

A Transmission Zero Position Control for 28 GHz Rectangular Waveguide Cavity Bandpass Filter

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Received: 27/10/2021

Accepted: 14/1/2022

ABSTRACT

This paper presents a method to control on single real-frequency transmission zeros (TZs) position in the reject band for third-order waveguide band pass filter (BPF). The external couplings are achieved by using a coaxial probes while the internal couplings are achieved by using short-circuit metallic posts. The TZs appear are generated by forming a triplet, i.e., multipath cancellation between non-adjacent resonators. The dimensions of the metal post between non-adjacent resonators are adjusted to control the position of TZs in the rejection band. A third order waveguide generalized Chebyshev BPF is simulated with HFSS at a center frequency of 28 GHz to validate the design method. The simulated insertion loss is 0.05 dB and the bandwidth (BW) is 500MHz. The simulation demonstrates the compatibility of the presented filtering structure with 5G applications.

Keywords:

TZ position control, rectangular wave guide filter, Generalized Chebyshev filter, 5G filter applications.

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1. INTRODUCTION (10 PT)

The high demand for data rates in modern communication systems requires increasing bandwidth and high-performance filters suitable for operating at high frequencies. Filters need to maintain low losses in the frequency spectrum occurring at the boundary between the different wireless communication systems while decreasing guard band [1][2]. The technique of cross-coupling between non-adjacent resonators allows the generation of TZs in the rejection, which results in miniaturized filters with high performance, suitable for required low loss applications[3]. Using the technique of cross-coupling can reduce the number of resonators, and thus, meet a specification with reducing insertion loss, size and cost [4]. The microwave BPF with TZs uses a direct and cross-coupling between the resonators to realize the required specifications, and the number of TZs depend on the numbers of cross-coupling [5]. For waveguide filters, the TZs can be produced by many cross-coupling techniques such as Cascaded Singlets and triplets [6]. In [7], cascaded-singlet waveguide filters have been

designed to produce transmission zeros in the rejection band using upper mode cavities. Singlet block consisted of a resonators working in the TE₂₀₁ was coupled to the source and load to produce the bypass couplings, and thus, transmission zeros.. This method can realise filters having transmission zeros equal to the number of reflection zeros. An example of a 3rd order filter has been designed at 30.75 GHz center frequency with NTZs above the passband.

In[8], an integrated ceramic waveguide bandpass filter with N+1 finite transmission zeros has been designed by using the triplet technique. The inductive direct coupling has been realized by introducing a post between cascade resonators in order to produce TZs above the passband. Examples of TZs below the passband has been shown by introducing a capacitive cross-coupling between the first and third resonators by using partial metallic posts. The filter has been designed to operate at 1.7 GHz center frequency.

This paper presents a method to control the position of TZs in the rejection band based on a triplet routing scheme. The filter has been

implemented in a rectangular waveguide technology. The filter configuration consists of cavity resonators having a conductivity of 5×10^7 S/m. The external couplings are achieved by metallic probes positioned at the first and last resonators. The internal couplings are achieved by metal posts positioned half-wavelength apart. The BPF was designed at 28 GHz with bandwidth(BW) of 500 MHz. The proposed filter is suitable for 5G applications.

2. DESIGN PROPOSED CAVITY RESONATOR

The cavity resonator is a section of rectangular waveguide has been short-circuited from both sides, as shown in Fig. 1.

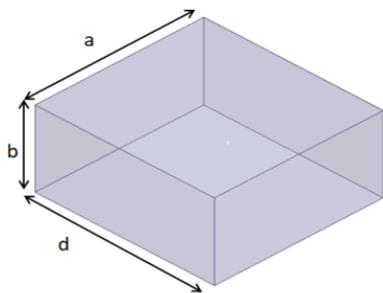


Fig. 1 Rectangular waveguide cavity resonator.

The frequency of resonator depends on the dimensions (width, height, length) of the rectangular cavity. The following dimensions are chosen for optimum out-of-band performance: $a=2b= 7.122\text{mm}$. The resonator operates at the dominant mode (TE_{101}) having a frequency of 28 GHz. The length of resonator (d) can be calculated by equation[9] (1).

$$f_0 = \frac{1}{2\sqrt{\epsilon\mu}} \sqrt{\left(\frac{l}{a}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{n}{d}\right)^2} \quad (1)$$

Where ϵ is the permittivity and μ is the permeability. l, n and m represent the half-wavelength variation of the electric field lines along the resonant dimensions: width (a), height (b), and resonant length (d). The resonant frequency for the dominant mode according to the change of the resonant length has been simulated by HFSS software as shown in Fig. 2. The relationship between the resonant frequencies and the length of the cavity is inversely proportional. The dominant frequency TE_{101} mode is a 28GHz occurs at $d=8.1299\text{mm}$.

