380 GHz Sub-Harmonically Pumped Mixer Based on Anti-Parallel Planar Schottky Diode

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Abstract—This paper presents the design and fabrication of a feed horn antenna integrated fix-tuned 380 GHz sub-harmonically pumped mixer, based on planar GaAs air-bridged Schottky anti-parallel diode from Rutherford Appleton Laboratory. The diode was designed and fabricated by millimeter technology group, Rutherford Appleton Laboratory, UK. The mixer's circuit configuration and cavity block are realized by joint simulation of ANSOFT's three-dimensional full-wave electromagnetic simulation software HFSS and AGILENT's circuit simulation software ADS. The mixer circuit is fully integrated with the microstrip circuit and the flip-chipped diode on suspended 50 μm thick quartz substrate, and whole fixed-tuned mixer cavity block is integrated with RF feed horn antenna, using least parts to minimize the cost, as well as maximize its potential convenience for circuit and block manufacture. The simulation and test investigation have good agreement and show state-of-the-art results. The experimental results show that over an IF band of 2.5–3.5 GHz, the mixer's conversion loss is lower than 10 dB with mean value 9 dB, and the mixer's equivalent noise temperature is less than 3000 K with mean value 2000 K. Besides, mixer equivalent noise temperature curve's variation trends show good consistency with conversion loss curve.

1. INTRODUCTION

Terahertz (THz) technology is a new research area which has been developed rapidly during last two decades. This topic involves electromagnetism, optoelectronics [1], optics, semiconductor physics [2], materials science, biology, medical science, etc. THz covers wideband electromagnetic radiation area from 100 GHz to 10 THz, and its ends connect to the microwave/millimeter wave and infrared/visible light, respectively. Owing to the long-term lack of effective THz sources and detection methods, THz application technologies make almost no development. This deficiency phenomenon of THz application technology is called 'THz gap' in the electromagnetic spectrum. Among various THz applications systems, important and also the first problem that we should solve is how to realize THz signal down-transformation, which requires THz receiver front-end. Sub-harmonically pumped (SHP) mixers employing an anti-parallel diode pair are key components for millimeter and sub-millimeter wave heterodyne receivers [3–5]. A few kinds of different diode based mixers have been demonstrated at THz frequencies. Among variety THz mixers, only the Schottky diode based mixer can work at room temperature, free from harsh low-temperature environment and usually using liquid helium to achieve.

When THz wave propagates in the atmosphere, there will be certain attenuation due to resonance with gas molecules, thus forming THz atmospheric attenuation characteristics. Between the atmosphere THz wave absorption lines, there are some relatively minor atmospheric absorption bands, and these minimum value attenuation peaks are called transparent window regions (atmospheric window) [6, 7]. In the millimeter/THz band, several atmospheric windows distribute at the center frequencies of 118 GHz,

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140 GHz, 183 GHz, 225 GHz, 380 GHz, 425 GHz, etc., and the relative bandwidth reaches about 20%, even 70% [8]. These bands will make great potential applications in THz atmosphere transmission. In this paper, 380 GHz is selected as our sub-harmonic mixer's working frequency.

This paper presents the design of feed horn integrated low-loss fixed-tuned 380 GHz SHP mixer, using least function parts to minimize the cost, as well as maximize its potential for circuit/block manufacture. The mixer's state-of-the-art characteristics are attributed to low parasitic RAL planar GaAs air-bridged Schottky anti-parallel pair diode AP1/G2, low-loss quartz suspended microstrip circuit, and joint modeling simulation of HFSS and ADS.

2. RAL PLANAR SCHOTTKY DIODE

Planar Schottky diode technology was firstly proposed by USA NASA Jet Propulsion Laboratory (JPL), as well as Virginia Diode Inc (VDI). For the past ten years, planar Schottky diode technology has made great progress and developed by a few research institutes. These diode series show good reproducibility of their characteristic parameters and are packaged as flip-chip which makes them easily mounted onto substrate [9, 10].

Rutherford Appleton Laboratory, UK also developed its advanced planar Schottky diode technology. RAL planar GaAs air-bridged Schottky anti-parallel pair diode AP1/G2 physical dimensions are 170 µm × 50 µm × 20 µm (thickness, including 19 µm GaAs substrate). Its scanning electron microscope (SEM) photo and 3D electromagnetic configuration model are shown in Fig. 1. With n-layer doping density $2 \times 10^{17}/\text{cm}^3$, the GaAs anti-parallel air-bridged Schottky diode AP1/G2 key characteristics parameters are shown in Table 1, and the investigation shows that AP1/G2 diode's cut-off frequency can be up to 8 THz.

