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A Wideband Tunable Power Divider for SWIPT Systems

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ABSTRACT A two-way tunable power divider for Simultaneous Wireless Information and Power Transfer (SWIPT) is proposed in this paper. The power divider divides the incoming power in such a way that maximum power is utilized for energy harvesting purposes and the rest of the power is used for information decoding purposes. This unequal distribution of power is realized by tuning the varactor diode’s reverse biasing voltages. A good matching performance is attained using the radial and short stubs at the input and one of the output ports, respectively. High isolation is achieved with the help of the resistor used for connecting the output ports of the power divider. The achieved power division ratios vary from 13:1 to 28:1. The tunable power divider is designed and fabricated at 2.4 GHz. The bandwidth measured at 10 dB return loss is 3.2 GHz and the isolation better than 12 dB is achieved between the output ports. The designed structure is compact and good consistency is observed between the simulated and measured results. The designed power divider may be used for future 5G wireless networks.

INDEX TERMS Reconfigurable power divider, tunable power divider, equal power divider, large power division ratios, arbitrary power division, unequal Wilkinson power divider.

I. INTRODUCTION

Simultaneous wireless information and power transfer (SWIPT) systems are becoming one of the appealing technology because of its ability to extend the lifespan of energy controlled wireless networks. SWIPT systems can provide many advantages to the upcoming cellular systems, particularly for the mobile users, as it utilizes the radio signal for transferring both information as well as energy. By superposing the transfer of information and power, SWIPT can help in having significant improvements in case of time delay, interference management, energy consumption, and spectral efficiency. For example, the same signal can be used for concurrently charging and calibrating the wireless implants, and can also be used as control signals for charging the wireless sensor nodes. SWIPT technology is of great importance for supporting the heterogeneous sensing applications for exchanging information and supplying energy to various ultra-low-power sensors. In addition, it can be integrated as an effective method for jointly supporting energy sustainability and high throughput in case of massive multiple-input multiple-output (MIMO), millimeter-wave technologies and upcoming cellular systems with small cells which can overcome the existing effects of path loss. The concept of SWIPT was initially presented in [1], where it was assumed that receiver would decode the information and harvest energy simultaneously. This assumption was not applicable for practical applications as it was not possible to decode the information with the help of energy harvesting (EH) circuits and also the operation of EH on the RF signal destroys the information content of the signal. Therefore, two solutions, time switching and power splitting, were presented in [2]. In case of time switching, different timeslots are allotted for EH and information decoding (ID) purposes so signal received in one time slot is either utilized for EH or ID purposes. However, in case of power splitting, the received signal splits in two different signals, where one signal is used for EH purposes and the other signal is used for ID purposes. As both operations are performed simultaneously, it makes power splitting technique more attractive for SWIPT systems as compared to the time

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switching technique [3]. Power splitting technique demands the optimization of the power splitting factor and higher complexity of the receiver but it helps in achieving instantaneous SWIPT because the incoming signal is used for both energy harvesting and information decoding purposes. Therefore, this technique is more useful to those applications which require critical energy/information or delay constraints [4]. Since, wireless communication can be established effectively with low signal to noise ratio (SNR) due to availability of highly sensitive receivers. Therefore, maximum power can be allocated for EH purposes and minimum power is used for ID. The tunable power divider is required in power splitting technique to divide the incoming signal into two signals either equally or unequally depending on the nature of the application.

