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Highly selective dual-band interdigital bandpass filter for C-band applications

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ABSTRACT

Miniaturization in the telecommunications field is deemed a current challenge and a critical demand in order to improve communication quality between the transmitter and the receiver while avoiding clutter issues. The main objective of this work is to design a miniature interdigital bandpass filter (IBF) using planar technology. The proposed bandpass filter is made up of three equidistant parallel-coupled lines carefully deposited on a small Rogers-5880 substrate possessing a full dimension of 10×10×1.6 mm^3, a relative permittivity ε_r=2.2, and a loss tangen of 0.0009. The proposed IBF has been designed and simulated using the HFSS software, which is a simulator that studies the electromagnetic behavior of radio frequency structures using cutting-edge finite element solvers. The reached outcomes present good electrical performance in terms of insertion loss S_{21}, reflection coefficient S_{11}, voltage standing wave ratio (VSWR), and selectivity, making the proposed IBF suitable for integration in small electronic devices for C-band applications (4 GHz to 8 GHz).

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1. INTRODUCTION

The rapid development of telecommunication systems and the exponential growth in the number of users owning wireless communication devices have allowed the creation and innovation of several technologies to simplify the exchange of information between the transmitter and the receiver [1]. The communication is carried out via a wireless communication system made up of several electronic components, among them, filters are deemed a primordial part of modern telecommunication systems such as radars, satellites, and cell phones [2]. Generally, a filter is a linear physical system considered a two-port quadrupole. This system performs a signal processing operation to eliminate unwanted frequencies and let through useful ones [3]. Typically, microwave bandpass filters are used in the telecommunications field to select a suitable frequency band while attenuating all unwanted frequencies. Traditionally, microwave filters were designed separately with dielectric resonators and metallic cavities. These kinds of filters called volumic filters provide excellent electrical performance, but unfortunately, they are bulky, heavy, and expensive [4], [5].

Planar filters represent a mutation and a technological revolution that have enabled designers to integrate their filters in small electronic devices while preserving space for other communication system components and avoiding congestion problems. A planar filter is composed of metal strips generally made of copper deposited on the upper face of an insulating substrate. These metallic strips called resonators are folded or coupled together to generate filtering functions [6]–[8]. Planar filters can be integrated with microstrip antennas and form single multifunctional devices capable of filtering and radiating which simplifies the communication chain and reduces interconnection loss [9]–[18]. In general, a microwave bandpass filter is considered a competitor if it meets the current trend's requirements which are compact size, high selectivity (high-quality factor), low insertion loss (close to 0 dB), low reflection coefficient (less than -10 dB), and affordable cost.

To date, a significant amount of research has been carried out to propose various planar bandpass filter designs. For instance, a planar interdigital bandpass filter was proposed in [19]. The simulated results showed an acceptable insertion loss value ($S_{21} = -1$ dB), however, a poor quality factor was achieved (Q=2.7) and the structure was deposited on the top face of a sizeable Rogers RO4003C substrate (>10×10 mm^2). In Abdulkareem *et al*. [20], a fan-shaped microstrip bandpass filter was suggested. The simulated results are satisfying in term of reflection coefficient ($S_{11} < -10$ dB), but a slightly high insertion loss ($S_{21} = -1.377$ dB) was obtained and the structure was implemented on a large RT/Duroid 6010.2 dielectric substrate (12×12 mm^2). A new compact bandpass filter using u-shaped resonators and distance gain size (DGZ) method was presented in [21], the simulated results show a good insertion loss value (-0.429 dB). However, a degraded quality factor was provided (Q=6.97) and the structure was deposited on a bulky RO4003C substrate (43.5×34.3 mm^2). In Juma'a *et al*. [22], a two square open loop resonators were designed and implemented on a Rogers RT5880 substrate. The obtained results were good in terms of insertion loss ($S_{21} < -1$dB) and reflection coefficient ($S_{11} < -30$ dB), but there is an issue of the large size (24.2×27 mm^2). Another bandpass filter consisting of parallel coupled lines was suggested in [23]. Although the simulated insertion loss was good ($S_{21} = -0.6$ dB), the structure was implemented on a slightly large Rogers RO4003C substrate (21.5×7.1 mm^2). As seen in the previous cited works, all the proposed structures presented an issue of the size, some of them presented a low quality factor and a high insertion loss, which degrades the quality of the filter and makes it difficult to integrate with small electronic devices.

For this reason, a small and compact interdigital bandpass filter (IBF) is designed. The suggested structure is composed of three equidistant parallel coupled lines carefully deposited on a miniature Rogers 5880 substrate possessing a total dimension (10×10×1.6 mm^3) relative dielectric constant ε_r=2.2, a loss tangent of 0.0009, and a thickness h equal to 1.6 mm. The compact structure and the brilliant performance reached by the suggested IBF prove its suitability for integration in wireless devices that support highly selective operation.

