Tunable dual-mode filtering power divider with harmonic suppression

Pengcheng Zhang, Xian Qi Lin, Yuan Jiang, and Yong Fan
EHF Key Laboratory of Fundamental Science, School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, People’s Republic of China
a) xqlin@uestc.edu.cn

Abstract: This paper presents a tunable dual-mode filtering power divider (TDFPD) with harmonic suppression. Two tunable dual-mode resonators are embedded into a power divider with equal power ratio to realize the proposed TDFPD. The odd-mode of the dual-mode resonator is rigorously designed to approach its even-mode so that the proposed TDFPD will show a harmonic suppression performance. Tuning elements sharing technology is also utilized to minimize the numbers of varactors. To demonstrate the proposed design, a prototype is designed and fabricated. The measurement shows the TDFPD can be tuned from 2.10 to 2.31 GHz with a return loss better than 15 dB and Harmonic suppression is better than 20 dB at the frequency range of 2.5 to 9 GHz. Good agreements are observed between measured and simulated results.

Keywords: tunable, filtering power divider, harmonic suppression

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

High-performance RF components with multiple functions are highly demanded in modern wireless communication systems. However, a multiple functional component usually has a larger size. It is an effective way to achieve both multiple functions and small size by using electrically tunable technology as reported to realize tunable filters with central frequency tuning [1, 2, 3]. Integrating multiple components into a single one is also a promising way for size reducing and multiple functions can also be obtained at the same time such as filtering power dividers [4, 5, 6, 7, 8, 9], which consists of a filter and a power divider. In [4], filtering power dividers are realized by adding filtering structure to the input or output lines. Moreover, in [5], bandpass filters are used to replace the transmission lines between the input port and isolation resistor to realize filtering power dividers. Multimode resonators are also used to achieve multimode and multiband filtering power dividers as reported in [6]. In [9], the authors presented a novel frequency-agile filtering power divider with constant absolute bandwidth and high selectivity. However, the tuning elements are significantly increased with the increasing number of the ports. That will enlarge the total size, increase the cost and complicate the circuit design.

Tunable components always suffer from poor harmonic suppression because the harmonics will shift along with the tuning passband frequency. Several methods can be used to overcome the problem, including using defected ground structure (DGS) [10], mismatching at the harmonics [11], and appropriate feeding position with not exciting harmonics [12]. However, there is no tunable filtering power divider with harmonic suppression reported in the past.

In this paper, a two-way tunable dual-mode filtering power divider with harmonic suppression is proposed. The number of the tuning diodes is significantly reduced by using the tuning diodes sharing technique. Two resonators with dual-mode performance are utilized to realize filtering function. Theoretical analysis of
the dual-mode resonator is deduced to illustrate the tuning mechanism. For verification, a prototype that can be tuned from 2.10 to 2.31 GHz is designed and measured.

2 Analysis and design of the TDFPD

Fig. 1(a) shows the proposed tunable dual-mode filtering power divider which is implemented by embedding two tunable dual-mode resonators into the two branches of a power divider with equal power ratio. An appropriate resistor is chosen to improve the isolation of two output ports. Each resonator has two varactors that are located at the central plane of the power divider. With this structure, the varactors located at the center plane can be merged together using tuning elements sharing technology. The topology of the proposed TDFPD is shown in Fig. 1(b) where S and L denote input port and output ports, respectively. Nodes 1 and 2 present tunable odd- and even-mode of the TDFPD, respectively.

Fig. 1. Schematic and topology of the proposed TDFPD. (a) Schematic, (b) Topology.

The passband of the TDFPD is composed of the two resonant frequencies of the tunable dual-mode resonator. Fig. 2(a) shows the schematic of the tunable dual-mode resonator which is composed of two coupled lines, two varactors and a shorted via at the central point. The via can be equivalent to a small grounded inductor $L_{\text{via}}$ which makes the resonator be dual-mode and no even-mode harmonic. The two varactors loaded at the end of the two coupled lines. Due to the position of the two varactors located at the central plane of the power divider, the two varactors are shared by two tunable dual-mode resonators. Since the structure is symmetrical, the odd- and even-mode method can be adopted to analyze the resonant frequencies.

