50 Years Development of the Microwave Mixer for Heterodyne Reception

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Invited Paper

***Abstract*—A brief technical historical review of mixer development, in its application as the frequency down-converter for the microwave and millimeter-wave heterodyne receiver, provides the background to discussion of mixer design, technology, and performance characteristics. In general terms, today's mixers designs are based on the 1970s principles, but technology progress in the solid-state frequency-mixing element and associated integrated circuits has been significant, with exploitation of the monolithic potential. Performance advancements have mainly been in the increased frequency capabilities of the planar Schottky barrier diode mixer, broad application of the three terminal devices, and balun implementation.**

***Index Terms*—Mixers.**

I. Introduction

THE terminology "mixer" may be applied to frequency mixing or frequency changing for down-conversion or up-conversion, and refers to a nonlinear element embedded in associated circuitry to provide the appropriate input and output terminals. The most common application is frequency "mixing" applied to heterodyne reception, in which two frequencies beat together in a nonlinear element to produce sum and difference frequencies.

This receiver principle may be traced to the early 1900s for radio reception, but World War II revived interest specifically for military radars at microwave frequencies. The microwave mixer still, today, provides the heart of the heterodyne receiver and is used in all types of microwave systems to meet the needs of both military and civil requirements, e.g., radars of all types, electronic warfare, guided weapons, communication, instrumentation, transportation, radio astronomy, etc. System applications now extend over the frequency range of at least 1–1000 GHz, moving into the terahertz region.

Stimulated by progress in system design techniques demanded by the increasing complexity of military and civil requirements, mixer research and development (R&D) has continued with much technology advancement in the semiconductor device frequency-mixing element and associated circuitry, progressing through the main phases of the traditional waveguide/coaxial configurations, the hybrid microwave integrated circuit (MIC) and the monolithic microwave integrated circuit (MMIC). The advent of the front-end low-noise amplifier has impacted on the original mixer prime design aim of low noise (high sensitivity) for many applications, introducing the use of more complex mixer designs with dynamic-range upper limit suppression of intermodulation products being an important characteristic.

The paper will present and discuss some generalized advancement in mixers, resulting from the large R&D effort applied to microwave and millimeter-wave receivers over the period from 1950 to 2000, much from personal experience.

List of Symbols

- Compression point (CP): Upper limit of dynamic range expressed in terms of 1-dB compression in output power as a function of input power. May be expressed as mixer Lc or $r.f$ to $i.f.$ receiver overall gain.
- Double-sideband (DSB): Operation of the receiver when it is receiving usable signals in both the signal and image bands.
- Dynamic range: Power difference between the minimum detectable signal and maximum signal that can be accepted before a specified compression can take place.
- FET: Field-effect transistor.
- Fif: Noise figure of the $i.f.$ amplifier.
- HBT: Heterojunction bipolar transistor.
- HEMT: High electron-mobility transistor.
- $1/f$: Flicker or low-frequency noise. Noise corner (n/c) being defined as the onset of ONF (Nr) increase with decrease of $i.f.$
- $i.f.$: Intermediate frequency.
- I: Image frequency, where $I = l.o. - i.f.$ when signal $= l.o. + i.f.$
- Image recovery (enhancement): Recovery of image power generated by the mixer with reconversion to $i.f.$ power leading to enhanced receiver overall noise figure or mixer conversion loss.
- Image rejection (suppression): Suppression of $r.f.$ input signals at the image frequency.
- Intercept point (IP3): Upper limit of dynamic range, expressed as a measure of the third-order intermodulation products generated by a second input signal arriving at the signal port along with the desired signal.

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- Lc/Gc: Mixer conversion loss/conversion gain: ratio of available signal power at radio frequency to the available output power at intermediate frequency.
- $l.o.$: Local oscillator.
- MESFET: Metal–semiconductor FET
- MISFET: Metal–insulator–semiconductor FET
- Nr: Noise ratio of the mixer nonlinear element: ratio of available noise power to that of a resistor equivalent to the mixer output resistance, at room temperature. Contributions are thermal, shot and flicker noise.
- ONF: Overall noise figure: sensitivity of a heterodyne receiver expressed as $\mathrm{ONF} = Lc(Fif + Nr - 1)$ assuming local-oscillator noise sidebands are suppressed.
- $r.f.$: Radio frequency.
- Single-sideband (SSB): Operation of the receiver when it is receiving a useful signal in the signal band only.
- Plo: Local-oscillator power.

Explanation of Mixer Circuits

Single-Ended Mixer (SEM): is the most basic and comprises a single-port circuit embedding a single mixing element with both $r.f.$ and $l.o.$ coupled externally. A merit is simplicity, but has the disadvantages of $r.f.$ loss due to external $r.f./l.o.$ coupling, and no suppression of $l.o.$ noise sidebands or intermodulation products.

Single-Balanced Mixer (SBM): combines two single-ended mixers via a four-port 3-dB coupler (balun), such that the $l.o.$ noise sideband products are balanced out. The circuit provides isolation between $r.f.$ and $l.o.$ ports, suppression of $l.o.$ A.M. noise products and even-order modulation products. The coupler (balun) defines many characteristics, particularly $r.f.$ bandwidth (may provide 90° or 180° phase difference between output ports, each with particular merits).

