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Design and Simulation of a Compact Microstrip Diplexer for Medical Applications Using FR4 Substrate

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ABSTRACT: **The paper describes the design and simulation of a small microstrip diplexer to be used in the medical wireless dual-bands (2 GHz, 3 GHz) using a low-cost FR4 substrate ($\varepsilon r = 4.7$, $h = 1.6$ mm, $\tan\delta = 0.015$). The proposed diplexer utilizes a T-junction design that consists of two bandpass filters that are attached to a shared input port to allow a high level of signal separation at two separate frequency bands focused on 1.6 GHz and 2.34 GHz. This is designed on the theory of transmission line and optimized with full-wave electromagnetic simulation. The results obtained show that the impedance is good with the values of return loss of 19.84 dB and 17.62 dB, respectively, at the two operating bands. The insertion loss is kept at around 2.8 dB on both channels, and a high isolation (more than 28 dB) is achieved, providing the channels with adequate separation. Despite the intrinsic dielectric losses of the FR4 substrate, the diplexer has stable performance with narrow fractional bandwidths of around 2.5-2.6 %, and therefore it can be used in selective biomedical communication systems. The suggested design presents an effective trade-off between performance, size, and cost, and it has a high potential of being used as a low-cost medical RF front-end.**

Keywords: *Microstrip, diplexer, FR4 substrate, narrow bands, medical wireless application*

1. Introduction

The fast development of wireless medical technology has led to a much higher demand for miniature, efficient, and cost-effective RF front-end devices. Applications that need a stable multi-band communications capability include wearable health monitoring systems, implantable medical devices, and wireless diagnostic equipment [1,2].

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A diplexer is a basic passive part of microwave technology that allows separating or combining signals of other frequencies. It enables a single antenna to be used in several frequency bands without taking into consideration the other frequency bands, which is vital in the present-days multi-standard communication systems [3, 4].

Microstrip technology is largely favored in such designs because it is low profile, simple to make, and can be combined with printed circuit board (PCB) manufacturing. Nonetheless, it is also difficult to design high-performance microstrip diplexers with FR4 substrate, because of its high dielectric loss and moderate permittivity [5, 6].

Many different diplexer designs have been described in the literature, all trying to improve various parameters, including the insertion loss, isolation, size, and selectivity. The conventional designs tend to use parallel-coupled line bandpass filters, open-loop resonators, and hairpin resonators in order to ensure compactness. More complex methods have proposed Stepped Impedance Resonators (SIR) to reduce size and operate in the multi-band, stub-loaded resonators to make resonators more selective and harmonic-free, Defected Ground Structures (DGS) to make resonators isolating and less mutually coupled, and strongly-inspired metamaterial structures which can make resonators much smaller and more selective. High-performance diplexers are commonly built on low-loss substrates like Rogers RT/Duroid, but these compounds are very costly to fabricate, as they require high costs. Conversely, FR4-based designs are not so developed because of a large loss tangent, but the realization of efficient diplexers on FR4 is still an active area of research, especially with low-cost biomedical systems [5-10].

In spite of such constraints, FR4 is still appealing for medical use due to its cheapness and universal distribution. Thus, the work aims to design and optimize a microstrip diplexer using FR4 and achieve reasonable RF performance.

2. Diplexer Design

The substrate used to design the diplexer is FR4 with a relative permittivity of ($\varepsilon r = 4.7$), thickness ($h = 1.6$ mm), and loss tangent ($\tan\delta = 0.015$). These material characteristics are limited to some extent by increased dielectric losses compared to low-loss substrates, but they also render FR4 a cost-efficient option in practical design. The main aim of this design is to achieve a dual-band diplexer capable of providing good performance in major parameters. Particularly, the design will be expected to reach a good return loss of less than (-10 dB), which means that there will be minimal signal reflection and power transfer. Also, the low-insertion loss is aimed at preserving the signal integrity and minimizing the attenuation in the passbands. Another critical requirement is high isolation of over 20 dB, as this is assured to provide good isolation between the two frequency channels and reduce any form of interference. With these performance measures and these constraints of FR4, the design attempts to offer a low-cost and efficient solution that can be used in other areas like biomedical systems, where affordability and size are commonly valued in addition to electrical performance. Figure 1 presents the diplexer topology.

