Mixer Technologies for Modern Microwave and Wireless Systems

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***Abstract:** Although mixer design is often viewed as a mature technology, there seems to be no end to the supply of creative new ideas for mixer circuits, or for new needs. Today, the needs of system designers are evolving from high-performance circuits to low-cost, manufacturable, and integrable designs. This particularly true of mixers for wireless, cellular, and other modern communication systems. In this paper we review the work in this area and examine some of the directions it can—and perhaps should—take.*

INTRODUCTION

Microwave mixers are a highly mature technology, so it would seem that there is little to discuss in terms of their technological progress. In fact, new and interesting circuits continue to be developed, and as new device technologies arise, they are frequently applied to mixers as well. Thus, it seems useful to review the status of mixer research and development, and to examine a few of the more interesting circuits and technological advances. Finally, it is also appropriate to discuss some of the perennial problems in mixer design, and what might be done about them.

BALUNS

Various kinds of passive baluns have been developed for broadband, balanced diode mixers. Conventional mixer baluns, however, are fabricated on suspended substrates and are not amenable to monolithic integration, so other types of baluns are needed. One of the greatest challenges is to create high-performance, low-cost broadband planar circuits suitable for monolithic integration.

As a mixer consists of little more than a number of solid-state devices and a balun, it is clearly necessary to understand balun technology. Baluns, not diodes, are invariably the limiting element in diode mixers, and often limit bandwidth and other aspects of performance in active FET and bipolar mixers. A balun can be viewed as a device that accepts a mixture of even and odd modes at its input, and produces a purely odd mode at its output. As such, an understanding of the even and odd mode properties is essential to an understanding of baluns.

The simplest type of passive balun is a pair of coupled lines having an appropriate odd-mode characteristic impedance and a high (ideally infinite) even-mode impedance. Achieving a high even-mode impedance in a suspended-substrate medium is possible, but on a high-ε_r microstrip substrate, it is not possible in any practical sense. Thus, it is necessary to use more intelligent methods instead of such "brute-force" techniques.

Marchand baluns [1] have been found to be quite useful for planar mixers. Earlier, we showed that such baluns were practical for broadband monolithic circuit applications [2], Figure 1. Early publications [3] indicated that compensated marchand baluns could achieve a 10:1 bandwidth with good input VSWR, although this is true only if the even-mode impedances of their coupled lines are infinite, and such broad bandwidths are rarely achieved in practice. Uncompensated baluns can achieve 3:1 bandwidth fairly easily, however, if the load impedances can be specified as part of the design. In star mixers, octave bandwidths are typical.

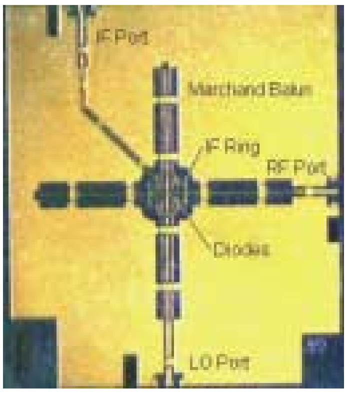

Figure 1. Star mixer using a planar Marchand balun [2].

A disadvantage of the Marchand balun is its size, especially at low frequencies. Wrapping the balun in a spiral reduces the size and increases the even-mode impedance, improving its performance [4]. Asymmetrical structures can also improve bandwidth in microstrip and CPW media [5], [6].

Wen et al. [7] describe a Marchand-like balun realized in LTCC using stepped-impedance, coupled-line sections. The resulting balun operates at 2.5 GHz with approximately 20% bandwidth at 15 dB return loss. Although not broadband, the balun is quite small, only 03.2x1.6x1.0 mm in size, and certainly exhibits enough bandwidth for most wireless applications in this approximate frequency range. Such baluns should be useful for a variety of RF and wireless circuits; indeed, LTCC may well become the preferred medium for many such circuits, as it allows a high degree of integration, with good shielding and propagation and loss characteristics, in the important frequency ranges from 1.0 to 6.0 GHz.

There seems to be no shortage of good, new ideas for baluns. Basroui and Prasad [8] describe a log-periodic balun structure, Raicu [9] describes an intriguing approach to balun design. He begins with a prosaic balun and optimizes it by rejecting the even mode. Kirkhart describes the use of a half-wave balun in a ring mixer structure. The mixer, shown in Figure 2, is small, low-cost, and exhibits moderate bandwidth.

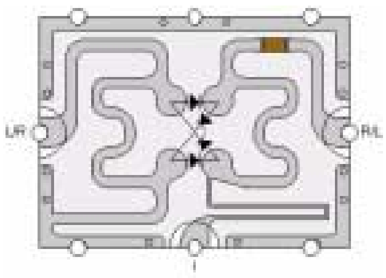

Figure 2. Diode ring mixer using a modified half-wave balun.

Active baluns have not been as successful as passive ones. The most common approach is to create a differential amplifier in either FET or bipolar technology. Such baluns, using silicon devices, work well at low frequencies. At high frequencies, however, the low drain-to-source resistance of GaAs microwave FETs, or the collector-to emitter impedance of bipolar devices, makes it very difficult to achieve the high impedance necessary for the current-source transistor. Then, that impedance is, effectively, in parallel with one of the differential devices, but not the other. The result is unbalance in the amplifier, which leads to unacceptable even-mode performance.

