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Three-Way Equal Filtering Power Divider for Modern Communication Systems

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Correspondence: Augustine O. Nwajana (a.o.nwajana@greenwich.ac.uk)**Received:** 7 January 2024 | **Revised:** 7 June 2024 | **Accepted:** 16 October 2024**Funding:** This research received no external funding.**Keywords:** 3-way | bandpass filter | FPD | microstrip | power combiner | power divider

ABSTRACT

This article proposes a three-way (3-way) equal filtering power divider (FPD) employing the microstrip compact folded-arms square open-loop resonator (FASOLR). The proposed FPD evenly distributes an input signal into three equal output signals. The design incorporates balanced signal power division, and filtering technology for the removal of unwanted frequency elements and aimed at enhancing signal quality and efficiency in the radiofrequency (RF) front-end of communication systems. The use of FASOLR in the design helps to achieve miniaturization by reducing the device footprint. Keysight's Advanced Design System (ADS) software is used for conducting the design simulations. The proposed FPD features a 2.6 GHz center frequency, with a 0.03 fractional bandwidth. The implementation is carried out on Rogers RT/Duroid 6010LM substrate with a dielectric constant of 10.7, a thickness of 1.27 mm, and a loss tangent of 0.0023. This design includes theoretical calculations, circuit modeling, microstrip layout design, and electromagnetic (EM) simulations. The good agreement between the theoretical and practical results verifies the proficiency of the FPD in delivering equal power outputs at the three output ports, and at the same time filtering out unwanted frequencies as required. The practical responses of the prototype FPD indicate a good return loss of better than 15.5 dB and an insertion loss of better than $4.77 + 0.34$ dB. The design prototype achieved a compact size of $0.31 \times 0.18 \lambda_g$. The results reinforce the design's competitive edge in performance and actual footprint. λ_g is the guided wavelength for the microstrip line impedance at the center frequency of the three-way equal FPD.

1 | Introduction

In the active environment of communication systems, the challenge of effective power division and allocation, and correct signal filtering has increased. Wilkinson Power Divider (WPD) is the traditional power division approach using quarter-wavelength transmission lines [1]. This type of power divider is popularly used in communication systems due to its good electrical isolation and simple structure [2]. The problem with WPD is that its operation in a communication system requires the use of an externally connected bandpass filter (BPF), as shown in Figure 1a. This

technique of using a transmission line to externally link the WPD with a filter will not only increase the physical size but will also lead to higher loss coefficient in the system [3]. In contrast to the traditional approach involving a BPF, a matching transmission line, and a WPD as separate components, the proposed integrated filtering power divider (FPD) consolidates all three components into a single device [4–11] as shown in Figure 1b. The role of the BPF within the proposed three-way FPD is to establish the required passband in the final device. The necessity of incorporating filtering techniques into WPD removes the complexity of having three separate devices in a communication system, as

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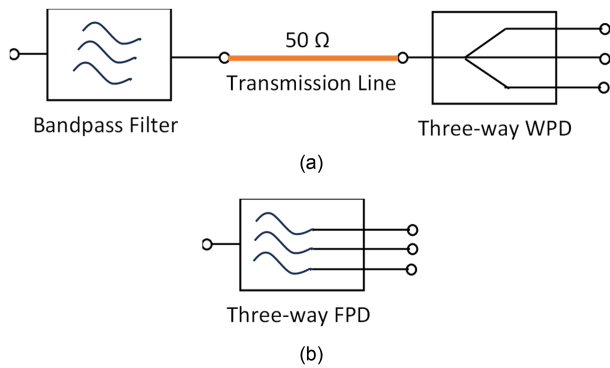


FIGURE 1 | Three-way power divider: (a) Conventional cascaded bandpass filter, transmission line, and three-way WPD; (b) proposed integrated three-way FPD [5].

shown in Figure 1a. Instead, a single device is used, as shown in Figure 1b, leading to a reduced footprint in the system. The proposed design also leads to reduced losses as the conventional tuning required in the matching transmission line of Figure 1a is absent in Figure 1b. The integrated FPD means reducing complexity, physical size, and losses.

