INTERMODULATION DISTORTION (IMD) IN MEDIUM-POWER DROP-IN FERRITE ISOLATORS AND CIRCULATORS

INTRODUCTION

One of the major applications for ferrite junction components is in base station amplifiers. Each amplifier module may include several isolators, which typically provide mismatch protection. In the case of the isolator placed between the power amplifier and the antenna, the primary purpose is protection against high levels of reflected power. The form factor of these isolators is drop-in, in which the large termination chips attached to the isolator base plate are capable of absorbing up to 200W average power.

Situated after the power amplifier, the isolator must handle the full RF power of about 100W or more. Since each base station amplifier may have several channels, non-linear distortion will present a problem. Various linearization methods are used to limit distortion in the amplifier, but they do not help reduce distortion in the isolator (except perhaps crest factor reduction).

The ferrite materials used in isolators are fairly linear up to a few watts. Above this level, the most significant non-linear effect is third-order Intermodulation Distortion (IMD). This is the result of two (or more) signals of different frequencies (F_1 and F_2) interacting in a region with non-linear transmission properties.[1] The third-order distortion products that may interfere in the receiver pass band are the difference frequencies $2F_1$-F_2 and $2F_2$-F_1. Higher order distortion products are usually several dB lower in amplitude. If third-order products are reduced, the higher order products should also drop by a similar amount.

IMD is measured as the ratio in power levels between the distortion signal and the input signal, in units of dBc. Typical IMD levels for isolators are about -80 dBc for two signal tones of 20W each. Usually ferrite isolators obey the theoretical behavior for varying the input signals, i.e., for each 1 dB change of input level, the IMD level changes by 2 dBc.

ANALYSIS

The generation and behavior of distortion signals can be worked out mathematically by assuming that a non-linear medium causes an output which can be expressed as a power series,

$$V_{out} = aV_{in} + b(V_{in})^2 + c(V_{in})^3 + d(V_{in})^4 + \ldots \qquad (1$$

where a, b, c, and d are constants, V_{in} is the input voltage, which in the case of two input frequencies is equal to $V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$. The phase can be ignored for this purpose, and inserting this expression for V_{in} into Equation 1 yields the following equation:

$$V_{out} = a\,(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t) + b(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)^2 + c(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)^3 + d(V_1 \cos\omega_1 t + V_2 \cos\omega_2 t)^4 + \ldots \qquad (2$$

When the individual terms are multiplied out, the third-order output is given by

$$\begin{aligned} V_{out3} = {} & (c/4)\{V_1^3(3\cos\omega_1 t + \cos 3\omega_1 t) + V_2^3(3\cos\omega_2 t + \cos 3\omega_2 t)\} + \\ & (3c/2)\{V_1 V_2^2 \cos\omega_1 t + V_1^2 V_2 \cos\omega_2 t\} + \\ & (3c/4)V_1 V_2^2\{\cos(\omega_1+2\omega_2)t + \cos(\omega_1-2\omega_2)t\} \\ & (3c/4)V_1^2 V_2\{\cos(2\omega_1+\omega_2)t + \cos(2\omega_1-\omega_2)t\} \qquad (3 \end{aligned}$$

Collecting only the difference terms for the third-order intermodulation distortion, we get

$$V_{im3} = (3c/4)\{V_1 V_2^2 \cos(\omega_1-2\omega_2)t + V_1^2 V_2 \cos(2\omega_1-\omega_2)t\} \qquad (4$$

When the input signals have the same amplitude V,

$$V_{im3} = (3c/4)V^3\{\cos(\omega_1-2\omega_2)t + \cos(2\omega_1-\omega_2)t\} \qquad (5$$

Since the distortion level is proportional to V^3, increasing the input signal by 6 dB will cause an 18 dB increase in the distortion level. Since the desired output signal also increases by 6 dB as a result of the input increasing by 6 dB, the increase in distortion level relative to the output is only 12 dB. Similarly, a 3 dB change in the input power causes the relative distortion power level to change by 6 dB. For example, if two 100W tones cause IMD levels of .001 mW, this is equivalent to –80 dB ratio between output and input, i.e. –80 dBc. If the input levels were changed to 50W, the IMD level would become –86 dBc. Referring to Equation 4 in which the amplitudes are different, a 3 dB change in power level of the higher frequency (F_2) will cause the higher IMD frequency ($2F_2$-F_1) to change by 3 dBc, and the lower IMD frequency to remain at the same relative level with respect to the input.

