# A 67 dBm $OIP_3$ Multistacked Junction Varactor

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***Abstract*—A multistacked varactor is presented for ultra-linear tunable radio frequency applications. The varactor elements are applied in anti-series configuration and are characterized by an "exponential" $C$-$V_R$ relationship. Third-order intermodulation ($IM_3$) is cancelled through proper harmonic loading of the terminals of the anti-series configuration. Multiple stacking is used to further increase the power handling and to minimize the remaining fifth-order distortion. The measured output intercept point ($OIP_3$) at 2 GHz is $> 67$ dBm for modulated signals up to 10 MHz bandwidth, while providing a capacitance tuning ratio of 3:1 with an average quality factor of 40 and maximum control voltage of 10 V.**

***Index Terms*—Adaptive systems, band-switching, impedance matching, low-distortion, tunable filters, tuners, varactors.**

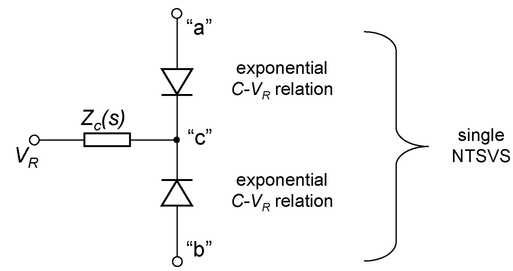


Fig. 1. Narrow-tone spacing varactor stack (NTSVS). $Z_c(s)$ is used to fulfill specific harmonic termination conditions for $IM_3$ cancellation.

## I. Introduction

RECENTLY, radio frequency (RF) adaptive systems have drawn a lot of attention, resulting in an intensive search for low-cost low-distortion tunable elements. Potential candidates are semiconductor diodes [1]–[4], MEMS switches/varactors [5], [6] and Barium Strontium Titanate (BST) varactors [7]. Although MEMS switched devices offer superior linearity ($OIP_3 > 70$ dBm) and $Q$, their application is limited due to their low-switching speed, size and non-continuous nature. BST-based varactors provide continuous tuning, but their linearity performance is still limited even when used in a multistack topology [7].

It is shown in [4] that high linearity for modulated signals can be achieved with proper harmonic termination using an "exponential" $C$-$V_R$ relationship. In this work, we further improve the linearity of the devices in [4] using a multistack topology. As a result, the linearity found in our experiments is comparable to that of MEMS switched devices.

## II. Varactor Structures

### A. Narrow-Tone Spacing Varactor Stack (NTSVS)

The varactor configuration of Fig. 1 exhibits no third-order intermodulation distortion ($IM_3 = 0$) for modulated signals with narrow-tone spacing or limited bandwidth by making use of a specific harmonic center-tap termination [4] and an "exponential" $C$-$V_R$ relation for the varactor diodes, i.e.,

$$C(V_R) = a_1 \exp(-a_2 V_R). \tag{1}$$

The parameters $a_1$ and $a_2$ provide flexibility in setting the varactor-stack parameters to the needs of the application, without affecting the $IM_3$ cancellation.

To achieve the $IM_3$ cancellation in practice, there must be a *low impedance* path (relative to the AC impedance of the varactor capacitance itself) between the center node $c$ and two RF terminals ($a$ and $b$) at low frequencies. At the same time, there must be a *high impedance* for the high frequency components (fundamental and higher harmonics) between the center node $c$ and terminals $a$ and $b$. When these conditions are met, the $IM_3$ will be cancelled and the remaining distortion is dominated by the much smaller fifth-order nonlinearity.

