A novel symmetrical folding miniaturized substrate integrated waveguide tunable bandpass filter

Kaiwei Zuo1 | Yongzhong Zhu1 | Xinying Cheng2 | Zhihao Meng1 | Yicheng Zhang1 | Zheyu Li1 | Xiaoyu Liu1

1Engineering University of Chinese People Armed Police, Xi’an, China
2Mobile Second Team of Armed Police Shanghai City, Shanghai, China

Abstract
In order to improve the utilization of spectrum resources, dynamic frequency allocation technology has become a method of spectrum saving. The research of electric tunable filter has received much attention in recent years. Substrate integrated waveguide (SIW) is a new technology of microwave integration in the field. The innovation of this article is to combine the SIW miniaturization technology with tunable technology. In this article, a miniaturized symmetrically folded substrate integrated waveguide (SFSIW) filter is designed. Based on the miniaturization of SIW filter, the center frequency can be adjusted electrically and the measured data show that the tunable filter can achieve eight states under the condition that the bandwidth below −3 dB remains approximately constant 300 MHz. The center frequency varies from 3.23 GHz to 3.9 GHz. The range of the filter’s insertion loss is 1.2 dB to 2.04 dB, and the return loss is higher than 20.9 dB. This filter has practical value in the electronic countermeasures of military communication.

KEYWORDS
filter, SFSIW, tunable

1 | INTRODUCTION

With the rapid development of modern wireless communication systems and the ever-increasing progress of military information technology, spectrum resources have become increasingly scarce. In order to improve the utilization of spectrum resources and the security of military information, spectrum technologies such as multiple passbands, frequency hopping, and dynamic frequency allocation are widely used, which greatly promote the development of tunable microwave devices. Tunable devices can not only reduce the number of devices required in different frequency bands in the system and realize system miniaturization, but also meet the needs of modern communications with multiple frequency bands, multiple performance, and anti-interference. Therefore, tunable microwave devices have a wide range of applications in high-tech fields such as mobile communications, radar, and electronic warfare systems.

SIW has characteristics such as low loss, high Q value, and easy integration, which has gradually attracted the attention of scholars in the application of tunable filters. Since 2010, scholars have designed a variety of SIW tunable filter structures, summed up in four main ways: The first is to achieve adjustable performance through the combination of tuning columns and electric...
tuning devices (such as PIN (Positive Intrinsic Negative) diodes, variable-capacitance diodes, RF MEMS (Radio frequency Micro-Electro-Mechanical Systems) switches, etc.) in References. However, the full-mode SIW structure makes the circuit size large. The second method is to achieve tunable performance through the combination of surface annular gaps and electrical tuning devices. For example, the varactors are loaded on the annular gaps, and large capacitance changes result in a very wide adjustment range in Reference. The third is to realize the magnetic tuning of the integrated waveguide resonator in the substrate by loading the ferrite material. In Reference, the electromagnetic adjustment of the SIW filter is achieved by changing the internal ferrite ferromagnetic resonance frequency by applying a bias magnetic field. However, the applied bias magnetic field requires the coil to be applied and adjusted. The reaction speed is slow, and there is additional noise. And with great energy consumption, it is difficult to be compatible with modern semiconductor devices. The fourth is to achieve tunable performance through mechanical tuning. A continuous adjustment of the center frequency by inserting radially moving copper pillars in the cavity of a circular SIW was achieved in Reference, but the volume is large and the tuning speed is slow.

SIW devices have attracted people’s attention due to their high quality factors, but the current research is still lacking in the degree of miniaturization. Current miniaturized SIW tunable resonators are mostly HMSIW (Half-mode substrate integrated waveguide) structures or QMSIW (Quarter-mode substrate integrated waveguide) structure, the size is still larger than the microstrip structure. Folding technology is widely used in the research of filter miniaturization, but there are few studies on the application of tunable filter in miniaturization. Moreover, the current miniaturized folding technology mostly adopts asymmetric folding, and there are few reports on symmetrically folded SIW technology. In this article, the novelty of the proposed SFSIW filter is embodied in two aspects. One is that the asymmetric folding miniaturization technology is more flexible than the symmetric folding miniaturization technology. Second, the tunable technology achieves many states and low insertion loss. The resonant frequency of the resonant cavity is changed by loading metalized vias in a symmetrically folded SIW cavity. The two-cavity SIW tunable filter based on the resonant cavity realizes the miniaturization (49 mm × 40 mm) and the center frequency is tunable.