In practice there typically are more than two input signals, causing many more intermodulation frequencies.[2] With only four channels, the number of third-order difference frequencies is 12, compared to 2 for the two-channel condition. However, there are 27 three-tone products of the type $F_1+F_2-F_3$. These may have four times the power of the two-tone products. Not all of these will cause interference, of course, but as the number of channels increases, the combination of in-band IMD gives rise to “spectral regrowth”.[3] The actual IMD level at any given frequency depends on the instantaneous phase and amplitude of the many individual distortion product frequencies.

Since testing with more than two tones requires an expensive test system, a rule-of-thumb conversion may be used to convert two-tone IMD levels to multi-tone IMD levels. For example, 8 signals combine to give IMD that may be 10 dB worse than equivalent two-tone measurements.

Measurements tend to confirm that IMD signal levels change by 3 dB (i.e., 2 dBc) for each 1 dB change of input signal over normal operating power and temperature ranges. The IMD level can be related to the third-order intercept point (IP_3), where extrapolated lines of drive power (at 1dB/1dB) and third-order IMD (at 3 dB/dB) would theoretically meet. To convert from third-order intercept point to IMD values in dBc, the following formula applies on the assumption that the 3 dB/dB law holds sufficiently well:

$$IMD = 2[IP_3 - P_{out}] \qquad 7)$$

where IP_3 and P_{out} are in dB (dBm or dBW).

CAUSES OF IMD IN FERRITE DEVICES

The theory of operation of junction circulators was established decades ago for above- and below-resonance conditions.[4,5] From these and other considerations, the major contributors to ferrite device non-linearity are:

1. **Proximity to Ferrimagnetic Resonance in Above-Resonance Devices.**[6,7] The same mechanism that causes the junction to circulate (κ/μ, the ratio of off-diagonal to diagonal elements in the permeability tensor) also causes IMD. To a certain extent, IMD level can be traded off against bandwidth. In general, a higher applied field brings better IMD performance, as the ferrimagnetic resonance is moved further away from the operating band. This reduces κ/μ and bandwidth, but often improves loss and temperature stability of the junction. Material porosity or cracked ferrite also contributes to IMD. Various methods are used to process ferrite materials to obtain small and uniform particle size to avoid local hotspots. However there does not appear to be any advantage for IMD in going beyond currently available materials. For similar reasons the applied magnetic field should be as uniform as possible in the ferrite region. Linewidth (ΔH) is not significant for IMD in above-resonance operation.
2. **Excitation of Spin Waves in Below-Resonance Devices.**[8] This should not really create problems for IMD because spin waves are avoided for another reason: they cause high losses in the ferrite junction. It can be controlled by selection of junction design parameters including bias field, ferrite properties such as linewidth (ΔH), and the use of rare-earth doped ferrite material. When not excited, the junction is quite linear. In estimating the spin-wave threshold, allowance must be made for worst-case peak power. If n channels are

multiplexed, the CW power of each must be multiplied by n^2 to estimate worst-case peak power (where all voltages add in phase). For CDMA applications, effective peak power is normally taken as 12 or 13 dB higher than CW power.

Unlike below-resonance devices, above-resonance devices do not exhibit spin-wave peak power limiting.

3. **Junction Design.** Since IMD is strongly affected by the strength of the RF field, methods to minimize fields in the junction should be addressed.
4. **Presence of Ferrous Metals.**[9] The hysteresis associated with permeable materials and a non-linear B-H curve produce IMD. Steel, Invar, and (to a lesser extent) nickel are typical offenders. Silver or gold plating over such ferrous-type materials does not resolve the IMD effects due to the RF magnetic fields not being constrained within the plating.
5. **Metal Surfaces and Contacts.**[10,11] Metallic junctions that have become oxidized can form inefficient rectifiers. Aluminum is commonly used in microwave components and readily forms oxides that can cause IMD. Also, non-linear tunneling can be introduced when metal junctions do not have sufficient contact pressure. IMD is produced through the mechanism of “conductivity modulation.”

