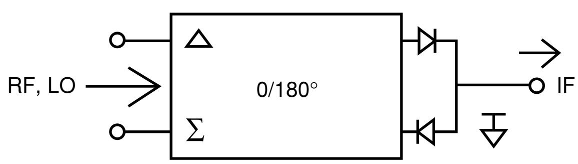
Questions and Answers about...

SINGLE-, DOUBLE- AND TRIPLE-BALANCED SCHOTTKY DIODE MIXERS

Q1: What are the differences between single- and double-balanced mixers?

A1: Before explaining this difference we should mention that a one-diode or unbalanced mixer is often used in economical receiver front ends, where tunable or fixed bandpass filters can easily separate the LO, RF and IF energy coupled to and from the diode. Early wideband receivers utilized two diodes in a single-balanced mixer circuit with a 90° hybrid to couple RF and LO power to a pair of diodes. This technique allowed overlapping LO and RF bandwidths without filters, but the isolation was dependent on how well the diodes were impedance matched. Broadband 180° hybrid balanced mixers eliminated this problem. The figure below shows the equivalent circuit and the single-tone intermodulation table of the MITEQ Model SBB0618LA1 biasable single-balanced mixer with 0 dBm LO applied to the in-phase port of the 180° hybrid and -10 dBm RF at the delta port. In this mode of operation only the RF energy is balanced or applied out of phase to each diode, with a subsequent reduction or cancellation of even harmonic mixing products (i.e., LO ± 2RF, LO ± 4RF).

Alternately, in any single-balanced mixer one could choose to apply the LO to the 180° port and observe suppression of the even harmonic LO products instead (2LO ± RF, 4LO ± RF etc.). The circuit and resulting products are shown below:



SINGLE-BALANCED RF/LO PORT

Δ = RF (-10 dBm)
Σ = LO (0 dBm)

RF HARMONIC			
3	45	46	41
2	38	42	41
1	0	17	15
	1	2	3

LO HARMONIC

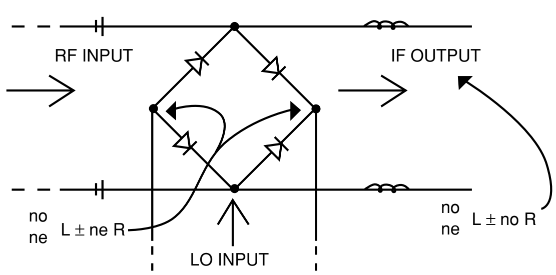
Δ = LO (0 dBm)
Σ = RF (-10 dBm)

RF HARMONIC			
3	49	53	40
2	28	44	28
1	0	30	15
	1	2	3

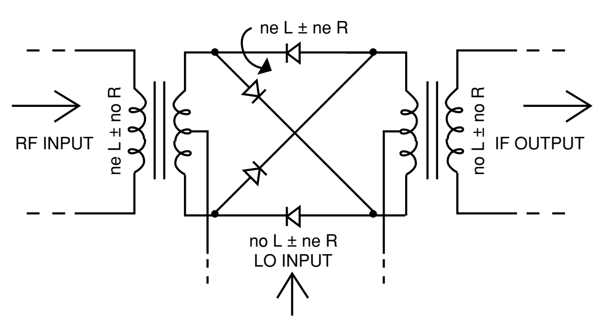
LO HARMONIC

Both single-balanced mixer configurations, however, suppress any RF or noise energy that may be present with the LO (common mode or noise rejection). In addition, single-balanced mixer circuits are particularly easy to bias and monitor the diode currents.

Alternately, one could also make an easily biasable single-balanced mixer with multioctave bandwidth coverage using a diode bridge (shown below). This appears very similar to the ring double-balanced mixer (also shown), but the key difference is that all even order products are canceled in the output of the double-balanced, whereas only even products of the RF are canceled in the single-balanced circuit. The MITEQ Model SBB0218LR5 uses this circuitry for RF coverage from 2 to 18 GHz and 2 to 26 GHz, however the IF output cannot overlap the RF coverage.



