Review of FET Ring mixer topologies for wireless communication

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Abstract. This paper presents an important component of the radio frequency transceiver called as mixer. It is a critical component and plays an important role as it has the ability for frequency conversion in RF systems. This paper focuses on double balanced ring topology of passive mixers. Ring mixer is one of the best example of passive mixers because of double balanced in nature. Double balanced is one of the most widely used topology as it suppresses both LO and RF at the output the of mixer. Various techniques have been used to improve the performance of standard topology of the ring mixer such as noise figure, linearity, conversion gain and port isolation, so these techniques have been re-viewed and compared with the previous studies. This paper also have brief discussion about a useful passive circuitry say balun and its designing with mixer as this is generally used to convert single ended signal to differential signal.

1. Introduction
In this section, brief discussion about mixer and its importance in RF communication systems has been presented. Mixer is an essential component in wireless communication systems. In general, a mixer is an electronic component that has three-ports [1-3] and uses a nonlinear element responsible for frequency conversion. Mixer has three ports which can be classify as the radio frequency that can be called as RF port, the local oscillator that can be called as LO port which are inputs and the Intermediate Frequency (IF) as output port. A mixer generates an output that consist of sum and difference frequencies of the two input signals. Fig 1. shows an ideal mixer with its three ports(RF,LO,IF). There are several classification of mixer based on the frequency components such as single ended mixers, can also be called as unbalanced [4] which produces RF and LO frequency in addition to the required IF frequency at the mixer output. They are generally made of single device (diode, Bipolar Junction Transistor (BJT), Field Effect Transistor(FET)). Other classification of mixer is single balanced mixers [5], they usually suppresses either of RF and LO frequency at the mixer output. An important topology of mixer is Double balanced mixers because of the property that they suppresses both RF as well as LO frequency at the mixer output (without the need of extra
These mixers have different circuit configurations depending upon their applications and specifications.

Generally, there are two important types of mixer based on the conversion gain or loss named as active mixers and passive mixers. Both the types of mixers have their own properties. However, active mixers provide high conversion gain and requires low LO power but there is a trade off between gain and linearity hence these mixers have poor linearity, where as passive mixer provides high linearity but requires large LO power. In active mixers, gain reduces rapidly with increase in bandwidth, but not in case of passive mixer because of high linearity. Several papers have presented different types of mixers. Gilbert cell is best example of active mixer [6-8].

In designing of mixer, double balanced topology is widely used in mixers weather it is active or passive. This topology has some advantages over other topologies such as single ended and single balanced. Double balanced topologies have better harmonics suppressions and high port-to-port isolation.

The parameters of RF such as noise figure, conversion loss or gain, linearity, power consumption, and port-to-port isolation are important for mixer designs.

2. Balun

A balun is a useful passive support circuitry that is used in designing of high frequency circuits[59]. The most important application of this circuit is connecting the single ended circuit to differential output circuit. The balun with 180 degree is a major component in balanced mixers, balanced modulators, phase shifters as well as in the applications of single ended to double balanced converters. Hence, this type of balun structure is beneficial in the analog circuits that require balanced input and output to improve the dynamic range of the circuits and to reduce the noise and to minimize high order harmonics.

So, whenever a circuit requires signals on two different lines that are with equal magnitude and opposite in phase with 180 degrees[14] than it need balun for this connection. However, several types of balun structure have been developed in many of the work, the transmission-line type balun is in interest as they are compact, and suitable for push-pull amplifiers and mixers[59]. In addition, balun can also perform impedance matching[62].

There are different types of balun designing depends on the factors as the first bandwidth requirement, second, the operating frequency, and the last, physical structure of the network means what type of component and in which configuration they are being connected and also single ended input is matched to input transmission line impedance (50ohm generally).
Main types of balun that are reported in literature:
- Flux coupled Transformer
- LC lumped balun
- Capacitive Coupled transmission line balun

2.1 Flux coupled or transformer type balun - It provides an arbitrary impedance ratio that can be easily tuned. It also provides DC isolation and ground isolation both. Fig shows the construction of a flux coupled balun transformer.

2.2 LC lumped balun - Balun can also perform impedance matching using lumped components, two capacitors and two inductors, which produces the ±90 degree phase shift. This type of balun structure is also called as “lattice type” LC balun or essentially a bridge as shown in fig 3.
2.3 Capacitive coupling or transmission line balun:
It is a set of coupled lines in which one end is grounded, so that equal and opposite signals can be induced by the coupling in both the lines. The microstrip transmission line can be used to define function in which the ground plane is simply tapered into a bottom transmission line. These types of balun has advantage of high frequency operation but disadvantage for low frequency operation.

