Terahertz Sideband Generator Array on Extended Silicon Dielectric Lens

Haiyong Xu, *Member IEEE*, Sami H. Hawasli, *Member IEEE*, Lei Liu, Member IEEE, Jeffrey L. Hesler, *Member IEEE* and Robert M. Weikle, II, *Senior Member*, *IEEE*

***Abstract*— Terahertz Sideband generator (SBG) array on an extended Silicon (Si) hemisphere lens has been investigated in this paper. High power handling capacity is achieved compared with single varactor waveguide design. The SBG array is fabricated on a GaAs substrate. The unit cell dimension is determined to be 40 µm × 40 µm with considering of only single Transverse Electromagnetic (TEM) mode propagation. Schottky planar varactor diode parameters have been chosen to match the optimized embedding impedance. The simulated diode anode diameter is 1 µm, and the finger length is 14 µm.**

***Index Terms*— Schottky diode frequency converters, lens antennas, submillimeter wave devices, submillimeter wave generation.**

I. Introduction

SIDEBAND generators have been investigated for many years to produce tunable high frequency signals, that have wide applications in scale radar range systems and molecular spectroscopy [1]. State-of-the-art performance, more than 55 µW, has been achieved using single whisker-contact diode waveguide-based SBG's at 1.6 THz [2]. To improve the robustness and reliability, planar varactor circuit waveguide based SBG's are investigated with an output power of 40 µW [3]. Nowadays the Far-Infrared (FIR) laser can produce a fixed 184 µm spectrum line (1.63 THz) with more than 147 mW power and 118 µm line (2.52 THz) with 143 mW, such as Coherent SIFIR-50 system [4], which exceeded a single varactor SBG power handling capability (approximately 10 mW at 1.6 THz). However, it is difficult to explore multi-diode topologies using waveguide-based SBG's over 1 THz due to limited space and assembling challenges. To address these problems, an integrated planar array, which is easy to assemble and has high power handling capacity, is investigated in this paper. This array is placed on a high-resistivity Si substrate lens, leading to high gain patterns and high Gaussian coupling efficiency [5] [6]. The layout of the 1.6 THz SBG array assembled on an extended Si substrate lens is shown in Fig. 1. A movable mirror acts as a tunable backshort to optimize the embedding impedance. The SBG array is fed by a coplanar-waveguide (CPW) transmission-line (Tline) as shown in Fig. 2. This SBG array contains 16 planar Schottky diodes fabricated on a GaAs substrate. The IF microwave signal and DC bias are fed into the array through the CPW Tline.

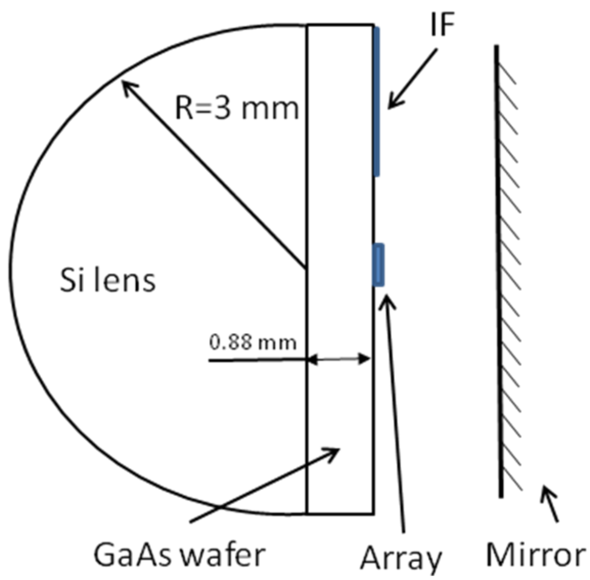

Fig. 1. SBG array assembled on an extended silicon substrate dielectric lens. Movable mirror acts as a backshort to tune the embedding impedance.

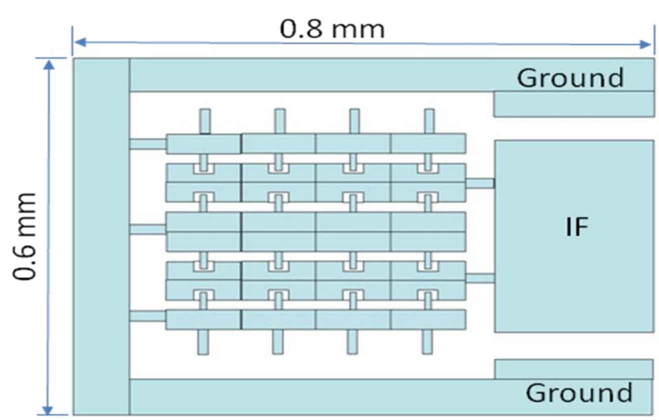

Fig. 2. The layout of SBG array consisting of 16 elements. CPW Tline is used to feed the array. The unit cell dimension is 40 µm × 40 µm.