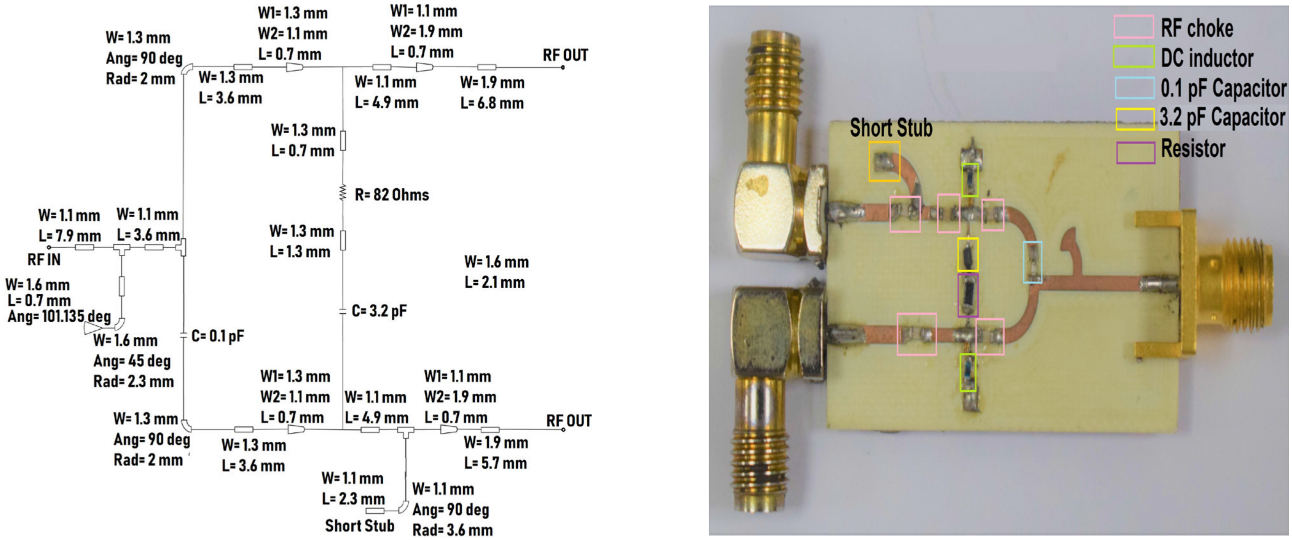
Power dividers are the fundamental elements and are utilized in different areas, such as mixers, antenna arrays, power amplifiers and various other types of equipment. Recently, tunable power dividers gained a lot of attention due to their potential advantages. Tunable power dividers are used for achieving high efficiency in power amplifiers. Tunable power dividers are presented in [5] and [6]; though, they have low tuning capability due to fixed power division ratio. Many structures of the power divider have been proposed in [7], [8], for achieving reconfigurable power division ratios. In [7], power divider, consisting of four states of power transmission controlled by switches, is presented. In [8], a tunable power divider with three pin diodes is presented for achieving a high division ratio in two alternative modes. Unequal reconfigurable power divider with the reconfigurable coupled line is presented in [9]. A large difference is necessary between the coupled line's even-mode and odd-mode impedances for achieving a high power division ratio. For realizing large between the even and odd-mode, a power divider comprising a microstrip slot like structure on the thick substrate is proposed in [10]. Though, the design of the presented power divider is complicated and still, it is hard to achieve high division ratios i.e. over 1:3. A two-way tunable power divider is proposed in [11] but the structure is designed for fixed frequency and also the passband selectivity of the structure is very poor. Designing microstrip based tunable power dividers is still a challenging task because of the difficulties in the fabrication of high impedance microstrip lines. Therefore, using varactor diode is one of the best technique for achieving high power division ratio in microstrip based tunable power dividers. A power divider consisting of transmission lines loaded with varactor diode is presented in [12]. The achieved power division ratio is within the range of 1:1 to 1:3.4. Similarly, variable division ratios are targeted using defected ground structure (DGS), in [13], with the incorporation of varactor diodes for designing the power divider. The measured division ratios at the outputs can be adjusted from 1:2.95 to 1:10.4 when the applied biasing voltage is tuned from 0 V to 10 V. However, it resulted into a system with the large structural area and also the fabrication of power divider using DGS is not easy.

A typical SWIPT system comprises of a single antenna attached with a 3-port tunable power divider. Port 1 of the power divider is used for RF power input while the Port 2 and Port 3, which are output ports of the power divider, are attached to EH and ID modules. The sensitivity of both modules is different as EH module requires maximum power and ID module demands a large signal to noise ratio (SNR). In this paper, a two-way tunable power divider is presented. The proposed structure consists of a varactor diode which helps in achieving different power ratios. By tuning the bias voltage of the varactor diode, the capacitance of the circuit changes which results in arbitrary power ratios at the output. This power divider is designed for SWIPT systems so that power divides unequally between the two ports in such a way that maximum power is utilized for energy harvesting purposes and minimum power for information decoding purposes. Initially, 3 dB power divider (PD) is proposed and then optimized for achieving the desired power ratios at the outputs followed by a tunable power divider. The remainder of this paper is organized as follows. Section II presents the design of the unequal power divider. The configuration of the tunable power divider using the varactor diode along with its measured performances is presented in Section III. Eventually, conclusions are presented in Section IV.

