Millimeter-wave Mixers for High Capacity Digital Radio Links

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ABSTRACT

This paper attempts to review the causes of nonlinearity in a resistive FET and anti-parallel diode pair mixers. Mixer linearity and spurious response are very important for high performance radio links. It has been found that the symmetry in the current-voltage characteristic and the reactive elements are the key to tackling intermodulation distortion generated in field-effect transistors. In an anti-parallel diode pair mixer, the intermodulation distortion is generated primarily by the nonlinear resistance and the local oscillator spurious signals are caused by asymmetry in the nonlinear capacitance. These insights supported by analysis are useful in formulating strategies and methodologies for improving mixer performance. Any performance enhancement achievable in these mixers will lead to cost-efficient radios.

INTRODUCTION

Telecommunication regulations worldwide require digital radio systems to be judicious in their usage of the available bandwidth. The choice of modulation scheme not only determines the bandwidth but also the bit-error rate and the robustness of the system to channel imperfections such as phase noise, nonlinearity, multi-path fading and dispersion. Correct choice of modulation scheme is crucial in the design of bandwidth-efficient digital radio systems. Demand for higher data-rates and need for regulatory compliance have helped quadrature-amplitude modulation (QAM) become one of the more dominant modulation schemes in various applications such as satellite communications, digital microwave links and point-to-point radios [1], [2], [3].

One of the critical requirements for a QAM-based system is the need for linearity. Distortion results in errors in QAM constellation diagram and compromises the integrity of the signal by degrading the signal-to-noise ratio. The nonlinearity in a mixer manifests in the form of unwanted distortion products. A mixer often sets the lower bound on the linearity of a transmitter making its performance critical to the design of QAM-based radios. Improved mixer linearity also allows transmitter operation at higher signal level removing the need for amplification in the signal path, further minimising components, cost and power consumption. In a receiver improved mixer linearity leads to higher low-noise amplifier gain, resulting in improved overall noise figure, threshold and dynamic range.

Mixer requirements are also determined by other aspects of radio performance. Some of these requirements are driven by market forces. One such critical force is radio system gain, which in conjunction with antenna gain, frequency and geographic location (which determines the rainfall patterns) sets the trade-off between radio link availability (subject to outages resulting from rain fade, wind, multi-path and equipment failure) and range for a given data rate and occupied bandwidth. Other requirements are driven by regulatory requirements such as adjacent channel interference in transmitters, dynamic range and susceptibility in receivers. Additional requirements can also arise out of the demand for reducing the complexity and thereby the cost of a radio.

The fundamental issues that have to be dealt with in efforts to improve radio performance and cost are linearity and spurious performance. The level of intermodulation distortion generated by a mixer is directly related to the mixer linearity. The third-order intermodulation distortion products pose concerns to the radio system, as they fall in the system passband causing interference and cannot be removed by filtering. The spurious product that necessitates increased

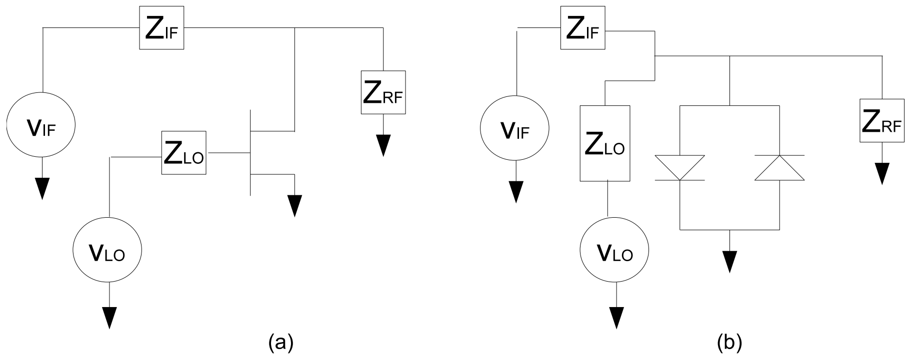


Fig. 1. Topology of (a) resistive FET mixer and (b) sub-harmonically pumped APDP mixer

amount of filtering is the local oscillator (LO) breakthrough. Lower level of spurious generation helps in the reduction of complexity and subsequently lower the cost, by decreasing the need for filtering and associated circuitry required in the signal path.

