3^{rd} Order Coupled-Resonator Bandpass Filter Assisted by Groove Gap-Waveguide Technology for 26-GHz Radio Link Diplexer

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Abstract: **This paper investigates the design of a bandpass-filter (BPF) intended for 26-GHz radio-link diplexer using Groove-Gap-Waveguide (GGW) technology. Its unit-cells consist of a rectangular metal-pin which is connected to a bottom metal plate and its other side is electromagnetically coupled to a top-plate with an air-gap of approximately λ/4 that creates a bandgap, preventing unwanted electromagnetic-wave propagation. An array of these unit-cells forms a cavity resonator, allowing wave propagation over a specific conductive region. To achieve the desired passband response, a rectangular slot-channel is milled on the bottom metal plate, perturbing the cavity modes and creating the desired filter characteristics.**

Keywords: **BPF, coupled-resonator, GGW, Diplexer, mm-wave.**

I. INTRODUCTION

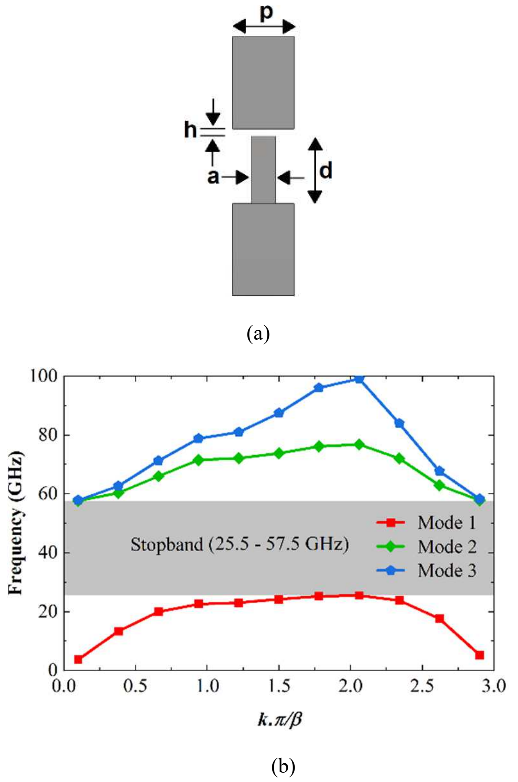
Filters are crucial front-end elements for choosing signals at particular frequencies, and their electrical responses are essential to the performance of millimeter (mm)-wave transceivers. A bandpass filter (BPF) accepts in-band signals to pass through while effectively rejecting undesirable out-of-band signals. To improve the performance of mm-wave transceivers, a BPF must be small with a high-quality factor (Q-factor), low noise figure (NF), low insertion loss (IL), high return loss (RL), good selectivity, and high out-of-band rejection (stopband rejection). While planar technologies, such as microstrip and coplanar waveguides, and substrate integrated waveguide (SIW) technology are appropriate for integration and easy to manufacture, they suffer from higher losses at enhancing frequencies and cavity resonances when encapsulated, disrupting their estimated performance [1]. This necessitates the development of innovative transmission line technologies for the mm- and sub-mm-wave bands. In contrast, gap waveguides (GW), composed solely of metal, allow waves to propagate in the air gap between two metal plates which one plate textured with a "bed of nails" structure to create a high impedance condition on the surface [2] – [4]. Due to their unique properties, GWs are particularly promising for mm- and sub-mm-wave applications, where substrate losses significantly limit filter performance. Hence, this paper aims to demonstrate the use of groove gap waveguide (GGW) technology for a bandpass diplex filter in 26-GHz radio links.

II. GGW BANDPASS DIPLEX FILTER

In this section, the design process of the proposed coupled-resonator band-pass diplex filter utilizing GGW technology step by step is discussed. First, the unit-cell model, which consists of a metal pin situated between two parallel metal plates is presented. Next, the cavity resonator formed by an array of these unit cells is designed. Subsequently, the feasibility of the construction of the bandpass filter using three cavity resonators is demonstrated. Finally, the optimized coupled-resonator BPF for a 26-GHz radio link diplexer, achieving a very low insertion loss of 0.4 dB across a wide passband of 170 MHz is realized.