Double Balanced Mixer (DBM): comprises four mixing elements connected as a quad, in ring, bridge or star form, and two baluns. Inherent characteristics provide cancellation of $l.o.$ A.M. noise, broad bandwidth, high isolation between all ports, suppression of even harmonics of $r.f.$ and $l.o.$ signals (high rejection of even-mode harmonics and reduction of the total number of possible intermodulation products), high signal handling (thus, high dynamic range), and thus, high dynamic range, low $i.f.$ impedance, and finally, the merit of a potential compact structure. Balun designs are of prime importance for accessing the quad terminals, both in design and implementation for performance and achieving the potential compact mixer structure.

Double–Double Balanced Mixer (DDBM): an extension of the DBM that comprises eight mixing elements and separate $r.f.$, $l.o.$, and $i.f.$ baluns, providing higher dynamic range and facilitates overlapping $r.f.$ and $i.f.$ bandwidths.

Image Rejection Mixer (IRM): normally combines two identical mixers (SEM, SBM, or DBM) in a phasing arrangement such that the image is out-phased or rejected, while the desired signals are unaffected. Also, may be achieved by a signal bandpass filter that rejects the image frequency and coupled to absorb image power generated by the mixer.

Image Recovery (Enhancement) Mixer: is basically an IRM phasing circuit in which the image power generated in one mixer is converted to $i.f.$ by the other mixer and vice versa, for Lc enhancement. Also may be achieved by a signal bandpass filter that reflects the mixer image power in the correct phase. Short-circuit image termination is preferable to open-circuit image termination to minimize and provide acceptable impedance levels. An image recovery circuit inherently provides image rejection, but not vice versa.

Antiparallel Sub-Harmonic Mixer (SHM): is a special case of a harmonic mixer when the $l.o.$ is one-half the fundamental frequency with two mixing elements of opposite polarity connected in shunt to produce a full-wave antiparallel arrangement and a symmetrical I–V characteristic. Unlike the harmonic mixer, the circuit suppresses the fundamental mixing products between $l.o.$ and signal and many higher order mixing products, and will provide down conversion from all sidebands where the sub-multiple is even with suppression of odd-order products, implying the capability of a similar conversion loss to that obtained from a fundamental mixer. $l.o.$ A.M. noise sidebands are suppressed.

Image Rejection Harmonic Mixer (IRHM): combines the IRM and SHM and provides suppression of harmonic intermodulation products.

II. WAVEGUIDE/COAXIAL MIXER

The early traditional mixers of the 1950/1960s era incorporated a resistive element that was mainly based on the 1940/1950s technology; basically consisting of an encapsulated point-contact diode produced by a tungsten whisker wire in pressure contact with a bulk p-type silicon (Si) semiconductor chip (epitaxial Si was introduced during the 1960s by some manufacturers). The structure was essentially a metal–semiconductor device based on the physical mechanism described by the Schottky theory of rectification [1]. The devices were encapsulated in standardized outlines and plug-in mounted in waveguide/coaxial-line single-ended and balanced mixer configurations (coupling provided by magic tee, slot coupler, rat race, etc.). In this period, however, many devices were designed to meet stringent ONF, $r.f.$, and $i.f.$ impedance specifications at selected signal frequencies, to meet the requirements of system fixed tuned mixer mounts. Diode encapsulations included the 3-GHz IN21 and 10-GHz IN23 ceramic capsules, the 3- and 10 -GHz coaxial type (U.K.), the 16-GHz IN78 and 35-GHz IN53 coaxial types, the 35-GHz integral waveguide (U.K.), and the millimeter-wave sharpless wafer plug-in waveguide (some outlines required opposite polarity types for balanced mixers). Toward the late 1960s, novel miniature reversible capsule outlines [e.g., metal–quartz–metal (MQM)] introduced greater flexibility and broader frequency capability.

A. Point-Contact Diode Status

Much of the point-contact work after the 1950s concentrated on achieving a production status of the earlier developed types. A greater theoretical understanding and a high degree of fabrication sophistication were achieved during this period, which led to the optimization of the semiconductor material properties with controlled surface treatment, and development of specialized techniques for forming the intimate metal–semiconductor interface of the wire-semiconductor contact. It should be mentioned, however, that an ideal forward I–V characteristic ($n = 1$) was never achieved with this technology and the I–V ideality factor (n) was typically 1.5; reverse voltage breakdown was in the 1–2-V region. The early performance characteristics of about 9.5 dB ONF ($Fif = 2$ dB, 45 MHz $i.f.$, $Plo = 1.0$ mW) and 14 dB ONF, at 10 and 35 GHz, respectively (Lc typically 6.0 dB and diode noise ratio typically 1.6 at 10 GHz), were the subject of steady development progress over the years. Plo ranged from 0.5 to 2.0 mW, with an input 1-dB CP of about -18 dBm. R&D also focused on millimeter-wave devices, exploring higher electron-mobility semiconductor rectifying junctions, and developing miniature encapsulations. From studies on semiconductor materials, it was found that bulk n-type germanium (Ge) in conjunction with a titanium wire offered potential performance merits (a satisfactory wire metal–gallium arsenide combination was never established), and the late 1950s/1960s saw the development of a range of Ge point-contact mixers [2], [3]. In many cases, Ge retrofits for the Si established types were developed providing 8.5 dB ONF at 10 GHz and 11 dB ONF at 35 GHz ($Fif = 2$ dB). The miniature reversible capsule types that were later introduced (including advanced metal–semiconductor techniques) achieved 6.5 dB ONF ($Fif = 2$ dB, 45 MHz $i.f.$) at 10 GHz, 8.5 dB ONF at 35 GHz [2], and about 14 dB Lc at 140 GHz.

