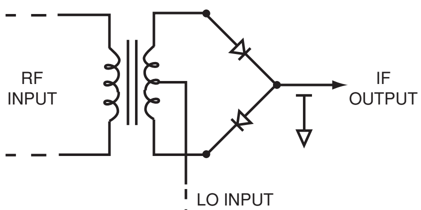
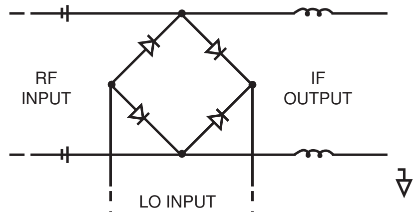
DOUBLE-SIDEBAND MIXER CIRCUITS

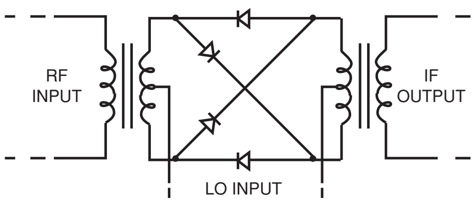
SBW SERIES
Waveguide RF,
SMA LO/IF



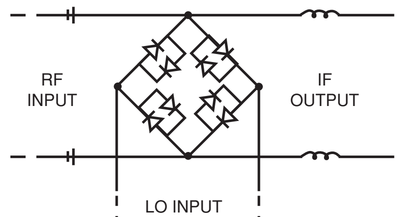
SBB SERIES
DC Biasable,
Low LO Power



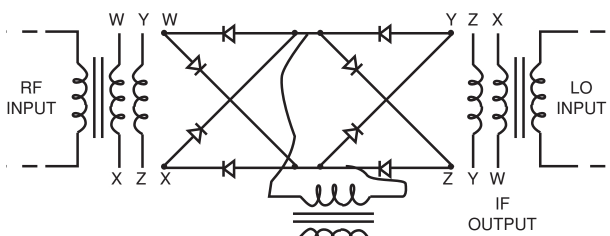
DB, DM SERIES
General Purpose



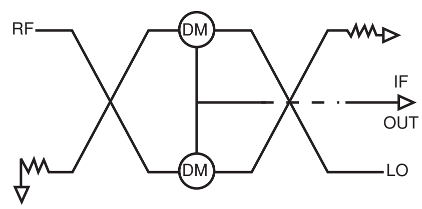
SBE SERIES
Even Harmonic
(1/2 LO)



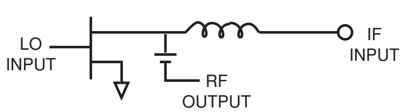
TB, TBR SERIES
Best Spurs,
Overlap RF/IF



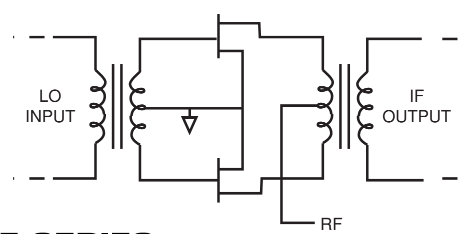
TIM SERIES
Low VSWR,
Load Insensitive



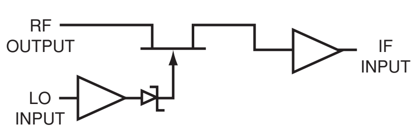
SF SERIES
General Purpose
High IP³/LO Ratio