Manuscript received 17 April 2009. This work was supported by the U.S. Army National Ground Intelligence Center (NGIC) under contract W911W5-06-R-0001.

Haiyong Xu, Sami H. Hasasli, Lei Liu and Robert M. Weikle, II are with the Charles L. Brown Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, (phone: 434-924-6575, e-mail: hx4g@virginia.edu)

J. L. Hesler is with the Virginia Diodes, Inc., 979 2nd Street NE, Suite 309, Charlottesville, VA 22903, USA.

II. SBG Design and Simulation

SBG using a single varactor diode is first simulated in Agilent's Advanced Design System (ADS) software. An equivalent circuit model is shown in Fig. 3. The varactor junction is modeled by a junction capacitor C_j, a series resistor R_s, a finger inductor L_{fg}, a finger to pad capacitor C_{fp} and a pad to pad capacitor C_{pp}. The initial design goal is to determine the varactor parameters required to produce a low loss and 180° phase shift, which means low SBG conversion loss [7]. To achieve the largest phase modulation, the junction capacitance is initially set to resonate with the finger inductance at the frequency of interest. This results in a short circuit and a reflection coefficient phase of 180 degrees. Off-resonance, the resonance circuit should present as large an impedance as possible to approximate an open circuit. Furthermore, the SBG embedding impedances from the diode junction are simulated for different anode sizes. For 1 μm diameter anode, the zero bias junction capacitance is estimated at 1.6 fF, while the series resistance is approximately 20 Ω. The optimized embedding impedance is found to be, Zem=46+j100 Ω at 1.6 THz, as shown in Fig. 4. The corresponding conversion loss is less than 9 dB. Based on the ADS simulated results, the circuit physical parameters are obtained and modeled in the Ansoft's High Frequency Structure Simulator (HFSS) software, which will accurately take all the parasitic parameters into account [3].

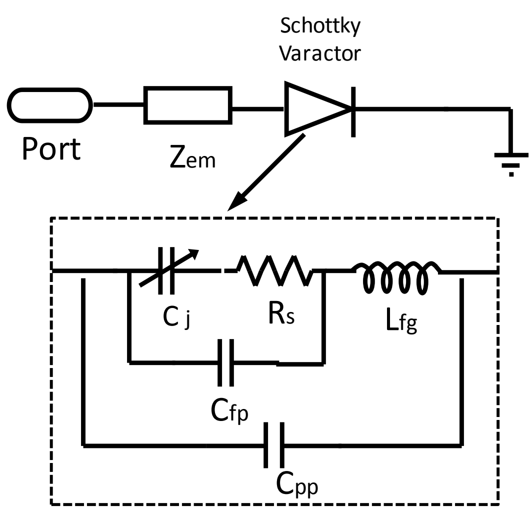

Fig. 3. Single planar Schottky varactor SBG equivalent circuit model. The varactor is modeled by finger inductance, junction capacitance, series resistance and parasitic capacitance

III. Waveguide SBG at 1.6 THz

Based on the simulation, a waveguide based SBG is designed, fabricated and measured. The integrated circuit includes a waveguide to microstrip transition, a planar varactor diode and a microstrip low pass filter, which is fabricated on a quartz substrate. A photograph of an integrated SBG circuit in a metal block is shown in Fig. 5. The integrated circuit width is 50 μm, and the thickness is 10 μm. The waveguide-to-microstrip transition is used to couple the LO power into the diode channel and sidebands (RF) back into the waveguide. The microwave IF signal is applied to pump the diode, while a low-pass microstrip filter integrated with the diode is used to resonate with the varactor and block the RF signal. After the assembling, the conversion loss measurement is conducted using one laser setup system. The output of laser beam is split into 2 parts. One part is used to pump the receiver mixer as a LO source. The other beam provides the RF carrier to the SBG. The output sidebands are reflected by a silicon etalon, which passes 99 % of the carrier laser power and reflects 80% of the sidebands. The sidebands are directed through a beam splitter by two mirrors to the mixer as the RF input signal. Finally, the mixer IF output is measured by a spectrum analyzer, which is the sideband power. After the path losses of the receiver system are calibrated, the SBG conversion loss is obtained and shown in Fig. 6.

