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2020 Asia-Pacific Microwave Conference

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Preliminary Program Book

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Technical Program — December 10, 2020 (Thursday)

Session	**Regular Session: RS17** **Resonators (1)**
Date/ Time	Thursday, December 10, 2020 / 9:00 – 10:40 (GMT+8)
Chair(s)	Girdhari Chaudhary (Jeonbuk National University); Masataka Ohira (Saitama University)
Zoom link	Room 5 (Zoom Conference ID: **818 3179 7872** / Password: **12345678**) https://us02web.zoom.us/j/81831797872?pwd=ZlVjeFRjU3Y2R1RXRm50b3dRQmdNdz09

9:00	A Microstrip Box-Type Coupling Bandpass Filter Using Even/Odd-Symmetric Electric Field Distributions of Half-Wavelength Resonator *Miho Ono, Masataka OHIRA and Zhewang Ma (Saitama University)*
9:20	Input-Reflectionless Balanced Wideband Bandpass Filter Using Multilayered Vertical Transitions *Li Yang and Roberto Gómez-García (University of Alcalá); Maoyu Fan (University of Electronic Science and Technology of China)*
9:40	Filtering Power Divider with Arbitrary Prescribed Phase Difference *Suyeon Kim, Girdhari Chaudhary and Yongchae Jeong (Jeonbuk National University)*
10:00	Hybrid Dielectric TE/TM Mode Resonator Filter with Wide Spurious Free Range and Transmission Zeros Generated by Higher Order Modes *Patrick Boe, Daniel Miek, Fynn Kamrath and Michael Höft (Kiel University)*
10:20	A Microwave Sensor for Leaf Moisture Detection Based on Split-Ring Resonator *YuHeng Yan, XianQi Lin, Zhe Chen, Yang Cai and Zhi Chen (University of Electronic Science and Technology of China)*

Filtering Power Divider With Arbitrary Prescribed Phase Difference

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***Abstract*— This paper presents a design of filtering power divider with the arbitrary prescribed constant phase difference between two different paths. The proposed circuit consists of a Wilkinson power divider (WPD) and N^{th}-order coupled line bandpass filters (BPFs) with different fractional bandwidths (FBWs). Closed-form design equations are derived for the efficient design of the proposed circuit. By controlling the FBWs of the BPF, the phase slope can be controlled, which can provide a flat phase difference over a wideband. For experimental validation, the proposed circuit was designed and measured at a center frequency of 2.90 GHz with 180° phase difference. The simulated and measured results coincide well with the theoretically predicted performances.**

Keywords—Arbitrary phase difference, coupled line, phase slope adjustment, Wilkinson power divider.

I. INTRODUCTION

Power divider with arbitrary prescribed constant phase difference is highly demanded in design and explorations of power amplifier, phase arrays, and antenna feeding networks for wireless communication. In realization of the arbitrary phase difference between two paths using Wilkinson power divider (WPD), an additional transmission line (TL) must be added to adjust phase difference. However, this conventional technique can provide phase difference only at center frequency (f_0) because of phase slope (or group delay) mismatch between two paths. Filtering power dividers, which can provide multi-functionality in a single device such as frequency selectivity and power division, are widely researched in recent [1]-[3]. One approach is to replace quarter-wave TLs in WPD with different filtering structures. Conventional filtering power divider can achieve arbitrary power division ratio, however, phase responses have only two states such as in-phase (0°) and out-of-phase (180°) [4]-[5].

Recent studies show that filtering power divider with an arbitrary prescribed phase difference is indispensable in various applications. Some efforts have been made in integrating the power divider and phase shifter within a single component. In [6], power divider with an arbitrary phase difference is presented, however, the specified phase difference can achieve only at f_0. Similarly, wideband 90° phase shifter is presented in [7] using modified composite resonant circuits for phase slope alignment. This work has achieved flat phase difference over a wide bandwidth, however, poor filtering response. In [8], a filtering power divider with arbitrary phase difference is presented but does not have arbitrary termination impedance.

In this paper, filtering power divider with arbitrary prescribed constant phase difference over a wide bandwidth is demonstrated. The constant phase difference between two paths has been achieved by controlling fractional bandwidth (FBW) of N^{th}-order coupled line bandpass filters (BPFs). And closed-form design equations are derived for calculating circuit parameters for the desire phase response.

