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# A KA-BAND THIRD-ORDER CROSS-COUPLED SUBSTRATE INTEGRATED WAVEGUIDE BANDPASS FILTER BASE ON 3D LTCC

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**Abstract**—This paper presents a novel third-order cross-coupled rectangular cavity filter by using standard low-temperature co-fired ceramic (LTCC) technology, in which the multilayer substrate integrated waveguide (SIW) is implemented. Particularly, the desired filter has a single finite frequency attenuation pole at j4.0 with asymmetrical frequency selectivity. An experimental band pass filter (BPF) has been fabricated and measured. The insertion loss of the filter is better than 4.2 dB, and the 1 dB bandwidth is about 1 GHz at the center frequency 35.8 GHz. Good agreement is obtained between the simulated and measured $S$-parameters of the proposed filter. This filter can be used in millimeter wave secondary surveillance radars.

## 1. INTRODUCTION

Modern radar communication transit/receive (T/R) module greatly stimulates the demands of small, lighter, more compact and high reliable passive components. High quality millimeter wave radar T/R requires waveguide narrow band pass filters (BPF) processing sharp frequency selectivity, low insertion loss. Thanks to the electrical similarity to a rectangular waveguide, substrate integrated waveguide (SIW) has been used to develop various high-performance millimeter wave waveguide filters [1–8]. Among these research works, those operating at Ka-band or above are usually fabricated by advanced processes such as low-temperature co-fired ceramic (LTCC), thick-film process [6–8, 14, 15], etc. LTCC technology is commonly used

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for designing compact circuitry because the same substrate can embed baseband/digital components with radio frequency (RF) miniaturized active and passive devices. The LTCC manufacturing method allows planar microwave circuits such as stripline-based circuits to be integrated easily into the substrate. Co-fired ceramic technology does not allow the formation of solid vertical planar conductors. However, the rectangular waveguide can be implemented in the substrate by using the via technology, which is substrate integrated waveguide.

With finite transmission zeros, elliptic or quasi-elliptic filters are now finding ever-increasing applications in a wide range of radar and mobile communication and sensing systems due to their high performance and compact size. According to the design process in [8], these filters are designed by introducing cross coupling between nonadjacent resonators to get the elliptic or quasi-elliptic function filter response. Based on the technology in [9, 10], this paper introduces a Ka-band third-order cross-coupled SIW filter by using LTCC technology. In the design, the resonators of the filter are rectangular SIW cavities which are fed by micro-strip lines on the same planar through slot apertures. Through magnetic and electric coupling among resonator cavities, the cross coupling is realized.

## 2. FILTER ANALYSIS AND DESIGN

In this paper, the center frequency and bandwidth of the filter are designed at 36 GHz and 900 MHz, respectively. Fig. 1 shows the geometric configuration and side view of the proposed SIW quasi-elliptic filter with source-load coupling on the basis of the negative coupling structure. In Fig. 1(b), the coupling between cavities 1 and 3 is realized by magnetic coupling through an inductive window in the common sidewall between them. The coupling between cavities 1 and 2 or between cavities 2 and 3 is realized through a same size rectangular window at the common wall [16, 17]. The desired filter with a single finite frequency attenuation pole at j4.0 is a three-pole cross-coupled resonator filter which has asymmetrical frequency selectivity. In this design, the coupling matrix has nonzero entry of $M_{1,3}$ for the desired cross coupling, which has nonzero diagonal elements accounting for asynchronous tuning of the filter [11]. By the certain technique of optimization adopted in [12], the generalized coupling matrix $[m]$ and scaled external quality factor $q$ of such a filter meeting these requirements can be extracted and given by (1) and (2), respectively.

$$[m] = \begin{bmatrix} -0.55288 & 1.25455 & -0.54575 \\ 1.25455 & 0.97128 & 1.25455 \\ -0.54575 & 1.25455 & -0.55288 \end{bmatrix} \tag{1}$$