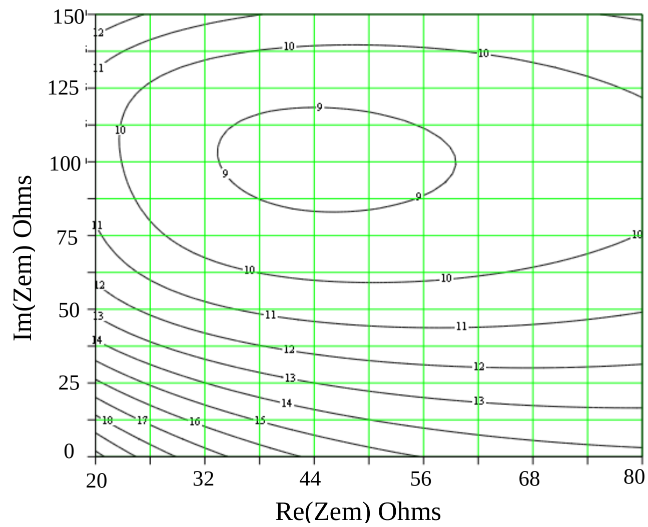

Fig. 4. ADS Simulated conversion loss corresponding to different embedding impedances for 1 μm diameter anode.

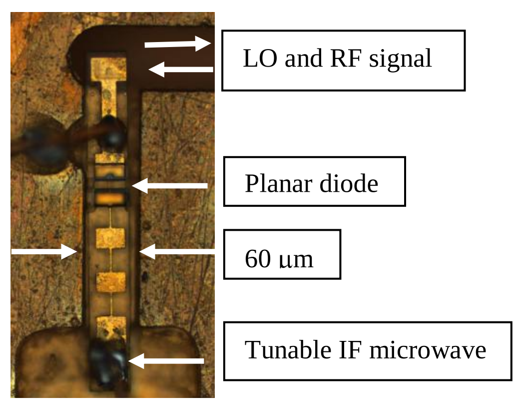

Fig. 5. Photograph of 1.6 THz integrated SBG circuit mounted in an open metal block. The circuit channel width is 60 μm. The varactor is pumped by a tunable IF microwave signal. The output RF signal will be LO +/- IF.

IV. Array Design

After the single varactor SBG measurement, the array is designed to achieve better power handling capacities. The Si lens diameter is first determined by balancing the Gaussicity and directivity [5]. At 1.56 THz, the free space wavelength, λ_0, is approximate 0.19 mm. The hemispherical lens radius is chosen to be 3 mm, which will give the R/λ_0 ratio 15.8, where R is the radius of the lens. The extension of the hyperhemispherical lens is initially set to be R/n=0.88 mm, where n is the index of refraction of the lens, and the Si dielectric constant, ε_r, is 11.7.

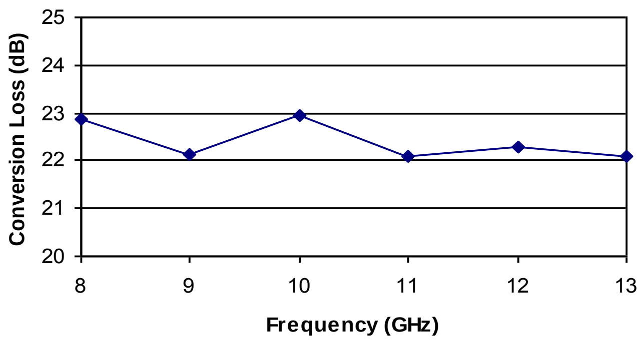

Fig. 6. Measured conversion loss of a signal varactor waveguide based SBG using a 1.6 THz FIR laser system.

An equivalent unit cell of the array is simulated with HFSS as shown in Fig. 7. Electric wall (E-wall) and magnetic wall (H-wall) planes are defined based on the array symmetry [8]. The two walls along the diode finger are H-walls, while the other two walls are E-walls. To avoid the higher order waveguide modes, the unit cell dimension must be less than a certain value. Based on the HFSS simulation, the unit cell dimensions are determined to be 70 µm × 70 µm for quartz substrate, while the unit cell dimensions for Si substrate will drop to approximately 40 µm × 40 µm. Ansoft's HFSS is used to optimized the diode parameters to match the best conversion loss as shown in Fig. 4. The varactor anode diameter is determined to be 1 µm, and the finger length is 14 µm, taking into account practical limitations on diode fabrication.

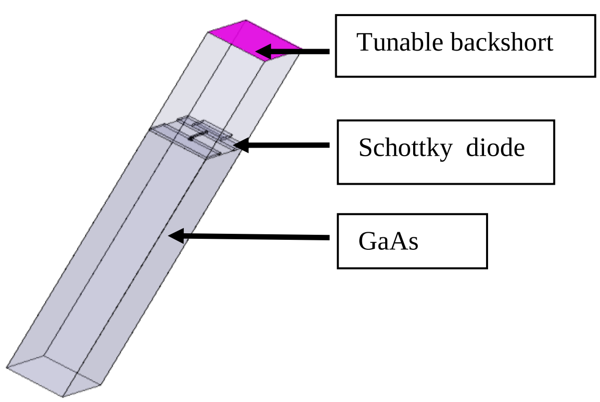

Fig. 7. An equivalent unit cell of SBG array using GaAs substrate. A mirror is used as a tunable backshort. E-walls are defined at two waveguide walls at the end of the diode, while H-walls are the two side waveguide walls parallel along diode finger. The array unit cell dimension is 40 µm × 40 µm.

