Passive Intermodulation Distortion in Microwave Networks From Coaxial Connectors

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Abstract

Coaxial connectors are frequently the dominant contributors to passive intermodulation distortion in high-frequency networks. This paper reports on recent progress regarding modeling passive intermodulation in microwave networks. In particular we report on the excellent accuracy attained using a method of modeling the effect of multiple point sources of passive intermodulation as applied to coaxial connectors. In addition, we demonstrate that the inclusion of ferromagnetic metals in low-passive intermodulation connectors does not necessarily degrade the nonlinear performance of the connector, in contrast to many published low passive intermodulation design guidelines.

1. Introduction

Passive intermodulation (PIM) is the distortion generated by the small nonlinear characteristics of passive RF components such as antennas and connectors. Passive nonlinearity is almost always a small effect, typically resulting in mixing products more than 100 dB down from the generating signal, which is usually insignificant compared to the levels of nonlinear distortion generated by active circuit components such as amplifiers. However, the large intermodulation products created in active components can usually be eliminated by filtering. PIM distortion cannot always be eliminated by filtering because it is generated by components that occur after the filter in the transmit path of the system. Thus, PIM is often the dominant source of nonlinear distortion in high-powered systems. As a result of the great difference in power between transmitted and receive signals in a communication system, passive intermodulation distortion levels as low as -150 dBc are potentially problematic sources of interference in many systems as the nonlinearity of passive components causes power at transmit frequencies to mix into the system's receive band. Passive intermodulation is most problematic in transmit/receive systems where transmit and receive bands are closely spaced. Communication frequency bands are becoming more densely populated, making passive intermodulation a growing concern in the wireless community. In this paper, we report on two efforts to understand and mitigate the problem of passive intermodulation-induced distortion. First, we report on a model used to predict the total PIM of a system comprised of many different PIM sources. Then, we demonstrate the successful low-PIM inclusion of a ferromagnetic metal (nickel) in the metal-metal contact of a coaxial connector, which may be used to improve the PIM performance of today's low-PIM coaxial connectors.

2. Analysis of Complex PIM-Producing Networks

All measurements in this study were taken using a Summitek SI-400C passive intermodulation distortion analyzer [4]. In this system, two high-powered carrier tones at frequencies f_1 and f_2 are transmitted through a duplexing filter to the device under test (DUT), which is terminated in a 50 Ω load. The purpose of the duplexer is to reject the high power carrier tones at the receiver port so that the low-level third order intermodulation product's signal can be detected. Spurious signals produced by passive intermodulation are generated in the DUT and propagate in both directions—"forward" to the matched termination and "reverse" to the duplexing filter (the sense of forward and reverse are taken relative to the propagation direction of the two large input tones generated by the external test system). The frequencies of the transmitted excitation tones and the measured intermodulation products are set by the transmit (Tx)- and receive (Rx)-bands of the duplexing filter. The power of the reverse-propagating intermodulation wave is measured at the receiver. For all measurements reported herein, the carrier tones were set at frequencies of 463 and 468 MHz, and unless otherwise specified were set at a transmit power of 42 dBm. The measured intermodulation product was at the frequency 2f1-f2 = 458 MHz.

2.1 Point-Source Model of Cascaded PIM Sources in Coaxial Assemblies

The ability to predict total PIM of a system incorporating multiple PIM sources could have many applications, potentially enabling near-noise-floor PIM measurements and allowing for engineers to account for PIM in the design phase of the creation of a circuit. Coaxial connectors are frequently the dominant contributors to passive intermodulation distortion in high-frequency networks [1]. While the linear properties of coaxial connectors (such as loss and characteristic impedence) are well-understood, less is known about their nonlinear properties that contribute to PIM. Also, a comprehensive methodology has only recently been presented to model the collective contribution of coaxial connectors to the total passive intermodulation distortion of a system [2]. We have previously found [3] that when the level of passive intermodulation of individual connectors is known, the collective intermodulation distortion due to coaxial connectors of the entire system can be predicted using simple circuit and transmission line theory.

Deats and Hartmann proposed a point-source model accounting for the total PIM produced by multiple different intermodulation (IM) sources [2] which reduces to

$$V_{IM}^{-} = \sum_{n=1}^{N} V_n \exp\left(j2\beta l_n\right) \tag{1}$$

when the effects of attenuation in the transmission lines connecting the sources of nonlinearity are neglected. Here, V_n is the voltage phasor produced by the nth nonlinearity in the system, β is the propagation constant at the IM frequency and l_n is the electrical length between the first and nth nonlinearity. V^{-}_{IM} is the total reverse-traveling IM voltage wave (the portion of IM that contributes to problematic distortion in most systems). Deats et. al used this model to account for the variation of PIM output as the frequencies of the fundamental transmit tones are varied. While the model predicts the qualitative behavior of PIM with regard to variation of frequency, only approximate agreement between predicted and measured values of PIM have been observed under these conditions. Much more stringent coincidence of measured and modeled levels of PIM has been observed recently when using this model to predict IM while varying, instead of frequencies of the fundamental tones (β), the electrical length between the connectors (l_n). For example, in Fig. 1 we show how by varying the spacing between two N-type connectors who produce a known quantity of PIM individually, we can cause the total PIM output of both connectors to be any value within a range of more than 30 dB. For this experiment, we designed a network to produce a target value of -93 dBm of PIM. This network is then used as an interposer to cancel out the PIM produced by an external circuit, resulting in 40 dB of cancellation of reflected PIM.

