Ferrite-Loaded Substrate Integrated Waveguide Frequency-Agile Bandpass Filter

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Abstract **─** In this paper, a ferrite-loaded substrate integrated waveguide (SIW) frequency tunable bandpass filter is presented. Two ferrite slabs are loaded at sidewalls of an SIW. When a DC magnetic bias is applied to the ferrite slabs, the equivalent width of the ferrite-loaded SIW is changed, which contributes to the tuning ability. As an example, a ferrite-loaded SIW frequency-agile bandpass filter is designed and fabricated according to this principle. Its center frequency can be adjusted from 12.35 GHz to 13.2 GHz. Within this frequency range, the insertion loss is changed from 2.3 dB to 3.9 dB and the return loss is better than 10 dB.

Index Terms **─** Bandpass filter, ferrite-loaded, frequency-agile, Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

Reconfigurable microwave devices have received much attention because of growing demands for dynamic spectrum management in smart and miniaturized wireless systems. Ferrite materials are widely used in magnetic control devices. This is because operating characteristics of ferrite materials can be controlled by applied DC magnetic bias. Combined with the currently popular substrate integrated waveguide (SIW) technology [1-5], many ferrite-loaded SIW components are presented in recent years, such as tunable filters [6-7], reconfigurable antennas [8-9], phase shifters [10], tunable cavity resonators [11], isolators [12-13], switches [14-15], etc.

Microwave frequency tunable bandpass filters are important components in future systems. In [4], an electrically and magnetically tunable SIW bandpass filter is proposed. However, it is complicated to apply the voltage control and the magnetic control simultaneously. In [16]-[18], lumped elements, such as PIN diodes and varactors, are utilized to construct SIW reconfigurable filters. Limited by the operating frequency and power handling capacity of lump elements, it is difficult to develop this kind of reconfigurable filter in high frequency band.

In [19], a new concept of frequency tunable bandpass filter is proposed based on the ferrite-loaded SIW and shortly discussed. Detailed design process and experimental result are presented in this paper. This type of filter can work in high frequency with simple configuration. By applying DC magnetic bias to the ferrite slabs, the equivalent width of the SIW is changed. Thus, the operating frequency of this bandpass filter can be reconfigured by the DC magnetic bias.

II. FILTER IMPLEMENTATION

In this section, we firstly investigate the electrical property of the ferrite-loaded SIW, and then obtain the equivalent width of the ferrite-loaded SIW when the DC magnetic bias is perpendicular to the direction of propagation. After that, a frequency-agile inductive post bandpass filter is designed based on the ferrite-loaded SIW.

In our design, the used dielectric substrate is the Taconic TLY-5 with a thickness of 1.52 mm. Its permittivity and loss tangent are 2.2 and 0.0009, respectively. The used ferrite material is YIG-1850. Its saturation magnetization value is 1850 Gs, relative dielectric constant is 14.5, and 3 dB line width is 20 Oe, respectively.

A. Ferrite-loaded SIW

Figure 1 illustrates the configuration of the SIW loaded with ferrite slabs. Two rectangular ferrite slabs are loaded along the conducting sidewall. W_f and L_f are the width and length of the ferrite slabs, respectively. The thickness of the ferrite slabs is the same as the substrate. Applied DC magnetic bias, dH, is perpendicular to the loaded ferrite slabs. According to [14],

$$\frac{1+\cos[2\pi f_c(W_2-2W_f)\sqrt{\mu_s\varepsilon_s}]}{1-\cos[2\pi f_c(W_2-2W_f)\sqrt{\mu_s\varepsilon_s}]}= \left(\frac{|\mu_f|\varepsilon_s}{\mu_s\varepsilon_f}\right)\tanh^2\left[2\pi f_c W_f\sqrt{|\mu_f\varepsilon_f|}\right]. \quad (1)$$

Submitted On: September 14, 2015
Accepted On: February 25, 2016

In (1), W_2 is depicted in Fig. 1, f_c is the cutoff frequency of the TE_{10} mode in the ferrite-loaded SIW, ε_s is the dielectric constant of the substrate, μ_s is the magnetic permeability of the substrate, ε_f is the dielectric constant of the ferrite, and μ_f is the effective permeability [20] of the ferrite, which can be written as:

$$\mu_f = \frac{\mu^2 - \kappa^2}{\mu} . \tag{2}$$

In (2), μ and κ are the permeability tensor elements of the ferrite material, which are related to the external bias, the saturation magnetization value and the operating frequency.