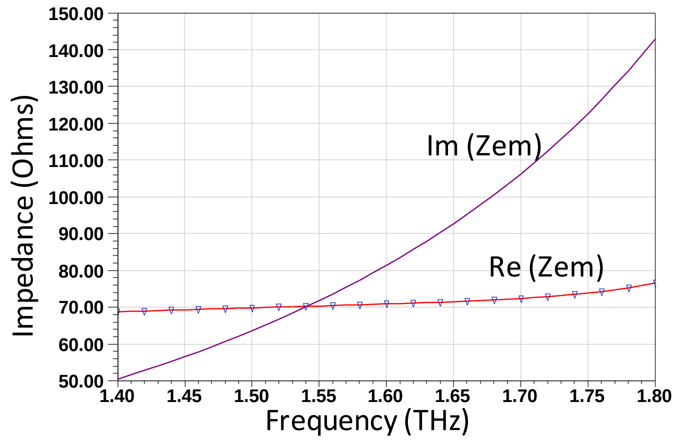

Fig. 8. Simulated embedding impedance of a unit cell. The diode anode size is 1 um, and the finger length is 14 µm.

The simulated embedding impedance versus frequency is shown in Fig. 8. The simulated embedding impedance is 70+j72 Ohms at 1.56 THz, which is expected to give a 10 dB conversion loss. This conversion loss doesn't account for circuit reflection and dielectric losses. Furthermore, the Gaussian beam coupling is calculated. The Gaussian laser beam is coupled into the array by an off-axis parabolic mirror with focus length 60 mm. To optimize coupling to the beam, the array is populated with 4 × 4 elements, and the array size will be 0.16 mm × 0.16 mm. The distance between the laser beam waist and the parabolic mirror is determined to 1.7 m, while the distance from the mirror to the Si lens is 61 mm.

V. CONCLUSION

A 1.6 THz SBG array with 16 elements on an extended silicon dielectric lens is investigated. Planar varactor diode parameters have been optimized to match the impedance, giving by a conversion loss contour map. The simulated SBG conversion loss is approximate 10 dB without considering of reflection and dielectric losses.

ACKNOWLEDGMENT

The authors would like to thank Dr. Zhiyang Liu from Tyco Electronics, Dr. Acar Isin and Dr. Bascom Deaver from Dept. of Physics, Univ. of Virginia, for their helpful discussion.

REFERENCES

[1] P. H. Siegel, "THz technology," in *IEEE Trans. Microwave Theory and Techniques*, vol. 50, no. 3, pp. 910-928, March, 2002.

[2] D. S. Kurtz, J. L. Hesler, T. W. Crowe and R. M. Weikle, "Submillimeter-wave sideband generation using varactor Schottky diodes," in *IEEE Trans. Microwave Theory and Techniques*, vol. 50, no. 11, pp. 2610-2617, Nov, 2002.

[3] H. Xu, G. S. Schoenthal, J. L. Hesler, T. W. Crowe and R. M. Weikle, "Nonohmic contact planar varactor frequency upconverters for terahertz applications," in *IEEE Trans. Microwave Theory and Techniques*, vol. 55, no. 4, pp. 648-655, April, 2007.

[4] Coherent Inc. web site, http://www.coherent.com/Lasers/index.cfm?fuseaction=show.page&id=779&loc=834

[5] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," in

IEEE Trans. Microwave Theory and Techniques, vol. 41, pp. 1738-1749, Oct., 1993.
[6] S. S. Gearhart and G. M. Rebeiz, "A monolithic 250 GHz Schottky-Diode Receiver," *IEEE Trans. Microwave Theory and Techniques,* vol. 42, no. 12, pp. 2504-2511, Dec., 1994.
[7] S. Kurtz, J. L. Hesler, T. W. Crowe and R. M. Weikle, "Submillimeter-wave sideband generation using varactor Schottky diodes", IEEE Trans. On Microwave Theory and Techniques, vol. 50, no. 11, pp. 2610-2617, Nov., 2002
[8] R. M. Weikle, "Quasi-Optical Planar Grids for Microwave and Millimeter-Wave Power," Dissertation California Institute of Technology, March, 1992.