Numerous WPDs have been proposed using various technologies. One such technology for crafting a 3-way wideband FPD replaces traditional WPD's quarter-wavelength ($\lambda/4$) transformers with multiple coupled lines [5, 12–14]. The design seeks to mitigate concerns related to circuit dimensions and insertion losses, offering an asymmetric 3-way equal FPD with high selectivity by employing two dissimilar quarter-wavelength transformers, one pair of short-ended parallel-coupled microstrip lines, one open-ended parallel-coupled line, and one 3-line parallel-coupled line to achieve equal energy subdivision. However, there is some variation between electromagnetic (EM) and circuit responses due to not considering open ends, and cross junctions in the ideal circuit [5]. A 3-line coupled configuration and $\lambda/4$ open terminals are employed in the modeling of a compact three-way wideband FPD featuring a 1:1:2 power ratio. It integrates parallel $\lambda/2$ open-circuit transmission lines for effective filtering. The design's flexibility is highlighted by independent control of center frequency and bandwidth for each passband through resonator parameters [12]. Whereas in [13], a compact 3-way power divider with wideband bandpass filtering was reported and it utilizes short-circuited-stub (SCS) loaded unequal power divider, unequal-width 3-coupled lines, and isolation resistors. Nonreciprocal FPDs are introduced in [14], which are compact devices that combine power division, combination, and bandpass filtering with magnet-less non-reciprocity using time-modulated varactors. A microstrip prototype with a WPD and modulated quarter-wavelength coupled line filters exhibits electrical reconfigurability, high rejection beyond the passband, and strong port isolation. The low quality-factor (Q-factor) typically exhibited by microstrip printed components causes high losses in the device. Improving the Q-factor of the varactors or using alternative resonator structures could enhance the overall performance of the device.

Substrate integrated waveguide (SIW) [15–18] is another technology recently deployed in the implementation of filtered power

dividers. This technology is compatible with single-layer PCB technology as reported in [15, 16]. A single-layer 3-way SIW FPD that achieved equal power distribution by using degenerated modes in rectangular SIW cavities was proposed in [17]. Employing waveguide theory, microstrip inset feedlines, and open-circuited stubs for impedance matching, the design achieved equal power division with good performances. However, the presence of a spurious mode at the operating frequency, despite efforts to suppress it, may have an impact on the stopband rejection and overall signal integrity. A three-way FPD using multilayer SIW technology was reported in [18]. This achieved both unequal and equal power division by integrating slotline-to-microstrip transition arrangements with TE₁₀₁ mode resonant cavities. The prototypes demonstrated effective performance with wide bandwidth, low insertion loss, and high in-band isolation, showcasing potential applications in advanced wireless communication systems. However, the complexity of the proposed design may limit its practical implementation in certain applications.

There have been proposals for power dividers incorporating composite right and left-handed (CRLH) structures [19, 20]. A compact dual-band three-way metamaterial power divider with an equal output phase was proposed in [19]. This employs fully printed CRLH structures for 900 MHz and 2.4 GHz bands, incorporating 2:1 unequal and 1:1 equal power dividers. The design initially introduced phase errors at three outputs, which were later corrected using a CRLH phase-compensating line [20] reported a compact three-way Bagley polygon power divider with a built-in bandpass response. It used innovative CRLH transmission lines for resonators and zero-degree transmission lines to shrink the circuit size while preserving isolation performance. The design ensures in-phase output ports and a broad upper stopband.

Various other techniques have been employed in designing power dividers to showcase enhanced performance and compactness [21–25]. Miniaturization of power dividers can be achieved using defected ground structures (DGSs). Split ring resonators (SRRs) are used as DGS in a three-way power divider to reduce its size. Unlike traditional methods involving loaded lines and repetitive structures, strategically placing defects achieves similar performance in a more compact design. This technique suggests potential applications of DGS in different microwave devices including diplexers and couplers and diplexers [21]. Two symmetric F-shaped DGS are employed in a three-way planar WPD divider which demonstrates strong overall ultra-wideband performance [22]. A three-way power splitter that uses a multimode patch resonator is proposed in [23]. This utilizes the unique characteristics of the equilateral triangle patch resonator modes for power division. To achieve the desired two-order filtering response, the design incorporates metal vias and slots to adjust the resonant frequencies. In [24], a unique three-way power divider featuring bandpass responses, employing folded net-type resonators to achieve compact size while serving twin functions of filtering and power division was proposed. The symmetric structure ensures equal power distribution with minimal magnitude imbalance. The design of a 2-way and a 3-way FPDs using a regular triangle patch resonator (RTPR) was proposed in [25]. The selection of resonator modes is based on their electric-field distributions, showcasing

