A low-loss Ka-band coupled-resonator bandpass filter based on the printed ridge gap waveguide (PRGW) technology is presented for millimetre-wave applications. The PRGW has been employed to allow electromagnetic-wave propagation in the air gap in order to avoid dielectric loss and improve transmission performance which is suitable for millimetre-wave applications. The bandpass filter is implemented with two transmission zeros which are easily obtained by adjusting the stub length of two T-shape stub-loaded resonators (SLR). From its simulation frequency response, the filter has an insertion loss of 0.8 dB, a return loss less than –20 dB during the passband and high selectivity in cut-off frequency. The prototype of the proposed filter is fabricated and tested and a good agreement can be observed between the measured and simulated results.

Introduction: Due to the rapid development of microwave and millimetre-wave integrated circuits, the communication system is drifting towards high frequency and data rate solution to accommodate the explosive expansion in future information era. The fourth-generation (4G) communication technology can no longer meet the demand of low delay, high capacity and low-power dissipation. The fifth communication system (5G) has been officially launched for commercial use in many areas, and the millimetre-wave technology could provide an effective means for high-speed transmission, occupying an important position in the wireless communication system, especially in the printed ridge gap waveguide (PRGW) technology.

The PRGW has been developed by replacing the metal ridge in ridge gap waveguide (RGW) [1] with microstrip lines connected with metal vias, and replacing the metal pins with the artificial magnetic conductor (AMC). As a result, the electromagnetic-wave propagates in the air gap and the dielectric loss is avoided [2]. The PRGW transmits the quasi-transverse electromagnetic mode (Q-TEM) wave, and has no mode conversion loss when integrated with TEM/quasi-TEM lines, such as microstrip lines. Therefore it is considered among the most important candidates for the 5G system. Due to the importance of such structure, more and more researchers have emerged. In [3], the PRGW has been employed to feed the two slot antennas working at 60 GHz which is also formed in the top plate of PRGW. The coupling reduction of more than 10 dB is achieved by removing a part of the top metallic plate of the PRGW between the two slots. Coupling reduction is achieved while maintaining a small distance of half wavelength between the two slots. Also, the coupling reduction covers nearly all the 12% impedance bandwidth of the slot antennas. In [4], a 3-dB planar quadrature hybrid coupler based on PRGW for 5G system has been presented, and it covers the band from 29 to 31 GHz, which is 6% relative bandwidth at 30 GHz, while the phase imbalance is 8° ± 5°. The proposed design has superior characteristics such as compactness, low-loss, and low dispersion, which makes the PRGW supports a quasi-TEM mode, which minimizes the signal distortion. Meanwhile, in [5], the proposed filter is employed as a new class of planar filter, which also shows promising low-loss behaviour at 30 GHz. The proposed filters are self-packaged that make them smaller and lighter than the microstrip filters that require the metallic box for packaging. However, the geometric structure of the proposed filter is complex and difficult to adjust/optimize due to the irregular corners.

In this paper, a low-loss 4-order coupled-resonator bandpass filter based on PRGW with two transmission zeros (TZs) is proposed for 5G millimetre-wave applications. The two TZs outside the passband can be easily obtained by adjusting the stub length of two T-shape stub-loaded resonators (SLR). The dispersion characteristics of PRGW are analysed according to [2] in Section II, precisely because of its low signal distortion which allows electromagnetic-wave propagation in the air gap that makes applications to millimetre-wave transmission possible. By extending the substrate layers, screw holes are added to stable the air gap for later measurement. The prototype of the proposed filter is fabricated and tested, where the measured and simulated results show a good agreement.

