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Nonlinear Characterisation for Microstrip Filters with Low Passive Intermodulation

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Abstract—This paper presents an RF CAD assisted approach to accurate characterisation of microstrip nonlinearities in planar microwave circuits fabricated on commercial printed circuit board laminates. The proposed methodology is employed for the analysis of the nonlinear effects in microstrip filters due to weak intrinsic distributed nonlinearity. The results of this study provide useful insights on the optimum design, modelling and characterisation of planar microwave components under linearity constraints.

Keywords—printed circuit boards, microstrip filters, nonlinearity, passive intermodulation, nonlinear characterisation

I. INTRODUCTION

Signal impairments in printed circuits arising from the intrinsic electrical nonlinearities of conductors and substrate materials have been duly recognised and studied since the early 1990-s, particularly in application to superconducting microstrip lines [1-3], as well as tuneable microstrip circuits on ferroelectric [4] and liquid crystal substrates. The important aspect of previous studies is the use of deterministic models of the intrinsic nonlinearity, albeit phenomenological and subject to experimental characterization. However, when it comes to the characterisation of intrinsic nonlinearities in ordinary planar circuits, fabricated on commercial RF laminate materials and operated at ambient temperatures, exact mechanisms and location of nonlinearities are usually unknown a priori, so that the net nonlinear response is rendered by multiple concurrent sources that may change in time under the influence of many unpredictable factors. The greater diversity and variability of the intrinsic and inserted transmission line (TL) nonlinearities, including both distributed and lumped (e.g., contact) sources, require a different approach to characterisation, modelling and mitigation of the passive intermodulation (PIM) generation in planar microwave circuits, resonators and filters.

In this paper, we propose an efficient RF CAD assisted approach to accurate characterisation of the sources and mechanisms of intrinsic nonlinearities in microstrip lines based upon the conventional two-tone PIM measurements. A simple physical model of distributed PIM generation in uniform microstrip lines is presented, as well as the model of microstrip width discontinuities. A numerical implementation of the developed model using commercial RF CAD software is proposed and a simple microstrip filter is simulated and measured.

II. RF CAD MODEL OF DISTRIBUTED PIM

Our recent experimental investigations of PIM generation in printed circuits fabricated on the base-station grade PCB laminates suggest that microstrip nonlinearities often result from the PCB processing. For the present study, we selected a set of tapered microstrip lines of different strip width, Fig. 1, fabricated on a single PCB panel and exhibiting discernible “black tin” contamination along the strip edges, see Fig. 1 and further discussion in [5].

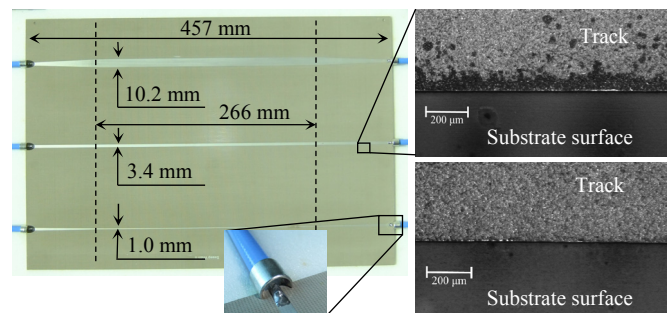


Fig. 1. Fabricated PCB with microstrip lines of different width (the reference uniform TL has the track width of 3.4 mm) and a close-up view of the track edge showing “black-tin” contamination, alongside the quality plating.

The material used for the circuit fabrication is a PTFE/ceramic based laminate with a low profile 1 oz. copper cladding, and this material is qualified as a low-PIM material. The conductor pattern was finished with a 1 μm immersion-tin plating. The microstrip lines were fitted with low-PIM microstrip launchers made of the high-performance coaxial cable assemblies. Figure 2 shows the results of the PIM measurements conducted on the test microstrip lines using a Rosenberger rack PIM analyser unit [5]. The instrument allows concurrent measurement of multiple PIM products at the input (reverse PIM) and output (forward PIM) of the device under test. The reverse (reflected) PIM products were measured by terminating the microstrip output in a low-PIM broadband load. The measured third-order PIM signal (PIM3) at frequency $f_{\text{IM3}} = 2f_1 - f_2 = 910$ MHz, with the carrier frequencies $f_1 = 935$ MHz and $f_2 = 960$ MHz, in the test microstrip lines appeared to be more than 30 dB higher than the level measured on the same layout and material processed by the same PCB workshop, but without discernible contamination at the strip edges.