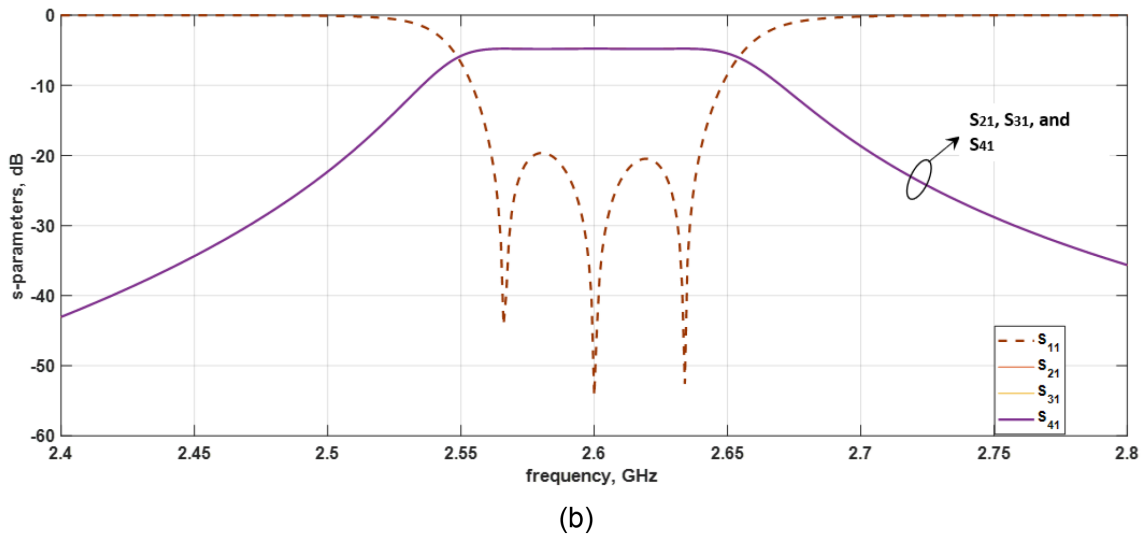
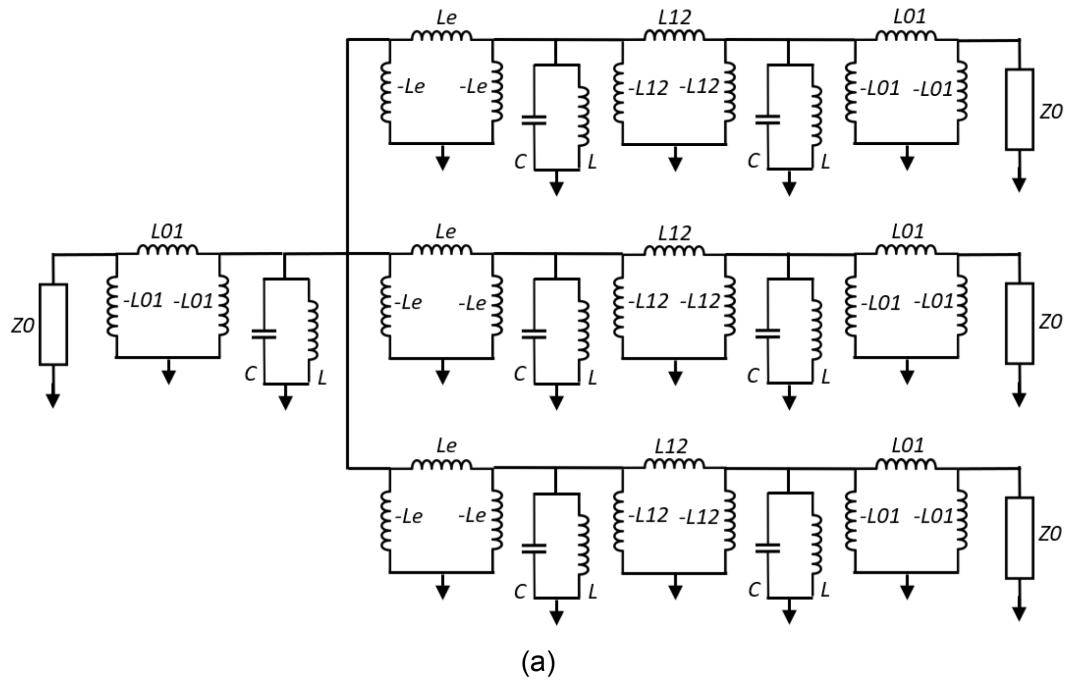


FIGURE 2 | Proposed 3-way equal FPD: (a) Circuit arrangement ($Z_0 = 50 \Omega$, $L_{01} = 3.0607 \text{ nH}$, $L_{12} = 3.4836 \text{ nH}$, $L_e = 6.0337 \text{ nH}$); (b) Simulation responses.

the RTPR's flexibility. The design incorporates an in-phase multi-way excitation scheme and strategically placed shorting posts for effective harmonic rejection, resulting in significantly extended stopbands.

