Harmonic Boosting for High Performance Mixers

Sudipto Chakraborty[1], Ching-Lang Lin[1], Babak Matinpour[2] and Joy Laskar[1]
[1]Yamacraw Design Center, School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta GA 30332 USA
Fax:(404) 894-5028, Email; sudipto@ece.gatech.edu

[2]RF Solutions Inc., Atlanta GA-30309 USA

Abstract: **We propose a novel harmonic boosting technique for development of high performance subharmonic mixers. This technique alleviates major problems associated with the use of 4th and higher order subharmonic mixers. By utilizing the odd-order harmonics of the main subharmonic LO, we demonstrate significant performance improvements while reducing the LO power. Measurements confirm a 6-dB savings in LO power level, up to 10-dB improvement in output P1dB and upto 6-dB improvement in conversion loss. Measurements also confirm that harmonic boosting does not degrade in-band LO leakage, IIP2 and dc offset levels, thus favoring its application in very-low-IF and direct conversion transceivers.**

Index Terms: **Harmonics, APDP, Mixers, Direct Conversion, VLIF, SOC.**

I. Introduction

With the tremendous growth of wireless communication industry, and migration to higher frequency and bandwidth, the need for better high frequency mixing techniques is becoming more and more significant. As a result, subharmonic mixing techniques, which were historically used for millimeter-wave applications, are no longer strangers to mainstream wireless applications such as cellphone and wireless local area network (WLAN) systems [1,2,3]. Subharmonic passive mixers that exhibit excellent linearity performance are becoming even more attractive for the next generation wireless hardware. However, one difficulty in integrating passive mixers on chip is the requirement of high LO power, which not only leads to significant problems through radiation and substrate coupling but also increases the power consumption of the LO buffers. This paper presents the development of a novel harmonic boosting technique that allows to reduce the main subharmonic LO frequency and reduce the LO power requirement.

Although our proposed technique is applicable to most subharmonic mixers, in this paper we are limiting the scope of our discussions to a basic mixer core consisting of an antiparallel diode pair (APDP) structure. Antiparallel diode pair topology has shown a great deal of potential in the past and has been well studied and implemented in practical receivers [1,2,4,5,6]. Earlier implementations of passive mixers based on APDP topology [1,2] focus only on its 2nd subharmonic operation which is quite suitable for low RF input frequencies (up to 6 GHz). As the RF frequency gets higher, on-chip integration of high quality oscillators becomes difficult. This provides the motivation to investigate techniques that allow the mixer core to operate at higher subharmonics (lower LO frequencies). However, the conversion loss and linearity performances achieved by application of single tone LO operating at 4th and 8th subharmonics are not very attractive as their contribution is less significant compared to the 2nd order subharmonic LO tone [7,8,9]. These performances can be greatly improved by inclusion of the third harmonic tone of the higher order subharmonic LO frequency under application (4th or 8th subharmonics in this case). Combining tones also helps reduce the LO power level requirement on the individual tones, thus favoring on-chip integration of such mixers for wireless transceiver applications. This proposed technique is referred to as "harmonic boosting" and exhibits lower conversion loss and higher linearity compared to the 2nd subharmonic operation of APDP based passive mixers.

The paper is organized as follows. First, the harmonic boost technique is presented with detailed analysis. Then the performance improvements achieved by harmonic boosting in terms of conversion loss and linearity is presented. These performance improvements are based on APDP circuit fabricated in a commercially available GaAs MESFET technology.

