PASSIVE INTERMODULATION DISTORTION IN FILTERS AND FERRITES

Much literature exists on the topic of Intermodulation Distortion (IMD). Most is relevant to the measurement of active devices,[1-3] where levels in the order of 40 dB below two equal tone carriers are to be expected. Junction Circulators, where spin-wave limiting is not being excited, exhibit IMD several orders of magnitude below that. Filters/Multiplexers are further orders of magnitude lower. Specifying and measuring Intermodulation Products (IMPs) pose some special problems at these low levels of distortion.

INTERMODULATION PRODUCTS – GENERAL DISCUSSION

A linear device gives an output which is strictly proportional to input:

$$V_{OUT} = aV_{IN} \qquad 1)$$

Whatever frequency is present at the input is also present at the output. If more than one frequency is present, only those frequencies will be present at the output, though at a different amplitudes.

A non-linear network will produce new frequencies. Intermodulation Distortion (IMD) occurs when IMPs are present. This will occur in any system where non-linearities exist. When various channels are excited simultaneously, system non-linearities cause new frequencies to be generated. If one of these new frequencies falls on an existing channel frequency, IMD will occur. If transmission on two or more channels causes an IMP to fall on an occupied receive channel, the signal being received can be obscured or obliterated completely, sometimes with disastrous results. Within limits, channel spacings can be set up so that IMPs, when generated, do not fall on other channels, but when bandwidths are limited and many channels are required, other solutions must be sought. Particularly troublesome are the odd order difference IMPs which occur near the frequencies which produce them.

The general case of a non-linearity is represented as a power series:

$$V_{OUT} = aV_{IN} + bV_{IN}^2 + cV_{IN}^3 + \ldots \qquad 2)$$

The coefficients depend on the nature of the non-linearity. New frequencies are generated by the higher order terms. For example, if only one frequency is present, the Vin^2 term will generate a DC level and second harmonic because:

$$\cos^2 \omega t = \tfrac{1}{2}(1 + \cos^2 \omega t) \qquad 3)$$

The Vin^3 term will produce a fundamental and third harmonic, because:

$$\cos^3 \omega t = \tfrac{1}{4}(3\cos \omega t + \cos^3 \omega t) \qquad 4)$$

The presence of a second frequency complicates the situation. The second harmonic of the second frequency will be added to the output, due to the Vin^2 term, as well as frequencies at the sum and difference of the two input frequencies:

$$(\cos \omega_1 t + \cos \omega_2 t)^2 = 1 + \tfrac{1}{2}(\cos 2\omega_1 t + \cos 2\omega_2 t) + \cos(\omega_2 + \omega_1)t + \cos(\omega_2 - \omega_1)t \qquad 5)$$

The third order term, V_{IN}^3, will produce fundamental and third harmonic of both frequencies, as well as sum and difference terms of the second harmonic of each frequency with the fundamental of the other frequency:

$$(\cos\omega_1 t+\cos\omega_2 t)^3 = {}^9/_4[\cos\omega_1 t+\cos\omega_2 t] + {}^1/_4[\cos 3\omega_1 t+ \cos 3\omega_2 t] + {}^3/_4[\cos(2\omega_1+\omega_2)t+\cos(2\omega_1-\omega_2)t + \cos(2\omega_2+\omega_1)t + \cos(2\omega_2-\omega_1)t] \quad 6)$$

As we take into account fourth order and higher terms, and introduce more frequencies, we see the broth thickening rapidly!

Fortunately the amplitude of the higher order products falls off rapidly as we get further out on the power series, and most of the new frequencies occur far away from ω_1 and ω_2, and can be easily filtered out.

The most troublesome ones are the third order difference IMPs. These are produced by the Vin^3 (third order) term of the power series. If w_1 and w_2 are close in frequency, $2\omega_1$-ω_2 and $2\omega_2$-ω_1 are close to ω_1 and ω_2, and filtering may not be possible. Other IMPs are also close in (e.g. $3\omega_1$-$2\omega_2$), but the amplitudes are smaller than the third order products, and are generally not as great a problem.

Specifically then we can zero in on the <u>Third Order IMP</u>:

$$Vin = A_1 \cos\omega_1 t + A_2\cos^2\omega_2 t$$

$$Vout = aV_{IN} + bV_{IN}^2 + cV_{IN}^3 + ...$$

$$cVin^3 = {}^c/_4 \, [A_1^3 (3\cos \omega_1 t + \cos^3\omega_1 t) + A_2^3 (3\cos \omega_2 t + \cos^3 \omega_2 t)]$$
$$+ {}^{3c}/_2 \, [A_1A_2^2 \cos \omega_1 t + A_1^2A_2 \cos \omega_2 t]$$
$$+ {}^3/_4 c \, A_1A_2^2 \, [\cos (\omega_1+2\omega_2)t + \cos (\omega_1-2\omega_2)t]$$
$$+ {}^3/_4 c \, A_1^2A_2 \, [\cos (2\omega_1+\omega_2)t + \cos (2\omega_1-\omega_2)t]$$

$$V_{IMP3} = {}^3/_4 \, cA_1^2A_2 \cos(2\omega_1-\omega_2)t + {}^3/_4 \, cA_1A_2^2\cos(2\omega_2-\omega_1)t \quad 7)$$

