Comparative Study of Broadband RF Subharmonic Mixers in Submicron Technology

Mudasir Bashir, M.tech Student, School of Electronics and Communication Engineering, Shri Mata Vaishno Devi University, Katra, J&K, India
mudasir.mir7@gmail.com

Anil Bhardwaj, Assistant Prof, School of Electronics and Communication Engineering, Shri Mata Vaishno Devi University, Katra, J&K, India
anil.bhardwaj@smvdu.ac.in

Abstract—With the advancements in wireless technologies a lot of concern has been given for designing RF circuits and the designers are trying to introduce new topologies to achieve better outputs whether be at transmitter or receiver section of a communication system and this in-turn has led to the development of individual components of these systems. In this paper, a review of various broadband configurations of the mixer component of receiver/transmitter is given. In general first the fundamental mixers (diode-based and FET-based) are reviewed and later on subharmonic mixer configuration are discussed in detail.

Keywords—Gilbert cell mixer, subharmonic mixers, direct conversion receiver, CMOS technology, DSB noise figure, isolation, anti parallel diode pair (APDP).

I. INTRODUCTION

With the advent of Wireless LAN and Wireless Internet the operating radio frequency (RF) for data transfer has been further pushed from 2.4 GHz, 3.5GHz and now around 20 GHz. This has directly led to the demands of more sophisticated system level designs of RF circuit and the designers are evolving novel high frequency chip architecture and designs. In order to accommodate higher data-rate systems and to avoid the increasingly cluttered frequency spectrum in the low-GHz area, many new systems will need to move to higher frequencies where new challenges in circuit design are encountered [1]. To address this issue, new circuit topologies need to be demonstrated that become increasingly advantageous as the frequency of operation is increased. We know that RF down-conversion mixer is one of the most important part of the system because its performance directly impacts on the overall performance of the whole front end receiver. For the down conversion of the input RF signal at the mixer circuit with LO frequency operating at a fraction of input signal subharmonic mixers are widely used. Due to the absence of dc offsets in subharmonic mixers they have gained a greater interests in direct conversion receivers. Initially in direct conversion receivers the subharmonic mixers were diode based and implemented in millimeter-wave technology but due to the recent advancements silicon bipolar technology they have found their applications at low frequencies also[12,13].

In this Paper, a review of various configuration of broadband mixer circuits are discussed with their topologies and performance matrices. First the fundamental mixers circuits i.e. diode-based and FET-based are discussed and then the subharmonic mixer with order 2 and 4 are discussed in detail.

II. FUNDAMENTAL MIXERS

A. Diode-based Mixers

Diodes are used extensively for designing mixer circuits. In the recent time, the diode-based mixers are generally designed for very-high frequencies applications where the use of complex transistor designs are difficult to implement due to their limited high-frequency performance.

B. FET-Based Mixers

There has been a lot of advancement in the field of mixer circuits with the introduction of field effect transistors. The most popular configuration of FET-based mixer circuit is the Gilbert-cell, shown in Fig 1 [2]. This mixer can be realised by using either bipolar transistors or field-effect transistors. Due to its double-balanced structure, the Gilbert cell results in several important advantages like excellent high port to port isolation, a reasonably high conversion gain.

Depending on how the current source is employed and due to the two stacked transistors, the Gilbert cell circuit is difficult to implement for low-supply and low-power applications. The noise figure of this configuration will be obviously high because of the increased number of active devices and resistors. If the mixer is to be implemented as a discrete component then a matching network will be required for obtaining a reasonable good input impedance. The matching network required can be
implemented using on-chip or off-chip capacitors or inductors or structures like transmission lines.

