Silicon micromachined K-band filters

Sumit Kumar Khandelwal, Deepak Bansal , Dr. K J Rangra
Council of Scientific and Industrial Research-
Central Electronics Engineering Research Institute
(CSIR-CEERI), Pilani-333031, Rajasthan, India
ksumit11@gmail.com

***Abstract*— This paper describes a substrate integrated waveguide (SIW) based filter at K band frequency on silicon substrate. TMAH etching is used to form the via-holes for SIW cavities. Simulations and comparison of TMAH and inductively coupled plasma (ICP) etched cavity has been presented. A micro-machined filter is made from rectangular cavities integrated into a silicon substrate and is fed by coplanar waveguide (CPW) transmission-lines through current probes. Simulated filter using TMAH etching shows insertion loss of 0.29dB and return loss of 21.96 dB.**

Keywords*— *Micromachined filters, Substrate integrated waveguide (SIW), inductively coupled plasma (ICP), TMAH

I. INTRODUCTION

In high frequency applications, microstrip devices are not efficient, and because wavelength at high frequencies are small, microstrip device manufacturing requires very precise control. At high frequencies, waveguide devices are preferred; however it is expensive and hard to fabricate whilst it has bulky volume and is thus difficult to integrate with other planar circuits [1]. Therefore a new concept emerged: substrate integrated waveguide. SIW is a transition between microstrip and dielectric-filled waveguide (DFW). Dielectric filled waveguide is converted to substrate integrated waveguide (SIW) with the help of vias for the side walls of the waveguide. Because there are vias at the sidewalls, transverse magnetic (TM) modes do not exist; Therefore, TE_{101} is the dominant mode.

Bulk silicon etching techniques, used to selectively remove silicon from substrates, have been broadly classified as dry etching (ICP-DRIE) and wet etching (TMAH) [3]. Inductively coupled plasma (ICP) deep etching is used to form the square via-holes of SIW cavities [4]. In case of TMAH etching, the vias have a pyramidal shape due to silicon wet etching properties [5]. Also, TMAH etching has the advantages of low process cost, simple equipment, better surface smoothness and lower environmental pollution [6].

II. THEORETICAL DESIGN DETAIL

For TE_{101} mode, the thickness of substrate is not important as it does not affect the cut off frequency of the waveguide. Therefore the substrate can be of any thickness; it only affects the dielectric loss (thicker=lower loss) and quality factor.

A. SIW Cavity

SIW based filters are simulated for high resistivity silicon substrate. Response for SIW filters is similar to that of rectangular waveguide cavities, the lowest resonance frequency is determined as;

$$f_r = \frac{C_0}{2\sqrt{\in_r}}\sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{L_{eff}}\right)^2}$$

where W_{eff} and L_{eff} are the effective width and length of the resonant SIW cavity, approximately given by

$$W_{eff} = W - \frac{D^2}{0.95p}$$

$$L_{eff} = L - \frac{D^2}{0.95p}$$

where D is the diameter of the metallic via, W and L are the width and length of the cavity, respectively, p is the space between metallic vias, C_o is the light velocity in vacuum, ε_r is the relative permittivity of the silicon substrate.

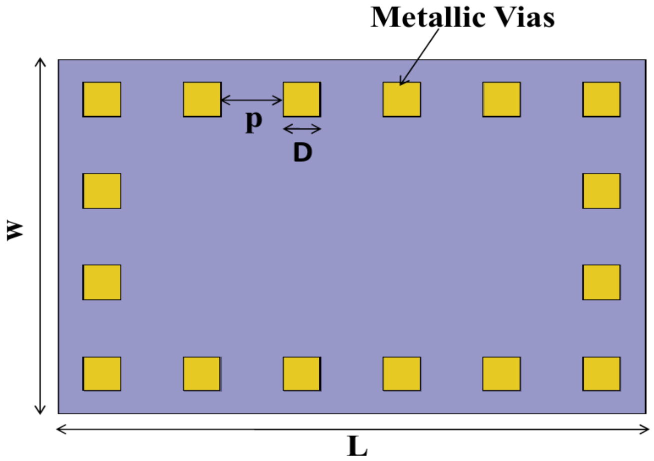


Figure 1. Configuration of micromachined SIW filter

B. Theoretical Calculations

For, Weff = L_{eff} = x (say)

$$f_r = \frac{C_0}{x\sqrt{2\in_r}}.$$

It is clear from the above equation that resonant frequency is inversely proportional to the size of cavity. It is interesting to note that, higher the pass band frequency smaller will be the size of cavity.