Two classes of mixers are considered in this paper. The first is a Field-effect transistor (FET) resistive mixer and the second is a sub-harmonically pumped anti-parallel diode pair (APDP) mixer. FET resistive mixers owing to their less onerous requirements on LO power have reduced level of LO spurious generation. FET resistive mixers also rely less on nonlinearity for mixing resulting in high linearity. Sub-harmonically pumped APDP mixers have inherent doubling of the LO frequency resulting in reduced LO spurious generation.

The paper investigates the performance issues of FET resistive mixers and APDP mixers in the context of radio performance, reducing complexity and lowering cost. The section mixers, introduces the operation of FET resistive mixers, explores the fundamental concepts, strengths and weaknesses. Anti-parallel diode pair mixers, their advantages, limitations are also elaborated. The analysis section contains a concise treatment of the nonlinear mechanisms present in FET resistive mixers, APDP mixers and the impact of nonlinearity on mixer performance.

MIXERS

Resistive FET Mixers

The resistive FET mixer achieves frequency translation through the use of a FET channel to provide a time-varying conductance. LO is applied to the gate of the FET to provide the varying conductance seen by the intermediate frequency (IF) signal applied at the drain, as show in Fig. 1.

Low intermodulation distortion is a result of the fact that the FET channel is nearly a purely linear resistance at the $V_{DS} = 0$ bias applied throughout the whole LO range. The effect can be seen in the simplified case in Fig. 4(a) where the dynamic load line is plotted on the FET drain IV, showing that throughout most of the mixing process the IF sees a linear conductance. The result is a reduction to the extent to which spectral components of the applied IF signal can intermodulate, preventing intermodulation distortion in the ideal case. In real devices, there is a small degree of non-linearity present, however, despite this, the linearity achieved remains better than other mixer topologies where the IF signal is presented to a highly non-linear conductance.

The trade-off for this high linearity is LO breakthrough. By biasing the drain at $0V_{DC}$ the gate-drain capacitance (C_{GD}) becomes a better path for the LO signal to propagate to the drain.

High linearity and adversely high LO breakthrough make this mixer topology most suited to low noise receivers. In transmitters, the high LO breakthrough becomes problematic and is a major hurdle for use in direct conversion or low frequency IF systems where output RF is very close to LO increasing filtering complexity.

Anti-Parallel Diode Pair Mixers

An APDP mixer requires half the LO frequency required in frequency translation. It gets progressively harder generating increased LO drive power as frequency of operation increases. APDP mixers alleviate the difficulties associated with generating adequate drive power at millimeter-wave frequencies. An APDP mixer contains two Schottky diodes connected in an anti-parallel arrangement and associated filtering and matching as shown in Fig. 1b. They generally have a low magnitude of even-order products (LO breakthrough, dc offsets) at the output and are therefore preferred in direct-conversion and low-IF conversion systems. APDP mixers also have the advantage of LO noise sideband suppression. They can withstand large inverse peak-to-peak voltages as the forward biased diode protects the reverse biased diode [4], [5], [6].

Owing to the strong nonlinearity of the Schottky diodes, APDP mixers generate significant amount of intermodulation distortion products. Any mismatch in the diodes can also lead to increased magnitude of even-order products such as LO breakthrough and dc-offsets alike. Major compensating advantages of an APDP mixer include its inherent balance that helps in rejecting the problematic LO spurious generation without the need for transformers. Research on APDP mixers to date has largely focused on the conversion efficiency, noise figure and inter-port isolation aspects [6], [7], [8]. Very little work has been done in investigating the two critical issues of third-order intermodulation distortion (IMD) and LO breakthrough.