2. INTERDIGITAL BANDPASS FILTER

An interdigital band-pass filter is made up of a series of resonators with lengths equal to the quarter-wavelength guided in the substrate. These resonators are placed next to each other forming a distributive coupling. To resonate the quarter wave filter we need to connect one end to the ground and the other to an open circuit as shown in Figure 1.

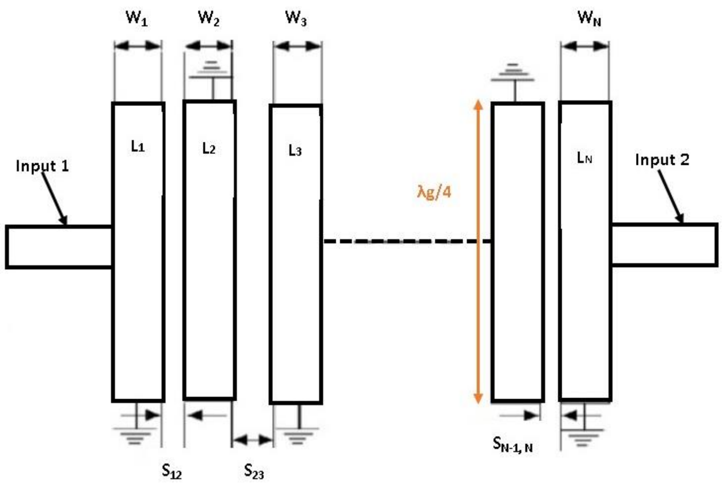


Figure 1. Topology of an n-pole filter with interdigitated quarter-wave resonators

3. PROPOSED INTERDIGITAL BANDPASS FILTER

Figure 2 exhibits the proposed design structure. The front side consists of a symmetrical microstrip transmission line powered from both sides by an impedance line of 50 Ω. Three lines of equal length and equidistant spacing are deposited on the upper face of Rogers's dielectric substrate as shown in Figure 2(a). Figure 2(b) shows the rear side of the proposed structure containing a copper ground plane with a rectangular slot deposited under the substrate to improve the electrical performance of the proposed IBF.

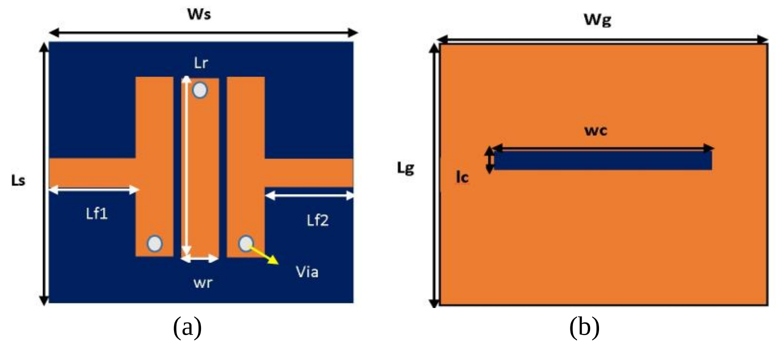


Figure 2. Structure of the suggested IBF: (a) front side and (b) rear side

The following theoretical equations are used to calculate the resonator's full dimension [24]. The resonator's width Wr is obtained using the following equation:

$$\frac{W_r}{h} = \frac{8\left(\frac{7\epsilon_r+4}{11\epsilon_r}A+\frac{\epsilon_r+1}{0.81\epsilon_r}\right)^{0.5}}{A} \tag{1}$$

Where,

$$A = exp\left(\frac{z_0}{42.4}\sqrt{\epsilon_r+1}-1\right) \tag{2}$$

Knowing that z_0 is the characteristic impedance of the line equal to 50 Ω. The resonator's length Lr is obtained using the following equation.

$$L_r = \frac{\lambda_g}{4} - \Delta L \tag{3}$$

Where ΔL represents the effective length of the resonator due to the overflow effect, and λg indicates the substrate's guided wavelength given by:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{\text{reff}}}} \tag{4}$$

Knowing that λ_0 denotes the wavelength in free space at the center frequency f_0, and the effective relative permittivity provided by the microstrip synthesis denoted as ϵ_{reff}.

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W_r}\right]^{\frac{-1}{2}} \tag{5}$$

The IBF dimensions are assembled in Table 1.

Table 1. Dimensions of the suggested IBF

Pramaeters	Dimensions (mm)	Parameters	Dimensions (mm)
Ls	10	Ws	10
$Lf1$	3	$Lf2$	3
Lr	8	Wr	1
lc	1	Wc	8
Lg	10	Wg	10

4. RESULTS AND DESCUSSION

The design was done using the HFSS software which is a simulator that studies the electromagnetic behavior of radio frequency structures using cutting-edge finite element solvers. The structure was first deposited on two different types of substrate which are FR4 epoxy and Rogers-5880, to see the effect of each one.