2 | MINIATURIZED TUNABLE CAVITY ANALYSIS

Folding technology is an important way to achieve the miniaturization of SIW. Figure 1 shows the evolution of symmetrically folded SIW resonators. Based on the original SIW resonators, it is symmetrically folded into the center of a four-sided cavity and then converted into a SFSIW cavity. The folding process reduces the SFSIW cavity area to 27% of the original cavity size, but the cavity thickness doubles.

The SIW cavity is evolved from a metal waveguide. The resonant frequency of the SIW cavity can be calculated by the equivalent length and width of the SIW, or the size of the cavity can be calculated in the case of

![Figure 1](image-url)  
**Figure 1** The evolution of substrate integrated waveguide (SIW) resonator

![Figure 2](image-url)  
**Figure 2** A, Comparison of resonant frequency before and after cavity folding and B, Relationship between center frequency and folding size
known design criteria, such as the resonant frequency. In Figure 2, when the side length \( L \) of the original SIW cavity remains unchanged (38 mm), the relationship between the resonant frequency of the cavity and \( D_1 \) is calculated by using different degrees of folding. Through the HFSS simulation, in Figure 2B, the resonant frequency of the resonant cavity changes by adopting different folding degrees of the cavity.

The SFSIW tunable cavity is shown in Figure 3. The cavity in this article consists of three metal layers and three dielectric layers which is Arlon AD260A (tan \( \delta = 0.0017 \)). The height of dielectric layer is \( h_1 = h_2 = 0.8 \) mm, and \( h_3 = 0.254 \) mm. The adjustable element in the top view of the resonant cavity is electrically adjustable by turning on or off the PIN diode. The length of the cavity enclosed by the two metallized holes in the resonant cavity is \( D_1 = 19 \) mm, \( D_2 = 8 \) mm, and the metal via diameter is \( d = 0.4 \) mm, and the distance between the centers of adjacent vias is \( p = 1 \) mm. As shown in Figure 3B, the adjustable structure is distributed in different positions of the cavity. In order to avoid the metal vias used for tuning being short-circuited with the upper metal layer, a square hole with a side length of 0.5 mm is opened around each tuning column. The size of these holes is much smaller than the size of the cavity, so the field distribution of the cavity is hardly affected. The tuning column passes through two layers of media, and the upper and lower ends are respectively connected to the metal spacer and the intermediate metal layer. The metal via of the upper dielectric layer is used to connect the switch with the upper metal layer. The upper dielectric substrate having a thickness of \( h_3 \) is used to load the adjustable component and the driveline (not shown) so as not to affect the performance of the lower cavity. Since the SIW thickness is much smaller than its width, only the TE mode can be transmitted in the SIW. The main mode of the filter is the TE101 mode. The resonant frequency is determined by Equation (1):

\[
f_{\text{res}} = \frac{1}{2\sqrt{\epsilon\mu}} \sqrt{\left(\frac{m}{a_{\text{eff}}}\right)^2 + \left(\frac{p}{b_{\text{eff}}}\right)^2}
\]

where \( m = 1, 2, 3 \ldots \), \( p = 1, 2, 3 \ldots \), \( \mu = \mu_0\mu_r \) and \( \epsilon = \epsilon_0\epsilon_r \), \( \mu_r \) and \( \epsilon_r \) are the relative permeability and relative permittivity, respectively.

When the adjustable structure of the PIN diode switch is energized and closed, the tuning column in the cavity is connected to the middle metal layer of the cavity through the upper metal via hole, so that the electric field in the cavity is disturbed and the resonance frequency of the cavity changes. When the switch is opened, the tuning column and the metal layer in the cavity are open, so the field of the main mode TE101 in the cavity is hardly disturbed and the resonant frequency is close. As shown in Figure 3C, a strong capacitance effect \( C_{\text{tm}} \) is generated between the intermediate metal layer and the upper metal layer, and the loading of the tuning column is actually parallel connection of \( C_{\text{tm}} \) and equivalent inductance. In the folded structure, the intermediate metal layer and the bottom metal form a strong capacitive effect \( C_{\text{bm}} \) in series with the upper cavity. The tuning columns
in the cavity are equivalent to L0-Ln inductors. The equivalent circuit of the resonant cavity is shown in Figure 4. In Figure 5, in order to analyze the influence of the position of the tuning column (A, B, C, D, E) on the electric field disturbance in the cavity, the tuning columns in different positions are respectively connected to the SFSIW cavity, the coordinates of the tuning column and the access state are shown in Table 1.