II. Harmonic Boosting Theory

Fig. 1 shows the basic APDP structure, along with a die photograph fabricated in Triquint's GaAs MESFET process. The total output current contributed by an APDP circuit with an input voltage waveform of $V_{LO}\cos(\omega_{LO}t)+V_{RF}\cos(\omega_{RF}t)$ is given by [1],

$$i = 2\alpha i_s \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} F(m,n,V_{lo},V_{rf})\cos(m\omega_{lo} \pm n\omega_{rf})t \qquad (1)$$

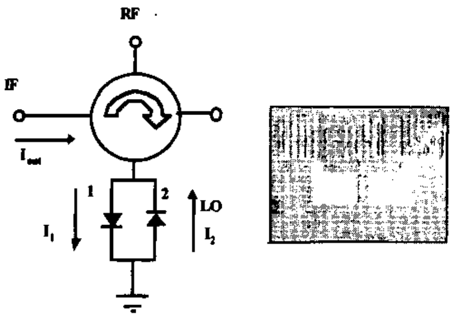

Fig. 1. APDP mixer core and die photograph

where $m+n$ is an odd integer, V_{LO}, V_{RF} are the amplitudes of LO and input RF voltages respectively, and $F(m,n,V_{LO},V_{RF})$ is a function depending on the mixing orders m,n and involves modified Bessel function terms. α is diode slope parameter ($\alpha \approx 38V^{-1}$) and i_s is the saturation current. The output current of APDP under single tone operation is denoted by $i_{-} = 2\alpha i_s I_k(\alpha V_{lo})\cos\{(2\omega_{lo} - \omega_{rf})t\}$, where k denotes the subharmonic order. The first few terms in the modified Bessel function series ($I_n(\alpha V_{LO})$), form a slowly decreasing sequence, with typical values of $V_{LO} = 0.6$ and $\alpha = 38$. Hence, as "k" increases from 2 to 4 and 8 (implying 4th and 8th order subharmonic operation), the conversion loss performance degrades.

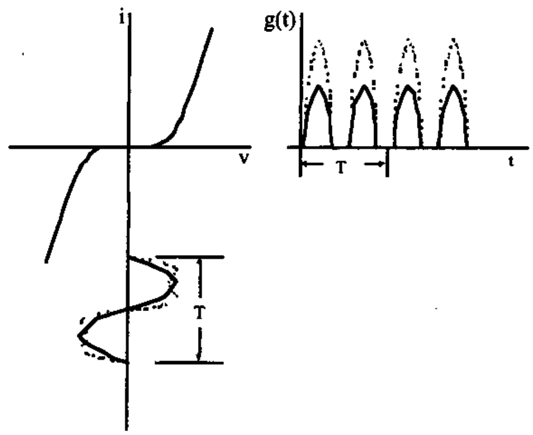

Fig. 2. Transconductance variation of APDP core with single tone LO (solid line) and harmonic boosting(dashed line)

However, if the LO voltage waveform approaches to the shape of a square wave, the Schottky diodes switch more efficiently and thus both conversion loss and linearity performances improve. The first two terms in the Fourier series expansion of a square wave contain frequencies of ω_{LO} and $3\omega_{LO}$, and provide a close approximation to the square shaped waveform. Mathematically, the LO input voltage can be represented by, $V_{LO} = V_{LO1}\cos(\omega_{LO}t) + V_{LO2}\cos(3\omega_{LO}t + \varphi)$. The transconductance of APDP is denoted by $g = 2\alpha i_s \cosh(\alpha V_{LO})$. Fig. 2 shows the improvement in transconductance obtained by harmonic boosting compared to single tone LO operation.