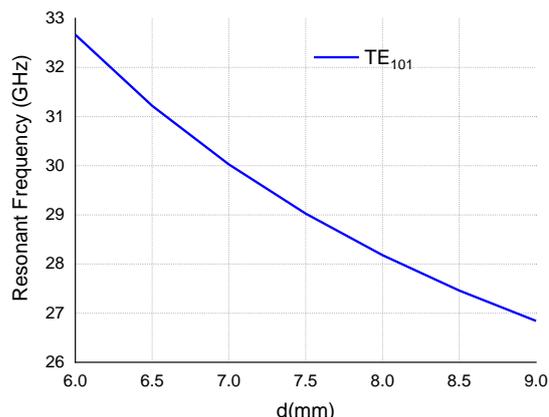


Fig. 2 The effect of length of resonator on frequency.

The dimensions of the resonators in generalized Chebyshev filter are calculated by amount of deviation in the resonant frequency of each resonator f_{ox} from the center frequency of the filter f_0 depending on the coupling coefficient of each element with itself M_{ii} in the coupling matrix of the filter[10].

$$f_{ox} = M_{ii} * B * W \quad (2)$$

$$f_{rnew} = f_0 + f_{ox} \quad (3)$$

The effective wavelength $\lambda_{g\ effective}$ is calculated:

$$\lambda_{g\ effective} = \frac{c}{f_{rnew}} \quad (4)$$

3. EXTERNAL COUPLING

In order to achieve the external coupling in the rectangular waveguide filter, a coaxial probe is used, which is placed in the region where the electric field is most intense in the first and last resonators of the filter. The inner conductor of the coaxial probe acts as an antenna to excite the energy inside the waveguide. There are four variables to determine the specifications of the probe, which are the diameter of the probe, its distance from the outer edge of the resonator, the height of the probe inside the resonator, and its distance from the side wall of the resonator as shown in Fig. 3. The length and diameter of the feed probe are changed in order to reach the value of external coupling (Q_e) through the following equation[2]

$$Q_e = 0.5\pi * f_0(\text{GHz}) * td(\text{ns}) \quad (5)$$

Where td is the group delay.

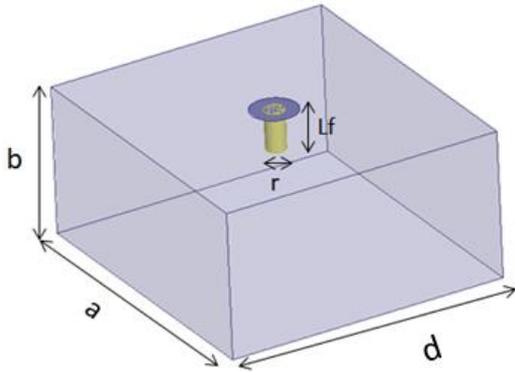


Fig. 3 Coaxial probe feeder.

The coupling factor was calculated with the change of the length and diameter of the probe as in Fig. 3. It is noted that the coupling factor is inversely proportional to the increase in the length and diameter of the probe. At a diameter of ($r=0.5\text{mm}$), the highest value of the external coupling factor when ($L_f=0.25\text{mm}$) is $Q_e=584.7$ until quickly reaching the lowest value of $Q_e=38.06$ when ($L_f=1\text{mm}$).

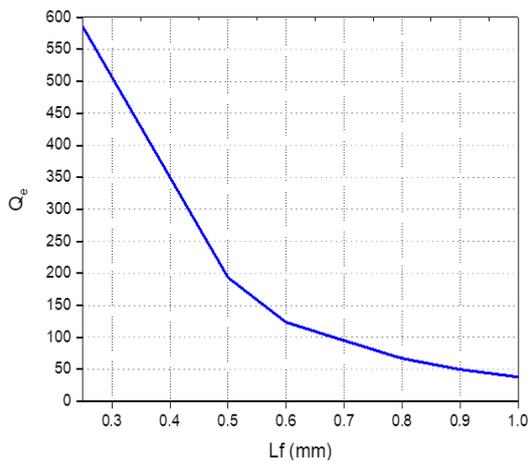


Fig. 3 Relationship of the length of the feed probe to the external coupling.

