RF Power Insensitive Varactors

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***Abstract*—In this paper, the influence of the RF voltage swing on the effective capacitance of continuously tunable capacitive devices, e.g., varactors, is investigated. Using Volterra series, equations are derived that describe the change in effective capacitance versus RF voltage, which are in agreement with simulations and have been verified by measurements. Comparing conventional and IM3 compensated varactor configurations, significant differences are found for their capacitance variation versus power. It is found that an anti-series configuration of two varactors with exponential $C(V_R)$ behavior and proper center-tap termination outperforms all other known varactor configurations and shows a maximum capacitance variation below 0.1% compared to 10% for conventional varactor elements using identical excitation.**

***Index Terms*—Effective capacitance, low-distortion, microwave devices, power dependency, radio frequency, varactor, varicap.**

I. Introduction

SEMICONDUCTOR based varactors are traditionally considered to be inappropriate for meeting the demands of future adaptive wireless communication systems due to their poor linearity. Over the last few years, this situation has been drastically changed by the introduction of special anti-series varactor topologies with proper center-tap terminations and dedicated doping profiles [1]–[3]. The resulting structures enable RF adaptivity without introducing any non-linear distortion. This makes them attractive devices for many applications including those that make use of higher RF signal powers, like handset power amplifiers. When using continuously tunable capacitive devices under high RF voltage swings [4], [5], the capacitance-voltage relation of these devices, will determine their effective capacitance, which may deviate from their value at the quiescent bias point. These phenomena may detune a filter or resonator, or introduce a power dependent phase shift when using adaptive RF circuitry. Therefore, to create reliable adaptive RF functionality, it is essential to know this power dependency, or select devices / topologies that result in the lowest achievable capacitance variation versus RF power.

II. Power Insensitive Varactors

Typically the effective capacitance of a quasi-static continuously tunable varactor varies with the amplitude of its applied RF signal, causing detuning of the total RF system in which the varactor is applied. To understand this phenomenon, we use a Volterra series analysis [6] for the circuit of Fig. 1. In this analysis, the voltage-controlled varactor is excited by an RF voltage signal with amplitude $\hat{A}$ and fundamental frequency f_0. The resulting capacitive current I_{var} flowing through the varactor at f_0 can be written as

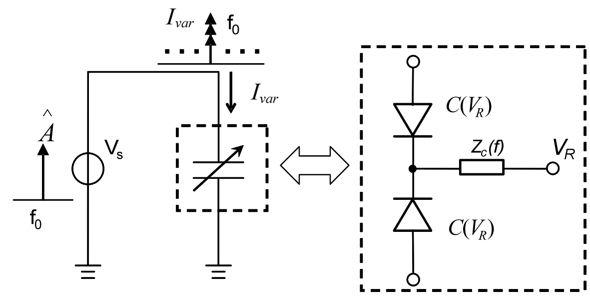

Fig. 1. Schematic used for the Volterra analysis of the varactors' capacitance variation due to the RF signal.

$$\begin{aligned} I_{var}(\omega_0) =& \hat{A}H_1(j\omega_0) + \frac{3}{4}\hat{A}^3 H_3(j\omega_0, j\omega_0, -j\omega_0) \\ &+ \frac{5}{8}\hat{A}^5 H_5(j\omega_0, j\omega_0, j\omega_0, -j\omega_0, -j\omega_0), \end{aligned} \quad (1)$$

where H_1, H_3 and H_5 are the first, third and fifth-order voltage-current transfer functions and ω_0 is the angular fundamental frequency. The capacitance variation of the varactor due to the RF signal is given by

$$\begin{aligned} \Delta C_{var}(\omega_0) &= \frac{I_{var}(\omega_0)}{j\omega_0 \hat{A}} - C_{linear} \\ &= \frac{1}{j\omega_0}\left[\frac{3}{4}\hat{A}^2 H_3(j\omega_0, j\omega_0, -j\omega_0)\right. \\ &\quad \left. + \frac{5}{8}\hat{A}^4 H_5(j\omega_0, j\omega_0, j\omega_0, -j\omega_0, -j\omega_0)\right], \end{aligned} \quad (2)$$