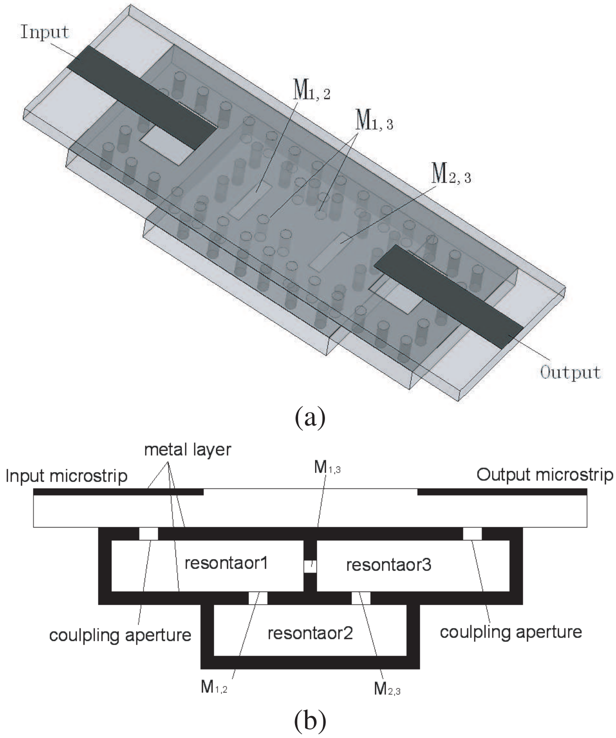


**Figure 1.** (a) Geometric configurations of the proposed SIW third-order cross-coupled filter. (b) Side view of the proposed SIW third-order cross-coupled filter.

$$q_i = q_o = 0.742 \tag{2}$$

where the $q_i$ and $q_o$ are scaled input and output quality factor, respectively.

Figure 2 shows the model of the basic resonator, and the initial size of the TE101-mode-based SIW cavity can be determined by setting the resonant frequency to the center frequency of filter by using the following formula [13]

$$f_0 = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\frac{1}{a_{\mathit{eff}}^2} + \frac{1}{b_{\mathit{eff}}^2}} \tag{3}$$

where

$$a_{\mathit{eff}} = a - \frac{d^2}{0.95s} \quad b_{\mathit{eff}} = b - \frac{d^2}{0.95s} \tag{4}$$

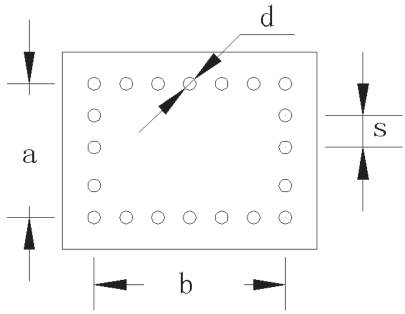


**Figure 2.** The structure of resonator cavity.

$f_0$ is the center frequency, $a$ and $b$ are the width and length of the TE101-mode-based SIW cavity, respectively. $d$ and $s$ are the diameter of metallized via holes and center-to-center pitch between two adjacent via holes, $c_0$ is the light velocity in vacuum, and $\varepsilon_r$ is the dielectric constant of the substrate. When $\varepsilon_r = 5.9$, $d = 0.2\,\text{mm}$, $s = 0.5\,\text{mm}$, $a = 2.1\,\text{mm}$, $b = 3\,\text{mm}$, the TE101 mode resonant frequency is about 37 GHz. It is clear that, the resonant frequency of TE101 mode in the basic cavity is a little higher than the desired frequency 36 GHz, because the real resonant frequency will be a little lower when the cavities are cascaded with each other and input or output.

From the Fig. 1, the coupling strength between two cavities depends on all of the geometrical parameters of the filter, which is described by using the following relation [11]:

$$k = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \tag{5}$$

where $f_1$ and $f_2$ stand for the high and low resonant frequencies, respectively, and $k$ is the coupling coefficient between two SIW cavity resonators. The input-output transformers of the filter are designed to give the required load $Q_e$ of the first and last cavities. Through the simulations of a micro-strip line coupled via a slot to the air filled SIW cavity, the relationship between the length of the external slots and phase response of $S_{11}$ is determined using

$$Q = {}^{f_0}\!/_{\Delta f} \tag{6}$$

where $Q$ is equal to the unloaded quality factor, $f_0$ is the frequency at which $S_{21}$ reaches its maximum value and $\Delta f$ is the 3-dB bandwidth. When the coupling matrix is chosen, an optimization procedure should be used to get the value of the filter size. According to (3), (4), (5) and (6), the initial geometrical parameters of coupling slots and cavities will

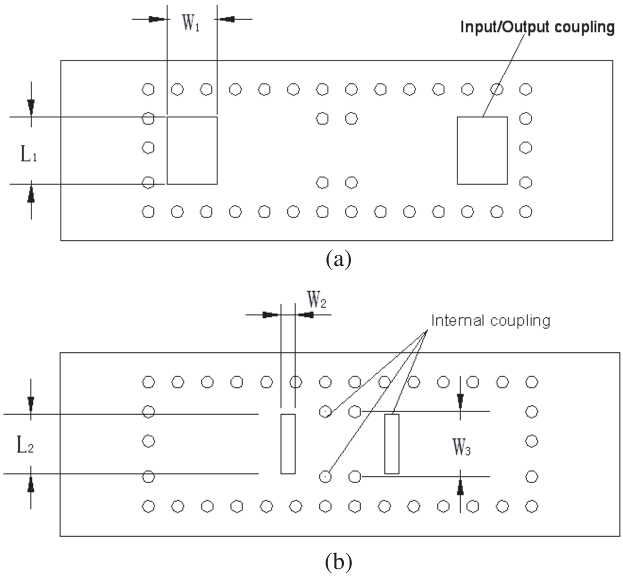


**Figure 3.** (a) Geometrical parameters of the input/output coupling structure. (b) Geometrical parameters of the internal structure.

