Design of a Compact Textile Bandpass Filter Based on Zigzag Stepped-Impedance Resonators for 5G Wearable Applications

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Abstract. In this paper, a small microwave bandpass filter operating at 3.5 GHz is designed and simulated for use in fifth-generation (5G) applications. The proposed filter is suitable for textile integration as it offers reduced size, low insertion loss and im-proved frequency selectivity by combining zigzag transmission lines with stepped impedance resonators (SIRs). CST Microwave Studio was used to simulate on a felt textile substrate. The flexible design is compatible with portable systems, fa-cilitating the constant mobility of the human body while maintaining constant electromagnetic performance. Thanks to these features, the proposed filter is an excellent option for wearable 5G systems, such as body sensor networks, Inter-net of Things applications and smart e-health wearables.

1 Introduction

The integration of electronics into textiles has enabled the development of wearable devices with new functionalities, capable of operating at radio frequency (RF) and microwave frequencies [1,2]. This development is based in particular on electronic textiles, which use conductive wires to ensure electrical conductivity. Wearable technology has developed considerably in recent years, attracting a great deal of interest from researchers. It is now being exploited in a wide range of applications, such as body networks [3], localization [4], fitness monitoring [5] and signal propagation control using metamaterials embedded in e-textiles [6]. E-textile devices share several key characteristics: low profile, light weight, wireless connectivity and multifunctionality.

In this context, microwave bandpass filters (BPFs) play a fundamental role in wireless communication systems. These components have to satisfy numerous requirements in terms of frequency performance, compactness and manufacturing cost. Recently, research has focused strongly on the miniaturization and integration of portable bandpass filters adapted to textile environments [7-12].

The design of bandpass filters is based on various approaches, of which the use of resonators is one of the most widespread. A resonator is an electromagnetic element with resonant

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behaviour, widely used in filters [13-15] as well as in other components such as diplexers [16-18]. There are two main types of resonators: localized-element resonators and distributed-transmission-line resonators. The former, based on discrete components such as inductors and capacitors, must be significantly smaller than a wavelength, which limits their efficiency at high frequencies. In contrast, distributed resonators, made up of transmission lines, are better suited to microwave applications, offering higher performance in this range. In these structures, the coupling between the resonators and the supply lines directly influences the frequency response, and the overall performance of the filter depends closely on the physical dimensions and properties of the substrate used.
The goal of the research is to develop a novel wearable pass-band filter for fifth-generation (5G) communication systems by combining zigzag lines with the stepped impedance resonator (SIR). This design aims to create a small structure with high selectivity, low insertion loss, and ease of implementation, making it especially suit-able for integration on textile substrates.

2 Methodology of Designing A Filter

In this work, attention is focused on the λg/4 type stepped impedance resonator (SIR), considered to be one of the most interesting of the various SIR configurations. This type of resonator is distinguished by its reduced dimensions, making it particularly well-suited to the design of compact bandpass filters. The fundamental structure of the quarter-wave SIR is depicted in Fig. 1.

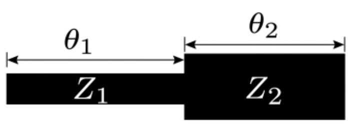

Fig. 1. Basic Structure of the Stepped Impedance.

The condition of resonance for SIR signal is given by [19]:

$$\frac{Z_2}{Z_1} = tan\beta_1 l_1 \; tan\beta_2 l_2 = K \; ; \theta_1 = \; \beta_1 l_1 \; and \; \theta_2 = \; \beta_2 l_2 \qquad (1)$$

Where Z_1 is the impedance of narrow section, Z_2 is the impedance of wider section and θ_1 and θ_2 are the electric lengths of narrow and wider section.
Starting from the basic resonator (Fig. 1), additional sections have been incorporated, as shown in Fig. 2. This configuration consists of four distinct sections, each characterized by a specific impedance (Z_1, Z_2, ..., Z_n) and a different length (θ_1, θ_2,..., θ_n).

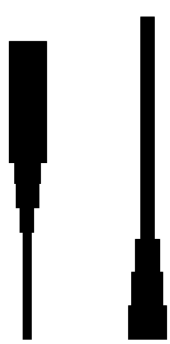

Fig. 2. Proposed Resonators Based on Multisection Stepped Impedance.

In order to design the new bandpass filter proposed in this work, the two resonators shown in Fig. 1 and Fig. 2 respectively were combined. This combination was achieved using zigzag lines, ensuring signal transmission between the two ports while contributing to the device's compactness and performance as depicted in Fig. 3.

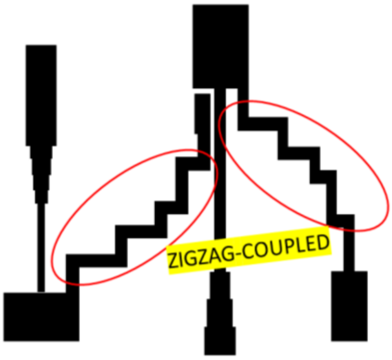

Fig. 3. Novel Zigzag Line Configuration.