SINGLE BALANCED (Bridge)



DOUBLE BALANCED (Ring)

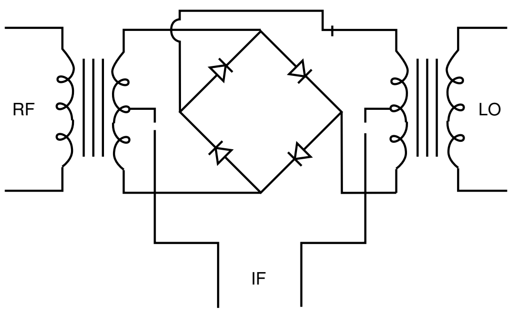
MITEQ 100 Davids Drive, Hauppauge, NY 11788 • TEL: (631) 439-9220 • FAX: (631) 436-7430 • www.miteq.com

BALANCED SCHOTTKY DIODE MIXERS (CONT.)

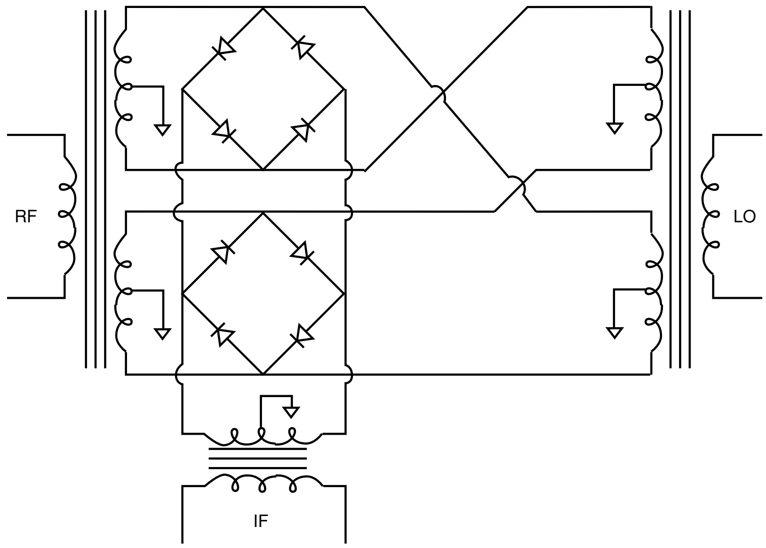
The double-balanced mixer circuit provides mutual isolation of LO, RF and IF energy, without filters, because of the combined properties of the ring diode circuit and wideband baluns. This results in suppression of all even-order harmonic mixing products of both the LO and RF (i.e., 2LO ± RF, LO ± 2RF, 2LO ± 2RF, etc.). The double-balanced mixer, however, requires 3 dB more LO power than the two-diode single-balanced circuit assuming, of course, that the same barrier voltage diode is used in each case.

Q2: What are the major differences between triple- (or double-double) and double-balanced mixers?

A2: The triple-balanced mixer employs two diode quads (eight junctions in total) fed by two power splitters at the RF and LO microwave baluns. The architecture allows both quads to be coupled together with mutual LO-to-RF isolation. The most significant advantage of this circuit is that the output IF signal is available at two separate balanced and isolated terminals with large bandwidth (typical 0.5 to 10 GHz). The IF signal and return path are isolated from both the RF and LO ports, thus allowing for overlapping frequencies at all three ports. A slight disadvantage of this circuit is that it will not yield a DC IF. In contrast, the standard microwave double-balanced mixer often uses diplexing techniques to separate the IF signal from the LO band. As a result, a microwave double-balanced mixer cannot support widely overlapping RF and IF frequencies while maintaining a DC response at the IF port. The theoretical single-tone spur product port cancellation relations are the same for each mixer circuit, however, in practice the triple-balanced mixer and only certain designs of double-balanced mixers with high port isolation yield the best spur suppression (MITEQ DM Series).



DOUBLE-BALANCED MIXER



TRIPLE-BALANCED MIXER

Q3: For what applications are triple-balanced mixers best suited?

A3: They are especially valuable for translating large bandwidth segments from one frequency range to another with low intermodulation distortion. The high IF-to-LO and IF-to-RF isolation of this class of mixers makes the conversion loss flatness much less dependent on IF frequency mismatches that almost always exist at the RF and LO ports. Recently MITEQ perfected a triple-balanced 4 to 40 GHz RF/LO mixer with a 0.5 to 20 GHz IF (Model TB0440LW1). Many customers are using this mixer with several fixed LOs to downconvert the 26 to 40 GHz portion of the millimeter band into existing receivers in the 0.5 to 18 GHz range. This mixer is also useful for upconverting the 0.5 to 18 GHz band into a fixed Ku-band second converter, thus eliminating the image response without tunable preselectors.