As shown in Fig. 2, the cutoff frequency calculated by (2) of the ferrite-loaded SIW varies with the DC magnetic bias. When the DC magnetic bias ranges from 0 to 0.16 T, the cutoff frequency varies from 9.51 GHz to 10.53 GHz.

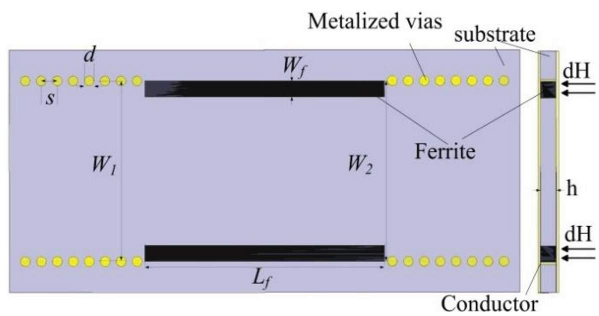


Fig. 1. Configuration of the ferrite-loaded SIW.

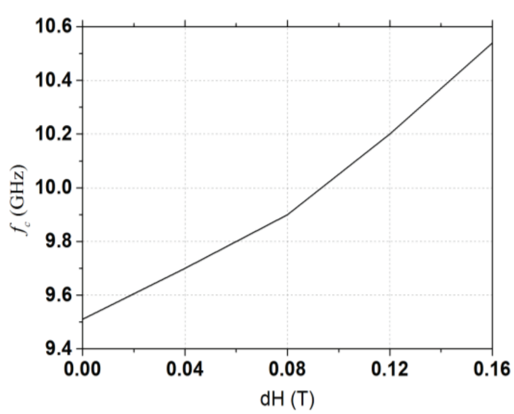


Fig. 2. Cutoff frequency of the ferrite-loaded SIW versus different internal bias dH.

Then, the equivalent width of the ferrite-loaded SIW, a_{eff}, can be calculated by:

$$a_{eff} = \frac{1}{2 f_c \sqrt{\mu_s \varepsilon_s}} . \tag{3}$$

As shown in Fig. 3, a_{eff} varies from 10.62 mm to 9.6 mm when the DC magnetic bias ranges from 0 to 0.16 T.

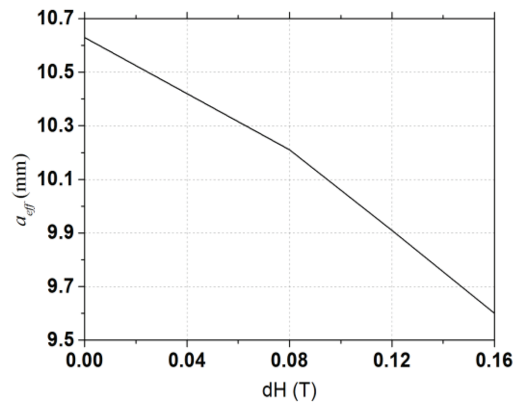


Fig. 3. Equivalent width of the ferrite-loaded SIW versus different internal bias dH.

B. Filter design

The configuration of the proposed ferrite-loaded SIW bandpass filter is shown in Fig. 4. Metalized posts are drilled on the centerline of the ferrite-loaded SIW. A maximally flat tunable bandpass filter is designed with a starting operating frequency band centered at 12.65 GHz Within the staring operating frequency band, the bandpass filter requires a bandwidth of 330 MHz and a minimum attenuation of 30 dB at 12.15 GHz. The tunable frequency range is 0.9 GHz. The design procedure of this kind of filter is listed as follows.