B. Image Recovery

The potential of image recovery to enhance receiver noise figure was explored with point-contact diodes by SSB techniques, using a high-Q filter located in the signal line. The studies did provide a better understanding of the process, but such circuits were not found to be practical, mainly as the result $r.f.$ filter losses, implied narrow-band operation and the nonideal diode I–V characteristic of the point-contact diode [2]. The mechanism, however, was observed with systems incorporating a high-Q transmit–receive (t.r.) cell (t.r. gas discharge valve) for receiver overload protection and, for some applications, it was practice to adjust the distance between the cell and mixer for optimum overall noise figure.

C. Tunnel (Backward) Diode

Additional to the metal–semiconductor, considerable research interest was expressed during the 1960s in the backward diode (a modified tunnel diode), for low flicker noise mixer applications (Doppler radars) and low drive mixers using solid state $l.o.$'s. Initially produced as retrofits for many Si point-contact mixers by employing a gallium (p-type dopant) plated gold whisker wire pulse bonded to the n-type Ge chip [4], [5], planar Ge backward diodes were developed in the late 1960s with an aluminum (p-type dopant) evaporated contact; producing a 3-μm-diameter junction with overlay. Their performance characteristics featured a low drive level ($Plo = 100\,\mu$W) with 8 dB ONF ($Fif = 2$ dB, MHz $i.f$) at 10 GHz, and a $1/f$ noise corner ≈100 kHz (compared with 1–5-MHz range for point-contact technology). A major disadvantage was a poor upper limit dynamic range.

D. Early Schottky Barrier Diode

The planar metal–semiconductor mixer diode, commonly known as the Schottky barrier, was introduced during the late 1960s. The process of evaporating the metal contact to produce the small area of the point-contact diode, without the need for the forming procedure, over came the point-contact limitations on choice of metal and semiconductor material and, in conjunction with advancing semiconductor epitaxial expertise, the technology permitted the use of higher mobility materials e.g., epitaxial n-type Si, epitaxial n-type gallium arsenide (GaAs) in combination with a range of metals, such as gold, titanium, nickel, etc. (Ge was not considered due to the lack of epitaxial techniques); epitaxial techniques introducing the application of lower doped (10^{16} cm^{-3} region) layers than with bulk semiconductors (10^{18} cm^{-3} region). The technology produced improved diode I–V characteristics compared with point-contact technology for equivalent operating frequency, i.e., higher I–V reverse voltage breakdown (>6 V) and near ideal forward I–V characteristics (n values < 1.1), with resulting diode noise ratio of ≈1.05 (MHz $i.f.$ range), Plo range 1–10 and 2–20 mW for Si and GaAs, respectively, and input 1-dB CP about -5 to 0 dBm. These advances led to greater flexibility in mixer design, allowing a broader operational $l.o.$ power range with potential of optimizing impedance levels (beneficial for 50-Ω transmission systems) and higher dynamic range. Although essentially a planar device being studied in conjunction with planar transmission lines for MICs, considerable attention was given to the development of retrofit devices for point-contact outlines for application in the pretuned mixer configurations of existing equipments, achieving, e.g., 7-dB ONF ($Fif = 2$ dB, 45 MHz $i.f$) at 10 GHz. Although wire-bonded chip techniques were used, a favored approach was use of a semiconductor chip with a matrix of 3–5-μm-diameter junctions that were probed by a pointed wire, generally termed the multidot (honeycomb) technique; the principle is still used today at submillimeter-wave and terahertz frequencies.

E. Spike Burnout

In the early years of the t.r. radar system, the receiver was protected from overload damage by a t.r. cell and the power leakage was in the form of voltage/time pulse consisting of a nanosecond spike followed by a flat response of the pulsewidth. The spike width under these conditions was, in general, shorter than the mixer diode thermal constant, and it was the energy within the spike that caused the damage; thus, it was normal practice to specify t.r. cells and mixer diode burnout ratings in terms of spike energy. The mechanism was extremely complex, the effect could be catastrophic, occur with time at an energy level below that which produced catastrophic damage, or be a recoverable temporary deterioration in sensitivity during the transmit pulse. Simulated spike leakage by dc or coaxial line were used for non-$r.f.$ diode testing specifications, but unfortunately, a reliable correlation was never established and dynamic tests were considered to be more meaningful. The physical cause of diode burnout was usually accepted to be the result of high temperatures produced at the junction leading to diffusion or melting, thus, with much dependency on junction area and the choice of metal–semiconductor; in practice, no significant difference was observed between silicon and germanium devices. The point-contact diode presented little maneuverability for high burnout design. The event of the Schottky-barrier diode, however, with its larger contact area for equivalent microwave performance and versatility of a range of contact metals offered great promise, but early experience with t.r. radar systems did not realize the assumed potential, thus triggering further studies. These indicated the influence of barrier metals and semiconductor material and its orientation, and that by selection significant improvements compared with point-contact technology could, in fact, be realized. For example, 10-GHz GaAs Schottky diodes could be designed withstanding t.r. cell leakage levels of about 1 erg/spike compared with about 0.2 erg/spike for point-contact technology [6]. Over this period much attention was also given to improving receiver protection by the application of solid-state devices; varactor limiters in conjunction with t.r. cells, p-i-n switches, p-i-n switch/limiter combinations, etc., and considerable improvement was made in reducing/eliminating narrow spike leakage [7]. Also, the advent of the $r.f.$ amplifier implied that the low-noise transistor became the criterion for receiver reliability [8]. Later years placed the emphasis on pulse damage with testing procedures exploring burnout effects for continuous, single, and successive microwave pulses for a range of pulse shapes/pulsewidths, etc. [9].