Q4: For what applications are microwave double-balanced mixers best suited?

A4: Double-balanced mixers are most utilized in lower cost applications where there is no requirement for overlapping RF and IF frequencies and moderate LO power is available. In addition, the DC-coupled output of the double-balanced design makes it a prime candidate as a building block for phase detectors, I/Q modulators and demodulators that operate over narrow or extremely wide bandwidths. Lower frequency torroid balun type mixers below 2 GHz often have excellent LO-to-RF balance or isolation (40 to 50 dB) and, therefore, function well as low offset phase demodulators or high carrier rejection I/Q modulators. Conventional microwave double-balanced mixers with tapered line baluns seldom exceed 20 dB LO-to-RF isolation. The MITEQ DM Series of double-balanced mixers uses a unique balun (patent pending) that yields 30 dB minimum LO-to-RF isolation over multioctave bandwidths and 40 dB typical over communication bands (Models DM0208LW2, DM0416LW2). In addition, the 4 to 16 GHz version has a DC to 4 GHz IF range with 30 dB minimum isolation to the RF and LO ports.

Q5: How much LO power is required for double- and triple-balanced mixers?

A5: Nonbiasable double-balanced mixers with so-called "zero bias" silicon Schottky diode quads will operate with +3 to +6 dBm LO power. Schottky diodes made with other junction metals and base semiconductor material, such as gallium arsenide (GaAs), can operate up to +23 dBm of LO power. The required LO power is usually determined by the desired input 1 dB compression point of the mixer and is typically specified at 5 dB above this level. Triple-balanced mixers typically require 3 dB more LO power than single-quad mixers since there are twice as many diode junctions.

Q6: What is meant by single- and two-tone intermodulation products?

A6: Using amplifier terminology, a single-tone input at a frequency (f_1) can produce outputs at the harmonic frequencies ($2f_1$, $3f_1$, $4f_1 ... mf_1$). Each harmonic has an input-to-output power slope equal to the order of the product (m). For example, if we double the input power (3 dB increase), we expect to see the 2nd harmonic frequency increase in power by 6 dB, the 3rd by 9 dB, etc.

In the case when two nonharmonically related tones are simultaneously fed into an amplifier, the output spectrum becomes more complex. The two tones can mix with each other due to the nonlinear transfer in the amplifier, and produce new additional signals (two-tone intermodulation products) of the order $m \pm n$. Certain products are of particular interest because no amount of input filtering can eliminate them, such as the two-tone third order (i.e., $2f_1 \pm f_2$ and $f_1 \pm 2f_2$). In this case, we recognize this as third order because $m + n = 3$.

The former discussion is applicable to mixers with the additional complexity that the power supply for a mixer is not DC, but a time-varying voltage classified as the LO signal. The LO does not switch the mixer in a sinusoidal fashion, but rather as a square wave and, therefore, an additional set of harmonics are present at the output of the device. Single-tone spurs are not only harmonically related to the frequency of the RF input signal (f_{RF}), but are also related to the harmonics of the LO input signal (f_{LO}). The output spurious signals are typically classified by their order (i.e., $mf_{RF} \times nf_{LO}$) and represented in a spur table or m x n matrix chart.

The two-tone third-order outputs of a mixer are defined the same way as for an amplifier, but are usually referred to the input. The LO shifts the third-order product into the IF range by the relation:

$$(m_1\ f_{RF1},\ \pm\ m_2\ f_{RF2})\ \pm\ n\ LO$$

The rules for determining the RF input to IF output power slope of each RF intermodulation product remain the same for all LO harmonics.

Q7: What determines the level of undesired single- and multitone intermodulation products in a mixer?

A7: This is a rather complex question that requires knowledge of the mixer circuit used, power ratio between the LO and applied RF, the order of the product, the degree of mixer circuit balance and the terminating impedances at each port, including out-of-band responses.

In general, mixer intermodulation products at multiples of the RF frequency are produced when the RF power level is sufficient to affect the conducting state of the diode or semiconductor used for the mixer switching action. Intermodulation products at multiples or harmonics of the LO frequency are caused by the nonsinusoidal resistance variation of the diodes due to the exponential forward voltage/current characteristic. Typically, RF harmonics can be reduced by increasing the LO power and mixer circuit complexity (i.e., single, double or triple balanced). Basically, when the incoming RF is subdivided between many diodes and the individual output IFs are recombined, each diode will generate disproportionally less intermodulation. However, each time we double the amount of diodes, both the LO power and the RF dependent intercept powers will double (+3 dB).