We have designed K band filter using TMAH etching, having center frequency 20 GHz, via hole opening as 450 µm and the distance between the two vias as 150 µm. The calculated dimension of square cavity was 3650 µm.

Also, we have designed K band filter using inductively coupled plasma (ICP) deep etching, having center frequency 20 GHz, via hole opening as 150 µm and the distance between the two via as 250 µm. The calculated dimension of square cavity was 3150 µm.

III. DESIGN OF EXPERIMENT

The external quality factor (Qe), representing CPW to input/output SIW cavity coupling, is deduced from the HFSS simulator.

The ideal Qe is found from:

$$Q_e = \frac{f_0}{\Delta f} g_0 g_1$$

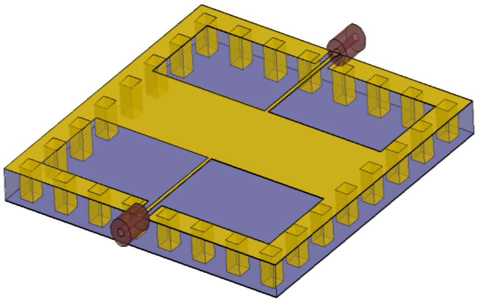
where f_0 is the center frequency of the filter and Δf is the bandwidth of the filter. This external coupling Qe can be extracted using simulated values of a single SIW-cavity. The value of Qe can be found from taking the fractional bandwidth which is defined as the bandwidth over a phase shift in S11 around the resonant frequency [2]. Defining the 180° bandwidth as Δf_{01}, the Qe is given by:

$$Q_e = \frac{\Delta f_{01}}{f_0}$$

Current probes will be used to connect the SIW cavity to the CPW lines. By performing a parametric analysis on a single cavity, the CPW to SIW coupling can be optimized to match the ideal Qe.

Using above design procedure, micromachined filter is designed on silicon substrate with a thickness of 275µm, a relative dielectric constant of 11.7, and dielectric loss tangent of 0.005.

(a) ***Using ICP etched cavity***- The via-hole design has a diameter of 150 µm and a space of 250 µm. For meeting the external quality factor, the dimensions of CPW-SIW coupling window is adjusted to 1.305mm×0.875mm, this result in the resonant frequency of the input/output SIW cavity shifting. The simulated filter response is shown in Figure 4; it is observed that the filter has a center frequency of 19.4 GHz with a 3 dB relative bandwidth of 3.2GHz.



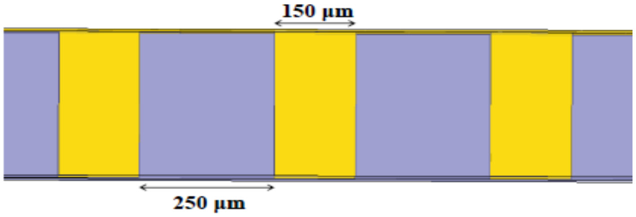


Figure 2. The scheme of ICP etched cavity, (a) 3D view; (b) Side view

(b) ***Using TMAH etched cavity***- The via-hole design has a diameter of 450 µm and a space of 150 µm. For meeting the external quality factor, the dimensions of CPW-SIW coupling window is adjusted to 1.260mm×0.9mm, this result in the resonant frequency of the input/output SIW cavity shifting. The simulated filter response is shown in Figure.5.