III. MIC

Production of point contact mixers continued into the late 1970s (possibly the 1980s) to meet requirements of established systems. R&D, however, was phased out during the late 1960s, when advances in planar semiconductor devices complemented by development of planar transmission lines introduced the feasibility of the miniature planar hybrid MIC.

A. Diode Technology

The event of MICs stimulated many advances in Si and GaAs Schottky barrier device technology (the higher electron mobility of GaAs being beneficial above about 12 GHz). Early semiconductor epitaxial technology utilized 0.2-μm layers, and this progressed rapidly to thinner layers. The late 1970s saw the introduction of the "Mottky" (Mott) diode for millimeter-wave frequencies (defined as the limiting case of a Schottky diode, such that the depletion layer extends through the epitaxial layer) [1], [10], barrier metals were explored for optimum barrier height depending on application. Early diode chips employed 20-μm-diameter contacts to facilitate wire bonding; later techniques used smaller junctions (3–10 μm) with 10–20-μm overlays. Much attention, however, during the late 1960s and early 1970s, was given to developing planar Schottky diodes for frequency ranging applications up to about 100 GHz in a form suitable for embedding in planar transmission lines e.g., microstrip, stripline, fin-line, etc., with emphasis placed on providing a pretesting capability structure. Leadless inverted device (LID) ceramic and quartz carriers, beam leaded devices, and flip chip were all explored in preference to application of direct-circuit wire-bonded chips. Additional to optimizing the rectifying junction, significant development was applied to minimizing the stray capacitance associated with the metal overlay of the dielectric layer linked with contacting the junction. Finger geometries were used for beam lead devices [11], [12], some using glass-bridge techniques for rugged structures, with application into the millimeter-wave frequencies [13]. Mott coplanar structures were designed for flip-chip bonding [14] and, during the 1980s, the planar doped barrier (PDB) diode (a majority carrier rectifying structure where the degree of asymmetry in the I/V characteristic may be independently controlled), was offered as an alternative to the Schottky barrier diode for low drive, reduced flicker noise, improved burnout [15], and also with application to the SHM [15], [16].

B. Mixer Circuits

The late 1960s saw the studies of mixer circuits using many planar transmission media, e.g., fin-line, microstrip, stripline, image guide, with the development of experimental balanced Schottky barrier diode single-ended and single-balanced MIC mixers (mainly using branch arm, rat race, Lange 3-dB couplers) up to about 12 GHz, demonstrating 6.5 dB ONF ($Fif = 1.5$ dB) at 10 GHz, and application to experimental integrated heterodyne receiver subsystems in the late 1960s. These techniques were extended as early as 1972, to development of millimeter-wave microstrip and fin-line circuit media and mixers; e.g., 30–40-GHz SBMs with ONF about 10 dB ($Fif = 1.5$ dB) and at 90-GHz SEMs with $Lc <$ 14 dB [17], [18].

Also of significance was the exploitation of interest in mixer circuit designs now realizable by planar MIC techniques, such as the DBM, IRM, and SHM, which were not practicable with waveguide/coaxial-line transmission media. A great deal of development attention was given to the DBM in the early 1970s, using discrete Schottky barrier diodes to form the quad or by encapsulated quad structures. The main problem of accessing the diode-quad terminals (at low frequencies by conventional center-tapped toroid transformers), was overcome by transmission-line baluns in three-dimensional structures or broadside coupled lines for the $r.f.$ and $l.o.$ and fine wire chokes with miniature decoupling capacitors for the $i.f.$ [19]. The concept launched much interest in broad-band balun design and configurations to eliminate via-holes and back metallization of structures; new ideas still being introduced in the late 1980s/early 1990s with coplanar waveguide, slot-line baluns applied to DBM and DDBM circuits [20], [21] (the latter demonstrated in monolithic technology also applicable to MIC). The original basis realized many broad-band mixer designs within the $r.f.$ region of at least 1–26 GHz and $i.f.$ band of at least 10 GHz, many with $r.f.$–$i.f.$ band overlap.

The potential merits of the antiparallel diode SHM (using wire-contacted diodes) were demonstrated for millimeter-wave frequencies in the early 1970s [22], with the principle applied to many following applications where pumping at one-half the signal frequency was an advantage for limited available Plo. Also, wide-frequency separation between $r.f.$ and $l.o.$ implied high isolation between these ports. Later years saw extensive MIC exploitation of the circuit basis at microwaves and millimeter waves with both diode and transistor elements, e.g., in 1991 application of the high electron-mobility transistor

(HEMT) [23]. The characteristics of the PDB diode were attractive for this type of mixer [15], [16].

C. Image Recovery/Rejection

The MIC topology reopened interest during the 1970s in image-recovery mixers to enhance receiver performance, and using the basis of SSB operation, many R&D studies were carried out to improve the understanding and achieve practical realization [24]–[26]. Circuits combined single-balanced and DBM designs, with the effect of image termination studied in some depth. Quad diode mixers designed for the low-impedance levels associated with image short circuit (in preference to image open circuit predicted theoretically for best Lc) became the preferred choice, and many research workers demonstrated better than 1-dB improvement in mixer conversion loss up to about 12 GHz [24]–[26].

