A New Method of Isolation Enhancement of Dual Band Band-Pass Filter Using Composite Mode Co-planar Waveguide Structure for 5G and Body Centric Applications

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Abstract
Frequency ratio or frequency difference of more than fifteen times between the two bands is difficult to realize particularly for millimetre-wave applications. This paper presents a large frequency ratio dual band band-pass filter for 5G communication and body-centric applications. The proposed filter has been studied and developed based on the mode-composite co-planar waveguide (MC-CPW). The proposed dual band band-pass filter comprises lower and higher bands designed independently with a high degree of freedom. In order to suppress the harmonics between the two bands, the lowpass filter is cascaded with the structure impedance matching to achieve the competent dual band band-pass filter response. The characteristics of the proposed dual band band-pass filter based on mode composite co-planar waveguide structure yield it as the promising and potential entrant for the multi-band operating systems particularly in 5G communication systems with body-centric applications. To certify the practicability and pre-eminence of the proposed filter, the simulated and measured results are compared and are found in good agreement with one another.

Keywords Large frequency ratio · 5G communication · Body centric applications · Mode-composite · SIW

1 Introduction
The wireless traffic demands are growing exponentially and need suitable resolutions for handling the huge amount of data. At present the communication systems are using microwave bands, taking advantage of different technologies like carrier aggregation and multiple-input multiple-output (MIMO). But, the staggering demands for multi-gigabits per second connections and systems can be achieved by advancing up to the spectrum of millimetre-wave (mm-wave). The study suggests that the applications of mm-wave beyond 20 GHz have been progressively playing a significant part in the profitable and commercial enhancement of the Ka-band satellite communication and 5G mobile communication. To meet the stringent demands and performance specifications at Ka-band and beyond, it is believed that an unavoidable requirement for the devices/components for the 5G communication is created. The losses at the higher frequencies linked to the planar and microstrip transmission lines are knowingly greater than those at the lower frequencies (Bhat et al. 2021b). Henceforth, substrate integrated waveguides (SIWs) provide the desired solution to minimize these losses. Though the components which are available commercially in the form of surface mount technology (SMT) and monolithic microwave integrated circuit (MMIC) technologies need to be wire encased or surface mounted to a planar type of structure. In order to avoid unnecessary losses effective transitions from waveguide technologies to planar technologies are preferred mainly in cost-effective applications such as satellite communications where the cost increases significantly or even results in system power shortage by an increase of just a few tenths of dB. The wireless communication systems with multiband operations have captivated great research attention in the last decade.

As a key element, a band-pass filter (BPF) with high-quality performance and miniaturized size is in good
demand and plays a crucial role in multi-function telecommunication systems. Different design approaches and technologies have been reported for the design of these dual band BPFs (Heng et al. 2013; Shi et al. 2014; Chuang and Wu 2015; Feng et al. 2016; Zhang et al. 2018; Iqbal et al. 2019). The reported works realized the preferred dual-band band-pass responses, but their passband bandwidths are comparatively narrow, confining their uses and applications in the current communication systems with high data rates. To overcome the above-mentioned issue, BPFs with dual-wideband based on the concept of transversal signal interaction are demonstrated in Sánchez-Soriano and Gómez-García (2014); Wang et al. (2018) and have been utilized to achieve the operation of dual-wideband (DWB) band-pass filters (BPFs). However, these filters cannot be structured by using the transmission lines having a uniform electrical length and will not produce equal-ripple performance in the passband. This leads to an increase in design complexity and a large variation in group delay.

Numerous pioneered works utilizing the Hilbert-fork resonator (HFR) (Janković et al. 2013) and stub-loaded resonator (SLR) (Xu 2016; Bhat et al. 2019) had been accomplished to realize the miniaturization of the filters. However, to achieve the size reduction the line width was decreased resulting in adverse in-band performance and quite narrow bandwidth. The wavelength-independent resonators (Yang et al. 2010) have been employed to attain the size minimization to solve the issues discussed earlier. Several design approaches have been reported in the literature for the dual band BPFs. However, most of them are centered on one or more significant properties at the expense of other characteristics. To design dual band BPFs with a large frequency ratio (LFR), a new approach based on the procedure of the aperture coupling has been proposed and demonstrated in Zheng et al. (2018). It has achieved the LFR of greater than 10 while attaining a size comparatively more compact, but the filtering structure has been designed and demonstrated using the multi-layered substrate which is very costly and difficult to process or fabricate as compared to the conventional filters made of the single-layer substrate. Therefore, an innovative mode to acquire the dual band BPF having the LFR utilizing the single-layered substrate would be preferable for numerous advantages, including the high performance and easy integration. The mode composite waveguide (MCW) comprises of three-layer substrates which provide the low loss characteristics and high performance in both the low and high band frequency limits owing to the suitable shielding structure. However, the mode composite coplanar waveguide (MCCPW) proposed in Su et al. (2019) has a simple geometry made of the only one-layer substrate. In this method, the SIW and quasi-CPW are combined resulting in the MC-CPW with enlarged working bandwidth suitable for the broader development of the multiband systems.