3 The Proposed BPF Filter

The compact microstrip band pass filter was specifically designed to operate at the frequency 3.5 GHz, with a total size of 25 × 23 mm², shown in Fig.4. Table 1 provides a summary of the suggested filter's design parameters.

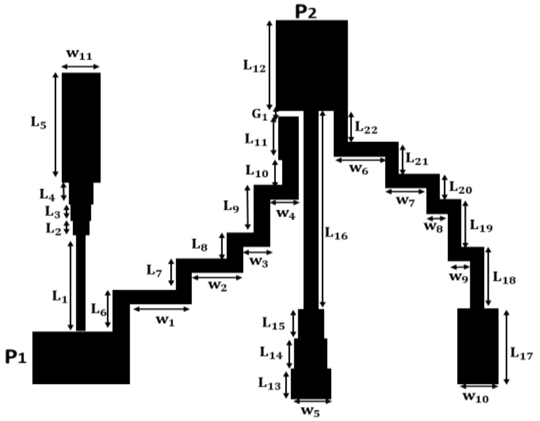

Fig. 4. The proposed BPF Filter.

Table 1. The proposed filter's dimensions.

Parameters	Values in (mm)	Parameters	Values in (mm)	Parameters	Values in (mm)
L_1	5	L_{12}	5.7	w_1	3.5
L_2	1	L_{13}	1.6	w_2	2.5
L_3	1.5	L_{14}	2	w_3	1.3
L_4	1.3	L_{15}	2	w_4	1.3
L_5	7.3	L_{16}	11.9	w_5	1.8
L_6	2.2	L_{17}	4.4	w_6	3.3

L_7	2.4	L_{18}	3.6	w_7	2.5
L_8	1.3	L_{19}	2.5	w_8	1.3
L_9	2.5	L_{20}	1.3	w_9	1.3
L_{10}	1.7	L_{21}	2.4	w_{10}	2
L_{11}	2.4	L_{22}	2	w_{11}	2
				G_1	0.5

4 Study Parameters

The impact of important factors on the proposed filter's matching can be seen by the simulation results shown in Figures 5 and 6. The gap G_1 was gradually changed, while all other filter parameters remained unchanged. Increasing G_1 was found to degrade the return loss while keeping the insertion loss comparatively constant. The optimal value of G_1, ensuring good matching, is 0.5.

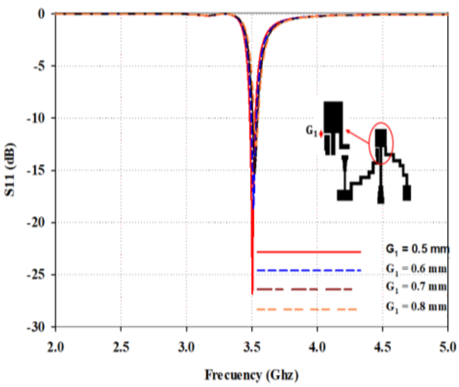

Fig. 5. Simulated S11 with varied G1.

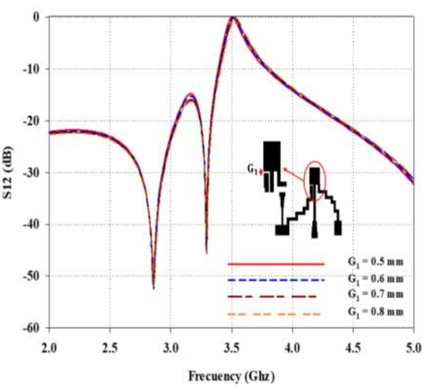

Fig. 6. Simulated S12 with varied G1.

5 Results And Discussion

The filter was developed and simulated using CST-MWS EM-simulation, with a felt textile substrate. This substrate has a relative permittivity of εr = 1.24, a low loss tan-gent tan(δ) = 0.0016, and a thickness of 0.88 mm. Additionally integrated is a copper layer with a tm = 0.035 mm.

The insertion loss at 3.5GHz is approximately 0.7dB, and the return loss is around 26dB, as shown in Figure 7.

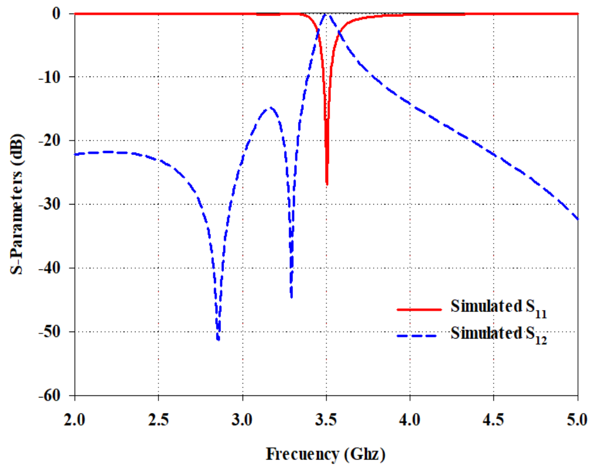

Fig. 7. Simulated S-Parameters.