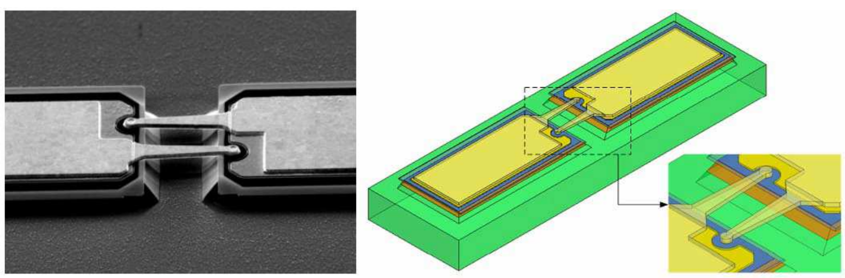
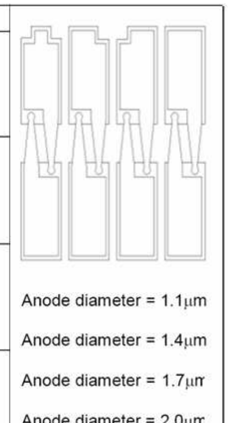


Figure 1. RAL planar GaAs air-bridged Schottky anti-parallel pair diode AP1/G2.

Table 1. GaAs anti-parallel air-bridged Schottky diode AP1/G2 characteristics parameters

Parameter	Symbol	Anode diameter (µm)	Min	Max	Unit	
Series Resistance	R_s	1.1	-	14.0	Ω	
		1.4	-	12.0		
		1.7	-	11.0		
		2.0	-	9.0		
Ideality	η	1.1	-	1.185	-	
		1.4	-	1.185		
		1.7	-	1.185		
		2.0	-	1.185		
Junction Capacitance (Calculated)	C_{JO}	1.1	1.42		$\times 10^{-15}$ F	
		1.4	2.29			
		1.7	3.38			
		2.0	4.68			
Saturation Current	I_S	1.1	-	2.5	$\times 10^{-15}$ A	
		1.4	-	3.5		
		1.7	-	5.0		
		2.0	-	6.5		

3. MIXER DESIGN

The circuit topologies used in millimeter and terahertz-wave Schottky mixers can be categorized into three kinds: single-diode mixer, balanced fundamental mixer and sub-harmonically pumped mixer. Among aforementioned mixers, modern millimeter/terahertz SHP mixer firstly proposed by Cohn et al. [11] and Schneider and Snell [12] in early 1970s is usually based on Schottky anti-parallel pair diode. The anti-parallel planar Schottky diode is a key component for SHP mixer, which can generate currents in twice of the LO frequency, further mix with the RF signal, as shown in Fig. 2. The anti-parallel diode pair based sub-harmonic mixer has its key advantage that the local oscillator requirements are easier to meet, because the LO frequency is only half corresponding to the fundamentally pumped mixers [13].

Thanks to the improvement of 3D electromagnetic solvers and nonlinear circuit simulators, fixed-tuned SHP mixers using discrete or integrated planar Schottky diodes have already demonstrated lower conversion loss than traditional mixers using mechanically tunable backshorts [14]. The discrete planar diode can be used for low conversion loss fixed-tuned mixers while providing significant cost reduction, up to 600 GHz [15].

The designed 380 GHz SHP mixer's RF input port connects to the integrated feed horn antenna, and its cavity is realized by a two-way split block, split among the interface of the 50 μm thick quartz substrate (Relative dielectric constant 3.78). As shown in Fig. 3, the anti-parallel diode pair is flip-chipped onto the suspended 50 μm thick quartz substrate in cavity channel, connected with RF/LO relevant circuits. Two step-impedance line low-pass filters are used to block the RF and LO frequency, respectively. The output IF signal will be via a sparkplug-style K Connector with glass bead and sliding contact through the low-pass LO filter. This feed horn antenna integrates suspended low-loss fixed-tuned 380 GHz sub-harmonically pumped mixer's cavity block, and the circuit configuration is shown in Fig. 4.

The performance of the mixer has been unite-simulated using Agilent's ADS and Ansoft's HFSS. Under 190 GHz LO frequency drive to the mixer, simulation results show that over an IF band of 2.5–3.5 GHz, 380 GHz SHP mixer's conversion loss is approximately 9 dB, as shown in Fig. 5.