CIRCUITS

We have found that the use of HBT devices, combined with emitter feedback, provide adequate even-mode rejection for many purposes. Figure 3 shows a Gilbert multiplier chip, designed for a broadband analog correlator, using a low-cost InGaP HBT process. The multiplier operates, with good responsivity, from 2 GHz to greater than 20 GHz. The responsivity, up to 18 GHz, is shown in Figure 4. The chip is approximately 1.6 mm square and includes an output amplifier.

A challenge of this design was to achieve ~20 GHz bandwidth using devices having an f_{max} on the order of 70 GHz. This was accomplished by introducing emitter feedback, combined with capacitance bypassing, and careful biasing of the individual devices. The inputs are resistively loaded to provide a good input VSWR and to improve the bandwidth, at some cost in responsivity.

A version of this circuit, without the output stage, was tested as a conventional RF mixer. With 11 dBm LO drive, it exhibited 6 dB conversion loss across the band. LO-to-IF and LO-to-RF isolations were moderate, 15 to 20 dB.

Even in a field as mature as this, creative,

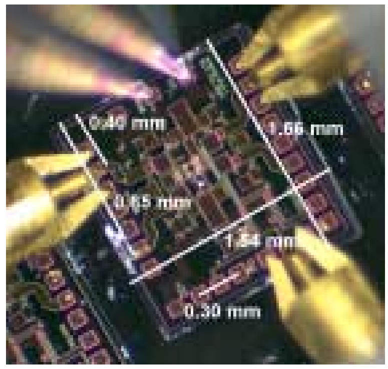

Figure 3. Gilbert multiplier chip.

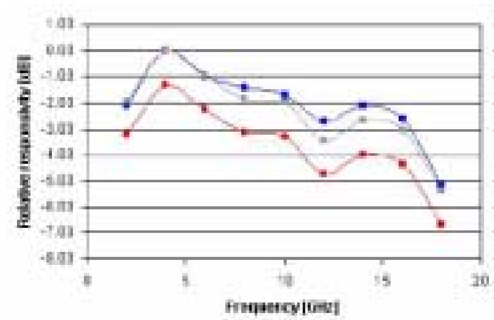

Figure 4. Relative responsivity of the Gilbert multiplier. The upper curves are at reduced bias, which increases the responsivity but decreases dynamic range.

fundamentally new ideas exist. An example is the use of new types of diodes to realize low-distortion mixers. Two examples are the use of GaN and other wide-bandgap materials to create diodes that, when strongly pumped, provide low distortion. It is well known that the use of a diode having a high “knee” (turn-on) voltage allows it to be pumped harder by the LO, and that high LO power is perhaps the most effective (but not necessarily most desirable) way to minimize intermodulation distortion in a mixer. Thus, creating a diode that allows high LO power represents a kind of “brute force” approach to the problem of minimizing distortion.

Alternatively, it is possible to adjust the shape of the I/V characteristic to optimize the distortion characteristics of the diode. This was done in [11], through the use of a *heterojunction interband tunneling diode* (HITD). Such diodes can be tailored to provide a largely square-law I/V characteristic over a reasonably wide voltage range, allowing low distortion. Conversion efficiency is somewhat less than with a conventional Schottky diode. The diodes exhibit a negative resistance region a few tenths of one volt wide. With only 5 dBm of LO power, a singly balanced mixer using an HITD exhibited 11 dB conversion loss and +17.5 dBm third-order intercept point.

Yet another approach to the development of low-distortion mixers is the FET resistive mixer. Such mixers have world-champion distortion performance, while requiring only moderate levels of LO power. This is especially important for many wireless applications, where interference levels are high and little LO power is available. GaAs MESFETs and silicon MOS devices seem to provide the lowest distortion levels; heterojunction FETs, having stronger channel nonlinearity, exhibit somewhat higher distortion levels. Properly designed, heterojunction FETs are capable of operation at high frequencies at very low LO power. However, at the low frequencies used for most wireless communication, the LO *input* power required by any microwave FET is very low; *available* LO power requirements are usually established by practical matching considerations.

In [12], Ellinger et al. describe several FET resistive mixers that display remarkably good dynamic range at LO power as low as –10 dBm, using an enhancement-mode MEFET. They also report mixers using a depletion-mode device and a deep depletion device. The latter has 5.5-dB conversion loss and a 16-dBm compression point with only 10 dBm LO power, all at 5.2 GHz. The mixers are designed with the use of a special model that was developed primarily for resistive FET circuits. The mixers are simple, single-device structures, configured as a series-switching unit.

