

X-band bandpass filter structure for passive radar using SIW technology

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ABSTRACT

This paper proposes an X-band bandpass filter structure for the Kolchuga passive radar system as an alternative to the Interdigital structure. The proposed structure uses substrate-integrated waveguide (SIW) technology with series-connected resonant frames arranged in a folded form. With the improved structure, the designed filter ensures the insertion loss, reflection coefficient in the pass band, and attenuation slope in the stop band requirements in the X-band for the Kolchuga radar while optimizing the size. Compared with the SIW bandpass filter using the conventional straight IRIS structure, the proposed filter structure reduces the size but achieves equivalent scattering parameters. The simulation results demonstrate the effectiveness of the proposed filter structure in meeting the required criteria and optimizing the size.

Keywords: Bandpass filter; X-band; Passive radar; SIW.

1. INTRODUCTION

Passive radar detects, measures, and tracks targets by leveraging available electromagnetic radiation sources in the environment, such as radio and television signals or signals emitted by targets [1]. Based on this working principle, passive radars often have a longer detection range than active radars with the same receiver sensitivity while ensuring stealth against enemy electromagnetic reconnaissance devices. With diverse input signal sources, microwave filters play a vital role in selecting input signals according to the desired frequency range for passive radars.

The X-band (8–12 GHz) is one of the frequency ranges utilized in passive radar systems such as Vera-NG and Kolchuga. In the Kolchuga passive radar, the X-band corresponds to Band 4, which includes eight receiving channels, among which Channel 22 operates within the 11–11.5 GHz range. To narrow the scope of the study, this paper focuses on the design of a filter circuit for a sub-band in the X-band, specifically Channel 22 of Band 4 (11–11.5 GHz) in the Kolchuga radar receiver. In this channel, the Kolchuga radar traditionally employs an Interdigital filter (IDT – Interdigital Transducer). However, it also has the disadvantage of relatively high insertion loss at high frequencies, such as the X-band. Furthermore, the filter performance is greatly affected by temperature, and it requires special materials based on semiconductor or ceramic platforms [2]. With low loss, high integration, compact size compared to traditional waveguide filters, simple fabrication, and low cost, filters using Substrate Integrated Waveguide (SIW) technology are emerging as a breakthrough solution in microwave frequency applications [3].

Based on SIW technology, the design of an X-band filter to replace the Interdigital filter for the Kolchuga passive radar is possible. Typical structures of filters using SIW technology are IRIS-type filters, which have structures similar to those of waveguide filters [4]. Positioned at the input stages of the receiver in the Kolchuga radar, the microwave filters are required to satisfy high frequency selectivity, low insertion loss, low return loss within the passband, and an appropriate size. Among these, frequency selectivity is the most important requirement for separating the receiving channels by frequency. To achieve high frequency selectivity, the number of resonator stages in the iris filter must be increased. This leads to an increase in the overall length of the filter due to its straight-coupled structure. To meet the primary technical specifications of the X-band filter for channel 22 in the 11–11.5 GHz frequency range and ensure the size constraints of the

Kolchuga passive radar, this paper proposes a novel filter structure based on SIW technology. This proposed filter employs resonant elements arranged in a folded configuration to reduce the length compared to conventional straight-coupled iris bandpass filters.

The remainder of this paper is organized as follows: Section 2 presents an improved bandpass filter structure using SIW technology with an improved structure; Section 3 details the design of the X-band bandpass filter for the Kolchuga radar; Section 4 discusses the simulation results; and section 5 concludes the paper.

2. IMPROVED BANDPASS FILTER STRUCTURE USING SIW TECHNOLOGY

With the advantages in reducing loss and size compared to traditional waveguide filters and IDT filters, SIW filters are suitable for radar applications. To ensure high frequency selectivity, the filter order is usually greater than or equal to 5 [5]. Figure 1 shows a typical IRIS-type SIW filter structure with a 6th-order configuration. Since the vertical metal walls are replaced by vias, the propagation modes in SIW are very similar to those in rectangular waveguides, though not exactly identical [6]. The filter in figure 1 can be analyzed based on the waveguide segment model as illustrated in figure 2.