Geometry of printed ridge gap waveguide: The AMC unit cell of PRGW and the PRGW model suitable for Ka-band are shown in Figures 1a and 1b, respectively. The metal patch is periodically arranged around the conducting ridge, and each metal patch is connected to the GND through the metal via to suppress any electromagnetic-wave leakage within Ka-band. The conducting ridge with vias of the PRGW is composed of the microstrip with the metal vias, which have the same size and period as the vias of AMC unit, and this will prevent the signal propagation in the substrate below the microstrip line. The air gap exists between the upper PEC and the substrate, while the air gap needs mechanical support to be stable in the actual prototype. PRGW is called an inverted microstrip line because it has some similarities to the microstrip line. The integral line in the wave-port excitation of normal microstrip line (with PEC above) is along the direction of +z and the electric-field energy is concentrated inside the substrate, as shown in Figure 2. For PRGW, although it seems that the conducting ridge is printed on the surface of substrate, it regards the air gap as a substrate with a dielectric constant of 1. Therefore, the width of the conducting ridge is calculated according to the air gap, the integral line in the wave-port excitation of PRGW is along the direction of –z and the electric-field energy is concentrated inside the air gap, as shown in Figure 3. On the whole, PRGW is like a microstrip line with air gap as the substrate, and is inverted on the AMC structure, so PRGW is called an inverted microstrip line.

The dimensions and dispersion diagram of AMC unit cell are shown in Figure 4. A substrate RO3003 with thickness of h, = 0.762 mm is used for the unit cell. The dimensions of the metal patch are selected to be with R = 0.75 mm, h, = 0.508 mm. All the vias are set as copper cylinders in the simulation and have a radius of 0.15 mm, and the period of unit cells is set to be 1.7 mm. The stopband operates between 21 and 33 GHz which covers the operate frequency of the bandpass filter, i.e.

![Image](https://example.com/image1.png)

Fig. 1 (a) AMC unit cell and (b) PRGW

![Image](https://example.com/image2.png)

Fig. 2 Cross-section of microstrip line

![Image](https://example.com/image3.png)

Fig. 3 Cross-section of PRGW

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30 GHz. When the height of air gap is smaller than a quarter of wavelength, the electromagnetic-wave will only travel along the conducting ridge and will be cut off in any other direction. The study in terms of stop bands for different geometries made with mushrooms and metal pins were already performed in [6–8]. The dispersion diagram of PRGW array is shown in Figure 5. It shows that the PRGW supports a quasi-TEM mode, which could minimize the signal distortion. All dispersion diagrams are generated by Computer Simulation Technology (CST) eigenmode solver.

**Structure of the proposed filter:** The 3D exploded model view of proposed 4-order coupled-resonator bandpass filter based on PRGW is shown in Figure 6, which includes three layer dielectric substrates. The dielectric substrate Duroid 3003 is used for the bottom layer with thickness of 0.762 mm. The bandpass filter is followed by the design guidelines provided in [9, 10], and is composed of half-wavelength microstrip line resonators which are coupled through the gap between them.

T-shape SLRs are applied to generate 2 TZs outside the passband. By adjusting the stub length of the two T-shape SLRs, the TZs outside the passband can be easily adjusted. The geometry of the bandpass filter is shown in Figure 7, the dimensions of it are selected to be with $w_1 = 1.98$ mm, $w_2 = 1.58$ mm, $w_3 = 1.18$ mm, $L_1 = 4.08$ mm, $L_2 = 0.8$ mm, $L_3 = 4.12$ mm, $L_4 = 2.6$ mm, $L_5 = 2.86$ mm, $g_1 = 0.18$ mm, $g_{12} = 1.26$ mm, $g_{13} = 0.18$ mm and $g_{14} = 0.5$ mm.

The medium layer includes two Duroid 5880 substrate plate with thickness of 0.508 mm. The two substrate plates not only provide stable mechanical support for the air gap, but also have feeding microstrip lines printed on the back of them for later measurement. The PEC at the top layer suppresses the leakage of electromagnetic wave in the vertical direction, and the AMC units around the conducting ridge suppress the leakage of electromagnetic wave in the horizontal direction as well. Therefore, the whole air gap looks like a transparent rectangular waveguide, in which the electric-field energy is concentrated as shown in Figure 8. At the same time, the proposed bandpass filter also achieves the purpose of PRGW to allow electromagnetic wave propagate in the air gap to avoid dielectric loss.