where C_{linear} is the original linear capacitance without RF excitation. It can be observed in (1) and (2) that when an RF signal is applied on the varactor(s), the third and higher-order mixing products that appear on the fundamental frequency modulate the RF current flowing through the varactor(s), i.e., the current is a compressive or expansive function [6] of the input RF voltage, resulting in capacitance variation. With this in mind, we can investigate the detuning of single and previously published low distortion varactor topologies that aim for the cancellation of their third-order intermodulation distortion (IM3) at $2f_1 - f_2$ and $2f_2 - f_1$ under two-tone excitation. These configurations, i.e., the distortion-free varactor stack (DFVS [2]) and the narrow tone-spacing varactor stack (NTSVS [3]), both have the topology shown at the right hand side of Fig. 1, but different $C(V_R)$ relations and center-tap connections. The DFVS is based on an anti-series connection of two identical

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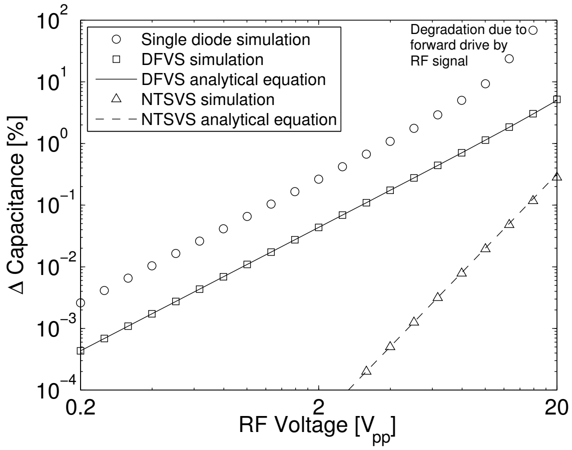


Fig. 2. Simulated capacitance variation relative to the linear capacitance in percentage versus the amplitude of the RF signal. f_0 = 2 GHz, C_0 = 20 pF and V_R = 5 V for both DFVS (V_{bi} = 1 V) and NTSVS (a_2 = 0.125 V^{-1}).

diodes with the $C(V_R)$ relationship of

$$C(V_R) = C_0 \left(1 + \frac{V_R}{V_{bi}}\right)^{-0.5}, \tag{3}$$

where C_0 is the capacitance at zero bias and V_{bi} is the built-in voltage. Furthermore, an 'infinitely' high impedance is necessary at the center-tap to fulfill the requirements for cancellation of the IM3 products at $2f_1 - f_2$ and $2f_2 - f_1$ under two-tone excitation. By solving the Volterra series, according to the methodology of [6], the capacitance variation (ΔC_{DFVS}) relative to the linear capacitance (C_{linear}) can be written as:

$$\frac{\Delta C_{DFVS}}{C_{linear}} = \frac{\hat{A}^2}{64(V_{bi}+V_R)^2} + \frac{7\hat{A}^4}{8192(V_{bi}+V_R)^4}. \tag{4}$$

The NTSVS is based on an anti-series connection of two identical diodes with the $C(V_R)$ relationship of

$$C(V_R) = C_0 \exp(-a_2 V_R), \tag{5}$$

where a_2 is the grading coefficient. To cancel the IM3 distortion, there must be a low impedance path between the center-tap node and the two RF terminals at low frequencies, while the high-frequency components at the center-tap node should experience high impedance, i.e., $Z_c(f)$ should be much larger than the AC impedance of the varactor diode itself at fundamental and harmonic frequencies. By solving the Volterra series, the capacitance variation (ΔC_{NTSVS}) relative to its linear capacitance is given by

