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Compact 3D monolithic microwave integrated circuit bandpass filter based on meander resonator for 5G millimeter-wave

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ABSTRACT

Bandpass filters for millimeter-wave band applications are typically designed using resonators. However, the design of a multilayer coplanar waveguide (CPW) monolithic microwave integrated circuit (MMIC) bandpass filter for 5G millimeter-wave band, n257 with operating frequencies from 26.5 to 29.5 GHz is still not available. Therefore, in this work, a compact bandpass filter for 5G millimeter-wave application was designed with multilayer CPW MMIC bandpass filter based on a meander resonator. The meander resonator of the bandpass filter was designed using low-loss multilayer CPW lines. In designing the bandpass filter, the resonator length and perturbation was utilized to optimize the resonance and bandwidth, and meander resonator was used to miniaturize the bandpass filter. As result, a compact bandpass filter with size of 0.75×0.75 mm^2 for 5G millimeter-wave band n257 was achieved. It has bandwidth of 3 GHz, an insertion loss of -2.87 dB and a return loss of -11.1 dB at frequency 28 GHz.

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1. INTRODUCTION

The development of the telecommunication system increased chip demand with higher requirements for size and performance, such as front-end devices for fifth-generation (5G) millimeter-wave bands. The 5G millimeter-wave band n257 operates from 26.5 to 29.5 GHz [1], [2]. To realize the compact device, the narrow circuit should be integrated. However, narrow circuit leads to high losses due to the current crowding at conductor edge. Therefore, the multilayer coplanar waveguide monolithic microwave integrated circuit (CPW MMIC) technique was proposed to reduce the crowding effect on the coplanar waveguide (CPW) line [3], [4]. As result, the multilayer CPW lines have low loss compared to the conventional CPW lines. Implementation of the multilayer CPW MMIC technique also increased the Q-factor of the metal-insulator-metal (MIM) capacitor, reducing the area spiral inductor and effectively integrated with p-HEMT transistors in amplifier design [5]–[9].

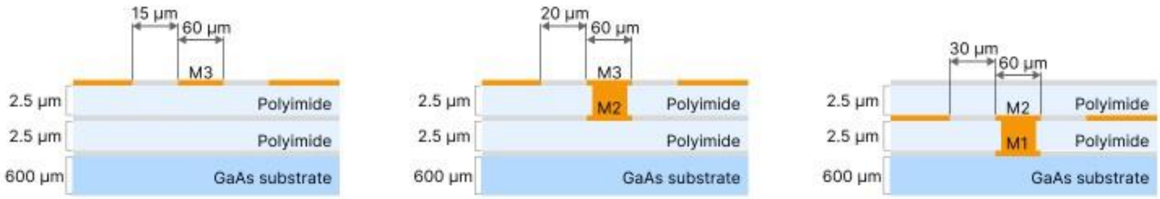
Due to the limited frequency for 5G millimeter-wave band n257, the bandpass filters are become crucial parts in telecommunication system to select the signal going through the operating frequency. Recently, the bandpass filter has been explored using integrated transistors [10]. However, the bandpass filters for frequencies above 20 GHz are challenging to realize due to the self-resonance of the lumped-elements and the availability of transistors [11]. The distributed elements are utilized for high frequency circuit design, including for various resonators such as stepped impedance resonators, open-loop resonators, and coupled-line resonators [12]–[15]. Another type of resonator was also applied to realization different application of bandpass filter, such as T-shape resonator for dual-band bandpass filter, stub resonator for ultrawideband bandpass filter, and stub loader for broadband filter with multifrequency suppression capability [16]–[18].

In the previous work, we presented the multilayer CPW MMIC bandpass filter using a meander resonator for X-band transceiver application at frequency 10 GHz [19]. In this work, the process of designing the bandpass filter was explained, starting from the modeling of low loss multilayer CPW lines up to miniaturizing the bandpass filter using meander resonators in order to realize the compactness of the bandpass filter operates at 28 GHz. The electric field of dual-mode on the bandpass filter, the effect resonator length and the perturbation size on the bandpass filter were also discussed in this paper.