A) Unit-Cell Design

The configuration of the unit cell is shown in Fig. 1(a). The main structural parameters for modeling the proposed unit cell to realize the coupled-resonator band-pass filter for a 26 GHz radio link diplexer are as follows: the pin's height (d) is 2.2 mm, its length and width (a) are 0.8 mm, the period between adjacent pins (p) is 2 mm, and the air gap above the pin (h) is 0.25 mm (approximately λ/4). The proposed unit cell was optimized to provide a wide stopband region between 25.5 GHz and 57.5 GHz, as shown in Fig. 1(b).



(a)

(b)

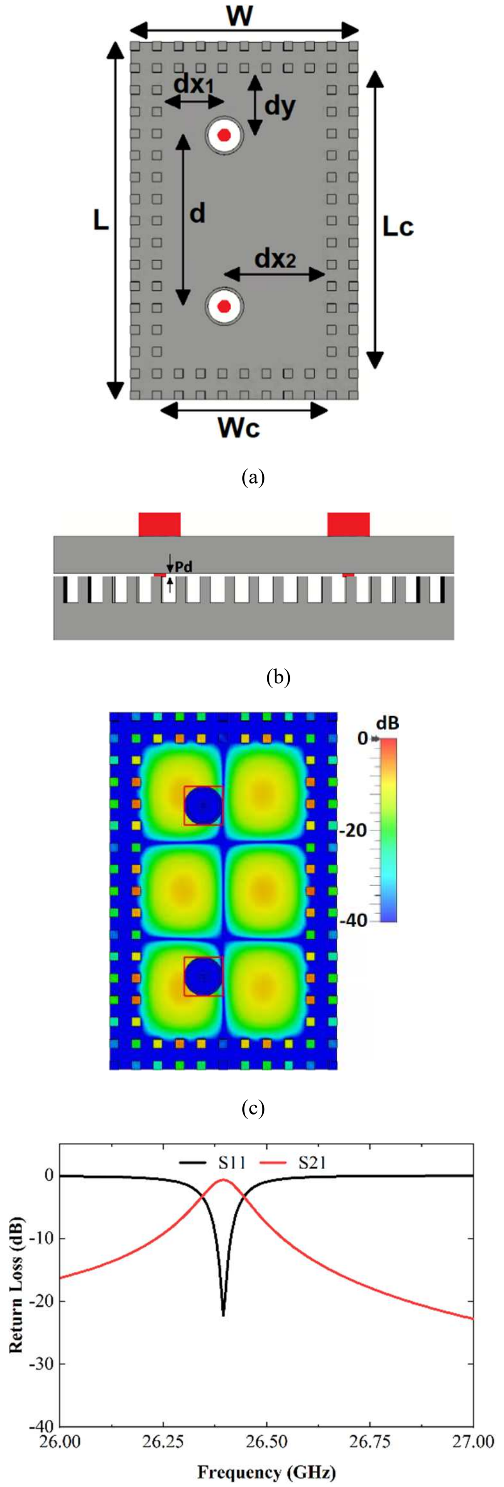
Fig.1. Proposed unit-cell, (a) layout, and (b) dispersion diagram.

B) Cavity Resonator Design Based on the GGW

The layout of the proposed cavity resonator, modeled with the GGW principle, is shown in Fig. 2. The top-view, showing the geometrical parameters, is presented in Fig. 2 (a). The top metal plate is hidden to provide a clearer view of the structural parameters. Fig. 2 (b) presents the side-view of the cavity resonator, illustrating the penetration depth (Pd) of the coaxial ports inside the cavity resonator area to excite it.