$$\frac{\Delta C_{NTSVS}}{C_{linear}} = \frac{a_2^4 \hat{A}^4}{768}. \tag{6}$$

It is indicated in the Volterra analysis that the current flowing through the varactors at the fundamental frequency is modulated by both third and fifth-order mixing products for the DFVS. In contrast, the third-order distortion component present at f_0 is cancelled in the NTSVS as shown in (6). Therefore, although both DFVS and NTSVS behave perfectly for IM3 cancellation at the frequencies of $2f_1 - f_2$ and $2f_2 - f_1$ under two-tone excitation, the NTSVS outperforms the DFVS in terms of capacitance variation due to RF signals as expected from (4) and (6). To illustrate this, the normalized DFVS and NTSVS with the same tuning range and maximum control voltage are simulated and compared with a conventional single diode using the ADS harmonic balance simulator. As shown in Fig. 2, very good agreement has been achieved between the simulation results and the analytical results predicted by (4) and (6). In addition, a slope of 4:1 versus voltage amplitude is observed for the NTSVS due to the absence of third-order mixing products, which is in contrast to the slope of 2:1 and the much larger capacitance variation for the cases of the single diode and the DFVS. It is worth mentioning that the NTSVS also outperforms the DFVS under reduced RF voltage swings where the effective tuning range of both varactor stacks is much larger. In conclusion, for an ideal varactor device the capacitance variation of the NTSVS is at least twenty times lower than the DFVS at full RF voltage swing (10 V) and even 100 times lower at 5 V RF voltage swing.

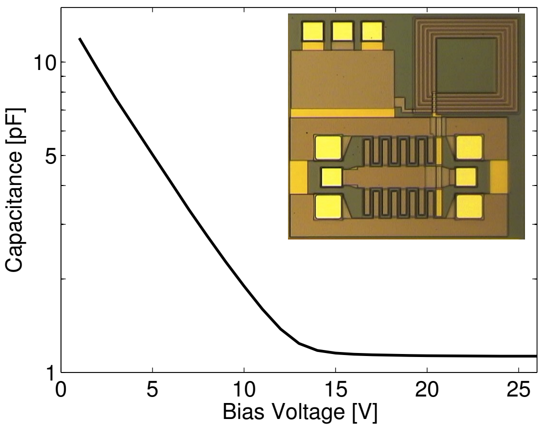
III. Experimental Results

To investigate the capacitance dependency vs. power, calibrated input impedance (Γ_{in}) measurements were performed at different power levels using an active loadpull setup [7]. We investigated a GaAs varactor device with exponential $C(V_R)$ relation, as presented in [8]. A microphotograph of the measured device is given as inset in Fig. 3(a).

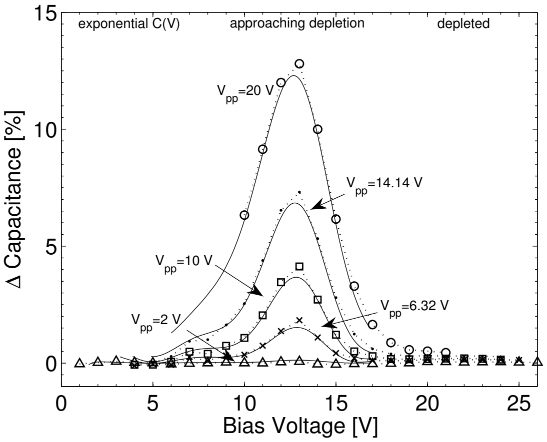
The capacitance of the devices placed in shunt is calculated from the measured Γ_{in} and Γ_L at 2 GHz, from which Y-parameters ($Y_{DUT} = Y_{in} - Y_L$) were calculated and converted into capacitance ($C = -\Im(Y_{DUT})/(2\pi f)$). The resulting measured capacitance voltage characteristic at low input power (~4 dBm) is given in Fig. 3(a). In this figure, three distinct regions can be identified. Up to ~10 V, the curve follows the exponential $C(V_R)$ characteristics. Above 10 V the device starts to become depleted until it is nearly fully depleted at the highest voltages. Note that in this region the contacts are still getting depleted somewhat further and small changes of the capacitance still occur.