When the odd-mode is applied, there is an electric wall at the central of the resonator. Under odd-mode excitation, it can be represented by half odd-mode circuit as shown in Fig. 2(b). The odd-mode admittance is given as follows:

$$Y_{\text{in,odd}} = Y_C - j Y_m \cot \left( \frac{\theta_m}{2} \right) \frac{f}{f_0}$$  (1)
where \( f \) represents the working frequency, \( Y_m \) and \( \theta_m \) the characteristic admittance and electrical length of the transmission line at the frequency of \( f_0 \), respectively. \( Y_C \) is the input admittance of the coupled line loaded a varactor with the capacitance of \( C/2 \) and is given as:

\[
Y_C = \frac{4 \sin \left( \frac{\theta f}{2 f_0} \right) + 2 \omega C \cos \left( \frac{\theta f}{2 f_0} \right) (Z_{oe} + Z_{oo})}{(Z_{oe} + Z_{oo}) \left[ 2 \cos \left( \frac{\theta f}{2 f_0} \right) - \omega C \sin \left( \frac{\theta f}{2 f_0} \right) (Z_{oe} + Z_{oo}) \right]} \quad (2)
\]

where \( \omega = 2\pi f \), \( \theta \) is the electrical length of the coupled line, \( Z_{oe} \) and \( Z_{oo} \) are the odd- and even-mode characteristic impedance of the coupled line, respectively.

For the resonant condition that \( \text{Im}(Y_{in,odd}) = 0 \), the odd-mode resonant frequency \( (f_{odd}) \) can be determined as:

\[
\frac{4 \sin \left( \frac{\theta f_{odd}}{2 f_0} \right) + 2 \omega C \cos \left( \frac{\theta f_{odd}}{2 f_0} \right) (Z_{oe} + Z_{oo})}{(Z_{oe} + Z_{oo}) \left[ 2 \cos \left( \frac{\theta f_{odd}}{2 f_0} \right) - \omega C \sin \left( \frac{\theta f_{odd}}{2 f_0} \right) (Z_{oe} + Z_{oo}) \right]} = Y_m \cot \left( \frac{\theta_m f_{odd}}{2 f_0} \right) \quad (3)
\]

Likewise, for the even-mode excitation, there is a magnetic wall at the central of the resonator. Under even-mode excitation, it can be represented by half even-mode circuit as shown in Fig. 2(c). The even-mode admittance is given as:

\[
Y_{in,even} = Y_C + Y_m \frac{1/(j\omega L_{via}) + jY_m \tan \left( \frac{\theta_m f_{even}}{2 f_0} \right)}{Y_m + 1/(j\omega L_{via}) j \tan \left( \frac{\theta_m f_{even}}{2 f_0} \right)} \quad (4)
\]

For the resonant condition that \( \text{Im}(Y_{in,even}) = 0 \), the even-mode resonant frequency \( (f_{even}) \) can be determined as:

\[
\frac{2 \sin \left( \frac{\theta f_{even}}{2 f_0} \right) + 2 \pi f_{even} C \cos \left( \frac{\theta f_{even}}{2 f_0} \right) (Z_{oe} + Z_{oo})}{(Z_{oe} + Z_{oo}) \left[ \cos \left( \frac{\theta f_{even}}{2 f_0} \right) - \pi f_{even} C \sin \left( \frac{\theta f_{even}}{2 f_0} \right) (Z_{oe} + Z_{oo}) \right]} = Y_m \frac{1 - 4\pi f_{even} L_{via} Y_m \tan \left( \frac{\theta_m f_{even}}{2 f_0} \right)}{4\pi f_{even} L_{via} Y_m + \tan \left( \frac{\theta_m f_{even}}{2 f_0} \right)} \quad (5)
\]
Because of the small value of the grounded inductance $L_{\text{via}}$ produced by the via, we assume that $L_{\text{via}}$ is equal to 0 nH. At this assumption, we can deduce $Y_{\text{in,odd}} = Y_{\text{in,even}}$, and further obtain $f_{\text{odd}} = f_{\text{even}}$ which means the odd- and even-mode frequencies are the same. Meanwhile, the harmonics caused by the even-mode will vanish when the odd-mode frequencies are moved to the even-mode frequencies.

To verify the above analysis, the full-wave simulation was carried out using High Frequency Structural Simulator (HFSS). The resonator is weakly coupled with two 50 $\Omega$ microstrip lines to investigate its resonant behavior. Fig. 3 shows the resonant frequencies of the dual-mode resonator. When $C$ is varied from 0.5 to 1.5 pF, the odd- and even-mode resonant frequencies decrease from 2.04 to 1.68 GHz at almost the same time and the first even mode also vanishes. With the characteristics of the resonator, a tunable power divider can be designed with dual-mode filtering performance and the harmonics caused by the even modes can be suppressed.