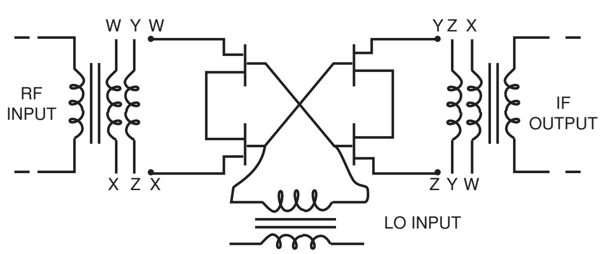
SBF SERIES
+30 dBm, IP³



SRD SERIES
Sampling,
0.5 TO 1.5 GHz LO

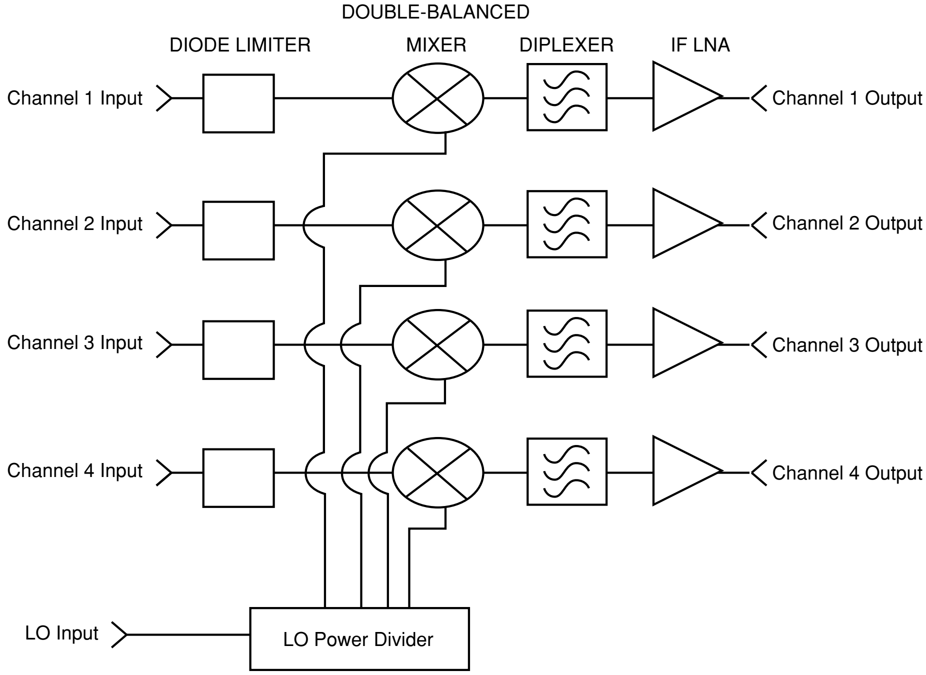


DBF SERIES
+36 dBm, IP³



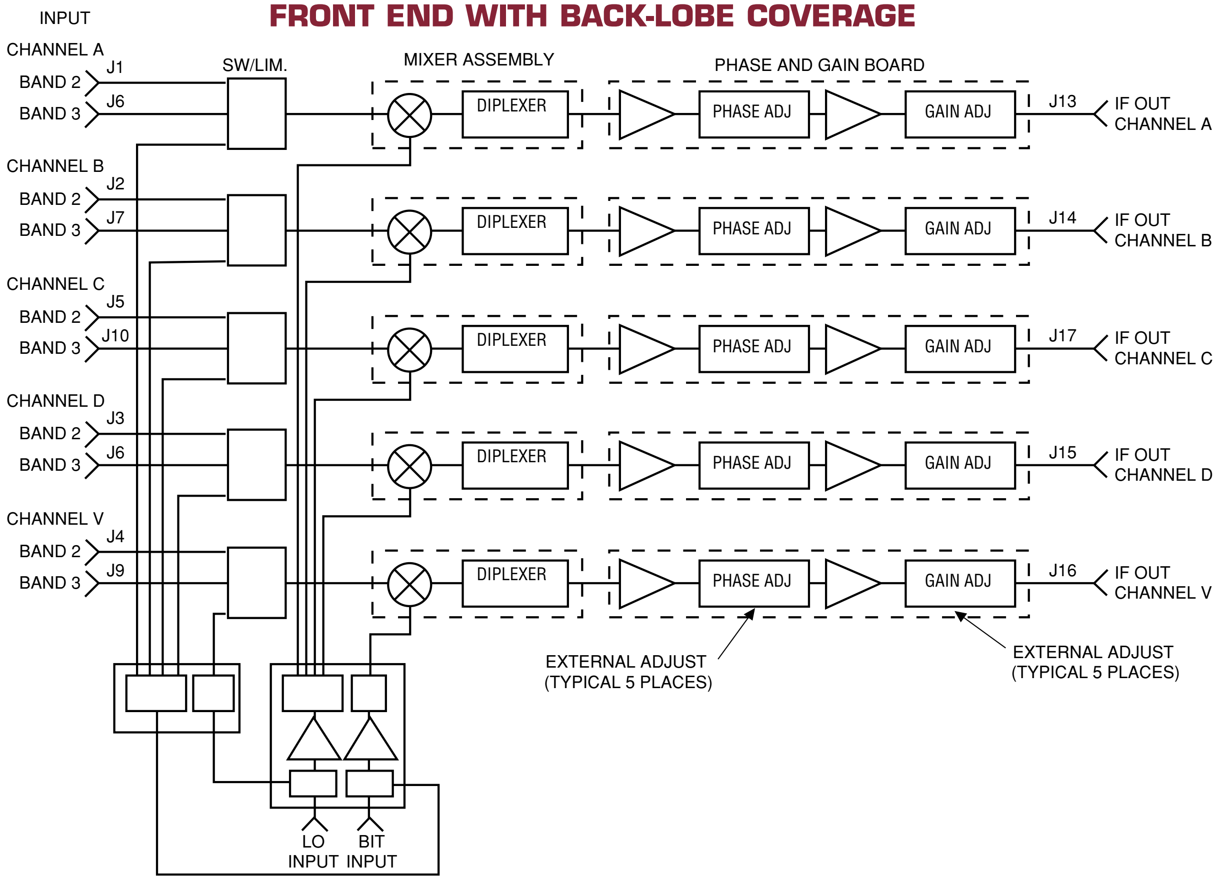
DA4 SERIES

BASIC FOUR-CHANNEL DIRECTION-FINDING FRONT END



DSS SERIES

EXTENDED FEATURE FIVE-CHANNEL DIRECTION-FINDING FRONT END WITH BACK-LOBE COVERAGE



Schottky diode mixers have generally been used as the front-end downconverter for commercial and military receivers. As the density of signals in a given channel increases, the input IP^3 rather than noise figure of the front end begins to limit the receiver's dynamic range.[1] The principles of operation and advantages of fundamental, harmonic and sampling mixers using MESFETs instead of Schottky diodes, as well as performance data obtainable with new MESFET equivalent circuits, are reported.

Don Neuf
MITEQ Inc.
Hauppauge, NY

The input RF compression power of any Schottky mixer is approximately 5 dB below the available LO power because both signals are simultaneously applied to the diodes. Under normal circumstances, it is not desirable for the RF to control the conduction state of the diode, which results in RF harmonics. Therefore, higher compression RF powers are achievable only with proportional increases in LO power. Greater LO power usually means higher receiver cost and volume, and lower battery life. Many designers have extended the original work in which MESFETs are used instead of Schottky diodes for greater mixer RF power handling with less switching or LO power.[2]