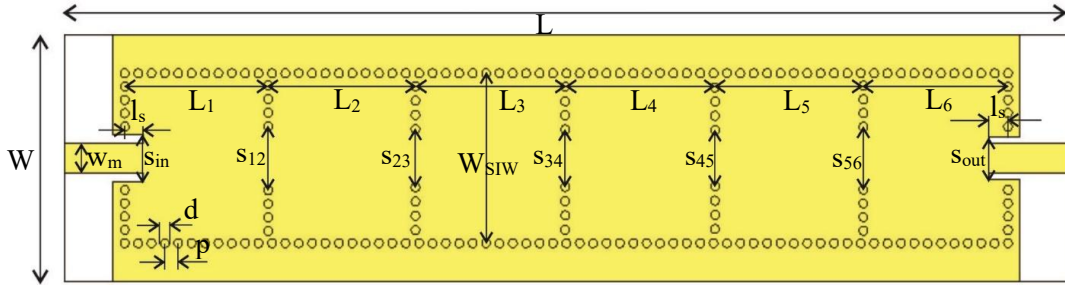


Figure 1. 6th order IRIS structured bandpass filter.

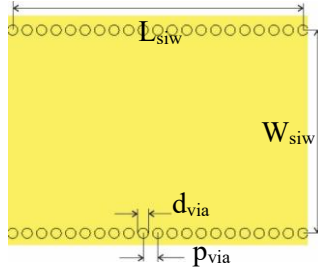


Figure 2. Basic structure of SIW.

In this filter structure, the TE₁₀₁ mode dominates. The following equation is used to calculate the resonant frequency of the SIW cavity's dominant mode [7]:

$$f_0 = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\pi}{w_{eff}}\right)^2 + \left(\frac{\pi}{l_{eff}}\right)^2} \tag{1}$$

Where μ_r and ϵ_r are the relative permeability and relative permittivity compared to vacuum. w_{eff} and l_{eff} are the effective widths and lengths, which are defined by physical dimensions as shown in the formulas below [3]:

$$w_{eff} = w_{siw} - \frac{d^2}{0.95p} \tag{2}$$

$$l_{eff} = l_{siw} - \frac{d^2}{0.95p} \quad (3)$$

The diameter d and the hole spacing p are given by the formulas [3]:

$$d < \frac{\lambda_g}{5} \quad (4)$$

$$p \leq 2d \quad (5)$$

To minimize leakage loss between adjacent via holes, the spacing between the holes and their diameter should be reduced, as these parameters affect the reflection loss of the waveguide segment as observed from the input port [8, 9].

The iris-based filter shown in figure 1 exhibits low insertion loss and good reflection loss, and demonstrates high-frequency selectivity based on the scattering parameters outside the passband [10]. However, the length of this six-stage filter is relatively large due to its straight-coupled configuration. In waveguide-based transmission lines used in radars, a folded structure can be employed to decrease the transmission line length. Based on this concept, this paper proposes a novel filter structure with six resonant elements arranged in a folded configuration as shown in figure 3. This structure is based on SIW technology with a series-coupled configuration but offers a reduced length compared to the conventional iris-based filter. The parameters L , W , and s can be determined using the equivalent waveguide width.

The filter is designed with an equivalent circuit corresponding to a six-resonator filter arranged in a folded configuration, with each resonator coupled to its adjacent resonators, as shown in figure 4.