A starting point in the design of isolators is to avoid the assembly methods and materials listed above that cause IMD (other than the inherently non-linear ferrite material). The remaining parameters that can affect IMD are ferrite $4\pi Ms$, the applied magnetic field, and the circuit size and shape. Isolators can operate over a range of $4\pi Ms$ values. Selecting higher $4\pi Ms$ values in turn requires higher applied magnetic field, and also larger circuit geometry than for a lower applied magnetic field. These parameter relationships are well known, but for good IMD performance the values of these parameters should be all be kept as large as possible. Higher Q circuits also produce better IMD, but the exact circuit shape is usually a proprietary matter.

Isolators that are designed for best IMD performance will have somewhat less bandwidth and higher insertion loss compared to isolators designed for high bandwidth and low insertion loss.

IMD TESTING

The simplest IMD test is done with two CW signals, though some specifications call for a more complex setup that mimics IMD performance in the overall system. Generally, results from two-tone measurements can be converted to equivalent multi-tone levels to assure compliance with a multi-channel or spectral regrowth requirement since the physical causality is identical. This allows the component manufacturer to keep a less expensive and more flexible IMD test bench.

Various schemes[1] exist for combining signals from sources F_1 and F_2 for the two-tone IMD test. Two methods are shown in Figures 1 and 2. In Figure 1, the two input signals are combined in the forward direction, as in a multi-carrier system. In Figure 2, the second signal is applied to the output of the ferrite component. This occurs typically in a transmitter combiner or where energy enters a transmitter from a co-located antenna and produces an IMD product. The IMD produced by the second method will generally be different by the isolation of the UUT isolator from a common feed scheme having identical power levels.

Since the two methods often use isolators/circulators in the test bench that are of the same type as those being measured for IMD distortion, some care is required to assure accurate results. Critical considerations are:

1. Isolation between sources must be sufficient for mixing not to occur in the sources. Isolators or circulators other than the Unit Under Test (UUT) must not see full power at both frequencies.
2. High-level mixing must not occur in the spectrum analyzer. The noise floor must be 6–10 dB below the IMD level being measured. Check that no spurious response is visible above the noise floor from the setup with the UUT replaced with a through connection. If a residual spur is seen that cannot be removed, a sharp filter can be used to reduce the level of F_1 or F_2, which will reduce the level of the spurious signal. In general, IMD level is not a strong function of frequency separation.
3. Signals F_1 and F_2 must be kept separate until they enter the UUT so that mixing does not occur external to the UUT. This is accomplished by using a hybrid combiner in the methods discussed here. The disadvantage is that half the input power is lost. However, the hybrid combiner allows arbitrarily small frequency separation and also provides a source match at the IMD frequencies. It is important to maintain source match at IMD frequencies since the ferrite junction acts more or less as an isotropic source for IMD production, i.e., a significant quantity of IMD is emitted from the input port, and if there are sufficient reflections due to a poor source match, adds vectorially to IMD emitted from the output port. The result is unequal IMD amplitude levels, even when input power levels are equal at the two source frequencies. Input cable lengths can also affect relative IMD amplitudes.

An identified IMD product should be verified by switching off one source at a time, making sure its signal and the IMD signal both disappear on the spectrum analyzer. IMD frequencies must be an integral multiple of the frequency difference between F_1 and F_2. The spectrum analyzer should be adjusted for a noise floor 6–10 dB, minimum, below the expected IMD level. When an IMD signal is lost below the noise floor, it may be necessary to slow the sweep, narrow the scan, and/or use averaging. If the sources and spectrum analyzer are synthesized, synchronizing all three instruments to one of the synthesizer 10 MHz clocks will further lower the noise floor.