The introduction of the low-noise $r.f.$ amplifier (LNA), however, offered improved receiver ONF performance compared to the potential of image-recovery mixers and drew attention to the requirement for high-power-level second-stage image (noise) rejection mixers, with many system needs focusing on the upper limits of the mixer dynamic range such as IP3 (together with high isolation between ports and broad $r.f/i.f.$ bandwidths). A combination of these characteristics became at least of equal importance to mixer design as high sensitivity, and further work on image recovery was thus phased out, with much development applied to the less complex IRM; specifically the phasing basis for low $i.f.$'s (megahertz region) or broad-band $r.f.$ Many diode-based image rejection (some with image enhancement) subsystems units were developed for frequencies up to 40 GHz during the 1970s, using two-diode and quad-diode mixers, typically achieving 6.5 dB ONF ($Fif = 1.5$ dB, MHz $i.f.$) at 10 GHz and 8 dB at 35 GHz, with image rejection about 20 dB. Some followed into production stages. The potential of the IRHM was reported in 1982 [27].

D. GaAs MESFET Mixers

Extensive studies were carried out during the 1970s on active single- and dual-gate GaAs MESFET mixer designs and, in general, these demonstrated the feasibility of conversion gain (thus reducing ONF dependency on Fif) [28]; circuit studies included the SBM, DBM, and application to the IRM [29]. HEMT mixers for millimeter-wave frequencies were studied in the 1980s [30]. The broad-band active distributed mixer circuit, based on distributed amplification, was demonstrated in 1984 [31]. In general, although there was significant R&D progress with MESFET mixers showing broad potential application, the medium noise figure coupled with poor $1/f$ characteristics, tended to limit their application and, in general, they were not accepted as being competitive with the Schottky barrier diode for many hybrid mixer circuits.

IV. MMIC

The MIC technologies and techniques formed the origin of many complex MIC subsystems developed after the 1970s and were applied to production in the 1980s; application of new developments is still continuing today. Advancements in MMIC technology, however, during the 1980s, realized its potential for further miniaturization with the prospects of low cost high-volume production.

A. GaAs

GaAs monolithic mixers were reported in the early 1970s [32], but it was not until the 1980s that the technology was sufficiently advanced to practically compete with the MIC. In the early days, it was common practice for GaAs MMIC circuits to be produced as individual chips, sometimes being individually packaged, but with increasing interest being given to interconnection for multifunction circuits. Diode technology was developed extensively during the 1980s, attention being given to interdigital finger geometry and air-bridge techniques for diode designs, with operation up to about 100 GHz, and many MMIC mixers based on MIC SBM design principles were developed during the 1980s within the $r.f.$ range of 1–100 GHz. These presented comparable performance to the MIC; e.g., SBM typically 6.5 dB ONF and 7.5 dB ONF ($Fif = 1.5$ dB, MHz $i.f.$) at 10 and 94 GHz, respectively ($Plo = 10$ mW).

The prospects of the GaAs MMIC to realize receiver-integrated structures including mixer and amplifiers using the same technology, together with exploiting the rapid advances in LNA transistors, re-encouraged interest in the three-terminal devices as the mixing element, with much emphasis in the 1980s/1990s being applied to passive (resistive) operation, i.e., device operated as a variable resistance element [33], where studies had demonstrated the potential of improved $1/f$ noise, lower dc power consumption, and better intermodulation products (higher dynamic range) compared with the active device. For example, studies on MESFET-, MISFET-, HEMT-, HBT (GaAs/InP)-based structures, reported IP3 characteristics typically 20 dBm for the SEM [34], [35] and studies of $1/f$ noise reported noise corners of <10 MHz for MESFET and 10–30 MHz for HEMT millimeter-wave technologies [36]. The Schottky diode formed from the gate–source/drain of transistor structures found interest as the mixing element using MESFET-, HEMT-, HBT-based technologies, to realize monolithic integration compatibility with processing several receiver circuit functions on a single chip [37]–[39]. Generally, it was shown that the MESFET may offer the merits of a low-cost process, HEMT low-noise figure, and HBT low $1/f$ noise and low drive.

Of particular significance to the progress of MMIC mixers (diode and transistor circuits) for broad-band SBM and DBM applications was the monolithic implementation of the balun, with the design aims of low loss, miniaturization (smallest possible line lengths), wide-band, and compatibility with integration of the whole mixer on a single chip; advancements are still continuing today. Some examples may include: 1) lumped-element (narrow bandwidths) [40]; 2) broad-band Marchand and side-coupled type baluns for octave bandwidths [41]; 3) compact wide-band active $l.o.$ port balun with gain [43]; 4) broad-band Marchand with spiral-shaped equal-length coupled lines [42]; and 5) compact planar spiral structures that behave like a bifilar balun [44].

