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Distortion Mitigation

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Engineered Passive Nonlinearities for Broadband Passive Intermodulation Distortion Mitigation

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Abstract—By adding controlled thicknesses of nickel and gold plating to the conductors of a coaxial transmission line, the magnitude of passive intermodulation produced by the transmission line can be controlled with precision. Theoretical predictions of distortion magnitude as a function of plating thicknesses are presented, along with an experimental validation. These adjustable-magnitude passive intermodulation sources are used to give a fourfold improvement in the bandwidth of techniques presented previously, demonstrating that cancellation can for the first time be achieved in bandwidths needed for cellular systems.

Index Terms—Coaxial connectors, communication system nonlinearities, interchannel interference, nonlinear circuits, nonlinear distortion, passive intermodulation (PIM).

I. INTRODUCTION

PASSIVE intermodulation (PIM) is a problematic type of nonlinear distortion encountered in many cellular telephony systems [1]. Passive nonlinearities that generate PIM distortion can occur in wireless system components such as antennas and their matching networks, which are not frequency-filtered by the system duplexing filter. PIM distortion generated in these components is not diminished by a system's filters and can cause severe interference if it falls in the system's receive band [2]. Because the causes and behavior of PIM are incompletely understood, mitigation of PIM distortion is a difficult task.

In this letter, we describe a method of creating artificial passive nonlinearities whose PIM output may be set by design to any level within a broad range by selectively electroplating the center conductor of a coaxial connector. Such "PIM standards" could have many uses, such as serving as calibration standards for PIM distortion analyzers, and aiding in phase detection for two-tone tests. These adjustable sources of PIM distortion also improve our method of mitigating PIM distortion in microwave networks [3] through broadband cancellation of the PIM produced by the system as shown in Fig. 1, allowing for higher signal quality and its attendant benefits.

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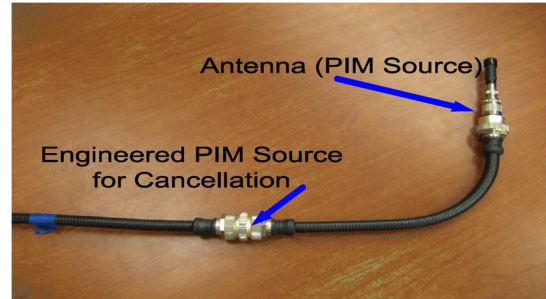


Fig. 1. Proposed improvement to the PIM cancellation method [3], allowing for PIM mitigation over larger bandwidths.

II. DESIGN OF ENGINEERED PIM SOURCES

PIM distortion in many passive components such as SMA and N connectors is caused chiefly by the electrical current's passage through the ferromagnetic metal in the connector. Several connectors incorporate nickel or steel outer conductors [4]; even completely gold-plated connectors incorporate a nickel underplate as a diffusion barrier and adhesion layer for the top layer of gold. Because nonlinear distortion is a product of conduction through the nonlinear ferromagnetic metal in such coaxial components [5], the magnitude of nonlinear distortion produced by the connector is dependent on how much of the current actually passes through this nonlinear metal. Therefore, a thicker plating of gold will lessen the amount of current traveling through the nonlinear nickel and decrease the amount of IM produced by the connector. In this letter, we quantify the relationship between IM production and gold overplate thickness. This knowledge allows us to dictate the PIM output of the coaxial connector.

The classical derivation of the skin effect phenomenon in a homogeneous metal can be extended in a straightforward manner to describe the behavior of current in coaxial transmission lines where multiple metal layers exist in the regions of current flow and the metal is therefore inhomogeneous in the transverse direction. The gold-on-nickel plated center conductor of a coaxial transmission line is such a situation. In the following discussion, we will refer to the nickel region with a subscript n , and the gold with a subscript g . The behavior of the current density in this system varies on the length scale of the skin depth in metal, which at our frequencies (~ 500 MHz) is on the order of micrometers. Because this is several orders of magnitude smaller than the radius of curvature of the center pin of the transmission line, we can treat the system with a Cartesian rather than cylindrical coordinate system, simplifying the following analysis.