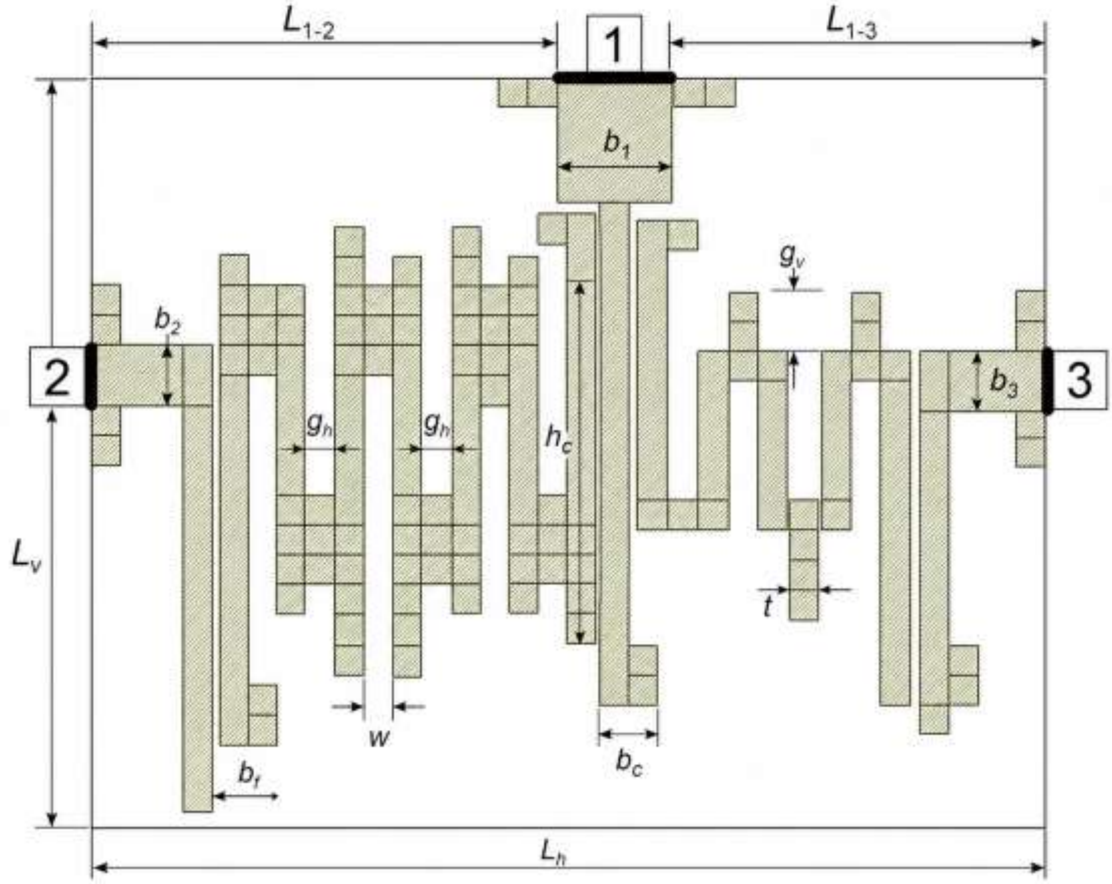

Figure 1: Proposed microstrip diplexer topology and dimensions in mm units: L_v=26 mm, L_h=32 mm, g_h= 1mm, w=1 mm, t=1 mm, b_1=4 mm, b_3=2 mm, b_c=2mm, g_v=2mm, h_c=12.2 mm, b_2=2 mm, b_f=2mm, $L_{1\text{-}3}$=12 mm, $L_{1\text{-}2}$=15.5 mm.