ANALYSIS

Intermodulation Distortion in Resistive FET Mixers

This mixer uses a two port non-linearity, with one port strongly excited and the other weakly to strongly depending on input signal power level. This combination presents a challenging mathematical problem to solve. There is a large pool of research into the fundamental limits on mixer performance [9], [10] and some excellent work to simplify the problem [12], however, all these works focus on conversion efficiency, neglecting distortion. Other methods of analysis exist that do handle intermodulation distortion and have proven to provide an excellent match between simulation and measurement [11]. These methods resort to numerical techniques to derive a solution, hiding the analytical link between intrinsic FET parameters and their effect on linearity.

Using the analysis method presented in [13], Fig. 2(a) and Fig. 3(a) show the effect that a small amount of channel non-linearity has on intermodulation distortion. This isolates the linearity of the drain conductance and its effect on intermodulation and shows the dramatic effect that channel linearisation can produce. There is, however, another method for input spectral components to mix and that is through the C_{GD} path to the gate. Here transconductance (g_m) non-linearity is involved and this is extremely non-linear during parts of the LO cycle. Since input power (P_{in}) is significantly small and that there will be attenuation through C_{GD}, followed by conversion loss in mixing due to the transconductance results in g_m-based mixing being a minor contributor of distortion and can therefore be ignored.

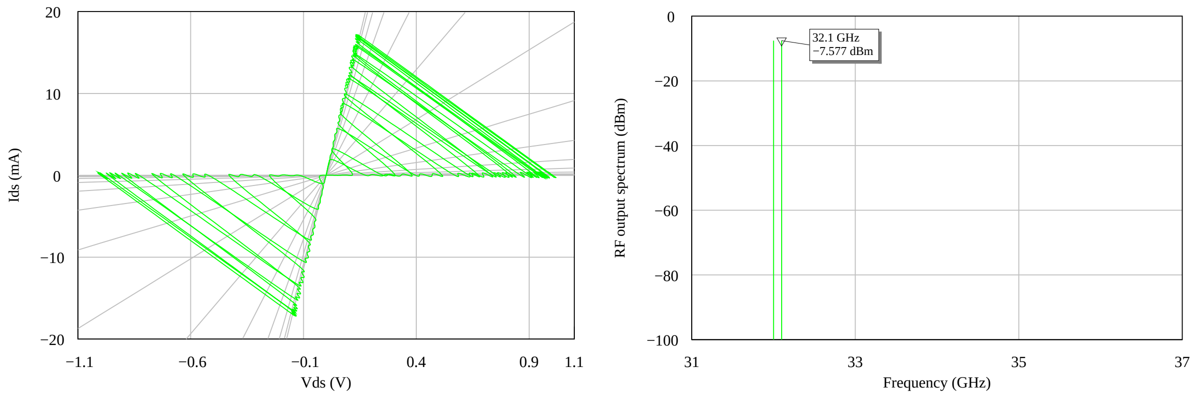
Based on the above analysis, and the fact that no distortion is generated in Fig. 2(a), it can be concluded that distortion in resistive FET mixers is mostly a result of drain conductance (g_{DS}) non-linearity during periods of the LO cycle between cut-off and maximum drain-source conduction, in the same manner in which distortion is generated in diode based mixers.

Unlike Fig. 3(a), the FET is symmetric in nature (Fig. 4(a)). To mathematically give this symmetry (1) must be obeyed.

$$i_D(v_{GS}, v_D) = -i_D(v_{GS} - v_D, -v_D) \tag{1}$$

However, to linearise the channel we want 2 to hold with G_n negligible for $n > 1$.