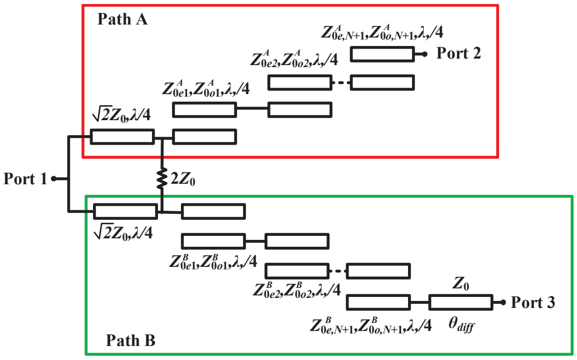
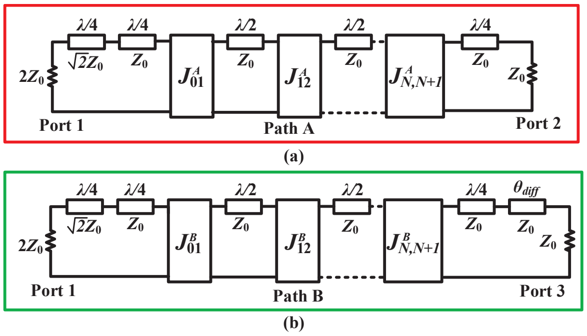


Fig. 1. Circuit diagram of proposed filtering power divider with arbitrary phase difference.



(a)

(b)

Fig. 2. Equivalent sub-networks during signal transmission between input and output ports : (a) path A between ports 1 and 2 and (b) path B between ports 1 and 3.

II. PROPOSED STRUCTURE DESIGN METHOD

Fig. 1 shows the circuit diagram of the proposed power divider with an arbitrary prescribed constant phase difference between two paths. The proposed circuit consists of WPD with an equal power division ratio and two N^{th}-order coupled line BPFs. The terminated impedances of three ports are 50 Ω.

Fig. 2 depicts the equivalent sub-networks of paths A and B during signal transmission between input and output ports. As seen from figures, each branch of the proposed power divider has its own respective N^{th}-order BPF with passband ripple L_{Ar}, but different fractional bandwidths (Δ_A and Δ_B). To synthesize the specified phase difference $\Delta\phi$ between two paths under specified passband ripple L_{Ar} can be determined as (1).

$$\Delta\phi = \angle S_{21} - \angle S_{31} = \theta_{diff}(f_0), \tag{1}$$

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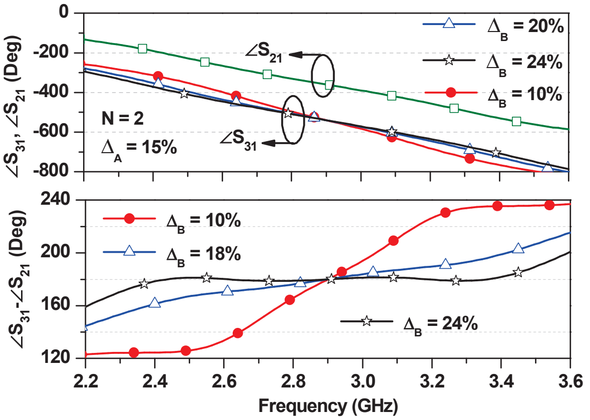


Fig. 3. Phase characteristics with ideal elements for different fractional bandwidths (Δ_A and Δ_B).

where θ_{diff} is an electrical length of TL connected at path B.

To achieve constant phase difference between two paths over wideband, the phase slope should be identical [8] as given in (2).

$$\left.\frac{d\angle S_{21}}{df}\right|_{f=f_0} = \left.\frac{d\angle S_{31}}{df}\right|_{f=f_0} \tag{2}$$

When N is an odd number, the phase slope values are given as (3).

$$\left.\frac{d\angle S_{21}}{df}\right|_{f=f_0} = -\frac{A}{f_0\Delta_A} - \pi^2 B\Delta_A \tag{3.a}$$

$$\left.\frac{d\angle S_{31}}{df}\right|_{f=f_0} = -\frac{A}{f_0\Delta_B} - \pi^2 B\Delta_B - \frac{\theta_{diff}}{f_0}, \tag{3.b}$$

where

$$A = 2\sum_{i=1}^{m-1} g_i + g_m, B = \frac{\prod_{i=1}^{m-1} g_i + 2\left[\sum_{i=1}^{m-1}\left(\prod_{j=1}^{m-1} g_j/g_i\right)\right]g_m}{4\prod_{i=1}^{m} g_i f_0}, m = (N+1)/2 \,. \tag{4}$$

