Ultra Linear Low-Loss Varactor Diode Configurations for Adaptive RF Systems

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Abstract—Two linear low-loss varactor configurations for tunable RF applications are compared. The wide tone-spacing varactor stack provides the best linearity for signals with relative large tone spacing like receiver jammer situations. The narrow tone-spacing varactor stack offers the highest linearity for in-band-modulated signals, and is better suited to adaptive transmitters. Both structures make use of a varactor with an exponential $C(V_R)$ relation, and so the different requirements of transmit and receive chains can be addressed in one technology. Both configurations have been realized in a silicon-on-glass technology. The measured $Q$ at 1.95 GHz is from $\sim 40$ to 200 over a capacitance tuning range of 3.5 with the maximum control voltage of 12 V. The measured OIP3 of both structures are roughly 60 dBm.

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

I. INTRODUCTION

RECENTLY, reconfigurable RF systems have received considerable attention, resulting in an extensive search for suitable adaptive RF components, which facilitate band switching, antenna mismatch correction and amplifier load tuning for improved efficiency. To meet the strict requirements of these wireless applications, an ideal tunable element will exhibit low loss, low dc power consumption, high linearity, high ruggedness, wide tuning range, high reliability, low cost, low area usage, and is continuously tunable with a high speed.

Microelectromechanical systems (MEMS) based switches [1], [2] can provide very low losses while consuming little dc power. When switching in fixed capacitors, very large capacitance ratios, very low loss and very high linearity can be accomplished. However, this approach is most useful when low-switching speed is acceptable and continuous tuning is not required. Also “hot switching” with RF power $>2$ W typically needs to be avoided to maintain good reliability. In general, MEMS switches require high actuation voltages (15–80 V) and are sensitive to reliability issues, although this has exhibited significant improvement recently.

The MEMS varactor [2]–[4] is considered to be less sensitive to reliability issues, and specific implementations can provide for continuous tuning. Nevertheless, these continuous tunable implementations can suffer from intermodulation distortion, since the position of the membrane can move with changes in the modulation envelope of the applied RF voltage [3], [5]. Moreover, its relatively small tuning range or high drive voltage constrains its RF performance. Also, its relatively small capacitance density makes it difficult to implement large valued capacitors. For this reason its application is mostly found above 5 GHz.

Other proposed tuning techniques, based on voltage-variable dielectrics, show a much higher capacitance density, while a moderate tuning range at a relatively low voltage can be achieved with a good quality factor. However, the poor linearity properties [6], [7] due to the inherently nonlinear nature of the ferroelectric materials limit their application. Their integration compatibility is also limited.

To avoid the limitations of MEMS and BST-based tunable capacitors, low distortion semiconductor varactor based solutions were proposed [8]–[14]. In this study, we focus on the implementation of two extremely linear varactor diode configurations with complementary linearity properties in a single varactor diode technology. These ultra-low distortion components can be utilized for the realization of tunable RF circuits, e.g., matching networks, filters [15], [16], phase shifters [17], [18] etc. Both varactor configurations use antiseries varactor diode configurations, where the diodes share the same exponential $C(V_R)$ depletion capacitance relation. However, the proposed structures differ in their harmonic termination and varactor area ratios, resulting in a fundamentally different linearity behavior versus tone spacing.

The first varactor configuration exhibits the highest linearity for modulated signals with wide tone spacing, and is hereafter named the wide tone-spacing varactor stack. This structure is a direct derivation of the earlier proposed high tuning range varactor stack [8]. The second structure has the highest linearity for narrowband modulated signals and is named the narrow tone-spacing varactor stack, and was discussed in [19]. For receiver applications the input signal is typically small in amplitude ($< -30$ dBm) relaxing the in-band linearity requirement. Therefore, for the receiver, the most troublesome distortion

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comes from strong out-of-band interferers whose undesired mixing products can fall in-band and pollute the reception of the desired signal. Note that in practical situations these interfering or jammer signals are typically separated from the desired signal by more than 100 kHz. As result the linearity for signals with larger tone spacing is most important. Considering the above, the wide tone-spacing varactor stack is a very attractive candidate for adaptive receivers. On the other hand, the linearity properties of the narrow tone-spacing varactor stack are best suited for the transmit path. Here, complex modulated signals with a high output power need to be handled without introducing channel-to-channel interference or increasing the error vector magnitude due to intermodulation distortion.