![Gilbert cell mixer](image)

A recent example of Gilbert-cell using CMOS 0.13 μm technology is presented in [3]. In this work, a down-convert mixer operating in a wideband of 9 GHz to 50 GHz was designed. This circuit is the typical modification of Gilbert-cell as shown in Fig 1. Since the differential configuration of mixer was implemented here so on-chip transformers were used to convert the single ended RF and LO signals into differential signals. The source follower buffers at the output were used to drive 50 Ohm of load which can be either the measuring device or next part of receiver section. Now in this paper, the $g_m$ of the RF transistors was increased by using current injection technique to improve the overall noise performance. This mixer resulted in conversion gain of >5 dB, RF-IF port to port isolation of over 40 dB, DSB noise figure of 16.4 dB and IIP3 was 1.2 dBm@20GHz in the said frequency range. The mixer circuit consumed 97 mW of power and had a relatively compact size at 0.5x0.5mm².

Another wideband CMOS Gilbert-cell mixer was presented in [4] which operated from 0.3 GHz to 25 GHz. In this paper, wideband input impedance matching was achieved using LC ladder matching networks. This circuit resulted in achieving a conversion gain of 10 dB from 10 GHz to 25 GHz, return loss was better than 7 dB from 3 GHz to 25 GHz. The power consumption of the mixer core circuit was 71 mW and port to port isolation was better than 25 dB. The area of the circuit was a bit larger i.e. 0.8x1.0 mm² because inductors were integrated on-chip.

III. SUBHARMONIC MIXERS

The major advantage of using direct conversion receivers is because there are no image frequency produced while frequency translation hence they eliminate the use of complex and expensive filtering techniques. Besides this in order to take advantage from lower LO frequency subharmonic mixer were introduced.

A. 2x Subharmonic Mixers

A large number of 2x SHM has been proposed (e.g. [6-11]). Majority of the SHM designs [6,7,9,10] have been implemented by the modification of the Gilbert-cell mixer to obtain a double frequency LO component for mixing with RF signal. The most common modification to Gilbert cell to subharmonic mixing is achieved by using the quadrature LO signal instead of differential signal. This is achieved by addition of another LO switching transistor stage [6-8]. Consider the example of circuit shown in Fig 3 where three level of transistors with the 0° and 180° LO signals are given to the middle LO-transistor level and 90° and 270° LO signals are given to gates of top LO-transistor. This topology doubles the LO frequency signal. Due to the use of three levels of transistors in this technique, a higher DC supply voltage is required than that of Gilbert cell and hence it may not be suitable for low-voltage applications.
The circuit shown in Fig 3 was introduced by [6]. In [6] the mixer was implemented in Si/SiGe HBT technology and a passive on-chip RC phase shifter for the generation of LO signals. The circuit operated from 1 GHz to 2 GHz with LO frequency ranging from 500 MHz to 1 GHz, with a DC supply voltage of 2.5V. This mixer circuit resulted in a conversion gain of 13.5 dB having a LO power of 10 dBm, a DSB noise figure of 10.4 dB and an IIP3 of 3.5 dBm.

In [7] also used the circuit shown in Fig 3 with a SiGe BiCMOS process. Here the circuit was designed for a frequency range of 5 GHz to 6 GHz with an IF of 50 MHz. In this work, polyphase filters were used to generate quadrature LO signal. The circuit resulted in voltage conversion gain of 6 db, IIP2 of 29 dBm, LO-RF isolation >50 dB. The chip area was 2.3x1.8mm² and a power consumption of 16.5 mW.

A circuit similar to Fig 3 was also used in [8] but it was implemented in CMOS 0.13 µm technology and was adjusted for passive operation. In this paper, RF pre-amp as well as LO and IF buffers are used and the circuit was designed for 24 GHz direct-conversion applications. The quadrature LO signals were generated by an off-chip 90° hybrid. The measured overall conversion gain was 3.2 dB, DBS noise figure of 10 dB, 2LO-RF isolation was 57 dB. The chip area was 0.9mm x 0.65mm with a power consumption of 13.6 mW.

