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Filtered Power Splitter Using Square Open Loop Resonators

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Abstract—A microstrip power splitter with band-pass responses is presented in this paper. The design is based on square open loop resonator topology. This filtered power splitter does not require quarter wavelength transformers and will result in a smaller size than a conventional Wilkinson power divider with integrated band-pass filter. It is a two-way equal power splitter with fifth order band-pass filter characteristics. The power splitter is designed to have Chebyshev band-pass response function. A theoretical analytical circuit model will be presented. From the theoretical model, a microstrip filtered power splitter will be designed and simulated. The proposed filtered power splitter is small in size and reduces circuit complexity. The power splitter is simulated and measured, and the results are presented.

1. INTRODUCTION

Recently, the development of telecommunication equipment has shown a tendency to produce components with unique capabilities and specific features such as ability to split signal to other devices and to be distributed. These microwave components can be designed using various approaches. Printed circuit board (PCB) fabrication is most suitable for planar circuit structure due to its low cost, ease of integration and compactness [1]. In most millimeter and microwave communications systems, Wilkinson power divider has played an essential role for splitting or combining power in numerous microwave applications such as mixers, balanced power amplifiers and feeding networks of antenna arrays. But due to band selectivity, which is poor because of band rejection of the conventional Wilkinson power divider, it suffered a major drawback. Recent studies have been shown [2–5] in which efforts have been made to improve the operational frequency of the power splitter passband selectivity. Also, the Wilkinson power divider has a large circuit size since at its desired frequency, it is composed of two quarter wavelength ($\lambda/4$) line sections. Ref. [2] presents an integration of single-stage coupled line band-pass filter and conventional Wilkinson divider. It satisfactorily implemented a power divider with a good filter response. The conventional $\lambda/4$ impedance section of a Wilkinson power divider is replaced by stepped impedance inter-digital coupling element in [3] which gives filtering properties and a good out of band rejection. In [4, 5], in order to achieve a better passband selectivity, the transmission path incorporates fourth-order and second/fourth-order quasi-elliptic filters, respectively.

Like power dividers, another essential component important in both transmitters and receivers is a band-pass filter. A band-pass filter is essential in RF front end to take a signal having a frequency of f_1 to f_2, and rejecting signals outside this range. To realize this, a filter waveguide technology is appropriate when considering low insertion loss. Up to now, there have been some work on the miniaturization of filters [6–12] and also proposals of several resonator types to miniaturize filter size. Among them are the uses of Stepped-Input Resonator [8] which gives a better stopband response and higher spurious resonant frequency with reduced circuit size and microstrip Square Open Loop Resonators (SOLR) [13] in which miniaturization was done using series capacitive loading of the resonators.

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A method of integration of power splitter and a band-pass filter into a single unit/component is essential to further reduce circuit size and cost of manufacturing. This gave rise to the proposition of filtering power dividers. In [14], a miniaturised power divider with band-pass characteristics based on coupled-resonator topology was presented, the reduced circuit was due to shrinking of assembled resonator. A filtering microstrip antenna array is presented in [15]. The design's feeding network consists of one power splitter and two baluns utilizing coupled resonator.

In this paper, a filtering power splitter is proposed. It is designed based on coupled resonator concept. It has the advantage of small size and reduction of complex circuitry. The Chebyshev filtered power splitter has been designed by deploying microstrip technology using square open loop resonators. The designed microstrip structure is constructed and tested to verify the proposed concept.

This paper is outlined as follows. Section 1 gives a brief introduction. Section 2 gives the approach used in the design. The microstrip design of the band-pass power splitter is given in Section 3, and Section 4 presents the simulated and measured results.

2. DESIGN OF IDEAL FILTERING POWER SPLITTER

A conventional Wilkinson power splitter is shown in Figure 1. The circuit contains two $\lambda/4$ transformers which results in a larger circuit size. A three-way coupling between adjacent resonators is used in place of the junction of conventional power splitter. The circuit area becomes smaller by implementing a coupled resonator network.