After determining the Δ_A, Δ_B, and θ_{diff} for specified phase difference, the circuit parameters of BPFs are determined as (5) [9].

$$J_{01}^{x} = \frac{1}{Z_0}\sqrt{\frac{\pi\Delta_x}{2g_1}}, \quad J_{N,N+1}^{x} = \frac{1}{Z_0}\sqrt{\frac{\pi\Delta_x}{2g_N g_{N+1}}} \tag{5.a}$$

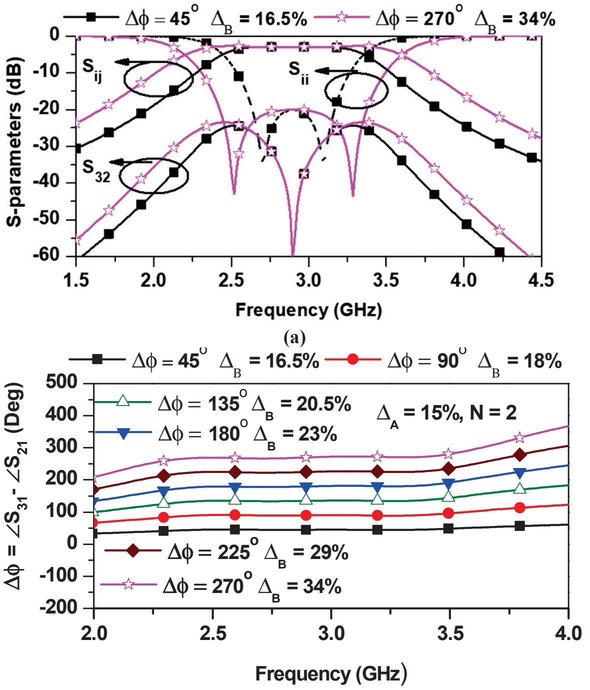
$$J_{i,i+1}^{x} = \frac{1}{2Z_0}\frac{\pi\Delta_x}{\sqrt{g_{i-1}g_i}}, i = 2,3,\cdots N \tag{5.b}$$

$$\left.Z_{0e,i+1}\right|_{i=0 \text{ to N}} = Z_0\left(1 + J_{i,i+1}^{x}Z_0 + \left\{J_{i,i+1}^{x}\right\}^2 Z_0^2\right) \tag{5.c}$$

$$\left.Z_{0o,i+1}\right|_{i=0 \text{ to N}} = Z_0\left(1 - J_{i,i+1}^{x}Z_0 + \left\{J_{i,i+1}^{x}\right\}^2 Z_0^2\right), \tag{5.d}$$

where $x = A$ and B.

Fig. 3 depicts the synthesized the phase responses of the proposed filtering power divider according to Δ_B. In this simulation, Δ_A is fixed with 15%, whereas Δ_B has been varied from 10-24%. As seen from this figure, the phase slope of path B is almost same with path A in condition of Δ_B = 24%, which results in constant phase difference over wide bandwidth.



(a)

(b)

Fig. 4. Simulation results with ideal elements with N = 2, Δ_A = 15%: (a) S-parameters and (b) phase differences between output ports.

From these results, it can be concluded that constant phase difference between two paths of the proposed filtering power divider can be achieved by controlling Δ_B. Similarly, Fig. 4 shows the synthesized results of the proposed filtering power divider with typical constant phase differences (45°, 90°, 180°, 225°, 270°), passband ripple L_{Ar} = 0.043, and N = 2. These results show that the proposed power divider provides constant phase difference, frequency selectivity, and excellent isolation characteristics at the same time.

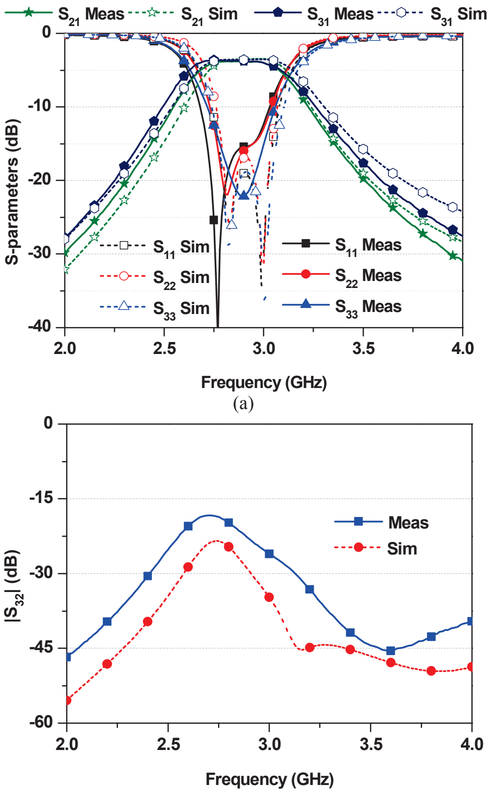
Table I: Circuit parameters of designed filtering power divider