Once the individual filters are designed, they are both attached to a single common input node to create the diplexer structure. The matching is optimized at this stage, and the reflections are minimized by matching impedances in order to supply efficient power transfer between the input and the output ports. The two channels are isolated with correct spacing and layout tuning, which decreases the undesired coupling and interference. To fine-tune the design, a full-wave electromagnetic simulation is conducted, and the physical dimensions can be fine-tuned, and performance measures, including return loss, insertion loss, and isolation, can be checked. This is done through an iterative process that makes sure that the final diplexer is functioning as per the desired specification, but is also stable and reliable throughout the operating frequency ranges.

In the original design, the diplexer uses the T-junction design with one input port (Port 1) and two output ports (Port 2 and Port 3) with two bandpass filter branches attached to the junction. Both the branches transmit a given frequency band and reject the other to provide suitable channel separation. The channels are carried out through the implementation of microstrip resonators, which are the heart of the design. The center frequency of each band is set by the resonant length of each individual section of microstrip, and the bandwidth is set by the coupling gap between resonances. Moreover, the width of the line of the microstrip sections is also selected with care to create the desirable characteristic impedance to facilitate efficient transmission of signals and efficient matching of the microstrip. This resonance length, coupling gap, and line width combination gives the design the flexibility required to have the required performance in terms of selectivity, isolation, and the loss of insertion.

A microstrip diplexer is also constructed based on the transmission line theory. The effective dielectric constant can be obtained as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5}$$

The guided wavelength is given by:

$\lambda_g = \frac{c}{f\sqrt{\epsilon_{eff}}}$

The resonator length is approximately:

L ≈ λg / 2

Where c is the speed of light and f is the center frequency.

3. Simulation Results and Discussion

Tables 1-5 and Figure 2 demonstrate the simulated S-parameters of the diplexer with the AWR EM simulator. Phases and group delays of the response of the projected microstrip diplexer are illustrated in Figures 3-4. The proposed diplexer is able to perform well in medical uses, as the results indicate. The simulated S-parameters of the proposed diplexer prove that it works effectively as a dual-band device and also separates channels. Two different passbands around 1.6 GHz and 2.34 GHz, depicting Channel 1 and Channel 2, are observed, respectively. The return loss is about 19.84 dB at 1.6 GHz, which is a good indication of impedance matching and efficient transfer of power. The return loss is below 17 dB at 2.34 GHz, which is an indication that matching performance is stable in both channels. The design is also confirmed by the nature of insertion losses. The S21 is about 1.6 GHz about -2.81 dB, and S13 is reduced to about -28 dB. At the higher frequencies, however, at 2.34 GHz, S13 is the first transmission path with the association of -2.79 dB, and S21 is less than -26 dB. This establishes that every channel is selective in sending signals to its output port. Isolation performance is also excellent, with S23 values exceeding 28 dB up to 38.97 dB. This guarantees insignificant channel interference. The 0.04 GHz and 0.06 GHz narrow bandwidths translate to fractional bandwidths of approximately 2.5% and 2.6%, to improve selectivity in medical applications. The T-junction design is effective in the combination of the two filters, and the tuning of the two channels will help ensure minimal signal interference between the channels. Although the use of FR4 as the substrate creates certain dielectric losses, the performance is still good enough to be used in the intended application. Some of the benefits of the design include: the design is low cost, it is in a compact design, and the design methodology is also simple, making it practical to be applied in the real world application. There are, however, certain drawbacks that are also noticed, including increased insertion loss compared to designs based on Rogers substrates and limited Q-factor owing to the intrinsic dielectric losses of FR4. However, in the case of a small medical communication system involving short range where cost and ease are of prime importance, the general performance of the diplexer is satisfactory and befitting to the use.