First, the minimum order, n, of the filter can be chosen according to the desired out-of-band rejection at the starting frequency without the DC magnetic bias. Then, the element values, i.e., g_0 to g_{n+1}, of the lowpass filter prototype can be calculated based on the method as described in [21]. Here, n=3, g_0=1, g_1=1, g_2=2, g_3=1 and g_4=1. After that, the lowpass filter prototype can be converted to the bandpass filter prototype through the K conversion as follows:

$$\frac{K_{01}}{Z_0} = \sqrt{\frac{\pi}{2} \frac{B_\lambda}{g_0 g_1}} , \tag{4}$$

$$\frac{K_{i,i+1}}{Z_0} = \frac{\pi B_\lambda}{2} \sqrt{\frac{1}{g_i g_{i+1}}} , \tag{5}$$

$$\frac{K_{n,n+1}}{Z_0} = \sqrt{\frac{\pi}{2} \frac{B_\lambda}{g_n g_{n+1}}} . \tag{6}$$

In (4)~(6),

$$B_\lambda = \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g0}} . \tag{7}$$

In (7), λ_{g1}, λ_{g2} and λ_{g0} are the guide wavelength at the edge and the center frequencies of the staring operating frequency band.

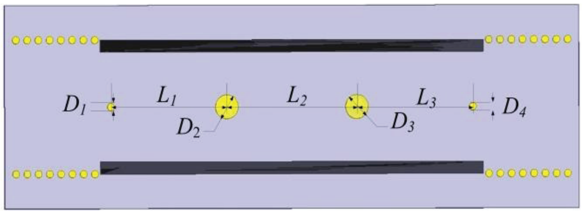


Fig. 4. Configuration of the proposed three-order frequency-agile filter.

Now, a bandpass filter can be realized based on the ferrite-loaded SIW structure. As shown in Fig. 5, an inductive post within a waveguide can be equivalent to the T-type network consisting of inductances and capacitances. When the metallized post is placed at the center point [22], there is

$$\frac{X_{ai}}{Z_0}-\frac{X_{bi}}{2Z_0}=\frac{a_{eff}}{2\lambda_g}\times\left[S_0-\left(\frac{\pi D_i}{2\lambda}\right)^2-\frac{5}{8}\left(\frac{\pi D_i}{2\lambda}\right)^4-2\left(\frac{\pi D_i}{2\lambda}\right)^4\left(S_2-2S_0\frac{\lambda^2}{\lambda_g{}^2}\right)^2\right], \tag{8}$$

$$\frac{X_{bi}}{Z_0}=\frac{a_{eff}}{\lambda_g}\times\frac{\left(\pi D_i/a_{eff}\right)^2}{\left(1+\frac{1}{2}\left(\frac{\pi D_i}{\lambda}\right)^2\right)\times\left(S_2+\frac{3}{4}\right)}. \tag{9}$$

In (8) and (9),

$$S_0=\ln\left(\frac{4a_{eff}}{\pi D_i}\right)-2+2\sum_{n=3,5\ldots}^{\infty}\left[\frac{1}{\sqrt{n^2-\left(\frac{2a_{eff}}{\lambda}\right)^2}}-\frac{1}{n}\right], \tag{10}$$

$$S_2=\ln\left(\frac{4a_{eff}}{\pi D_i}\right)-\frac{5}{2}-\frac{11}{3}\left(\frac{\lambda}{2a_{eff}}\right)^2-\left(\frac{\lambda}{a_{eff}}\right)^2\sum_{n=3,5\ldots}^{\infty}\left[\sqrt{n^2-\left(\frac{2a_{eff}}{\lambda}\right)^2}-n+\frac{2}{n}\left(\frac{a_{eff}}{\lambda}\right)^2\right]. \tag{11}$$

Besides, a_{eff} can be calculated by (3). Combined with (8)~(9), the equivalent parameters of posts in the ferrite-loaded SIW structure can be calculated with dH=0.