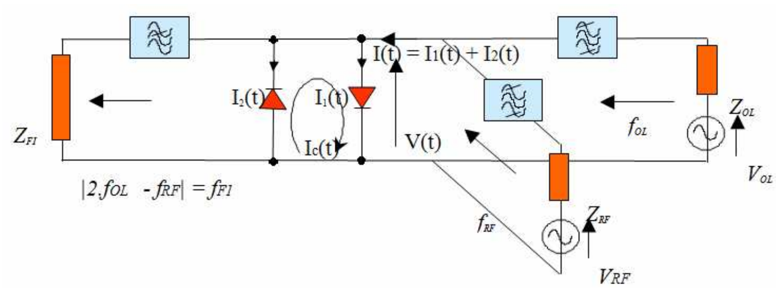


Figure 2. Schematic diagram of anti-parallel Schottky diode based SHM mixer.

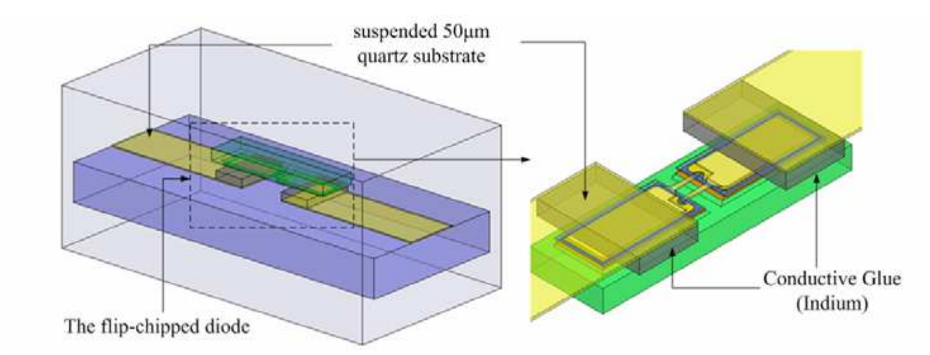


Figure 3. The flip-chipped diode on 50 μm suspended quartz substrate in cavity channel.

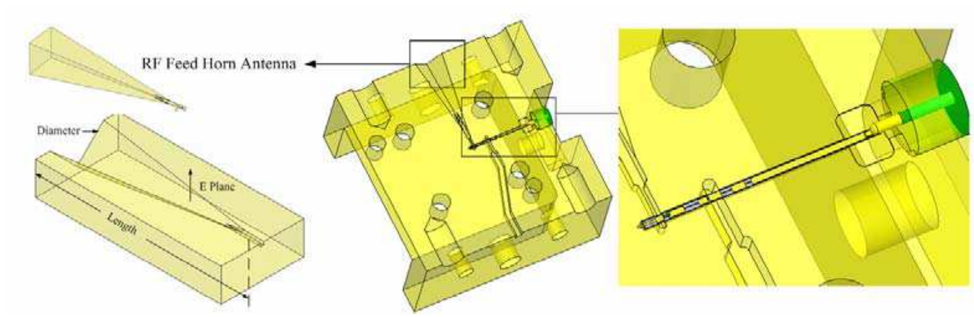


Figure 4. The designed SHP mixer's cavity block and circuit configuration.

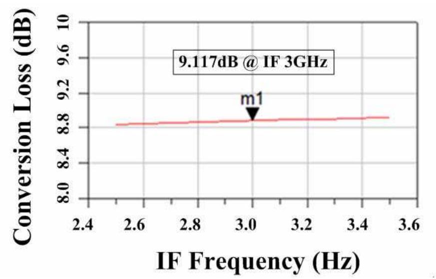


Figure 5. 380 GHz SHP mixer simulation results.

