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# A NOVEL BANDPASS FILTER OF SUBSTRATE INTEGRATED WAVEGUIDE (SIW) BASED ON S-SHAPED EBG

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**Abstract**—A novel S-shaped electromagnetic band gap (EBG) middling bandwidth bandpass filter based on substrate integrated waveguide (SIW) was proposed. The filter was designed based on the band-stop characteristics of EBG by etching different dimensional S-shaped on the surface of substrate integrated waveguide. The bandpass filter with a center frequency at 7.765 GHz and relative fractional bandwidth 7.31% shows good bandpass characteristics with frequency band between 7.38 $\sim$ 7.94 GHz, while the insertion loss is less than 1.6 dB and achieve middling bandwidth in SIW by EBG and has the advantage of bandpass, low insertion loss, compacted and good selectivity etc.. The good agreement between the measured results and the simulated results demonstrates that the design of this proposed filter is effective.

## 1. INTRODUCTION

In recent years, the application of electromagnetic band gap (EBG) has become popular in microwave and millimeter-wave circuits [1]. As a complex periodic structure which has a frequency response of transferring passband and return stopband, EBG can be used in periodic metal cell structure embedded in medium material. Initially, EBG structure was only used in photonic frequency. Afterwards, academician found that the structure can be used in other frequency even the frequency of microwave and millimeter-wave by adjusting its size [2, 3]. The application of EBG in microwave and millimeter-wave

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has attracted academician's strong interest. EBG have been applied to design of antenna and microwave apparatus, such as filter, power divider and coupler.

Recently, a convenient and interesting planar scheme called substrate integrated waveguide (SIW) has already attracted much interest in the design of microwave and millimeter-wave integrated circuits [4–7]. The SIW is synthesized in dielectric substrate with linear arrays of metallic vias which can also be treated as a periodic structure [8, 9]. SIW components inherit the advantages of the rectangular waveguide such as high factor, low insertion loss, and high-power capability. This scheme is also feasible for designing ridged waveguides in low-temperature co-fired ceramic. The SIW components such as filters, multiplexers, antennas, and power dividers have been studied by researchers. Such tremendous research progresses shows that the SIW can be deployed in the design of microwave and millimeter-wave integrated circuits with very promising performances.

With the appearance of substrate integrated waveguide (SIW), many EBG was applied to the design of SIW filter. The SIW filter with EBG can achieve ultra-wideband [10–12]. But most of them is ultra-wideband (bandwidth $\geq 25\%$) filter while the design of middling bandwidth ($1\%{\sim}10\%$) is few. Most middling bandwidth SIW filter is lacuna structure, but the size of lacuna structure filter is bigger than that of EBG substrate filter. So the design of middling bandwidth EBG bandpass filter based on SIW is significance.

In this paper, the middling bandwidth filter is designed based on the characteristic of EBG bandstop and characteristic of SIW highpass by etching different dimensional S-shaped on the surface of substrate integrated waveguide. Comparing with the similar lacuna structure SIW filter, the return loss and size of the S-shaped EBG filter is better. The theory of EBG is introduced in Section 2, and the bandpass filter is designed in Section 3. In Section 4, experiments are provided and discussed with measured results, followed by conclusions in Section 5.

## 2. THEORY OF EBG

When electromagnetic wave transmits in this periodic medium structure, the echo dispersion occurs if wavelength is in proportion as the size of cycling structure, so that distribution of electron energy is no longer continuous. The structure with this characteristic is called electromagnetic bandgap structures-EBG. Electromagnetic wave with some frequencies can not transmit, which seems like forming forbidden area [13–16].

The application of EBG is based on the occurrence and size of the bandgap, so that the theory of EBG is introduced at the beginning of designing. The theories of different EBG structures are unique. Cycling EBG structure arose that dispersion wave phasic is cycled. A series of dispersing wave occur repeatedly in reverse and counteract with each other, so frequency bandgap occurs. Hereinbefore theory is Bragg dispersion theory. The bandstop characteristic of EBG is correlative with the size of cycling cell and relative permittivity of medium. EBG also has slow-wave characteristic and high impedance characteristic. Because of stoping electromagnetic wave transmitting in some frequency, EBG has filtering characteristic [17].

Based on Bragg dispersion theory

$$2k = k_{bragg} \frac{2\pi}{a} \tag{1}$$

$k$ is wave-guide model wavecount, $a$ is cycle spacing of EBG. The relationship between $a$ and $\lambda_g$ is as follows:

$$a = \frac{\lambda_g}{2} \tag{2}$$

Cycle spacing of EBG is half of the wave-guide wavelength. $\lambda_g$ can be acquired based on equivalent relation between SIW and wave-guide.