Here, the impedance inverter can be calculated by use of these equations:

$$\frac{K_{i,i+1}}{Z_0}=\tan\left(\frac{\Phi_i}{2}-\arctan\frac{X_{bi}}{Z_0}\right), \tag{12}$$

$$\Phi_i=-\arctan\left(2\frac{X_{ai}}{Z_0}-\frac{X_{bi}}{Z_0}\right)+\arctan\frac{X_{bi}}{Z_0}. \tag{13}$$

Taking the result calculated from (4)~(7) into (12) and (13), the required X_{ai} and X_{bi} can be calculated. Thus, the dimensions of the ferrite-loaded bandpass filter can be determined.

Then, the distance between adjacent center vias is determined by the following equation:

$$L_i=\frac{\lambda_g}{2}\left[1+\frac{1}{2\pi}(\Phi_i+\Phi_{i+1})\right]. \tag{14}$$

After the tunable filter is designed at dH=0, the tuning range can be determined as follows. When a nonzero DC magnetic bias is applied to the ferrite slabs, the center frequency of the bandpass filter can be calculated by:

$$f_0=f_cL_i\frac{1}{\sqrt{L^2_i-\left[1+\frac{1}{2\pi}(\Phi_i+\Phi_{i+1})\right]^2}}. \tag{15}$$

In (15), D_i and L_i are kept constant, f_c is related with dH. As shown in Fig. 6, the computed result agrees well with the simulated one.

Now, the performance of the filter can be improved based on the full-wave optimization implemented by HFSS. The dimension of the ferrite slab is firstly optimized. For the structure as shown in Fig. 1, a bigger W_f leads to a better tuning ability but a worse return loss. Then, other parameters of the ferrite-loaded SIW bandpass filter are optimized slightly based on the calculated parameters. The final parameters are: W_1=W_2=11.2 mm, d=0.6 mm, s=1 mm, W_f=1 mm, L_f=34 mm, L_1=L_3=10.4 mm, L_2=11.6 mm, D_1=D_4=0.6 mm and D_2=D_3=2 mm.

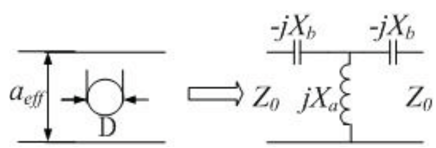


Fig. 5. Metalized post in a waveguide and its equivalent circuit.

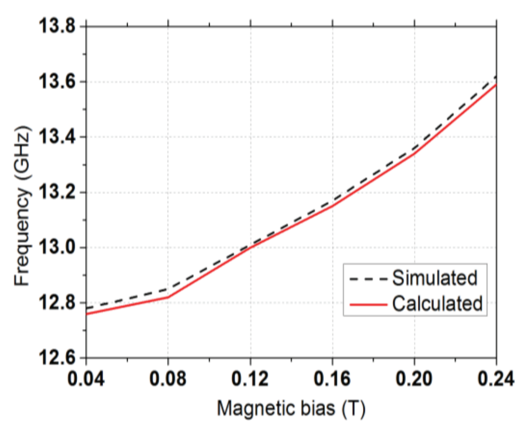


Fig. 6. Operating frequency of the bandpass filter versus DC magnetic bias.

III. EXPERIMENT RESULTS AND DISSCUSSION

As shown in Fig. 7, a ferrite-loaded SIW frequency-agile bandpass filter is fabricated. A transition from the coaxial cable to the SIW [23] is employed in this design convenient for the test.

HFSS from Ansys is used in this work. Simulated results of the designed filter are shown in Fig. 8. When the internal magnetic bias is increased from 0 T to 0.24 T, the operating frequency of the filter can be adjusted from 12.65 GHz to 13.6 GHz. The return loss is better than 15 dB within the range. The insertion loss is changed from 1.9 dB to 3.8 dB. At the same time, the 3 dB bandwidth is decreased from 2.6% to 1.85%.