MESFETs can basically be used in either of two modes for multiplication of the LO and RF signals. In the active mode, the LO and RF signals are applied to the gate (or dual gate) and the IF signal is recovered from the drain. The drain also has a positive DC voltage, thus providing some gain to the frequency conversion process. In the passive mode, the LO is applied to the gate of the MESFET, while the RF and IF are both connected between the drain and source. No DC voltage is used on the drain, although a small negative voltage is used at the gate.

In the passive mode, the LO at the gate essentially switches the drain/source channel between high and low resistance states. Unlike the active mode, no gain is achieved but the resulting conversion loss is similar to a Schottky mixer including low phase noise. This paper emphasizes the passive MESFET mode because of its superior third-order distortion.

Distortion is generated in any Schottky diode mixer primarily from the exponential shape of the junction voltage and current, as shown in Figure 1. The small-signal RF resistance of a Schottky mixer is approximately equal to the average value of the time varying slope of the E/I curve, which at the knee, is quite nonlinear. By contrast, the passive MESFET drain/source resistance is almost linear at two different LO bias voltages. The symmetry of the MESFET curves about the origin (V_{DS} = 0) also accounts for the low odd order RF distortion products, such as 3RF ± LO and $2RF_1 \pm RF_2$. In this passive mode, the MESFET channel acts as an LO voltage time-dependent linear resistor. In contrast, the active MESFET mixer has an RF input gate source resistance and intermodulation similar to the Schottky diode mixer.