This article proposes a compact three-way FPD (or combiner) that delivers equal amount of power to each of its output ports while at the same time attenuating unwanted frequency components. Hence, the proposed integrated FPD acts as a three-in-one device since it consolidates three components (a BPF, a matching transmission line, and a WPD) into a single device, as shown in Figure 1. The proposed device removes the complexity of having three separate devices in a communication system by replacing all three with a single device, leading to reduced footprint in the system. The design also leads to reduced losses as the conventional tuning required in the matching transmission line

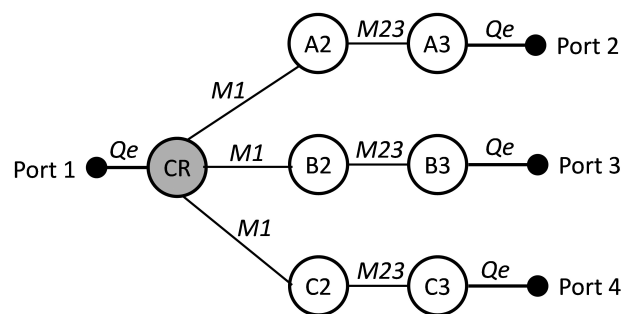


FIGURE 3 | Coupling arrangement for the proposed equal FPD.

of Figure 1a is absent, as seen in Figure 1b. The design employed a BPF as opposed to the use of lowpass filter (LPF) in achieving the filtering function in the proposed device. Employing a LPF in

