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Design and Fabrication of a Miniature Band Pass Filter to Enhance Frequency Bandwidth for Improved Data Transfer Rates in 5G Communication

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Abstract: **-** This paper presents the design and fabrication of a miniature band pass filter (M-BPF) using microstrip technology. The focus of this paper is to highlight the advantages of 5G communication in high data transfer rate applications. The test BPF is introduced with a bandwidth ranging from 7.6-9.8 GHz. It demonstrates good return loss and group delay, while also being miniaturized. The design is implemented on a Rogers RT/Duroid 5880 substrate. The proposed filter is manufactured and characterized, with the fabrication results providing support for the simulation results. The measurement and electromagnetic (EM) simulation results presented in this paper show a good correlation. The design of the M-BPF incorporates the GRN technique for resonator geometry, the stepped-impedance resonator (SIR) technique for impedance matching and reducing the effect of substrate admittance/capacitance, and electromagnetic coupling (EMC) for resonator network coupling based on the direct-coupled resonators (DCR) technique. The dimensions of the M-BPF are 1.4 × 1.5 mm2.

Keywords: Miniature band pass filter (M-BPF), microstrip, scattering parameters, electromagnetic coupling (EMC), direct-coupled resonators (DCR)

I. INTRODUCTION *(HEADING 1)*

In today's world, the demand for wireless communication applications is growing. This has created higher expectations from consumers for fast and effective communication. As a result, advanced transmission speeds have become necessary [1]. The development of mobile communication technology has been greatly influenced by the progression of wireless communications, leading to the emergence of the Fifth Generation (5G) [2], [3], [4], [5]. One area where wireless communication and technology have made significant progress is the use of wearable antennas in wireless body area networks (WBANs) [6]. The 5 GHz band, with its wide bandwidth and high data rate, holds great potential for the development of WBANs and is increasingly being used for wearable antenna applications [7]. Furthermore, 5G smart grid networks can establish edge and fog computing with intelligent control and automation. To achieve faster and more efficient communication, 5G utilizes higher millimeter-wave frequencies in the microwave spectrum. These frequencies range from 0.6 to 3.7 GHz (LOW), 3.7 GHz to 24 GHz (MID), and 24 GHz and higher for communications technology and the Internet [8-11]. [8-11]. A larger frequency spectrum is required to some extent due to the need for higher data rates. Applications like WiMAX and CDMA operate in the GHz range. These 5G mobile communication systems require high-integration, low-cost, and high-speed data transmission. Bandpass filters (BPFs) are considered potential techniques to meet the requirements of 5G mobile communications as vital components of wireless communication systems. These BPFs should have a compact size, low loss, and wide passbands [12-16]. Improving insertion loss performance requires these filters to have a compact size, low loss, and wide passbands [17]. In recent times, high-performance miniature microstrip band filters have been increasingly used in telecommunication systems and circuits, especially in RF/microwave circuits. There has been a growing trend in utilizing the frequency selection level technique [18-22] for low-pass filters. A previous study [23] developed and replicated a straightforward approach to designing a band-pass filter using two square open-loop resonators. In [24], a design for the complementary split resonator (CSRR) is presented, which downsizes microwave devices implemented in planar technology, such as filters and diplexers. In [25], the Stub Loaded Multiple Mode Resonator (SL-MMR) method creates a microwave band-pass filter for 5G mid-band applications with a fractional bandwidth of 12.8% (500 MHz impedance bandwidth). In [26], a band-pass filter is introduced that uses a rectangular strip stepped impedance resonator (SIR) based on multilayer high-temperature ceramic (HTCC) technology. Achieving bandpass filters requires microwave coupled lines band-pass

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filters [27]. In [27], the differences between the simulated and implemented performance are attributed to uncalculated factors and the impact of the metal casing. However, the main limitations lie in the potential occurrence of undesired stimulation states due to disparities between the simulated and implemented outcomes. In [28], a parallel-coupled microstrip band-pass filter is designed for GSM band applications using half wavelength long resonators and admittance inverters with specific parameters. However, it is important to simulate the layout in order to confirm practical efficiency, and the reflection ratio exhibits relatively unfavorable performance.