2. METHOD

2.1. Multilayer CPW line

In order to design an optimal bandpass filter, the multilayer CPW lines as the resonator element in the bandpass filter, should be designed to have low losses. The variation of the multilayer CPW lines' structures were illustrated in Figure 1, where the multilayer CPW lines designed using gallium arsenide (GaAs) substrate with thickness of 600 µm. These lines have three layers of Aurum (Au) as the metal conductor with each thickness of 0.8 µm, and two-layers polyimide (PI1) and (PI2) each with thickness of 2.5 µm. Figure 1(a) shown the multilayer CPW line at metal layer 2 (M2) expanded to metal layer 1 (M1). This is similar to the cross-view resonator line in the bandpass filter design from the previous study [20]. Figure 1(b) shown the multilayer CPW line at metal layer 3 (M3) with expanded to metal layer 2 (M2), and Figure 1(c) shown the multilayer CPW line with planar metal on layer 3 (M3).



(a) (b) (c)

Figure 1. The variation multilayer CPW lines, (a) planar M3, (b) expanded M3,2, and (c) expanded M2,1

The characteristic impedance (Z_0) and the dissipation loss of the multilayer CPW lines were analyzed using scattering parameter by utilizing (1) and (2). Where Z_{sys} is the system impedance of 50 Ω, S_{11} is the return loss and S_{21} is the insertion loss [3], [4]. The CPW lines' characteristics in the form of characteristic impedance and the dissipation loss are shown in Figure 2.

$$Z_0 = Z_{sys}\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{1}$$

$$Dissipation\ Loss = 10\ log\left(\frac{1-|S_{11}|^2}{|S_{21}|^2}\right) \tag{2}$$

Figure 2 (a) shows the variation of the multilayer CPW lines those have characteristic impedance of 50 Ω with range of frequency between 5 GHz to 15 GHz. The data show that the resonance effect occurs within multilayer CPW lines; between frequencies 20 GHz up to 30 GHz due to the length of the designed transmission lines of 2398 µm. Figure 2(b) demonstrates the dissipation loss of the measured multilayer CPW line having a good agreement with the simulation result. The simulated multilayer CPW line planar M3, expanded M2,1, and expanded M3,2 have dissipation losses peaks of 0.42, 0.21, and 0.19 dB/mm respectively. These has been compared with the measured planar M3 multilayer CPW line that has dissipation loss of 0.43 dB/mm at 43 GHz [21].

It has been demonstrated that the expanded M3,2 have the lowest dissipation loss as well as having more compact size. This is due to the gap between metal conductor and the ground is 10 m smaller compares to Expanded M2,1 CPW line that has the gap size of 30 m. These designs and their characteristics analyses were desirable to gain more knowledge in developing filter design that utilized low loss CPW line.

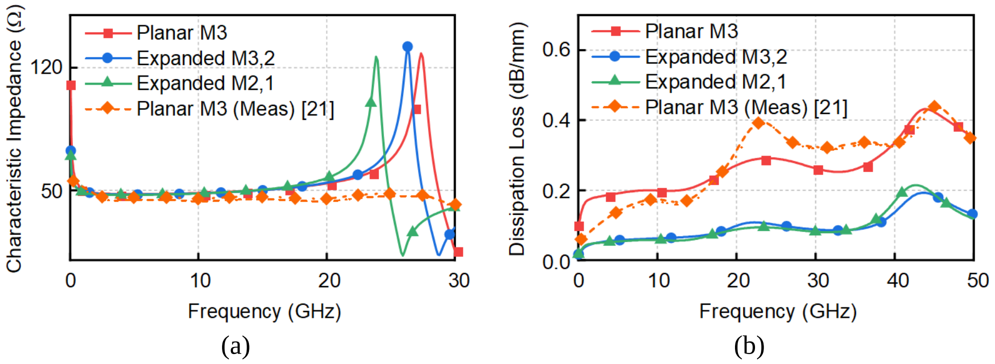


Figure 2. The characteristics of multilayer CPW lines, (a) characteristic impedance and (b) dissipation loss