3 Fabrication and measurement

A TDFPD prototype is designed and fabricated to verify the proposed idea. The dimensions are shown in Fig. 4(a) and Fig. 4(b) presents the fabricated prototype with the size of 28.0 $\times$ 29.8 mm. The circuit is designed on a Taconic RF-35 substrate with the thickness of $h = 0.508$ mm, the relative permittivity of $\varepsilon_r = 3.5$ and dielectric loss tangent $\delta = 0.0018$. Infineon BB857 varactors with tuning range of 0.5–6.5 pF are utilized as the tuning elements. The bias resistor $R_b = 11$ k$\Omega$, the capacitor $C_b = 1$ pF and the isolation resistor ($R$) is 100 $\Omega$.

The measurement has a good agreement with the simulated results as shown in Fig. 5. As can be seen, the central frequency of the TDFPD can be tuned from 2.10 to 2.31 GHz with the control voltage of the varactors varied from 7.5 to 30.0 V. Within the tuning range of the passband, $S_{21}$ and $S_{31}$ are both better than 9.0 dB and reach the top of 7.7 dB at 2.18 GHz indicating the loss caused by the filtering and power division is 4.7 to 6.0 dB as shown in Fig. 5(b). Fig. 5(a) and Fig. 5(c) shows the return loss is better than 15 dB and isolation between port 2 and port 3 is better than 20 dB over the tuning range. The first odd-mode harmonic is suppressed below about $-40$ dB, and first even-mode harmonic is lower than $-20$ dB due to
mismatching as shown in Fig. 5(d). Therefore, the harmonic suppression of the design power divider is more than 20 dB at the frequency range of 2.5 to 9.0 GHz.

The tuning elements quantity of a tunable filtering power divider may be increased with the increasing number of resonant modes and output ports. It is a critical issue to decrease the tuning elements number of a circuit because many tuning elements will raise cost, complexity and some other bad influence of the circuit. So, we define a factor–Tunable Elements to Ports and Modes Ratio (TPMR):

![Fig. 4. Fabricated reconfigurable dual-mode filtering power divider prototype. (a) Physical layout and dimensions (unit: mm), (b) Measured prototype.](image)

![Fig. 5. Simulated and measured results of the TDFPD prototype (control voltage: black lines $-3.00$ V, gray lines $-15.0$ V, light gray lines $-7.5$ V). (a) $S_{11}$, (b) $S_{21}$, (c) $S_{23}$, (d) $S_{21}$ at the frequency range of 1.5 to 9.0 GHz.](image)
\[ \text{TPMR} = \frac{\text{Number of tunable elements}}{\text{Number of output ports} \times \text{Number of modes}} \] (6)

to evaluate the usage of the tunable elements due to the increasing number of the output ports.

There are two varactors used in the proposed TDFPD, which means the TPMR is only 0.5. Compared with some other filtering power dividers in Table I, the proposed TDFPD has the smallest TPMR. Although the proposed FRFPD has such a small TPMR, the insertion loss is still high. This is because of the large bandwidth and low Q-factors of the varactors. Hence, an improvement of the insertion loss can be achieved by utilizing high Q-factor varactors and widening the work bandwidth.

### Table I. Comparison with some other tunable filtering power dividers

|          | Freq (GHz) | IL (dB) | Isolation (dB) | No. of modes | Tunable | Harmonic Suppression | No. of Diodes | TPMR |
|----------|------------|---------|----------------|--------------|---------|----------------------|---------------|------|
| [7]      | 1.7–2.1    | 0.6–1.2 | >25            | 1            | Yes     | No                   | 4             | 2    |
| [8]      | 0.71–0.82  | 1.2–2.5 | >20            | 1            | Yes     | No                   | 4             | 2    |
| [9]      | 0.62–0.82  | 1.8–2.4 | >16            | 1            | Yes     | No                   | 8             | 4    |
| This work| 2.10–2.31  | 4.7–6.0 | >20            | 2            | Yes     | Up to 2\text{nd}     | 2             | 0.5  |

### 4 Conclusion

A two-way tunable dual-mode filtering power divider is introduced in this letter. The central frequency of the power divider can be tuned by the varactors with a harmonic suppression property. The varactors are reduced by utilizing tuning elements sharing technology. Compared to all the researches on tunable filtering power dividers before, the proposed TDFPD has the smallest TPMR of 0.5. This power divider and tuning elements sharing technology can be applied in reconfigurable wireless communication systems.

### Acknowledgments

This work was supported in part by NSFC (No. 61571084), in part by EPRF (No. 6141B06120101), in part by NDSTI (No. 1716313ZT00802902), and in part by NKIF (No. 201751000700006).