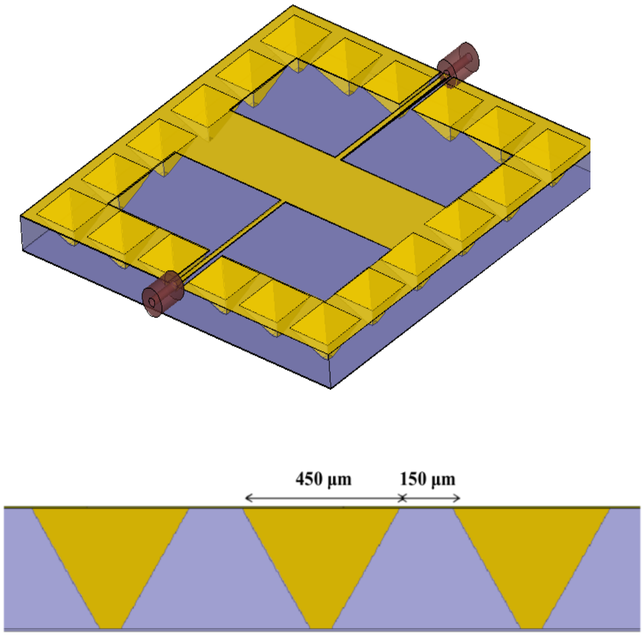


Figure 3. The scheme of TMAH etched cavity, (a) 3D view; (b) Side view

by using HFSS. Figure 4 and 5 are typical simulated result of ICP DRIE and TMAH etched based K band pass filter respectively. Figure 4 shows the plot of simulated S-Parameters (S11, S21) of the bandpass filter for ICP DRIE etching based cavity. It is observed that the filter has a center frequency of

19.4 GHz with a 3 dB bandwidth of 3.2 GHz covering the frequency ranges from 17.8 GHz to 21 GHz. The designed filter has an insertion loss of 0.27 dB and return loss of 32.06 dB.

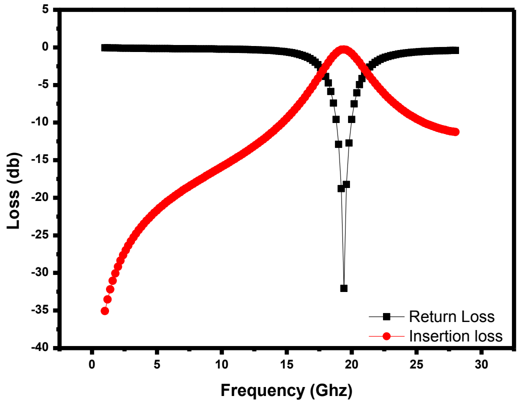


Figure 4. Simulated results for ICP-DRIE etched SIW filter

Figure 5 shows the plot of simulated S-Parameters (S11, S21) of the bandpass filter for ICP DRIE etching based cavity. It can be seen that the filter has a center frequency of 19.4 GHz with a 3 dB bandwidth of 4 GHz covering the frequency ranges from 17.4 GHz to 21.4 GHz. The designed filter has an insertion loss of 0.29 dB and return loss of 21.96 dB.

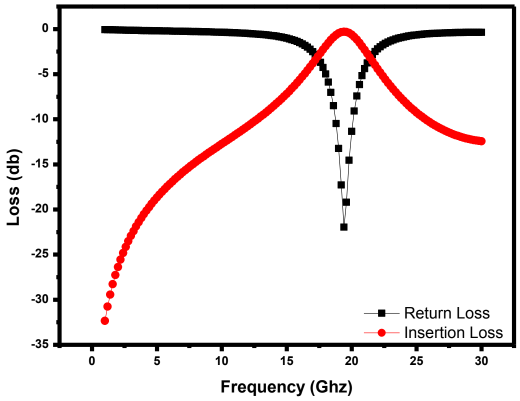


Figure 5. Simulated results for TMAH etched SIW filter

The microwave K bands are used primarily for radar and satellite communications while the infrared K band is used for astronomical observations. Table1 shows the comparisons of measured return loss and insertion loss using ICP and DRIE etched cavity.

TABLE 1
RESULT COMPARISION

Etching	Central frequency, GHz	Return Loss, db	Insertion loss, db
ICP	19.4	32.06	0.27
TMAH	19.4	21.96	0.29

Two lines or devices are well matched if the return loss is high. A high return loss is therefore desirable as it results in a lower insertion loss. Figure 6 shows the phase change in S11 and S21 with the frequency for ICP etched SIW filter. The measured external quality factor was 6.06.