This paper presents a simple and efficient dual band BPF utilizing the systematic design method. This sufficiently addresses the majority of the important characteristics and essential properties required for the narrow-band BPFs with dual band operations. The proposed dual band BPF offers the reliable inter-band separation between the two bands, intense stopband attenuation, miniaturized and low-cost fabrication properties. The proposed dual band BPF with the LFR of approximately better than 22.2 dB using a substrate of single-layered and simple design has never been achieved and discussed in the state of art published works to the best of the authors’ knowledge. This dual band BPF is surely deployable in multi-band operating systems like the future 5G mobile communication which requires a large in-band frequency gap or frequency ratio between its low and high range of frequencies. This filter exhibits and achieves high operational efficiency with high rejection between the two passbands.

2 Dual Band BPF Structure and Design Principle

To implement the microwave and mm-wave circuits, the most common structures like the microstrip line and SIWs with comparable sizes are considered for different operating frequencies significantly. The realization of the dual-band BPF generally depends on the dual-mode type of structures which results in minimal frequency isolation or ratio between the bands. To extend the frequency ratio the method of feeding two elements operating at two specific frequencies is a favourable one. As reported in Qin and Xue (2012); Shen et al. (2016); Chen et al. (2006); Zhang and Xue (2007); Gao et al. (2017) the size of these two elements must be equivalent and the structure of feeding should provide the proper impedance matching at the two specified frequencies in order to assure the effectual feeding. However, the operating frequency ratio incorporated by the two elements with the comparable size and the same structure may not be larger. Additionally, the bandwidth of the various feeding types such as the Co-planar waveguide (CPW) feed (Zhang and Xue 2007; Gao et al. 2017), and the edge coupling feed (Chen et al. 2006) are not enough
wide. All of them results in a small isolation or minimal frequency ratio between the two passbands.

3 Structure of Mode Composite Co-planar Waveguide (MC-CPW)

The combination of the SIW and the quasi-CPW in the form of a composite transmission line results in MC-CPW. Figure 1 shows the basic assembly of the MC-CPW and its cross-sectional view. The MC-CPW can support quasi-CPW and SIW transmission modes. Meanwhile, the centre conductor is the SIW with metal surfaces on both sides connected through the array of metallic vias/holes. These two modes present the characteristics of high rejection in the middle band because of the SIW’s enclosing assembly. The SIW mode naturally exhibits the filtering of high-pass modes and it is most likely utilized to produce the high-frequency band. However, the quasi-CPW exhibits the TEM mode and has no cut-off frequency. Therefore, to explore a dual band BPF in both the low and high-frequency band operation using the two modes, the utilization of the MC-CPW is a promising idea.

4 Design Principle

The basic design principle of the dual-band BPF is mainly centered on the MC-CPW as illustrated in Fig. 2a. It comprises of the two impedance matching structures (IMSs) operating as the switch dependent on the frequency. This IMS attributes the function of switching at the same time supporting the high separation/isolation between the two modes of transmission and permits to design and implement the filter of two interested bands by means of different modes independently. The quasi-TEM mode is the working mode for the low-frequency path. In addition to this, the low pass filter (LPF) is utilized to suppress the spurious bands generated by the BPF in the lower band. However, the microwave signal in the path of high frequency is transformed to TE_{10} mode in such a way that the LPF may not influence the high-frequency performance. Without the mode switching, it is very hard to achieve the large frequency ratio within a filter comprising of dual-band. The filter having dual-mode operation mainly based on the MC-CPW has various advantages: it can help to achieve the large frequency ratio or the isolation between the two operating passbands, provides the reliable freedom to design these two bands independently, and integrates all the circuits on a single-layered substrate material. The basic principle for the design of the dual band BPF based on MC-CPW is summated as follows:

1. In the first step, the SIW section in the MC-CPW acts as the centre conductor of the quasi-CPW part in order to determine the dimensions of the SIW, which should remain fixed.
2. The higher-order harmonics should be suppressed and the pattern for the quasi-CPW must not influence the area chosen for the SIW part.
3. Both the modes corresponding to the quasi-CPW and SIW can be excited individually. It means when the device is working over the higher band frequency operation, the TE_{10} is excited and completely opposite for the quasi-SIW mode when it is over the lower-band frequency operation. The same characteristics of the IMS are simulated and illustrated in Fig. 2b.

In reference to a different range of frequencies, the MC-CPW plus IMS may be considered as the separator for modes. Due to its unique topological geometry, the isolation can be relatively high between both signal paths (low and high frequency operating bands). Therefore, a dual band BPF can be developed and derived by exploiting this property. For simplicity, the demonstration of the high-band operation of the proposed dual-band filter based on MC-CPW utilizes the conventional SIW filter and this is attained by cascading the half-wavelength resonators and inductive metallic vias/holes.

Figure 3a shows its equivalent circuit, where the K-inverter comprises of the transmission line segment and the metalized vias/holes of the SIW. All the parameters of the SIW filter can be synthesized and analyzed by attaining the comparison of the theoretically calculated and the EM Software (HFSS) simulated results. The procedure for the design of the high-frequency BPF based on MC-CPW...
follows the most popular, very accurate, and effective synthesis method of the J-K inverter (Tang et al. 2005).

The proposed SIW BPF designed is a fifth-order (i.e., \( n = 5 \)) filter having a centre frequency \( C_f \) of 38 GHz and covering the bandwidth of 36–39 GHz. 1, 0.9812, 1.3824, 1.7917, 1.3824, 0.9812, and 1 are the \( g_0 \) to \( g_6 \) values with the attenuation (return loss). Equation (1) is used to calculate the normalized K-inverter impedance value for the \( n \)th-order filter and the values calculated for \( K_{0,1}–K_{5,6} \) is 0.3920, 0.1318, 0.0912, 0.0912, 0.1318, and 0.3920. The equivalent circuit comprises of a K-inverter and a \( \lambda/4 \) open-ended transmission line of SIW on each side of it. The ideal K-inverter is having a phase shift of \( -90^\circ \), and hence, the phase shift for each element will be \(-90^\circ, +90^\circ, -90^\circ\).

\[
K_{0,1} = \frac{\lambda_{gSiw}}{\lambda_0} \sqrt{\frac{\pi W}{2 g_0 g_1}}
\]  

(1)

\[
K_{k,k+1} = \left( \frac{\pi W}{2} \frac{\lambda_{gSiw}}{\lambda_0} \right)^2 \sqrt{g_{k+1}}
\]  

(2)

where \( K = 1, 2, \ldots, n-1 \)

\[
K_{n,n+1} = \frac{\lambda_{gSiw}}{\lambda_0} \sqrt{\frac{\pi W}{2 g_n g_{n+1}}}
\]  

(3)

where, \( \lambda_{gSiw} \) is the SIW-guided wavelength, \( g_k \) is the value of the prototype for the \( n \)th-order lowpass filter, \( \lambda_0 \) the free-space wavelength, and \( W \) the relative bandwidth of the BPF.

The Eq. (4) gives the S-parameter (\( S_{21} \) dB) values of each element and these are given as \(-3.4732, -12.2817, -14.8746, -148.746, -12.2817, \) and \(-3.4732 \). The same parameters have been compared with the counterparts i.e., simulated parameters presented in Fig. 3b, which provides the optimized \( Si \) value and confirms displays the results in terms of magnitude and phase of the \( S_{21} \). Meanwhile, the conditions to satisfy the \(-90^\circ \) phase shift
for each element, the final length, and the length of compensation for each side of the SIW-based transmission line are presented in Eqs. (5) and (6), respectively.

\[
S = \begin{bmatrix}
1 - K^2 & \frac{2K}{1 + K^2} \\
\frac{2K}{1 + K^2} & 1 - K^2 \\
-\frac{j}{1 + K^2} & \frac{j}{1 + K^2}
\end{bmatrix}
\]  

(4)
Fig. 4 The proposed structure of BPF and its equivalent circuit. 