The potential advantages offered by MMIC mixer technology, particularly with three-terminal devices, are now being exploited across the range of mixer circuits. For example: 1) down-converters that may combine a combination of mixer, $r.f.$, $i.f.$, and $l.o.$ amplifier circuit functions [45]; 2) antiparallel diode SHMs [46]; 3) IRMs realized by signal filter for narrow-band $r.f.$ or gigahertz $i.f.$'s applications to meet simplicity and low-cost requirements, such as DBS reception [47] and, more recently, HEMT SHM MMIC single-chip 38–38.6-GHz transceivers [48]; 4) IRMs using phasing techniques for broad-band $r.f.$ or megahertz $i.f.$ applications, in 1986, as a single-chip MMIC 4-GHz down-converter utilizing two Schottky barrier diode DBM's [49] and, more recently, broad-band 24–44-GHz DBM harmonic IRMs [50]; and 5) active HEMT distributed mixers with application to broad-band receivers [51].

B. Silicon

Discrete Si and GaAs Schottky barrier mixer diodes achieve similar ONF characteristics up to about 12 GHz, with Si providing the lower barrier height (thus, Plo) and better $1/f$ noise (100-kHz noise corner compared with 500-kHz noise corner for GaAs). Si offers useful application into the millimeter-wave frequency region, but due to its higher electron mobility, GaAs provides the higher cutoff frequency and better performance, particularly at frequencies above about 40 GHz, and with the advent of GaAs MMICs it has predominated as the technology basis. The superior $1/f$ characteristics of Si, however, may offer a better ONF performance for some applications (e.g., FMCW radar) up to approximately 100 GHz.

Due to its potential for low cost, small size, and reproducibility for multicircuit integration there has been a continuing progressive interest in Si to challenge GaAs for monolithic circuits, including application to frequency conversion. Silicon bipolar-based technology active mixers have provided attractive characteristics, e.g., a silicon bipolar MMIC SEM with approximately 15-dB gain at 11 GHz for -5–0-dBm Plo, possible applications up to 20 GHz [52], and a 2-GHz active DBM silicon Gilbert cell (emitter–coupled-transistor pair) with approximately 15-dB Gc, SSB ONF 16 dB, -18-dBm IP3 for 0-dBm Plo and possible operation up 6 GHz [53]. Progressive research is continuing into Si- and SiGe-based monolithic integrated millimeter-wave circuits (SIMMWICs), and associated coplanar Schottky diode SBM circuits have been reported exhibiting approximately 8.0-dB Lc at 77 GHz [54].

V. APPLICATION ABOVE 100 GHz

Applications above about 100 GHz, promoted mainly by radio astronomy, but finding exploitation in spectroscopy, satellite remote sensing, etc., is a specialized field, but mixer technology and many design principles are based on the lower frequencies. Cryogenic cooled receivers have a particular attraction for many applications. The mixer can be characterized by conversion loss Lc, by noise temperature Tm, and $i.f.$ amplifier noise temperature Tif. Although other mixer elements are available, generally, low-parasitic GaAs Schottky barrier (Mottky) diode single-ended mixers are employed, with quasi-optical diplexing techniques to couple the $l.o.$ and signal. Mixer mounts normally utilize waveguide horn-feed forms

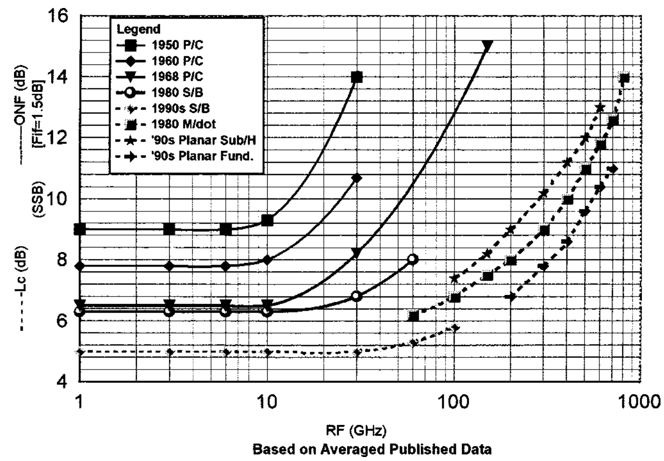

Fig. 1. Conversion loss (Lc) and overall noise figure (ONF) as a function of radio frequency ($r.f.$).

TABLE I
COMPARISON OF POINT CONTACT AND SCHOTTKY BARRIER DIODE 1970/1980s CHARACTERISTICS (10 GHz $r.f.$)

	I-V "n"	SSB ONF	Lc	Plo	In CP	Nr	1/f n/c
Si P/C	1.5	7.3	5	0.5 to 2	-18	1.25	2 Mhz
Ge P/C	1.3	6.5	4.5	0.3 to 1	-20	1.15	1 MHz
Si S/B	1.05	6.3	4.5	1 to 10	-5 to 0	1.05	100kHz
GaAs S/B	1.05	6.3	4.5	2 to 20	-5 to 0	1.05	500kHz
		dB	dB	mW	dBm		
		Fif=1.5dB				i.f.=45MHz	

of construction or may employ open structure (quasi-optical) techniques or printed antenna. The advent of the Schottky barrier diode in the 1960s was fully exploited for radio astronomy using the low parasitic whisker contacted multidot (honeycomb) technology. Typical room-temperature Lc values of 6.0 dB in the 100-GHz frequency region for fundamental operation were achieved in the early 1970s with 2–3-μm-diameter junctions and 6.5 dB for subharmonic mixing in the 200-GHz region in the late 1970s with 1.5-μm-diameter junctions. Since then, steady advancements have been made both in device and receiver submillimeter-wave technologies and techniques. The 1980s saw application up to about 1000 GHz using the same earlier technology basis [55], and the 1990s further improvement in room-temperature conversion loss. Currently, however, developments of high-quality low-parasitic planar air-bridge diodes have promoted the interest in planar technologies beyond 100 GHz [56], [57], and this technology, utilizing MIC-waveguide techniques, is providing a competitive performance to the wire-contacted diode single-ended mixer. Further, application to the SHM is providing an alternative option to fundamental operation for frequencies as high as 640 GHz [58]. Recent work is exploring the potential of the MMIC [59], [60]. Terahertz frequencies, however, generally still employ advanced low-parasitic whisker-contacted techniques (0.25-micrometer-diameter anodes) [61].

