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# Nonlinear Signal Distortions in Contacts of Rough Conductors

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**Summary**

The main sources of nonlinear signal distortion in joints of good conductors are discussed. It is shown that the passive nonlinearities of electrical, thermal and mechanical types are intrinsically linked despite their distinctively different time scales. It is shown that roughness of the contact surfaces plays an important role in passive intermodulation (PIM) in conductor joints. Suppression of nonlinear distortions and PIM in the contacts of the good conductors requires mitigation of several concurrent nonlinear multiphysics effects of diverse physical nature.

## 1. Introduction

The growing demands of the wireless and satellite communications pose major challenges to radio frequency (RF) hardware. The stringent requirements of the integrity of information signals push the limits of passive devices whilst weak nonlinearities of the RF front-end and antennas debilitate the system performance. Constituent materials and contact junctions proved to be the main sources of passive nonlinearities in RF devices. The state-of-the-art RF materials exposed to the high power of RF signals still exhibit weakly nonlinear behaviour and generate frequency harmonics and PIM products. Nonlinearities of "linear" passive devices manifest themselves in spurious emission, noise and distortion of the information signals.

The main sources of passive nonlinearities and PIM generation in conductor joints include Metal–Insulator–Metal (MIM) junctions, electro-thermal effects, surface roughness and mechanical deformations. The effects of high RF power on the contacts and junctions of conductors with rough surfaces were studied in coaxial connectors and waveguide flanges. But the practical means of mitigating nonlinear distortions and PIM in passive RF circuits remain mostly semi-empirical.

## 2. Nonlinearities at the Junctions of Conductors with Rough Surfaces

The main sources of passive nonlinearities in contact joints of good conductors originate in the (i) electromagnetic, (ii) thermal and (iii) mechanical effects. The electromagnetic interactions in the contact joints are the fastest and their speed is dictated by RF signals. The thermal processes are slower, being limited by the heat flow at the contact spots. The mechanical deformations are even slower. Despite their different time scales, these effects are intrinsically coupled. For example, heat generated by RF losses causes thermal expansion of the contact spots that alters the contact resistance.

The electrical, thermal and mechanical nonlinear sources in the contact junctions have very different functional dependencies. Namely, conductivity varies exponentially with the voltage applied to the MIM junction, whilst its electrothermal nonlinearity is of Kerr type. The nonlinearities of the mechanical deformations are of mixed type, represented by a combination of algebraic and exponential functions. Therefore, the nonlinear contact joints of good conductors are described by multiscale multiphysics models. The main sources of the passive nonlinearities in the contacts of rough surfaces are illustrated by the examples of good conductors with rough surfaces. The main mechanisms of PIM in contact joints of good conductors are discussed in [1].

## 3. Electromagnetic Nonlinearity of Contacts of Rough Conductors

Charge tunnelling and current constriction are the fast nonlinear effects in the contacts of good conductors with rough surfaces, see Figure 1. The high-power RF carriers funnel free charges through the contact spots of asperities. The resulting tunnelling current flows through thin insulating films separating the touching asperities. The tunnelling resistance of the insulating layer and shunt capacitance of the asperities determine the current flow. At the insulator layer thickness ~3-5 nm, commensurate with the free path of electrons, the tunnelling current is practically negligible. Then the capacitive reactance of a contact joint is smaller than the tunnelling resistance and noticeably affects a junction impedance.

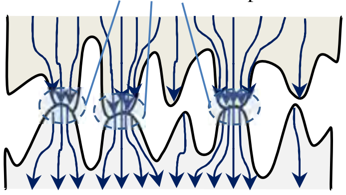


**Figure 1.** Contact of conductors with rough surfaces.

Current constriction by asperities is an inherent feature of the contacts with rough surfaces. The constriction resistance varies with the number of the compressed asperities, sizes of their contact spots and thicknesses of the insulating layer. When the size of the contact spot is larger than the mean free path of electrons, the current constriction becomes practically negligible. So, in the high-quality contacts, the constriction current is less than 1%, and can be ignored. Then the transport of the tunnelling charges is predominantly diffusive and the contact resistance is dictated by the nonlinear contact resistivity.