The coupling scheme of the filtered power splitter is shown in Figure 2. The solid lines represent the coupling path, and each of the nodes represents a resonator. At resonance, there is coupling of signal energy from port 1 to port 2 through resonators 1, 2, 3, 4 and 5, and from port 1 to port 3 through resonators 1, B, C, D and E. The circuit is similar to joining two identical 5-pole bandpass Chebyshev

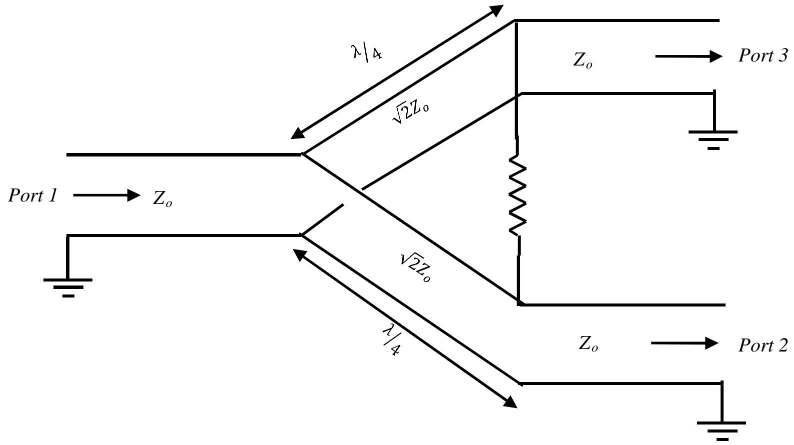

Figure 1. Conventional Wilkinson power splitter, **reproduced courtesy of The Electromagnetics Academy**

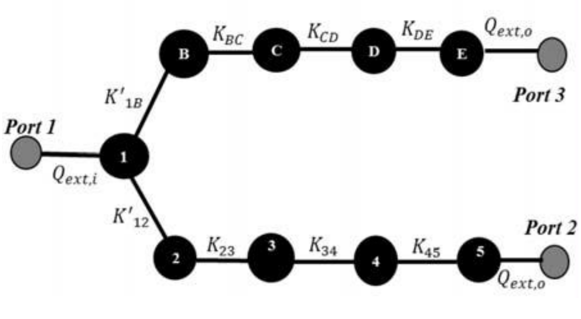

Figure 2. Coupling arrangement of a five-pole Chebyshev band-pass filtered splitter, **reproduced courtesy of The Electromagnetics Academy**

filters at a common resonator 1.

The conventional theory based on coupled resonator bandpass filter knowledge is applicable here. The external quality factor, Q_{ext}, and the coupling coefficient, k_{nm}, can be determined using the usual method used in band-pass filter design as described in [17]. To ensure an equal power split in the two splitting paths, the coupling coefficients are k'_{12} and k'_{1B} and made to equate to $k_{12}/\sqrt{2} = k_{1B}/\sqrt{2}$, where k_{12} and $k_{1\text{B}}$ are the coupling coefficients of a standard band-pass filter. This coupling value is based on the theory of establishing equal power splitting, with half power delivering to each branch and having the same return loss performance for each branch [16, 19].

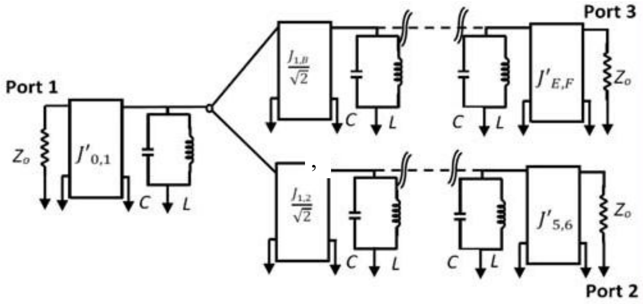

Figure 3. Equivalent circuit of a five-pole Chebyshev bandpass power splitter ,
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Figure 3 gives the equivalent circuit of a 5-pole bandpass filter. The admittance J — Inverter method is used to determine the coupling between resonators. g is the normalised low-pass filter value, Z_o the characteristics impedance and $k = 1$ to n, where n is the order of the filter