More recently, MESFETs (metal epitaxial semiconductor field effect transistors) have been utilized for passive mixing by applying the LO signal to the gate source junction and RF/IF to the drain source junction. The principal advantage of these mixers is much lower levels of the single-and two-tone third-order products for a given amount of LO power. For example, a typical Schottky diode mixer has a 3 dB greater input IP^3 power level than the LO power, but the MESFET version is 10 dB higher. The MITEQ Model SBF0812HI3 (8 to 12 GHz) has an input IP^3 level of +33 dBm when using +23 dBm LO.

Intermodulation levels in most mixers are influenced by external and internal terminating impedances at the RF, IF and LO ports. Internally terminated and load insensitive mixers are also available, including a new MITEQ design that redirects reflected IF, RF and sum energy to separate ports (patent pending).

In general, a good practice is to:

1. Use a mixer requiring a high or medium drive level.
2. Use a mixer with the high interport isolation (i.e., good balance).
3. Have broadband resistive terminations at all ports (beyond the desired pass bands). If this is not possible, use a broadband termination at the IF or RF port.
4. Compare each mixer design by measuring data in the system reflection environment actually encountered.

Q8: What are the differences between the DB and DM Series of double-balanced mixers?

A8: The DB Series of mixers utilize the more conventional tapered ground microstrip balun (invented in 1972 at RHG by present MITEQ personnel). This balun is ideally suited for extremely broadband microwave applications (2 to 18 and 1 to 30 GHz), requiring modest LO-to-RF isolation (20 dB typical). The major limitations of this design relate to the high and unsymmetric balun leg impedances, making it difficult to achieve high IF frequency coverage with DC capability.

More recently at MITEQ, we have perfected a new more symmetric balun which yields typical LO-to-RF isolation of 35 dB over 4 to 1 bandwidth ratios. This design is synthesized from double- and triple-tuned microwave filter theory and, therefore, has much higher out-of-band rejection than conventional double-balanced mixers. In addition, the IF capability is greatly extended. For example, the Model DM0520LW1 has an IF coverage of DC to 8 GHz with simultaneous RF and LO coverage of 5 to 20 GHz.

Q9: What advantage does the new DM and FDM mixer baluns offer for narrow RF bandwidth applications?

A9: In general, the new balun design exhibits best performance at band center and, therefore, the narrower band units yield progressively better LO-to-RF isolation (45 dB typical for 10 percent bandwidth units). In addition, the spurious mixing products of these microwave units are similar to that expected from VHS/UHF double-balanced mixers having similar isolation. The 10 percent RF bandwidth units typically have the same RF skirt selectivity as a two-pole filter, thus reducing the system input preselection requirements (see Model FDM0325HA1).

Another advantage of the FDM design is that the LO and IF coverage are relatively broadband and one can choose an IF frequency that causes the RF image response to fall on the skirt of the balun, thus yieding image rejection without the usual more expensive matched mixers and hybrid circuit topology.

Finally, special versions of the FDM design can be optimized for simultaneous image rejection and image recovery in selected communication bands requiring relatively high IF frequencies. The typical conversion loss in this mode is 3.5 dB.

Q10: What is the principle advantage of even harmonic mixing?

A10: Aside from requiring an LO at half the normal frequency, one can achieve ultra-high (-55 to -60 dB) rejection of the LO leakage out the RF port relative to the input power. This means an input isolator can often be eliminated, but more important, for linear upconverter or modulation requirements, the carrier rejection can be maintained at high levels. Some customers employ pairs of I/Q even harmonic up- and downconverter mixers for lower cost data links. The principle disadvantages of the even harmonic mixer are slightly higher (2 dB) conversion loss, more LO power sensitivity and, of course, doubling of the LO phase noise.

Questions and Answers about...