Since the theory of the narrow tone-spacing varactor stack has been already extensively studied in [19], in this study, we focus in Section II on the analysis of the wide tone-spacing varactor stack, yielding its required varactor area ratio for third-order intermodulation (IM3) cancellation. The remaining fifth-order intermodulation (IM5) distortion for the wide tone-spacing varactor stack has been characterized by a compact expression, while the influence of the center-tap impedances on the linearity as a function of tone spacing has been analyzed. To experimentally verify the theory and compare the resulting performances, both topologies (wide tone-spacing varactor stack and narrow tone-spacing varactor stack) have been implemented on the same silicon-on-glass wafer, yielding the first practical realization of the antiparallel/antiseries linear varactor topology. The resulting structures have been characterized for \( C(V_R) \) and \( Q(V_R) \), and their linearity performance is reported in Section III. Section IV concludes this paper with a comparison of the two varactor linearization techniques.

II. WIDE-TONE SPACING VARACTOR STACKS

A. Third- and Even-Order Distortion Cancellation

The high-linearity wide tone-spacing varactor stack configuration with four diodes in the antiparallel/antiseries connection is a special case of the high tuning range varactor stack proposed in [8] and is shown in Fig. 1. We consider the IM3 current through the source impedance at frequency \( 2f_1 = f_2 \), which we will determine using Volterra analysis [20].

The center-tap impedance is set to infinity for all frequency components present in the circuit \( (Z_c(s) \equiv \infty) \) and the ratio of the diode areas \( (D_1/D_2) \) is set to \( X \). For simplicity, we assume the frequencies of the two-tone voltage source are identical \( (f_1 \approx f_2 \approx f_{RF}) \). The resulting expression for the IM3 is given by:

\[
\text{IM3}|_{Z_c(s)\equiv\infty} = -\frac{3(c_0c_2X^2 - 2c_2X - c_0c_2X + c_0c_2)(X + 1)^2}{4c_0^2(2Xs_{RF}c_0Z(s_{RF}) - X - 1)(2Xs_{RF}c_0Z(s_{RF}) + X + 1)^2}
\]

(1)

where \( c_1 \) and \( c_2 \) are the capacitance Taylor coefficients of each varactor diode with \( V_R \) being the reverse applied voltage with a positive value, \( Z_0(s) \) is the source impedance, \( s_{RF} \) is the complex RF center frequency \( (j\omega_{RF}) \) of the two-tone signal, and \( A \) represents the voltage amplitude of the source signal. Since we aim for integration in the same technology as the narrow tone-spacing varactor stack [19], the proposed configuration will share the doping profile with the related \( C(V_R) \) relation [19], i.e.,

\[
a_1 = a_1 \exp(-a_2 V_R)
\]

(3)

Fig. 1. Schematic of the antiparallel/antiseries connection of the diodes with exponential \( C(V_R) \) relation.
the source impedance $Z_s(s)$ and the particular values of $a_1$ and $a_2$.

The antiparallel/antiseries topology enforces opposite phases of the even-order nonlinear current sources so no even-order components leave the varactor structure. To illustrate this point, consider the second-order Volterra series of the schematic shown in Fig. 2.