II. UNEQUAL POWER DIVIDER

Initially, a 3 dB power divider at 2.4 GHz is designed on Advanced Design System (ADS) using microstrip transmission lines. Rogers $RO4350B^{TM}$ substrate having dielectric constant ϵ of 3.48, the thickness of 0.762 mm, and tanδ of 0.0031 is used in fabricating the design as it offers low losses at higher frequencies and also for its cost-effectiveness. The overall size of the 3 dB power divider is $(39.2 \times 26.5)\ mm^2$. The simulated and measured results of the 3 dB power divider show that the return loss (RL) and isolation (IS) at 2.4 GHz are better than −19 dB and −16 dB respectively. The designed 3 dB power divider is wideband as it covers the frequency range of 1.5 to 3.2 GHz.

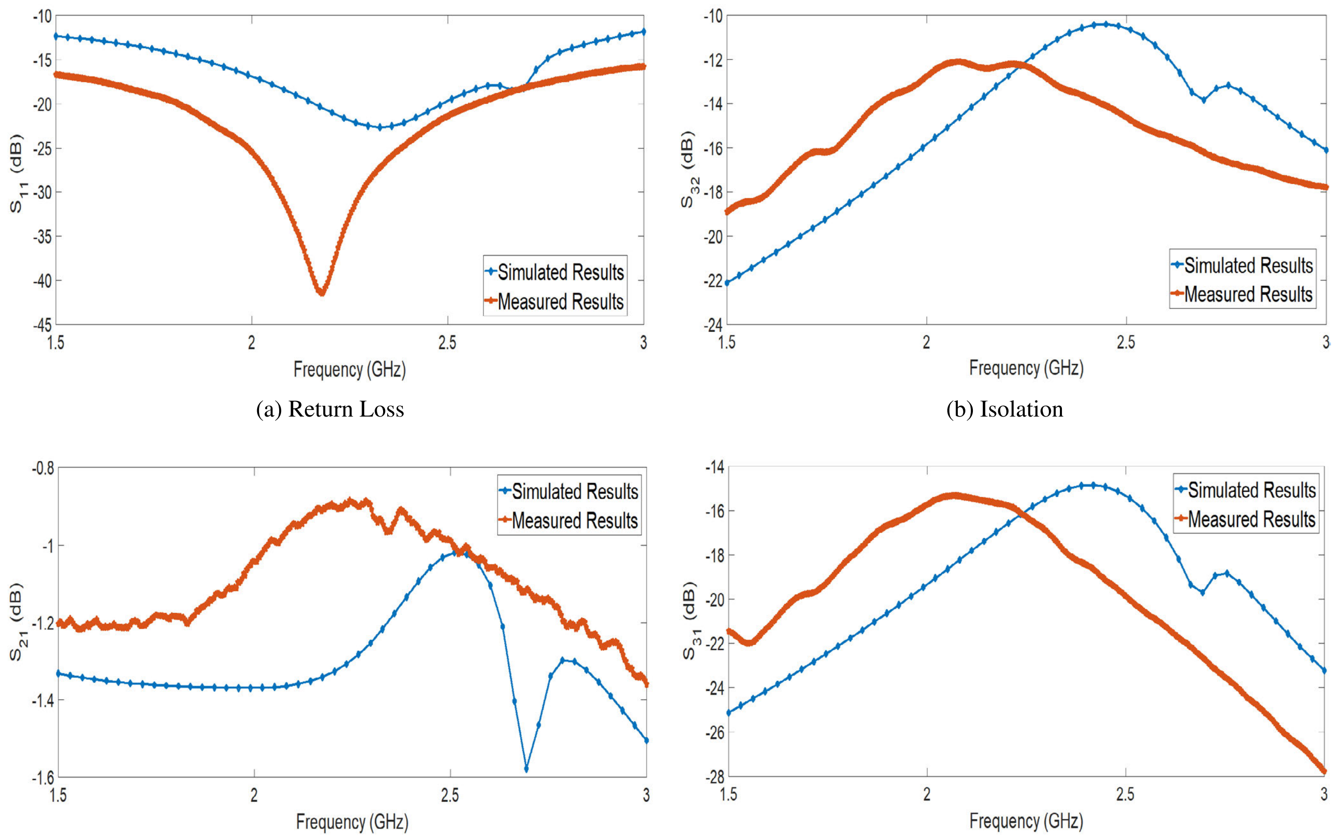
After designing the 3 dB power divider, a 2-way unequal power divider is proposed by making the required changes in the 3 dB power divider circuit. Capacitors are introduced because the well-known topology of the Wilkinson power divider is restricted to small output ratios, (k = (P2:P3) < 4), due to its unrealistic narrow widths associated with the required lines of high impedances. One capacitor is attached with one port of the power divider and the other capacitor is attached along the bridge that links the two output ports of the power divider as shown in figure 1 (a). The capacitor changes the impedance of one output port and this creates the difference in impedance of both output ports. When the signal enters in the power divider through input port, then this difference in impedances of the output ports (port 2 and port 3) helps in achieving unequal power ratio at the outputs. Radial stub at port 1 (input port) and short stub at port 3 (one of the