MARCHAND TYPE BALUN[59] is a type of capacitive coupling transformer similar to tapered balun used in most of the literature. Some applications of this type of balun are balanced mixers, push pull amplifiers etc. It provides high bandwidth and easy to implement. The marchand balun has improved phase and amplitude balance due to which it has wider bandwidth in compare with the other balun designs. Fig 4 shows the operating principles of marchand type balun.

3. Ring mixer

In this work, double balanced topology of passive mixers has been taken with high preference. Passive mixers have high linearity, high conversion loss but require high LO power as compared to active mixers. Hence, one of the important challenge in passive mixers is high LO power requirement. For improvement of the linearity or the dynamic range of the mixer, various techniques are presented by the authors[17-20]. A lot of paper have been worked on ring mixer which is the well known example of double balanced topology of passive mixer with, different applications because it
suppresses both Lo and RF at the output of the IF port. Several techniques of ring mixers have been reviewed in this paper.

![Diode Ring Mixer](image1)

Figure 6. A diode ring mixer[28]

![FET Ring Mixer](image2)

Figure 5. An FET ring mixer[29]

FETs have superior dynamic range[63] in terms of linearity and also these types of ring mixers are easily integrable.

4. Literature review of FET Ring Mixer

Several different techniques have been used to improve the linearity and reduce the LO drive level. The ring mixer can be operated in one of the regions that is called as weak inversion region[22] in which low LO drive level and low dc power level can be achieved by operating the MOS transistor in this region. Although, operating MOS transistors in weak inversion biasing region have lower gain and low transit frequency response($f_T$) that are the disadvantages for designing of IC at high frequencies.
In weak inversion region, the two distinct characteristics of a MOS transistor occur: first, the channel current \( I_d \) becomes independent of \( V_{ds} \), and the second is linear dependency of transconductance on the channel current where as in the region of strong inversion, the channel current is directly proportional to the drain to source voltage \( V_{ds} \) (due to the effect of channel length modulation). Hence, in this region the channel current is significantly smaller as compared with that in region of strong inversion.

A high speed, low dc drive and low LO power up/down conversion ring mixer for broadband applications by using the technique of weak inversion [22]. This paper presented up or down conversion ring mixers with high speed and also with low-LO-drive level, low dc level using weak inversion technique for radio applications. The proposed mixers achieved low LO power condition and improved conversion loss under operating the transistors in weak inversion.
In order to achieve high speed operation for millimeter wave wireless Gigabit transmission, an IF transimpedance amplifier buffer and broadband RF architecture have also been implemented. Designing of RF mixer using GaAs pHEMT technology of 0.13um has been implemented in [23] by operating transistors in weak inversion region. Gallium Arsenide has a higher electron mobility than Silicon. It is 8500cm sq/(Volt.sec), that is 5 times larger than silicon 1400cm sq/(V.s), that allows transistors to operate at very high frequency as compared with Silicon. They have low noise performance, due to very high mobility of the carrier and low parasitic of resistive device, specially at high frequencies. A low local oscillator drive level, down conversion ring with low conversion loss, on GaAs pseudomorphic high electron mobility transistor so called pHEMT process has also been presented.
Various SHM (subharmonic mixer) topology architecture that are based on Gallium Arsenide pHEMT have been reported. In addition to this, a down conversion ring with very much low LO power using the technique of weak inversion for X-band has reported in [30]. This paper achieved ultra low power of local oscillator and exhibits low power of dc while maintaining the conversion gain for X-band applications. To verify the feasibility of the technique of weak inversion the mixer has been designed and fabricated in CMOS 0.18-um technology. To bias the transistors of the mixer core, they introduce a way of dc through IF buffer amplifiers at weak inversion biasing region. To reduce the power level of LO, weak inversion technique has been adopted in which $V_{gs}$ is lower than the threshold voltage ($V_{th}$) which provides a very good performance on efficiency of transconductance that is generally written as the ratio of $g_m$ to $dc$ ($g_m/dc$) than strong region. Fig shows[9]
the down conversion ring mixer for X-band with If Buffer providing a dc way for biasing in weak inversion[30].

It can also be observed that passive mixers require large LO power (~10dBm) for reasonable conversion gain without any biasing. So, weak inversion technique improves the conversion loss with very low LO drive level and the resistive mixer with biasing on gate further improves the conversion gain. Therefore weak inversion technique are useful for the mixers driven by low LO drive level. Hence this work has been achieved the lowest LO drive level and consumption of low-dc-power with enough conversion gain.