The contact resistivity of MIM junctions is usually evaluated by Simmons models [2]. Accuracy of Simmons model has been assessed for thin insulating layers of thicknesses ~ 0.5 – 1 nm by comparison with the WKB model. The calculations show that at low voltage bias in Al-$Al_2O_3$-Al junction, inaccuracy of Simmons model can exceed ~40% and it rapidly grows to several orders of magnitude at bias voltages above the potential barrier height.

## 4. Thermal Nonlinearity of Contacts of Rough Conductors

Heat generation is an inherent property of electromagnetic (EM) wave interactions with imperfect conductors and their contact joints. This multiphysics process couples the electric and thermal domains as the dissipative losses of high-power RF signals generate heat. This heat alters the resistance of conductors and causes their thermal expansion and mechanical deformations. Ambient temperature also has a notable impact on the effect of thermal nonlinearities [3]. These nonlinear effects are interlinked despite the time scales of the thermal and mechanical processes considerably longer.

Electrothermal PIM (ET–PIM) caused by self-heating due to conductor and dielectric losses couples electrical and thermal domains by the thermal modulation of resistivity. The heat due to RF losses alters the resistance of a conductor, and this results in the generation of PIM products. The theory of the ET–PIM and related experiments have revealed modulation of the baseband resistivity of conductors by the heat oscillations and resistivity variation due to modulation of the RF carriers. The dissipative losses and self-heating proved to be the critical factors in the ET–PIM generation by the contacts with rough surfaces.

The heat, generated by the high-power RF signals, causes the thermal expansion and deformation of contact surfaces and their joints. The contact areas of asperities and the conductor resistivity increase with temperature but a pace of their growth depends on the relation between the temperature coefficient of resistivity, the thermal expansion of the contact areas and asperity deformations. These nonlinear thermal effects alter the contact resistance and cause the nonlinear signal distortions.

## 5. Mechanical Nonlinearities of Conductor Contacts

Contact resistances of rough surfaces depend on asperity deformations by external pressure. The asperity compression and contact area expansion are the result of mechanical stresses, material elasticity and surface finish. At low pressure, the compressed asperities are subjected to elastic deformations and enlargement of their contact spots. When contact pressure increases, the compressed asperities experience plastic deformations and hardening of their contact regions. This results in the lesser expansion of the contact areas and a smaller variations of contact resistivity. These nonlinear effects of strain hardening and softening are accounted in the resistivity of a contact spot [4].

Contacts of conductors with rough surfaces stronger deform the touching asperities. The compressed asperities expand laterally, and their contact areas increase, depending on the material stiffness and surface coatings. The contact spots, exposed to the RF power, are also heated due to dissipation losses in conductors. Heat softens the asperities, and the thermal expansion and softening of the contact spots also cause plastic deformations and creep of the compressed asperities. These effects have been studied in RF MEMS. In the case of frustoconical contact asperities with a small radius of the undeformed frustum tip, the contact radius $r_c(t)$ of the squashed asperity slowly increases with time $t$, and its empirical dependence is given in [5].

## 6. Conclusions

The main sources of passive nonlinearities in contact joints are broadly cast in the three main groups of (i) electrical, (ii) thermal and (iii) mechanical. The underlying physical mechanisms of these nonlinearities are intrinsically linked despite the significant difference in their time scales. The fast electromagnetic interactions occur at MIM junctions and follow the pace of the RF signals. Much slower thermal processes have the speed of heat flow, and the effects of the mechanical deformations develop even slower. It is shown that roughness of the contact surfaces considerably increases nonlinearity of the contact joints, especially at RF frequencies. The electrical, thermal and mechanical contact nonlinearities have very different types and time scales but act concurrently. Therefore, the analysis of PIM in contact joints of good conductors requires multiscale multiphysics models which take into account the distinct types of interacting sources of nonlinearity.

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