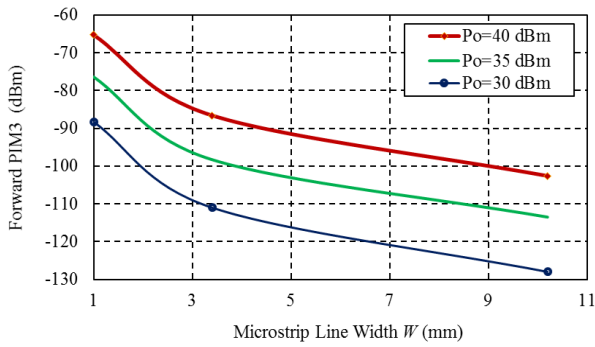


Fig. 2. Measured forward PIM3 on the test microstrip lines of different width

The characteristic decrease of the PIM level versus the microstrip width in Fig. 2 indicates a conductor-type nonlinearity, so that the lower edge current density on wider strips at carrier frequencies results in respectively lower PIM level. The effect of the return current on the ground-plane is much weaker due to the smoother current distribution. From the perspective of the PIM modelling it is reasonable to assume continuous distribution of the conductor nonlinearity over the signal strip surface, thus ignoring the actual discreteness of the “black tin” PIM sources at strip edges.

The chosen modelling approach is based on nonlinear equivalent circuits, whereby the circuit behaviour is represented with equivalent components characterised by their explicit dependence on the microstrip geometry and materials. In particular, the nonlinear transmission line models have been extensively used for the analysis and modelling of distributed PIM generation in printed transmission lines and applied to the analysis of nonlinear effects in microstrip resonators and filters [3, 7]. The utility of such an approach, especially when location of the nonlinear sources is concerned, determines our choice of the methodology for nonlinear characterisation.

In this study, we use the harmonic balance solver and X-parameters for cascading nonlinear components in Keysight ADS software, [6]. For characterisation of microstrip nonlinearity, the model of a uniform microstrip line has been implemented with the cascaded T-networks representing electrically short, viz. 5° long, sections of transmission line, see Fig. 3(a), so that the effects of the TL discretisation become negligible. The microstrip nonlinearity has been modelled by the equivalent circuit resistors as a static polynomial of the electric current magnitude, viz.

$$R(I) = R_0 + \sum_{n=1}^N R_n |I|^n \quad (1)$$

The real-valued nonlinear coefficients R_n have been retrieved for each test microstrip line by fitting the simulated forward PIM3 products to the measured data in a range of carrier power values, see Table I. Figure 3(b) shows the comparison of the simulation results and measurements. It has appeared that the fitting accuracy strongly depends on the model order, so that at least three polynomial terms were required to achieve irreducible residual error. The latter can be attributed to the systematic error in the PIM measurements. Also, the model proved to be sensitive to the carrier power and

an accurate prediction of higher order PIM products from the PIM3 measurements required even more polynomial terms, [7]. The results in Fig. 3(b) also show that the model estimated using the forward PIM3 measurements gives noticeable error in the reverse PIM3 simulation. Since the test lines were well matched in a sufficiently broad frequency range, the carrier standing wave effects on the reverse PIM are unlikely to be the cause of the observed error. On the other hand, effects of the actual nonuniform distribution of the PIM sources on the PIM generation on microstrip lines have never been studied before.

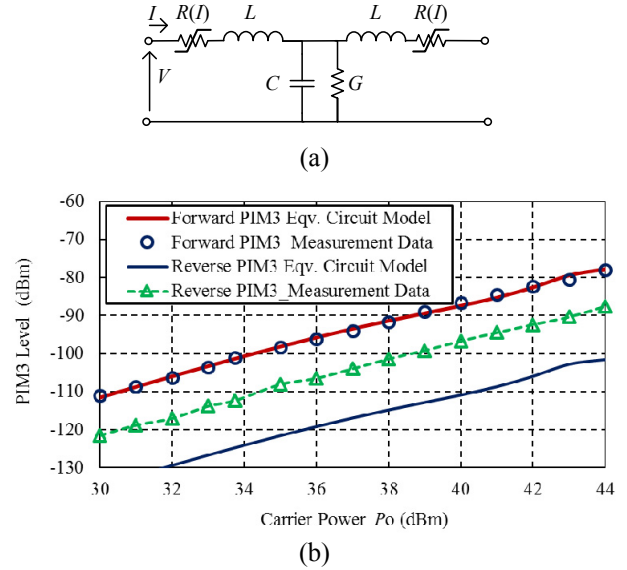


Fig. 3. (a) CAD model of the TL unit cell and (b) comparison of the estimated model with experimental data.