$$J_{0,1} = J_{5,6} = J_{E,F} = 1$$

$$J'_{0,1} = J'_{5,6} = J'_{E,F} = \frac{1}{Z_o}$$

$$J_{k,k+1} = \sqrt{\frac{g_1^2}{g_k g_{k+1}}} \Bigg/ Z_o \tag{1}$$

C and L are the self-capacitance and inductance respectively, given by Equation (2), where $\omega_o = 2\pi f_o$, f_o is the fundamental frequency and Δ the fractional bandwidth of the filter.

$$C = \frac{g_1}{\Delta \omega_o Z_o}; \quad L = \frac{1}{\omega_o^2 C} \tag{2}$$

The coupling coefficient, k, and the input/output external quality factor, Q_{ext}, can be determined by [20] as given in Equations (3) and (4).

$$k_{k,k+1} = J_{k,k+1}\sqrt{\frac{L}{C}} \tag{3}$$

$$Q_{ext,i/o} = \omega_o Z_o C \tag{4}$$

The theoretical values of the external quality factor for ports 1, 2 and 3 are all determined as 19.423.

Figure 4 gives the simulated result of the filtered splitter circuit and shows that it has a centre frequency of 2 GHz and a minimum return loss of not greater than 20 dB. This is in conformity with the original design specification. This is in conformity with the original design specification.

3. MICROSTRIP DESIGN OF BANDPASS POWER SPLITTER

3.1. Design Procedure

The proposed filtered Chebyshev power splitter has been designed and implemented using the microstrip technology. The Square Open Loop Resonators (SOLR) topology is deployed. This topology is used

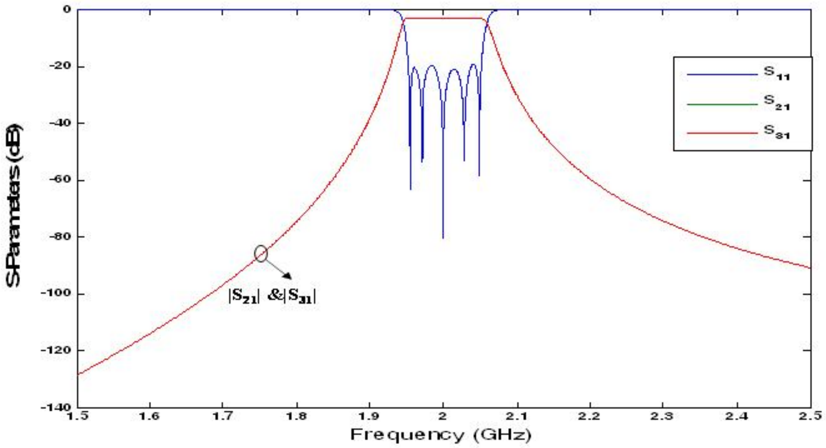


Figure 4. Ideal circuit model responses for proposed five-pole Chebyshev filtered power splitter, **reproduced courtesy of The Electromagnetics Academy**

since it has the advantage of size, weight and cost reduction; also, compared to waveguide cavity cross-coupled filters, it is more flexible to construct a variety of cross-coupled planar filters [18]. The calculated circuit model is simulated using Keysight's Advance Design System (ADS) EM simulator software. Figure 2 shows the resonators and coupling arrangement. These resonators are arranged to realise couplings only between the adjacent resonators.

The following specifications are used in the design of the fifth order Chebyshev band-pass power splitter. The center frequency, f_o, is designed to be 2 GHz. The passband return loss of port 1, R_L, is 20 dB, a fractional bandwidth, Δ of 5% and a characteristics impedance, Z_o of 50 Ω.