2.2. Filter design

The multilayer CPW MMIC bandpass filter based on a resonator in this work was designed with a perturbation in one corner of the filter. The resonator formed by low loss multilayer CPW line as demonstrated previously in Figure 2. Furthermore, the resonator length has been utilized to control the operating frequency. In the proposed design as shown in Figure 3, the relation between resonator length (l) and the guided wavelength (λ_g) is defined in (3), whereas the total length resonator is equal to $4l$, and n is the mode number. The frequency resonance (f) of the 2-port ring resonator is given as (4), where ε_{eff} is the effective dielectric constant, and c is the speed of light [22], [23]. Based on this mathematical model, the dimension of bandpass filter becomes smaller as frequency increases. The bandpass filter for the millimeter-wave application was designed based on multilayer CPW line expanded on M3,2 with variation resonator length as shown in Table 1.

$$4l = n\lambda_g \quad (3)$$

$$f = \frac{nc}{n\lambda_g\sqrt{\varepsilon_{eff}}} \quad (4)$$

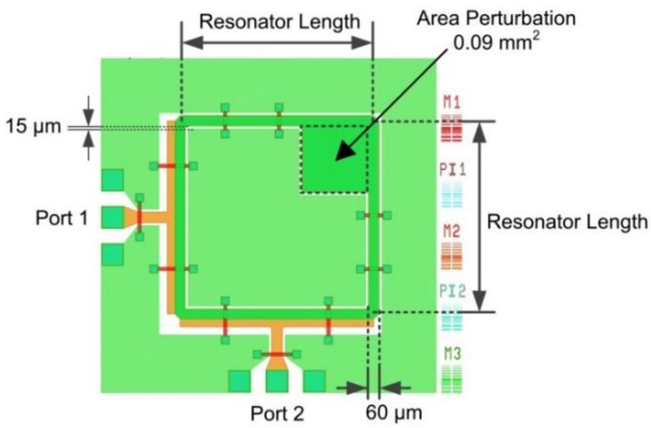


Figure 3. Layout of multilayer CPW MMIC bandpass filter with M1, M2 and M3 as metal layer 1, 2 and 3 respectively and PI1 and PI2 as polyimide layer 1 and 2

Table 1. The dimension of bandpass filter

Parameter	Bandpass Filter
Resonator width (µm)	60
Resonator length (µm)	1,200, 1,100, 1,000, and 900
Resonator gap to ground (µm)	15
Perturbation area (mm^2)	0.09
Vertical gap from port in/out to resonator (µm)	2.5

The electromagnetic modelling of the multilayer CPW MMIC bandpass filter has been demonstrated in their characteristics as shown in Figure 4. The insertion loss of bandpass filters with a perturbation area of 0.09 mm^2 have an equal value of -2.44 dB for various resonator lengths of 1,200, 1,100, 1,000, and 900 µm as shown in Figure 4(a). Furthermore, the bandpass filter has a resonance frequency of 25, 27.1, 29.7, and 32.6 GHz as demonstrated in Figure 4(b). It has also shown that the multilayer CPW MMIC bandpass filter can be realized at frequency 28 GHz by utilizing a resonator with length of 1,057 µm. Another important study explained in this work that the size of the perturbation within the filter can increase the coupling coefficient of even-odd mode to obtain more bandwidth for the bandpass filter [19]. When even-mode applied, an open circuit due to a magnetic wall occur along the symmetry plane and the total signal (S_e) leaving the input port, given by (5) [21], [24].

$$S_e = S_{11} + S_{12} \tag{5}$$

When odd-mode applied, a short circuit along due to an electric wall occur along the symmetry plane and the total signal (S_o) leaving the input port was given by (6) [21], [24].

$$S_o = S_{11} - S_{12} \tag{6}$$

where, S_{11} is return loss and S_{12} equal with insertion loss. The relation of even-odd mode and complex propagation constant $(\gamma = \alpha + j\beta)$ was given by (7) [21].

$$\tanh \gamma l = \sqrt{\left(\frac{1+S_o}{1-S_o}\right)\left(\frac{1-S_e}{1+S_e}\right)} \tag{7}$$

The coefficient coupling of dual-mode can be calculated from the odd-mode frequency (f_o) and the even-mode frequency (f_e) as given by (8) [25], [26].