### B. Linearity Improvement by Using Multistack Topology

When connecting $N$ varactor stacks in series, the applied RF voltage will be divided over the $N$ stacks. Since the (remaining) nonlinearities of these varactor stacks are excited with a voltage that is $N$ times lower, their resulting nonlinear currents will be reduced. One of the key advantages of the NTSVS over (typically) $IM_3$ dominated varactor stacks is, besides its already much higher initial linearity, the further increased linearity improvement when using these multiple stacks. To support understanding at this point, we consider the external terminal current of the (stacked) varactor in Fig. 2. We use $I_{single}$ to represent a single varactor stack and $I_{N\_stacked}$ for $N$ varactor stacks in series (Fig. 2(a) and (b)). When keeping the total capacitance the same, the capacitance of multiple stacked varactors must be $N$ times larger than the original single varactor stack. Logically, the *fundamental* currents will be identical when applying the same RF voltage, i.e.,

$$I_{single}(f_{fund}) = I_{N\_stacked}(f_{fund}). \tag{2}$$

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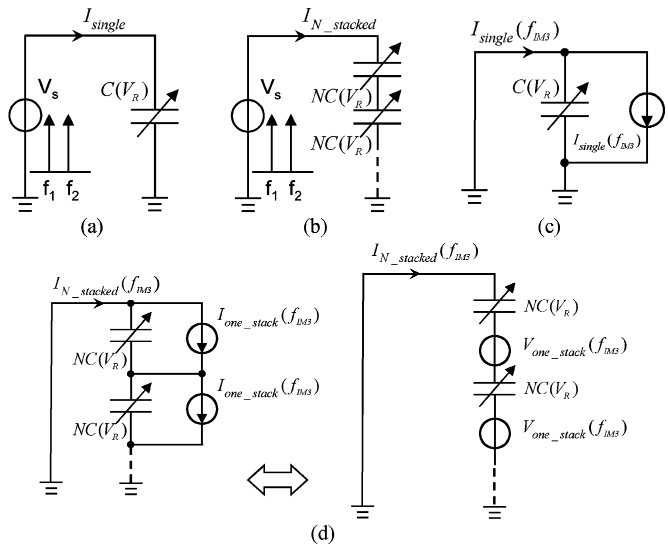


Fig. 2. (a) Schematic for a single-varactor stack; (b) schematic for the $N$-varactor stacks; (c) schematic to calculate third-order or fifth-order response for the single varactor stack; and (d) schematic to calculate third-order or fifth-order response for the $N$-varactor stacks.

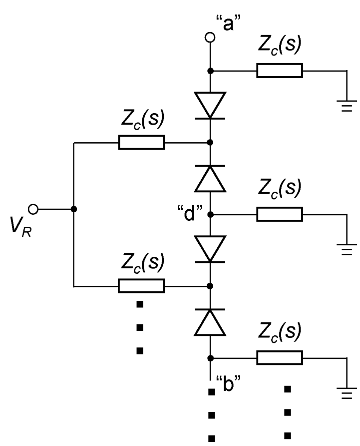


Fig. 3. Multistack topology for the NTSVS.