4. INTER RESONATOR COUPLING

The coupling between the resonators is achieved either by inductive coupling or capacitive coupling, both couplings were done by using posts. In general Chebyshev waveguide filters, the internal coupling is done by direct inductive couplings and other cross couplings are determined by specifying whether the TZ are above or below the pass band. If the TZ is the above of the pass band, then the cross coupling is done by inductive coupling.

4.1. Inductive coupling

For a rectangular waveguide filter, inductive internal coupling between the resonators can be achieved by placing circular post

perpendicular to dimension (a) and parallel to dimension (b) of the waveguide. They are placed at intervals of half a wavelength, as shown in Fig. 4.

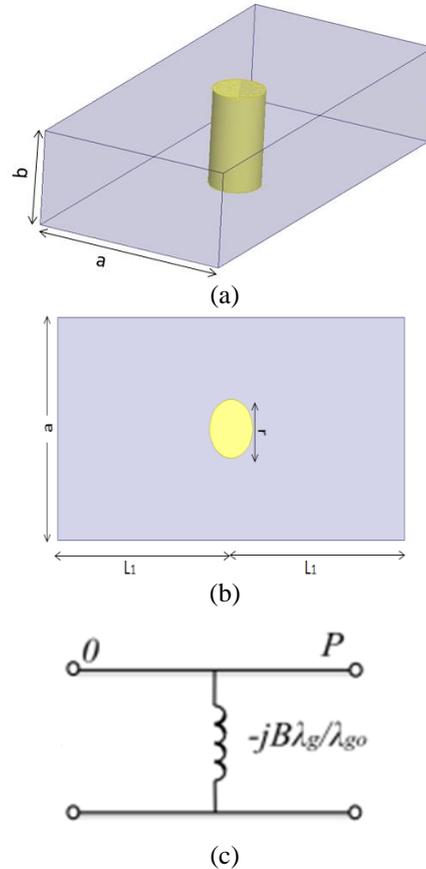


Fig. 4 Inductive coupling between two resonators using a post (a) 3D view (b) top view (c) equivalent circuit.

From the equivalent circuit shown in Fig. 4, the ABCD matrix of the post (conductor) is [8]:

$$T = \begin{bmatrix} 1 & 0 \\ -\frac{jB\lambda_g}{\lambda_{g0}} & 1 \end{bmatrix} \quad (6)$$

Where B is susceptance, λ_g is e Guide wavelength and λ_{g0} is Guide wavelength at resonance frequency.

4.2. Capacitive coupling

This is achieved by using a partial post of diameter (r) perpendicular to dimension (a) and parallel to dimension (b) with depth (h) placed between two resonators of length, each of which is half-wavelength as shown in Fig. 5. The amount of coupling to be achieved is a function of the diameter and depth of the post within the waveguide.

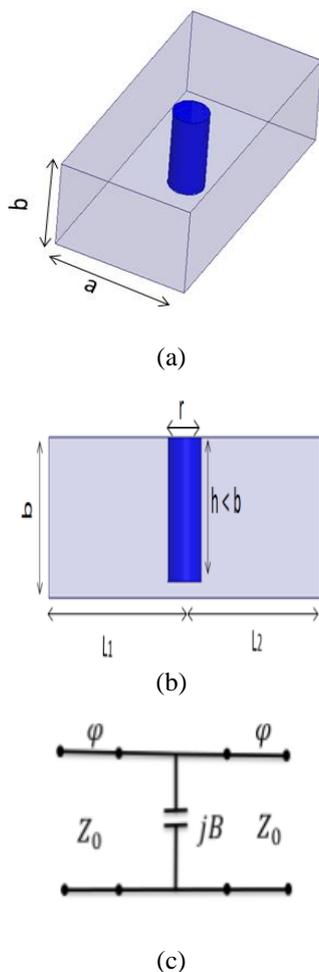


Fig. 5 Capacitive coupling between two resonators using a post (a)3D view (b) top view (c) equivalent circuit.