Wavelength of SIW can be acquired by following expressions.

$$\lambda_g = \frac{2\pi}{\beta} \tag{3}$$

$$\beta = \sqrt{k_0^2 \varepsilon_r - \left(\frac{\pi}{w}\right)^2} \tag{4}$$

The $k_0 = (2\pi f_0)/c$ is wavecount in freedomspace, $\varepsilon_r$ is relative permittivity of medium, $w$ is equivalent width of SIW.

When the material of substrate is chosen, cycling cell has effects on characteristic of stopband of dispersed EBG structure and makes against miniaturization of circuit. So academicians find another EBG structure theory called local resonance theory, which shows that EBG substrate forms bandgap based on resonance effect of cycling cell self. In fact, when EBG is designed in practice, two kinds of theory are effective for EBG bandgap.

## 3. DESIGNING OF PROCESSED

### 3.1. Analysis of S-shaped Cell Characteristic

Bandpass filter of SIW Based on S-shaped EBG is etched with different dimensional S-shaped on the surface of substrate integrated waveguide. For the frequencies electromagnetic wave in electromagnetic band gap,

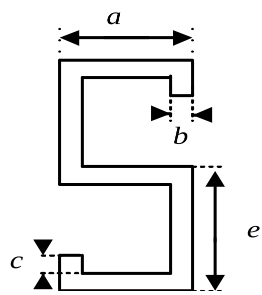


**Figure 1.** The S-shaped structure resonant unit cell.

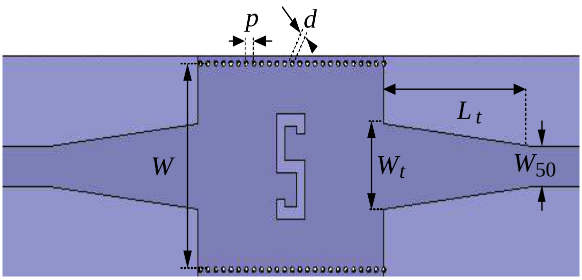


**Figure 2.** Configuration for the proposed SIW-EBG filter.

S-shaped structure can bring stopwave characteristic. Because of better highpass characteristic of SIW, EBG used in SIW can bring filter characteristic.

Figure 1 shows S-shaped structure resonant unit cell and equivalent circuit models. In order to validate bandgap characteristic of S-shaped EBG, one S-shaped cell was simulated and analysed by Ansoft HFSS11. SIW includes dielectric substrate with $\varepsilon_r = 2.2$, $\tan\sigma = 0.001$, $h = 1$ mm, diameter of the metallic via hole $d = 0.4$ mm, and cylinder spacing $p = 0.8$ mm, $W = 15.6$ mm, the parameter of one S-shaped structure: $a = 2.1$ mm, $b = 0.7$ mm, $c = 1.5$ mm, $e = 5.8$ mm. Figure 2 is configuration of one S-shaped EBG SIW cell.

As the Figure 3 shows, the SIW etching one S-shaped cell has stopwave characteristic in high frequency area(about 10 GHz) and stopband characteristic has occurred, but standard SIW has not the characteristic. The Figure 4 shows that phase of S-shaped has changed acutely at about 10 GHz, and validates one S-shaped cell has stopwave characteristic in high frequency. So SIW can achieve bandpass filter characteristic by the structure.