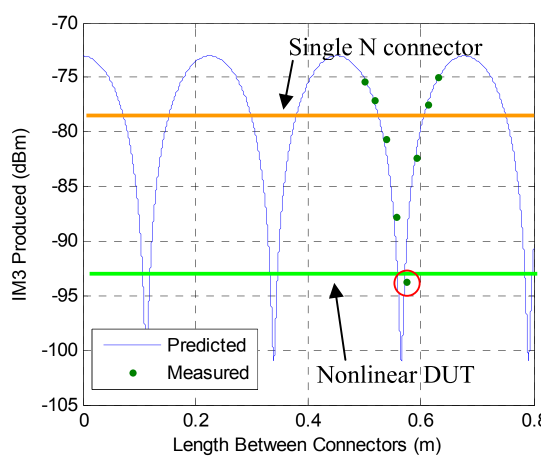

Fig. 1 Differing levels of IM produced by varying the spacing between 2 PIM-producing coaxial connectors. The orange bar shows the PIM level of the connectors individually. The green bar shows the target PIM level of the DUT at -93 dBm

3. PIM Reduction Benefits Of Hard-Soft Contacts

While the ability to predict the total PIM output of a system is useful, broad-band lowering of system PIM can only easily be accomplished through the reduction of PIM in the individual components of the system. As the unsoldered metal-metal junction in coaxial connectors is the major contributor to PIM in many microwave networks, a method of reduction of PIM produced by this junction would be of significant interest. We report here on the successful inclusion of ferromagnetic metal at the metal-metal junction in DIN 7/16 coaxial connectors without degrading the PIM performance on the connector, and explain how inclusion of hard metals such as iron or nickel on one side of the coaxial connector may substantially improve the PIM performance of the connector.

In many systems, the point nonlinearities at non-soldered contacts such as are found in coaxial connectors and bolted waveguide flanges [5] have been identified as principal contributors to passive intermodulation. While the physical causes of nonlinearity at unsoldered electrical junctions have not been isolated, many studies have been performed that give insight into this junction nonlinearity. In particular, a study by Arazm and Benson [6] suggests how these surface films may be more effectively breached in simple butted contacts (such as the outer conductor contact of a coaxial connector) where a mechanical "wipe" connection is not possible. In [5] PIM is studied experimentally as a function of compressive contact force between contacts composed of several different types of metal. For all the metals studied, it was found that the heterogeneous contact of a relatively hard metal with a relatively soft metal always produced lower PIM than the homogeneous contact of either two hard or two soft metals. For example, it was found that while homogeneous steel-steel contacts produces high IM distortion, a heterogeneous hard-soft contact where steel was mated with copper produced a drop in PIM to below the floor of the measurement system, a reduction in PIM by at least 50 dB.

It is conjectured that the pairing of a hard and soft metal allowed one metal to strongly deform under the impress of the other, the harder metal perhaps embedding itself at points into the softer metal. Thus the PIM-producing interfacial films on the softer material are pierced by the harder, and the films on the harder metal are pushed aside as the softer metal flows across it. The strong deformation of the softer metal effects a mechanical "wipe" action on the microscale, breaching the surface films and creating a more linear contact.

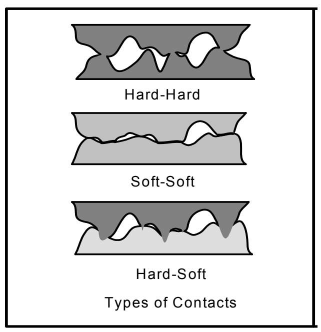

Fig. 2. Illustration of the three different types of metal contacts, showing how hard-soft contacts maximize both film penetration and contact area.

This finding gives an indication of how current low-PIM connectors such as the DIN 7/16 type may be improved to provide even better PIM performance—a simple replacement of one of the contacts with a significantly harder metal would likely bring about better PIM performance in the contact and the connector as a whole. Unfortunately, such a replacement is not a simple matter. In general the hardest metals used in contacts are all ferromagnetic materials and strong producers of nonlinear distortion due to their field-intensity-dependent magnetic permeability. In fact, all studies of PIM-producing materials to date have advised system designers to avoid using these harder metals because of their strong nonlinearity [1],[5]. However, in the next section we give an example of how harder, yet ferromagnetic materials can in fact be used in low-PIM connectors without producing unwanted levels of IM distortion.