From the basic theory of circuits, the value of the capacitive can be written as [11]:

$$jB = 2\pi f c \tag{7}$$

$$c = \frac{B}{2\pi f} \tag{8}$$

It is also possible to calculate the value of the capacitance between two metal plates that has an area A separated by a distance of $d_{separation}$

$$c = \frac{\epsilon_0 \epsilon_r A_{area}}{d_{separation}} \tag{9}$$

The dimensions of the inductive or capacitive posts are adjusted to achieve the inter-resonator coupling coefficients M_{ij} .

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for } i = 1 \text{ to } n - 1 \tag{10}$$

Where FBW is fractional bandwidth and g_i is Lowpass prototype element values[12].

$$g_1 = \frac{2 \sin\left[\frac{\pi}{2N}\right]}{\sinh\left(\frac{\ln\left(\coth\frac{L_R}{17.37}\right)}{2N}\right)} \tag{11}$$

$$g_i = \frac{4 \sin\left[\frac{(2i-2)\pi}{2N}\right] \sin\left[\frac{(2i-1)\pi}{2N}\right]}{4(\gamma^2 + \sin^2\left(\frac{(i-1)\pi}{N}\right)) g_{i-1}} \quad \text{for } i=1,2,3..N \tag{12}$$

$$g_{N+1} = \begin{cases} 1 & \text{for } N \text{ odd} \\ \coth^2\left(\frac{\beta}{4}\right) & \text{for } N \text{ even} \end{cases} \tag{13}$$

The required coupling bandwidth between the filter resonators is calculated.

$$\text{coupling bandwidth} = B.W * M_{ij} \tag{14}$$

Fig. 6 shows the relationship of the inductive coupling bandwidth with the diameter of the post. It observed that, the coupling bandwidth is inversely proportional to the diameter of post. The largest simulated bandwidth has been recorded at $r=0.25\text{mm}$, while the coupling vanishes close to 1.5mm .

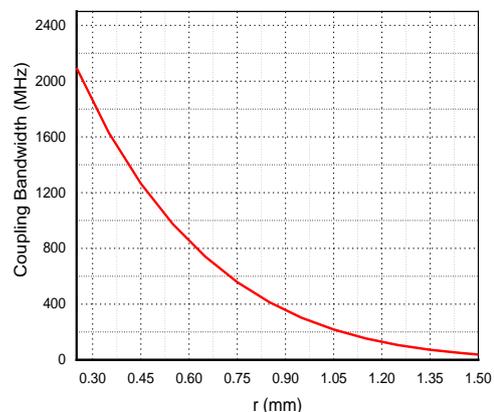


Fig. 6 Relationship of the inductive coupling bandwidth of a single post against the diameter of the post.

Fig. 7 illustrates the relationship of the capacitive coupling bandwidth with the diameter of the post. It shows that the coupling bandwidth are increasing with increasing the diameter and depth of the post. The varing of coupling can be achieved until 1000MHz.

5. DESIGN OF GENERALIZED CHEBYSHEV TYPE WAVEGUIDE FILTER

To design a generalized Chebyshev waveguide filter, we need to generate TZs in the rejection band

of the filter response by using the cross coupled triplet technique.

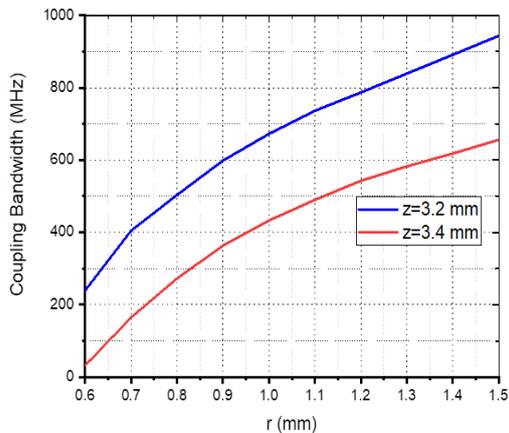


Fig. 7 Relationship of the capacitive coupling bandwidth with the diameter of the post at varying depth inside the resonator.

5.1. Design of 3rd order filter (TZ) below the passband

A third-order filter with a transmission zero below the passband was designed using a generalized Chebyshev rectangular waveguide with cross-coupling from resonant 1 to resonant 3 as shown in Fig. 8.

