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A Novel HBT Frequency Doubler Design for Millimeter-Wave Applications

Tom K. Johansen, Viktor Krozer, Jens Vidkjær, and Torsten Djurhuus

Abstract—In this paper we present a novel HBT frequency doubler design for millimeter-wave application. HBT frequency doubler theory is described which leads to accurate design equations for improved performance. The developed theory shows that a substantial improvement in the HBT frequency doubler operation can be achieved using a novel second harmonic feedback network. Preliminary measurements on a frequency doubler implemented in a high-speed InP DHBT technology demonstrates an increase in the maximum output power from -14 dBm to -11.5 dBm at an input frequency of 31.4 GHz due to the presence of the second harmonic feedback network. We demonstrate here that the 3 dB improvement in performance is directly due to the feedback mechanism.

Index Terms—Coplanar waveguides (CPWs), InP HBT, millimeter-wave frequency doubler, monolithic microwave integrated circuits (MMICs).

I. INTRODUCTION

FREQUENCY multipliers are important building blocks in LO chains for radar and wireless communication systems. In these applications it is desirable to use oscillators operating at lower frequencies and with higher spectral purity. The conversion gain of passive multipliers has a fundamental limit of $1/n^2$ where $n$ is the frequency multiplication factor [1]. To overcome this limit one can implement frequency multipliers with active devices. Approximate design methodologies exist for FET based multipliers [1]-[2], however these methods are not easily applicable to HBT based frequency multipliers due to the highly nonlinear base-emitter junction.

A millimeter-wave SiGe HBT frequency doubler design based on reactive termination at the second harmonic at the input side and the fundamental at the output side was reported in [3]. A potential problem with this approach is that optimum reactive terminations may let the frequency multiplier operate close to the unstable region [2]. Recently, Ku- and Ka-band balanced configurations of the SiGe HBT frequency doubler with second harmonic reactive termination was reported in [4]. The balanced configuration leads to higher output power but requires a differential oscillator. In [5], a Gilbert-cell based broad-band InP DHBT frequency doubler was reported, but it suffers from excessive power consumption due to the large transistor count.

This paper reports on a HBT frequency doubler design based on a novel second harmonic feedback network. A simplified nonlinear analysis based on the harmonic-balance technique is performed to estimate the optimum excitation for HBT frequency doubler performance. It turns out to be a signal containing a second harmonic component which must be generated by feeding part of the second harmonic output signal back to the input. A millimeter-wave frequency doubler design including the second harmonic feedback network has been implemented in a high-speed InP DHBT technology. Preliminary measurements verifies the benefits of the second harmonic feedback network.

II. FREQUENCY DOUBLER THEORY

A simplified nonlinear model of a HBT frequency doubler with its embedded impedances is shown in Fig. 1. The HBT is driven from a voltage source $V_s(t)$ with source impedance $Z_s(\omega)$ at its base and is terminated at the collector with a load impedance $Z_L(\omega)$. The source impedance is assumed to short-circuit all frequency components except the fundamental while the load impedance short-circuits all frequency components except the second harmonic. Three nonlinearities, the base current $I_b/\beta f$, the collector current $I_c$, and the base-emitter diffusion capacitance $C_d$, are included in the model along with fixed parasitic resistances $R_0$, $R_a$, and $R_c$. The base-emitter depletion capacitance $C_j$ is weakly nonlinear and can be represented by its time-averaged value. Assuming a sinusoidal voltage across the internal base-emitter junction $v_{bei}(t) = V_{bei} + 2V_b \cos(\omega_n t)$, the collector current is represented as

$$I_c = I_e e^{V_{bei}/V_t} e^{2V_b/V_t} \cos(\omega_n t) = I_e h_{fe} \sum_{n=-\infty}^{n=\infty} I_n(x) e^{j\omega_n t}$$

(1)

where $I_n$ represents modified Bessel functions of order $n$ and $x = 2V_b/V_t$ is the normalized drive level [6]. In Fig. 2 the normalized DC and harmonic components of the collector current are shown versus the conduction angle. For a given maximum current rating $I_{\text{MAX}}$, the second harmonic current is maximized at a conduction angle around $180^\circ$ or equivalent.
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TABLE I
ELECTRICAL PARAMETERS FOR THE NONLINEAR INP DHBT MODEL
\((A_e = 10 \times 2.0 \mu m^2)\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_s) [fA]</td>
<td>4.5</td>
<td>(R_c) [(\Omega)]</td>
<td>9.9</td>
</tr>
<tr>
<td>(N_f)</td>
<td>1.13</td>
<td>(\tau_f) [(pS)]</td>
<td>1.7</td>
</tr>
<tr>
<td>(\beta_f)</td>
<td>28.1</td>
<td>(C_{je}) [fF]</td>
<td>20.2</td>
</tr>
<tr>
<td>(R_b) [(\Omega)]</td>
<td>23.0</td>
<td>(C_{bc}) [fF]</td>
<td>20.2</td>
</tr>
<tr>
<td>(R_e) [(\Omega)]</td>
<td>3.0</td>
<td>(X_{cjc})</td>
<td>0.69</td>
</tr>
</tbody>
</table>

\[Z_s(\omega) = 2\omega_{int+}^2 \phi s_2 \cos(2\omega_{v2} + \phi s_2)\]

\[Z_L(\omega) = V_{cc} (t) + Q_1 V_{b0} + 2V_{s1} \cos(\omega_{int+} \phi s_1) \]

\[i_c(t)\]

Fig. 3. Improved excitation scheme for the HBT frequency doubler.