We note that:

1) c is the coefficient on the third order term in the power series, and is a complex number.
2) If $A_1 = A_2$, the IMP's are equal in amplitude. If $A_1 > A_2$, the $2\omega_1$-ω_2 term is the stronger term. If $A_2 > A_1$, the converse holds.
3) If A_1 is incremented (by say 1 dB), the $2\omega_1$-ω_2 term moves by twice that amount (2dB) while the $2\omega_2$-ω_1 term moves by the same amount (1dB). If A_2 is incremented, the converse holds.
4) If w_1 is incremented (say by 100 KHz), the $2\omega_1$-ω_2 term moves by twice that amount (200 KHz) while the $2\omega_2$-ω_1 term moves by the same amount (100 KHz). If ω_2 is incremented, the converse holds.
5) AM occurring on either channel will show up on the other channel and at both IMP frequencies, due to the A_1A_2 product.
6) FM occurring on either channel will show up on the IMP frequencies according to the rule of note 4).

107 WOODMERE ROAD • FOLSOM, CA 95630
TEL: (1) 916 351-4500 • FAX (1) 916 351-4550
E-MAIL: nardawest@L-3COM.com • www.L-3COM.com/narda

CAUSES OF IMD IN FILTERS AND FERRITES

These devices can be made nearly linear over large RF voltage excursions. Major contributors to non-linearity are:

1) Presence of ferrous metals in the region of high RF fields:[4-5] The hysteresis associated with permeable materials and a non-linear V-I curve produce IMD. Steels, Invar and Nickel are typical offenders.

2) Metals in contact:[6,7,8] This can form an inefficient rectifier; Cuprous Oxide is a p-Type semi-conductor. “Tunneling” through a thin oxide layer between similar metals is another mechanism.

3) Micorarcing:[6] Non-touching surfaces in close proximity can microarc above a certain potential, especially at high temperature and altitude.

4) Electrostriction of Dielectrics [5] and Magnetostriction of Ferrite material.

5) Excitation of spin-wave modes in Below Resonance Ferrite Devices: [9] This can be controlled by appropriate selection of design parameters and Rare-Earth doped Ferrite material.

6) Proximity to Ferromagnetic Resonance in Above Resonance Ferrite Devices:[10] The mechanism which causes IM generation also causes the non-reciprocity in the Ferrite medium. To a certain degree, IMP level can be traded off against bandwidth.

With the exception of the Cuprous Oxide formation, these non-linearities have point or odd-symmetry and thus favor the production of odd order IMPs.

MEASUREMENT OF LOW LEVEL IMP

Various schemes exist for combining signals from f_1 and f_2 Sources for two tone IMD testing. [11-12] Since the schemes often use Filters and Ferrite Junction Circulators of the same type being measured for IMD, some care is required to assure accurate results. Critical considerations are:

1) Isolation between Sources must be such that mixing doesn’t occur at a significant level in the Sources.

2) f_1 and f_2 energy must be directed such that mixing doesn’t occur in the Spectrum Analyzer, typical dynamic range being 70 dB.

3) f_1 and f_2 signals must be kept separate until they enter the UUT so that mixing doesn’t occur external to the unit; to the extent possible.

Two typical schemes are shown in Figs. 1 and 2. The first combines signals in the forward direction, as in a multicarrier system containing an Isolator, Filter or Multiplexer. The second combines a forward traveling signal with one introduced through the output port, typical of an Isolator application where energy could enter the Transmitter from a co-located Antenna or Transmitter Combiner and produce a strong IMP. The IMP produced by these two schemes will generally be different in the case of an Isolator.

An identified IMP should be verified by switching off one source at a time, making sure that its signal and the IMP disappear on the Spectrum Analyzer. The frequency relationship must be an integral multiple of the frequency difference between f_1 and f_2. Varying the amplitude of f_1 and f_2 signals should follow the power law of Eqn. 7); Note 3). When a barrel is inserted in place of the unit, the IM level should decrease several dB below the reading with the unit in place to assure the IMP is being generated in the UUT and not the connectors leading to and from it. The Spectrum Analyzer should be adjusted for a noise floor 6-8 dB, minimum, below the IMP for an accurate reading. Signals weaker than -140 dBm cannot be detected, when an IMP is below the noise floor, it may be necessary to increase the drive power until a signal is noted and extrapolate the result using the rules of Eqn. 7).[13]

DISCUSSION

Measurements taken at this Facility tend to confirm results of other Investigators.[10-13] Above-Resonance Circulator Junctions fed with two +44 dBm carriers by the scheme of Fig. 1, produce a 3rd order IMP in the order of -63 dBc to -102 dBc depending on junction size and packaging techniques employed. The first unit uses nickel plated steel for both magnetic return path and RF ground plane. The same unit produces an IMP at -87 dBc when fed by the scheme of Fig 2 and results extrapolated by the rules of Eqn. 7). A Lumped Element VHF Circulator in the 118-136 MHz band produced on IMP 9 dB worse than a Distributed version,[11] both fed on the scheme of Fig. 2. Below Resonance devices of IMP levels -140 to -160 dBc have been reported.[12] Diplexers are routinely -150 dBc (production versions) to -170 dBc[12] at these drive levels.