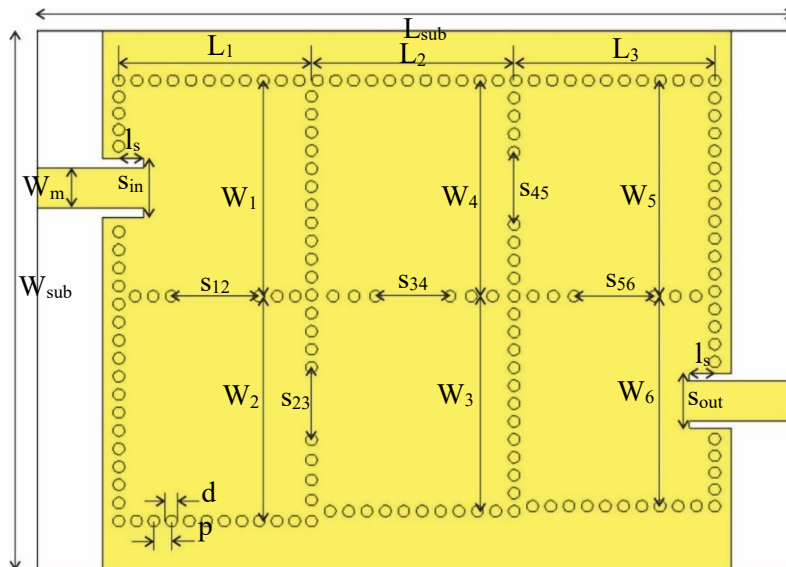


Figure 3. Proposed filter structure.

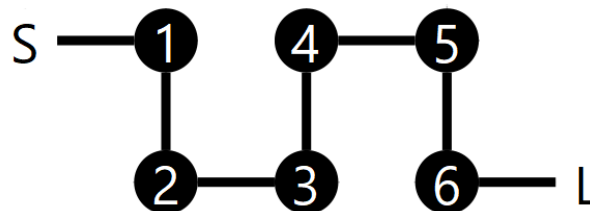


Figure 4. Pairing diagram of the filter according to the proposed structure.

3. DESIGN OF AN X-BAND BANDPASS FILTER FOR THE KOLCHUGA PASSIVE RADAR

3.1. Define design requirements

The technical specifications of the X-band input filter for the Kolchuga passive radar system are presented in table 1. To achieve an attenuation slope greater than 100 dB/decade, the designed filter must have an order of at least 6. In addition, the insertion loss must not exceed 5 dB, and the overall size must remain within the allowable range.

Table 1. Main technical indicators of the X-band receiver input filter for the Kolchuga radar.

No	Technical parameters	Unit	Required value
1	Operating frequency range	GHz	11 ÷ 11.5
2	Insertion loss in band 11 ÷ 11.5 GHz	dB	≤ 5
3	Attenuation slope	dB/decade	≥ 100
4	Reflection loss in the passband	dB	≤ -15
5	Length	mm	≤ 60
6	Width	mm	≤ 40
7	Height	mm	≤ 20

When designing microwave filters for radars, the insertion loss in the passband is usually chosen to be less than 3 dB [11-13]. Therefore, this paper designs an X-band filter for the Kolchuga radar with an insertion loss of less than 3 dB. To obtain the insertion loss of less than 3 dB and an attenuation slope greater than 100 dB/decade, this study selects a six-stage SIW-based filter with an improved structure as shown in figure 3.

3.2. Calculation results

With the filter order selected according to the above criteria table, the design process begins with the synthesis of the coupling matrix for the filter [14]. As a result, the values of the normalized coupling matrix are shown in table 2.

Table 2. The normalized coupling matrix of the filter.

	S	1	2	3	4	5	6	L
S	0.0	1.00211	0.0	0.0	0.0	0.0	0.0	0.0
1	1.00211	0.0	0.84299	0.0	0.0	0.0	0.0	0.0
2	0.0	0.84299	0.0	0.61108	0.0	0.0	0.0	0.0
3	0.0	0.0	0.61108	0.0	0.58340	0.0	0.0	0.0
4	0.0	0.0	0.0	0.58340	0.0	0.61108	0.0	0.0
5	0.0	0.0	0.0	0.0	0.61108	0.0	0.84299	0.0
6	0.0	0.0	0.0	0.0	0.0	0.84299	0.0	1.00211
L	0.0	0.0	0.0	0.0	0.0	0.0	1.00211	0.0

The resonant frequency of each cavity resonator is 11.24722 GHz, and the coupling bandwidths between the resonators are as follows: $CBW_{S,1} = 0.501054$ GHz, $CBW_{1,2} = 0.421493$ GHz, $CBW_{2,3} = 0.305542$ GHz, $CBW_{3,4} = 0.291699$ GHz, $CBW_{4,5} = 0.305540$ GHz, $CBW_{5,6} = 0.421493$ GHz, and $CBW_{6,L} = 0.501054$ GHz. The external quality factors are $Q_{S,1} = Q_{6,L} = 22.3999$.