The main findings of [29] clude the successful implementation of a UWB band-pass filter with dual notched bands, demonstrating good agreement between simulated and measured results, as well as effective suppression of dispensable bands at 3.5 GHz and 7.5 GHz in the WiMAX band and X-band. However, this study also identifies some limitations, such as challenges related to the size of the notch filter, achieving good broadband and sharp skirt selectivity, potential leakage of the floor, and the need for better frequency selection performance and a more compact structure. Additionally, the study highlights the difficulty in achieving flexible adjustment of the transmission zero [29]. The paper [30] presents a compact wideband microstrip bandpass filter designed for the 3.5GHz frequency range. This filter exhibits exceptional performance for upcoming "5G" mobile standards, as well as for WIMAX and WLAN applications [30]. Chen et al. proposed a new miniature microstrip filter-antenna with broad stop-band characteristics [31]. This filter-antenna has an 8% fractional bandwidth in the frequency range of 2.36-2.55GHz and a gain of approximately 1.8dBi. It also has a stop-band that extends to 7.8GHz with a gain of less than -18dBi [31]. However, this study has certain limitations. It lacks universality in the method and insufficient consideration of spurious responses. Additionally, the filter and antenna components are larger compared to other RF front-end components, and there is a rapid decrease in gain in the stop-band for the SIR filter-antenna [31]. The main findings of [32] include the successful simulation and fabrication of a two-resonator microstrip bandpass filter for WIFI applications, despite some fabrication difficulties. The study also identified discrepancies between substrate characteristics in datasheets and reality, which affect the filter's center frequency and bandwidth [32]. However, it is important to acknowledge the limitations of this study. One such limitation is the existence of discrepancies between the experimental and simulation results, which can be attributed to impedance matching issues. Additionally, there is a possibility of prototype corruption and discrepancies in center frequency and bandwidth. These discrepancies arise from differences in substrate characteristics between the datasheets and the actual samples [32]. The paper [33] highlights the notable features of the proposed miniature planar quad-band BPF. These features include its ability to cover various frequency bands for different applications, its compact size, and its exceptional performance. The key findings of [34] include the suggestion and creation of a compact bandpass filter with U-shaped resonators and Defected Ground Structures. This filter demonstrates low insertion loss, high rejection level, and a sharp roll-off performance at 5.8 GHz, making it suitable for WLAN applications. The implemented coupling method allows the second-order bandpass filters to be compact, while still operating as a second order Chebyshev response with low insertion loss and good rejection at 5.8 GHz. However, there are some limitations to this study. Increasing the filter order results in increased filter size and insertion loss. There is also a high transition band on the higher band of the filter, poor rejection in the lower band, and poorly matched S 11. Additionally, there may be possible discrepancies between simulated and measured results due to fabrication defects and substrate tolerance [34]. The primary discoveries of [35] include the compact design of the filter structure, the utilization of source to load coupling to enhance the transmission coefficient and create two TZs in the upper stop-band, and the dispersion analysis to examine the MTM property of the filter structure. This study has certain limitations, such as possible disparities between the simulated and measured S-parameters due to substrate and fabrication factors, as well as potential restrictions in the accuracy and applicability of the dispersion analysis for investigating the metamaterial property of the designed filter structure [35]. This study focuses on the design and fabrication of a unique miniature band-pass filter. The main objective is to enhance the frequency bandwidth in order to achieve higher data transfer rates for microwave and 5G communication systems. The proposed design offers several advantages. Firstly, its bandwidth is wider compared to other designs in the literature. This increased bandwidth is crucial for high data rate signal transmission in various applications, including portable devices and communication radars. Additionally, the use of coupled transmission lines in this design enhances the scattering parameters. Moreover, the resonator network in this design boasts a simple configuration and small dimensions, enabling wider bandwidth and reduced time delay in signal transmission.