The second-order Volterra kernel for the voltage at input node $a$ is

$$H_{2a}(s_1, s_2) = \frac{\left[ X(I_{NL2a2} - I_{NL2a3}) - (I_{NL1a2} - I_{NL1a3}) \right] Z_s(s_1 + s_2)}{2(s_1 + s_2)Xc_0Z_s(s_1 + s_2) + X + 1} = 0$$

where

$$I_{NL2a2} = I_{NL2a3} = \frac{(s_1 + s_2)X^2c_1}{2s_1Xc_0Z_s(s_1) + X + 1}$$  

$$I_{NL2a4} = I_{NL2a3} = \frac{(s_1 + s_2)Xc_1}{2s_1Xc_0Z_s(s_1) + X + 1}$$  

are the second-order nonlinear current sources. From (5), it is clear that as long as the mismatch of $D_1 - D_4$ and $D_2 - D_3$ is small, $H_{2a}(s_1, s_2)$ will be close to zero, and no second-order distortion current flows into the source impedance. Therefore, no second-order voltage components will develop across the varactor structure and secondary mixing (which can lead to IM3) is avoided; this yields an IM3 cancellation condition independent of source impedance. A more elaborate analysis shows that all even-order distortion components vanish, resulting in a tunable capacitor with no residual distortion with an order lower than five.

$B$. Influence of Fifth-Order Distortion on Linearity

Although this approach is very effective in cancelling the IM3 and all even-order intermodulation, IM5 is still present. When solving for the fifth-order Volterra series, we assume $Z_c(s) \equiv \infty$ for the center-tap connections and $X = 2 \pm \sqrt{3}$. Next, we substitute the $C(V_R)$ relation (3) into the IM5 formulation. To simplify the analysis, we assume $f_1 \approx f_2 \approx f_{RF}$ and $Z_s(s) \to 0$, providing us the IM5 products that appear at $2f_1 - f_2$ and $2f_2 - f_1$, namely,

$$IM5 \approx \frac{5}{288} \frac{1}{\alpha_2} A^4$$

where $\alpha_2$ is the exponential coefficient of the $C(V_R)$ relation (3) and $A$ is the voltage amplitude of the two-tone test signal at the fundamental frequencies. This situation represents the worst case condition since, for $Z_s(s) \to 0$, all fifth-order current will flow through the source impedance, which approximates a short-circuit condition.

Based on (7), the fifth-order intercept point (IIP5) can be expressed as

$$IIP5 \approx \frac{2.75}{\alpha_2} \text{ (V)}$$

The resulting linearity is independent of the reverse bias voltage. In order to be consistent with further discussions, we replace $\hat{A}$ with $V_{RF,\text{peak}}$, which is the peak amplitude of the two-tone input voltage signal. Hence, (7) can be rewritten as

$$IM5 \approx \frac{5}{288} \frac{1}{\alpha_2} \left( \frac{V_{RF,\text{peak}}}{2} \right)^4$$.

In practical cases, the value of $\alpha_2$ varies from 0.028 to 0.54 V^{-1} [19], yielding IIP5 values from 5.1 to 98.4 V. Note that since the IM5 drops at the rate of 80 dB per decade, outstanding linearity can be achieved for even modest IIP5 values.

$C$. Influence of Center-Tap Impedance on Linearity

In Section II-A, it was assumed that the center-tap impedance ($Z_c$) is infinite for all frequency components so it has no influence on the RF operation. In practical situations, this requires that the center-tap impedances should be much higher than the ac impedances of the varactors themselves. This requirement is difficult to fulfill for the baseband frequency component of a two-tone signal ($f_2 - f_1$) when the tone spacing approaches zero. For the resulting baseband frequency, the capacitive reactance of the varactors increases without bound as the tone spacing approaches zero. Consequently, there is a lower frequency limit of tone spacing where the third-order distortion cancellation is violated; hence, this configuration is called the wide tone-spacing varactor stack.

In practical implementations of the wide tone-spacing varactor stack, similar to what has been done for the uniformly doped distortion-free varactor stack configuration in [8] and [10], an integrated resistor [see Fig. 3(a)] can be used for the dc biasing networks of the center-tap. For a wide tone-spacing varactor stack configuration as depicted in Fig. 1, using resistive center-tap connections, the simulated distortion components at $2f_1 - f_2$ as function of tone spacing ($f_2 - f_1$) are depicted in Fig. 4, which confirms the conclusion above. When the tone spacing is relatively small, the third-order distortion is no longer canceled, and the IM3 distortion has a value of
As one can observe, the corner frequency is ten times larger than the single resistor case [see Fig. 3(a)] since 