MESFET MIXERS

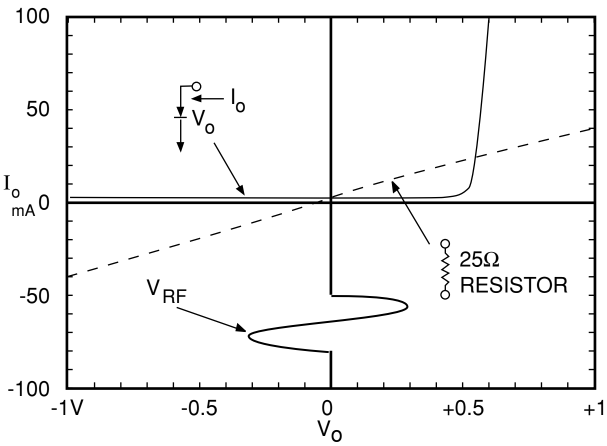
Q1: What does MESFET mean?

A1: Metal Epitaxial Semiconductor Field Effect Transistor (i.e., the gate electrode is a metal to semiconductor junction similar to a Schottky diode).

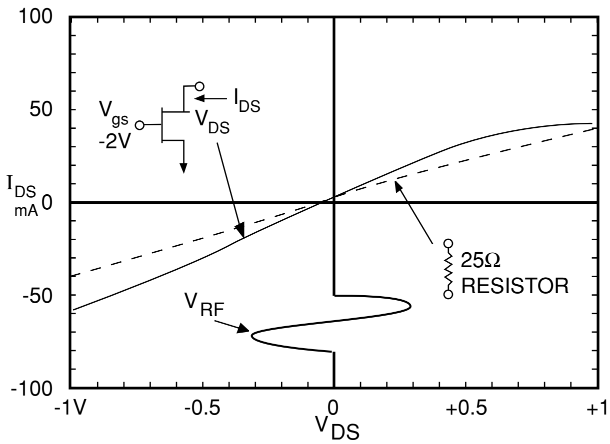
Q2: Why use a MESFET for mixing instead of a Schottky diode?

A2: The principal advantage of a FET mixer is a reduction in the third-order distortion, thus yielding improved single-tone (i.e., LO ± 3RF) and two-tone (2RF, - RF_2 - LO) intermodulation products relative to a Schottky diode mixer that operates at the same LO power. The figure below illustrates the source of mixing distortion (E/I characteristic) of a Schottky diode and a typical MESFET.

SCHOTTKY DIODE



MESFET



The dotted sine wave represents an applied RF signal across each semiconductor junction at the instant that the LO voltage is zero (in the case of the MESFET curve a fixed negative bias on the gate results in the E/I VD curve shown). The most significant difference in the two curves is how they each compare to an ideal fixed 50 ohm resistor, shown by the dotted straight line. The resistor, of course, would yield no distortion in the resulting current sine wave. We notice that the deviation from a straight line for the Schottky diode is considerably greater, thus yielding a poor IP^3 at this bias point. The measured IP^3 of both mixers is the average of the instantaneous IP^3 distortion at each LO operating voltage. The input IP^3 of a MESFET mixer is typically 10 dB or greater than the LO power. A general rule for Schottky diode mixers is 3 dB greater than the LO power (the intercept powers of mixers are usually specified relative to the maximum signal power at the input). The third-order intercept point of amplifiers is, therefore, relative to the output port.

In addition, the linear mixing region of a Schottky diode is approximately 5 dB below the applied LO power since both the RF signal and LO signal exist at the same terminal. However, a FET mixer, configured in the passive mode, has the LO applied to the gate and controls the drain to source channel resistance with low power. RF and IF signals that are present at the drain cannot easily modulate the channel resistance and, therefore, produce an RF 1 dB compression point approximately equal to the LO power. At the lower switching rates (UHF and VHF frequencies) the power difference is more dramatic (e.g., a FET switch controls +25 dBm RF with microwatts of gate power).

Another difference between the MESFET and the Schottky diode is that the latter is a two-terminal device and, therefore, requires filters or multiple diodes and balanced circuits to separate the LO, RF and IF circuits (this is essential when signal LO and RF bandwidth overlap). The MESFET is a three-terminal device and allows decoupling between the LO (gate to source) and RF/IF circuitry (drain to source). Single- and double-balanced FET mixer circuits also exist.

Q3: What are the disadvantages of a MESFET mixer relative to the Schottky device?