RESULTS

Above-resonance drop-in isolators fed with two +43 dBm common feed carriers (as in Figure 1) produce third-order IMD between –65 dBc and –95 dBc, depending on the bandwidth, junction size and packaging techniques employed. Production isolators are available with IMD of –85 dBc over wide temperature ranges for frequency bands between 800 and 2200 MHz. Typically these devices are somewhat larger than conventional isolators since they have larger and stronger magnets and bigger circuit geometries. Because of the higher $4\pi M_s$ and higher fields used at higher frequencies, isolators in the 2200 MHz range have slightly better IMD (a few dB) than those in the 800 MHz range.

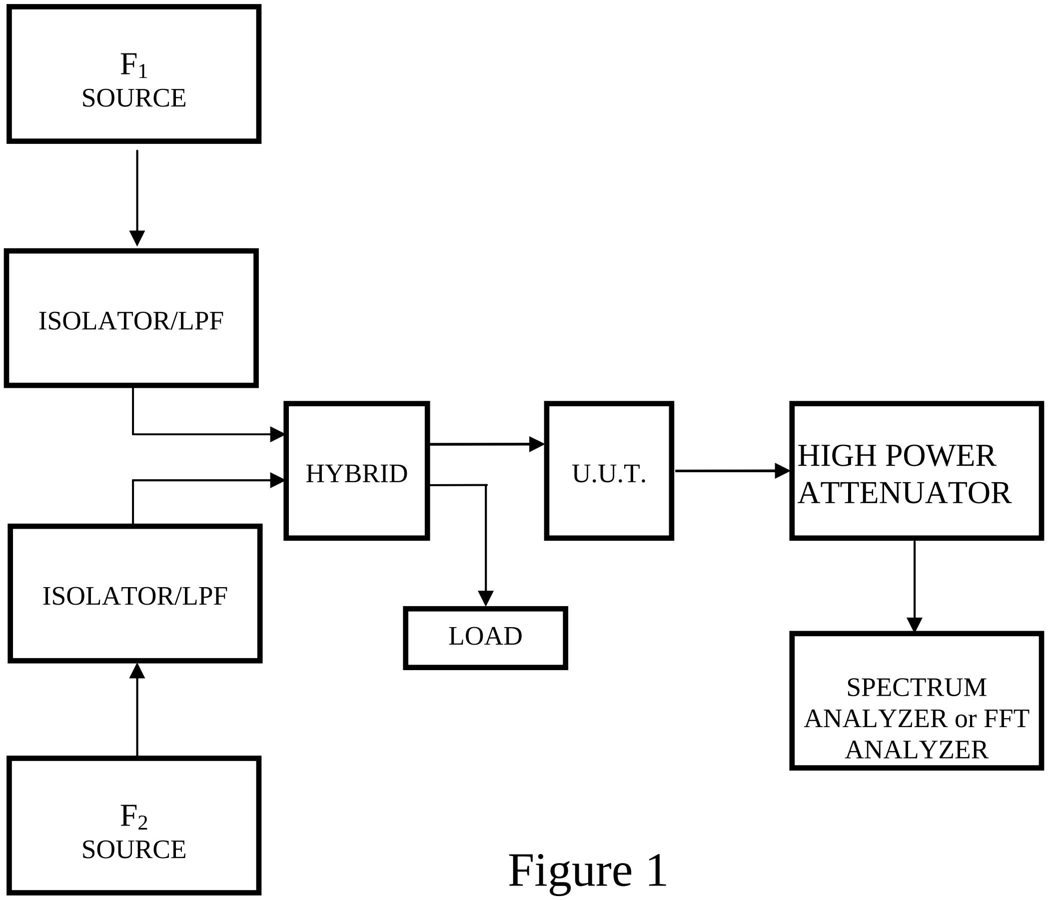

Figure 1
F_1 and F_2 Common Feed

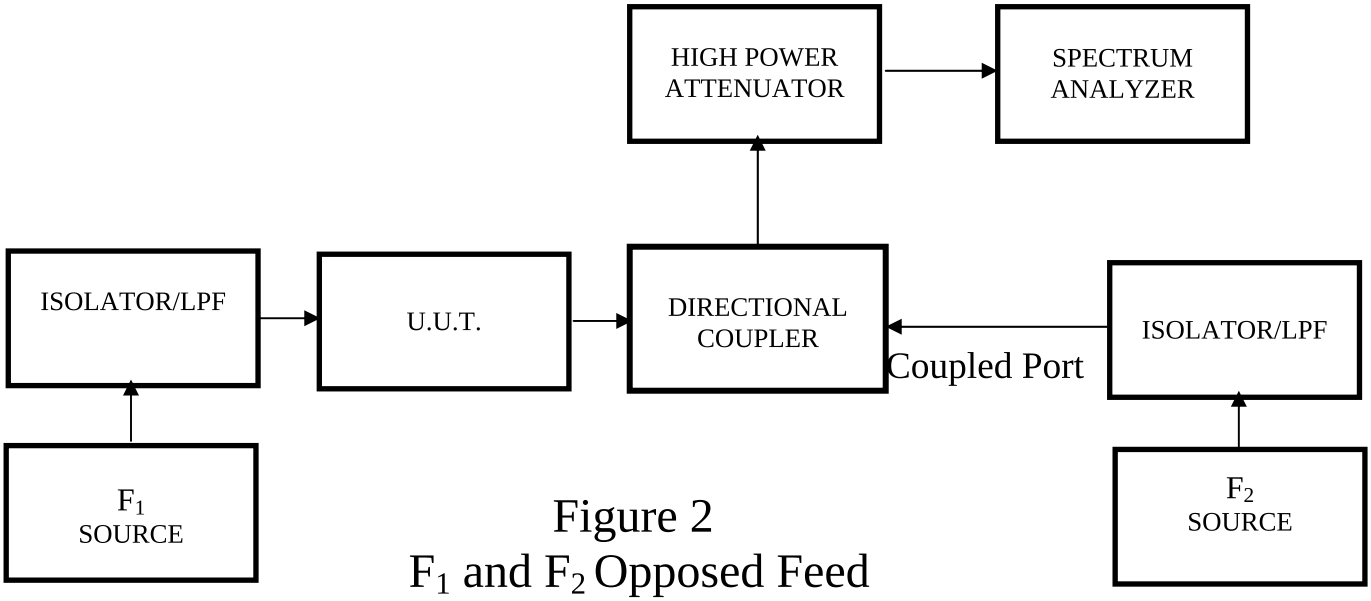

Figure 2
F_1 and F_2 Opposed Feed

BIBLIOGRAPHY

1. Billings, R. D., *"Passive IMD in Ferrites and Filters,"* Narda-West Catalog, Application Notes, p. 48.
2. Simons, K.A., *"The Decibel Relationships Between Amplifier Distortion Products,"* Proceedings IEEE, Jul. 1970, p. 1071.