Fig. 4. Collector current waveform calculated with the frequency doubler theory (-) and ADS harmonic balance simulation (-x-).

TABLE II
CALCULATED HARMONIC VOLTAGE COMPONENTS AND INPUT IMPEDANCE FOR AN INP DHBT FREQUENCY DOUBLER \((f_{in} = 41.75\,GHz)\).

<table>
<thead>
<tr>
<th>(V_{bc}) [V]</th>
<th>(2V_{s1} \phi s_1) [V]</th>
<th>(2V_{s2} \phi s_2) [V]</th>
<th>...</th>
<th>(Z_{in}) [(\Omega)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.727</td>
<td>0.216</td>
<td>0.194</td>
<td>...</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Available. The electrical parameters of the nonlinear model for the InP DHBTs used in this work are given in Table. I. The harmonic voltage components and input impedance required for the sinusoidal voltage across the internal base-emitter junction are determined from (6) and (7), extended to include the base-collector capacitance. Fig. 3 illustrates an improved excitation scheme for the HBT frequency doubler. Notice that both the magnitude and phase relation are important for appropriate harmonic voltage component generation across the internal base-emitter junction. Table. II gives the calculated harmonic voltage components and input impedance required for the design of an InP DHBT frequency doubler operating at \(f_{in} = 41.75\,GHz\) and having an optimal normalized sinusoidal drive level of \(x = 4.6\). The base bias voltage is calculated to keep the peak current below \(I_{max} = 20\,mA\). The collector current waveform obtained using this excitation is shown in Fig. 4. A strong second harmonic component is evident in the output collector current waveform. Furthermore, it is observed that the peak value of the collector current is kept slightly below \(I_{max}\). The excellent agreement with ADS\(^2\) harmonic balance simulation verifies that a sinusoidal drive level has indeed been obtained across the internal base-emitter junction. In other words, design equations for improved frequency doubler performance have been obtained.

The second harmonic voltage needed for the excitation determined from design equations must be generated by feeding part of the output signal back to the input. The influence from higher harmonics is not as important and will therefore be ignored. The frequency doubler including the novel second harmonic feedback network is shown in Fig. 5. The parallel tuned circuit assures maximum isolation between input and output of \(Q_1\) for the fundamental frequency signal and presents a pure reactance at the second harmonic. This reactance forms a voltage divider together with the input matching network at the second harmonic. The purpose of \(Q_3\) is to control the amount of feedback. If the control voltage \(V_{cntl}\) is set to zero the second harmonic feedback network is turned off.

Fig. 5. Schematic of frequency doubler including second harmonic feedback network.

ADS\(^2\) 2004A, Agilent Technol Inc., Palo Alto, CA
At the second harmonic frequency the input matching network presents a pure reactance to the base of \( Q_1 \), which is assured by splitting the shunt stub at the input into two parts as shown in Fig. 5. If one of these is \( \lambda / 4 \) long at the fundamental frequency it turns into a short circuit at the second harmonic and is transformed as a pure reactance along the transmission line towards the input of \( Q_1 \). This susceptance adds to the admittance of the short-circuited shunt stub feeding base bias to \( Q_1 \). Stable operation of the HBT frequency doubler is assured by short-circuiting the fundamental frequency component at the output through a \( \lambda / 4 \) long open stub.

IV. EXPERIMENTAL RESULTS

The frequency doubler was fabricated in a high-speed InP/InGaAs DHBT circuit technology developed at the Alcatel-Thales III-V laboratory. The transistors in this technology exhibit 180/210 GHz \( f_t/f_{max} \), breakdown voltage \( B V_{CEO} > 7 \text{V} \) and yield better than 99% [9]. The technology also offers three Au/Ti metallization layers, Ti resistors, and SiN metal-insulator-metal (MIM) capacitors. The photomicrograph of the fabricated frequency doubler is shown in Fig. 6. The chip size with pads is 1.4x1.6 mm\(^2\). Coplanar waveguide (CPW)transmission lines are implemented using ADS momentum or HFSS\(^3\).

Preliminary on-wafer measurements have been performed on the fabricated circuit. The measurement result given here correspond to a substrate height of 350 \( \mu\text{m} \) instead of 120 \( \mu\text{m} \) assumed in the design of the frequency doubler. This has little influence on the performance of the CPW structures, however, the small interconnects around the second harmonic feedback network will behave differently, leading to an overall low conversion gain, and downward shift in frequency. Despite of these complications, the benefits of the second harmonic feedback network is evident in the output power versus control voltage shown in Fig. 7. In this figure a rise in output power of 2.5 dB is observed when the second harmonic feedback network is active. For a properly operating HBT frequency doubler the expected increase in output power is more than 6 dB.

V. CONCLUSION

A nonlinear theory have been developed using the harmonic balance principle which leads to accurate design equations for HBT frequency doublers. Due to the strongly nonlinear base-emitter junction optimal performance for a HBT frequency doubler requires a second harmonic voltage components within its excitation. This second harmonic components must practically be generated by feedback. A HBT frequency doubler including a novel second harmonic feedback network was purposed. The experimental results demonstrated a 2.5 dB increase in second harmonic output power when the second harmonic feedback network was active.

REFERENCES


\(^3\)HFSS v.9, Ansoft Corp., San Jose, CA

Fig. 6. Microphotograph of the feedback frequency doubler. (1.4x1.6 mm\(^2\) with pads).