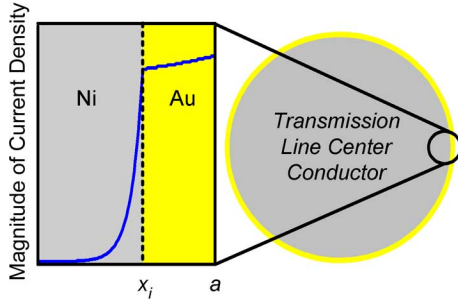


Fig. 2. Depiction of current density in the gold-plated center conductor of a coaxial transmission line composed of nickel, where x_i is the location of the interface between the two metals and a is the outer radius of the center conductor. Because the skin depth in gold is much greater than that in the nickel region, the bulk of the current is concentrated in the gold region, even though its thickness is only a fraction of a skin depth.

The current density J varies as a function of transverse position x and is governed by the one-dimensional diffusion equation [6]

$$\frac{d^2 J_i}{dx^2} = j\omega\sigma_i\mu_i J_i \quad (1)$$

where the subscript i on the permeability and conductivity refers to these quantities in the separate metal regions. The solution for the magnitude of the current densities is the standard sum of real exponential functions which is derived in many texts [6]. Because the gold-plated nickel conductor shown in Fig. 2 is a two-layer system, we utilize the boundary condition relating the first spatial derivatives of the current densities in the two region at their interface $x = x_i$

$$\frac{1}{\mu_n\sigma_n} \frac{dJ_n}{dx} = \frac{1}{\mu_g\sigma_g} \frac{dJ_g}{dx}. \quad (2)$$

This boundary condition can be derived by integrating (1) across an infinitesimal region spanning the boundary. The other three boundary conditions are more familiar, being: the continuity of current density across the boundary between the regions, the fact that the current density decays to zero deep into the nickel region, and that the integration over the solution of (1) yields the total current flowing through the conductor. These four boundary conditions can be applied to the general solution of (1), yielding an analytical description of the current density in the plated center conductor of the coaxial line. One such current density profile is shown in Fig. 2.

We see in Fig. 2 that the skin depth of nickel is much smaller than that of gold (about 1/20th the size). Owing to its ferromagnetic nature, nickel has a rather large magnetic permeability μ , roughly 400 times that of gold [7]. As a result of this, most of the current is concentrated into the gold layer, even for gold film thicknesses much less than a skin depth. For example, we find that a one-skin depth thick coat of gold over a nickel underplate confines 90% of the current to the gold layer, diminishing the current in the nickel layer by an order or magnitude. As gold thickness increases, current continues to shift to the gold region, but at a diminishing rate: a 2δ gold thickness results in 97% current confinement to the gold layer.

The intermodulation produced by most nickel-containing connectors is entirely dependent on the current carried by the

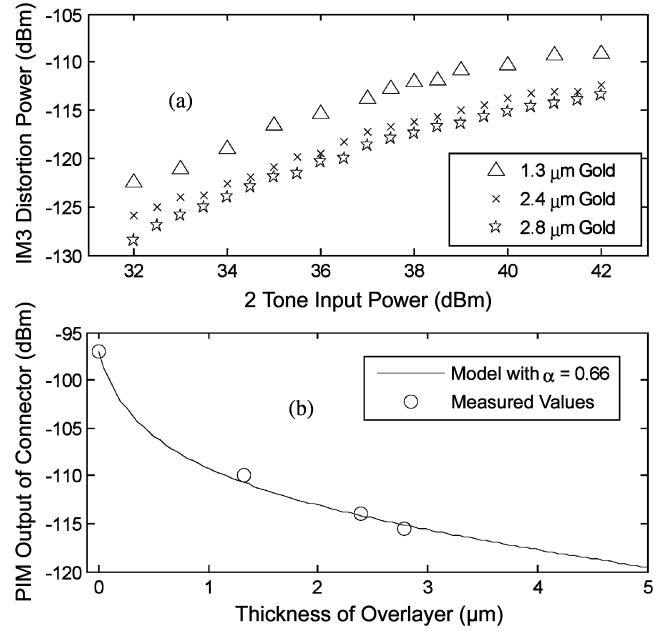


Fig. 3. (a) PIM versus input power for the three gold-plated connectors. (b) Predicted PIM output of a nickel- and gold-plated DIN 7/16 coaxial connector, as a function of gold layer thickness.

nickel layer in the system. Thus, an analytical expression for the production of IM from a short length of coaxial line as a function of gold thickness is given by

$$PIM = \alpha 20 \log_{10} \int_0^{x_i} [J_n(x)] dx + \beta (dBm) \quad (3)$$

where $J_n(x)$ is a function of x_i . The quantities α and β are experimentally determined quantities.