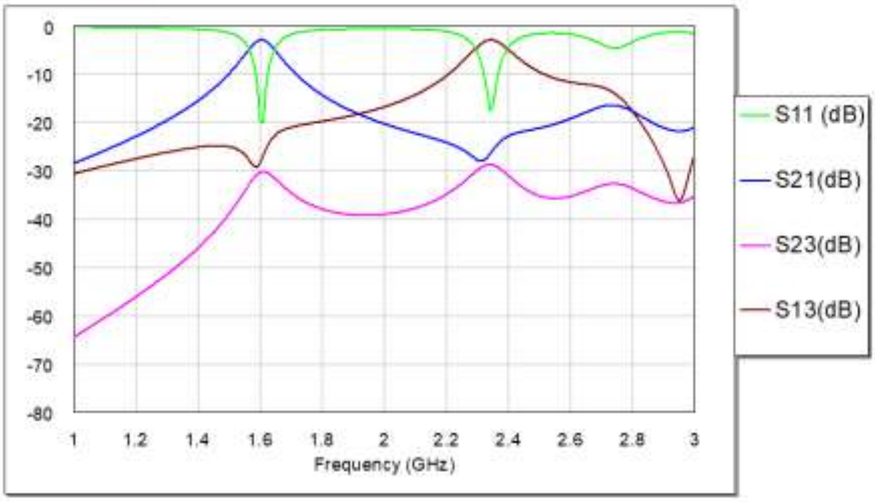

Figure 2: Simulated S-parameters of the proposed diplexer

Table 1: Peak Performance at Resonance Frequencies

Parameter	Band 1 (~1.6 GHz)	Band 2 (~2.34 GHz)
S11 (Return Loss)	-19.84 dB	-17.62 dB
Insertion Loss	-2.81 dB	-2.79 dB
Isolation (S23)	-30.08 dB	-28.65 dB

Table 2: Bandwidth

Band	Frequency Range	Bandwidth	FBW
Band 1	1.58–1.62 GHz	0.04 GHz	~2.5%
Band 2	2.30–2.36 GHz	0.06 GHz	~2.6%

Table 3: Isolation (S23)

Frequency	Isolation (dB)
1.6	-30.08
2.0	-38.97
2.34	-28.65
2.8	-33.61

Table 4: Return Loss (S11)

Frequency	S11	Quality
1.6 GHz	-19.84	Excellent
2.34 GHz	-17.62	Very Good
Outside	>-5	Poor (Expected)

Table 5: Channel Selectivity

Condition	S21	S13	Observation
1.6 GHz	-2.8	-28	Ch1 active
2.34 GHz	-26	-2.8	Ch2 active