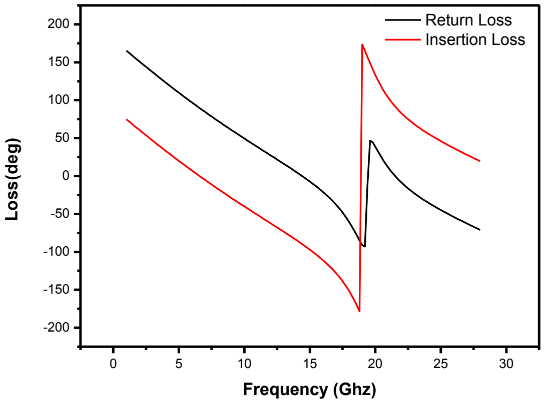


Figure 6. Simulated results for ICP-DRIE etched SIW filter

Figure 7 shows the phase change in S11 and S21 with the frequency for TMAH etched SIW filter. The measured external quality factor was 4.85.

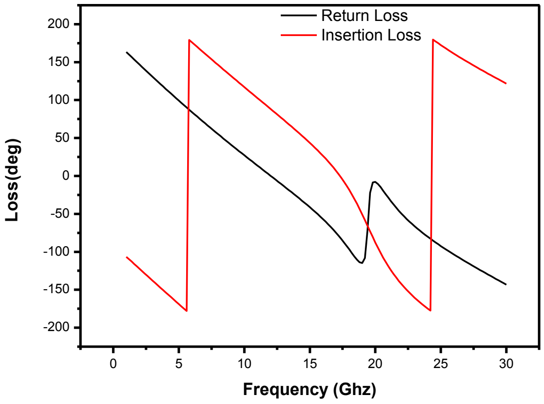


Figure 7. Simulated results for TMAH etched SIW filter

CONCLUSION

Silicon micromachined SIW filter is designed and simulated using a HFSS Software. This small sized monolithic silicon micromachined filter will results in low cost, high performance and easy integration with planar circuits. The return loss and insertion loss is comparable in both ICP-DRIE and TMAH etched cavity filter. Also, TMAH etching has the advantages of low process cost, simple equipment, better surface smoothness and lower environmental pollution. Thus, TMAH etched cavity filter results in better approach method in terms of cost and complexity.

ACKNOWLEDGMENT

The authors wish to thank Dr. Chandrasekhar, Director CEERI Pilani for his constant support and encouragement during this work.

REFERENCES

[1] R. Wang, L.-S. Wu and X.-L. Zhou, "Compact folded substrate integrated waveguide cavities and bandpass filter," *Progress In Electromagntics* Research, Vol. 84, 135-147, 2008.

[2] P.Blondy, A.R. Brown, D. Cros and G.M. Rebeiz, "Low loss micromachined filters for millimeter-wave telecommunication systems," IEEE MTT-S Int. Microwave Symposium Digest, pp.1181-1184, March 1998

[3] G.T.A .Kovacs, N.I.Maluf, and K.E. Petersen, "Bulk Micromachining of Silicon," Proceedings of the IEEE, Vol. 86,1998 ,1536 – 1551, 1998

[4] Yu Yuanwei, Zhang Yong, and Zhu Jian, "Monolithic silicon micromachined Ka-band filters," Microwave and Millimeter Wave Technology, 2008. ICMMT 2008, Vol. 3, 1397 – 1400, 2008

[5] P. Ferrand, M. Chatras, D. Baillargeat, P. Blondy, S.Verdeyme, J. Puech, and L. Lapierre, "A novel compact quasi planar silicon filter at 45 GHz based on metallic periodic structure," Microwave Conference, 2003. 33rd European, Vol.2, 805 - 808, 2003.

[6] Jinwen Zhang, Wai Cheong Hon, Lydia L W Leung and K J Chen, "CMOS-compatible micromachining techniques for fabricating high-performance edge-suspended RF/microwave passive components on silicon substrates," J. Micromech. Microeng , Vol. 15, 328–33, 2005