The order of the intermodulation generally determines its re-growth rate α , or the order at which the distortion power grows as a function of input power. For example, third-order distortion results from a cubic nonlinear process. This distortion generally varies as the cube of the input power, or with a rate of 3 dB per dB of input power [8]. Therefore, one might assume that by simply cubing the current passing through the nickel layer (setting $\alpha = 3$), we may accurately model the variation of PIM produced by the transmission line as a function of the gold thickness. However, as can be seen in Fig. 3(a) for passive nonlinearities contributing to PIM in wireless systems, this 3 dB/dB slope rule is commonly found not to hold, dropping to less than 1 at high powers! Recent findings explain the power dependence of α and allow its value to be calculated [9]. However while our method can describe the relative change of PIM as the thickness of the gold layer changes, it cannot predict its absolute value. For the logarithmic expression we use here as (3), this absolute magnitude is fit with an additive constant β which also may be determined by experiment.

In order to verify the method of predicting PIM as a function of gold overplate thickness, we plated the center conductors of a series of DIN 7/16 connectors with the described system of nickel and gold metal layers. A relative magnetic permeability of 400 was assumed for nickel [7], resulting in a skin depth of $0.33 \mu\text{m}$ at our test frequencies. Skin depth in gold for this test

was $3.64 \mu\text{m}$. All connectors received $2 \mu\text{m}$ of nickel plating, which at several skin depths was chosen so that the nickel layer is effectively semi-infinite. The connectors received gold overplate thicknesses of 0 (no gold plate), 1.3, 2.4, and $2.8 \mu\text{m}$. Plating thicknesses were measured with a Tencor Alpha-Step profilometer. Passive intermodulation distortion measurements were performed with a Summitek 400C Passive Intermodulation Distortion Analyzer [10]. We used a two-tone test with carrier frequencies at 463 and 468 MHz, and a forward power of 42 dBm per tone. The reflected third-order PIM at $2f_1 - f_2 = 458 \text{ MHz}$ was measured in this test.

The PIM versus gold thickness values are displayed in Fig. 3. Also displayed in Fig. 3 is the analytical prediction of PIM versus gold plating thickness given by (3), with $\alpha = 0.66$ and β set so that the (3) gave a prediction of -97 dBm of PIM when no gold was plated on the connector, to match the measured value. After these parameters were determined, the PIM of the three gold-plated connectors was then predicted correctly by the model, as shown in Fig. 3. The good agreement of the experimentally measured values of PIM output by these connectors confirms that this method may be used to engineer the PIM output of these artificial PIM sources, allowing them to be used in various applications.

III. APPLICATION TO IMPROVED PIM CANCELLATION

As an example, one application of adjustable sources of PIM power is to create broadband cancellation networks to eliminate PIM in wireless systems. In the previous study [4], we constructed a nonlinear “interposer network” consisting of two PIM sources separated by a length of transmission line to match the unwanted PIM generated by a system. This “interposer network” can now be replaced with a single artificial PIM source, allowing for improved accuracy and bandwidth of PIM cancellation.

The improvement in the bandwidth of the cancelling network is shown by plotting the total IM of previous cancellation method and the improved method as a function of the spacing of the carrier tones of the two-tone test. Because of the frequency dependence of the electrical length of the transmission line in the interposer network, PIM cancellation is achieved only over a narrow bandwidth (0.7%). By replacing the frequency-dependent interposer network with a broadband adjustable PIM source such as those constructed of coaxial connectors as described in this letter, the bandwidth of the PIM mitigation technique proposed in [3] is improved by over 400% to 2.9%, as shown in Fig. 4.

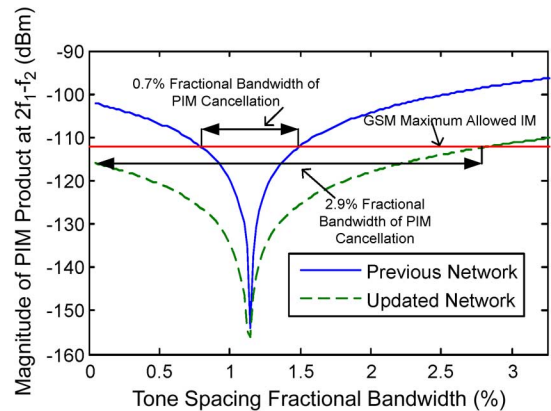


Fig. 4. Improvement (by simulation) of the cancellation and bandwidth of the method of PIM mitigation proposed in (dotted line) and the improvement in bandwidth enabled by the adjustable PIM sources discussed in this work (dashed line). GSM IM standard as reported in [11].

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