In [9], another implementation of same circuit shown in Fig 3 was done in CMOS 0.18 µm technology where an RC-CR phase shift network generates the required Lo signals. The circuit operates in 5GHz band resulting in a conversion gain of 9.5 dB, LO-RF of 48 dB, IIP3 of 7.5 dBm and the power consumption was 17.5 mW.

A typical modification of the Gilbert cell to enable 2x subharmonic mixing was introduced by [10] using a 0.35 µm BiCMOS technology. The circuit shown in Fig 4 employs only two transistor levels but interchanges the positions of the LO and RF transistor (i.e. the RF transistors are on the top and the LO are on the bottom). As shown in Fig 4 here a quadrature LO signal is also required. In [10], circuit with an RF signal at 1.9 GHz and an LO signal at 900 MHz was designed. It resulted in a conversion gain of 7.5 dB, SSB noise figure of 10 dB, input 1-dB compression point was 8 dBm, IIP3 was 3 dBm and a power consumption of 24 mW.

[11] presents a comparison between three most common transistor-based 2x subharmonic mixer topologies. (1) Circuit shown in Fig 3 (three level), (2) LO transistors on the bottom and RF transistors on the top (Fig 4), and (3) LO transistors on the top used in [12]. Through this comparison it was found that as in Fig 3 circuit operates with the lowest LO power levels, but at the same time requires a higher DC supply voltage when compared with other two topologies. Also the circuit in Fig 3 has the lowest maximum operating frequencies out of all three topologies. The bottom LO subharmonic mixer shown in Fig 3 results in higher linearity, RF-IF isolation and noise figure. The third topology [12] results in a higher 2LO-RF isolation and a higher conversion gain.

One thing got clear here that the requirement of quadrature LO signal in 2x subharmonic mixer is very common (e.g. [9, 10, 12]).

There are several other circuits which are not based on Gilbert cell and are used to realize 2x subharmonic mixers using FETs. Consider the example of [13], here the RF signal was applied to the gate of FET and the LO signal was given to the bulk connection of FET (using CMOS 0.18 µm technology). The injecting of LO signal into the bulk of the transistor results in modulation of threshold voltage and exploits the non-linearity resulting in subharmonic mixing. The measured conversion gain was 10.5 dB, 1dB compression point was 12 dBm and the IIP3 was 3.5 dBm. The circuit operated with RF frequency 2.1 GHz and LO frequency 1.025 GHz and produced a DSB noise figure of 17.7 dB and power consumption was 2.5 mW.

In [14] a 31 GHz 2x subharmonic mixer was demonstrated in 90 nm CMOS technology. As shown in Fig 5 it operates either with RF signal applied to gate and LO applied to the source. The capacitor Cg acts as a DC block whereas Ls and Cs act a high pass filter. Vg provides FET's gate bias through a large resistor Rg. The important feature of this circuit is that it can operate with either a 2fLO or 3fLO or in other words it can be used both as 2x subharmonic mixer or 3x subharmonic mixer. The conversion loss for the 2x SHM was between 8 dB to 11 dB and for 3x SHM it was 12 dB to 15 dB. An IIP3 of 3 dBm for the 2x

![Fig 3: Basic 2x subharmonic mixer circuit used in [6-9]](image-url)
SHM and 7 dBm for 3x SHM. The dimensions of fabricated chip were 0.9mm x 1.0mm.

B. 4x Subharmonic Mixers

A large number of 4x SHMs have been demonstrated [15-20]. In these diodes were used to perform mixing operation which reduced the conversion gain. In order to obtain a greater conversion gain an anti parallel diode pair (APDP) configuration was used for mixing purposes, and infact majority of 4x SHMs use this configuration for their operation. The simple model of APDP is shown in Fig 6.