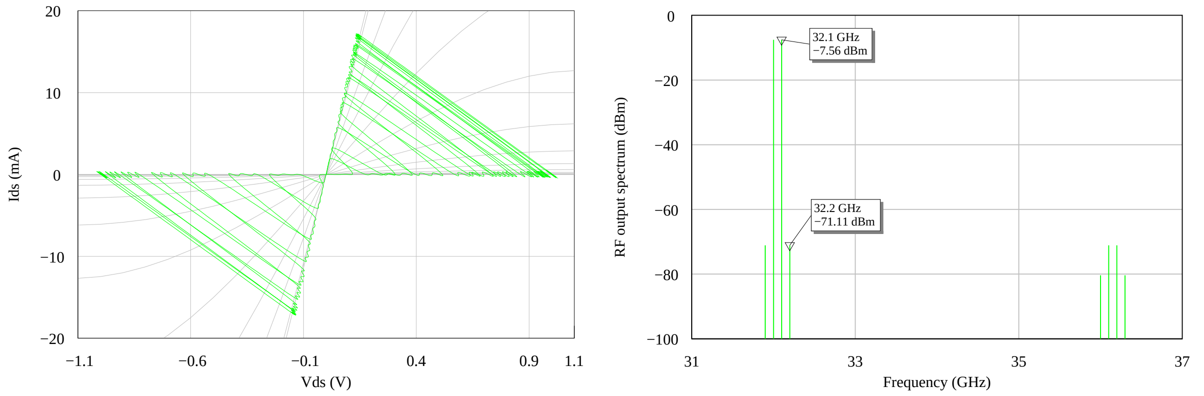
$$i_D(v_{GS}, v_D) = (\sum_n G_n v_D^n) f(v_{GS}) \tag{2}$$



(a) Modelled DC IV with overlayed dynamic response

(b) Spectrum at RF output. Intermodulation is below numerical noise floor

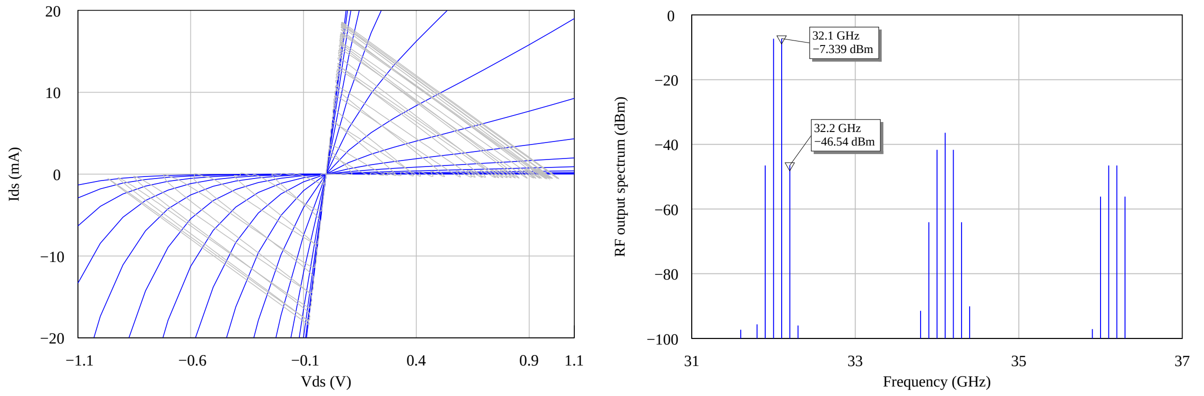
Fig. 2. Simplified linear model of drain conductance



(a) Modelled DC IV with overlayed dynamic response

(b) Spectrum at RF output

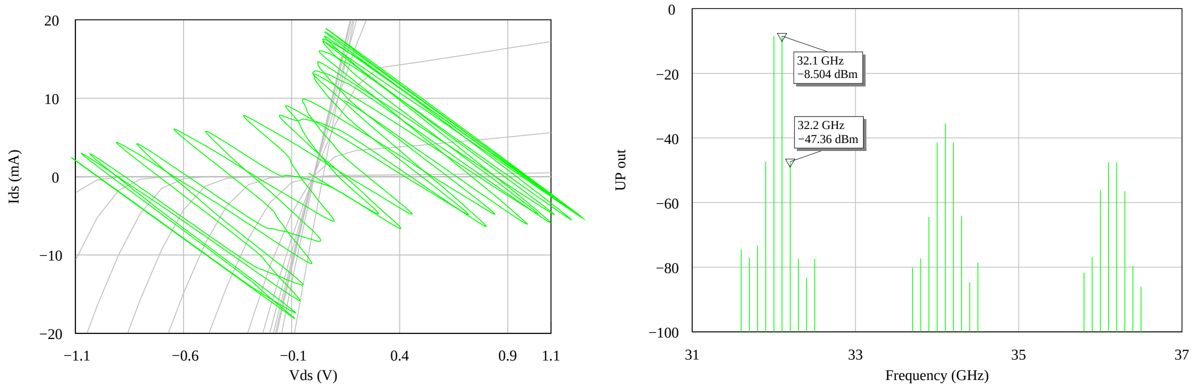
Fig. 3. Small amount of 3rd order non-linearity added to drain conductance has significant effect on intermodulation