**Results and discussion:** The proposed bandpass filter has been simulated using HFSS and simulated S-parameters are presented in Figure 9. The 4-order bandpass filter has a relative bandwidth of 7.3% over the entire frequency band of 29.8 to 32 GHz. In the whole passband, the return loss (S11) is basically less than $-20$ dB, and the insertion loss (S21) is about $-0.8$ dB. There are two TZs at 27 GHz and 33 GHz outside the passband respectively and the out-of-band inhibition reaches $-30$ dB. As a result, the attenuation out of passband is sharp than a high selection performance can be obtained.

The fabricated bandpass filter is shown in Figure 10. The screw holes are designed in accordance with the method of extending the substrate layer in [11] and no new dielectric loss is introduced. The there-layer structure can be held in place very well by six screws. The measurement setup of the fabricated bandpass filter is shown in Figure 11, and
the bandpass filter is assembled in test fixture which is used for high frequency measurement. The measured S-parameters of the fabricated bandpass filter is shown in Figure 12 along with the simulated results. The central frequency of the 4-order bandpass filter is slightly offset, with one pole missing in the passband, and the working bandwidth is not significantly reduced. In the passband from 28 to 32.3 GHz, the return loss is basically less than $-15\,\text{dB}$, which is basically around 1.1 dB, and the in-band flatness is good. It is a pity that the out-of-band inhibition performance at high frequency is slightly receded. The above deviation may come from the machining tolerance for the length of coupled-resonators, or because the thickness of the copper lead to air gap is not tight enough which introduced little radiation loss. Overall, the measured result and simulated result agree well.

**Conclusion:** A low-loss 4-order coupled-resonator bandpass filter based on PRGW with two TZs has been fabricated and simulated. The TZs outside the passband can be easily obtained by adjusting the stub length of the two T-shape SLRs compared to other microstrip cascade filters. The structure and design have been described in detailed, and the bandpass filter operates at 30 GHz, which can be employed for 5G millimetre-wave application. The proposed bandpass filter is easy to integrate with other microwave and millimetre-wave circuits and has a broad application prospect in the 5G communication applications.

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**References**

1 Kildal, P.-S., et al.: Local metamaterial-based waveguides in gaps between parallel metal plates. *IEEE Antennas Wirel. Propag. Lett.* 8(4), 84–87 (2009)
2 Raza, H., et al.: Microstrip-ridge gap waveguide-study of losses, bends, and transition to WR-15. *IEEE Trans. Microwave Theory Techn.* 62(9), 1943–1952 (2014)
3 Attia, H., et al.: 60 GHz PRGW slot antenna array with small separation and low mutual coupling. In: *Global Symposium on Millimeter-Waves (GSMM)*, pp. 1–3. IEEE, Montreal, Canada (2015)
4 Ali, M.M.M., Shams, S.I., Sebak, A.: Printed ridge gap waveguide 3-dB coupler: Analysis and design procedure. *IEEE Access* 6, 8501–8509 (2018)
5 Sorkherizi, M.S., Kishk, A.A.: Fully printed gap waveguide with facilitated design properties. *IEEE Microwave Wireless Compon. Lett.* 26(9), 657–659 (2016)
6 Shams, S.I., Kishk, A.A.: Design of 3-dB hybrid coupler based on RGW technology. *IEEE Trans. Microwave Theory Techn.* 65(10), 3849–3855 (2017)
7 Sorkherizi, M.S., Kishk, A.A.: Transition from microstrip to printed ridge gap waveguide for millimeter-wave application. In 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1588–1589. IEEE, Vancouver, BC, Canada (2015)
8 Pucci, E.: New low loss inverted microstrip line using gap waveguide technology for slot antenna applications. In: *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, pp. 979–982. IEEE, Rome (2011)
9 Hong, J.-S.: Microstrip Filters for RF/Microwave Applications. Wiley, Hoboken, NJ (2011)
10 Matthaei, G.L., Jones, E.M.T., Young, L.: *Microwave Filters, Impedence-Matching Networks, and Coupling Structures*. Artech House, Norwood, MA (1980)
11 Sorkherizi, M.S., Kishk, A.A.: Self-packaged, low-loss, planar bandpass filters for millimeter-wave application based on printed gap waveguide technology. *IEEE Trans. Compon. Packag. Manuf. Technol.* 7(9), 1419–1431 (2017)