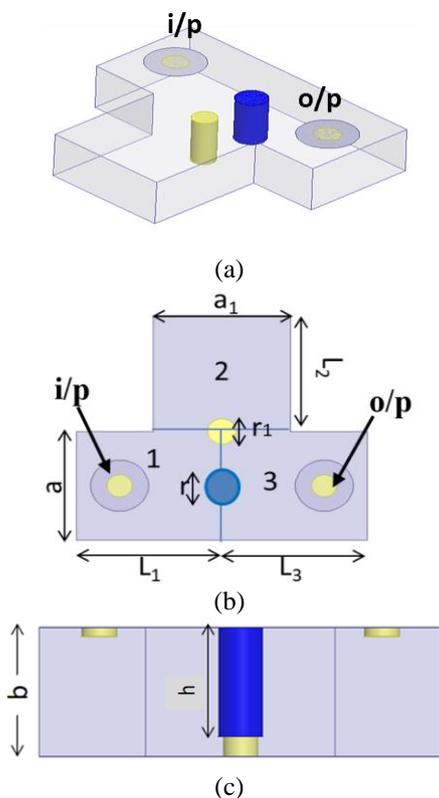


Fig. (8) A third-order filter with a TZ below the passband 3D view (b) top view (c) side view.

Direct coupling between resonators 1 and 2 and between resonators 2 and 3 are achieved by placing a post in the intersection of the three resonators, with diameter (r) and depth (b) to provide inductive coupling between those resonators, while cross-coupling is achieved between resonators 1 and 3 By placing a post between these two resonators, with a diameter (r₁) and a depth (h) for h<b, in order to achieve a capacitive coupling between the two resonators that works to achieve the transmission zero below the passband. The position of the (TZ) can be controlled by controlling the post diameter and depth. The filter specifications shown in the table below.

Table 1: Specifications of the Chebyshev generalized filter below of the passband

central frequency	28GHz
bandwidth	500MHz
Insertion loss	≥0.05dB
Filter order	3
Return loss	≤ 20dB

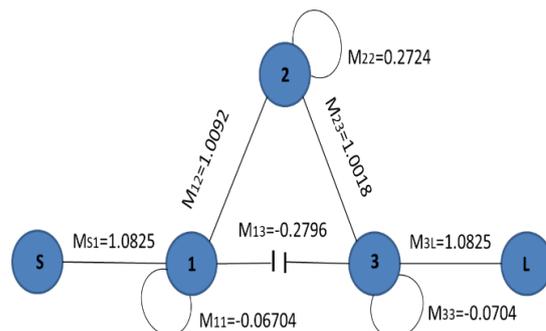


Fig. 9 Coronal shape of the coupling coefficients of a third-order generalized Chebyshev filter with (TZ) below the passband.

From the equations (1)-(4) and from the coupling coefficient M_{ii} was shown in Fig.(9). It can be calculated the length of each resonators according to European Standard WR28 ($a=2b= 7.122mm$). Also, the dimensions of inductive and capacitive couplings depending on the values that shown in Fig. 6 and Fig. 7.

The filter was simulated with the dimensions shown in table (2). The frequency response is shown in Fig. 10. The result shows that the return loss is 20dB at the passband and the bandwidth is 500MHz. The roll off speed on the side below the passband is large due to the presence of the (TZ) at the frequency of 27.1GHz.

To control the TZ position, the strength the cross-coupling bandwidth should be changed through change the diameter (r) for post with optimize the other dimensions as shown in Fig. 11.

Table 2: Calculated and optimal values of the generalized Chebyshev filter with a TZ below the passband.

Variable	Calculated	Optimized(mm)
a	7.122	7.122
b	3.556	3.556
a ₁	7.95	7.95
L ₁	8.152	8.444
L ₂	7.1866	7.47
L ₃	8.152	8.444
r	1	0.9441
r ₁	0.75	0.74
h	3.387	3.387

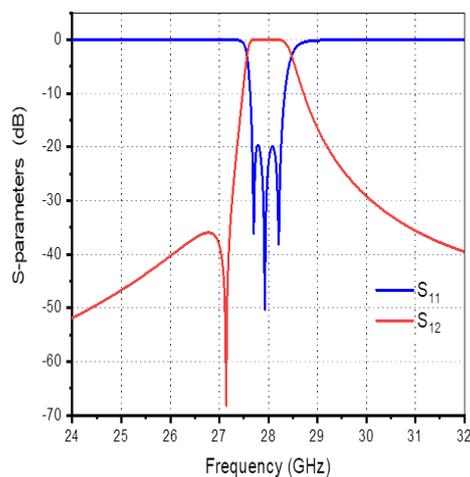


Fig. 10 S-parameters of a third-order generalized Chebyshev BPF with a TZ below the passband.