(a) Schematic

(b) Fabricated design

FIGURE 1. **Unequal power divider.**



(a) Return Loss

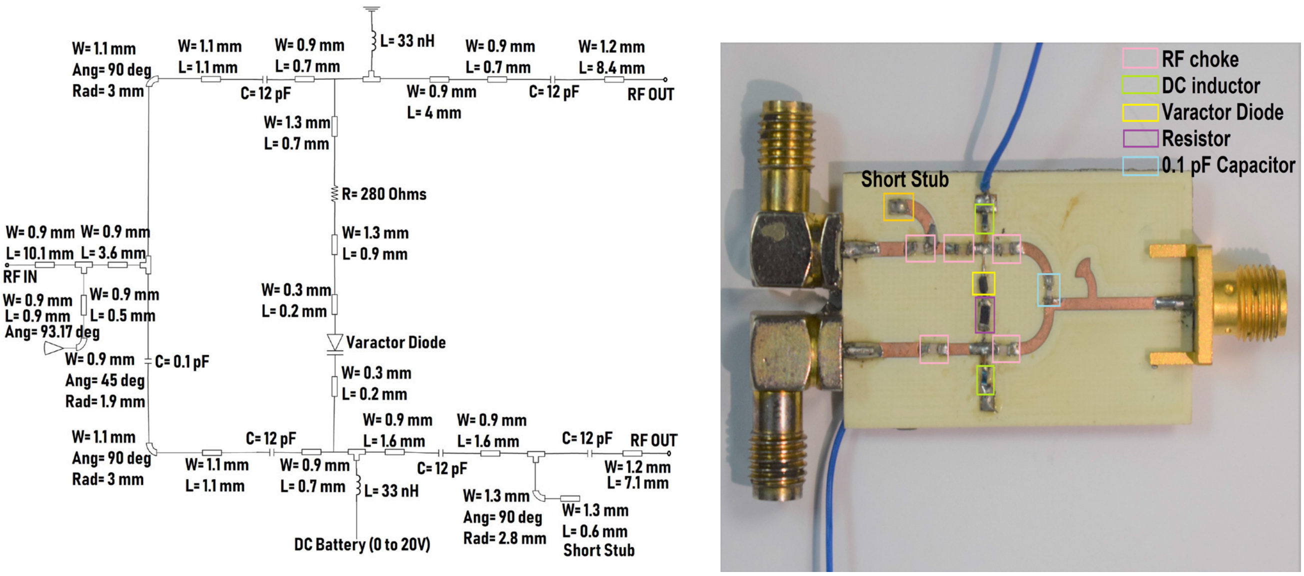
(b) Isolation

(c) S_{21}

(d) S_{31}

FIGURE 2. **Simulated and measured results of unequal PD.**

output port) are introduced for eliminating the mismatching between the impedances that occurred due to the change in the overall capacitance of the circuit. Since capacitors and resistor are used in the design so momentum co-simulation is required for investigating the behaviour of the unequal power divider. The unequal power divider's overall size is



(a) Schematic (b) Fabricated design

FIGURE 3. Tunable power divider.

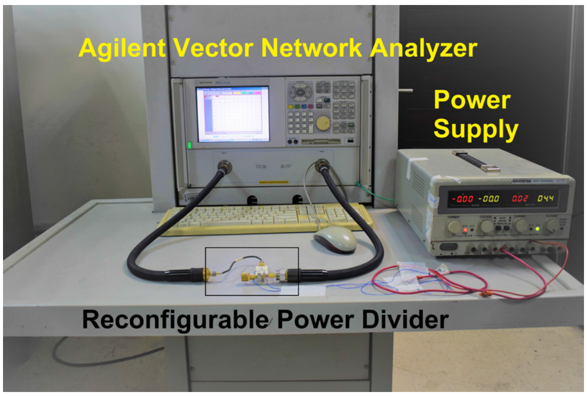


FIGURE 4. Test Setup.