The table below gives the normalized Low Pass (LP) parameters of the lumped circuit at a return loss of 20 dB.

Table 1. Lumped element g values, **reproduced courtesy of The Electromagnetics Academy**

g	g_1	g_2	g_3	g_4	g_5	g_6
1	0.9714	1.3721	1.8014	1.3721	0.9714	1

The expressions for coupling coefficient, $k_{n,m}$, and external quality factor, Q_{ext}, have been provided in Eqs. (3) and (4). k'_{12} and k'_{1B} represent the coupling between the common resonator 1 and the next resonator towards Port2 and Port3, respectively. This gives: $k'_{12} = k'_{1B} = 0.0306$, $k_{23} = k_{34} = k_{BC} = k_{CD} = 0.032$, $k_{45} = k_{DE} = 0.043$ and $Q_{ext,i} = Q_{ext,o} = \omega_o Z_o C = 19.428$.

To determine the coupling space between microstrip resonators, two coupled microstrip resonators are simulated, and the two resonance mode frequencies are extracted as f_1 and f_2, where f_1 is the lower resonance mode and f_2 the higher resonance mode. The coupling coefficient can be calculated as

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \quad \text{where } k \text{ is the coupling coefficient.} \tag{5}$$

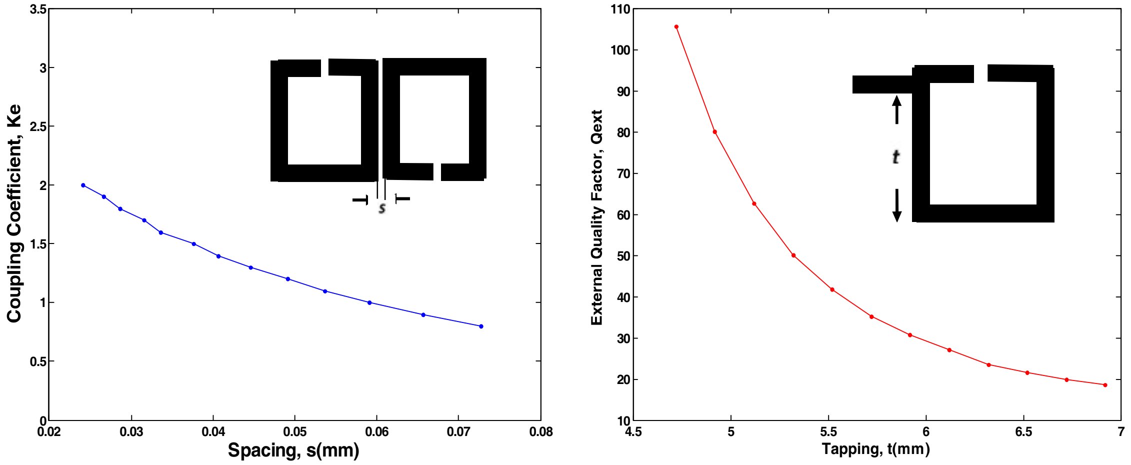
Figure 5(a) shows the simulated curve of the coupling coefficients as a function of the coupling space between the microstrip resonators.

To determine the tapping point, t from the input and output resonators, the arrangement as shown in Figure 5(b) (inset) is designed and simulated. The insertion loss curve is used to determine the external quality factor, Q_{ext}, using:

$$Q_{ext} = \frac{f_0}{\delta f@-3\,\text{dB}} \tag{6}$$

where $\delta f@-3\,\text{dB}$ is the 3 dB bandwidth of the curve and f_0 the resonant frequency.

Figure 5(b) shows the external quality factor as a function of the tapped location along the microstrip resonator.