\[ f_{\text{center}} = \frac{1}{10 \pi R_c (\alpha_0 V_{\text{RF-peak}})^2} \]

where \( f_{\text{center}} \) is the center-tap frequency. As one can observe, the corner frequency is inversely proportional to the product of the center-tap resistance and the varactor capacitance. In order to improve the linearity performance at low-tone spacing, the center-tap configuration [shown in Fig. 3(b)] with a series resistor and antiparallel diode bias was proposed in [8] and [10], whose effect can be observed in Fig. 4. If the antiparallel diodes are not forward biased, they provide very high impedance extending the high linearity operation of the wide tone-spacing varactor stack to very low-tone spacing.

Note that for this configuration, the dc leakage current of the reverse-biased diodes will limit the linearity at ultra-low tone spacing since a small forward bias of the center-tap diodes will yield a drop in their ac impedance \( R_D \). For slightly higher tone spacings, the zero-bias capacitance \( C_D \) of the antiparallel diode pair limits the IM3 to a small constant value, consequently it is best to use small diodes in the center-tap connection. Above the corner frequency (in this case approximately 40 MHz), defined by (11), fifth-order distortion constrains the linearity. Note that the corner frequency is ten times larger than the single resistor case [see Fig. 3(a)] since \( R_c (100 \, \text{k} \Omega) \) is ten times smaller, which is consistent with (11). Fig. 4 shows that the wide tone-spacing varactor stack clearly offers superior linearity over the single diode (with comparable effective capacitance), especially at relatively large tone spacing.

D. Comparison Between Single Diode, Wide Tone-Spacing Varactor Stack, and Narrow Tone-Spacing Varactor Stack

The narrow tone-spacing varactor stack and wide tone-spacing varactor stack are compared with single diodes in Table I in terms of topology, harmonic conditions, area ratio required for IM3 cancellation, total area for a given capacitance (relative to the single diode), maximum RF voltage, and linearity. It indicates that both varactor stacks, with suitable harmonic terminations, dramatically outperform the single diode in terms of linearity since all distortion components with an order less than five are cancelled, while the residual fifth-order distortion at \( 2f_1 - f_2 \) is extremely low. For the varactor stacks, the antiseries configuration will distribute the applied RF voltage over the two diodes. Therefore, the maximum allowable RF voltage \( V_{\text{RF-peak}} \), which is constrained by the forward bias and breakdown of the individual diodes, will be correspondingly increased, yielding higher power handling and linearity. The only cost of the antiseries connection is the extra chip area needed to implement the same capacitance value. However, due to the high capacitance density of semiconductor
TABLE I

<table>
<thead>
<tr>
<th>Topology</th>
<th>Center-Tap Impedance</th>
<th>Area Ratio for IM3 Cancellation</th>
<th>Maximum Allowable $V_{RF, max}$</th>
<th>Total Area for a Given Capacitance $IP2$</th>
<th>$IP3$ at $2f_1 - f_2$</th>
<th>$IP4$</th>
<th>$IP5$ at $2f_1 - f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>single diode</td>
<td>single</td>
<td>none</td>
<td>no cancellation</td>
<td>$\frac{1}{2} V_{RF, max}$</td>
<td>$A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>narrow tone-spacing</td>
<td>anti-series</td>
<td>zero at low frequency</td>
<td>infinity at other frequencies</td>
<td>$V_{RF, max}$</td>
<td>4$A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>varactor stack</td>
<td>(Fig. 3(c))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wide tone-spacing</td>
<td>anti-series/anti-parallel</td>
<td>2 ± $\sqrt{3}$</td>
<td>infinity for all frequencies</td>
<td>$2 \sqrt{\frac{3}{2}} V_{RF, max}$</td>
<td>6$A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>varactor stack</td>
<td>(Fig. 3(a) and (b))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* $V_{RF, max}$ is the maximum reverse applied voltage, which equals the breakdown voltage [19].

