A Miniature W-band Substrate-Integrated Waveguide Cavity Bandpass Filter Using GaAs-based IPD Technology

Yin-Cheng Chang[#1], Ta-Yeh Lin[#], Jiayou Wang[*^], Shuw-Guann Lin[#], Chao-Ping Hsieh[#],
Yi Huang[^], Shawn S. H. Hsu[*], Da-Chiang Chang[#]
[#]Taiwan Semiconductor Research Institute, National Applied Research Laboratories, Hsinchu, Taiwan
[*]Institute of Electronics Engineering, National Tsing Hua University, Hsinchu, Taiwan
[^]Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, U.K.
[1]yincheng.chang@narlabs.org.tw

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***Abstract*—This paper presents a miniaturized substrate-integrated waveguide (SIW) cavity bandpass filter (BPF) using integrated passive device (IPD) technology for W-band applications. With two side-by-side SIW cavities coupling via an aperture, the cavities resonate in the TE_{101} mode to determine the center frequency. Also, the transmission zero at a higher frequency is created owing to the excited TE_{102} mode. By varying the aperture width, the bandwidth (BW) of the filter could be determined via coupling strength and the TE_{102} mode frequency. With a center frequency of 100 GHz, the proposed SIW filter demonstrates a 3-dB BW of 5.1 GHz (97.4–102.5GHz) with a low insertion loss (*IL*) of only 1.89 dB, and the return loss is better than 20 dB in the passband. This work achieves a low *IL* and fractional BW (FBW) of 5.1 % with a compact size of 1.48 mm^2, which is among the best compared to previously reported W-band chip BPFs.**

***Keywords*—bandpass filter (BPF), cavity, IPD, substrate-integrated waveguide (SIW), W-band.**

I. INTRODUCTION

With the advantages of wide bandwidth and low atmospheric attenuation, W-band is suitable for a wide range of applications including automotive radars, satellite communication, astronomy, defense, and security screening applications. The bandpass filter (BPF) is an essential component of the RF front end in the system for frequency selectivity. Unlike other active circuits which could be fully integrated on one chip, the BPF is often implemented by a different technology owing to performance considerations. For example, the waveguide filters [1]-[2] realized by the milling or micromachining process could achieve excellent insertion loss and selectivity. However, the physical size makes it difficult to be integrated with other circuits in a compact system. On the other hand, the system-in-package (SiP) solution is popular, which allows the integration of the planar-like RF front-end circuits and components together on one carrier substrate. With the advantages of a high-quality factor and simple process, the integrated passive device (IPD) technology is an excellent candidate for SiP applications to achieve high-level integration and low cost at high frequencies.

The chip-scale planar transmission line filters [3]-[4] could fulfil the requirement of a compact size for SiP with a fractional BW (FBW) of about 10%. However, the passband insertion loss (*IL*) would deteriorate if the required FBW is relatively small for high selectivity. The substrate-integrated waveguide (SIW) structure provides a good compromise between the planar transmission line filter and traditional waveguide. Compared with the planar filter, the designs based on SIW demonstrate lower loss, high selectivity, and higher power-handling capability. In addition, the SIW BPF is much easier to be integrated into a system than the bulky traditional waveguide. A 5-pole Chebyshev BPF [5] achieves a fractional BW (FBW) of only 2.4 % with a core size comparable with the transmission line filters. A SIW filter [6] not only achieves a small FBW of 3.4% but also realizes the out-of-band rejection using higher-order mode resonances.

In this work, a low *IL* and miniature SIW cavity BPF is proposed for a sub-THz sensing system that adopts the superheterodyne transceiver topology with an IF frequency of around 5.8 GHz. The system has a carrier frequency of 100 GHz and requires a filter BW of 5 GHz. Different from the typical SIW filter structure [7]-[8], the proposed BPF utilizes two side-by-side cavities with an aperture coupling at the center to control the transmission zero and further determine the BW. A miniaturized BPF with a 5.1 % FBW and 1.89 dB *IL* by using GaAs-based IPD technology is demonstrated.