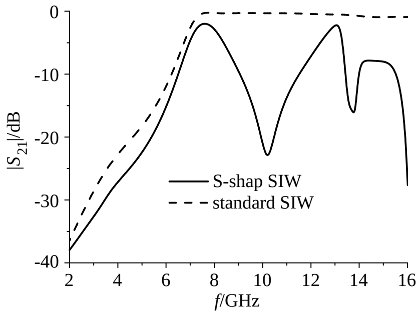


**Figure 3.** The $S_{21}$ simulated results of one-cell SIW-EBG.

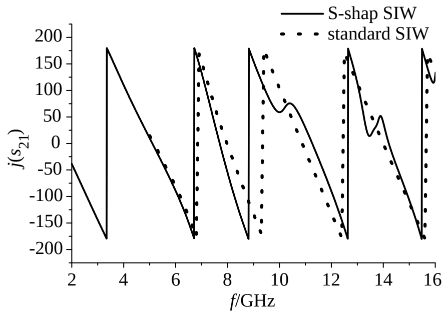


**Figure 4.** The phasic simulated results of one-cell SIW-EBG.

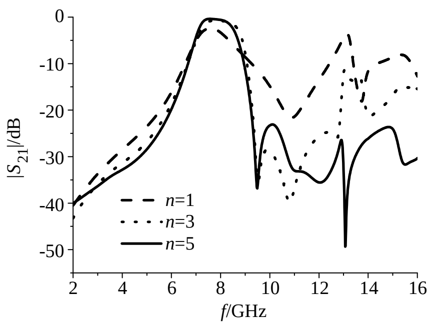


**Figure 5.** Band-stop characteristics of different amount cell.

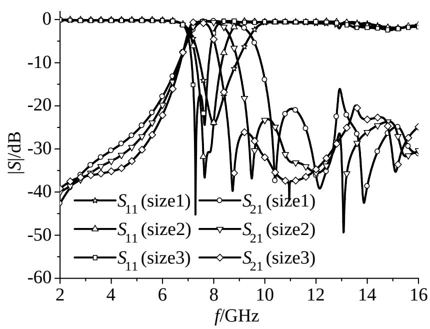


**Figure 6.** The simulated results of three different size.

## 3.2. The Effect of the Amount of Cycling Cell on Bandpass Characteristic of Filter

In the design of microwave and millimeter-wave circuit, The amount of cycling cell has important effect on transmitting characteristic of SIW. In order to analyze the effect of the amount of cycling cell on transmitting characteristic of EBG-SIW, different amount of cycle cell ($n = 1$, $n = 3$, $n = 5$) are simulated. Figure 3 is simulated bandstop characteristic result of different amount of the cells.

The Figure 5 shows that: with increasing amount of cycling cell, stopband characteristic become distinct and stopband width become wider, but the change of center frequency is not distinct. However, the increasing amount of cycling cell will results in the increasing of filter's size.

### 3.3. The Effect of Gap Extent on Bandpass Characteristic of Filter

The theory of equivalent circuit shows that S-shaped gap extent $e$ has the effect on the parameter of capacitance and inductance in equivalent circuit, and then has the effect on resonance frequency. In order to analyze stopband characteristic of different gap extent S-shaped filters, three different gap extent S-shaped filters is simulated. Figure 1 is size of three different gap extent, Figure 6 shows the simulated results.

The Figure 6 and Table 2 show that: with increasing gap extent $e$, the change of the beginning frequency of 20 dB return loss is not distinct, but beginning frequency of stopband in high frequency area is lessening, and center frequency of passband is also lessening. With increasing gap extent $e$, accumulating electric charge in metal patch and earth-plate is increasing which result in the increasing of equivalent

**Table 1.** Three different size cell.

| | $e_1$ (mm) | $e_2$ (mm) | $e_3$ (mm) |
|---|---|---|---|
| Size 1 | 5.3 | 4.3 | 3.3 |
| Size 2 | 5.8 | 4.8 | 3.8 |
| Size 3 | 6.3 | 5.3 | 4.3 |

**Table 2.** The simulated results of different size.

| Size | passband frequency | center frequency | fractional bandwidth |
|---|---|---|---|
| 1 | 7.77∼8.34 GHz | 8.055 GHz | 7.07% |
| 2 | 7.48∼8.05 GHz | 7.765 GHz | 7.34% |
| 3 | 7.59∼7.77 GHz | 7.68 GHz | 2.34% |

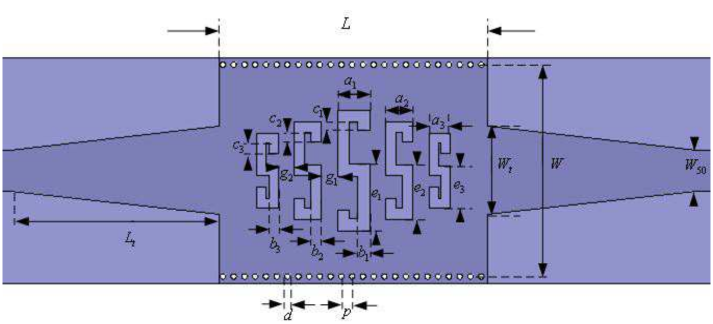


**Figure 7.** Configuration of filter.

capacitance. Meanwhile, equivalent parallel connection resonance circuit capacitance is increasing, while the resonance frequency (center frequency) is reducing. So the center frequency can be adjusted by adjusting gap extent $e$.

## 4. THE RESULT OF SIMULATED AND MEASURED

Based on the above simulation and analysis of the transmission characteristics of the S-shaped EBG-SIW, a 5-pole S-shaped bandpass filter is designed. The configuration of SIW with EBG structure is shown in Figure 7. The size of the practical model of filter is optimized as the result in Table 3.

The equivalent circuit of 5-pole S-shaped bandpass filter is shown in Figure 8. The equivalent circuit is simulated by ADS and the simulated result is shown in Figure 9. The Figure 9 shows that: the equivalent circuit simulated results agree well with that of HFSS, which demonstrates that the equivalent circuit is effective.