THE E/I CHARACTERISTICS OF (a) A SCHOTTKY DIODE AND (b) A MESFET

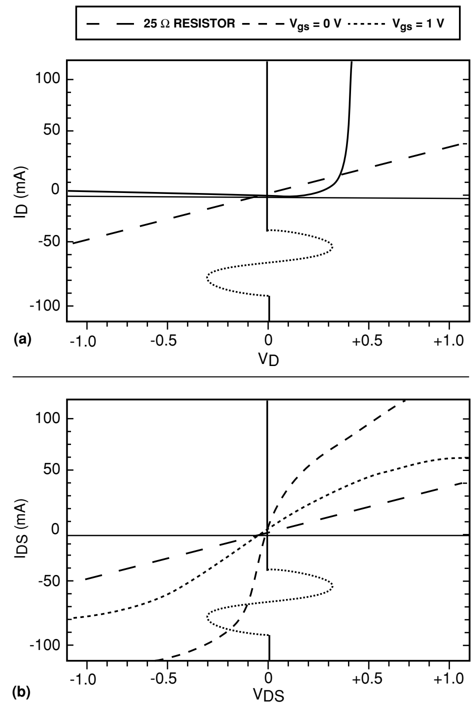


FIGURE 1

FUNDAMENTAL LO MIXER CIRCUITS

The basic mixer design problem arises in situations that require LO, RF and IF circuits to be coupled efficiently to a common semiconductor element, while requiring each port be decoupled or isolated from one another. Various multiple diode single-, double- and triple-balanced circuits have evolved that rely on different coupling modes for port separation. Figure 2 shows the double-balanced Schottky diode mixer circuit and a MESFET version of the same circuit. The Schottky circuit advantages are its low cost and its performance. It has an IP^3/P_{LO} equal to 0 to 5 dB, maximum IP^3 of +25 dBm above 2 GHz and a P_{1dB}/P_{LO} equal to -5 dB. The MESFET mixer is easy to bias and has an IP^3/P_{LO} equal to 5 to 15 dB, an IP^3 maximum of greater than +35 dBm and a P_{1dB}/P_{LO} of 0 dB. The MESFET circuit is usually chosen for receiver design because of its increased RF dynamic range with the same LO power as normally employed for the Schottky mixer. The cost of the passive MESFET mixer is usually higher, but must be weighed against

FUNDAMENTAL, HARMONIC AND SAMPLING MESFET MIXERS CIRCUITS

FUNDAMENTAL DOUBLE-BALANCED MIXING CIRCUITS; (a) A SCHOTTKY AND (b) A MESFET

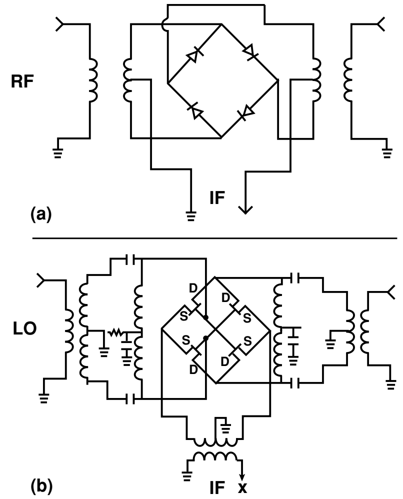


FIGURE 2

the extra cost of a higher power LO source needed to get the same dynamic range using Schottky diodes. When operation at low LO power is desired, the double-balanced MESFET mixer, shown in Figure 3, has the additional advantage that the separate LO gate circuit is more easily DC biased than a continuous ring-quad of diodes. The 1/f and uniform thermal phase noise of the Schottky diode and passive MESFET circuits are similar.