Figure 6 (1) is the electric field distribution of the intermediate metal layer when there is no tuning column to access the cavity, and the tuning columns in five positions A, B, C, D, and E are respectively connected to the SFSIW resonator according to different combinations. The tuning column is shorted to the middle metal layer of the cavity, the electric field is disturbed, and the resonant frequency changes. By comparing the electric field distribution after the access of different tuning columns, the two ends of the chamber are connected to a matching load. After HFSS electromagnetic simulation, it is found that when the number of tuning columns is larger, as shown in Figure 6 (5), the resonant frequency of the chamber is higher. When the tuning column is placed at the maximum value of the electric field (the minimum value of the magnetic field), the frequency changes the most, and the farther away from the center of the electric field, the less the resonance frequency changes.

The SIW cavity can be equivalent to a planar L-C resonant cavity with a resonant frequency $f_0 = 1/(2\pi\sqrt{LC})$. When the switch is closed, the tuning column accesses the cavity and the tuning column generates a surface current, so that the tuning column can be seen as an inductance $L_P$ in parallel, the value of which depends on the intensity of the electric field where the tuning column is located. Near the center of the cavity, the electric field value is the largest, and the $L_P$ value is the smallest. Therefore, when the tuning column is inserted near the center of the cavity, the resonant frequency has the largest variation, and its value is given by $f_0 = 1/(2\pi\sqrt{L_{eq}C})$, where $L_{eq}$ is the parallel value of $L$ and $L_P$.

In Figure 6, different tuning columns are respectively inserted into the resonant cavity, and the resonant characteristics of the cavity are shown in Figure 7. By selecting the appropriate tuning column position, the resonant frequency of the cavity can be adjusted to the desired value. The resonant frequency that changes with the electric field inside the cavity is the premise of designing the tunable cavity. Through analyzing the adjustable characteristic of the single resonant cavity, it lays the foundation for the design of the tunable filter.

### 3 | SFSIW TUNABLE FILTER DESIGN

The SFSIW tunable filter is cascadingly arranged with the inductive coupling window between the cavities. Figure 8 shows the overall structure of the SFSIW tunable filter. From the structure diagram of the SFSIW tunable filter, it can be seen that the filter consists of four layers of Arlon AD260A ($\varepsilon_r = 2.6$, tan$\delta = 0.0017$) material and three metal layers. The upper and lower two dielectric layers are used only for isolation and installation of
adjustable units. The main cavity of the filter is the middle three metal layers and two dielectric layers. A microstrip line with an impedance of 50 Ω is symmetrically distributed at both ends of the cavity as a feed for the cavity. The filter’s size parameters are shown in Table 2.

In the cascade design of the cavity of the filter, due to the folding characteristics of the SFSIW cavity, the two cavities in the cascade process have the same direction and the opposite direction. This article uses the inverse cavity cascade to design the filter. In the analysis of the resonance characteristics of the resonant frequency of the SFSIW, the effects of five different position-tuning columns on the resonator cavity have been listed. In order to analyze the resonant characteristics in the cavity as comprehensively as possible, eight tuning columns A, B, C, D, E, F, G, H, A’, B’, C’, D’, E’, F’, G’, H’ are reserved in the two resonant cavities during the design process of the SFSIW tunable filter. The method for determining the position of the tuning column in the cavity can be referred to the electric field distribution diagram in the cavity of Figure 6, and the electric field distribution of the cavity is relatively strong around the folded groove of the SFSIW resonator. The purpose of adding a tuning column in the cavity is to change the equivalent inductance between the upper metal layer and the intermediate metal layer, thereby causing an electric field disturbance in the cavity to change the resonant frequency of the cavity. This method of adjusting the center frequency by loading the tuning column can be referred to the

**FIGURE 6** Analysis of tunable characteristics of symmetrically folded substrate integrated waveguide (SFSIW) resonator

**FIGURE 7** Symmetrically folded substrate integrated waveguide (SFSIW) resonant cavity adjustable characteristics

**FIGURE 8** Symmetrically folded substrate integrated waveguide (SFSIW) tunable filter overall structure diagram

**TABLE 2** Parameters of filter size (unit: mm)

| L1 | L2 | L3 | L4 | D3 | D4 |
|----|----|----|----|----|----|
| 49 | 40 | 5  | 4  | 38 | 13 |
literature.\textsuperscript{1} As shown in Figure 9, in order to more intuitively describe the filter size structure, each filter structure is projected onto the $xy$ plane, and the position coordinates of each resonance column are shown in Table 3. The filter is fed with an intermediate metal layer and the matching load is connected by soldering the SMA connectors at the two feed ports Port 1 and Port 2. For easy measurement, this filter uses SMA08 type connector, the overall thickness of the filter is not greater than the distance between the inner and outer pins of the connector.

