A Heterostructure Barrier Varactor Sideband Generator

Haiyong Xu, Jeffrey L. Hesler, Yiwei Duan, Thomas W. Crowe, Robert M. Weikle, II

University of Virginia, Charlottesville, VA, 22904, USA

Department of Electrical and Computer Engineering

Abstract — **A heterostructure barrier varactor (HBV) sideband generator (SBG) is investigated for the first time. Compared with Schottky varactor SBG's, odd sidebands are suppressed and higher output power is possible. Preliminary measurements at 200 GHz have shown conversion efficiencies of 10-15 dB over a 10 GHz tuning range. Simulations and theoretical models are presented to predict and confirm these results. The subharmonic SBG design described in this paper is scaleable to submillimeter wavelengths and can yield a highly tunable CW power source when used in conjunction with a fix-tuned laser.**

I. INTRODUCTION

The heterostructure barrier varactor (HBV) was first proposed in 1989 [1] and is currently used for a variety of applications, including frequency multiplication at millimeter and submillimeter wavelengths [2]-[4]. This device is also promising for other high frequency applications, such as sideband generation [5]. The HBV exhibits a symmetric capacitance-voltage characteristic with a relatively high modulation ratio and power handling capacity [3]. These properties make the device well-suited for subharmonic parametric sideband generation.

To date, the best performance obtained from a sideband generator at submillimeter wavelengths employed a whisker-contacted varactor diode operating at 1.6 THz [6]. The conversion loss of this device was measured to be 14 dB with an output power of 55 μW. In this paper, a new type of SBG is investigated that consists of a flip-chip mounted HBV device. The symmetric capacitance-voltage (C-V) characteristic suppresses odd harmonics, permitting sideband generation at frequencies of $2f_p + f_m$, where f_p is the pump frequency and f_m is the frequency of the carrier signal. The HBV SBG can achieve high power handling capacity by epitaxial stacking of barriers. This results in higher breakdown voltages and allows the generation of higher levels of sideband power. In this paper, the operating principles, modeling, design, and measurements of a prototype HBV sideband generator operating at 200 GHz are presented and discussed.

II. BASIC THEORY AND SBG ARCHITECTURE

Sideband generators (SBG's) produce high-frequency tunable sidebands by mixing a fixed high-frequency source with a tunable microwave oscillator. In principle, the pump signal that modulates the SBG's impedance may be at either a high (submillimeter) or low (microwave) frequency. However, high-power pump sources are easier to obtain in the microwave region and low conversion loss can be achieved with microwave pumping [7]. In fact, with all sideband frequencies terminated in matched loads, a carrier-to-sideband conversion loss of 3.94 dB can be obtained by modulating the SBG impedance between an open and short circuit with 50% duty cycle [6].

Figure 1 shows a photograph of the prototype 200 GHz flip-chip mounted HBV SBG investigated in this work. The carrier to be modulated is applied through a rectangular waveguide and a waveguide-to-microstrip transition couples the carrier signal from the waveguide to the HBV. The sidebands generated by the pumped HBV are reflected back to the waveguide. The microwave pump signal is applied to the HBV through a microstrip low-pass filter. The pump signal modulates the HBV impedance and, consequently, the phase of the reflected carrier.

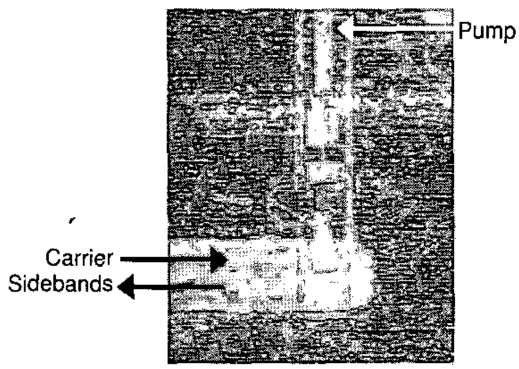

Fig. 1. The photograph of 200 GHz SBG open block

The SBG circuit was fabricated on a fused-quartz substrate and mounted into a microstrip channel of the waveguide block. An HBV chip was soldered to the

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circuit. The microstrip low-pass filter through which the microwave pump is used to resonate the capacitance presented by the varactor and thereby produce a phase modulation near 180°.