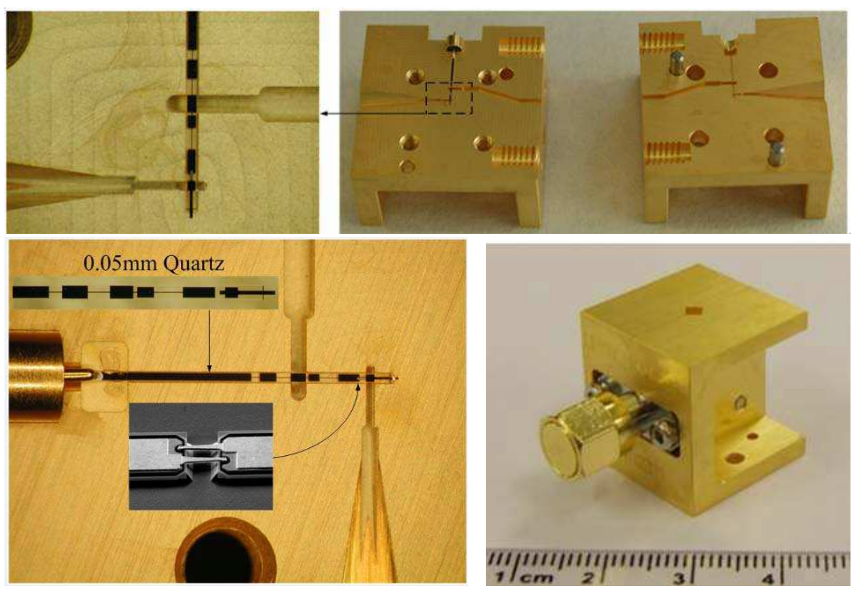


Figure 6. The 380 GHz SHP mixer circuits, split block photos.

4. FABRICATION AND TEST

The mixer cavity and its circuit are fabricated, assembled at millimeter technology group's (MMT) Precision Development Facility, UK Rutherford Appleton Laboratory. The assembled 380 GHz SHP mixer's whole cavity block dimension is 20 mm × 20 mm × 20 mm. The mixer's detailed circuits and split block photos are shown in Fig. 6. Cavity up-side is integrated with rectangular RF feed horn antenna. Down-side is a standard LO input waveguide, and left-side is a sparkplug-style K connector connecting to the output IF signal chain.

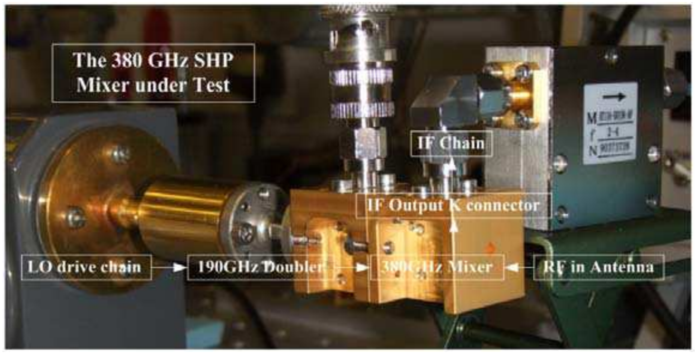


Figure 7. The 380 GHz SHP mixer under test.

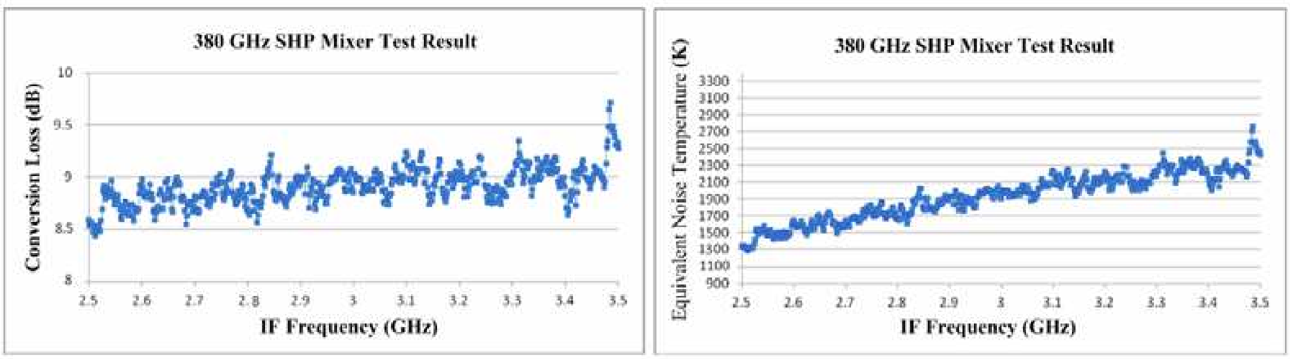


Figure 8. The 380 GHz SHP mixer test results.

The mixer is tested under 4 mW local oscillator drive chain at 190 GHz frequency, and the IF output signal connects to 2.5–3.5 GHz span vector network analyzer. State-of-the-art test results are obtained as shown in Fig. 7. Over an IF band of 2.5–3.5 GHz, the mixer's conversion loss is lower than 10 dB with mean value 9 dB and in good agreement with simulation results. The mixer's equivalent noise temperature is less than 3000 K with mean value 2000 K, and equivalent noise temperature curve's variation trends show good consistency with conversion loss curve, as shown in Fig. 8.