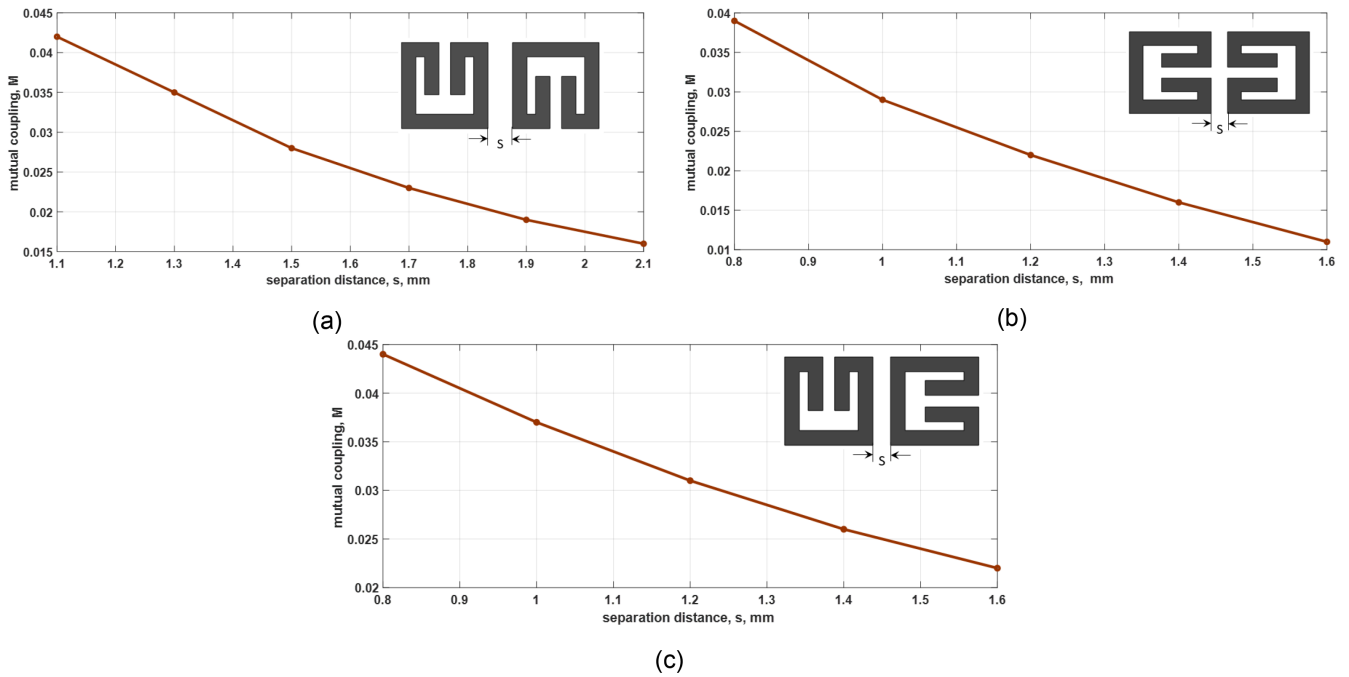


FIGURE 4 | Mutual coupling coefficient extraction technique: (a) Mixed coupling—type I; (b) Electrical coupling; (c) Mixed coupling—type II.

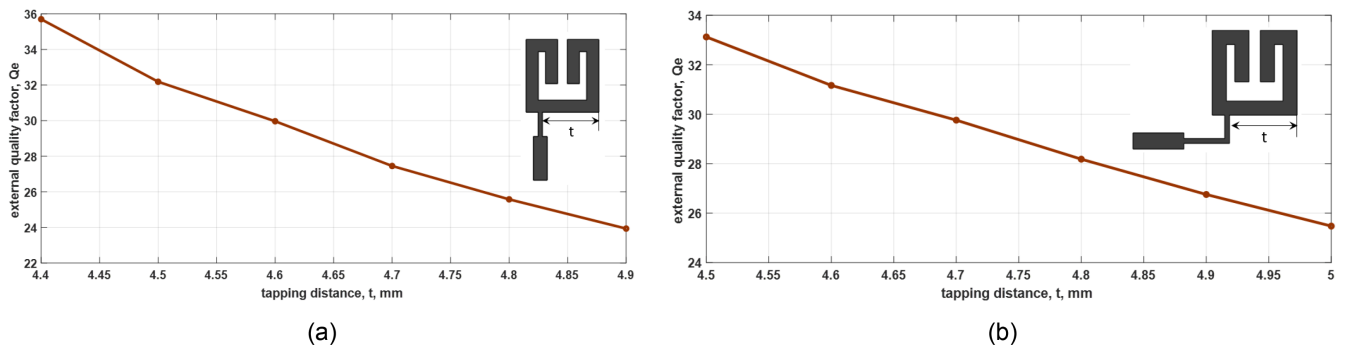


FIGURE 5 | External quality factor extraction technique: (a) Type I; (b) Type II.

the design will make for a complex design as two LPFs need to be placed back-to-back (or use one LPF and one highpass filter) to achieve a passband. To avoid this complexity, the proposed design uses a single BPF for simplicity. To achieve further miniaturization, the proposed design implementation employs the compact microstrip folded-arms square open-loop resonator (FASOLR) reported in [26]. The FASOLR has been found to have a small side length of $1/8$ the length of the conventional quarter-wavelength resonator employed in the realization of the traditional WPD reported in [1].