(a) Modelled DC IV with overlayed dynamic response

(b) Spectrum at RF output

Fig. 4. Symmetric simplified model with drain conductance non-linearity through symmetry alone



(a) Modelled DC IV with overlayed dynamic response

(b) Spectrum at RF output

Fig. 5. Response with accurate full large signal model of 2x75 pHEMT device

Substituting 2 into 1 and simplifying gives the relation 3.

$$G_1 v_D \left[f(v_{GS}) - f(v_{GS} - v_D) \right] = 0 \tag{3}$$

This shows that a single symmetric device inherently has some non-linearity in the channel, resulting in intermodulation distortion. Symmetric FET IV from equations of the form in 1 is shown in Fig. 4. This more closely matches the DC response shown in Fig. 5(a) which depicts the response of a very accurate FET model. The model used has been verified against measurements in [14]. As can be seen in Fig. 4, the largest non-linear region is not at $V_{DS} = 0$, instead a small amount of V_{DS} bias can be seen to provide a situation where there is linearity over a larger range of P_{in}. This result agrees with the results thoroughly derived in [15].

More importantly, the analysis suggests that a static V_{GS} analysis of g_{DS} non-linearity, which is a simple weakly non-linear case amenable to volterra analysis, may provide a sufficiently accurate analytic solution and is the subject of future work.

Nonlinearity in APDP Mixers

Nonlinear circuits such as an APDP mixer, under multi-tone excitation are analysed by Harmonic Balance (HB) technique. Analysis of distortion in an APDP mixer requires either a nonlinear model of the diode pair or a non-linear model for each diode, in addition to the frequency domain representation of the surrounding linear networks. The often used formulation of the diode nonlinearity is the SPICE diode model, initially implemented for the transient analysis simulator, SPICE [16]. The same model has been translated for use in commercial HB simulators. HB analysis of mixer circuits incorporating the SPICE diode model is the dominant means of analysing mixer response to two-tone excitation.

But such an analysis based on SPICE diode model reveals no insights into how nonlinearities behave and which nonlinearities are responsible for what distortion products. More ever incorporating the LO-spurious causing diode-imbalance of an APDP by means of a SPICE formulation is cumbersome and it also requires precise knowledge of parameters causing the imbalance or mismatch. It is important to understand the role of nonlinearities, as it may help in devising techniques to tackle distortion and LO spurious. Insights so gained, may also help in identifying physical aspects of the diode that influence the strength of the nonlinearities. The nonlinearity of a diode is represented by a one-terminal voltage-dependent resistance and a one-terminal voltage-dependent capacitance as shown in (4) and (5). These equations form the basic frame work of the SPICE model and other formulations as such.

$$i(v) = I_s \left[e^{v/v_T} - 1 \right] \tag{4}$$

$$c(v) = \frac{c_{jo}}{\sqrt{1 - \frac{v}{\phi_{bi}}}} \tag{5}$$

The diode voltage is denoted by v, saturation current by I_s and diode thermal voltage by v_T in (4). The term c_{jo} in (5) is the zero-bias junction capacitance and ϕ_{bi} is the built-in diode potential [17]. These equations when adapted to the case of an anti-parallel diode pair result in (6) and (7). The format of (6) and (7) show an odd-symmetry in the current-voltage characteristic and an even-symmetry in the capacitance-voltage characteristic.

$$i(v) = I_s \left[e^{v/v_T} - e^{-v/v_T} \right] \tag{6}$$

$$c(v) = \frac{c_{jo}}{\sqrt{1 - \frac{v}{\phi_{bi}}}} + \frac{c_{jo}}{\sqrt{1 + \frac{v}{\phi_{bi}}}} \tag{7}$$

These functions do not analytically convey a great deal of information about the non-linear dynamics of the anti-parallel diode pair. Such information can be better gleaned by representing the nonlinear resistance and the non-linear capacitance by polynomials. Modeling physical phenomenon such as non-linearities and resulting distortion in APDP mixers with polynomials is not without pitfalls. Polynomial functions generally tend to be valid over a finite range and beyond this range they can take values that are non-physical. But the conditions under which an APDP mixer operates, such as finite range of large-signal LO usually encountered in practice means modeling distortion with polynomials is a legitimate approach.