In order to validate availability of the filter, the filter is fabricated

**Table 3.** Dimensions of filter (mm).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $W$ | $L$ | $L_t$ | $L_{50}$ | $h$ | $W_t$ | $W_{50}$ | $\varepsilon_r$ |
| 15.6 | 19.5 | 15.5 | 5 | 1 | 6.5 | 3 | 2.25 |
| $a_1$ | $a_2$ | $a_3$ | $b_1$ | $b_2$ | $b_3$ | $c_1$ | $c_2$ |
| 2.4 | 2 | 1.6 | 0.9 | 0.8 | 0.7 | 1.5 | 1.5 |
| $c_3$ | $e_1$ | $e_2$ | $e_3$ | $g_1$ | $g_2$ | | |
| 1.5 | 5.8 | 4.8 | 3.8 | 1.2 | 1.2 | | |

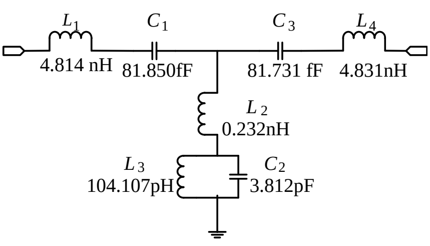


**Figure 8.** The equivalent circuit of 5-pole S-shaped bandpass filter.

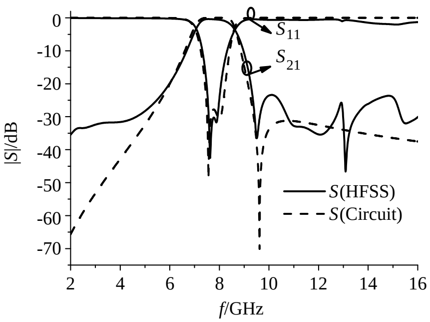


**Figure 9.** The equivalent circuit simulated result.

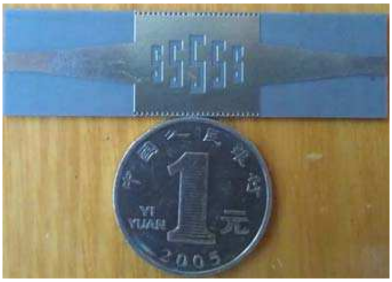


**Figure 10.** The real object of bandpass filter.

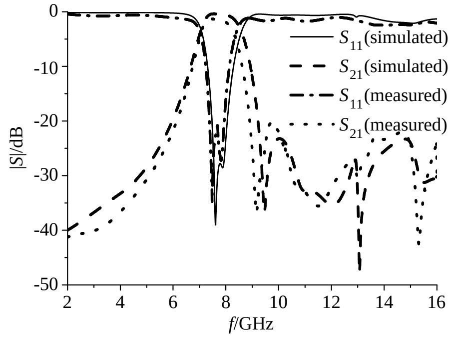


**Figure 11.** Simulated and measured of $S$-parameter.

and measured. The real object of bandpass filter is shown in Figure 10 and the simulation and measurement results of the filter are plotted in Figure 11. The result simulated by HFSS11 shows that the full frequency passband is from 7.48 to 8.05 GHz. The center frequency is 7.765 GHz, and the fractional bandwidth is 7.34% with the return loss less than 20 dB. The simulation insertion loss is approximately 0.64 dB and reflection loss is better than 20 dB in the passband. The simulation results occur transmission zeros at 9.46 GHz. It was measured with an HP8720ET network analyzer. The full frequency passband is from 7.38 to 7.94 GHz. The center frequency is 7.66 GHz, and the fractional bandwidth is 7.11% with the return loss less than 20 dB. The measured insertion loss is approximately 1.6 dB and reflection loss is better than 20 dB in the passband. The measurement results occurs transmission zeros at 9.18 GHz. Some discrepancy can be observed between the measured and simulated insertion loss, owing to fabrication inaccuracy and the additional loss from SMA connectors, which has not been included in the simulation. From the photographs of these filters, we can see that the proposed filters have a small size that is comparable to a coin. This makes them favorable for microwave and millimeter-wave applications.

## 5. CONCLUSION

This study has investigated the wave propagation problem of the SIW loaded by S-shaped. The electric dipole nature of the S-shaped has been utilized to achieve a forward passband in a waveguide environment. This passband is located below the waveguide cutoff and gives different characteristics when the orientations of S-shaped are varied. Based on this passband, a new family of filters using these novel structures are proposed, designed, and verified by experiments. The working principle has been discussed and presented. The dispersion and phase properties have been investigated. The equivalent-circuit models have been derived and analyzed. The filter design methodology has been examined. These filters are easy for integration, have a small insertion loss, and have a high selectivity with the help of transmission zeros. Improved stopband rejection is also attainable by slightly revising the configuration of the unit cells to suppress the propagation of the mode. The principle and approach of miniaturization for the waveguide filters are also illustrated. The results from our analysis and experiments are in good agreement with the previous known literature data. These bandpass filters based on S-shaped are suitable for practical applications.

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