5. CONCLUSION

This paper presents the design of anti-parallel Schottky pair diode based suspended 380 GHz subharmonically pumped mixer. This SHP mixer is designed as a fix-tuned component integrated with RF feed horn antenna. Driving by 4 mW 190 GHz local oscillator chain, over an IF band of 2.5–3.5 GHz, the 380 GHz mixer's mean conversion loss is 9 dB, and the mixer's mean equivalent noise temperature is approximately 2000 K. Experimental and simulated results are in good agreement.

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REFERENCES

1. Nguyen, T. K., T. A. Ho, I. Park, and H. Han, "Full-wavelength dipole antenna on a GaAs membrane covered by a frequency selective surface for a terahertz photomixer," *Progress In Electromagnetics Research*, Vol. 131, 441–455, 2012.
2. Huang, Y., L.-S. Wu, M. Tang, and J. Mao, "High-performance resonator based on single-walled carbon nanotube bundle for THz application," *Journal of Electromagnetic Waves and Applications*, Vol. 28, No. 3, 316–325, 2014.
3. Wei, H.-C., C.-L. Hsiao, and R.-M. Weng, "A broadband low power high isolation double-balanced subharmonic mixer for 4G applications," *Progress In Electromagnetics Research*, Vol. 138, 143–155, 2013.
4. Zhang, B., Y. Fan, Z. Chen, X. F. Yang, and F. Q. Zhong, "An improved 110–130-GHZ fix-tuned subharmonic mixer with compact microstrip resonant cell structure," *Journal of Electromagnetic Waves and Applications*, Vol. 25, Nos. 2–3, 411–420, 2011.
5. Hotopan, G. R., S. Ver-Hoeye, C. Vazquez-Antuna, A. Hadarig, R. Camblor-Diaz, M. Fernandez-Garcia, and F. Las Heras Andres, "Millimeter wave subharmonic mixer implementation using graphene film coating," *Progress In Electromagnetics Research*, Vol. 140, 781–794, 2013.
6. Burch, D. E., D. A. Gryvnak, and R. R. Patty, "Absorption of infrared radiation by CO_2 and H_2O experimental technologies," *Journal of Opt. Soc. Amer.*, Vol. 57, 885–895, 1967.
7. Yuan, T., H. B. Liu, J. Z. Xu, et al., "Terahertz domain spectroscopy of the atmosphere with different humidity," *Proc. SPIE.*, Vol. 5070, 28–37, 2003.
8. Crowe, T. W., W. L. Bishop, and D. W. Porterfield, "Opening the terahertz window with integrated diode circuits," *IEEE Journal of Solid-State Circuits*, Vol. 40, No. 10, 2104–2110, 2005.
9. Carlson, E. R., M.V. Schnider, and T. F. McMaster, "Subharmonically pumped millimeter-wave mixers," *IEEE Trans. Microwave Theory Tech.*, Vol. 26, No. 10, 706–715, 1978.
10. Thomas, B., A. Maestrini, and G. Beaudin, "A low-noise fixed-tuned 300–360-GHz sub-harmonic mixer using planar Schottky diodes," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 12, 865–867, 2005.
11. Cohn, M., J. E. Degenford, and B. A. Newman, "Harmonic mixing with an antiparallel diode pair," *IEEE Trans. Microwave Theory Tech.*, Vol. 23, No. 8, 667–673, 1975.
12. Schneider, M. V. and W. W. Snell, "Harmonically pumped stripline down-converter," *4th European Microwave Conference*, 599–603, 1974.
13. Marsh, S., B. Alderman, D. Matheson, and P. de Maagt, "Design of low-cost 183 GHz subharmonic mixers for commercial applications," *IET Circuits Devices Syst.*, Vol. 1, No. 1, 1–6, 2007.
14. Hesler, J., W. R. Hall, T.W. Crowe, R. M. Weikle, B. S. Deaver, Jr., R. F. Bradley, and S. K. Pan, "Fixed-tuned submillimeter wavelength waveguide mixers using planar Schottky-barrier diodes," *IEEE Trans. on Microwave Theory Tech.*, Vol. 45, No. 5, 653–658, 1997.
15. Poterfield, D., J. Hesler, T. W. Crowe, W. Bishop, and D. Woolard, "Integrated terahertz transmit/receive modules," *Proc. 33rd Euro. Microwave Conf.*, 1319–1322, Munich, Germany, 2003.