Process-Dependence of the Even-Order Nonlinearity in Anti-Parallel Diode Pair Mixers
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Abstract—Diode mismatch in an anti-parallel diode mixer can generate a product at the second-harmonic of the local oscillator frequency. This product is referred to as the virtual local oscillator leakage. Variability in the fabrication process results in diode mismatch and is noticeable as an asymmetry in the current-voltage characteristics. Its impact on the virtual local oscillator leakage is analyzed by studying two populations of circuits with different diode sizes, fabricated using a six inch Gallium Arsenide heterojunction bipolar transistor process. Each population contained thirty circuits, within the same quarter-wafer.

Index Terms—Microwave mixers, millimeter wave mixers, mixers.

I. INTRODUCTION

Anti-Parallel Diode Pair (APDP) mixers require the local oscillator (LO) to produce only half the frequency required for mixing. They are a cost-effective alternative at millimeter-wave frequencies, where fundamental oscillators are difficult to implement [1], [2]. An anti-parallel connection results in a current which is an odd-function of the applied voltage. The resulting transfer function contains no even-order terms. As a result an ideal APDP circuit provides an inherent suppression of products at the even-harmonics of the LO frequency. The product at the second-harmonic of the LO frequency is referred to as the virtual LO leakage [3], [4].

However mismatch between the diodes and the resulting current asymmetry can generate even-order nonlinear terms in the current-voltage characteristic. These even-order nonlinearities result in the degradation of virtual LO leakage performance [3]. The diode mismatch is a result of the process variability and the asymmetry in the current-voltage characteristic itself can be seen as a measure of this process variability. Asymmetries in the diode parameters have been found to affect the virtual LO leakage [4], [5].

An APDP mixer needs to be compensated for the worst-case process variation. This requires some way of determining the optimum features such as the diode size, which offer the best immunity from process variability. Process variation results in different values of the diode parameters between the diodes. The extent of these differences can be expressed as a ratio of the forward-biased parameter to the reverse-biased parameter. Here the asymmetries are defined as

\[
I_0 \text{ Asymmetry} = \frac{I_{0f}}{I_{0r}} \tag{1}
\]

\[
V_T \text{ Asymmetry} = \frac{V_{Tf}}{V_{Tr}} \tag{2}
\]

\[
R_s \text{ Asymmetry} = \frac{R_{sf}}{R_{sr}} \tag{3}
\]

where \(I_{0f}, I_{0r}, V_{Tf}, V_{Tr}, R_{sf}, R_{sr}\) represent the forward and the reverse pairs of the saturation currents, the diode thermal voltages and the series resistances respectively. The ideality factors are contained within the definitions of the diode thermal voltages. A schematic representation of the asymmetries in an APDP circuit can be seen in Fig. 1.

Fig. 1. Schematic of anti-parallel diodes and the associated model of the diode parameters.

It might be reasonable to expect the virtual LO leakage to correlate with the diode parameter asymmetries. But no such correlation was found in the two populations of APDP circuits investigated. A statistical relationship found between the \(I_0\) asymmetry and the \(V_T\) asymmetry can be used to explain the absence of correlation. If there is a correspondence between the process variation and the even-order nonlinearities present in the current-voltage characteristic, then an even-order power-law is expected between the \(I_0\) asymmetry and the \(V_T\) asymmetry. Furthermore, if this correspondence is adequately described by a dominant even-order nonlinear term in the current-voltage transfer function, then identifying it can be a useful design guide in improving virtual LO leakage performance.

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Section II describes the fabrication process, the experimental setups used for measuring the current-voltage characteristic and the virtual LO leakage. It also describes the diode parameter extraction. The statistical correlation identified between the $I_o$ asymmetry and $V_T$ asymmetry and its implications are presented in Section III.

II. OBSERVATION

Two populations, each comprising thirty APDP circuits fabricated using a Gallium Arsenide (GaAs) heterojunction bipolar transistor (HBT) process, have been investigated to quantify the affect of the process variation on the virtual LO leakage. The test setup is shown in Fig. 2.

A. Device Process

Anti-parallel diode pair circuits were fabricated using the WIN Semiconductor's 1 $\mu$m GaAs HBT process, which has an $f_T$ of 65 GHz. The Schottky diodes are vertical structures with square-geometrical areas of 25 $\mu$m$^2$ and 49 $\mu$m$^2$ respectively. The Schottky junction was achieved by using the first metal layer as the gate (cathode), the $n^+$ layer of the sub-collector as the buffer-layer, the $n^-$ layer of the collector as the epi-layer and the collector contact as the metal (anode).