Table 1 lists the typical measured data of a 1.8 GHz MESFET mixer at +30 and +20 dBm LO powers. In each case, the input IP^3 is approximately 10 dB greater than the LO power. The ratio of IP^3 to LO power is dependent upon the channel doping profile of the MESFET and the LO port reflection coefficient. The input RF 1 dB compression power is approximately equal to the LO power for this mixer, and it will accept an RF input power of +30 dBm when the LO is also at this power. Perhaps the term power mixer is more descriptive of this device. Thus, each MESFET in this double-balanced quad has a 1 dB RF compression of +24 dBm. Another interesting advantage of the passive MESFET mixer relative to a Schottky diode mixer is the burn-out RF power limit. A general rule used by Schottky diode manufacturers is 75 mW maximum CW power for each diode junction or +300 mW (+25 dBm) for a quad. The average high frequency MESFET will accept an RF power or DC power across the drain and source of 250 mW (50 mA at 4 V) and 1 W for the quad. The described L-band mixer can survive 25 W CW. In actual practice, the thermal resistance of the microwave copper circuitry and that of the Schottky or MESFET ceramic packages must be considered.

THE 1.8 GHz MESFET MIXER'S TYPICAL PERFORMANCE

RF/LO FREQUENCY (GHz)	1.7 to 1.9
Input IP^3 (dBm)	
@ 30 dBm LO	+40
@ 26 dBm LO	+36
IF RESPONSE (MHz)	**50 to 2000**
Isolation (dB)	
LO/RF	25
LO/IF	30
SWR	
RF	2
LO	3
IF	2

TABLE 1

A 1.8 GHz DOUBLE-BALANCED MESFET MIXER

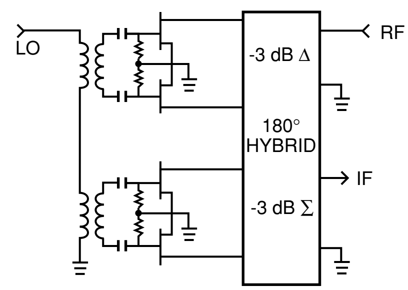


FIGURE 3

Figure 4 shows the X-band MESFET mixer circuit using quadrature coupled single-balanced mixers. This four-FET circuit has three unique system advantages. The input IP^3 is not affected by IF circuit mismatches (it is termination insensitive). The LO-to-RF isolation is typically 30 dB, and the input LO and RF VSWRs are low and nearly independent of LO power, that is, the circuit behaves as if ferrite isolators were used at these ports. A 12 to 18 GHz scaled version of this mixer circuit was produced with a 2 to 4 GHz IF output. Table 2 lists the X-band MESFET mixer's performance. The listed performance was measured with an LO power of +25 dBm. However, when DC bias is used at the gates, operation at +13 dBm LO is possible with 2 dB higher conversion loss.