TABLE II
COMPARISON OF IP3 CHARACTERISTICS

	Type	Device	r.f.	Lc	SSB NF	Plo	Input IP3	Ref
SEM	Diode	S/ Barrier	10	5.5	5.5	10	5 to 10*	Typical
SEM	Passive	GaAs MESFET	10	6.5	6.6	10	21.5*	[34]
SEM	Active	GaAs MESFET	10	-6	5	10	16*	[34]
SEM	Passive	GaInAs MISFET	10	7	7	20	30	[35]
SEM	Passive	S-D PsMESFET	10	6.9		10.5	25.5*	[63]
SEM	Passive	PHEMT	60	10		10	28	[64]
SBM	Passive	PHEMT	60	8.5		10	30	[64]
SEM	Passive	InP HEMT	94	10*	10	10	20	[38]
SEM	Active	InP HEMT	94	0.8	9	10	8	[38]
SBM	Diode	InP HEMT S/diode	94	10	10	10	13	[38]
			GHz	dB	dB	dBm	dBm	
				*Plo=3.4dBm	Fif = 0dB		*Output	

The progress of low-noise HEMT amplifiers exceeding 100 GHz, however, as at lower frequencies, could make mixer noise performance a secondary consideration, with the dynamic-range characteristic becoming of primary concern, implying the desirability for the application of more complex mixer configurations.

VI. Performance Discussion

Comparisons of mixer data can present problems. Mixer sensitivity may be expressed in terms of DSB or SSB noise figure (or noise temperature), with or without $i.f.$ amplifier noise contribution, for megahertz or gigahertz range of $i.f.$'s or by conversion loss/gain. Designs may be for broad-band or narrow-band $r.f.$ and $i.f.$ Integration may imply probe measurement techniques [62].

Historically, point-contact mixers were specified (by approved standards) in terms of SSB overall noise figure, with suppression of $l.o.$ noise sidebands ($l.o.$ filter), at a specified $i.f.$ amplifier noise figure and frequency, and with reference to the mixer signal terminals. This basis tended to hold into the 1980s, including some early packaged MIC mixers, but largely as the result of multicircuit integration, conversion loss has become common practice to interpret resistive mixer performance (although recognized that it may not reflect possible degrading sensitivity contribution of the device generated noise Nr).

Fig. 1 presents a very generalized picture to indicate the overall trend of room-temperature resistive mixer achievable sensitivity performance over the period 1950 to 2000. The 1950s–1980s are depicted by SSB ONF ($Fif = 1.5$ dB), and by Lc for the 1990s Schottky barrier diode and frequencies above 100 GHz, based on available averaged published meaningful data (DSB data corrected by adding 3 dB).

At frequencies below 100 GHz, the ONF improvement for the point-contact diode from the 1950s to approximately 1970 is clearly shown, with the late 1960s provided a very acceptable performance up to at least 40 GHz (1968 data is predominantly Ge). The event of the Schottky barrier diode did not provide a great ONF advantage over the Ge point contact up to about 12 GHz, the benefit being derived from Plo flexibility, Nr near 1.0, improved upper limit dynamic range, and reduced $1/f$ noise (and, of course, planar structure), but became significant at higher frequencies (data includes Si and GaAs, predominantly GaAs above approximately 40 GHz). Approximate calculation of Lc for the 1968 point contact and 1980 Schottky barrier data, indicates an Lc about 5 dB up to about 12 GHz, comparable with the 1990 Schottky barrier technology. The flattening of conversion loss above about 30 GHz in the 1990s may be attributed to the progress in device technology to minimize planar stray capacitive parasitics, applied to both the MIC and MMIC basis. It should be noted that the data is predominantly for SEM configurations, thus presenting the device sensitivity capability.

Table I provides a broad summary of 1970/1980s point contact (representing the status toward the end of development) and Schottky diode performance characteristics at 10 GHz, indicating the characteristic merits of the Schottky barrier technology.