4.1. Simulated reflection and transmission coefficients for Rogers-58880 and FR4 epoxy substrates

It is clearly remarked in Figure 3 that the structure of the interdigital filter deposited on the upper face of the Rogers 5880 substrate has much greater electrical performance than that of the FR4 epoxy substrate. Using the Rogers substrate, a dual-band IBF has been achieved, as a result, a double resonance frequency is attained, whereas using the FR4 epoxy, only a single band with a single resonance frequency was obtained. As observed in the following figure, poor reflection and transmission coefficients (S_{11}) or (S_{21}) were obtained for the FR4 epoxy substrate $S_{11} \geq -20$ dB and $S_{21} \leq -2$ dB resulting in a high insertion loss value which is unpreferred for planar technology design.

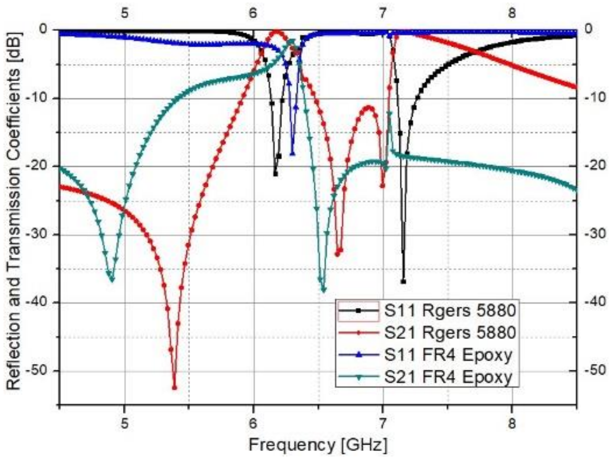


Figure 3. Reflection and transmission coefficients versus frequency for FR4 epoxy and Rogers-5880 substrates

4.2. Details of chosen results

Figure 4 depicts the electrical performance of the IBF structure deposited on the upper side of the Rogers-5880 substrate. As remarked in this figure, the filtering operation is performed on two bands belonging to the C band with a reflection coefficient value $S_{11} < -20$ dB for both resonant frequencies 6.17 GHz and 7.16 GHz, which proves a good impedance matching and implies that 90% of the power is transmitted while 10% is reflected due to the discontinuity effect.

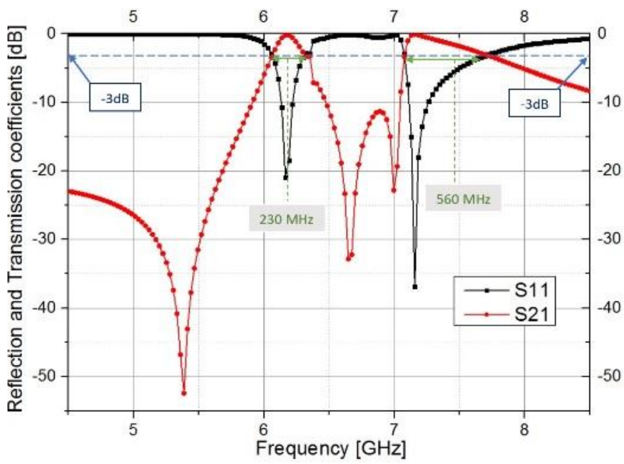


Figure 4. Reflection and transmission coefficients versus frequency

It is also observed that the filter provides a very good band rejection of less than -50 dB with an insertion loss value of S_{21} equal to -0.13 dB and -0.11 dB at 6.17 GHz and 7.16 GHz, respectively. The proposed IBF has two -3 dB bandwidths equal to 230 MHz and 560 MHz, respectively. Knowing that the two resonance frequencies are 6.17 and 7.16, the quality factor (Q) can be calculated for each band and it can be deduced that the filter is highly selective for the first frequency band and has good selectivity for the second one. The quality factor can be calculated using the following equation where f_r is the resonant frequency for each frequency band.

$$Q = \frac{f_r}{-3dB \text{ Bandwidth}} \quad (6)$$

4.3. Voltage standing wave ratio

Figure 5 presents the simulated voltage standing wave ratio versus frequency for the dual-band IBF. As seen in this figure, the IBF has a low voltage standing wave ratio (VSWR) equal to 1.73 and 0.15 at the resonance frequencies 6.17 GHz and 7.16 GHz, respectively. This confirms the previously obtained results and that the IBF has a good impedance match with a low number of reflected waves which is desirable for the planar technology design.