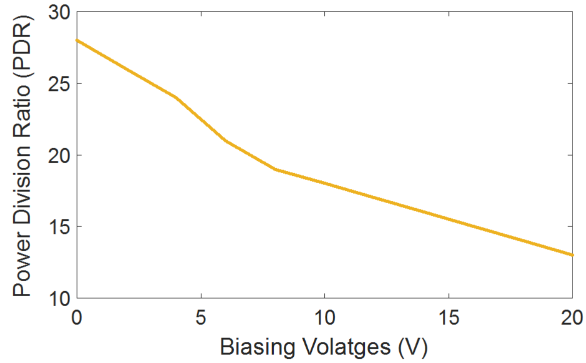


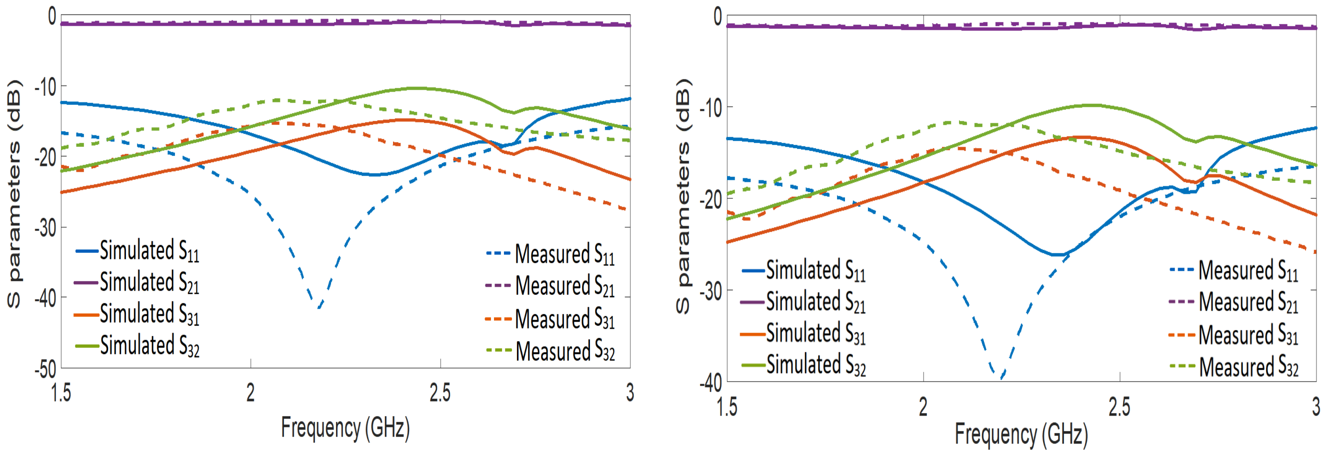
FIGURE 5. Power Division Ratio vs Biasing Voltages of Varactor Diode.

(28 × 12) mm^2. The fabricated structure of unequal power divider is presented in figure 1 (b).

Figure 2 (a) depicts the simulated and measured RL of the unequal power divider. It is clear from the figure that the RL better than −22 dB is achieved at 2.4 GHz and better than −10 dB is achieved across the frequency band 0.1 to 3.3 GHz. Simulated and measured IS of the unequal power divider is given in figure 2 (b). It is clear from the figure that the isolation better than −10 dB is attained across the wide frequency band which also covers the desired frequency of 2.4 GHz. From figure 2 (c) and (d), it can be observed that the value of S_{21} is −0.94 dB and the value of S_{31} is −15.435 dB, therefore 28:1 unequal power ratio is achieved at the power divider's output ports. In simulated results, the value of S_{21} and S_{31} is −1.12 dB and −14.9 dB respectively, so the power ratio achieved at output ports is 24:1.

III. TUNABLE POWER DIVIDER

After achieving the unequal power ratio at the output, a tunable power divider is then presented. As shown in figure 3 (a), the capacitor, attached along the bridge that links the two legs of the power divider, is replaced by the varactor diode (SMV2020-079LF) for tuning purposes. The size of the depletion region enhances when the reverse voltage of the diodes increases. Likewise, the depletion region's size decreases when the reverse voltage of the varactor diode decreases. Hence, the variation in the diode's reverse bias voltage can change the capacitance of the varactor diode. When the overall capacitance of the circuit becomes tunable, different power ratios can be obtained at the outputs. DC biasing circuit is also introduced in the structure of the power divider. Since lumped components (varactor diodes, capacitors, inductors, and resistor) are used in a design so momentum co-simulation is required for investigating the