FUNDAMENTAL, HARMONIC AND SAMPLING MESFET MIXERS CIRCUITS

A TERMINATION-INDEPENDENT MESFET MIXER

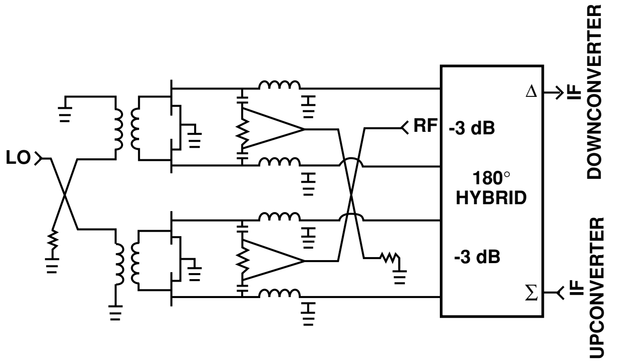


FIGURE 4

AN EVEN-HARMONIC BALANCED, SCHOTTKY DIODE MIXER

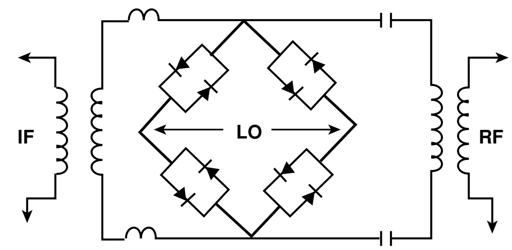


FIGURE 5

PERFORMANCE OF THE X-BAND MESFET MIXER

RF (GHz)	8	8.5	9	9.5	10	10.5	11	11.5	12
LO (GHz)	6	6.5	7	7.5	8	8.5	9	9.5	10
Input IP^3 (dBm)	37	37	37	37	36	37	34	37	36
Conversion loss (dB)	8	8	7.9	7.7	7.5	7.9	8.2	8.5	9
Input P1 dB (dBm)	26	27	26	25	25	25	25	25	24
LO/RF isolation (dB)	30	34	36	32	32	40	34	34	32
Return loss (dB)									
RF	25	25	23	21	20	17	16	15	15
LO	15	16	20	22	20	19	18	20	23
LO = 26 dBm Bias = -15 V									

TABLE 2

THE SCHOTTKY DIODE MIXER'S TYPICAL PERFORMANCE

RF frequency (GHz)	8 to 18
RF power (dBm)	-3
LO frequency (GHz)	4 to 9
LO power (dBm)	+7
IF output (GHz)	DC to 1
Upconverter carrier rejection (dB)	45
Conversion loss (dB)	10

TABLE 3

HARMONIC LO MIXING CIRCUITS

It is becoming increasingly popular, particularly at mm-wave frequencies, to use Schottky diode mixers that operate at one-half or one-third the normal LO frequency, that is, second- and third-harmonic mixing.[3,4] At these frequencies, there is a considerable savings in the cost of the LO and a reduction in LO reradiation because of the higher inherent 2LO-to-RF isolation of these mixers. Figure 5 shows a typical 8 to 18 GHz even-harmonic balanced, Schottky diode mixer using an LO frequency at one-half the RF. Its performance as a downconverter is listed in Table 3. The unusually high 2LO-to-RF isolation (60 dB) of this circuit also makes it useful as an upconverter for digital quadrature amplitude modulation radios because linear upconverters or modulators require high suppression of the LO or carrier in order to maintain accurate RF quadrature phase I/Q states.

The even-harmonic mixer is generally more popular than third-harmonic mixing because the even harmonic has approximately the same conversion loss as fundamental mixing, whereas third-harmonic mixing is typically 10 dB poorer than fundamental mixing. However, an even-harmonic Schottky mixer generally has 6 to 10 dB poorer input RF compression compared to fundamental Schottky mixing because the LO power for optimum conversion loss is more critical and often lower. Once again, the MESFET has a useful role in upgrading the dynamic range of a mixer. Figure 6 shows a MESFET even-harmonic mixer. Table 4 lists its performance.

A MESFET EVEN-HARMONIC MIXER

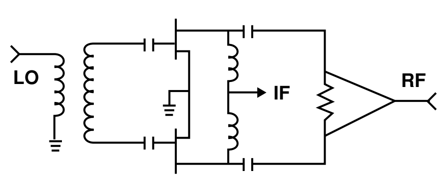


FIGURE 6

THE MESFET EVEN-HARMONIC MIXER'S TYPICAL PERFORMANCE	
RF frequency (GHz)	5 to 6
RF P1 dB (dBm)	+10
LO frequency (GHz)	2.5 to 3
LO power (with bias) (dBm)	+13
IF frequency (GHz)	DC to 1
Conversion loss (dB)	10
Isolation (2LO/RF) (dB)	30

TABLE 4

The circuit yields approximately 10 dB conversion loss at +13 dBm LO power and exhibits 1 dB RF compression at +10 dBm. The half frequency LO is applied through a 180 degree balun to the gates of the two identical MESFETs. The drain-to-source lead pairs are connected in parallel. Therefore, each FET has the same RF and IF signal. During one LO cycle each FET conducts during its corresponding positive half cycle, which produces two low impedance states across the RF terminals during each LO cycle, effectively doubling the input LO switching rate. The incident RF and reflected IF energy is separated by a diplexer. This circuit is only balanced with respect to the LO/RF and will not reject RF or IF harmonic spur products. The thermal output noise of an even-harmonic mixer is identical to a pad, but any LO phase noise is doubled in the mixing process.