The measured results are shown in Fig. 9. Because of boundary conditions at the surface of the ferrite sample [20], the value of the actually applied external bias, dH' is bigger than the internal bias dH. When the external magnetic bias is varied from 0 T to 0.34 T, the center frequency of the ferrite-loaded SIW bandpass filter can be tuned from 12.35 GHz to 13.2 GHz. Besides, the 3 dB bandwidth is decreased from 4.8% to 3.2%. The insertion loss is changed from 2.3 dB to 3.9 dB. Over the whole working frequency, a better than 10 dB return loss is achieved.

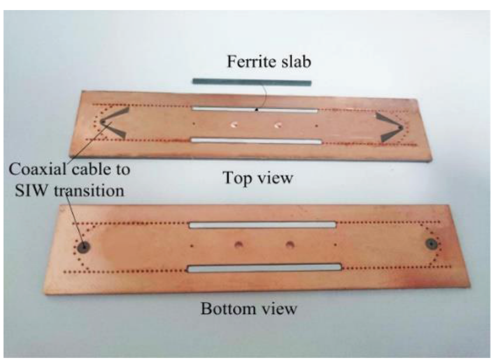
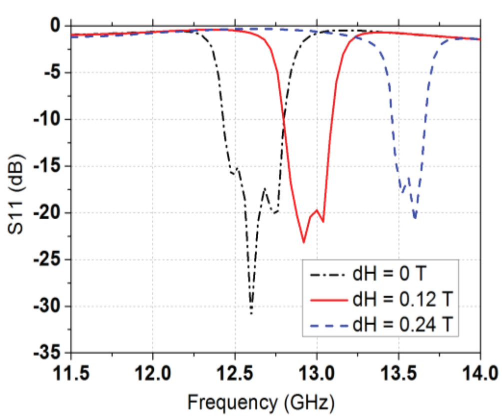
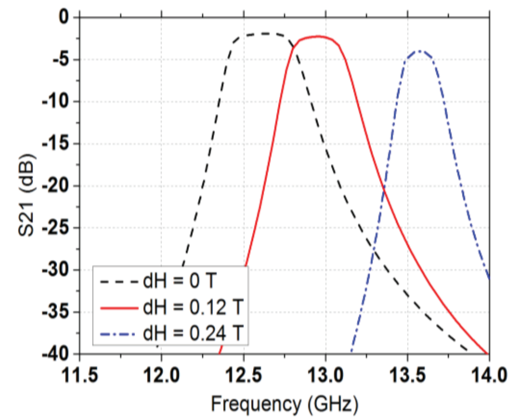


Fig. 7. Photograph of the fabricated ferrite-loaded SIW frequency-agile bandpass filter.

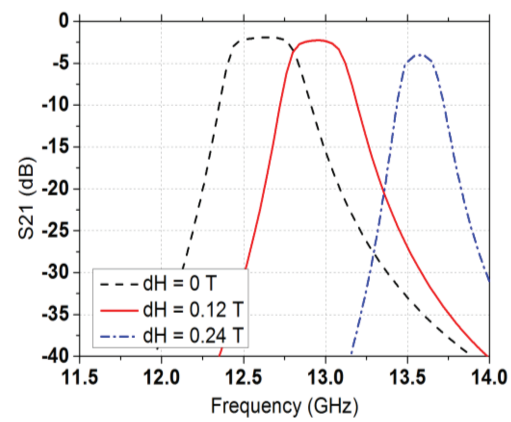


(a)

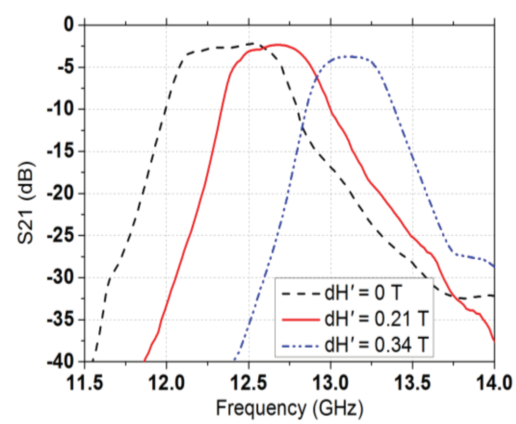


(b)

Fig. 8. Simulated S-parameter of the designed filter with different internal magnetic bias, dH. (a) Return loss and (b) insertion loss.