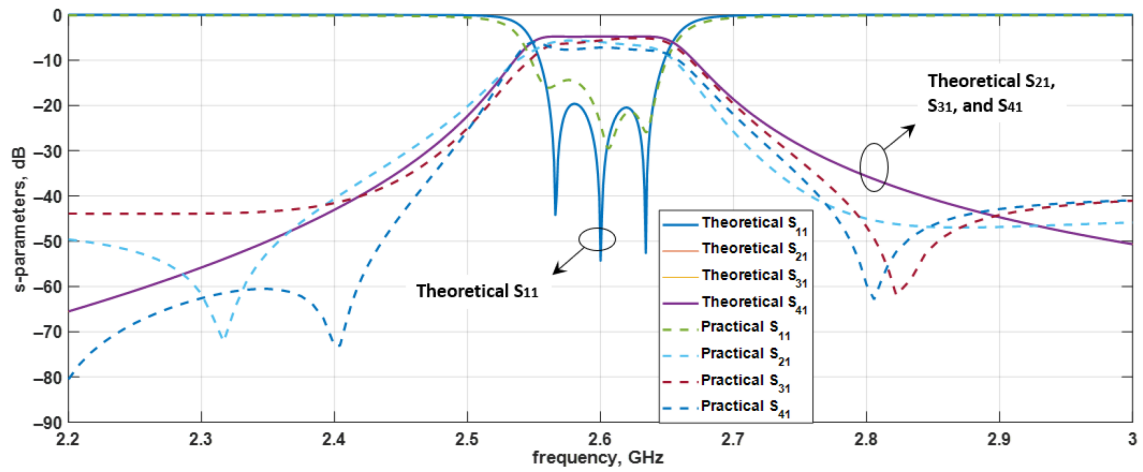
2 | Theoretical Circuit Configuration

The circuit configuration for the proposed integrated FPD is achieved by first designing three identical BPFs using the standard normalized Chebyshev lowpass prototype filter element values of $g_0 = g_4 = 1.0$, $g_1 = g_3 = 0.8516$, and $g_2 = 1.1032$. The design center frequency is chosen as 2.6 GHz, with a fractional bandwidth (FBW) of 0.03, and the input/output characteristic impedance (Z_0) of 50 Ohms. The bandwidth design constraint

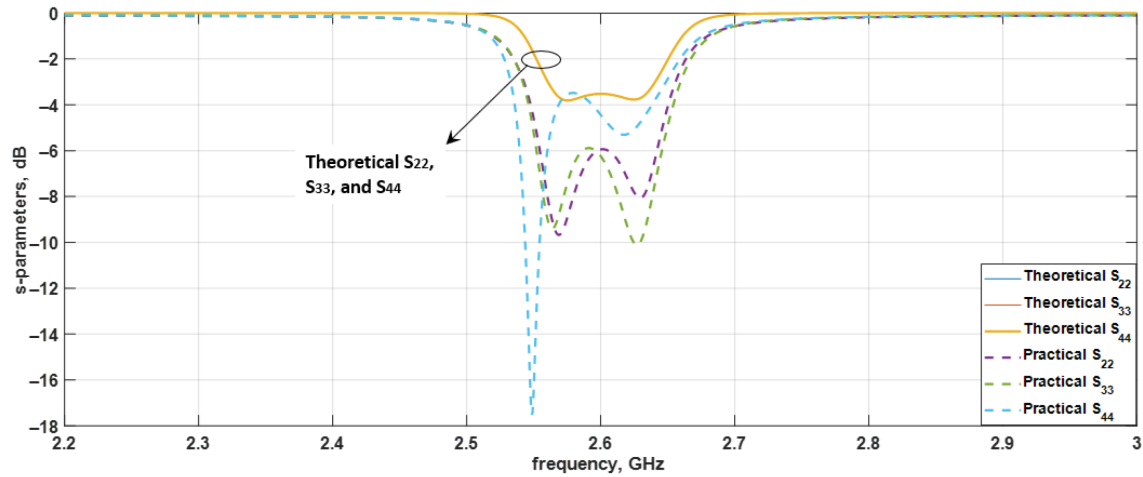
or requirement for the filter employed in forming the proposed FPD is fixed at 3% of the specified center frequency. Hence, the filter design method employed in this research work considers network and component values that meet the required bandwidth constraint. Therefore, the proposed FPD bandwidth is only controlled during the component filter design phase. The identical filter circuits were designed based on the technique reported in [27, 28] and then coupled together to achieve the integrated FPD circuit arrangement shown in Figure 2a. The simulation responses of the circuit arrangement for the proposed three-way FPD are shown in Figure 2b.

3 | Microstrip Layout and Practical Arrangement

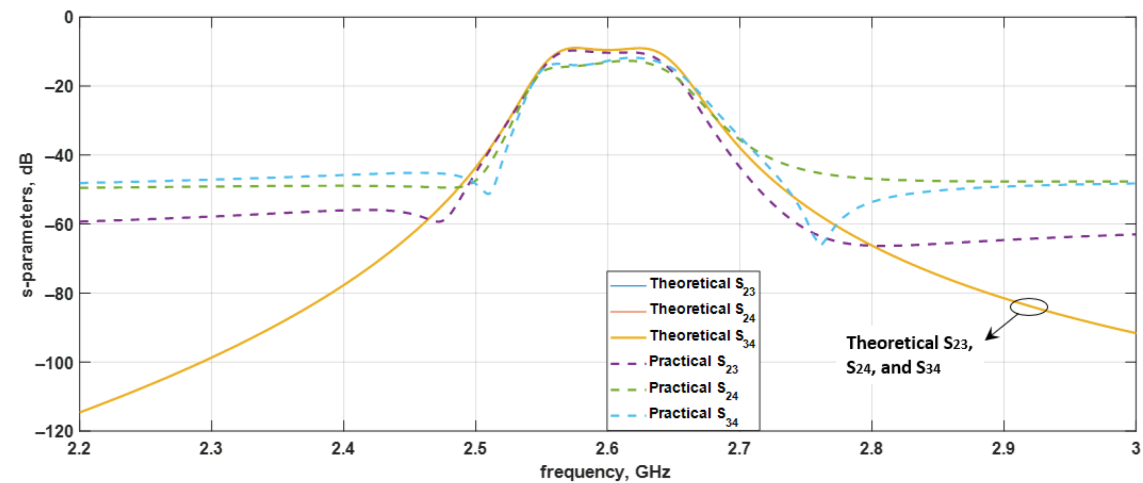
The equal FPD design and simulation were carried out using microstrip technology, and the FASOLR was used to implement the layout. The width and guided wavelength for designing the FASOLR are determined from [26]. Advanced design system (ADS) EM Simulation Software was used to create and