In [15], an APDP was used for a direct up converter using the basic circuit as shown on Fig 6. In this paper, RF and IF filters were implemented by an RF/baseband duplexer. In order to minimize the LO input reflection coefficient a transmission line matching network was used. A baseband signal was used with a 10 GHz LO signal to produce 40 GHz RF output signal. The measured conversion gain was quite high (21 dB to 15dB as we increased LO power from 6 dBm to 11 dBm), isolation between RF and IF ports were >30 dB.

In [16], a MMIC implementation of the APDP circuit of 94 GHz quadruple subharmonic mixer (4x SHM) was designed and measured using GaAs MESFET technology, as shown in Fig 6. In this work, stub filters were used at the IF and LO ports and a coupled line bandpass filters was used at the input RF port. Here the 94 GHz RF signal was mixer with 23.5 GHz LO input signal to obtain an IF of 100 KHz. The measured conversion gain of this circuit was 11.4 dB and the input 1-dB compression point was a 6dBm. The chip had an area of 0.9mm x 1.4mm.

In [17], a 4x SHM was presented again using the same APDP configuration but in a hybrid implementation with two packaged diodes and a 10 mil duroid substrate. In this work, an RF signal of 38.5 GHz to 40 GHz (upper Ka-band) and the LO frequency was in X-band to produce an IF output at 2.5 GHz. Transmission line stub filters were used for matching and filtering purposes. The measured conversion loss of this circuit was 9 dB and the return loss for the RF, IF, and LO ports was approximately -20 dB,-20 dB and -15 dB respectively.

In [18] a GaAs-based MMIC APDP 4x SHM was presented which uses a number of anti parallel diodes along with transmission line stub filters to extract the IF signal at \(\omega_{IF} = 4\omega_{LO}\). In this design the single APDP is replaced by a triple APDP implementation. (Six diodes in total). The purpose of this topology was to reduce the conversion loss of the mixer by minimizing the diode series resistance. The simulated circuit operated in a frequency range of 50 GHz to 65 GHz with a LO input frequency range of 12 GHz to 16 GHz. The minimum conversion loss for the circuit is 11 dB with a 7 dBm LO input signal. The LO-IF, LO-RF isolation was 17 dB and 33 dB. Linearity measurements were not given in this work.

In [19], a V-band MMIC based on APDP circuit was presented. This work used GaAs PHEMT technology along with CPW transmission lines, stub filters for RF and LO signals, lumped element inductor and capacitors for IF matching and low pass filtering and FETs for amplification. The RF signal was 60.4 GHz with LO frequency of 14.5 GHz producing an IF of 2.4 GHz. The measured conversion gain was 0.8 dB for an input LO power of 12 dBm. The LO-RF and LO-IF isolations were > 40 dB and the area was 1.9mm x 2.6mm.

Now, there are only few cases where 4x Subharmonic mixers are designed without using any diodes as demonstrated in [20]. In this work, several stubs for RF and LO filtering are used in a cascade configuration with GaAs MESFETS. The FET used here generates and enhances the fourth harmonic of the LO input signal and then mixes it with the RF signal.
The circuit operates with an RF range of 59.4 GHz to 60.9 GHz with LO input frequency of 14.5 GHz. For matching and low-pass filtering lumped inductors and capacitors were used. The circuit resulted in a conversion gain of 2.5 dB to 3.4 dB for LO input power of 13 dBm. The LO-RF and LO-IF isolation were 46.2 dBm and 53.6 dBm respectively and chip area was 1.9 mm x 1.8mm.

IV. CONCLUSION

Gilbert cell mixer is the most common configuration used in designing fundamental FET based mixer though other designs have also been demonstrated. Now, due to the concept of direct receivers the Subharmonic mixers have become of much importance which can be of different orders based on their LO signal. One thing got obvious here that SHM most commonly need quadrature LO signal for frequency translation of input RF signal. Generally, and as expected, 4x SHMs have more loss than 2x SHMs, which in turn generally have more conversion loss that fundamental mixers. In most cases, 4x subharmonic mixers do not exhibit a conversion gain.

References