In theory, anti-parallel connection of two Schottky diodes results in a current-voltage characteristic with odd-symmetry and a capacitance-voltage characteristic with even-symmetry. These characteristics can be approximated by the polynomials functions in (8) and (9). The terms a, b, c, d, e, f are the coefficients of current-voltage relationship and the terms c_0, c_2, c_4, c_6, c_8 are the coefficients of capacitance-voltage function. Odd symmetry of the current-voltage characteristic results in a function with only odd-power terms and the even-symmetry results in a capacitance function with only even-power terms. It should be noted that a capacitance-voltage function with even-power terms is equivalent to a charge-voltage function with odd-power terms. As a result APDP mixers should not produce any even-order products.

$$i(v) = av + bv^3 + cv^5 + dv^7 + ev^9 + fv^{11} \tag{8}$$

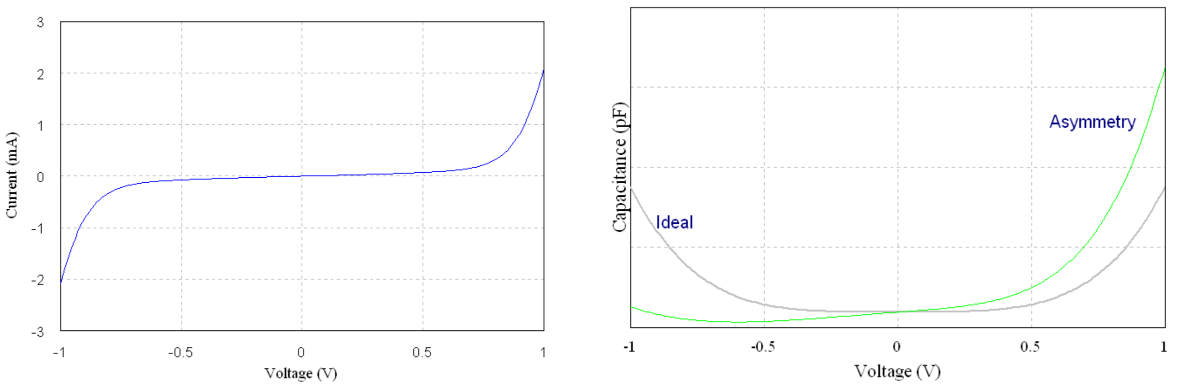
$$c(v) = c_0 + c_2 v^2 + c_4 v^4 + c_6 v^6 + c_8 v^8 \tag{9}$$

But in reality this is not true as LO breakthrough and dc-offsets are present at the output owing to diode imbalance or mismatch. To truly represent the real behaviour of an APDP mixer either or both of the functions shown in (8) and (9) should be modified to include the LO-breakthrough inducing diode-mismatch. Whether asymmetry must be added to either one or both of (8) and (9) is a subject of further investigation.

Based on the a polynomial formulation implemented to match the measured performance of a real APDP mixer, inclusion of asymmetry to the capacitance function of (9) as shown in (10) is necessary to account for the measured LO breakthrough. Modified C-V polynomial formulation of (9) shown in (10) along with the I-V polynomial of (8) has been used to accurately predict the IMD performance, conversion efficiency and LO breakthrough of a real APDP mixer across a finite range of LO drive powers and frequencies [18]. The I-V characteristic of a real APDP mixer using the odd-function in (8) can be seen in Fig. 6(a). The asymmetry present in the capacitance-voltage characteristic can be seen in Fig. 6(b) in the backdrop of the ideal characteristic. The accuracy of this modified polynomial formulation diminishes beyond a certain LO drive power as can be seen from the measured and simulated output spectrums of the real APDP mixer shown in Fig. 7(a) and Fig. 7(b) [18].