3. Maas, S.A., *"Volterra Analysis of Spectral Regrowth,"* IEEE Microwave and Guided Wave Letters, Vol. 7, No. 7, 1997, pp.192-193.
4. Bosma, H., *"On Stripline Y-Circulation at UHF,"* IEEE Transactions MTT, Jan. 1964 p. 61.
5. Fay, C. and Comstock, R., *"Operation of the Ferrite Junction Circulator,"* IEEE Transactions MTT, Jan. 1965, p. 15.
6. Wu, Y.S., Ku, W.H., Erickson, J.E., *"A Study of Non-Linearities and Intermodulation Characteristics of 3-Port Distributed Circulators,"* IEEE Transactions MTT, Feb. 1976, p. 69.
7. Erickson, J.E., *"Intermodulation Reduction in VHF Communications Systems,"* Rome Air Development Center, RADC–TR-75-224, Sept. 1975.
8. Suhl, H., *"The Non-Linear Behavior of Ferrites at High Microwave Signal Levels,"* Proc. IRE, Vol. 44, 1956, pp. 1270-1283.
9. Jargon, J.A., DeGroot, D.C., Reed, K.L., "*NIST Passive Intermodulation Comparison for Wireless Base Station Equipment*" 52nd ARFTG Conference Digest, Dec. 1998, p.128
10. Bond et al, *"Intermodulation Generation by Electron Tunneling Through Aluminum-Oxide Films,"* Proceedings IEEE, Dec. 1979, p. 1643.
11. Arzam et al, *"Non-Linear Metallic Contacts at Microwave Frequency,"* IEEE Transactions, EMC, Aug. 1980, p.142.