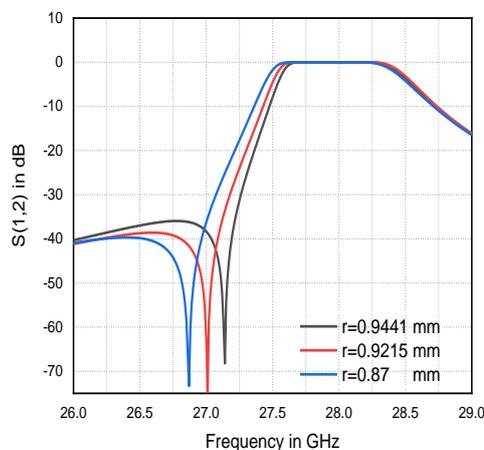


Fig. 11 Insertion loss response with controlling (TZ) position below the passband.

5.2. Design of 3rd order filter (TZ) above the passband

A third-order filter with a TZ above the passband is designed using a generalized Chebyshev function in rectangular waveguide with cross-coupling between resonant 1 to resonant 3 as shown in Fig. 12.

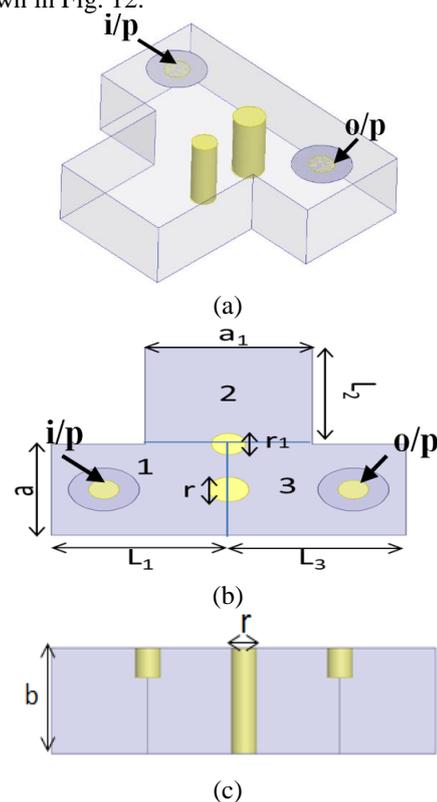


Fig. 12 A third-order filter with a passing zero above the passband (a) 3D view (b) top view (c) side view.

The direct couplings have been realized by inserting a post which is shorted between top and bottom of the waveguide cavity. The inductive cross-coupling is achieved between resonators 1 and 3 By placing a post between these two resonators, with a diameter (r₁) and a depth (b). The filter specifications are shown in the table (2).

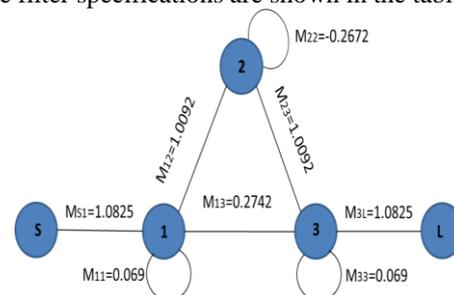


Fig. 13 Coronal shape of the coupling coefficients of a 3rd order generalized Chebyshev filter with TZ above the passband.

By using the equations (1)-(4) and the values of coupling in Fig. 13, the dimensions of filter can be determined as shown in table (3).

Table 3: Calculated and optimal values of the generalized Chebyshev filter with a (TZ) above the passband

Variable	Calculated (mm)	Optimized(mm)
A	7.122	7.122
B	3.556	3.556
a ₁	7.95	7.95
L ₁	8.11	8.434
L ₂	7.31	7.5
L ₃	8.11	8.434
R	1.1	0.9631
r ₁	0.7873	0.825

Fig. 14 shows the simulated frequency response of 3rd order generalize Chebyshev BPF with a TZ above the passband. The results show that the return loss is 20dB at the passband and the bandwidth is 500MHz. The roll off at the above of the passband was large compared to the normal case due to a TZ at the frequency 29GHz.