The coupling between the two resonant cavities is realized through the inductive window formed by removing the common metal vias and this way achieves the magnetic coupling between the cavities. Two sets of frequency adjustable switches are symmetrically arranged in the two cavities of the filter, and the tuning column can be loaded into the SFSIW cavity by controlling the access of the vias through the switch. The center frequency of the filter can be adjusted by changing the resonant frequency. By controlling eight groups of 16 tuning columns to be accessed or not, there are 216 kinds of adjustable states. However, eight diode switches were used to achieve the adjustment, and the author selected six typical states for display in Reference \textsuperscript{2}. Through a large number of electromagnetic simulations, eight states with better transmission curves were selected and displayed in Table 4, in which 0 represents PIN diode switch disconnection, and 1 represents connection.

The simulation results are shown in Figure 10A. When the tuning column is connected to the tunable filter in different positions and the bandwidth below 3 dB is fixed (320 MHz), the center frequency can be adjusted from 3.38 GHz to 3.89 GHz. The simulation results show that the insertion loss of the filter is lower than 0.5 dB, and the return loss is higher than 21 dB. Figure 11 is a physical map of the SFSIW tunable filter. DC power supply is used to control the ON/OFF of the PIN diode, and different positions of the tuning column are inserted into the resonator of the filter. At the end of the wire in Figure 11, a bias network similar to Figure 12 is applied to ensure maximum isolation between the bias line at the operating frequency and the SIW filter. Figure 10B shows the measured results. The tunable filter can achieve eight states under the condition that the bandwidth below 3 dB is approximately constant 300 MHz. The center frequency varies from 3.23 GHz to 3.9 GHz. The general measured results show that the range of the filter's insertion loss is 1.2 dB to 2.04 dB, and the return loss is higher than 20.9 dB. It can be seen from the measured results that the result has less error in the entire passband.

![FIGURE 9 Symmetrically folded substrate integrated waveguide (SFSIW) tunable filter schematic](image)

| Post | $x$ | $y$ | Post | $x$ | $y$ | Post | $x$ | $y$ | Post | $x$ | $y$ |
|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|
| A    | -9.5| 27  | E    | -9.5| 13  | A'   | 9.5 | 27  | E'   | 9.5 | 13  |
| B    | -16.5| 27 | F    | -2.5| 13  | B’   | 2.5 | 27  | F’   | 16.5| 13  |
| C    | -16.5| 20 | G    | -2.5| 20  | C’   | 2.5 | 20  | G’   | 16.5| 20  |
| D    | -16.5| 13 | H    | -2.5| 27  | D’   | 2.5 | 13  | H’   | 16.5| 27  |

![TABLE 3 Position coordinates of tuning column of symmetrically folded substrate integrated waveguide (SFSIW) adjustable filter (unit: mm)](table)

| State | ABCDEFGHA'B'C'D'E'F'G'H’ | State | ABCDEFGHA'B'C'D'E'F'G'H’ |
|-------|--------------------------|-------|--------------------------|
| I     | 0000000000000000        | V     | 1000100010001000        |
| II    | 1000000000001000        | VI    | 1100000100011100        |
| III   | 0001000100000000        | VII   | 1100111111111100        |
| IV    | 0000001000100000        | VII   | 0101010101010101        |

![TABLE 4 Tuning column access status](table)
Compared with the previous research results, the miniaturized tunable filter manufactured in this article has a large adjustable center frequency (670 MHz), and the combination of the substrate integrated waveguide and the PIN diode makes the insertion loss small (1.2 dB–2.04 dB) with better transmission characteristics in Table 5. The advantages of this filter in tunable performance are mainly reflected in the large absolute bandwidth adjustable range and low insertion loss. At the same time, in Table 6 the size reduction ratio of filters designed in this article has great advantages compared with previous miniaturization technologies such as HMSIW, QMSIW, SFIW, and so forth. The tunable filter designed by the SFSIW miniaturization technology of the present invention has the advantages of high miniaturization, small insertion loss, large adjustable center frequency range, and constant absolute bandwidth compared with the previous research results.