III. HBV SBG DESIGN AND SIMULATION

An equivalent circuit model for the HBV sideband generator is shown in fig. 2. The HBV is modeled by a junction capacitance C_j, a series resistance R_s, a finger inductance L_{fg}, a finger to pad capacitance C_{fp} and pad to pad capacitance C_{pp}. The main design goal is to determine the varactor parameters and load impedance required to produce a full 180° phase modulation. To achieve this phase modulation, the junction capacitance should resonate with the finger inductance at the frequency of interest. This results in a short circuit and a reflection coefficient phase of 180°. Off-resonance, the HBV should present as large an impedance as possible to approximate an open circuit.

The HBV's used in this project were fabricated in the University of Virginia Semiconductor Device Laboratory. The two layer physical parameters of these devices are given in table 1. For this prototype SBG, a two layer HBV chip is used. A scanning electron micrograph of one of the HBV chips before dicing is shown in fig. 3.

To obtain an optimized SBG conversion loss, the following design steps are followed:

1. The chip C-V curves are measured. An example is shown in fig. 4. As seen in the figure, the capacitance-voltage characteristic is highly symmetric.
2. Ansoft's High Frequency Structure Simulator (HFSS) is used to simulate the entire structure as shown in fig. 5. In this simulation, ohmic losses are neglected. Coaxial ports (ports 3 and 4 in fig. 5) are used at the varactor anode junction, as described in [8]. Using this technique, all of the varactor parasitic parameters including the filter circuit are taken into account. However, the nonlinear junction cannot be simulated since it varies with the pumping voltage. The four-port *s*-parameter set is exported into a data file for use in nonlinear circuit design software.
3. A 4-port network in Agilent's Advanced Design System (ADS) software is used to simulate the entire circuit, including the HBV. The reflection coefficient at the waveguide port is simulated with the coaxial ports (port 3 and 4) joined by a series resistor and junction capacitor [3]. The measured C-V relation is used to model the junction capacitance. The overall simulation of S_{11} is plotted in fig. 6.