Based on equations (4) and (5), the selected via hole diameter is 0.7 mm, and the spacing

between adjacent via holes is in the range of 1.1–1.2 mm. This spacing is adjusted for each resonator frame wall to match the measurement step of 0.01 mm in the simulation. The substrate used is Rogers 5880, with a dielectric constant $\epsilon_r = 2.2$, $\tan \delta = 0.0009$, and a thickness of 0.787 mm. A 6th-order filter is designed based on the coupling matrix presented in table 2, and the dimensions of its components are detailed in table 3.

Table 3. Filter dimensions according to the proposed structure.

N _o	Parameters	Value (mm)	N _o	Parameters	Value (mm)	N _o	Parameters	Value (mm)
1	L _{sub}	46.31	9	W ₄	13.2	17	S ₄₅	4.5
2	W _{sub}	32.97	10	W ₅	13.2	18	S ₅₆	5.08
3	L ₁	11.74	11	W ₆	12.85	19	W _m	2.44
4	L ₂	12.35	12	S _{in}	3.61	20	l _s	1.54
5	L ₃	12.22	13	S _{out}	3.32	21	d _{via}	0.7
6	W ₁	13.2	14	S ₁₂	5.47	22	p _{via}	1.1 ÷ 1.2
7	W ₂	13.77	15	S ₂₃	4.52			
8	W ₃	13.18	16	S ₃₄	4.65			

Table 3 shows that the length and width dimensions of the proposed filter are 46.31 mm and 32.97 mm, respectively. These values satisfy the filter size requirements in table 1.

4. RESULTS AND DISCUSSIONS

With the filter dimensions of the proposed structure determined in table 3, the design and simulation of the filter parameters can be conducted using specialized design software. Figure 5 illustrates the scattering parameters and electric field distribution of the proposed filter obtained from the CST Studio Suite 2024 microwave design software.

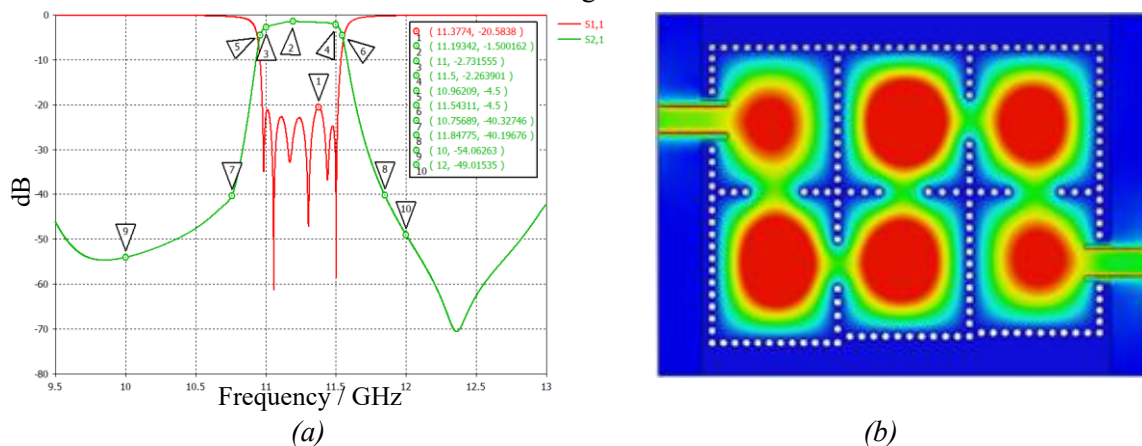


Figure 5. Simulation results of the proposed filter: (a) Scattering parameters S₂₁ and S₁₁; (b) Electric field distribution at the center frequency 11.25 GHz.