With consideration of frequencies above 100 GHz, the Fig. 1 1980 data represents the wire-contacted multidot GaAs Schottky (Mottky) diode SEM structures of that period. Recent planar technology is now almost performance competitive with wire-contacted structures up to about 650 GHz, and the 1990s data represents predominately planar technology. Although

TABLE III
COMPARISON OF Lc/NF AND IP3/CP CHARACTERISTICS

	Type	Device	r.f.	Lc	SSB NF	IF	Plo	In IP3	In CP	Ref
SBM	Passive	FET	2-27	6-15		1G	17	24-37	18.5	[65]
SBM	Active	FET	1.1	-16.7	5.2	130M	0	7.5*		[70]
SBM	Passive	PHEMT	50 to100	11.6		50M	4		0	[41]
SBM	Passive	PHEMT	77	8.8		50M	4		0	[41]
DBM	Diode	S/B	6 to18	5 to 8.5		1G	10		6	[20]
DBM	Passive	FET	2 to 8	8 to 9			23	30		[66]
DBM	Passive	FET	4 to 18	8 to 12		1 to 2G	7	>18		[42]
DBM	Diode	FET s/diode	6 to 18	5 to 10			15		>8	[67]
DBM	Diode	PHEMT s/diode	14 to 32	6 to 9	6 to 9	dc-8G	11	18	11	[68]
DDBM	Diode	S/B	1 to 18	8.5		M	20	25		[19]
DDBM	Diode	S/B	6 to 20	7.5		2 to 7G	17	20	8.5	[21]
SHM	Diode	S/B	26 to 36	10 to 12			11	13	2.5	[69]
SHM	Passive	HEMT	10	6.5		0.1 to 2G	12		10	[23]
SHM	Passive	PHEMT	10	8	8.5	1G	16	13	-2	[46]
SHM	Active	PHEMT	10	-5	12	1G	16	10	-2.5	[46]
			GHz	dB	dB	Hz	dBm	dBm	dBm	
					Fif=0dB			* Output		

there is a wide spread in available data, the 1990s data tends to fall into two categories: the fundamental operation SEM and the antiparallel SHM, with the SEM indicating the better performance by a factor of almost 2 : 1. Although progress is being made with the MMIC, it is not yet competitive with the hybrid planar configurations, e.g., 16.5 dB Lc at 180 GHz for a subharmonic InP HEMT diode mixer [60].

In general, the three-terminal device mixer has not presented a significant noise-figure performance advantage over the Schottky barrier diode, the passive transistor mixer Lc performance falls well within the spread of diode mixers for frequencies below 100 GHz. The active device sensitivity can only be expressed meaningfully in terms of ONF, but active gate-fed mixers may require less Plo and display the better ONF performance. The passive (resistive) transistor characteristics have, however, indicated a particular benefit in terms of dynamic range upper limit defined by IP3, thus, useful application to the high-level second-stage mixer for LNA microwave receivers. There is a widespread in published IP3 data (this may be quoted at output or input) for various three-terminal device technologies and circuit designs, and the potential of the transistor compared with the Schottky barrier diode may best be compared for the SEM. Some published IP3 data based on references in this paper is summarized in Table II, and some example comparisons of Lc/NF and IP3/CP characteristics are indicated in Table III for a range of mixers.

With reference to Table II, [63] also presents a comparison of spike-doped PsMESFET, ion-implanted MESFET, power PsHEMT, and n-p-n HBT as a ratio measure of two-tone third-order intercept to Plo, and indicates ratios of 22.0, 13.9, 14.2, and 10.2, respectively, compared with zero for a typical diode; [64] presents IP3 data for 60-GHz resistive pseudomorphic HEMTs (pHEMTs) with reactive feedback between gate and drain, with application to direct conversion receivers (converts $r.f.$ signal direct to baseband); and [38] presents a comparison of resistive, active, and Schottky mixer configurations compatible with InP HEMT technology.

With reference to Table III, [70] combines two dual-gate FET with built-in active baluns for personal-communication-system applications; [67] and [68] utilize transistor Schottky diodes (monolithic processing integration compatibility). Although not included as a Table III characteristic, the SHM provides >55 dB $r.f.$ to $l.o.$ isolation compared with the 15–30-dB range for the other mixers. In general terms, IP3 for the broad-band (e.g., 1–18 -GHz region) DBM falls in the range of 15–30 dBm (10–20 -dBm Plo) for a passive transistor quad compared with about 15 dBm (10-dBm Plo) for a diode quad, with similar Lc in the 6.5–9.0-dB range.

Current transistor mixer technologies and techniques embrace many options including circuit and modes of operation, and a detailed performance data analysis is outside the scope of this paper. Unfortunately, generally sensitivity based on Lc

data tends to lack ONF qualification, of particular significance for megahertz and below intermediate-frequency applications, where there appears little information on flicker-noise characteristics of the transistor mixer for its various operational modes (referenced reports indicate $1/f$ noise corners in the 10–30-MHz range for low flicker-noise passive transistors [36], compared with the 100–500-kHz range for 10-GHz Schottky barrier diodes [15]).

VII. Some Conclusions

As the result of extensive R&D investment, mixer technology and techniques have advanced considerably since the traditional mixer of 50 years ago incorporating point-contact technology, particularly through the significant steps of the Schottky barrier diode and transistor, applied to the MIC and MMIC.

Currently, the MMIC performance characteristics compete with those of the MIC and offer the mixer designer the miniaturization and reproducibility advantages of MMIC technology, with the capability to meet a wide range of system needs up to approximately 100 GHz, thus providing a specific choice of mixer circuit and embedded frequency-mixing element depending on application.

Noteworthy mixer technology and performance progress is being made above 100 GHz where sensitivity is still of prime importance, and planar technology is offering almost competitive performance to the wire-contacted multidot structure. Advances, however, of low-noise HEMT amplifiers exceeding 100 GHz, may soon imply the desirability for receiver second-stage high-level mixers.

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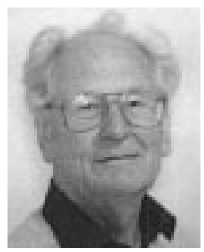

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