III. EXPERIMENTAL RESULTS

To confirm the theory of Section II, the wide tone-spacing varactor stack was implemented, along with the narrow tone-spacing varactor stack, using the dedicated silicon-on-glass technology [21]–[23] at the Delft University of Technology, Delft, The Netherlands. The starting material is a 4-in silicon-on-insulator wafer on which the specific varactor profile has been grown epitaxially. In this test run, we aimed for varactor devices with a breakdown voltage of 20 V, capacitance tuning range of 6:1, and epi-layer thicknesses of 1.1 $\mu$m were realized. For these varactors MEDICI [24] simulations predicted a quality factor of 50 at zero bias.

**A. Measurement of the $C - V_R$ and $Q - V_R$ Dependence**

As mentioned earlier, the advantages of the wide tone-spacing varactor stack over the distortion-free varactor stack (with its uniform doping profile) are its higher capacitance tuning range and its compatibility with the narrow tone-spacing varactor stack, which has superior linearity with narrow tone spacing. From the technology point of view, the implementation of the $N_{ac} = 2$ doping profile, and the resulting exponential $C(V_R)$ relationship, is critical for achieving optimum performance. To

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Fig. 5. Measured $C = V_R$ and $Q = V_R$ dependence as function of reverse control voltage ($V_Q$) at 1.95 GHz.

Fig. 6. Microphotograph of the 10-pF-wide tone-spacing varactor stack used in the linearity measurements with 500-k$\Omega$ center-tap resistor.

tone-spacing varactor stack, using the dedicated silicon-on-glass technology [21]–[23] at the Delft University of Technology, Delft, The Netherlands. The starting material is a 4-in silicon-on-insulator wafer on which the specific varactor profile has been grown epitaxially. In this test run, we aimed for varactor devices with a breakdown voltage of 20 V, capacitance tuning range of 6:1, and epi-layer thicknesses of 1.1 $\mu$m were realized. For these varactors MEDICI [24] simulations predicted a quality factor of 50 at zero bias.

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**Fig. 7.** Measured distortion components at $2f_1 - f_2$ versus output power for single diode and the wide tone-spacing varactor stack with the center-tap resistance of 500 $\Omega$ (for both cases: the effective zero bias capacitance = 10 pF, $f_{center} = 2$ GHz, $a_{2} = 0.0896$ $V^{-1}$, and $V_R = 5$ V).
verify the $C(V_R)$ relation, we measured the capacitance density of a single diode with a zero bias capacitance of 1 pF. Its $C(V_R)$ and $Q(V_R)$ behaviors are shown in Fig. 5. The $C(V_R)$ behavior exhibits a straight line in the logarithmic plot as a function of reverse voltage, indicating a near-ideal exponential $C(V_R)$ relationship. The measured quality factor is 43 at zero bias. However, at 11.5 V, the $Q$ has already increased to 192, indicating the advantage of copper plating. Above 11.5 V, the varactor suffers from a steep increase in leakage current due to imperfections in the epilayer; this restricts its useable voltage range, and consequently, also the upper limit for $Q$.

**B. Linearity Measurement of the Wide Tone-Spacing Varactor Stack**

To verify the linearity of the wide tone-spacing varactor stack, we have measured the shunt wide tone-spacing varactor stack with an effective zero bias capacitance of 10 pF in a two-port configuration using a 500-kΩ resistive center-tap connection (see Fig. 6).

The linearity testing is performed using a two-tone signal ($f_{center} = 2$ GHz) with varying tone spacing [25]. Fig. 7 plots the measured distortion components at $2f_1 - f_2$ as a function of output power for different values of tone spacing. It can be observed that the linearity improves with the increase of tone spacing and a superior linearity over that of the single diode is obtained for a tone spacing higher than 10 MHz. Note that the linearity at high tone spacing is comparable to that of the measurement setup as shown for the tone spacing of 10, 30, and 80 MHz in Fig. 7. Since at these linearity levels it becomes difficult to separate the nonlinearities resulting from the varactors from that of the measurement setup, a conservative boundary of trust is marked as “measurement limitation” in Fig. 7 and the...
Fig. 12. Simulated linearity contours and measured linearity points as function of the source impedances of the remaining IM5 components in the source current at $2f_1 - f_2$ in dBc for different values of tone spacing. The envelope peak voltage over the varactor stack is kept constant at 8 V (effective zero bias capacitance = 10 pF, inductance at terminations = 20 nH, $f_{center} = 2$ GHz, $\alpha_1 = 0.0896$ V$^{-1}$, and $V_T = 5$ V). (a) Tone spacing = 1 MHz, (b) Tone spacing = 10 MHz, (c) Tone spacing = 40 MHz, (d) Tone spacing = 52 MHz.