$$K = \frac{f_o^2 - f_e^2}{f_o^2 + f_e^2} \tag{8}$$

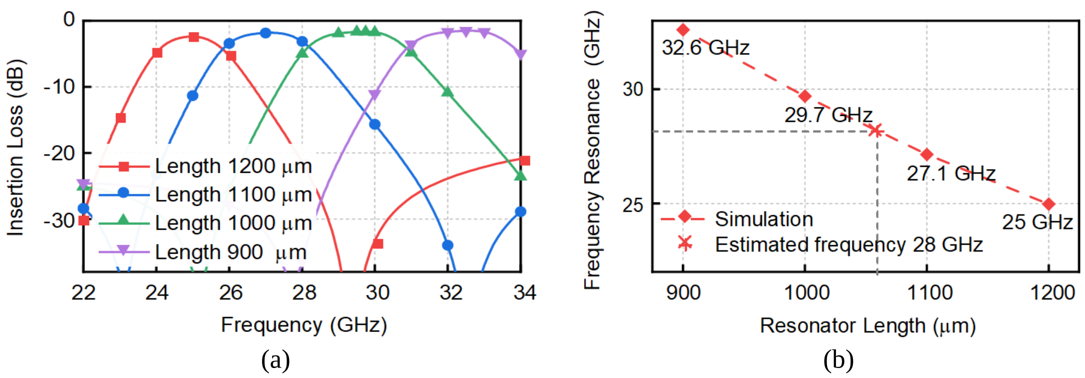
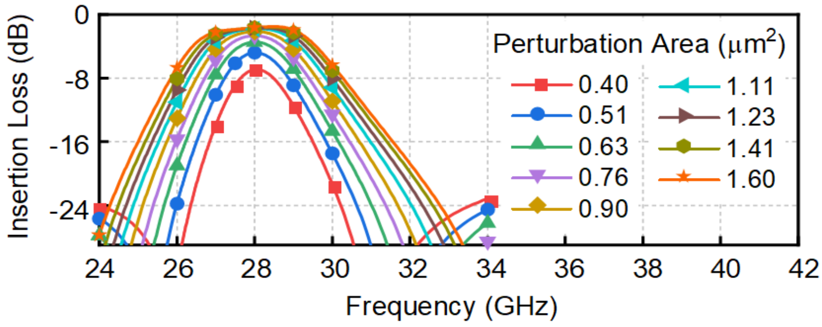


Figure 4. The characteristics of multilayer CPW MMIC bandpass filter with various resonator lengths of 1,200, 1,100, 1,000, dan 900 µm, (a) the insertion losses, and (b) the frequency resonances

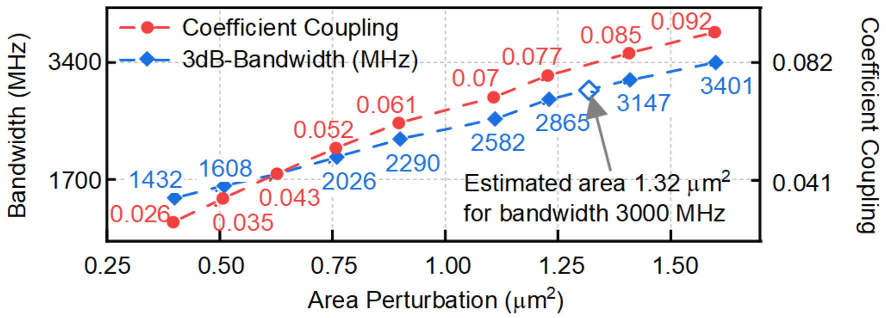
3. RESULTS AND DISCUSSION

The effects of various perturbation areas, from 0.4 μm^2 up to 1.6 μm^2 have been investigated in this work to optimize the insertion loss and bandwidth of the bandpass filter at the frequency of 28 GHz as shown in Figure 5. The bandpass filter has been demonstrated to achieve an optimal insertion loss and bandwidth by enlarging the perturbation area. As shown in Figure 5(a), the maximum insertion loss was achieved at -1.64 dB with bandwidth increased up to 3,400 MHz. Therefore, the area perturbation for optimal design was estimated at 1.32 μm^2 and the 3dB-bandwidth of 3,000 MHz was obtained, as demonstrated in Figure 5(b).