The conversion loss penalty is severe for harmonic mixing above n = 2. For example, a third-harmonic mixer made from a ring-type Schottky mixer is typically $(1/n)^2$ or 10 dB poorer than fundamental mixing. Other odd-harmonic products of square wave ring switched mixers follow the same relation unless reactive terminations of unused output frequencies are provided. Sometimes a step-recovery diode (SRD) is used to generate a comb of output frequencies as an LO source. A conventional Schottky diode mixer will have progressively higher conversion loss in direct proportion to the spectral power output of the SRD pulse harmonic. If only one harmonic of the comb is filtered and amplified, low conversion loss is possible, but is considered the same as fundamental mixing. Fortunately, high conversion efficiency can be achieved from a mixer using LO harmonic ratios of 10 to 100.

SAMPLING MIXER CIRCUITS

Using sampling mixer circuits the amplitude of any repetitive RF signal can be detected by periodically sampling or connecting a small capacitor with a diode or MESFET switch and charging it with the unknown voltage. Figure 7 shows the sampling mixer concept. If the switching action (typically in picoseconds) occurs at an exact or submultiple (one, one-half, one-third, ... one/n) of the unknown measured frequency, then the capacitor charging voltage or sampled RF waveform is identical during each switching instant. Since the switching diode is off (high resistance) between samples (typically in nanoseconds), the average capacitor voltage would not discharge, but rather after many RF cycles would eventually reach the amplitude of the RF signal. In some cases, such as in a phase-locked sampling loop, the capacitor will have zero average voltage because the samples are timed or in-phase with the exact zero crossings of the RF signal.[5] At this point, a small change in sampling frequency phase will yield the positive or negative peak values of the unknown sinusoidal RF signal. Typically, in the phase-locked application, the sampling capacitor voltage is amplified with a high input impedance operational amp and the phase of the much higher frequency-locked source is forced to agree with the multiplied phase of a typically 1 GHz reference or sampling frequency. In other sampling mixer applications, the multiples of the sampling frequency are chosen to be slightly different in frequency by the desired IF of the receiver. In general, the sampling mixer can accommodate slight frequency changes or unknown RF signal bandwidths, provided that the reference LO has a frequency that is at least twice that of the RF information bandwidth, that is, the Nyquist criteria. Under-sampling is a commonly used term to describe bandpass RF signal sampling. The receiving system penalty paid for the savings of a microwave LO source is multiple responses spaced by the fundamental LO frequency, and therefore, the RF bandwidth is restricted to be less than half the LO frequency to prevent response folding. A bandpass filter preceding the sampling mixer would eliminate other narrowband harmonic responses.

The sampling mixer is capable of lower and flatter conversion loss than the discussed harmonic mixer, provided that the following circuit conditions are met. The sampling gate time should be less than a one-half cycle at the highest RF frequency. The sampling rate is required to be considerably higher than the IF frequency. The sampling capacitor and IF load resistance time constant should be much greater than the period of the RF being sampled.

THE SAMPLING MIXER CIRCUIT CONCEPT

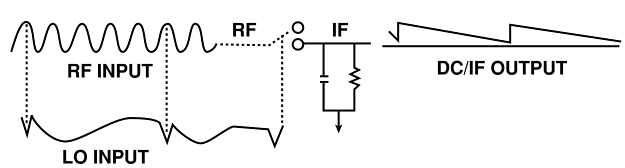


FIGURE 7

The RF input compression power of the sampling mixer generally is higher than the harmonic mixer, particularly if a MESFET is used as the switch. The RF input compression point of a harmonic mixer is related to the harmonic current of the Schottky diode, and falls off as 20 log 1/n.

Figure 8 shows the sampling mixer circuits of the Schottky diode and the MESFET, while Figure 9 shows their relative performance. Both units had approximately 100 to 400 MHz IF frequency ranges and could accommodate wide bandwidth receiver signals or fast phase-locked loops. The MESFET switch input RF compression power was approximately +13 dBm, whereas the Schottky version was 0 dBm, using the same SRD power. Newer I/Q and image rejection MESFET sampling mixers are currently being developed as preparation for a lower cost, low noise front end. A low noise input amplifier and 1 GHz LO will allow 500 MHz operating bandwidths up to 26 GHz.