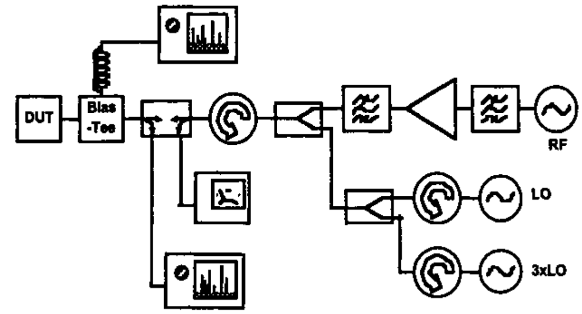

Fig. 3. Harmonic boost technique and experimental setup

Fig 3 illustrates the harmonic boosting test setup. LO and RF ports have been isolated from each other. In this approach, an LO frequency is injected along with its 3rd harmonic tone. In particular, the fundamental frequency denoted by ω_{LO} here is usually a subharmonic of the LO tone used for conventional even order APDP. For even harmonic mixers for direct conversion or very low IF (VLIF) applications, $\omega_{LO} = \frac{1}{2}\omega_{RF}$. The power level of the 3rd harmonic tone is considered to be less than or equal to that of the fundamental LO tone under consideration, to ensure the use of lower power level of the 3rd harmonic. The difference in power levels between the fundamental and its 3rd harmonic tone will be denoted by "back-off" from now onwards.

Other requirements for practical implementation of harmonic boosting technique include a broad LO power tuning range over which performance improvements should occur, and addition of minimum overhead in the system. The boosting technique should allow the circuit to retain its conversion loss and linearity performances over a power tuning range of at least 2-3dBs, otherwise the local oscillator needs to maintain extremely high level of stability in output power. In addition, increase in back-off while retaining the performances is also very attractive as this means lower power injection of the high frequency tone.

III. Experimental Results

For conversion loss and linearity performances, an IF of 40 KHz has been assumed, with incoming RF frequency of 1.80004 GHz. Three different LO subharmonic tones have been considered : 0.9GHz (2nd subharmonic), 0.45GHz (4th subharmonic) and a combination of 0.45GHz and 1.35GHz (4^{th} subharmonic with harmonic boosting). LO tones at 0.45GHz and 1.35GHz have been considered with various back-off values and phase differences.

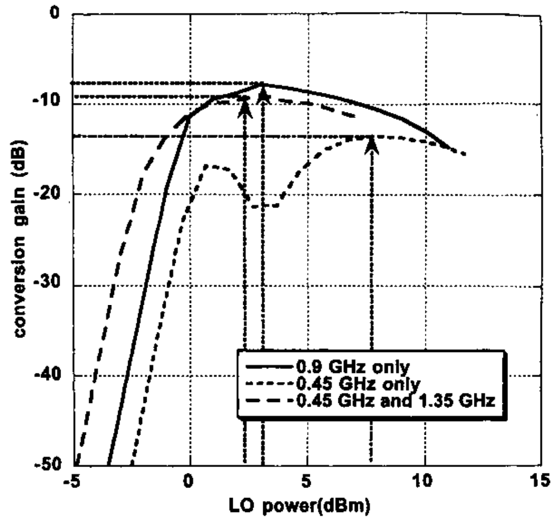

Fig. 4. Measured conversion gain versus LO power level

Fig. 4 shows the measured conversion gain profiles as a function of LO power with a 4-dB back-off. It indicates a flattening in the conversion loss profile with the inclusion of their 3^{rd} harmonic tones, which is favorable to incorporate moderate LO power variations. It is also observed from Fig. 4 that inclusion of 3^{rd} harmonic tone eliminates the nulls in conversion loss profile, which is attractive for a broad LO tuning range operation. Also, the conversion gain performance is independent of the relative phase difference between the two tones which has been verified with application of 45°,90°,135° phase shifts between two LO tones. From Fig. 4 it is seen that harmonic boosting improves the conversion loss by 4 dB, while reducing the LO power level by 5 dB with a back-off of 4 dB for the 3^{rd} harmonic tone. These performances become better with a lower backoff value, indicating an increase in the power level for 3^{rd} harmonic LO tone. However, the optimum conversion loss is 2-dB lower than that achieved with 2^{nd} harmonic operation.

Fig. 5 shows the measured conversion gain profiles as a function of input RF power for various configurations at optimum LO power levels for conversion gain. It is observed that the input P1dB improves by approximately 3 dB compared to the 4^{th} subharmonic operation. Input P1dB increases further with reduction of back-off, similar to conversion loss performance.