II. DESIGN OF PROPOSED MINIATURE BANDPASS FILTER

Figure 1 illustrates the schematic configuration of the Miniature bandpass filter.

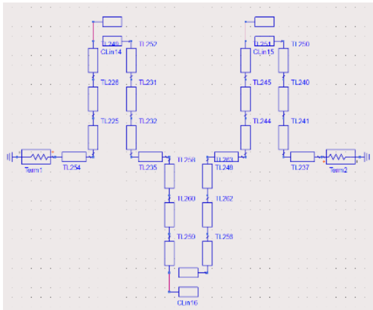

Fig. 1. Schematic of the proposed BPF design

The suggested design can be executed by employing a passive bandpass filter (BPF) using microstrip technology. Furthermore, the dominant transverse electric-magnetic (TEM) mode can be utilized through microstrip transmission lines. The filter can be designed in thin substrate models, such as II-shaped and U-shaped. Equations (1-2) are utilized to calculate the effective dielectric constant, characteristic impedance of the microstrip line, and the substrate's height, given its permittivity [36-38].

$$\begin{cases} \varepsilon_{re} = \dfrac{\varepsilon_{r+1}}{2} + \dfrac{\varepsilon_{r-1}}{2}\left\{\left(1+12\dfrac{h}{w}\right)^{-0.5} + 0.04(1-\dfrac{w}{h})^2\right\} & for\ \dfrac{w}{h}<1 \\ Z_c = \dfrac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left(\dfrac{8h}{w}+0.25\dfrac{w}{h}\right) & for\ \dfrac{w}{h}<1 \end{cases} \qquad (1)$$

$$\begin{cases} \varepsilon_{re} = \dfrac{\varepsilon_{r+1}}{2} + \dfrac{\varepsilon_{r-1}}{2}\left\{\left(1+12\dfrac{h}{w}\right)^{-0.5}\right\} & for\ \dfrac{w}{h}>1 \\ Z_c = \dfrac{\eta}{\sqrt{\varepsilon_{re}}}\left\{\dfrac{w}{h}+1.393+0.677\ln\left(\dfrac{w}{h}+1.444\right)\right\}^{-1} & for\ \dfrac{w}{h}>1 \end{cases} \qquad (2)$$

The impedance and admittance modes can affect the losses of the filter, and Eq. 3 gives the dielectric loss coefficient concerning microstrip lines [30].

$$\propto_d = 8.686\left(\frac{\varepsilon_{re}-1}{\varepsilon_r-1}\right)\frac{\varepsilon_r}{\varepsilon_{re}}\frac{\tan\delta}{\lambda_g} \qquad (3)$$

In this paper, we have used coupled transmission lines to design the desired bandpass filter. One simple method for calculating the parameters of these coupled transmission lines is to use the coupling factor. By utilizing the coupling factor, we can determine both the even and odd mode impedance, which in turn allows us to calculate the remaining parameters of the line [39].. Equation (4) demonstrates the relationship between the coupling factor and the even and odd mode impedances of the coupled line pair.

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \qquad (4)$$

The characteristic impedance, denoted by Z_0, is calculated based on the odd mode impedance (Z_{0o}) and the even mode impedance (Z_{0e}) of a pair of coupled lines. The coupling factor is represented by C .