(a) (b)

Figure 5. (a) Coupling Coefficient against spacing. (b) External quality factor against tapping, **reproduced courtesy of The Electromagnetics Academy**

The graphs of Figure 5(a) and Figure 5(b) are used to determine the physical dimensions of the power splitter. From the graphs, the following are obtained: $s_{12} = s_{45} = s_{1B} = s_{DE} = 1.43\,\text{mm}$; $s_{23} = s_{34} = s_{BC} = s_{CD} = 1.77\,\text{mm}$ and $s'_{12} = s'_{1B} = 1.8\,\text{mm}$, $t = 6.88\,\text{mm}$.

3.2. Final Circuit Layout

The microstrip power splitter is achieved by using 9 multi-coupled SOLR as shown in Figure 6. Using Rogers RO3210 substrate with dielectric constant of 10.8 with loss tangent of 0.0023 and thickness of 1.27 mm, the designed circuit is fabricated on this substrate. A copper conductor with conductivity of 5.8×10^7 Siemens/m is used for the top and bottom of the microstrip. The figure also gives the final microstrip schematic layout including its physical dimensions. The effective area is measured $0.97\lambda_g \times 0.90\lambda_g = 0.873\lambda_g^2$, where λ_g is the guided wavelength in mm at 2 GHz. The physical dimensions are given in Table 2.

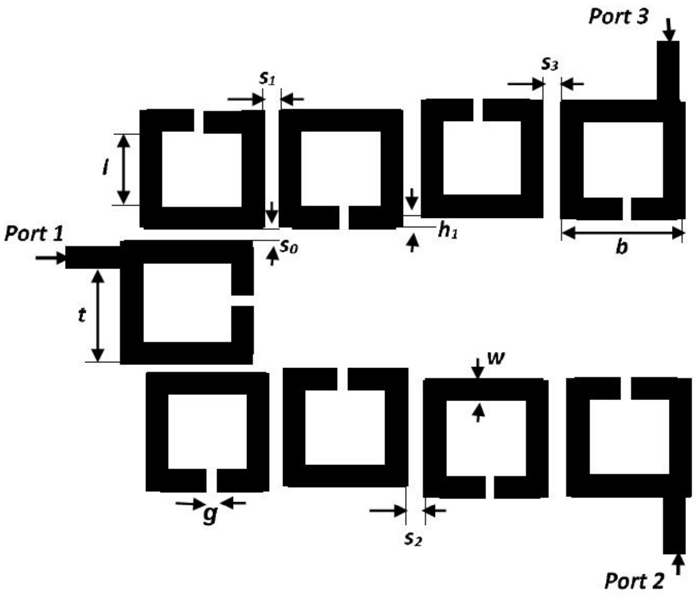


Figure 6. Microstrip schematic layout, **reproduced courtesy of The Electromagnetics Academy**

Table 2. Physical dimensions of the filtering power splitter (mm), **reproduced courtesy of The Electromagnetics Academy**

Dimension	Value	Dimension	Value
s	1.28	h_1	0.61
s_1	1.65	g	0.44
s_2	1.39	w	1.12
s_3	1.57	t	6.88
l	7.00	b	8.12

4. SIMULATION AND MEASURED RESULT AND ANALYSIS

The full wave simulation is carried out in Keysight's ADS EM simulation platform. Printed circuit board technology is used to construct the circuit, and the proposed filtering power splitter is measured using Agilent Vector Network Analyser. The proposed splitter is designed to operate at 2 GHz. The values given in Table 2 are employed in realizing the power splitter layout given in Figure 6.