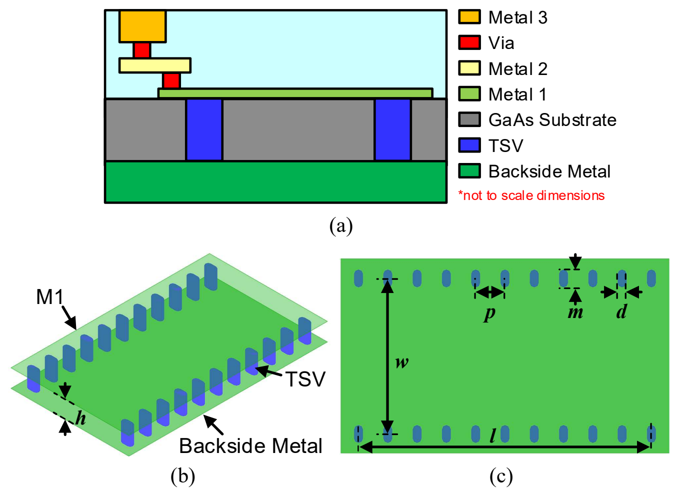

Fig. 1. GaAs-based IPD SIW: (a) cross-section of GaAs IPD technology, (b) SIW structure realized in IPD, and (c) top view of the SIW structure.

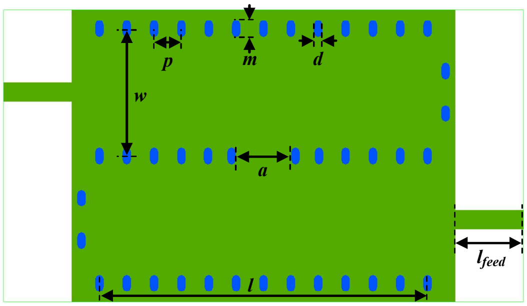

Fig. 2. Top view with dimensions of the proposed BPF.

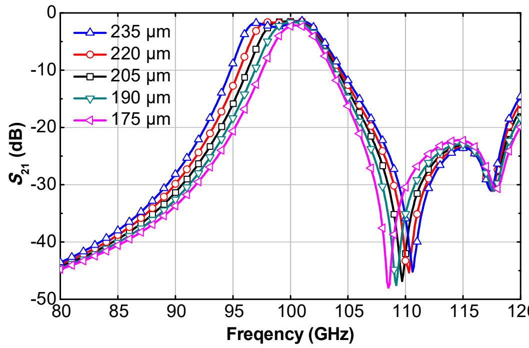

Fig. 3. Effect of aperture width on transmission zero and bandwidth.

II. SIW Cavity Filter Design

A. GaAs-based IPD Technology

The technology used in this work is a GaAs-based IPD process provided by WIN Semiconductors, which a passive-only process for RF applications. The passive components such as filter, balun, or power divider can be implemented using this process with high-quality factor and low cost. Fig. 1 shows the cross-section of the adopted IPD technology, including three metal layers embedded in the polymer on the GaAs substrate with a backside metal plane. With the feature of through substrate via (TSV), the metal layers above the substrate could be connected to the backside metal as a well-defined reference ground. The thickness of the GaAs substrate is 100 μm with a dielectric constant (ε_r) of 12.9 and a loss tangent (tanδ) of 0.001. The metallic Au layers with a conductivity (σ) of 4.1 $\times 10^7$ S/m from the bottom to the top are denoted by Metal 1 (M1), Metal 2 (M2), and Metal 3 (M3) with the thicknesses of 1, 2, and 4 μm, respectively. The top metal layer is designated for high Q passive elements.

B. Band-pass Filter Design

Fig. 1(b) and 1(c) illustrate the SIW structure realized by the IPD technology, in which M1 and the backside metal are utilized as the top metal and the bottom metal respectively and two rows of oval TSVs are employed as the side wall, connecting M1 and the backside metal to form the SIW structure. The width (d) and length (m) of the oval TSV is 30 μm and 60 μm respectively, and the pitch (p) between two adjacent TSVs is set as 100 μm in the proposed design. Note that the height (h) of the SIW is much smaller than the width (w) and length (l), and hence only the TE modes exist in the SIW.

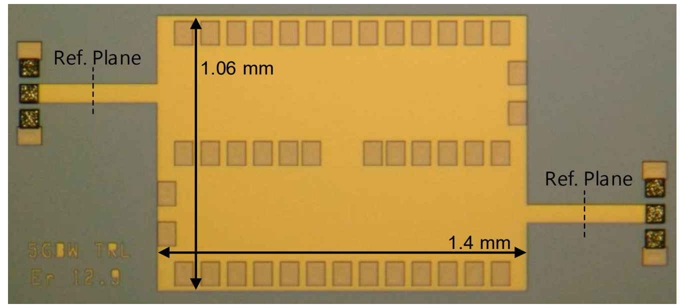

Fig. 4. Photograph of proposed SIW cavity BPF.