(a) 0V (28:1)

(b) 8V (19:1)

FIGURE 6. **S parameters of tunable PD.**

TABLE 1. **Comparison with some reported tunable power dividers.**

Ref.	Frequency (GHz)	PDR	RL (dB)	IS (dB)	IS Fractional Bandwidth
[5]	3	6:1, 4:1, equal split PD	-20	>15	66%
[6]	L-band	1:1, 1:2, 1:5	>-15	better than -22	44%
[7]	2.45	1:1, 1:2, 1:3, 1:4	>-20	>-25	30%
[8]	5	over 1:5	-30	>-15	40%
[9]	2.14	1:2	-23	-27	75%
[10]	0.9	1:3, 1:0	-25	>-15	89%
[11]	0.7 to 1.4	1:1 to 1:2.4	>-10	>-15	100%
[12]	0.95	1:3.4	>-16	-18	89%
[13]	1.45	1:2.95 to 1:10.4	-30	-20	107%
[14]	2.4	1:1 to 1:10	>-15	-	-
This work	**2.4**	**13:1 to 28:1**	**>-20**	**>-12**	**250%**

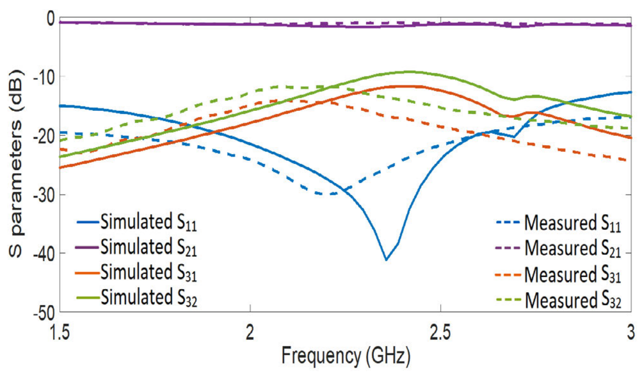


FIGURE 7. **S parameters of tunable PD at 20V (13:1).**

behaviour of tunable PD. The fabricated design of the tunable PD is presented in figure 3 (b).

For evaluating the performance of all the designs of the power divider, the prototype is physically tested with Agilent Vector Network Analyzer (E8362B). S parameters are recorded to validate the performance. Input from VNA is feed to port 1 while the output is taken from port 2 to port 3. The test setup figure is given in figure 4. Figure 5 presents the graph of power division ratio versus biasing voltages. The graph shows that 13:1 to 28:1 PDR can be achieved by varying the biasing voltage of the varactor diode from 0 to 20V. Figure 6 (a) illustrates that the values of return loss, isolation and the power ratio at 2.4 GHz, when tunable power divider operating at 0V, is -24.3 dB, -13.7 dB and 28:1 respectively. These values are exactly the same as that of the unequal power divider as shown in figure 2. The simulated and measured values of return loss, isolation and achieved power ratios against 0V, 8V, and 20V of the varactor diode are arranged in figure 6 (a), (b) and figure 7 respectively. It is obvious from the figures that by tuning the biasing voltage of the varactor diode, the power ratios between 13:1 to 28:1 can be achieved. The slight difference between the simulated and measured results may be attributed to the substrate tolerances and fabrication imperfections. Table 1 shows the comparison of the designed power divider with the reported tunable power dividers. It can be seen that the proposed power divider has higher PDR and IS fractional bandwidth compared to the other dividers included in the comparison.

IV. CONCLUSION

An efficient tunable power divider operating at 2.4 GHz is designed in this paper. The presented power divider is designed for the SWIPT system and it helps in dividing the incoming signal into two signals with unequal power distribution. A varactor diode along with matching stubs is used in the power divider. The achieved power division ratios vary from 13:1 to 28:1 by tuning the reverse voltage of the varactor diode. The achieved power division ratio is the highest reported ratio as per the author's knowledge. The bandwidth measured at 10 dB return loss is 3.2 GHz and the isolation better than 12 dB is achieved between the output ports. The designed structure is compact and the results illustrate that different power ratios along with good matching at all ports and good isolation between the output ports are achieved through tunable power divider. The proposed design may be used for future 5G wireless networks. Furthermore, this power divider can also be designed for Ultra High Frequency (UHF) which will be explored under the considerations of a preferred compact size system.

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