A3: There are two, cost and LO VSWR, particularly for broad bandwidth applications. At the present time, the fabrication process for making 4 silicon diodes in a quad configuration is considerably less costly than that of 4 GaAs MESFETs, therefore, if the P1 dB or IP^3 requirements are moderate (up to +10 and +20 dBm respectively), a Schottky diode device is adequate. For P1 dB and IP^3 of greater than +17 and +27 dBm, the MESFET cost may be justified in view of the extra cost of an LO amplifier needed for the Schottky device. The Schottky device will typically require LO powers of +24 dBm to achieve IP^3 of +27 dBm, whereas the MESFET mixer requires only +17 dBm LO power.

Another difficulty of designing octave and multioctave bandwidth MESFET mixers is impedance matching the FET gate circuit to a 50 ohm source impedance. Unlike the Schottky mixer, the FET gate circuit is not driven into full conduction during LO operation, but rather swings from pinch-off to zero bias and thus always has a high reflection coefficient. For narrow bandwidth applications, one can impedance match to the low series resistance of the gate and achieve large voltage swings with little LO power (a desirable condition). More recently at MITEQ, we have achieved octave bandwidth operation with 15 dB or more gate return loss by employing balanced circuitry. This technique has been employed to make a series of octave high level (P1 dB = +23 dBm input) MESFET mixers from 6 to 18 GHz that are suitable for a second-stage image rejection mixer following a high-gain low-noise RF preamplifier.

Q4: What are the differences between active and passive FET mixing?

A4: Active FET mixers are typically DC biased like an amplifier and employ a dual gate or two series FETs. The LO and RF signals are applied to separate gates and the IF signal (or sum frequency) is coupled from the drain. This circuit yields low IP^3 and moderate gain with high shot noise at low IF frequencies.

Passive FET mixers have conversion loss and noise similar to Schottky diode mixers. The RF signal is applied across the drain source channel of the MESFET without any DC drain voltage. The LO signal is fed to the gate, effectively modulating the channel resistance. This produces a mixing action with the sum and difference appearing across the drain source. External or self gate biasing is used to prevent forward gate conduction from the LO signal, however, since no average current is drawn, the main noise source in this mixing is thermal.

Q5: Are there preferred frequency ranges for MESFET mixers?

A5: No, since the advantage of their high IP^3 with moderate LO power has been proven at UHF through millimeter bands.

Q6: Where should MESFET mixers be used?

A6: In any application requiring high dynamic range. For example, in receiver front end downconverters where one or more high level RF signals result in intermodulation distortion spurs (such as in EW, radar or communication front ends). MESFET mixers are also well suited to second-stage mixing following a low-noise, high-gain RF preamplifier. In the latter usage a filter or imageless mixer must be used to reject the added noise. A typical communication example is in any wireless cable TV link where up to 60 tones will be frequency multiplexed onto a single carrier. In this case, the Schottky diode mixer is no match for the spur handling capability of the MESFET mixer.

Q7: What about the relative cost of Schottky diode versus MESFET mixers?

A7: Broadband double- and triple- (double-double) balanced Schottky mixers are a mature technology and are available from many suppliers. Therefore, diode mixers are more likely to be the winner in any moderate quantity cost contest where LO power is easily available. In addition, the unbiased Schottky diode does not require a separate DC power supply. However, when the issue is maximum RF power handling with low LO power, the comparison is not always obvious. Particularly, when a separate LO amplifier may be required to supply the extra 6 dB needed to make the Schottky diode mixer perform at the same signal powers as the FET mixer. Typical cost ratios put the MESFET mixer 2 to 4 times higher in unit price to that of the Schottky mixer. This can often compensate the cost of an LO amplifier or the enhancement in overall system performance.

Q8: Is the MESFET mixer more susceptible to burnout from a high power RF pulse or CW signal when compared to a conventional Schottky ring?

A8: Quite the contrary, since the RF is applied across the channel (drain source) of the FET, the FET power dissipation is more like the limits for the DC supply power in a FET amplifier. The CW RF power limit of a typical 10 GHz balanced MESFET mixer is approximately 1 watt (the CW power limit of a typical Schottky ring mixer is about 300 mW). Thus, in some system applications, an RF limiter is not required.

Q9: What about the noise level of FET versus Schottky diode mixers?

A9: When using FETs in the passive mode (no average drain current), the 1/f and thermal noise is very similar to GaAs Schottky diode mixers, i.e., corner frequency (defined as the point where the 1/f noise equals the thermal noise) is about 100 kHz.

Q10: Are MESFET mixers more temperature sensitive than Schottky diode mixers?