(a)



(b)

Fig. 9. Measured S-parameter with different total applied external magnetic bias, dH'. (a) Return loss and (b) insertion loss.

Because of machining errors, there exists a frequency shift of about 0.3 GHz compared with Fig. 8. The reason that causes the frequency offset is analyzed as follows. There exist two grooves in the substrate through normal PCB process. This fabrication is not so accurate. The tolerance of the groove in the substrate is firstly discussed. As shown in Fig. 10, when W_2 varies 0.1 mm, the center frequency will change about 0.1 GHz. Besides, as shown in Fig. 11, when the width of the ferrite slab increases 0.05 mm, the center frequency of the filter will move about 0.05 GHz. That means machining errors of the groove and the ferrite slab make main contributions to the frequency shift. Furthermore, the roughness of the groove also has an impact on the performance of the filter.

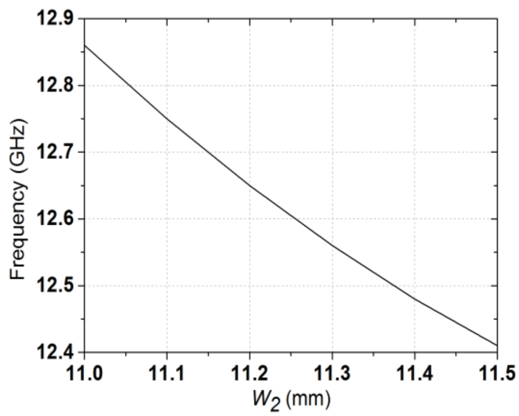


Fig. 10. Tolerance of W_2.

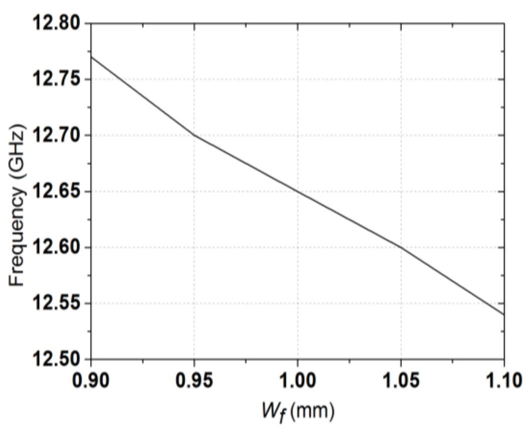


Fig. 11. Tolerance of the width of the ferrite slabs W_f.

IV. CONCLUSION

A new tunable ferrite-loaded SIW frequency-agile bandpass filter is designed and fabricated in this paper. It achieves the tuning ability by applying DC magnetic bias to the ferrite slabs, which are loaded along the partly metalized sidewall of the SIW. The fabricated ferrite-loaded bandpass filter can be tuned from 12.35 GHz to 13.2 GHz with a return loss of less than 10 dB when the external magnetic bias varies from 0 T to 0.34 T. The measured results agree well with the simulated ones.

ACKNOWLEDGMENT

This work is supported in part by Science Foundation for Distinguished Young Scholars of Sichuan Province under 2015JQO005, in part by Fundamental Research Funds for the Central Universities under grant ZYGX2014Z008, in part by Program for New Century Excellent Talents in University under grant NCET-13-0089, in part by the Foundation for the Author of National Excellent Doctoral Dissertation of PR China under grant number 201338, and in part by the National Program for Support of Top-Notch Young Professionals.

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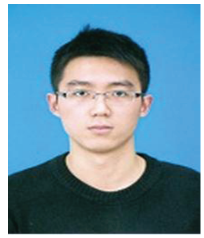

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