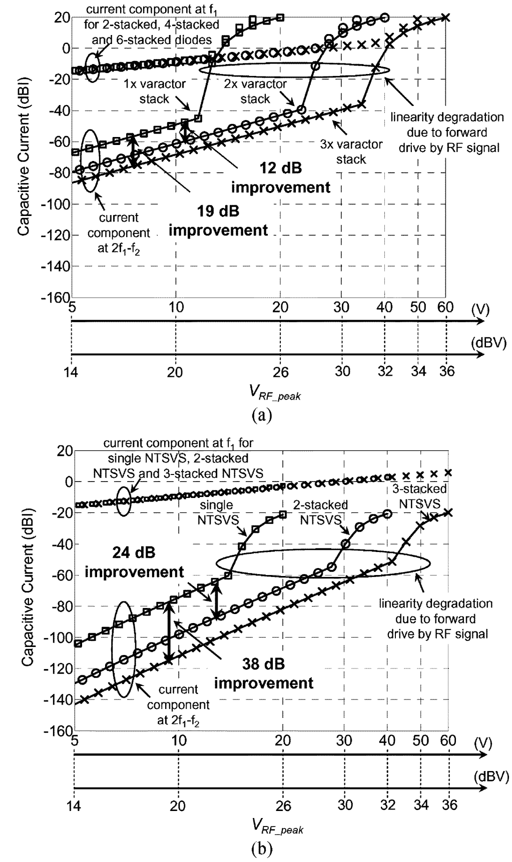


Fig. 4. Simulated capacitive linear and nonlinear terminal current versus peak voltage of a two-tone RF signal: (a) $IM_3$ dominated case for $N$-varactor stacks using varactors with an exponential $C(V_R)$ relation but with *incorrect* harmonic termination; (b) $IM_5$ dominated case for the same varactors in a $N$-stacked NTSVS configuration. The diode parameters are: $a_1 = 20$ pF for a single varactor stack and NTSVS, 40 pF for a double varactor stack and double NTSVS configuration, 60 pF for a triple varactor stack and triple NTSVS configuration, for all diodes $a_2 = 0.11\ \mathrm{V}^{-1}$ while the applied reverse bias ($V_R$) is 5 V in all situations.

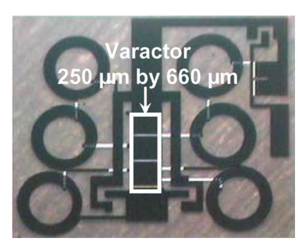


Fig. 5. The 2.7 pF three-stacked NTSVS used for the measurements (six 20 nH inductors are used to implement the harmonic baseband "short" while providing high impedance for the fundamental and harmonics).

The equivalent circuits for the single stack and $N\times$ varactor stacks to calculate the nonlinear third-order intermodulation ($IM_3$) components are shown in Fig. 2(c) and (d) respectively. To calculate the $IM_3$ current for the $N\times$ varactor stack, the individual nonlinear current sources can be converted to their Thevenin representation as illustrated in Fig. 2(d). The related $IM_3$ voltage across one of the $N\times$ varactor stacks is

$$V_{one\_stack}(f_{IM3}) = \frac{I_{one\_stack}(f_{IM3})}{j\omega NC(V_R)}. \quad (3)$$

So the equivalent non-linear current for the total stack can be found by a Norton transformation:

$$I_{N\_stacked\_IM3}(f_{IM3}) = \frac{N \cdot V_{one\_stack}(f_{IM3})}{\frac{1}{j\omega C(V_R)}} = I_{one\_stack}(f_{IM3}). \quad (4)$$

Therefore, the resulting $IM_3$ current for the $N$-stack configuration is equal to the $IM_3$ current of one varactor stack in this multistack configuration. Consequently, for an $IM_3$ dominated $N\times$ varactor stack, the $IM_3$ current is proportional to: $(V_{RF}/N)^3$, since stacking reduces this RF voltage by a factor of $N$, the resulting third-order nonlinear current sources are

$$I_{N\_stacked\_IM3}(f_{IM3}) = I_{one\_stack\_IM3}(f_{IM3}) = N \cdot I_{single\_IM3}(f_{IM3}) \left(\frac{1}{N}\right)^3. \quad (5)$$

where the first "$N$" is a result of the larger area compared to a single varactor stack and the "$(1/N)^3$" is a result of the RF voltage splitting. Consequently, multiple-stacking results in

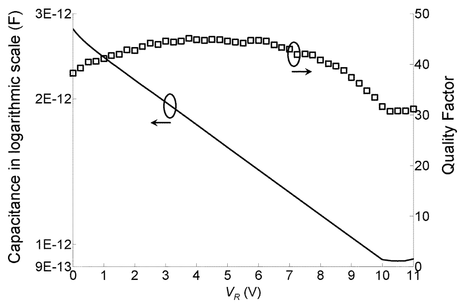


Fig. 6. Measured $C$-$V_R$ and $Q$-$V_R$ dependence at 2 GHz. Note that the $C(V_R)$ measurements yield a straight line in the logarithmic plot as a function of reverse voltage, indicating a near-ideal exponential $C(V_R)$ relationship.