The multilayer CPW MMIC bandpass filter with area perturbation of 1.32 μm^2 and with resonator length of 1,057 µm has been studied as presented in Figure 6. The layout modelling is presented in Figure 6(a). The optimal performance at frequency 28 GHz has been achieved as shown in Figure 6(b). The multilayer CPW MMIC bandpass filter has an insertion loss of -1.62 dB, return loss of -18.6 dB, and 3 dB-bandwidth of 3 GHz, as shown in Figure 6(b). Furthermore, it is crucial to study the electric field distribution as shown in Figure 7. The electric field distribution of the dual-mode bandpass filter while phase 0° at port-1 and phase 0° at port-2 resulting zero electrical current along the symmetry line, also known as even-mode excitation as presented in Figure 7(a). The electric field distribution of the dual-mode bandpass filter while phase 0° at port-1 and phase 180° at port-2 resulting electrical current distributed along the symmetry line, also known as odd-mode excitation as shown in Figure 7(b).

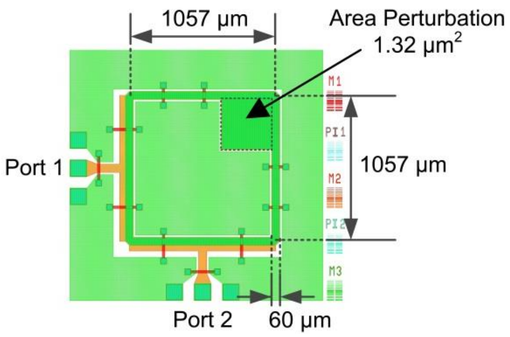


(a)

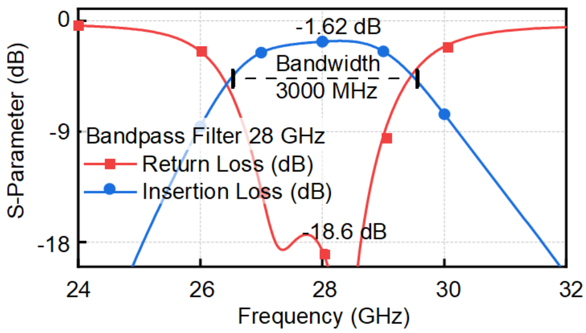


(b)

Figure 5. Effect of perturbation area to (a) Insertion loss and (b) bandwidth and coefficient coupling of multilayer CPW MMIC bandpass filter



(a)



(b)

Figure 6. The multilayer CPW MMIC bandpass filter layout design for operating frequency of 28 GHz (a) the top view design and (b) its S-parameters characteristics

In order to realize a miniaturized bandpass filters, meander resonators have been utilized in the design [27], [28]. Therefore, the meander line as the basic element for the meander resonator was designed to obtain equal characteristic impedance with the multilayer CPW line using the scattering parameter as shown in (2) [3], [4]. The meandered design has been demonstrated in this work as shown in Figure 8. The layouts of non-meander multilayer CPW line that has length of 1,057 μm, and meandered multilayer CPW line with length of 760 μm has been studied and presented in Figure 8(a) and Figure 8(b) respectively. Furthermore,

Figure 8(c) demonstrates the equal characteristic impedance of 49.5 Ω at 28 GHz between both designs. It has been demonstrated that more compact size has been realized using meandered multilayer CPW line. In order to obtain a compact bandpass filter design, the perturbation was designed on metal-2, overlapped with the ground plane on metal 3. The bandpass filter was miniaturized with a meander resonator that has length of 748 µm and a perturbation area of 0.073 µm^2. The miniaturized of bandpass filter was achieved with insertion loss of -2.87 dB, return loss of -11.1 dB at 28 GHz. A similar performance was successfully achieved with a compact bandpass filter using meander resonator. Its 3 dB-bandwidth of 3 GHz occurs between 26.5 and 29.5 GHz.