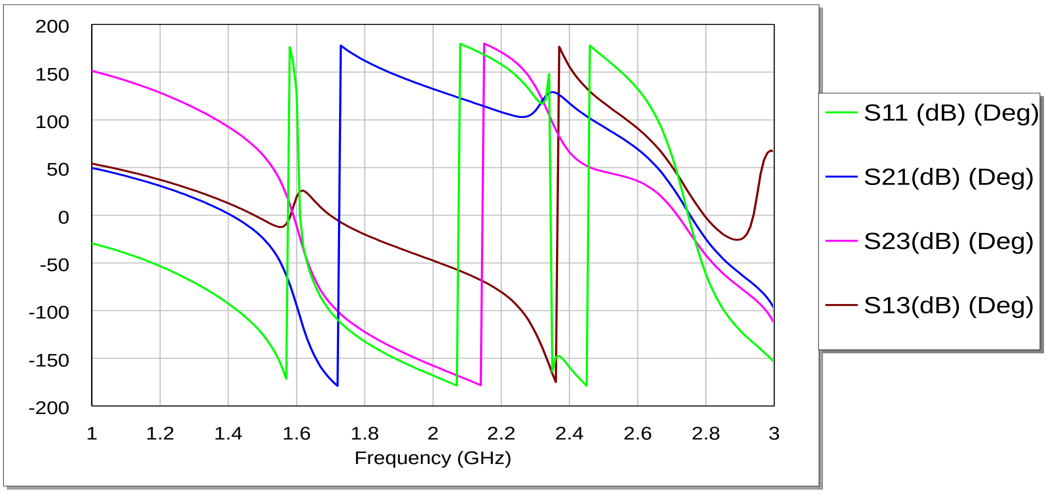

Figure 3: Phase response based on S-parameter

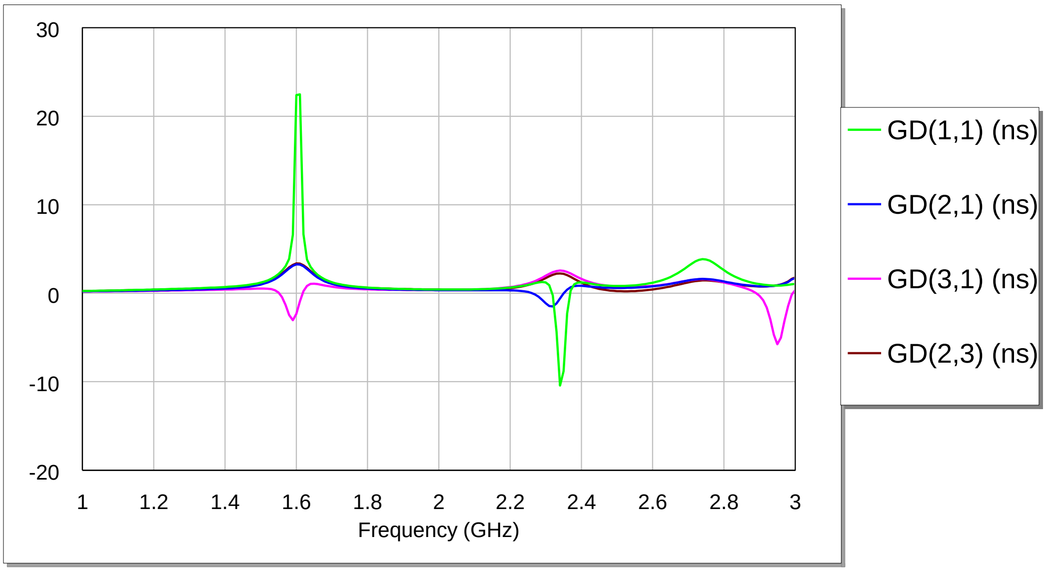

Figure 4: Group delay response based on S-parameter

4. Conclusion and Future Scopes

A small version of a dual-band microstrip diplexer has been effectively designed and simulated using FR4 substrate. About 1.6 GHz and 2.34 GHz operation in the design is realised at good impedance matching, low insertion loss, and high isolation. These properties will guarantee consistent biomedical performance.

The imperfections of FR4 notwithstanding, the diplexer still has an acceptable efficiency but has a lower fabrication cost. The selectivity is enhanced by the narrow bandwidth, and hence the design is applicable in targeted medical systems. The proposed diplexer is a useful and affordable solution to RF front-end applications.

In addition to fabrication and measurement, when considering the design of the diplexer in the future, it can be assumed that there are various ways in which it can be improved to increase its performance and applicability. A significant step will be to fabricate and experimentally validate the diplexer to verify the results of the simulation and determine the behavior in the real world. Defected Ground Structures (DGS) could go a long way to enhancing isolation and minimizing undesirable coupling, and miniaturization methods based on metamaterials could enable even smaller designs to be made without compromising performance. The other possible extension that can be useful is the incorporation of the diplexer with antennas to produce small RF modules that can be used in portable medical equipment. The design could also be extended to include multi-band diplexers or multi-band triplexer systems to achieve wider communication needs besides dual band. Lastly, optimizing the design parameters using AI-based techniques might result in a higher level of performance parameters like reduced insertion loss, high isolation, and increased overall reliability.

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