following figures. Consequently, conservatively speaking, the OIP3 will be larger than 56 dBm for a tone spacing larger than 10 MHz. Note that we use here OIP3 rather than IIP3 since a significant part of the input power will be reflected by the varactor shunt impedance. Therefore, the output power level is a better measure of the actual RF voltage over the varactors. It is this voltage that determines the resulting IM3/IM5 levels [see (9) and (10)].

Normally, it is handy to consider the $2f_1 - f_2$ or $2f_2 - f_1$ components as function of power (in dBc) to verify if the third-order distortion is truly cancelled and only IM5 distortion remains. Note that for this condition, a 4:1 slope should be found. However, in our experiments the distortion level is so low that this phenomenon is difficult to verify experimentally. Fortunately, we also implemented varactor stacks with an area ratio of 1.9 instead of 3.7, which we have tested for their linearity as reference. These devices have a 50% area ratio offset with respect to the ideal ratio needed for IM3 cancellation. By comparing the linearity of the ideal wide tone-spacing varactor stack with these structures, the IM3 cancellation was verified. As shown in Fig. 8, the correctly dimensioned wide tone-spacing varactor stack clearly offers superior performance over the wide tone-spacing varactor stack with 50% area ratio offset, especially for the tone spacing larger than 10 MHz.
C. Linearity Measurement of the Narrow Tone-Spacing Varactor Stack

The wide tone-spacing varactor stack configuration offers a complementary linearity solution to the narrow tone-spacing varactor stack [19]. When diode leakage currents are small, the center-tap impedance conditions are relative easily implemented through the use of a high valued resistor and potentially antiparallel diodes. Such a network can be implemented in a relatively small area. Therefore, for most situations, the complete wide tone-spacing varactor stack structure can be made more compact than the narrow tone-spacing varactor stack, which requires low impedance baseband connections, often implemented as inductors.

As addressed in [19], the narrow tone-spacing varactor stack offers the highest linearity for narrowband signals and has been implemented, in this study, on the same wafer as the wide tone-spacing varactor stack. Note that this structure is less sensitive to diode leakage currents and is more suitable for fast modulation of the center-tap voltage. Due to the more favorable splitting of the RF voltage over the antimeras varactor diodes, the narrow tone-spacing varactor stack power handling is better than that of the wide tone-spacing varactor stack. It is these properties that make it an excellent choice for the implementation of adaptive transmitters, capacitive modulators or even dynamic load-line amplifiers.

To test the linearity of the narrow tone-spacing varactor stack and compare it to the wide tone-spacing varactor stack, a two-port configuration of a shunt 10-pF narrow tone-spacing varactor stack with 20-nH terminations is used (Fig. 9). This configuration is measured using a two-tone signal ($f_{\text{center}} = 2$ GHz) with varying tone spacing. Fig. 10 plots the measured distortion component at $2f_1 - f_2$ as a function of output power for different values of tone spacing. It can be observed that the linearity improves with decreasing tone spacing. Again, the measurement accuracy is limited by the measurement system nonlinearities, while conservatively speaking, the OIP3 $> 57$ dBm up to 30-MHz tone spacing.