The SIW cavity operating at the fundamental TE_{101} mode can be designed based on the following equations [9]-[10],

$$f_{TE_{101}} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{1}{w_{eff}}\right)^2 + \left(\frac{1}{l_{eff}}\right)^2} \tag{1}$$

where

$$w_{eff} = w - \frac{d^2}{0.95p}, \quad l_{eff} = l - \frac{d^2}{0.95p} \tag{2}$$

μ_r and ε_r are the relative permeability and relative permittivity of the dielectric, c_0 is the light velocity in vacuum, w_{eff}, and l_{eff} are the width and length of the cavity, respectively. With an l of 1000 μm for the SIW, the width (w) can be calculated as 470 μm at f_0 of 100 GHz according to (1)-(2). The analytical equations provide a guideline for the initial design, and the full-EM 3D simulation is carried out for design optimization.

To form the desired passband response with a sufficient out band rejection, it is essential to create a transmission zero at a proper frequency above f_0. Different from the traditional approach where the poles and zeros are designed based on the coupling matrices, a coupling aperture is introduced to create transmission zero. Fig. 2 shows the proposed SIW filter structure, where two SIW cavities are placed side by side and share the same TSVs sidewall in the middle. An aperture at the center of the common wall is opened, and the electromagnetic energy can be magnetically coupled from the upper cavity to the lower cavity at the TE_{101} mode at around f_0. On the other hand, the TE_{102} mode appears at a higher frequency, which would eliminate the coupling between two cavities and create a transmission zero.

Fig. 3 shows the simulated results, which indicate how the passband characteristics of the filter vary with the aperture width a. As can be seen, a is an effective parameter to reduce IL and control the bandwidth. When the width of the aperture increases, the coupling effect becomes stronger with less insertion loss. Also, the zero moves to a higher frequency for a wider 3-dB BW. As a result, the desired BW of 5 GHz with a steep roll-off skirt can be achieved to satisfy the system specifications. The dimensions of the final optimized filter are specified as follows: w = 464 μm, l = 1200 μm, a = 203 μm, p = 100 μm, d = 30 μm, and m = 60 μm. The cavity size is 1.48 mm^2 (1.4 mm × 1.06 mm). Note that two feeding microstrip lines (l_{feed} = 250 μm and w_{feed} = 70 μm) with Z_0 of 50 Ω are employed at the input and output for on-wafer GSG pad probing, which can also be connected directly to an antenna on the same substrate for the sub-THz SiP sensing system in the future.

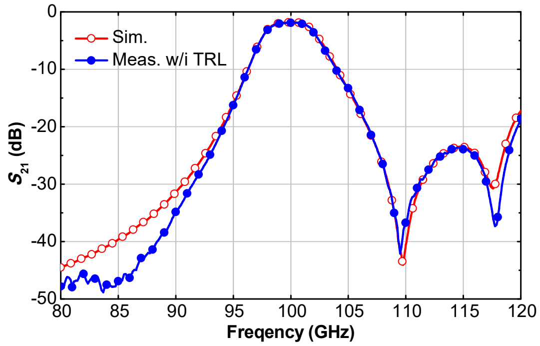

Fig. 5. Simulated and measured S_{21} of the proposed SIW filter.

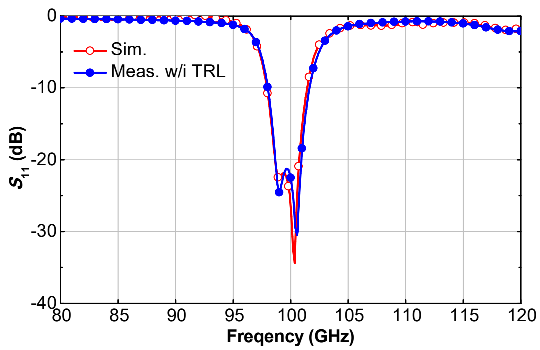

Fig. 6. Simulated and measured S_{11} of the proposed SIW filter.

Table 1. Performance comparison with prior works.

Ref.	Tech./Type	f_0 (GHz)	FBW (%)	*IL* (dB)	Size* (mm^2)	Size (λ_0^2)
[3]	Quartz/CPW	97	10	2.5	~1	0.105
[4]	GaAs/CPW	94	11.7	2.5	0.9	0.088
[5]	GaAs/SIW	93	2.4	4.8	~2	0.192
[6]	GaAs/SIW	93	3.4	4.3	~7.26	0.699
[11]	Si-BCB/SIW	101.5	11.8	4.6	>5.56	0.637
This work	GaAs/SIW	100	5.1	1.89	1.48	0.165