$$c(v) = c_0 + c_1 v + c_2 v^2 + c_3 v^3 + c_4 v^4 + c_5 v^5 + c_6 v^6 + c_7 v^7 \tag{10}$$

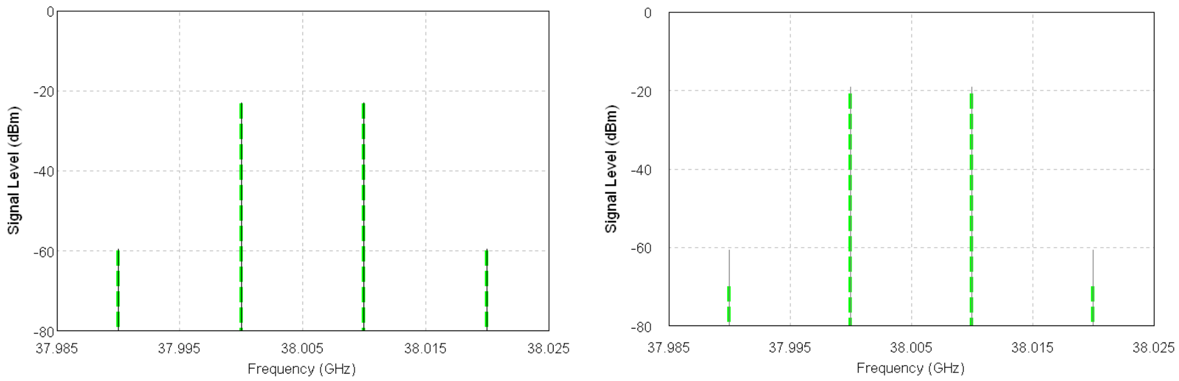
The presence of odd-symmetry in the I-V function results in the generation of odd-order products such as fundamental frequency converted product and the third-order intermodulation distortion products. Asymmetry in capacitance seems to be a probable cause of LO breakthrough and dc-offsets. Although the capacitive nonlinearity owing to the asymmetry



(a) Modelled dc IV

(b) Asymmetry in CV characteristic

Fig. 6. Simulated odd-symmetry in current-voltage characteristic and asymmetry in the capacitance-voltage characteristic of an APDP mixer.



(a) APDP Spectrum at an LO drive power of +12dBm

(b) APDP Spectrum at an LO drive power of +16dBm

Fig. 7. Super-imposed measured and simulated output spectrums of an APDP mixer showing the upper and lower fundamental frequency-converted products and the third-order products. Diminishing accuracy of the model evident at higher LO drive levels.

does contain even-order terms (corresponding charge function contains odd-order terms) capable of producing the third-order distortion products, the magnitude of these terms is quite small that their contribution is marginal. The nonlinear resistance and nonlinear capacitance both produce complimentary, albeit different distortion products in an APDP mixer. The format of these analytical functions in (8) and (10) verified against measurement in [18] point to the nonlinear resistance being the dominant mechanism of intermodulation distortion generation and the capacitance being the primary cause of LO breakthrough.

Based on the above analysis, it may be possible to optimise diode size, doping concentration and number of fingers for improved LO breakthrough performance. Changing these parameters may also affect mixer linearity, resulting in a trade-off with the spurious LO. The standard diode figure of merit 'f_T' commonly used is inadequate for the purpose of assessing APDP mixer linearity or LO spurious performance. To truly understand the relationship between diode size, mixer linearity and LO breakthrough it is necessary to devise a new figure of merit.

There must also exist a trade-off between conversion efficiency and spurious LO reduction. Conversion efficiency is very much a factor of diode access resistance (series resistance) and it is difficult to affect diode capacitance one way or another without changing access resistance. Conversion efficiency is tradeable for improved LO spurious performance particularly in transmitters, where loss in signal can be offset elsewhere in the chain without losing significant savings brought on by reduction in filtering. In the case of a receiver this is less desirable as degradation in conversion gain results in increased noise figure.