THE SAMPLING MIXER CIRCUITS USING (a) SCHOTTKY DIODES AND (b) A MESFET

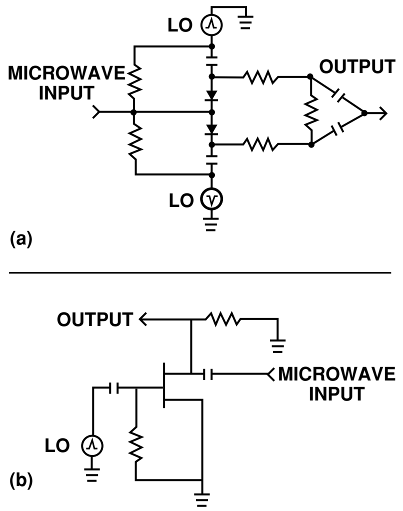


FIGURE 8

PERFORMANCE OF (a) SCHOTTKY DIODES AND (b) MESFET MIXERS

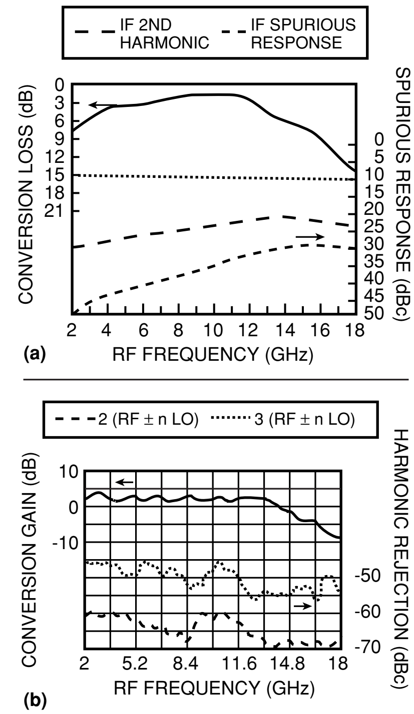


FIGURE 9

MIXER PRODUCTS

CONCLUSION

This paper has demonstrated that almost any existing Schottky diode mixing circuit can benefit in RF power handling capacity by substituting MESFETs. Additional advantages are increased circuit isolation without baluns and/or bias options by virtue of the three-terminal structure of the MESFET. These advantages are particularly helpful in more complicated mixing circuits, such as image rejection types following a high gain input low noise amplifier (LNA). In many existing front-end upgrades, the increased sensitivity of the LNA carries a trade-off in dynamic range by compression of the following imageless mixer due to the increased RF gain. This problem could be avoided with more LO power, but increased LO power would increase the cost of the system upgrade. As a result, front-end designs using broad bandwidth or image rejection mixers with MESFETs are growing in popularity.

Figure 10 shows the dynamic range and input noise figure trade-offs of typical 4 to 8 GHz LNAs with a MESFET second-stage mixer. The corresponding LO power needed to prevent mixer overload at the input RF power is also shown. Other harmonic and sampling MESFET image rejection mixers are currently being developed.

THE LNA - MESFET MIXER'S (a) INPUT DYNAMIC RANGE AS A FUNCTION OF (b) THE LNA'S PERFORMANCE

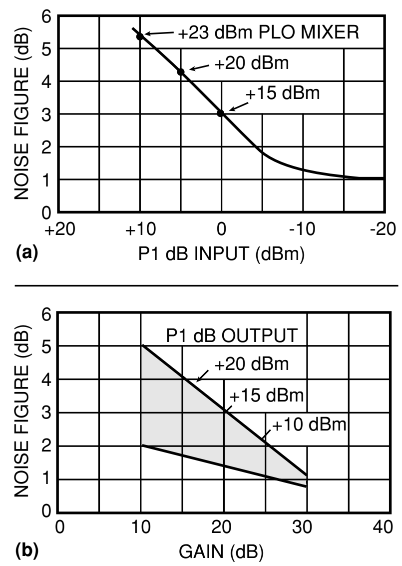


FIGURE 10

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