Any rigorous scientific investigation must include validation of its results, which is why the lumped-element equivalent circuit is so crucial. The electrical behavior of the filter was modeled in this study by obtaining its LC equivalent circuit, shown in figure 8, from the simulated structure.

The scattering parameter results of the ADS simulations (Fig. 9), which show good agreement with those of the EM simulation, validate the lumped-element equivalent circuit. In addition to explicitly describing crucial circuit elements such as resona-tors and coupling effects, this circuit model offers in-depth performance analysis in terms of insertion loss, isolation and bandwidth.

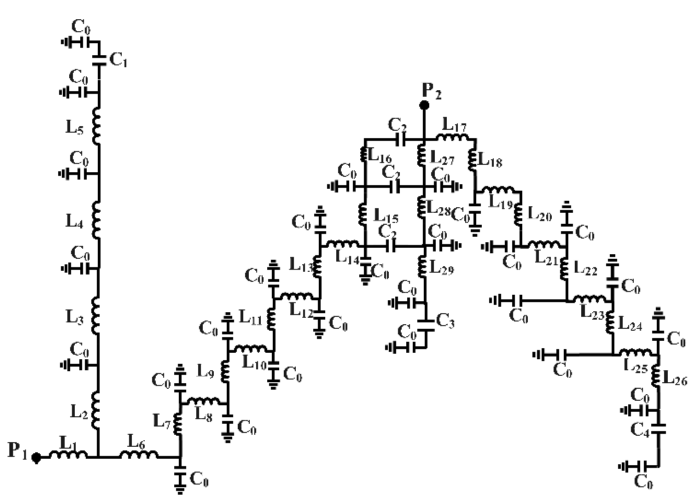

Fig. 8. Schematic of the Equivalent Lumped Element Circuit.

In ADS, the values of L and C are frequently determined by S-parameter-based optimization. However, the above formulas can be used to find approximate initial values before optimization.

Series inductance L: $$L = Z_0 \frac{l Z_0 \sqrt{\varepsilon_{eff}}}{c} \quad (2)$$

Shunt capacitance C: $$C = \frac{l\sqrt{\varepsilon_{eff}}}{Z_0 C} \quad (3)$$

l :microstrip line length.
Z_0:characteristic impedance.
The optimal values of these parameters are given as follows:
$C_0 = 0.231\text{pF},\ C_1 = 20.4\text{pF}, C_2 = 35\text{pF},\ C_3 = 6.6\text{pF}, C_4 = 7.715\text{pF}, L_1 = 8.44\text{nH},\ L_2 = 241.1\text{nH},\ L_3 = 59.605\text{nH}, L_4 = 0.5\text{nH}, L_5 = 59.205\text{nH}, L_6 = 1.755\text{nH}, L_7 = 8.435\text{nH}, L_8 = 2.1\text{nH}, L_9 = 5.375\text{nH}, L_{10} = 0.97\text{nH}, L_{11} = 6.425\text{nH}, L_{12} = 96.735\text{nH}, L_{13} = 24.05\text{nH}, L_{14} = 24.315\text{nH}, L_{15} = 23.00075\text{nH}, L_{16} = 300.35\text{nH}, L_{17} = 2.165\text{nH}, L_{18} = 1.52\text{nH}, L_{19} = 13.4\text{nH}, L_{20} = 34.84\text{nH}, L_{21} = 69.00069\text{nH}, L_{22} = 9.64\text{nH}, L_{23} = 450.05\text{nH},\ L_{24} = 450.05\text{nH}, L_{25} = 30.3007\text{nH}, L_{26} = 48.00057\text{nH}, L_{27} = 28.385\text{nH}, L_{28} = 46.36\text{nH}, L_{29} = 1.755\text{nH}.$

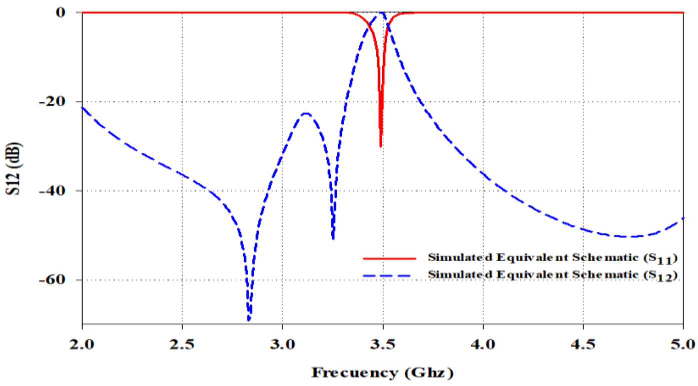

Fig. 9. Simulated S-Parameter of the Equivalent Lumped Element Circuit.