In order to compare results made at different power levels it is necessary to extrapolate results [Eqn. 7)]. This assumes that the constant c in Eqn. 2 is indeed constant with drive power. Our measurements for both Ferrites and Filters tend to confirm the 3dB/dB law for 3rd order IMPs. Other Investigators, however, have found differently.[2,4,8,12] The mechanisms suggested in section 2 are complex and it is unlikely that V-I curves would follow any simple “law”. The tunneling effect[7,8] is time variant. Cuprous oxide[6] contaminants will also build with time. Microarcing[6] is likely a threshold phenomenon. How far the region of “Behaving Distortion”[14] extends in real devices is the subject of another study. The validity of the concept of intercept point, where extrapolated lines of drive power (at l dB/dB) and third order IMP (at 3 dB/dB) would meet, as an objective measure of IMP rests on the constancy of c. The fifth order term, e, produces third order IMP as well as other products, which adds vectorially to that produced by the c term. Since the system must saturate at some power level, the IMPs must deviate significantly from the n dB/dB “law” at some lower power level.

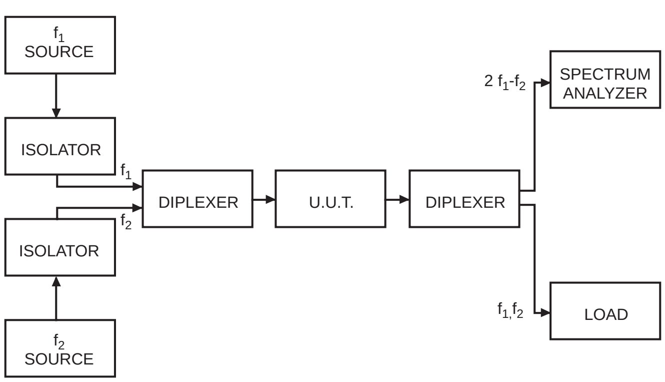

Figure 1. f_1 and f_2 Forward Feed

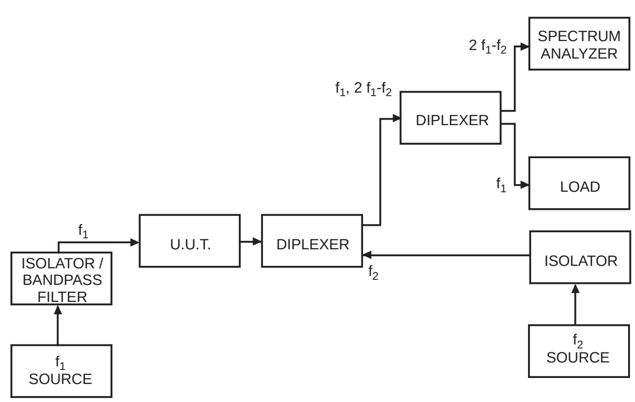

Figure 2. f_1 and f_2 Opposed Feed (Isolator Only)

BIBLIOGRAPHY

1. Perlow, S.M. "Basic Facts about Distortion and Gain Saturation". Applied Microwaves, May 1989, p. 107.

2. Simons, K.A. "The Decibel Relationships between Amplifier Distortion Products". Proceedings IEEE, July 1970, p. 1071.

3. Minisian, R. "Intermodulation Distortion Analysis of MESFET Amplifiers using Volterra Series Representation". IEEE Trans. MTT, Jan. 1980, p. 1.

4. Bailey et al "A Study of Non-Linearities in Nickel", J. Appl. Phys., 1979, p.453.

5. Kumar, A. "Passive IM Products Threaten High-Power Satcom Systems". Microwaves and RF, Dec. 1987, p. 98.

6. Amin et al "Coaxial Cables as Sources of Intermodulation Interference at Microwave Frequencies". IEEE Trans. EMC Aug. 1978, p. 376.

7. Bond et al "Intermodulation Generation by Electron Tunneling Through Aluminum-Oxide Films". Proc., IEEE Dec. 1979, p. 1643.

8. Arzam et al "Non-Linear Metallic Contacts at Microwave Frequency". IEEE Trans. EMC, Aug. 1980, p. 142.

9. Suhl, H. "The Non-Linear Behavior of Ferrites at High Signal Levels". IRE Transactions MTT. Oct. 1956, p. 1270.

10. 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.

11. Erickson, J.E. "Intermodulation Reduction in VHF Communications Systems". Rome Air Development Center RADC-TR-75-224, Sept. 1975.

12. Kudsia et al "A High Power Low Passive Intermodulation UHF Duplexer for Space Application". IEEE MTT-S Digest, 1979, p. 437.

13. Harrison, W. H. "Multiplexers, Filter Key to FLTSatCom". MSN. June 1979, p. 50.

14. Hiller, G., Caverly, R. "Predict Intercept Point in PIN Diode Switches". Microwaves and RF., Dec. 1985, p. 103 and Jan. 1986, p. 111.