4. Inclusion of Nickel in Low-PIM Connectors

The production of PIM in low-PIM coaxial connectors such as the DIN 7/16 connector is believed to take place at the unsoldered metal-metal contact [1]. It is also known that ferromagnetic metals with nonlinear magnetic permeability produce high levels of passive intermodulation, and as such are not recommended for low-PIM applications. However, it is unknown as to whether this high level of PIM in ferromagnetic metals such as nickel is dominated by the current-concentration points of contact at the metal-metal junction, or by the distributed generation of PIM along the length of a ferromagnetic conductor. In order to identify the effect of different metal platings on the PIM produced by a coaxial connector, we selectively electroplated the outer conductor ((a) and (b) in Fig 3) and center pin and receptacle ((c) and (d) in Fig. 3) of several DIN 7/16 connectors with either copper, gold, nickel, and silver. This electroplate was performed without damaging or disassembling the connectors, so the portions of the inner and outer conductors that were covered with the Teflon dielectric plug were not exposed to the plating solution and were not plated. Thus these regions retained their original silver coating applied by the manufacturer as the surface layer of metal through which all but the current through the contact was conducted. After plating, the samples were then subjected to a two-tone test to measure the level of reflected IM generated.

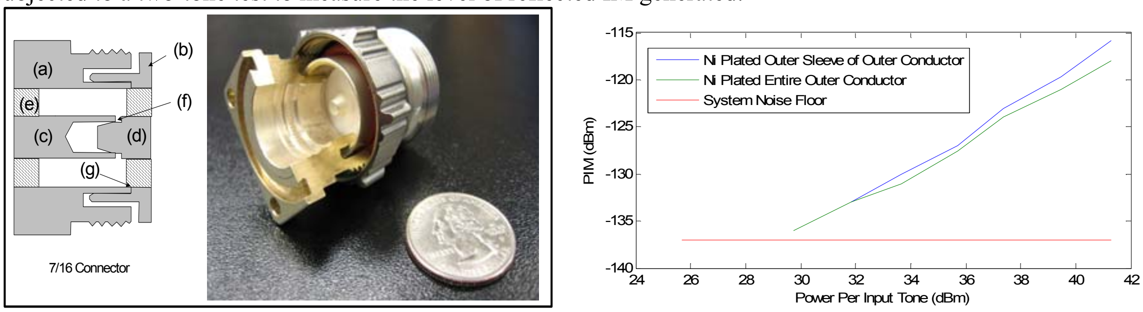

Fig. 3. Overview of experiment with DIN 7/16 connectors: To the left is a schematic cross-section of a mated 7/16 junction, with the female side to the left. Labeled are (a) the inner sleeve of the outer conductor, (b) the outer sleeve of the outer conductor, (c) the receptacle of the inner conductor (d) the pin of the inner conductor, (e) the Teflon dielectric material, (f) the inner conductor point of contact, and (g) the outer conductor point of contact. To the right is a photograph of cross-sectioned female DIN outer conductor inserted into a male connector. Also shown to the right is a measurement of a DIN connector with parts (a) and (b) coated with nickel, and also with only part (b) nickel-coated. The two measurements show essentially identical PIM levels (within 3 dB).

If we examine Figure 3, we see that for the outer sleeve (a), conduction through the plated metal only occurs at the contact point (g). Outside of the point of contact, all the metal in the outer sleeve (a) through which electricity passes is covered by the dielectric plug. As stated earlier, the metal surface that is covered by the dielectric plug is not electroplated. Therefore, the particular geometry of this connector allows us to see in isolation the IM produced at the contact by the presence of nickel in the contact. To the best of our knowledge, this high degree of isolation between distributed and point sources of nonlinearity has not been achieved in any previous study of IM-producing metal-metal contacts. We recorded an IM magnitude of -118 dBm when the inner sleeve ((a) in Fig. 3) of the conductor was nickel coated and the outer sleeve was coated with one of the other metals. This same value was seen when both conductors were coated with nickel as well. Most importantly, no detectable IM was observed when only the outer sleeve of the conductor { (b) in Fig 3} was coated with nickel. We believe that this is the first time that an electrical contact composed partly of nickel achieved an IM level below the -168 dBc level, which is the measurement floor of our system. Furthermore, the connection is a butt contact, which would benefit from the hard-soft contact configuration described in the preceding section. An estimation of the level of IM produced by the very short section of nickel in this plating configuration is -143 dBm, which is almost 20 dB lower than the measurement floor of our system. Thus, the inclusion of ferromagnetic metals in low-passive intermodulation connectors does not necessarily degrade the nonlinear performance of the connector, in contrast to prevalent belief. This is potentially of great importance because the inclusion of a hard ferromagnetic metal at a coaxial connector's metal-metal contact could substantially reduce the passive intermodulation output of the connector.

5. References

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