### TABLE 5 Comparison of previous research results with tunable filters

| Ref. | Tunable technology     | CF (GHz) | FBW (%) | IL (dB) | Dimensions       |
|------|------------------------|----------|---------|---------|------------------|
| 1    | RF MEMS                | 1.2–1.6  | 3.7 ± 0.5 | 2.2–4.1  | 114 mm × 80 mm   |
| 2    | PIN diodes             | 1.55–2   | 2.3–3   | 5.4     | 83 mm × 62 mm    |
| 3    | Lumped tuning elements | 0.58–1.22| 4 ± 0.2 | 2.05    | 80 mm × 30 mm    |
| 4    | Ferroelectric ceramics | 2.95–3.57| <5.4    | 2.6–3.3 | 12.5 mm × 9.5 mm |
| 5    | Mechanical tuning      | 12.6–15  | 19.2    | 1.7–2.8 | -                |
|      | This work              | 3.23–3.9 | 7.7–9.2 | 1.2–2.04| 49 mm × 40 mm    |

Abbreviations: CF, center frequency; FBW, fractional bandwidth; IL, insertion loss.

### 4 | CONCLUSION

This article proposes a miniaturization technology for symmetrically folded substrate integrated waveguides (SFSIW). By comparing with existing literature, this article adopts the method of symmetric folding SIW miniaturization, which further consummates the miniaturization theory. At the same time, aiming at the application of tunable...
technology in the filter field, a SFSIW two-chamber tunable filter is designed in this article. The center frequency can be adjusted under the condition of relatively stable bandwidth, and it is better to expand the tunable technology in miniaturization. In terms of insertion loss, the filter studied in this paper is lower, which has advantages over previous research results. This research progress in the field of filters has great use value.

ORCID
Kaiwei Zuo https://orcid.org/0000-0001-7670-2576

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AUTHOR BIOGRAPHIES

Kaiwei Zuo was born in Jiangsu, China. He received the BS degree in Command Automation from the Engineering University of Chinese People Armed Police, Xi’an, China in 2014, and the MS degree in Army Command Academy from the Engineering University of Chinese People Armed Police, Xi’an, China in 2016. He is currently pursuing the PhD degree in Armed Police Communications with Engineering University of Chinese People Armed Police, Xi’an, China. His current research interests include adjustable microwave filter and miniaturized microwave filter. E-mail: zkwcapf@163.com.

Yongzhong Zhu was born in Anhui, China. He received the BS degree in communication engineering from Engineering University of People’s Armed Police, the MS degree in military communication from Engineering University of People’s Armed Police, and the PhD degree in Electronic Science and Technology from Xidian University, in 2002, 2005, and 2008, respectively. From 2009 to 2011, he was a postdoctoral fellow with Northwestern Polytechnical University. Since 2012, he has been an associate professor of microwave engineering with Engineering University of People’s Armed Police. His research interests are in microwave antennas and devices, wireless communications, and information systems. E-mail: haiyihaiyi@hotmail.com.
Xinying Cheng was born in Xi’an, China. She received the BS degree in Command Automation from the Engineering University of Chinese People Armed Police, Xi’an, China in 2014, and the MS degree in Army Command Academy from the Engineering University of Chinese People Armed Police, Xi’an, China in 2016. Her current research interest is armed police communication. E-mail: cxx19920711@qq.com.

Zhihao Meng was born in Hubei, China. He received the BS degree in communication engineering from Engineering University of People’s Armed Police in 2017, and he is now studying for a master’s degree at Engineering University of People’s Armed Police. His research interests are mainly in microwave antennas. E-mail: 1563144650@qq.com.

Yicheng Zhang was born in Hebei, China. He received the BS degree in Electronical Information Science and Technology from Hunan Normal University in 2017. He is currently working toward the MS degree in Engineering University of People’s Armed Police. His research interests are in microwave devices, wireless communications, and information systems. E-mail: 1326536607@qq.com.

Zheyu Li was born in Hubei, China. She received the BS degree in communication engineering from Engineering University of People’s Armed Police in 2018, and she is now studying for a master’s degree at Engineering University of People’s Armed Police. Her research interests are mainly in microwave antennas. E-mail: lzyewe@163.com.

Xiaoyu Liu was born in Inner Mongolia, China. He received the BS degree in communication engineering from Engineering University of People’s Armed Police in 2018, and he is now studying for a master’s degree at Engineering University of People’s Armed Police. His research interests are mainly in microwave antennas. E-mail: lxywjgd@163.com.

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