6 Applications Of The Proposed Textile Filter In 5G Systems.

With a center frequency of 3.5 GHz, this textile filter holds great promise for fifth-generation (5G) applications, particularly in the fields of embedded communication systems, the Internet of Things (IoT) and e-health. Simplicity of integration into wearable clothing or accessories, which need to adapt to the continuous movements of the human body in dynamic environments, requires this flexibility as shown in figure 10. The textile filter could thus be used to enhance the connectivity of body sensors, guarantee reliable communication in mobile environments and encourage the creation of new generations of smart clothing for 5G applications.
The filter has been developed to respond to the various structural distortions, such as bending (figure 10), caused by body movements. These distortions can alter the electromagnetic characteristics of the filter and therefore influence its performance. It is therefore essential that the performance of washable filters remains constant despite these restrictions. Therefore, it is crucial to examine how the flexion affects the filter's overall performance.

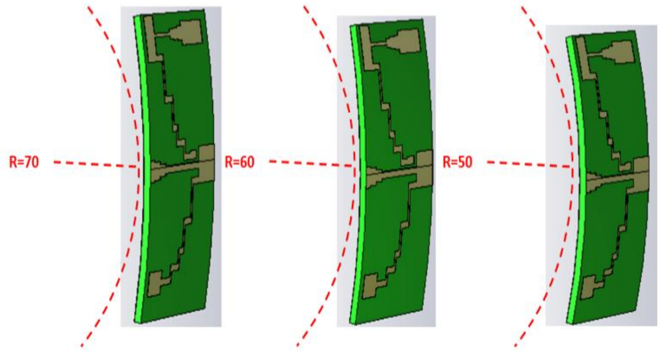

Fig. 10. Bending of the proposed Filter.

Three different bending radii were examined: 70 mm, 60 mm, and 50 mm. The impact of bending at these radii was compared with the filter's performance in a flat configuration. Figure 11 shows the simulated reflection coefficients for each case. The results show that the filter maintains a satisfactory fit, with a return loss consistently below -24 dB in all bending scenarios. In addition, a slight shift to the left of the resonant frequency is observed in the bending case compared to the flat state. It is important to note that bending has no effect on the fractional bandwidth of the filter in any of the configurations examined.

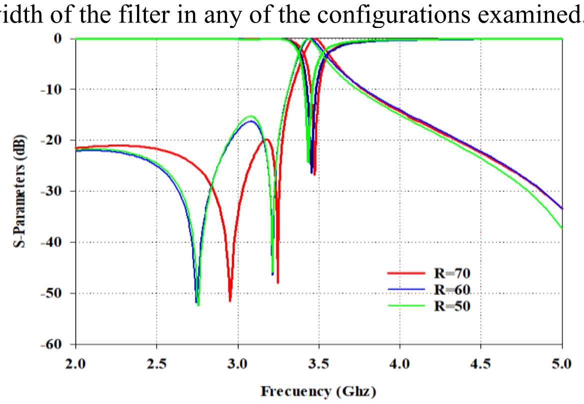

Fig. 11. Simulation of the filter under different bending radii.

Our proposed filter is compared with various filters that have been referenced in the literature in Table 2. As can be seen, the filter that is being presented exhibits better adaptation and lower insertion losses. it has a smaller size compared to the designs presented in [10–12].

Table 2. Comparative performance improvements with recently published.

Refs	Fc (GHz)	Return loss (dB)	Insertion losses (dB)	Substrate type/ Dielectric constant	Size (mm2)
[10]	2.4	>14.3	1.59	Polydimethylsiloxane(PDMS) 2.8	41.1 x31.0
[11]	2.45	26	1	FPCB 2.17	40 x 48.2
[12]	2.42	20	0.34	Flexible polyimide (PI) 3.5	20.9 x 43.1
This work	3.5	>26	0.07	Felt textile	25 x 23

7 Conclusion

This work simulates and designs a small microwave bandpass filter that operates at 3.5 GHz for fifth-generation (5G) applications. By combining zigzag transmission lines with stepped impedance resonators (SIRs), the proposed filter offers improved frequency selectivity, low insertion loss and reduced size, making it suitable for tex-tile integration. A felt textile substrate was used for simulation using CST Micro-wave Studio. The flexible design allows continuous mobility of the human body while maintaining coherent electromagnetic performance, making it compatible with wearable devices. These features make the proposed filter an excellent choice for wearable 5G systems, including Internet of Things applications, body sensor net-works and smart e-health wearables.

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