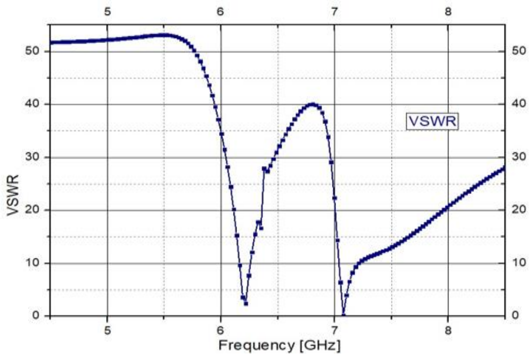
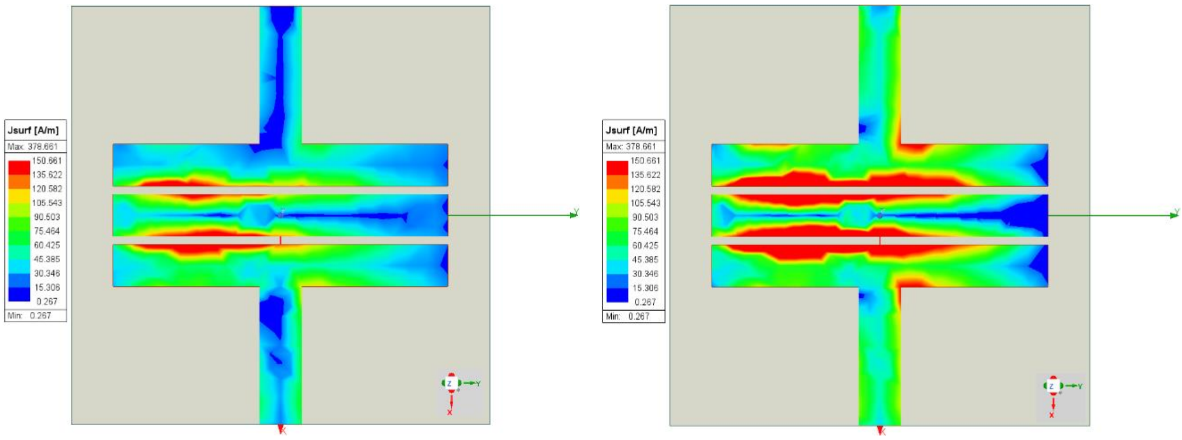


Figure 5. Voltage standing wave ratio versus frequency for the dual-band IBF

4.4. Distributed current density

Figures 6(a) and 6(b) depict the distribution of current density over the IBF's surface at the resonant frequency of 6.17 GHz and 7.16, respectively. It can be observed in both figures that all the colors on the scale are distributed over the surface of the three coupled resonators. The blue color indicates a weaker coupling effect, whereas the red color represents a stronger one. It is also remarked that the current intensity is much higher at the resonance frequency of 7.16 GHz compared to that obtained at the frequency of 6.17 GHz which is compatible with the previous results.



(a) (b)

Figure 6. Distribution of current density: (a) at 6.17 GHz and (b) at 7.16 GHz

5. COMPARISON STUDY

Table 2 compares the performance and the characteristics of the proposed IBF with other recently proposed filters. Resonant frequency (fr), insertion loss ($In.Loss$), size, and quality factor (Q) were chosen as parameters for this comparison. It can be deduced that the proposed IBF has a small and compact size compared to other designed filters; it is also very selective and has the lowest insertion loss values, making it competitive and suitable for integration in small electronic devices.

Table 2. Comparison study

References	fr (GHz)	Q	$In.Loss$ (dB)	Size (mm^2)
[19]	6.31	2.7	-1	>10×10
[20]	3.41/ 6.14	–	-0.7/ -1.377	12×12
[21]	2.4	6.97	-0.429	43.5×34.3
[25]	1.93/ 2.41	6.89/ 5.02	-0.6/ -0.5	28.3×21.7
[26]	2.45/ 5.8	8.16/ 14.5	-1.3/ -2.2	–
[27]	2.4	20	-0.91	22×22
Proposed IBF	6.17/ 7.16	26.82/ 12.78	-0.13/ -0.11	10×10

6. CONCLUSION

A compact interdigital bandpass filter with planar technology approach was suggested in this paper. The proposed design has a small size 10×10 (mm^2) and performs very well in terms of insertion loss (-0.13/-0.11) dB and reflection coefficient $S_{11} < -20$ dB for both resonant frequencies 6.17 GHz and 7.16 GHz, respectively. The proposed IBF provides a good rejection band less than -50 dB and proves a high selectivity making it competitive and suitable for integration with small electronic devices, such as microstrip antennas operating for C-band (4 GHz to 8 GHz) applications. This integration will result in a single multifunctional device able of radiating and filtering. Consequently, this will reduce the interconnection loss and simplify the wireless communication chain complexity.

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