(a) The view of the top and bottom structure, and 

(b) The schematic diagram of the proposed MC-CPW based dual band BPF.

Fig. 5 Simulated results of two bands and mutual effect. 

(a) variation in lower band, 

(b) variation in high band.
\[ \Delta l = \frac{\theta + 90°}{2 \times 360} \lambda_{G}\text{SIW} \]  

\[ l = \frac{\lambda_{G}\text{SIW}}{2} + \frac{\theta + 90°}{2 \times 360} \lambda_{G}\text{SIW} \]  

where \( \Delta l \) is the element length of compensation and \( l \) is the final length on each side of the SIW transmission line.

It comprises of the IMS, MC-CPW, and the filter in the high- and low-band of frequencies. The IMS behaves as the switch to change the modes. For this reason, the microwave signal i.e., low-frequency will pass via the inductance (\( L_1 \)) of the quasi-CPW with the TEM mode. While as the signal at the high frequency will lead to the SIW, and generates the fundamental mode as \( \text{TE}_{10} \) for the structure of the filter. The modes are divided into two different paths by the IMS.

In this way, the independent design of both the high and low bands of the frequency for the BPF can be carried out. To merge these modes and attain the response of dual band operation, the same transition is applied and the IMS operation in the schematic diagram is accomplished by using an interdigital capacitor. For the higher frequency band, the space utilization problem is feasible, as a consequence of LFR for the proposed filter with dual-band operation. Therefore, some techniques are required to apply for miniaturization or methods to suppress the harmonics, resulting in size reduction of the filter for low-band frequency and alleviating the issue discussed earlier.

Due to the large frequency ratio, the filter size is quite large and the utilization of space is very weak. Hence, the size reduction of the proposed MC-CPW based filter for practical applications becomes necessary. The analysis in
terms of the design of the quasi-CPW filter is very crucial for the lowpass and BPF. It offers the fundamental theory for the filter development based on the MC-CPW, particularly for the part of the quasi-CPW. Some of the deciding observations about the quasi-CPW are summarized as:

1. It is regarded as the combination of the CPW and microstrip lines. Hence, the design method for the quasi-CPW can be referred to as the CPW and the microstrip lines-based filters.

2. It provides a large tuning range of the impedance because of the newly proposed structural parameter.

An improved dual band BPF with the size reduction is proposed and presented based on the above discussion. The most important point is size reduction or miniaturization of the filter for its lower band frequency with LFR. The proposed structure of the dual band BPF based on MC-CPW with SIRs is illustrated in Fig. 4a and the corresponding low band equivalent circuit is shown in Fig. 4b. The symmetrical $\lambda/4$ SIR is used in this design, which offers the replacements for the cascaded lowpass and BPF. In order to authorize and certify the independence of design for the high and lower frequency bands, Fig. 5a represents the study of S-parameters for the value $L_1$ in the lower-frequency band of the BPF. While Fig. 5b shows that when the lower-band parameter is fixed, the higher frequency band can be varied. These results suggest and validate the high design of freedom for both the bands of the BPF. The SIR offers the function of harmonic suppression and size reduction, explained as follows:

The experimental set-up of filter and compared results. 

**Fig. 8** Experimental set-up while testing the filter and its top and bottom view. 

**Table 1** Comparison between the proposed dual band BPF reported in this paper and other state of the art dual band BPFs