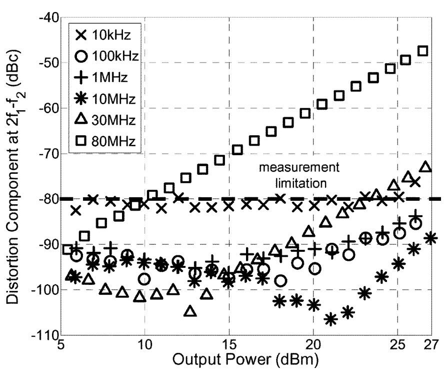


Fig. 7. Measured distortion components at $2f_1 - f_2$ versus output power at different tone spacings for a two-tone input signal with the $f_{center}$ of 2 GHz $(\text{capacitance at zero bias voltage} = 2.7\ \text{pF}, V_R = 5\ \text{V})$.

a reduction of the distortion current by a factor of $N^2$, i.e., $40\log(N)$ dB.

By contrast, for an $IM_5$ dominated device, like the NTSVS used here, the nonlinear $IM_5$ currents that appear at $IM_3$ frequencies ($2f_1 - f_2$ and $2f_2 - f_1$) are proportional to the 5th power of the RF voltage over the elements in the stack, thus

$$I_{N\_stacked\_IM5}(f_{IM3}) = I_{one\_stack\_IM5}(f_{IM3}) = N \cdot I_{single\_IM5}(f_{IM3}) \left(\frac{1}{N}\right)^5. \quad (6)$$

So for an $IM_5$ dominated device using $N$-stacks results in a reduction of the non-linear current by a factor of $N^4$, i.e., $80\log(N)$ dB, which is twice the linearity improvement found for an $IM_3$ dominated device.

From the above it can be concluded that it is very important to maintain the $IM_3$ cancellation in a multistack topology. One can achieve this by providing the proper harmonic terminations at nodes $a$, $b$ and $d$ as shown in Fig. 3. This is verified in Fig. 4(a) and (b), using ADS's Harmonic Balance simulator, by plotting the capacitive current of the external terminals at $f_1$ and $2f_1 - f_2$ with correct and incorrect harmonic terminations respectively. Note that for an objective comparison, the number of stacked diodes is kept the same for both cases. It can be observed that the $IM_5$ dominated nonlinear current is much smaller to start with, while the linearity improvement found for increasing $N$, is double of that in the $IM_3$ dominated cases.

## III. Experimental Results

In order to check the effectiveness of the multistack topology, a 2.7 pF 3 × stacked NTSVS as shown in Fig. 5 is implemented using a dedicated silicon-on-glass technology developed at the Delft University of Technology [8].

The measured quality factor at 2 GHz is approximately 40 and the capacitance tuning ratio is 3:1 with the maximum control voltage of 10 V (Fig. 6). Note that even better quality factor can be achieved if diode leakage currents are reduced; in that case the quality factor will increase with $V_R$.

The linearity testing is performed using a two-tone signal ($f_{center} = 2$ GHz) as function of power using the setup described in [9]. Fig. 7 plots the measured distortion components at $2f_1 - f_2$ as a function of output power for different values of tone spacing. Note that the linearity of signals with tone spacing below 30 MHz is comparable to that of the measurement setup and for that reason the conservative boundary of trust is marked as "measurement limitation" in Fig. 7. Conservatively speaking the measured $OIP_3$ is larger than 67 dBm up to 10 MHz bandwidth, which is 22 dB better than the reported nine-stacked BST varactor in [7] and comparable to MEMS switched devices.

## IV. Conclusion

The multistack topology is used to improve the linearity and power handling of the NTSVS without seriously degrading the quality factor, while capacitance tuning range and control voltage remain unchanged. Due to its $IM_5$ dominated nonlinearity, the use of the NTSVS multistack topology yields a dramatic linearity improvement, which is double of that found in $IM_3$ dominated devices. The experimental data confirms this, yielding a record high linearity for continuously tunable capacitances regardless of the technology of implementation.

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