The channel resistance of silicon devices is considerably more linear than that of GaAs or other III-V materials. This makes silicon MOS devices ideal for use in FET resistive mixers in the lower RF region. A important advantage of MOSFETs, for FET resistive mixer use, is that their gates cannot be driven into rectification, as can junction FET devices. When that occurs, distortion increases dramatically. When MESFETs are used in such circuits, the optimum LO level usually is close to the rectification point, so drift in the LO level can cause gate rectification and a concomitant decrease in performance. Parasitics, unfortunately, are greater in MOSFETs, and because of the lower mobility of silicon, the device must be larger to achieve a desirable channel conductance. These factors limit MOSFET resistive mixers to, at most, a few GHz, with currently available technology. Advanced MOS devices, now becoming available, may extend this limit considerably in the future.

Figure 5 shows the circuit of a four-FET, doubly balanced mixer, and Figure 6 shows the input IP3. Conversion loss was 6 to 8 dB, from 500-1000 MHz, for all the cases shown. The device used in this mixer was a silicon-on-sapphire MOSFET from Peregrine Semiconductors, Inc. This mixer required at least 17 dBm to achieve peak performance, but more careful matching and transformer design could reduce the LO requirements by at least 1 to 2 dB. The mixer is designed to operate with either positive or negative bias voltage; however, zero-voltage operation is also practical.

Gould et al. [13] also describe a CMOS FET resistive mixer for use in receiver chips at 900 and 1800 MHz. These chips exhibit conversion loss of only 6.4 dB, and show only 0.5 dB conversion-loss variation over an LO range of 8 to 18 dBm, implying that 8 dBm is adequate

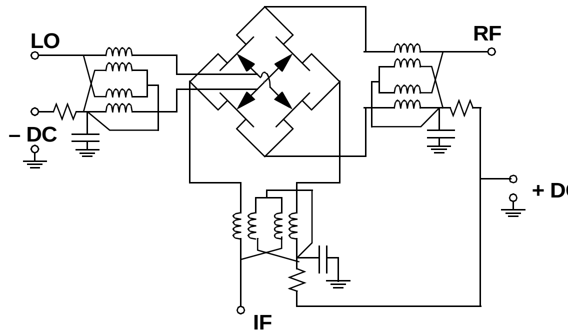

Figure 5. Circuit of a doubly balanced resistive MOS-FET ring mixer.

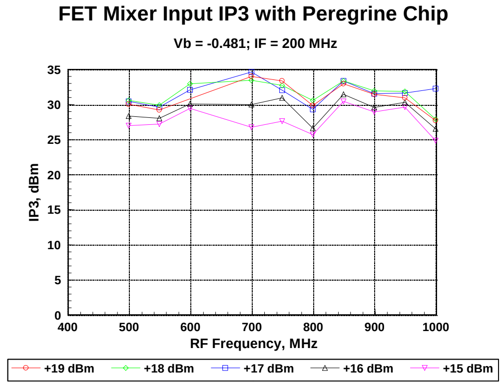

Figure 6. IM performance of the circuit in Figure 6.

to achieve good conversion loss. They report an input IP3 of 19.7 dBm and 21.7 dBm for the 900 and 1800 MHz mixers, respectively. At the same time, the RF and LO ports are both matched to better than 16 dB return loss. NMOS devices only are used for the mixers. Similarly, switching-mode CMOS mixers are described in [14].

PERENNIAL PROBLEMS

There are a number of problems in mixers that are continually troublesome, and have only partial solutions, at best. We examine some of them here.

1/*f* Noise

In mixers that convert directly to baseband, such as low-cost FMCW sensors and direct-conversion receivers, 1/*f* noise frequently limits the performance. 1/*f* noise is present in all devices. I t can be especially troublesome in diode mixers.

There is some evidence that FET resistive mixers exhibit lower levels of 1/*f* noise than diode or active mixers, and this is sometimes the justification for their use. More mature technologies tend to have lower levels of 1/*f* noise than newer technologies, probably because of the overall quality of the materials and processes. At present, little work has been done on minimization of 1/*f* noise for mixer applications.

LO Rectification and DC Offset

Balanced mixers, theoretically, have zero dc voltage across their diodes. In practical mixers, however, the balance is never perfect, so a dc output voltage exists. It comes from the unequal rectification of the LO in the mixer's diodes. It is an especially severe problem in mixers that convert to baseband and have a swept-frequency LO. Thus, it is a troublesome phenomenon for FMCW radars used in low-cost automotive and other consumer applications.

Various kinds of compensation methods have been proposed; for example, the use of second-harmonic LO injection was recently shown to be useful [15]. The fundamental problem in most of these techniques is sensitivity; that is, the performance changes greatly with only small drifts in circuit parameters. The changes are caused by temperature, aging, vibration, or other characteristics of the severe environment in which such circuits must operate. A good solution to this problem would do much to make open many low-cost sensor applications.

Distortion

Distortion in mixers continues to be a problem in virtually all systems. Wireless systems, which must operate in severe interference environments, are especially susceptible. Mixers are frequently the dominant components in establishing a system's distortion performance.

CONCLUSIONS

In spite of the maturity of the field, there are continual new developments in mixer technology. These include new circuits, new devices and device technologies, and improved performance, especially in terms of distortion. Much remains to be done, however, as certain perennial problems are still resistant to solutions. We look forward to seeing more creative work on such issues in the future.

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