The design process is as follows: a rectangular cavity in the GGW was selected. Although this cavity is not a completely closed structure, it functions similarly to a fully enclosed resonator, exhibiting a comparable electromagnetic field pattern, as depicted in Fig. 2 (c). The cavity is made in the area shaped by the groove between the nails on the bottom plate and the flat metal plate on top. Fields are confined to the groove zone without requiring any metal contact between the two metal surfaces. The bed of nails imposes a cut-off for the parallel-plate modes in the air gap between the two surfaces, preventing fields from expanding through this gap and keeping them confined to the cavity or groove zone.

The dimensions of the geometrical parameters are L=32.8, W=20.8, Lc=27.2, Wc=15.2, d=15.6, dx1=dy=5.8, dx2=9.4, Pd=0.3 mm. The remaining parameters are the same as those mentioned in the unit-cell section. The S-parameters of the cavity resonator are plotted in Fig. 2 (d). It is evident that the return loss is below 10 dB across the 26.37–26.41 GHz range, with an insertion loss of 0.71 dB at the resonance frequency of 26.4 GHz. Therefore, the proposed single cavity resonator provides a narrow passband of 40 MHz.



(a)

(b)

(c)

(d)

Fig.2. Cavity resonator based on GGW technology, (a) top-view, top plate is hidden to show a better view on the geometrical parameters,

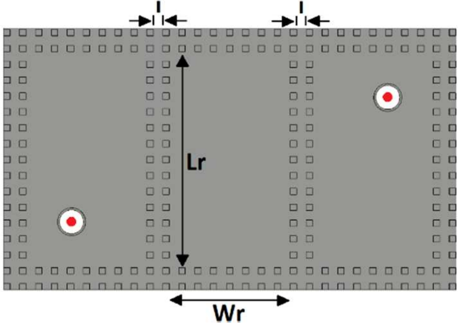
(b) side-view showing the penetration depth of the coaxial ports inside the cavity resonator, (c) electric field pattern of the cavity resonator in the GGW, and (d) return-loss (S_{11}) and insertion-loss (S_{21}). The design is carried out using CST Microwave Studio.

C) 3rd Order BPF based on GGW Concept

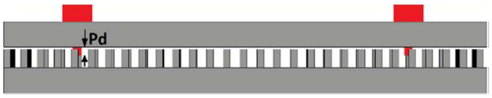
To realize a third-order bandpass filter for the 26-GHz radio link diplexer application, the cavity resonator designed in the previous section was utilized. Its configuration is shown in Fig. 3. During the design process, it was discovered that coupling between adjacent resonators could shift the resonance frequency of the cavities. To evaluate and quantify this frequency shift, an eigenmode analysis was conducted using CST Microwave Studio. The optimized dimensions of the resonator were determined to be Lr = Lc = 27.2 mm and Wr = Wc = 15.2 mm, as shown in Fig. 3 (a), which is matched with the dimensions of the cavities designed in the previous section.

The physical interval (i) between adjacent resonators, which achieves the desired coupling coefficients, was determined using CST Microwave Studio. Various values of the interval (i) were investigated, and the required value was found to be i = 1.2 mm to achieve the necessary external Q-factor. Additionally, the penetration depth (Pd) of the coaxial cables inside the cavity resonators to excite them and achieve the required return and insertion losses is Pd = 1 mm, as shown in Fig. 3 (b), which is three times deeper than the single cavity configuration shown in the previous stage.

The return and insertion losses of the proposed third-order filter based on the GGW technology are plotted in Fig. 3 (c). The S-parameter behavior shows that the proposed filter has a 20 MHz passband across 26.49 – 26.51 GHz with a resonance at 26.50 GHz and an insertion loss of 0.52 dB. The results indicate that the return and insertion losses of the filter are not stable for the 26-GHz radio link diplexer application. Therefore, further improvements are necessary to achieve the required performance for this application, which is discussed in the next section.