Figure 5a shows that the filter with the proposed structure has an operating frequency band (measured at -3 dB relative to the frequency with the minimum insertion loss) of 10.96 GHz to 11.54 GHz. In the 11 to 11.5 GHz frequency range, the filter achieves an insertion loss better than 2.73 dB. The simulation results also indicate a reflection loss of less than -20.58 dB. This value indicates that the filter achieves good impedance matching with the transmission line. The attenuation slopes in the stopbands on the left and right are 154 dB/decade and 100 dB/decade, respectively. These attenuation slope values meet the requirements specified in table 1. Figure 5b shows the filter's performance with a strong electric field intensity at the center of the resonant

elements. In this figure, there is almost no energy outside the via array, indicating that the via array effectively minimizes wave leakage.

To evaluate the size improvement compared to the conventional iris-based bandpass filter, this study compares the parameters of the proposed filter structure with those of the conventional six-stage iris-based filter, as shown in figure 1. With the working frequency band and scattering parameters in table 1, the dimensions of the conventional iris-based filter are provided in table 4. Figure 6 illustrates the scattering parameters from two structures.

Table 4. Dimensional parameters of IRIS type filters.

№	Parameters	Value (mm)	№	Parameters	Value (mm)	№	Parameters	Value (mm)
1	L	83.05	8	L ₄	12.38	15	S ₃₄	4.47
2	W	19.2	9	L ₅	12.24	16	S ₄₅	4.51
3	W _{siw}	13.2	10	L ₆	11.96	17	S ₅₆	4.91
4	W _m	2.44	11	S _{in}	3.65	18	l _s	1.57
5	L ₁	11.91	12	S _{out}	3.38	19	d _{via}	0.7
6	L ₂	12.19	13	S ₁₂	5.04	20	p _{via}	1.1 ÷ 1.2
7	L ₃	12.37	14	S ₂₃	4.55			

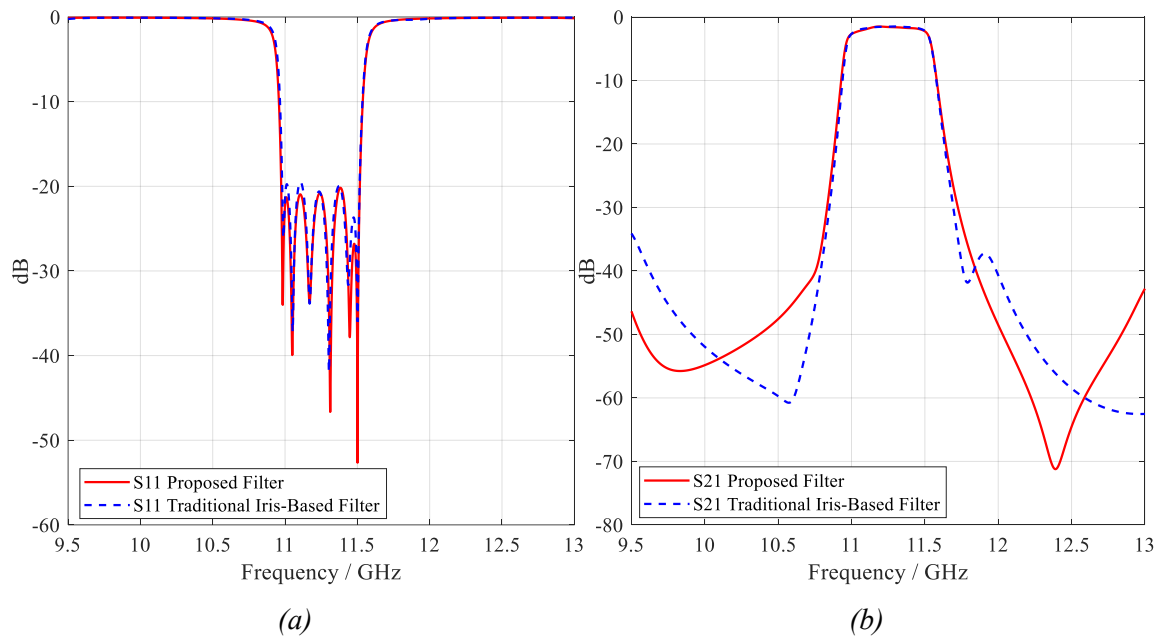


Figure 6. Comparison of scattering parameters between the proposed filter and the traditional IRIS filter. (a) Comparison of the S11 parameter, (b) Comparison of the S21 parameter.