$$Z_0^2 = Z_{0e} Z_{0o} \tag{5}$$

The even and odd mode impedances, denoted as Z_{0e} and Z_{0o}, are determined by combining Equation (4) with Equation (5). This combination results in the initial design equations:

$$Z_{0e} = Z_0 \sqrt{\frac{1+C}{1-C}} \tag{6}$$

and

$$Z_{0o} = Z_0 \sqrt{\frac{1-C}{1+C}} \tag{7}$$

One of the most important considerations in the design of parallel-coupled line structures is determining their physical dimensions. When designing, we often come across the challenge of determining the physical dimensions of a proposed parallel-coupled line structure. The width of the coupled line, the spacing between the coupled lines, and the length of the coupled lines can be considered given Z_{0o} and Z_{0o}. In [32, 39], an approximate synthesis technique is presented to determine the values of $\frac{w}{h}$ and $\frac{s}{h}$ based on Z_{0o} and Z_{0e}. Calculating these parameters can be complex and time-consuming. As a result, many researchers rely on MATLAB programs to estimate the ratio of $\frac{w}{h}$ and $\frac{s}{h}$ [32, 40, 41]. The proposed design of the Bandpass Filter (BPF) can be implemented on a thin substrate using II-shaped and U-shaped models. The width-to-height ratio of the microstrip substrate is considered in two different conditions, which can affect the filter's performance. The design process involves selecting the appropriate substrate material, determining the resonator geometry, and choosing the feeding mechanism. Simulation tools can also be used to optimize the filter's performance by adjusting various design parameters, such as resonator size, shape, substrate material, and feeding mechanism. Once the design is finalized, the BPF can be fabricated using standard printed circuit board (PCB) techniques. Careful assembly and testing are necessary to ensure that the filter meets the desired performance specifications. It is important to note that the design process may require iterative refinement using simulation tools to achieve the desired performance specifications. There are several techniques for enhancing the bandwidth of 5G filters. These include using a distributed element structure, employing resonant structures with a high Q factor, or utilizing metamaterials. These techniques help increase the bandwidth while maintaining low insertion loss and high selectivity. Another approach for bandwidth enhancement is to incorporate multiple resonators into the filter design, such as coupled resonators or dual-mode resonators. By using multiple resonators, the filter's bandwidth can be increased without compromising selectivity or insertion loss. In summary, bandwidth enhancement is a crucial aspect of filter design for 5G communication systems. Various techniques, including distributed element structures, resonant structures with high Q factors, metamaterials, and multiple resonators, can be employed to achieve high bandwidth and low insertion loss. In the proposed BPF, the LC structure is designed using passive impedance circuits. The proposed filter can be used in various technologies with different bandwidths and resonator geometries, such as DCR [42].

A miniature microwave filter is a small device that is used to selectively allow or reduce specific frequencies in the microwave range. It is commonly used in microwave communication systems, radar systems, wireless devices, and other applications that require precise frequency control. The main purpose of a microwave filter is to let the desired microwave signals pass through while blocking or reducing unwanted signals or noise. By doing this, filters help to maintain signal quality, minimize interference, and enhance overall system performance. Depending on the specific application needs, filters can be designed to operate within certain frequency bands or have a wideband response. The term "miniature microwave filter" refers to filters that are made to be compact in size. This is achieved through the use of advanced technologies and miniaturization techniques like microstrip, stripline, or surface-mount technology (SMT). These filters are typically made with smaller components such as miniaturized resonators, capacitors, and inductors. Miniature microwave filters offer several benefits including space-saving, reduced weight, and improved integration capabilities. They are commonly used in portable electronic devices, compact communication systems, and applications where size and weight are important factors. The specific design and characteristics of a miniature microwave filter depend on factors such as the desired frequency range, bandwidth, insertion loss, selectivity, and other performance requirements of the application.

III. FABRICATION AND MEASUREMENT RESULTS

The proposed BPF is fabricated using a 0.5 mm thick Rogers 5880 substrate, which has a relative permittivity $\varepsilon_r = 2.22$ and loss tangent $\tan\delta = 0.0009$. The corresponding fabricated prototype is shown in Fig. 2. The size of the proposed filter, excluding the feeding lines, is 1.4 mm × 1.5 mm.