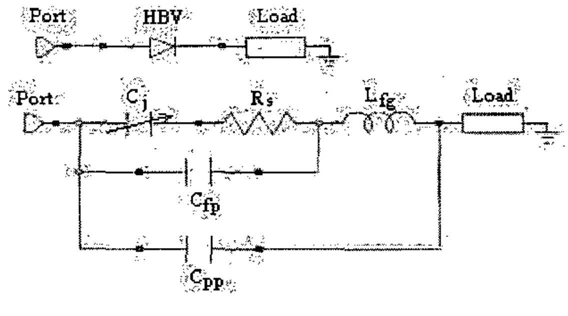

Fig. 2. Equivalent circuit of the sideband generator

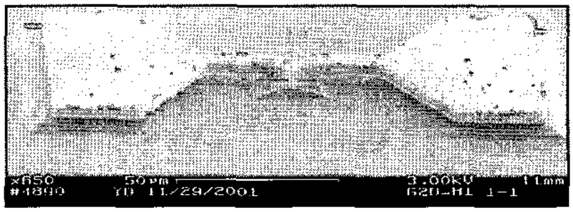

Fig. 3. The SEM photo of an HBV chip

TABLE 1

HBV EPITAXIAL LAYER CHARACTERISTICS

Layer	Thickness	Doping	Material
n^{++} contact	10 nm	n^{++}	InAs
n^{++} contact	40 nm	n^{++}	$In_xGa_{1-x}As$
n^{++} contact	100 nm	n^{++}	$In_{0.53}Ga_{0.47}As$
modulation	300 nm	10^{17} cm^{-3}	$In_{0.53}Ga_{0.47}As$
spacer	5 nm	undoped	$In_{0.53}Ga_{0.47}As$
spacer	5 nm	undoped	$In_{0.52}Al_{0.48}As$
barrier	3 nm	undoped	AlAs
spacer	5 nm	undoped	$In_{0.52}Al_{0.48}As$
spacer	5nm	undoped	$In_{0.53}Ga_{0.47}As$
modulation	300 nm	10^{17} cm^{-3}	$In_{0.53}Ga_{0.47}As$
spacer	5 nm	undoped	$In_{0.53}Ga_{0.47}As$
spacer	5 nm	undoped	$In_{0.52}Al_{0.48}As$
barrier	3 nm	undoped	AlAs
spacer	5 nm	undoped	$In_{0.52}Al_{0.48}As$
spacer	5nm	undoped	$In_{0.53}Ga_{0.47}As$
modulation	300 nm	10^{17} cm^{-3}	$In_{0.53}Ga_{0.47}As$
n^{++} buffer	3 μm	n^{++}	$In_{0.53}Ga_{0.47}As$
substrate		semi-insulating	InP

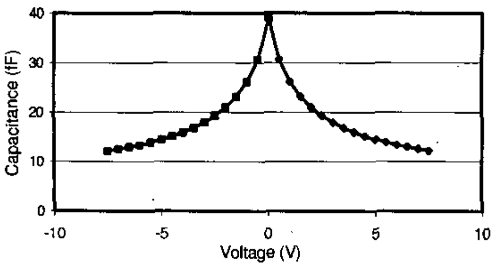

Fig. 4. HBV capacitance characteristics

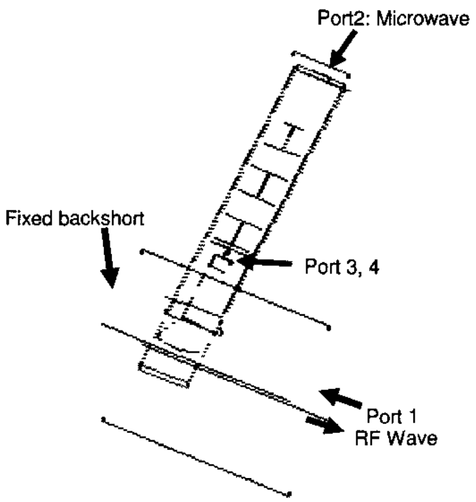

Fig. 5. HFSS simulation structure

IV. Power Handling and Conversion Loss

A microwave source applied through the microstrip low-pass filter provides the pump voltage to modulate the HBV. To achieve the best performance, the pump voltage should be adequate to fully modulate the device. We can relate the microwave pump power to the modulation voltage by noting that the HBV junction capacitance is small and, consequently, can be approximated as an open circuit at the microwave pump frequency.

Epitaxial stacking in an HBV can be used to increase the power handling capacity and permits a lower capacitance to be achieved. For the 2-layer 200 GHz HBV SBG, roughly 110° of phase shift can be achieved with 24 dBm of pumping power, corresponding to a 19.6 V peak to peak voltage swing. The measured S_{11} at 200 GHz corresponding to this microwave pump power is shown in fig. 6. This measurement was performed on an HP 8510C vector network analyzer with external WR-5 extensions (Oleson Microwave, Inc.). The difference between measurement and simulation is likely due to ohmic losses that were neglected in the simulation.

The SBG conversion loss is calculated by assuming this reflection SBG to be a phase-shift-keying (PSK) modulator. The pump signal modulates the junction capacitance and thus the phase of high frequency carrier, $S_1(t) = A \cdot e^{j\omega_c t}$. At the same time, the carrier wave amplitude is also modulated to a lesser extent due to the series resistance, R_s. The complex output wave can be expressed as

$$S(t) = A \cdot e^{jw_c t} \cdot B(t) \cdot e^{j\theta(t)} = A \cdot B(t) \cdot e^{jw_c t + j\theta(t)} \tag{1}$$

where ω_c is the carrier frequency, $B(t)$ and $\theta(t)$ are the reflection coefficient's magnitude and phase. Using Fourier analysis, the sideband conversion loss is calculated to be 13.4 dB based on the measured S_{11}.