From figure 6, the scattering parameters of both filters are equivalent. With the same scattering parameter performance, the length of the proposed filter is only 46.31 mm, whereas the iris-based filter has a length of 83.05 mm. Therefore, the proposed filter structure significantly reduces the overall length compared to the conventional iris-based filter.

To better demonstrate the effectiveness of the proposed filter, this study compares the parameters of the proposed filter and other X-band filters using SIW technology in the literature [15-18]. The comparison results are shown in table 5.

Table 5 shows that at the center frequency the insertion loss of the proposed filter is 1.55 dB

while in [15-18], these values are 2.1 dB, 3.3 dB, < 3 dB, and 2.65 dB, respectively. For the 6th order microwave filters for radar, the insertion loss of the proposed filter is significantly smaller than that of the filter in [18]. In addition, the reflection loss of the proposed filter at the center frequency is also considerably smaller than the reflection loss of the filters in [15-18].

Table 5. Comparison with other published works. Here, Ref, reference; Sub, substrate; Order, filter order; FBW, fractional bandwidth; RL, return loss; IL, insertion loss; NI, no information. IL and RL are calculated at the center frequency or the operating frequency.

Ref	Center frequency f_0 [GHz]	Sub	Order	3-dB FBW[%]	RL[dB]	IL[dB]	Upper stop band $ S_{21} < -20dB$
[15]	9	5880	3	5.5	12	2.1	$1.06f_0$
[16]	8.25	5880	3	1.1	15	3.3	NI
[17]	10.2	4003C	3	23.5	>10	< 3	$1.5 f_0$
[18]	10.1	5880	6	4.45	>10	2.65	$1.47 f_0$
This work	11.25	5880	6	5.1	23	1.55	$1.03f_0$

5. CONCLUSIONS

This paper has proposed an X-band bandpass filter structure for the Kolchuga passive radar based on SIW technology, with resonant cavities arranged in a folded configuration. The design and simulation results demonstrated that the proposed filter structure satisfied the requirements for the X-band filter in the Kolchuga passive radar in terms of operating bandwidth, insertion loss, reflection loss, and stopband attenuation slope, while significantly reducing the size compared to the conventional iris-based structure. With these characteristics, the proposed filter structure could also be adapted for other frequency bands in passive radar systems.

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TÓM TẮT

Cấu trúc bộ lọc thông dải băng tần X cho đài ra đa thụ động sử dụng công nghệ SIW

Bài báo đề xuất một cấu trúc bộ lọc thông dải băng tần X cho hệ thống ra đa thụ động Kolchuga thay thế cho cấu trúc Interdigital. Cấu trúc đề xuất sử dụng công nghệ ống dẫn sóng tích hợp chất nền (SIW) với các khung cộng hưởng nối tiếp được bố trí theo dạng gấp khúc. Với cấu trúc đề xuất, bộ lọc được thiết kế đảm bảo các yêu cầu về suy hao chèn, hệ số phản xạ trong dải thông và các yêu cầu về độ dốc suy hao trong dải chặn ở băng tần X cho đài ra đa Kolchuga trong khi tối ưu được kích thước. So với bộ lọc thông dải SIW sử dụng cấu trúc IRIS thẳng truyền thống, cấu trúc bộ lọc đề xuất giảm được kích thước trong khi vẫn đạt được các thông số tán xạ tương đương. Các kết quả mô phỏng minh chứng cho hiệu quả của cấu trúc bộ lọc đề xuất trong việc đáp ứng các chỉ tiêu yêu cầu và tối ưu kích thước.

Từ khoá: Bộ lọc thông dải; Băng tần X; Ra đa thụ động; SIW.