Moreover, a wide-band passive mixer based on 0.25um CMOS technology has been presented in [31]. This work describes broad-band resistive mixer fully integrated. In addition, this mixer has been achieved a moderate conversion loss with a small gate bias at very low LO power level. This paper has been presented a resistive mixer having biasing voltage on gate that is near threshold. This below gate bias voltage exhibits superior broad-band RF and IF impedance matching, and also exhibits very nice linearity. This property of passive mixers is suitable for both homodyne as well as for heterodyne transceivers for various applications of wireless communication.
Moderate CL can be achieved by using small gate bias voltage at very low LO power. A Resistive ring mixer for ultra-wideband range in 0.18um CMOS technology has been reported in[29]. In this paper down conversion resistive mixer has been design using CMOS 0.18um process. Mixer downconverts the RF signals to a fixed IF. To achieve wideband frequency response they used wideband matching at input RF port and at IF port they used source follower as output buffer.

The time variant channel resistance of a transistor can be used for frequency mixing in resistive mixers. In linear region transistor behaves as variable resistor. When voltage at gate increases, the resistance of the channel decreases, hence the desired IF signal is generated by mixing of products of LO and RF. Generally, the turn-on resistance as well as the capacitance are the main components by which there can be control of the bandwidth of the resistive mixer.

Further improve the wideband input matching, Shunt resistors are used. No matching circuitry has been used at LO port so that circuit area would be minimum. Hence this type of mixer are used in the UWB communication systems with high dynamic range [34-40].
In addition to this, a passive mixer with integrated baluns has been presented in [41]. This was the first presented double balanced passive mixer with integrated RF and LO baluns. Mixer has very compact design because of absence of RF and LO matching circuits and hence suitable for homodyne and heterodyne transceivers for wireless application. This mixer exhibits excellent linearity and low conversion loss and good RF and IF impedance matching without matching circuits. The insertion phase from a Low pass filter lags the insertion phase from a high pass filter [43].

![Figure 13 Ring mixer with LC lumped integrated baluns][41]

The mixer has a high impedance due to no matching at the LO ports and hence dissipated pretty little LO power.

A resistive fet ring mixer using 0.18um CMOS process has also been presented in [25]. This is the highest frequency resistive fet ring mixer using cmos technology. This mixer has on chip baluns, and to increase the isolations the inductors are used at the output port (IF). A gate voltage Vg is applied to reduce the LO power.
Two RF and LO baluns using marchand type transformer[59] [61] have been designed with ring mixer core. The two colis that are used as quadrature coupler, connected to the signal port of transformer of the balun and then connected to an open port. Due to lower insertion loss they have been chosen broadside-coupled lines rather than that of edge coupled.
| Selected References | Frequency Band (GHz) | Mixer Type | Technology | Topology | Technique | Important Results |
|---------------------|---------------------|------------|------------|----------|-----------|-------------------|
| [22]                | 40-110              | Field effect transistor (FET) ring mixer | 90-nm CMOS Low power process | Double balanced | Weak inversion With IF buffer | LO 2dBm CG 1±2dB DC 7.2mW |
| [23]                | 30-43               | FET ring | 0.13umGaAs pHEMT | Double Balanced | Weak inversion | LO 3dBm CG 4±2dB DC 29.3mW |
| [30]                | 9-15                | FET ring | 0.18 um CMOS technology | Double balanced | Weak inversion | LO 8dBm CG 1±1.5 DC 2mW |
| [29]                | 1-11                | FET ring | 0.18um CMOS technology | Double balanced | Wideband matching | LO 9dBm CL 7±0.5dB DC 3mW |
| [31]                | 2-9                 | FET ring | 0.25-um CMOS technology | Double balanced | Broadband RF matching and small gate biasing | CL 6.4dB DC 0mW RF Return 18dB loss |
| [41]                | 2-6                 | FET passive mixer | 0.18 um CMOS | double balanced | Ring mixer with Integrated Balun | LO 10dBm CL 7.8dB RF 19.3-10.3 |
5. Conclusion

In this paper, several ring mixer topologies and linearization techniques of passive ring mixer as well as balun design techniques are reviewed and compared on the basis of mixer parameters such as conversion loss or conversion gain, linearity, third order intercept, return loss, LO power and DC power consumption. A very low LO power can be achieved by using weak inversion technique. By employing small gate biasing and wideband RF matching, moderate conversion loss can be achieved with pretty low LO power. RF mixer with on chip balun has also been reviewed which improve the wideband matching with resonable conversion gain as well as the linearity of the mixer. Different types of balun as flux coupled, LC lumped balun, marchand types of balun has also been discussed in this review paper.

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