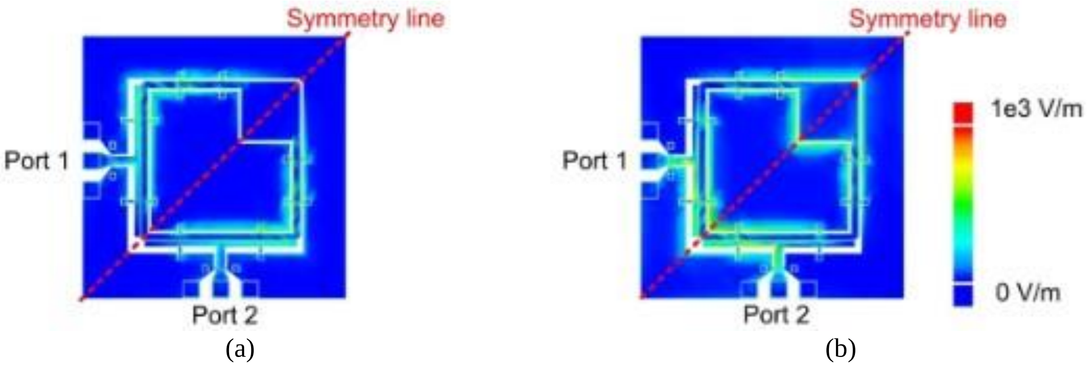


Figure 7. Electric field distributions of dual-mode bandpass filter at frequency of 28 GHz (a) the even-mode excitation and (b) the odd-mode excitation

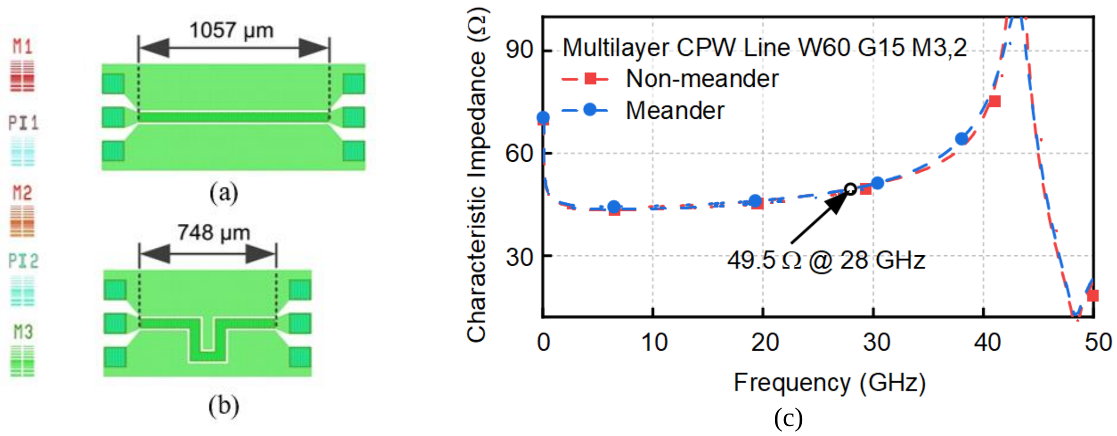


Figure 8. Layout design of (a) non-meander multilayer and (b) meandered multilayer CPW line with width of 60 µm, gap 15 µm, and expanded M3,2 and theirs (c) characteristic impedances

Based on the designs that have been presented in this work, layout comparison of multilayer bandpass filters and their respective S-parameters have been shown in Figure 9. Figures 9(a) and (b) shown the layout comparison of multilayer bandpass filters before and after miniaturization. A meander resonator has significantly reduced the size of multilayer bandpass filter. The multilayer bandpass filter had a resonator length of 1,087 µm before the miniaturization, and the resonator occupied an area of 1.18 mm^2. After miniaturization, the multilayer bandpass filter has a resonator length of 778 µm, with the resonator occupies an area of 0.61 mm^2. Figure 9(c) shows the S-parameters comparison of multilayer bandpass filters before and after the miniaturization. The miniaturized bandpass filter has an insertion loss of -2.87 dB and return loss of -11.1 dB at 28 GHz with bandwidth of 3,000 MHz. It is also shown that the frequency and bandwidth of the miniaturized BPF are similar with bandpass filter before the miniaturization. These results are also compared with previous research as presented in Table 2. In this paper, the compact bandpass filter has been realized for frequency 28 GHz with the resonator structure has been designed based on multilayer MMIC CPW line.