Path A	Δ_A (%)	Z_{0e1}, Z_{0o1} (Ω)	Z_{0e2}, Z_{0o2} (Ω)	Z_{0e3}, Z_{0o3} (Ω)	
	10	86.15, 37.51	66.48, 40.34	86.15, 37.51	
Path B	Δ_B (%)	Z_{0e1}, Z_{0o1} (Ω)	Z_{0e2}, Z_{0o2} (Ω)	Z_{0e3}, Z_{0o3} (Ω)	θ_{diff}(°)
	12.8	92.66, 37.63	72.32, 38.86	92.66, 37.63	180

III. EXPERIEMENT RESULTS

For experimental validation, the circuit is designed and fabricated at f_0 of 2.90 GHz with a constant phase difference of 180°. The passband ripple, filter order N, and Δ_A are specified as 0.043, 2, and 10%, respectively. Based on design specification, the calculated circuit parameters of the proposed filtering power divider are given in Table I. The circuit is fabricated on Taconic substrate with dielectric constant of 3.2 and thickness of 31 mils. The simulation was performed using ANSYS HFSS 19.

Fig. 5 shows the simulated and measured S-parameters. The measurement results agreed well with simulations. The



(a)

(b)

Fig. 5. Simulation and measurement results.

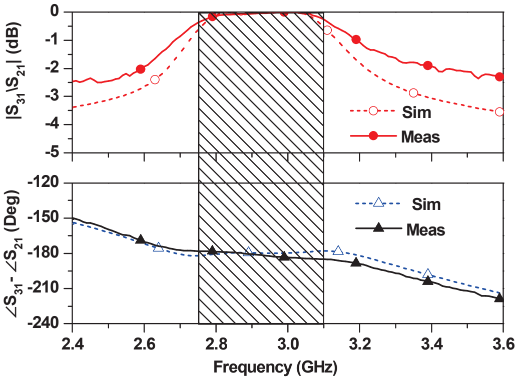


Fig. 6. Simulation and measurement magnitude and phase imbalances.

measured in-band $|S_{11}|$, $|S_{22}|$, and $|S_{33}|$ at f_0 are determined as 15.5 dB, 16.01 dB and 21.62 dB, respectively. The measured $|S_{21}|$ and $|S_{31}|$ are determined to be 3.84 dB and 3.78 dB, respectively. Similarly, isolation between output ports ($|S_{32}|$) is 22.94 dB at f_0 and higher than 18.32 dB in 2-4 GHz frequency range.

Fig. 6 depicts the simulated and measured magnitude ($|S_{21}|/|S_{31}|$) and phase ($\angle S_{21}$-$\angle S_{31}$) imbalances. As observed from the figure, the proposed circuit provides the constant phase difference between two paths over wide bandwidth. The measured magnitude and phase imbalances are within ±0.2 dB and 180 ± 3.22°, respectively, over the frequency range of 2.78-3.09 GHz (310 MHz bandwidth). A photograph of fabricated circuit is shown in Fig. 7.

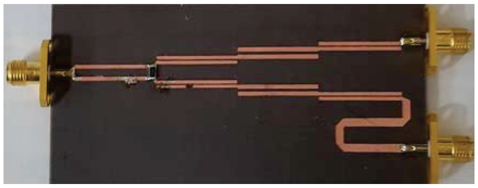


Fig. 7. Photograph of fabricated filtering power divider with arbitrary phase difference.

IV. CONCLUSION

In this paper, we demonstrated a filtering power divider with an arbitrary prescribed constant phase difference between two paths based on coupled line bandpass filters. The proposed power divider can provide constant phase difference within bandwidth and frequency selectivity as compared to traditional power dividers. The synthesized design equations show that constant phase difference response can be achieved by controlling fractional bandwidths of bandpass filters. Both analytical and experimental results are demonstrated for validation of the proposed circuit. The proposed filtering power divider is the potential for various applications of wireless communication because of their low magnitude and phase imbalances.

ACKNOWLEDGMENT

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