Figure 7 depicts the EM lossy simulation insertion loss of the input to the output ports ($|S_{21}|$ and $|S_{31}|$), and the return loss at input port ($|S_{11}|$). The measured return loss is better than 15 dB, and the

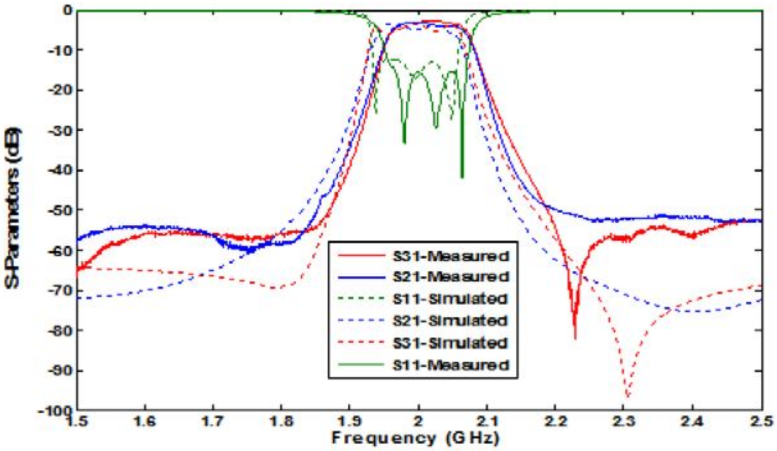
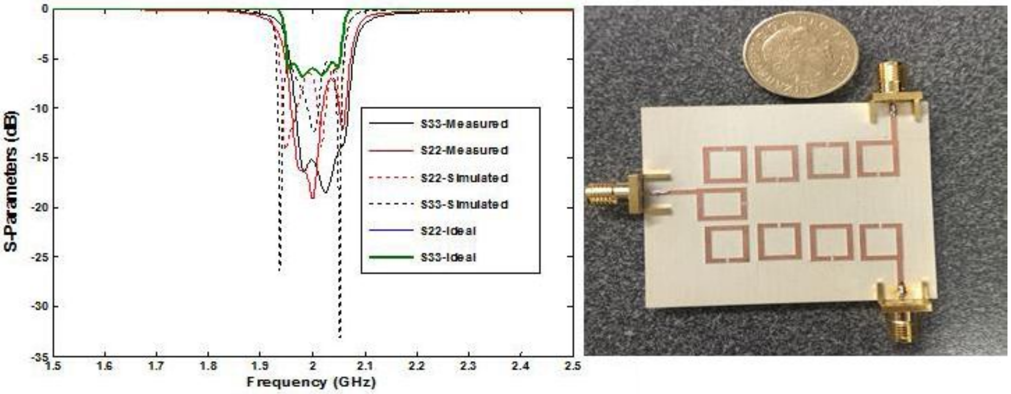


Figure 7. Simulated and measured responses of the fifth order filtering bandpass power filter, **reproduced courtesy of The Electromagnetics Academy**



(a) (b)

Figure 8. 5-pole filtered power splitter. (a) Output ports return loss results. (b) Pictorial view, **reproduced courtesy of The Electromagnetics Academy**

insertion losses of port 2 and port 3 path are 3.12 dB and 2.99 dB ±18% of ripple, respectively. The fractional bandwidth is about 6%. In the EM simulation, the minimum return loss is approximately 20 dB, and the output ports insertion losses are at 3 dB while the fractional bandwidth for this design is 5%. The return loss responses of the output ports 2 and 3 ($|S_{22}|$ and $|S_{33}|$) are given in Figure 8(a), which shows that the ideal return losses on both ports are better than 5.40 dB. The return losses of output ports 2 and 3 are better than 13 dB and 6 dB, respectively for measured power splitter.

5. CONCLUSION

A fifth order Chebyshev Bandpass filtered power splitter is explored. The proposed design has eliminated the need for an additional power splitter when a filtered power splitter is required. The design is simulated and constructed. Measurement is also carried out to verify the design topology, in which there is reasonable good agreement between the simulated and measured results. This design topology validates the concept of the proposed design procedure, i.e., the power splitting can be achieved by merely changing the coupling coefficient of the adjacent resonators at the splitting point. However, there is a drawback in this design which is the isolation of the output ports and the poor matching of the output ports. The good isolation between ports 2 and 3 cannot be easily achieved in the current design. However, this proposed design is still useful for filtered power splitting applications where there is not signal returning from ports 2 and 3.

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