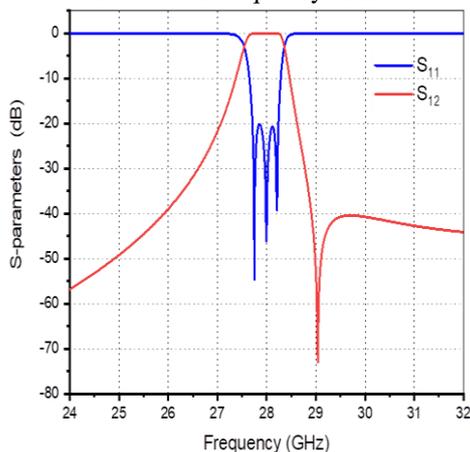


Fig. 14 S-parameters of a third-order generalized Chebyshev type filter with a (TZ) above the passband.

The position of the a TZ can be controlled by controlling the post diameter as shown in Fig. 15. The waveguide BPF filter is compared with other tilitures as summarised in Table 4. It is shows

that the proposed filter is competitive in terms of insetion loss and suppression.

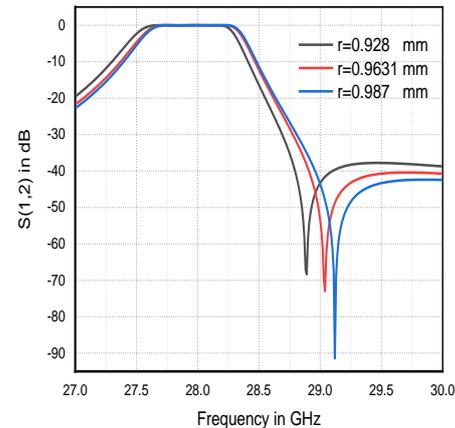


Fig. 15 Insertion loss response with controlling (TZ) position above the passband.

Table 4: Performance comparison with previous works.

Ref	f ₀ (GHz)	FBW (%)	S ₁₂ dB	order	fs/f ₀
[13]	8	8.12	0.9	2	2.25
[14]	5.2	4	1.2	2	1.73
[15]	2.98	1.07	1.25	3	1.25
[16]	3.8	1.05	0.26	3	1.13
[17]	5.5	58	0.5	3	1.63
This work	28	1.7	0.1	3	1.5

6. CONCLUSIONS

The external couplings are realized by coaxial probes where the length of the probe determine the amount of coupling. The intra couplings of the filter have been realized by using inductive posts which is shorted between the top and bottom. A third order filter generalized Chebyshev waveguide was simulated by HFSS software. The center frequency and the bandwidth were 28GHz, 500MHz respectively which are meet the specification of 5G applications. TZ) position control has been achieved the change in the dimeter and height of post between the resonators 1 & 3.

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التحكم في موقع الصفر الانتقالي لمرشح تمرير الحزمة باستخدام دليل موجة عند تردد 28 جيجا هرتز

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الملخص

يقدم هذا البحث تحكماً في موضع الصفر الانتقالي (TZ) في نطاق الرفض لمرشح الدليل الموجي لتمرير الحزمة من الدرجة الثالثة (BPF). تم تحقيق الاقترانات الخارجية باستخدام المجس المحوري. بينما تم تحقيق الاقترانات الداخلية باستخدام الاقطاب. يظهر TZ بسبب الاقتران العابر بين الرنانات 1 و 3. وتستخدم أبعاد القطب العابر للتحكم في موضع TZ في نطاق الرفض. يتم محاكاة دليل موجي من الدرجة الثالثة معمم Chebyshev BPF Generalized باستخدام برنامج HFSS بتردد مركزي يبلغ 28 جيجا هرتز، وخسارة الإدراج هي 0.05 ديسيبل وعرض النطاق (BW) هو 500 ميغا هرتز. من خلال نتائج المحاكاة يظهر هناك توافقاً جيداً مع تطبيقات G.5 والقدرة على اختيار عرض منطقة الحماية بين حزم الشركات

الكلمات الدالة :

التحكم في موضع الصفر الانتقالي لمرشحات امرار الحزمة ، الاقتران العابر في مرشحات دليل الموجة ، مرشحات امرار الحزمة المناسبة لتطبيقات الجيل الخامس للاتصالات.