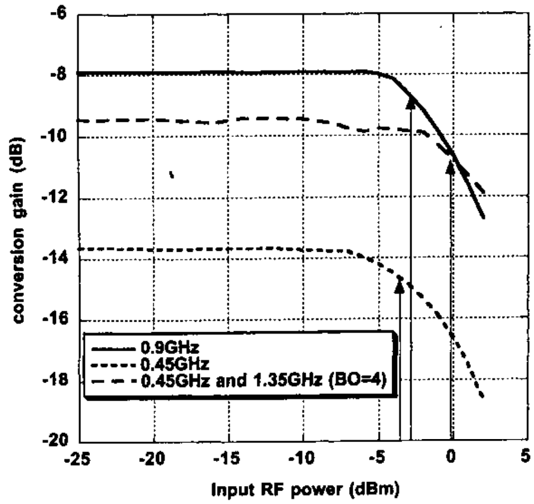

Fig. 5. Measured conversion gain versus input RF power

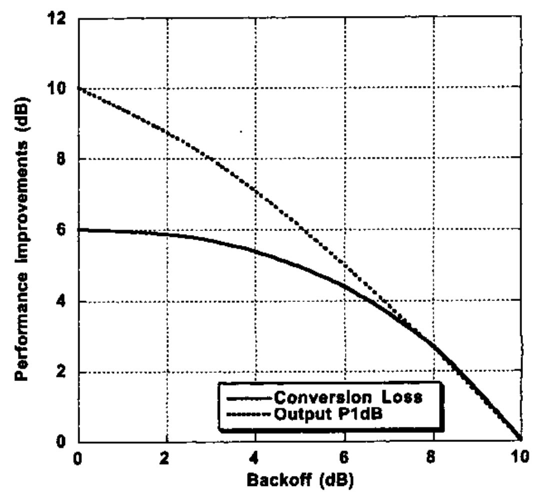

Fig. 6. Measured Performance improvements achieved with harmonic boosting versus various back-off values

As the diodes switch rapidly, the switching distortions decrease and linearity improves under harmonic boosting technique. Fig.6 illustrates the performance improvements in conversion loss and output P1dB as a function of different back-off levels in case of 4^{th} subharmonic (0.45GHz) operation. These performance improvements are relative to those achieved with only a single tone LO operating at 4^{th} subharmonic. As the back-off increases, the effect of additional tone at 3^{rd} harmonic decreases and the performances tend to be similar to those with single tone operation.

Advantages of harmonic boosting technique include : 1) lower frequency operation of the LO tone (4^{th} subharmonic or higher) , 2) improvement in loss, linearity at a lower LO power level compared to 2^{nd} subharmonic operation , 3) easy generation of additional tone to perform boosting as it is a harmonic tone of the LO frequency, 4) no performance dependence on phase difference between the two tones under consideration.

It is also seen that harmonic boost technique doesn't degrade in-band LO leakage and dc offset performances of the APDP based mixer compared to those achieved in 2nd subharmonic mixing operation. This has been observed with introduction of mismatch between the two diodes. Hence the technique is quite attractive for low power direct conversion and VLIF transceivers.

IV. Conclusion

We have established and successfully implemented a novel harmonic boosting technique with APDP based mixer core. This technique is shown to reduce both LO frequency and power requirements while achieving superior linearity performances in compromise with the conversion loss performance. A 10dB improvement in output P1dB, 6dB improvement in conversion loss and 6dB reduction in LO power is achieved, compared to a single tone operation at 4th subharmonic LO tone. The frequency of operation can be further reduced (e.g. 8th subharmonic) to facilitate better on chip integration of high performance oscillators at low frequencies. The harmonic boost technique doesn't degrade DC offset, IIP2 and in-band LO leakage, making it an excellent candidate for low power direct conversion and VLIF transceivers for emerging wireless communication applications.

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