B. Current-Voltage Characteristics

A dc bias ranging from $-1.26$ to $+1.26$ volts in 30 mV steps was applied to the sixty circuits used in the investigation. The resulting APDP current was measured to a precision of 1 nA at a controlled temperature of 300 K.

C. Virtual LO Leakage

The virtual LO leakage at 36 GHz was measured by applying a single-tone at 18 GHz to an APDP circuit as shown in Fig. 2. A low pass filter with 50 dB rejection was used to eliminate second-harmonic contribution from the source.

D. Diode Parameter Extraction

A diode-parameter extraction methodology utilizing a semi-log plot of the measured APDP current and the applied bias has been used. The slopes and the intercepts of the straight-line fits to the forward and the reverse currents, provide $V_{TR}$, $V_{TR}$ and $I_{off}$, $I_{or}$ respectively. The forward and reverse parameters of $R_{qf}$ and $R_{qr}$ were determined by the ratios of the voltage deviations from the straight-line fits (at the forward and reverse currents) to the forward and reverse currents respectively [6].

E. Results

The virtual LO leakage measured in every circuit for both populations at 12 dBm LO has been plotted against $V_T$, $I_o$ and $R_s$ asymmetries in Figs. 3, 4 and 5 respectively. The data show no correlation between the LO leakage and the process variation. The absence of correlation has also been found for 10, 15 and 18 dBm LO in both the populations.

This is contrary to what is generally expected, considering the measured asymmetries are considerable. This implies an existence of correlation between the diode parameters or an asymmetry in the diode parasitics. Simulations have confirmed that intrinsic diode parameter asymmetries outweigh any reasonable variances in the diode parasitics towards the generation of LO leakage. Since diode parameter asymmetries are considerable, asymmetries in the parasitics have been ruled out as potential sources of virtual LO leakage.

Fig. 2. Setup for measuring the virtual LO leakage in an APDP circuit.

Fig. 3. Above data sets of measured virtual LO leakage and $V_T$ asymmetry for the 25 $\mu$m$^2$ and 49 $\mu$m$^2$ populations have correlation coefficients of 0.14, 0.3, respectively.

Fig. 4. Above data sets of measured virtual LO leakage and $I_o$ asymmetry for the 25 $\mu$m$^2$ and 49 $\mu$m$^2$ populations have correlation coefficients of 0.15, 0.3, respectively.
III. STATISTICAL POWER LAW

To help explain the absence of correlation observed in Section II, the Taylor series representation of the even-order nonlinearities in the APDP current is considered

$$I_{2LO}(v) = \sum_{k=1}^{n} \frac{1}{2k!} \left[ g_{2k}(V) \right]_{V=0} v^{2k}$$  \hspace{0.5cm} (4)

where $k$ and $n$ are positive integers, $I_{2LO}$ represents the virtual LO leakage, $v$ is the time-varying voltage at the APDP terminal and $g_{2k}$ is the $2k$th-derivative of

$$I(V) = I_{0} e^{-\frac{V}{V_{TR}}} - I_{0} e^{-\frac{V}{V_{TR}}}.$$  \hspace{0.5cm} (5)

A condition for no virtual LO leakage is given by

$$g_{2k}(V)_{V=0} = 0.$$  \hspace{0.5cm} (6)

It follows, from substituting (5) into (6) that

$$\left[ \frac{I_{0}}{(V_{TR})^{2k} e^{\frac{V}{V_{TR}}}} \right]_{V=0} - \left[ \frac{I_{0}}{(V_{TR})^{2k} e^{\frac{V}{V_{TR}}}} \right]_{V=0} = 0.$$  \hspace{0.5cm} (7)

If the input voltage of an APDP circuit was sufficiently low then the resulting even-order nonlinearity in (4) can be approximated by a finite series. If a single term in this series was dominant over all others then (7) would result in

$$\frac{I_{0}}{I_{cr}} = \left( \frac{V_{TR}}{V_{TR}} \right)^{2n}$$  \hspace{0.5cm} (8)

where $2n$ is the index of the dominant term.

The relationship in (8) is found to exist for each test population, which validates the assumption that a single term even-order dominates all others in (4). The 25 $\mu m^2$ and 49 $\mu m^2$ populations investigated here closely follow (8) in Figs. 6 and 7, respectively. The close conformity confirms that the term is sufficiently dominant that it can adequately describe the even-order nonlinearity in the current-voltage characteristic. Thus the index of the dominant term can be used as a figure of merit of the virtual LO leakage performance.

REFERENCES