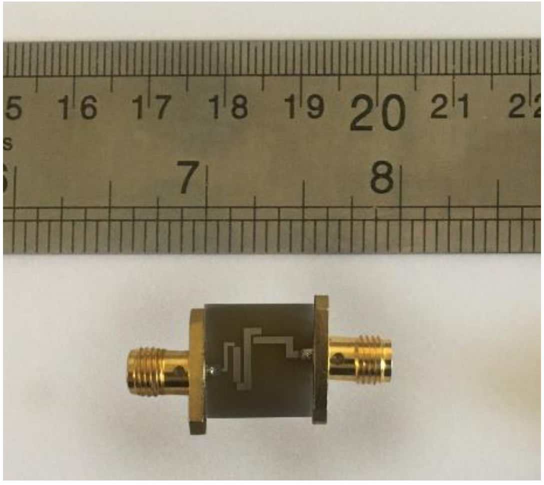

Fig. 2. The Fabricated circuit of the proposed BPF

The filter's frequency bandwidth for low-band 5G communication applications is in the range of 7-9.8 GHz, with a frequency response range of 2.8 GHz. The proposed BPF achieves the highest bandwidth compared to similar designs, making it an important feature for signal transmission in wireless radar systems. The use of coupled transmission lines allows for a compact resonator network and a miniature BPF. The SIR technique improves matching, while the GRN technique enhances the frequency response and reduces the size of the resonator network. The EMC and DCR techniques enable direct coupling of electromagnetic waves, resulting in improved scattering parameters. MATLAB-based filter design software code is used to calculate the filter parameters. The fabricated prototype's transmission and reflection characteristics are measured using an Agilent N9928A vector network analyzer, and the results are presented in Table 1. The frequency response range of the filter for scattering parameters is depicted in Fig. 3, while the time delay factor is shown in Fig. 4. Table 2 provides a comparison between the proposed design and previous works, highlighting the superiority of the proposed filter. Additionally, Table 2 presents the delay parameter in the signal transfer function, which is significantly reduced in this study. As a result, the signal is transmitted through the resonator network with minimal delay, mitigating signal attenuation caused by substrate effects.

Tab. 1. Specifications and results of the proposed BPF.

Frequency Response of BPF		**Protocol**
7.6 GHz to 9.8 GHz		5G for Uplink-Downlink
Return Loss (dB)	**Isolation (dB)**	**TD (F(GHz),T(us))**
-62.406	-59.22	BPF < TD

Travel-Signal (Transmission)	**Application**	**Size**
4.4 (us)	Large subcarrier spacing for super extra data in 5G microwave transmission	1.4 mm × 1.5 mm
Technology	**Material**	**Model**
Coupled transmission line	Rogers.5880	BPF

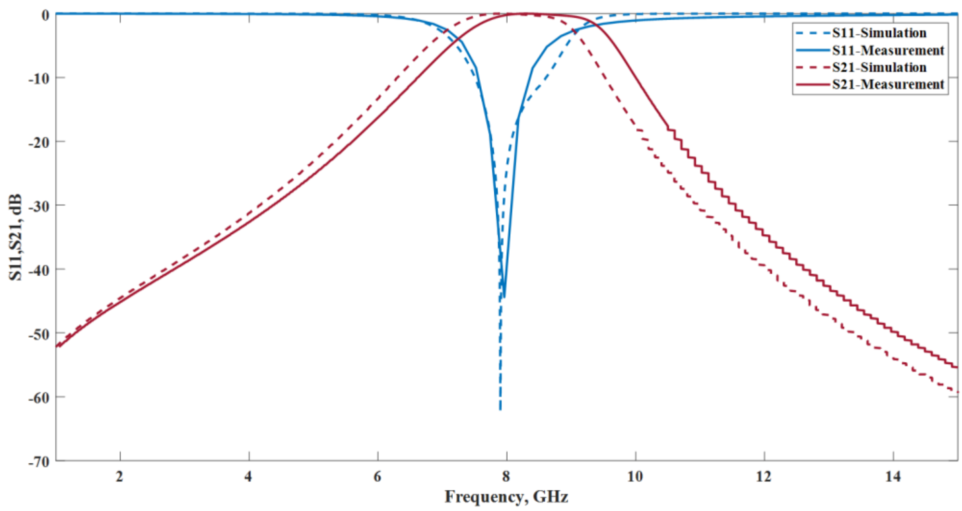

Fig. 3. Frequency response of the proposed BPF.