For a given RF input power / RF voltage swing, the DC control voltage of the varactor stack is swept such that no forward biasing or reverse breakdown of the varactor devices can occur. This process is repeated for increasing RF voltage swings up to the point where the maximum power handling of the probe (+33 dBm) is reached. From the measurements described, the change in capacitance value with respect to the low-power condition, as function of control voltage at different drive levels has been plotted in Fig. 3(b). Note that the change in effective capacitance is the lowest where the $C(V_R)$ relation of the varactor devices is purely exponential or constant, the former represents the useful operating range for adaptive RF behavior. The highest power dependency of the effective capacitance is found when the devices are biased in, or close to, the transition range of the $C(V_R)$ curve.

This data can also be presented as effective capacitance versus RF voltage swing at different bias control voltages (Fig. 4). From these results it can be concluded that when biased at 5 V the capacitance behaves close to an ideal exponential $C(V_R)$



(a)



(b)

Fig. 3. (a) Measured capacitance-voltage characteristics of the DUT (NTSVS, a_2=0.183 V^{-1} [8]) using a low power level ($\sim$4 dBm, 2 GHz), the inset shows a microphotograph of the DUT. (b) Measured (dotted line with symbols) and simulated (continuous line) change in capacitance as function of bias voltage for different RF power levels, expressed as peak-to-peak voltage.

device and indeed, as suggested by the theory, exhibits nearly no change in effective capacitance value ($\Delta C < 0.1\%$). When biased at a value where the $C(V_R)$ behavior strongly deviates from the exponential dependency, the change in effective capacitance is the highest (V_R = 13 V). When the device is fully depleted and the change in capacitance is very small (V_R = 20 V), the change in effective capacitance is again small, but still exceeds the case where the device is biased in its exponential operating range (V_R = 5 V). Note that the supporting harmonic balance simulations are based on a polynomial fit of the measured low power $C(V_R)$ data of Fig. 3 (a) and assume an ideal bias network.

IV. Conclusion

In this paper, a Volterra series analysis has been used to accurately predict the capacitance dependence of continuously tunable varactors as function of RF voltage swing. The theory provided has been verified by simulations and is also supported by experimental results. It was shown for the first time that anti-series configured varactors having an exponential $C(V_R)$ relation and a low impedance center tap connection, exhibit the lowest capacitance variation with RF voltage. Compared to conventional varactor configurations, at least a twenty times lower dependency was achieved.

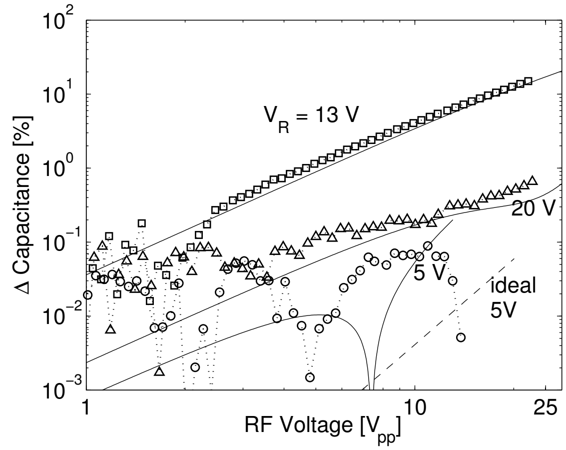


Fig. 4. Simulated (continous line) and measured (dotted line with symbols) change in effective capacitance as function of RF voltage at 2 GHz for given bias voltages. The dashed line indicates the simulated result at V_R=5 V for the ideal exponential NTSVS.

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