(a)



(b)



(c)

FIGURE 7 | Theoretical and practical results comparison: (a) Differential mode responses; (b) Single-ended output ports responses; (c) Isolation responses.

20 dB return loss of the theoretical/ideal results. The achieved practical minimum insertion loss is recorded as $4.77 + 0.34$ dB, where the 4.77 dB part is the standard theoretical inherent characteristics return loss of any three-way equal FPD device as reported in [3]. The achieved variation in return losses of 0.34 dB

between the theoretical and the practical equal FPD results is very good when compared to the state-of-the-art as captured in Table 1. The transmission zeros indicated in Figure 7a are due to the resonance circuits in the shunt-only network shown in Figure 2a. The resonance circuits are then transformed to their

TABLE 1 | Performance comparison of the proposed FPD to relevant literature.

References	f_0 (GHz)	Filter Order	Size (λg) ²	TL ^a	RL ^b (dB)	IL ^c (dB)	Selectivity	Isolation
[5]	1.36	3	0.1853	Microstrip	> 19.5	4.77 + 0.40	High	> 10.2
[12]	3.50	3	0.1440	Microstrip	> 15.0	4.77 + 2.18	Medium	> 20.1
[13]	1.50	4	0.1593	Microstrip	> 14.2	4.77 + 0.80	Medium	> 10.3
[17]	6.45	2	3.6666	SIW	> 13.6	4.77 + 1.10	Low	—
[18]	11.80	2	1.2789	SIW	> 16.3	4.77 + 0.80	Medium	> 16.0
[20]	3.50	2	0.1320	Microstrip	> 14.5	4.77 + 1.43	Low	> 10.1
This work	2.60	3	0.0558	Microstrip	> 15.5	4.77 + 0.34	Medium	> 10.1

^aTransmission line.^bReturn loss.^cInsertion loss.

corresponding resonant elements in Figure 6a, which produces the transmission zeros in the stopband. The single-ended output port responses shown in Figure 7b also confirm the good agreement between the theoretical and practical results of the proposed equal FPD. The theoretical and the practical isolation responses (S_{23} , S_{24} , and S_{34}) of the proposed three-way filtering power are shown in Figure 7c. The proposed design achieved an in-band isolation of better than 10.1 dB across all bands of the proposed FPD.

5 | Conclusions

A balanced three-way FPD that receives input power and delivers an equal amount of output to its three output ports has been developed and realized using microstrip technology. The design implementation is based on the compact FASOLR for device miniaturization. The proposed FPD operates at a 2.6 GHz center frequency, with a 3% FBW. The realization and fabrication are carried out on Rogers RT/Duroid 6010LM substrate with a dielectric constant of 10.7, a thickness of 1.27 mm and a loss tangent of 0.0023. The theoretical and practical results of the proposed FPD indicate good agreement with a return loss of better than 15.5 dB, an insertion loss of better than 4.77 + 0.34 dB, and an in-band isolation of better than 10.1 dB. The fabricated device achieved a compact size of $0.31 \times 0.18 \lambda g$. The compact design is well-suited for modern multifunctional communication systems due to its low insertion and return losses, sharp selectivity, and integrated filtering capability.

Author Contributions

Augustine O. Nwajana: conceptualization, formal analysis, writing – original draft, supervision, project administration, resources. **Rose Paul:** methodology, software, validation, investigation, writing – review and editing, visualization, data curation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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