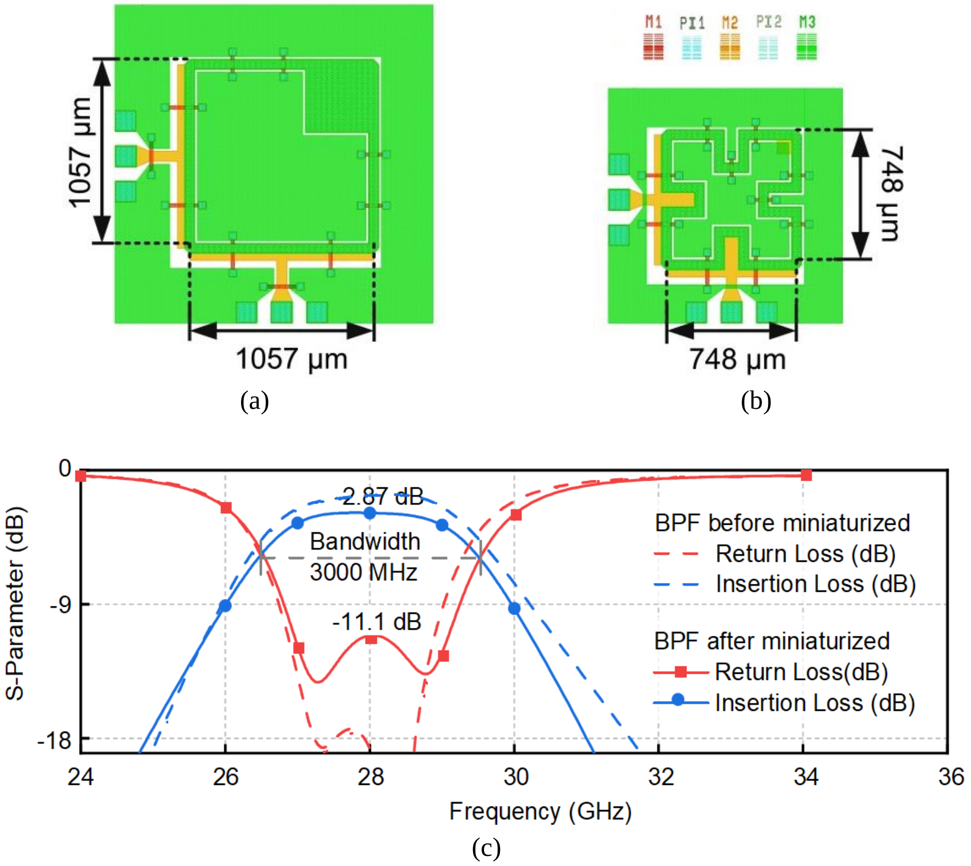


Figure 9. The layout comparison of the multilayer bandpass filters, (a) before and (b) after miniaturization, and (c) their respective return and insertion losses

Table 2. The design of bandpass filters in this work and previous research

Ref.	Size (mm^2)	Frequency (GHz)	Bandwidth (MHz)	Insertion loss (dB)	Return loss (dB)	Technology
[29]	1.23 x 2.55	28	3,100	-2.5		On-chip, GaAs
[30]	1.5 x 1.5	28	7,812	-1.3	< -17.6	Multilayer PCB
Before miniaturize	1.06 x 1.06	28	3,000	-1.62	-18.6	Multilayer CPW
After miniaturize	0.75 x 0.75	28	3,000	-2.87	-11.1	MMIC, GaAs

4. CONCLUSION

This work has demonstrated a multilayer CPW line and its utilization in designing a compact multilayer CPW bandpass filter based on dual-mode resonator. A bandpass filter for frequency 28 GHz was designed for the 5G millimeter-wave band requirement, where the optimal frequency and 3 dB-bandwidth achieved by utilizing dual-mode resonator with one perturbation applied on its corner. As the results, the multilayer CPW MMIC bandpass filter has insertion loss of -1.62 dB, and return loss of -18.6 dB at 28 GHz. The investigation of the electrical field distribution of the dual-mode bandpass filter has shown to have a good agreement with the even-odd mode excitation theory. In addition, the resonator of the bandpass filter was reduced by 50% using meander approach. Therefore, this work has demonstrated more compact design with competitive performance of bandpass filter for 5G millimeter wave applications.

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