CONCLUSION

The effect of non-linearity in FET drain conductance and how device symmetry contributes to this has been investigated. This has identified two key design focuses for further increasing linearity in resistive FET mixers; channel linearisation and a move away from a symmetric mixing element.

The current-voltage characteristic of an APDP mixer is the primary contributor of intermodulation distortion where as the asymmetry of capacitance-voltage characteristic is the cause of LO spurious.

The causes of distortion so identified in both these types of mixers, help lay the foundation for further work on optimising the device properties for improved mixer performance which will translate to improved radio performance.

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References

[1] A.Burr, “Modulation and Coding for Wireless Communications,” Prentice Hall/Pearson Education, 2001

[2] J.Bellamy, “Digital Telephony,” Second Edition, John Wiley and Sons, NJ, USA, 2003

[3] R.L.Freeman, “Telecommunication System Engineering,” Third Edition, John Wiley and Sons, New York, NY, 1996

[4] M.V.Schneider and W.W.Snell Jr., “Harmonically pumped stripling downconverter,” *IEEE Trans. MTT*, vol. 23, pp. 271-275, Mar1975.

[5] M.Cohn, J.E.Degenford and B.A.Newman, “Harmonic Mixing with an Antiparallel Diode Pair,” *IEEE Trans. MTT*, vol. 23, pp. 667-673, Aug 1975.

[6] K.Itoh, A.Lida, Y.Sasaki and S.Urasaki, “A 40GHz Band Monolithic Even Harmonic Mixer With An Antiparallel Diode Pair” IEEE MTT-S IMS Digest pp.879-882, 1991

[7] H.Okazaki and Y.Yamaguchi, “Wide-band SSB Subharmonically Pumped Mixer MMIC” IEEE Trans. Microwave Theory Tech., vol. MTT-45, no.12, pp.2375-2379, Dec 1997

[8] W.Chen, S.Chen, J.Tsai, T.Huang and H.Wang, “A 38-48-GHz Miniature MMIC Subharmonic Mixer” EGAAS 2005 pp.437-440, Oct 2005

[9] Alexander J. Kelly, “Fundamental Limits on Conversion Loss of Double Sidelband Resistive Mixers,” IEEE Trans. Microwave Theory Tech., vol. 25, no.11, pp.867-869, Nov 1977

[10] A. A. Saleh, “Theory of resistive mixers,” Research Monograph #64, The MIT Press, Cambridge, MA.

[11] Richard B. Swerdlow, “Analysis of Intermodulation Noise in Frequency Converters by Volterra Series,” IEEE Trans. Microwave Theory Tech., vol. 26, no.4, Apr 1978.

[12] Klas Yhland, “Simplified Analysis of Resistive Mixers,” IEEE Microwave and Wireless Components Letters, vol. 17, no. 8, pp.604-606, Aug 2007.

[13] L. Powles, A. E. Parker and Simon J. Mahon, “Linearity Asymmetry in FET Resistive Mixers,” Proceedings of SPIE on Microelectronics, MEMS and Nanotechnology, Dec 2007.

[14] James Brinkhoff, Anthony E Parker, Simon J Mahon, and Gerry McCulloch, “Symmetric Hemt Drain Current Model For Intermodulation Distortion Prediction,” Workshop on Applications in Radio Science, NSW, Australia, 15-17 Feb. 2006.

[15] J. A. Garcia et. al, “Resistive FET Mixer Conversion Loss and IMD Optimization by Selective Drain Bias,” IEEE Trans. Microwave Thoery Tech., vol. 47, no. 12, Dec 1999.

[16] G.Massobrio and P.Antognetti, “Semiconductor Device Modeling With SPICE,” Second Edition, McGraw Hill Professional, USA, 1993.

[17] S.Maas, “Nonlinear Microwave and RF Circuits,” Artech House, Boston, MA, 2003

[18] V.Gutta, A.Fattorini, A.E.Parker and J.Harvey, “Nonlinearity of Anti-Parallel Schottky Diodes For Mixer Applications,” Proceedings of SPIE on Microelectronics, MEMS and Nanotechnology, Dec 2007.