be determined by an eigenmode solution solver of HFSS. Fig. 3 shows the geometrical parameters of the internal and input/output coupling structure. By the optimization technique of HFSS, the design target can be achieved when $W_1 = 0.86\,\mathrm{mm}$, $W_2 = 0.24\,\mathrm{mm}$, $W_3 = 1.1\,\mathrm{mm}$, $L_1 = 1.16\,\mathrm{mm}$, $L_2 = 1\,\mathrm{mm}$.

Figure 4 shows the simulated results of the designed filter with full wave field solver HFSS. It can be seen in Fig. 4 that the proposed filter has a center frequency of 36 GHz with a bandwidth of 900 MHz, and it has a single finite frequency attenuation pole at 37.74 GHz. The maximum return loss of the proposed filter is $-19\,\mathrm{dB}$.

## 3. FABRICATION AND MEASUREMENT

A satisfying filter was fabricated using a thirteen-layer LTCC substrate Ferro-A6, with the relative permittivity $\varepsilon_r = 5.9$, the loss tangent $\tan\sigma = 0.0015$, the thickness of each layer $t = 0.096\,\mathrm{mm}$, and the diameter of via used to build SIW is 0.2 mm. The fabricated filter sample is shown in Fig. 5, the size of this filter is $9.5 \times 3.1 \times 1.3\,\mathrm{mm}^3$.

The filter is packaged in a cavity and measured with Agilent E8363B network analyzer. The $S$-parameters results of the filter with a single finite frequency attenuation pole at 37.48 GHz is shown in

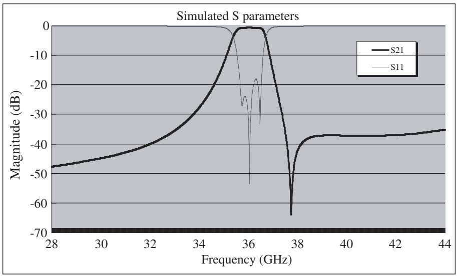


**Figure 4.** Simulated results with HFSS software.

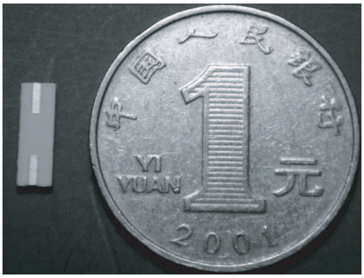

**Figure 5.** Photo of fabricated filter.

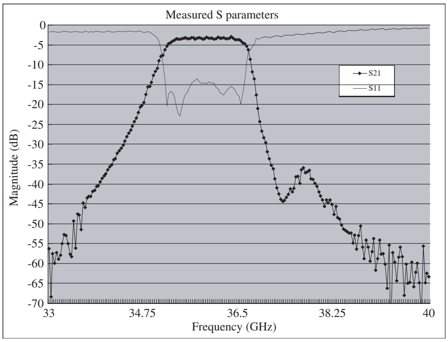


**Figure 6.** Response curves of the SIW third-order cross-coupled filter.

Fig. 6 the center frequency is 35.8 GHz, and the insertion loss is better than 4.2 dB with 1 GHz bandwidth. There is good agreement between the measured and simulated $S$-parameters, except a small frequency shift and a little discrepancy in the in-band insertion loss presented. This is mainly caused by the inaccuracy in the characterization of relative permittivity and loss tangent of LTCC at 36 GHz. On the other hand, all metallic vias and metal surfaces are assumed to be perfectly conducting in our design, which will also result in the discrepancy in the measured and simulated in-band insertion losses. The frequency shift may also be affected by the manufacturing tolerance.

## 4. CONCLUSION

A novel third-order cross-coupled rectangular cavity filter is presented in this paper, which is realized using the technique of multilayer SIW and fabricated using standard LTCC technology. In the design, an experimental filter with a center frequency of 35.8 GHz and a bandwidth of 1 GHz has been fabricated and tested. The test results show good agreement with that from the EM simulation. The insertion loss is better than 4.2 dB, and the attenuation is 42.2 dB at the single finite frequency attenuation pole of 37.48 GHz. Its good performance, small size and relatively simple structure make it a good candidate as an integrated filter for Ka band radar systems.

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