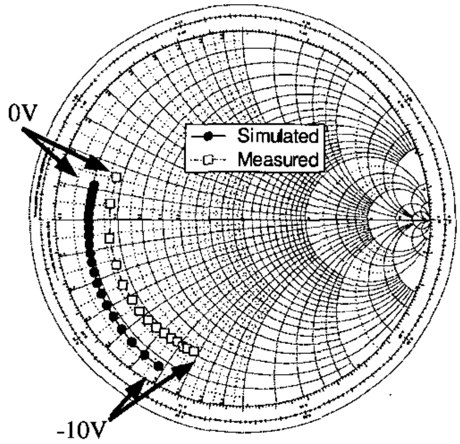

Fig. 6. Measured and modeled reflection coefficient (S_{11}) of the HBV sideband generator.

V. Measurements

The 200 GHz HBV SBG test setup consists of WR-10 and WR-5 waveguides, attenuators and isolators. A synthesizer followed by 2 frequency doublers is used to provide approximately 120 mW power at 100 GHz. After passing through a 100-200 GHz frequency doubler, the 200 GHz carrier power provided to the SBG is more than 20 mW as measured by an Anritsu power meter. A WR-5 isolator is used to reduce the reflected signal. However, the large insertion loss of the WR-5 isolator and WR-5 direction coupler reduce the carrier power at 200 GHz to approximately 1mW. The pump microwave power is fixed at 24 dBm.

The reflected signals, both carrier and sidebands, are fed to a WR-5 directional coupler, and then to a 200 GHz subharmonic mixer. The IF output of the mixer is sent to an Agilent 8565E spectrum analyzer. After calibrating out the mixer losses, the SBG conversion loss is calculated, which is shown in fig. 7. Over 10 GHz of frequency tuning range and an average carrier-to-sideband conversion loss of 13 dB is achieved with 0 dBm input carrier power, which is in agreement with the theoretical value. The spectrum at the mixer IF port (with 0.5 GHz SBG pump signal) is shown in fig. 8. The central peak in the spectrum is the reflected carrier signal. The first upper and lower sidebands are separated by 1 GHz from the carrier, as expected.

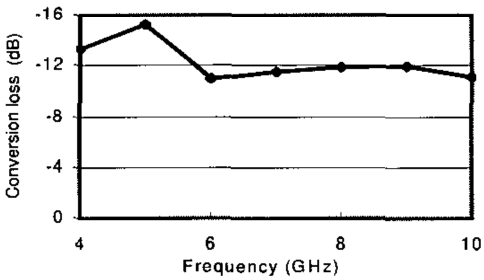

Fig. 7. SBG conversion loss

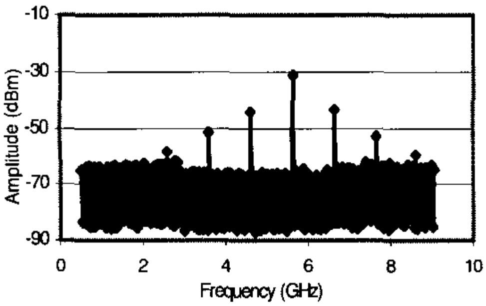

Fig. 8. SBG spectrum with 0.5 GHz IF input

VI. Conclusion

An HBV SBG is investigated for the first time. High power handling capacity is obtained and odd-order sidebands are suppressed. A conversion loss of 10-15 dB is achieved. This proof-of-principle investigation will provide valuable information for the design of submillimeter-wave upconverters based on HBV sideband generation. An optimized HBV SBG fabricated through monolithic integration is expected to give a conversion loss of 10 dB.

Acknowledgement

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