*size: core area only

III. Experimental Results and Discussion

Fig. 4 shows the chip micrograph of the proposed SIW cavity BPF using GaAs-based IPD technology with a core size of 1.06 mm × 1.4 mm. On-wafer measurements were performed by a Keysight N5227B PNA microwave network analyzer with two Keysight N5293AX03 frequency extenders for the frequency range up to 120 GHz. The TRL calibration was conducted before the *S*-parameters measurements to remove the parasitic of the GSG pad with a 250-μm feeding line on both sides. The reference planes are shifted as indicated in the figure. Fig. 5 shows the simulated and measured *IL*. An excellent agreement can be observed, where the minimum *IL* is only -1.89 dB in the passband. The transmission zero contributed by the aperture coupling locates at 109.5 GHz with an attenuation of 42.1 dB which offers an excellent frequency selectivity. The 3-dB bandwidth is 5.1 GHz (97.4–102.5GHz) with a center frequency (f_0) of 100 GHz. The measured return loss is better than 20 dB within the passband as shown in Fig 6.

The measured results are compared with the previously published W-band chip BPFs as listed in Table 1. The proposed BPF shows the lowest *IL* with a relatively small FBW. Note that [3] and [4] achieved the smaller FBW < 3.5% but sacrificed the *IL* in the passband. It should be emphasized that the proposed BPF achieves the smallest size among the SIW-based BPFs [5], [6], and [11] listed in Table 1.

IV. Conclusion

A W-band miniature SIW cavity bandpass filter with a low insertion loss has been demonstrated in GaAs-based IPD technology. By using two side-by-side SIW cavities with a coupling aperture, the resonance of cavities can determine the center frequency at 100 GHz, and a transmission zero can be created by the aperture to obtain the desired bandwidth and out-band roll-off skirt. Based on the measurements, a minimum insertion loss of 1.89 dB with a 3-dB FBW of 5.1 % can be obtained. Compared with previously reported SIW chip BPFs in a similar frequency range, the proposed filter demonstrated the lowest insertion loss with a very compact size of only 1.48 mm^2.

Acknowledgment

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References

[1] C. A. Leal-Sevillano, J. R. Montejo-Garai, J. A. Ruiz-Cruz, and J. M. Rebollar, "Low-loss elliptical response filter at 100 GHz," *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 9, pp. 459–461, Sep. 2012.Waveguide

[2] X. Liao, L. Wan, Y. Yin, and Y. Zhang, "W-band low-loss bandpass filter using rectangular resonant cavities," *IET Microw., Antennas Propag.*, vol. 8, no. 15, pp. 1440–1444, Jul. 2014

[3] F. Aryanfar and K. Sarabandi, "Characterization of semilumped CPW elements for millimeter-wave filter design," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 4, pp. 1288–1293, Apr. 2005.

[4] H. J. Kwon, S. W. Moon, D. An, M. K. Lee, S. J. Lee, B. C. Jun, H. C. Park, and J. K. Rhee, "94 GHz CPW branch-line bandpass filter for planar integrated millimeter-wave circuits," in *Proc. Asia–Pacific Microw. Conf.*, Dec. 2006, pp. 1565–1568.

[5] Z. Xu, D. Zhang, G. Zhao and H. Sun, "A W-band SIW filter based on 90 nm GaAs MMIC technology," in *Proc. Asia-Pacific Conf. on Antennas and Propag.*, 2017, pp. 1–3.

[6] Y. Xiao, P. Shan, Y. Zhao, H. Sun, and F. Yang, "Design of a W-band GaAs-based SIW chip filter using higher order mode resonances," *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 2, pp. 104–106, Feb. 2019.

[7] D. Deslandes and K. Wu, "Single-substrate integration technique of planar circuits and waveguide filters," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 2, pp. 593–596, Feb. 2003.

[8] T.-Y. Chiu and C.-H. Li, "Low-loss low-cost substrate-integrated waveguide and filter in GaAs IPD technology for terahertz applications," *IEEE Access*, vol. 9, pp. 86346–86357, 2021

[9] D. M. Pozar, *Microwave Engineering*, 4th Ed., Wiley, 2012.

[10] Y. Cassivi, L. Perregrini, P. Arcioni, M. Bressan, K. Wu, and G. Conciauro, "Dispersion characteristics of substrate integrated rectangular waveguide," *IEEE Microw. Wireless Compon. Lett.*, vol. 12, pp. 333–335, Sep. 2002.

[11] J. Corsi et al., "A Millimeter-Wave Substrate Integrated Waveguide Filter in Si-BCB Technology," in *Proc. Eur. Microw. Conf*, 2022, pp. 849–852