In order to confirm that the narrow tone-spacing varactor stack can provide superior linearity for any surrounding circuit condition, the source–pull setup of Fig. 11 is used. In these experiments, the two-tone source voltage ($V_s$) is adjusted with the tunable source impedance such that for all loading conditions the voltage amplitude over the varactor ($V_{\text{varactor}}$) stack is kept close to $4$ V for each tone yielding an envelope peak voltage of $8$ V. Since the varactor stack is reverse biased at $5$ V and the RF voltage will split over the varactor diodes, the diodes are operated close to their maximum voltage swing, but will remain reverse biased at all times. The frequency components of the resulting source current are used to monitor the linearity of the varactor. Due to the fact that the inductors satisfy the low-impedance requirements for the baseband signals, source independent IM3 cancellation takes place. The remaining IM5 components in the external current at $2f_1 - f_2$ in dBc, relative to the fundamental, has been simulated as function of the source impedance and plotted as contours of constant distortion for different values of tone spacing (Fig. 12). From these results, we conclude that the narrow tone-spacing varactor stack element in this experiment provides an $\text{IM}5 < -60$ dBc for any source impedance up to 10 MHz bandwidth. At higher tone spacing (40 and 52 MHz), the linearity degrades as expected. Since the linearity of the varactor outperforms that of the measurement setup in most of the conditions, only several points can be accurately measured for a tone spacing of 40 and 52 MHz. These measured results are also indicated in Fig. 12(c) and (d) and confirm the trend of the simulated linearity. Note that a slightly inductive source yields the “worst” linearity since, in combination with the capacitive varactor stack, it provides a close to perfect ac short causing all available nonlinear current to flow through the source.

D. Overview of the Narrow Tone-Spacing Varactor Stack and Wide Tone-Spacing Varactor Stack

In order to complete our overview for the linearity of the narrow tone-spacing varactor stack and wide tone-spacing varactor stack, we plot the measured and simulated distortion component at $2f_1 - f_2$ as a function of tone spacing at an output power level of 15 dBm (Fig. 13).

According to the simulation results, the wide tone-spacing varactor stack starts to offer better linearity than the narrow tone-spacing varactor stack above 5 MHz tone spacing for the center-tap impedances indicated. Note that the implementation of the center-tap impedance determines the linearity bandwidth. For example, when using a higher impedance for the wide tone-spacing varactor stack center tap (now 500 kΩ), the high linearity operation can be extended to much lower frequencies. Taking the influence of the leakage current into account, the measurement results of the wide tone-spacing varactor stack
match the simulation quite well. It can be observed that for the wide tone-spacing varactor stack structure the presence of the leakage currents will cause a modulation of the center-tap voltage for narrow tone spacing, resulting in linearity degradation. Even if so, the combination of the narrow tone-spacing varactor stack and wide tone-spacing varactor stack provide a superior linearity (below the measurement limitation: \(-80\) dBc) for the whole range of the tone spacing, making them very attractive candidates for many RF applications.

IV. CONCLUSION

For the first time, two extremely linear varactor configurations for tunable RF applications have been successfully implemented in a single silicon-on-glass process technology. When considering their linearity versus tone spacing, the wide tone-spacing varactor stack and the narrow tone-spacing varactor stack design approaches offer complementary linearity behavior, with the wide tone-spacing varactor stack performing best with wide-tone spacing and the narrow tone-spacing varactor stack performing best with narrow tone spacing. This makes them very suitable to handle the different requirements of adaptive receivers and transmitters in a single varactor technology. Due to the almost perfect control of the doping profile and ohmic contacts, a close to ideal exponential \(C(V_R)\) relation and quality factor were realized. This accurate \(C(V_R)\) behavior yielded a measured linearity performance of OIP3 > 56 dBm for the wide tone-spacing varactor stack and OIP3 > 57 dBm for the narrow tone-spacing varactor stack, which is compatible with the requirements of most demanding wireless applications. Their usability in practical circuit conditions was demonstrated through source-pull simulations and measurements, illustrating that high linearity can be maintained in all cases. Their integration capabilities, compact size, high reliability, low-cost implementation, high speed, high quality factor, and free to choose tuning and control voltage range make them very interesting components for the implementation of ultra-linear high-performance adaptive RF systems.

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REFERENCES

and SBMicro.

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