(a)



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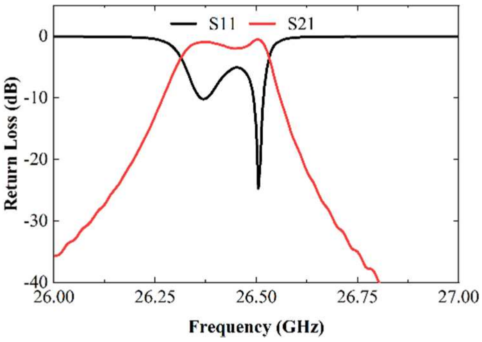
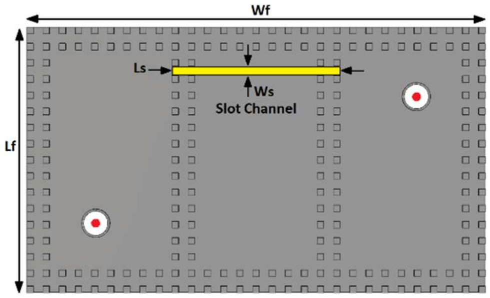


(c)

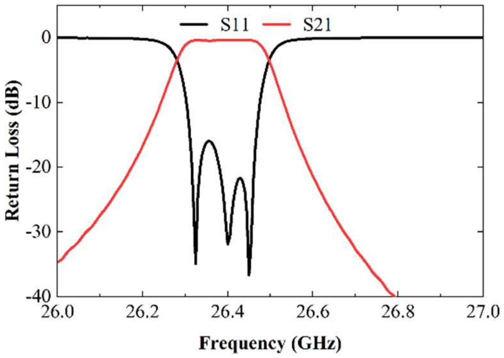
Fig.3. Configuration of the proposed third order BPF, (a) top-view, (b) side-view to show the penetration depth, and (c) return-loss (S_{11}) and insertion-loss (S_{21}).

D) 3rd Order Coupled-Resonator GGW BPF

A feasible method for enhancing the return loss of a system is to introduce a narrow slot channel onto the bottom metal plate of the gap waveguide where the resonator is located [5]. This approach helps both to excite and to extract the signal. In this design, a strategically positioned rectangular slot channel is created on the bottom metal plate of the resonator, as demonstrated in Fig. 4 (a). The dimensions and characteristics of this slot channel have been fine-tuned through 3D electromagnetic simulations conducted using CST Microwave Studio. The length (Ls) and width (Ws) of the slot are 20.8 mm and 1.0 mm, respectively. The length (Lf) and width (Wf) of the optimized GGW-based BPF are 32.8 mm and 56.8 mm, respectively. The other geometrical parameters remain the same as in previous stages.



(a)



(b)

Fig.4. Topology of the 3rd order coupled-resonator GGW BPF, (a) top-view, and (b) return-loss (S_{11}) and insertion-loss (S_{21}).

The return-loss and insertion-loss performances of the proposed filter are plotted in Fig. 4 (b). As shown, there is a significant enhancement in return-loss and a reduction in insertion-loss, confirming the effectiveness of the proposed slot channel resonator approach. The passband now covers 170 MHz between 26.30 and 26.47 GHz, showing an improvement of over eight times compared to the previous 20 MHz passband. Additionally, the insertion-loss has decreased to 0.4 dB, representing more than 20% reduction compared to the previous case without the slot channel. These results indicate that the proposed 3rd coupled-resonator BPF assisted by the GGW technique is a suitable candidate for 26-GHz radio link diplexer applications.

III. CONCLUSION

The feasibility of using GGW technology to realize a third-order coupled-resonator BPF for 26-GHz radio link diplexer applications was studied and investigated. Initially, a unit cell based on the GGW was modeled and used to implement a cavity resonator. The dimensions of the cavity resonator and the penetration depth of its coaxial cables were optimized to provide a passband at the 26-GHz band with appropriate return-loss and insertion-loss values. Subsequently, the proposed single cavity resonator was utilized to realize a third-order BPF. To achieve a wide passband around 26 GHz, a rectangular slot channel was milled inside the cavity resonator to excite and transmit the signal, achieving a high return-loss of more than 30 dB and a low insertion-loss of less than 0.4 dB. The results confirm that further development of the proposed coupled-resonator approach assisted by GGW can lead to the realization of various high-performance BPF structures for different applications across the millimeter- and sub-millimeter-wave spectrums.

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