A10: No, particularly if one employs zener voltage regulating diodes in the MESFET gate bias circuit. Each type mixer will then commonly have a conversion loss variation of +0.25 dB for a temperature variation of +50°C when using a constant LO power.

Q11: Are there passive modes of operation for the MESFET mixer other than LO on gates and RF/IF on the drain source?

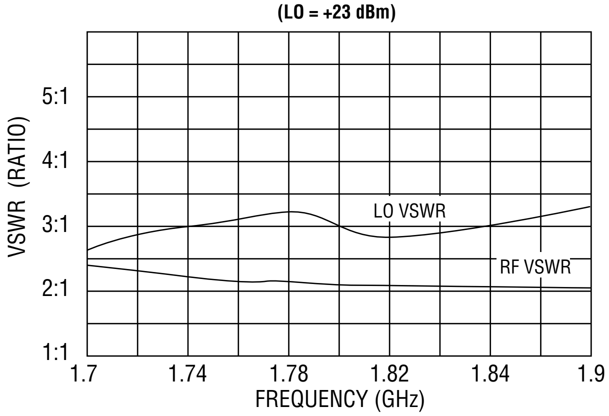
A11: It is possible to get very low conversion loss (-3 to 0 dB) by applying LO between the drain and source and RF to the gate with IF output at the drain. In this mode of operation, the LO periodically powers the FET into the active amplifier region and one obtains normal amplifier gain less the Fourier LO switching coefficient (approximately -6 dB). The input IP^3, burnout and noise figure for this mode of operation are all considerably lower than drain source mixing. The lower limit of noise figure for this mode of operation is 3 dB because of the image response.

Q12: What are the performance characteristics of a typical MITEQ narrow bandwidth MESFET mixer?

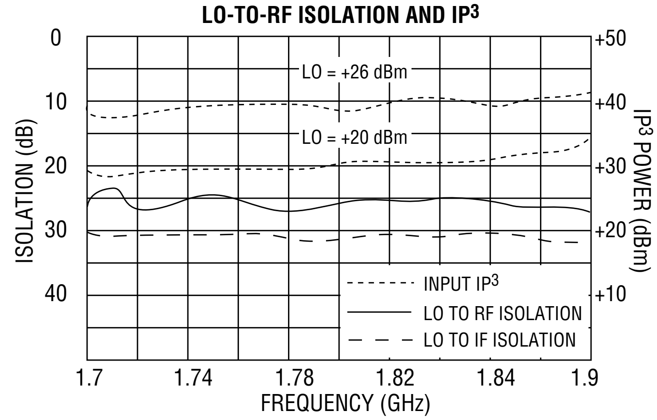
A12: The curves below show averaged measured data on four L-band units:

TYPICAL TEST DATA
MODEL DBF1800W3

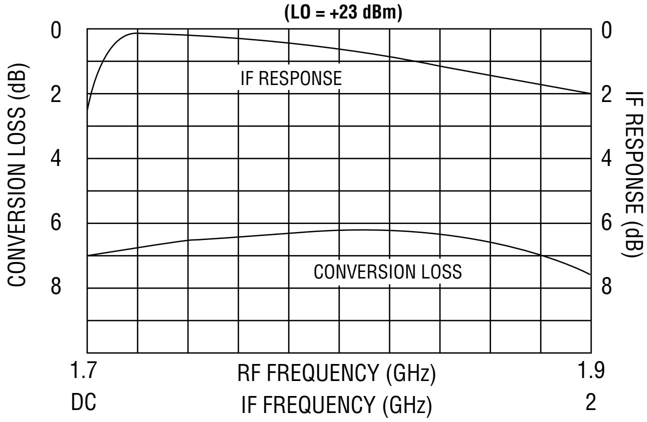
RF AND LO VSWR
(LO = +23 dBm)



LO-TO-RF ISOLATION AND IP3



CONVERSION LOSS
RELATIVE IF RESPONSE
(LO = +23 dBm)



SINGLE-TONE (m) RF x (n) LO SPUR LEVEL
RELATIVE (dBc) TO REF (RF = -10 dBm, LO = +26 dBm)

RF HARMONIC					
5	> 100	-	-	-	-
4	> 100	> 100	> 100	-	-
3	82	95	> 100	> 100	> 100
2	68	70	80	80	85
1	REF	50	47	70	58
	1	2	3	4	5

LO HARMONIC