pF, at f_0, respectively.
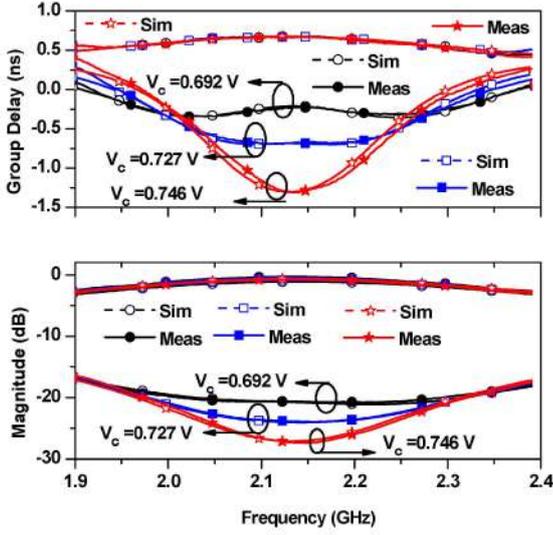
Fig. 8. Simulated and measured transmission magnitude and group delay characteristics.
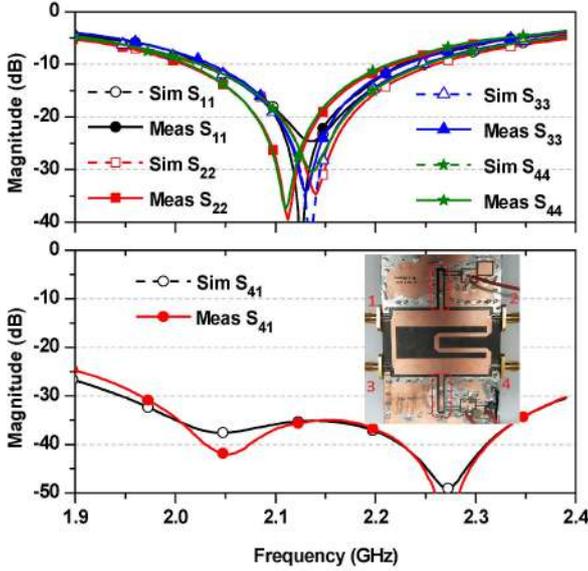

Fig. 9. Simulated and measured return losses and isolation characteristics of the fabricated circuit.

As shown in Fig. 7, the input impedance of TL terminated PIN diode is obtained with almost zero imaginary parts. Fig. 8 shows the simulated and measured the transmission magnitudes and GDs of the designed coupler. As noted from these results, the measurement results are well agreed with simulation results. From measurement, it is determined that magnitude and GD through transmission port 3 and 1 varies from -20.57 to -27.35 dB and 0.2 ns to -1.3 ns at $f_0 = 2.14$ GHz, respectively. The NGD FBW of the measured prototype are given as 21.14% to 15.88%. Similarly, the magnitude and GD through port 2 and 1 are varied from -0.805 to -0.282 dB and 0.689 to 0.692 ns at f_0.

Fig. 9 shows the simulated and measured return losses and isolation characteristics. The measured return losses and

isolation are higher 25 dB and 35.80 dB at f_0. A photograph of the fabricated circuit is also shown in Fig. 9.

IV. CONCLUSION

In this paper, an arbitrarily terminated coupler with tunable negative group delay response and power division ratio is demonstrated. The proposed coupler provides the tunable negative group delay through port 3 and 1 where as positive group delay through port 2 and 1. The analytical design equations are provided to calculate the circuit parameters. The proposed coupler is experimentally validated by fabricating the circuit at the center frequency of 2.14 GHz. The proposed circuit has the wide negative group delay-bandwidth as compared to the conventional power divider. The proposed circuit is expected to apply in various RF communication circuits and systems such as analog predistortion amplifier and cancellation circuits.

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