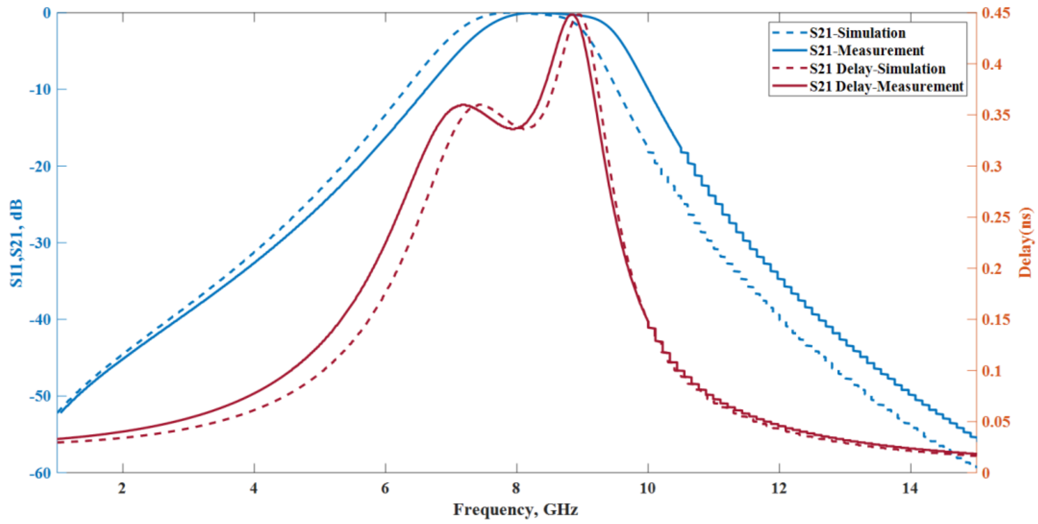

Fig. 4. Time delay versus frequency response of the proposed BPF

Tab. 2. Comparing the results of the proposed BPF with previous designs.

Ref.	Frequency (GHz)	Fractional Bandwidths (%) in -10 dB Return Loss	Minimum Return Loss (dB)	Dimension (mm2)
[12]	1.690-1.879	10	-12.5	16×15
[35]	2.21-2.72	26.12	-14.90	24.93×20.45
[34]	5.65-5.89	-	-19.8	-
[31]	1.8-1.9	5.4	-60	3×1
[33]	1.2-1.5	22	-26	3.65×1.6
[36]	2.36-2.55	12	-23	-
[30]	27.5-29.4	15	-20	7×4
[25]	3.7–4.2	12.8	-19	25 × 50
[26]	2-2.54	7	-17	7×4.8
This Work	7.6-9.8	66	-44.406	1.4 × 1.5

IV. COCLUSION

The present study involves the design and simulation of an M-BPF using microstrip technology. The M-BPF was designed to operate within a wide frequency bandwidth of 7.6-9.8 GHz, which covers the low-band 5G communication protocol. To expand the frequency response range, the proposed M-BPF was simulated utilizing the ADS software. The design offers a broader band-pass response in comparison to the microwave bandwidth, enabling high-rate data transfer over short and medium distances in communication devices and radar systems. Furthermore, the proposed M-BPF has a wide range of potential applications in the electronic industries. It is recommended to explore the development of diplexer and triplexer designs based on the proposed model for the 5G protocol.

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