| Ref                  | C.F ($f_1$, $f_2$) GHz | Frequency ratio ($f_2/f_1$) | Insertion loss (dB) | Isolation (dB) | Design method   | Size ($\lambda_x \times \lambda_y$) |
|----------------------|------------------------|-----------------------------|---------------------|----------------|-----------------|------------------------------------|
| Xu et al. 2013a)     | 1.49, 6.44             | 4.32                        | 0.1, 0.8            | > 32           | Microstrip      | 0.135 × 0.123                     |
| Xu et al. 2013b)     | 1.96, 5.58             | 2.85                        | 0.52, 1.1           | > 30           | Microstrip      | 0.4 × 0.05                        |
| Zhou et al. 2017     | 12, 17                 | 1.417                       | 1.16, 2.32          | > 30           | SIW             | 0.4 × 1.22                        |
| Shen et al. 2011     | 2.4, 5.75              | 2.4                         | 1.4, 1.6            | > 30           | SIW             | 0.17 × 0.07                       |
| Bhat et al. 2021a)   | 28.3, 38.5             | 1.36                        | 1.1                 | > 28           | SIW             | 0.82 × 0.45                       |
| Zheng et al. 2018    | 2.35, 29.8             | 12.71                       | 0.94, 1.32          | > 22           | Microstrip and SIW (Multi-layer)  | 0.46 × 0.34                       |
| Proposed work        | 2.4, 38                | 15.83                       | 0.4, 1.2            | > 35           | MC-CPW          | 0.345 × 0.15                      |
1. The $f_0$ i.e., the frequency of the fundamental resonant shifts towards the lower band of frequency because of SIR, which implies that the filter’s lower frequency band can be achieved using the same physical length of the SIR in comparison to the conventional resonators like a stub. Consequently, the size of the SIR should be smaller for the desired and fixed band.

At the same time, the 1st harmonic i.e., $f_1$ of the SIR will be pressed towards the higher frequency, and this purpose is more advantageous to the harmonic suppression. Furthermore, lowpass filter order can decrease further for the same mid-band attenuation in the region of the near-passband, which results in the more compactness of the filter.

Figure 6 shows that the frequency ratio ($f_1/f_2$) is controlled by the impedance ratio i.e., $Z_1/Z_2$. It illustrates that the frequency ratio and impedance ratio are proportional to each other. Therefore, a large impedance ratio is favourable for the concern of miniaturization and harmonic suppression. It is noteworthy that the harmonic suppression can be achieved by IMS as given in Fig. 2. Hence, by using the proper design of the frequency band and the SIR with IMS, the higher spurious band is promptly suppressed and thus decreases the size of the filter. This is also resulting in a very compact size filter with a frequency ratio of more than fifteen times. The centre frequency for both bands is 2.4 GHz and 38 GHz, respectively. The simulation results of the proposed filter are discussed in detail in the next section.

5 Simulation and Measured Results

The dual band BPF proposed in the above section has been simulated and fabricated using the Rogers substrate material of RT/Duroid 5880, having the relative permittivity $\varepsilon_r = 2.2$ and a thickness of 10 mils (0.254 mm). The measurement setup for the filter is shown in Fig. 7 using the network analyzer of Agilent Technologies N5247A and the picture of the filter fabricated and connected through probes. Figure 8 illustrates the compared and the simulated results in terms of S-Parameters. This figure shows that the simulation results and experimental results have close consistent with each other and verify the design concept. The measured insertion losses at the centre frequencies of the two bands i.e., 2.4 GHz and 38 GHz are 0.5 dB and 1.2 dB, respectively. The attenuation loss or return loss within both the bands is better than 48 dB and 55 dB for the first and second bands, respectively. Moreover, the isolation of greater than 20 dB is found in the stopband between the two passbands from 6 to 35 GHz, signifying the high isolation.

The performance comparison of the proposed dual band BPF presented in this paper and other state of art dual band BPFs has been summarized in Table 1. Notably, high midband rejection and large frequency ratio can be recognized in this contribution with distinguished freedom of design.

6 Conclusion

In this paper, a BPF comprising of dual-band has been proposed, realized, and demonstrated based on the SIW and MC-CPW. The proposed filter also provides a high potency of freedom to design each band individually. A single-layered RT/Duroid 5880 substrate material has been utilized to fabricate the proposed BPF operating at the center frequency of 2.4 GHz and 38 GHz having a dielectric constant of 2.2 and thickness of 0.254 mm or 10 mils. To verify the results of the design concept, a BPF having a large frequency separation or frequency ratio has been designed, fabricated, and tested. The proposed filter demonstrates the simulation results and experimental results have close consistency with each other in terms of losses i.e., return loss and insertion loss. It is extremely difficult to achieve and realize such a kind of frequency response using the conventional methods of filter design. Therefore, it is concluded that the proposed BPF is a promising candidate for the 5G communication with the multiband operation and high-frequency ratio. The filter performance in terms of bandwidth and selectivity can be improved by employing new techniques and configurations for the resonator elements. This type of filter topology can also support the applications in body-centric networks and devices like antennas, low-noise amplifiers, power amplifiers, and many more.

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Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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