TABLE I. EXTRACTED RESISTIVE NONLINEARITY PARAMETERS FOR THE REFERENCE UNIFORM MICROSTRIP LINE USING THE POLYNOMIAL MODEL (1).

n	R_n (Ohm/A n)
0	0.01178
1	1.27621×10^{-6}
2	6.039×10^{-7}

To investigate the latter phenomenon, a near-field mapping of the PIM3 product distribution was performed at $f_{M3} = 910$ MHz and carrier power of 43 dBm along the reference uniform microstrip line. A low-PIM open-ended coaxial E-probe was connected to the receiver port of the PIM analyser, while the TL under test was terminated in a broadband low-PIM load. Figure 4 shows the calibrated results of the near-field mapping, alongside the two simulated curves. One simulation (‘Uniform Model’) was performed using identical 15° unit cells with the parameters as in Table 1, whereas the other curve (‘Nonuniform Model’) was obtained by scaling independently the nonlinear coefficients for every 45° segment according to the nonuniform source distribution (‘Sources Distribution’) shown (relative to the coefficients in Table 1). The intensity distribution was estimated by fitting to the measured curve and appeared to be well correlated with the actual distribution of the larger

clusters of “black-tin” specks observed by visual inspection. The results in Fig. 4 suggest that nonuniform distribution of microscopic nonlinear sources constitutes an important factor in the analysis and modelling of distributed PIM generation.

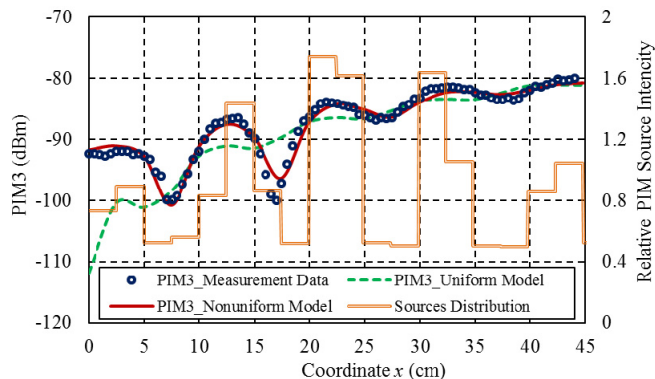
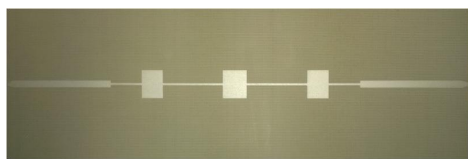


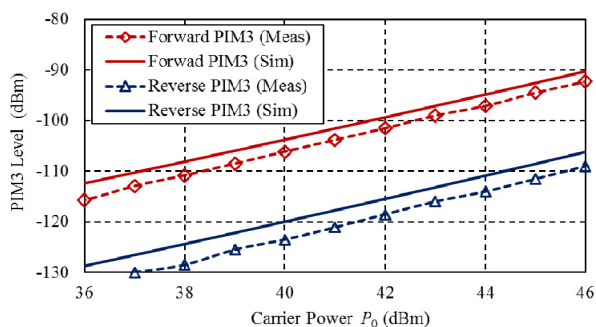
Fig. 4. Near-filed mapping and simulations of the PIM3 distribution along the reference uniform microstrip line, see Fig. 1.

III. ANALYSIS OF NONLINEAR EFFECTS IN MICROSTRIP FILTER

The semi-empirical model of microstrip nonlinearities outlined in the preceding section is applied here to the analysis of simple microstrip filters. Figure 5(a) shows the layout of a low-pass microstrip filter comprised of nine sections of uniform microstrip lines of various widths and lengths, and eight step discontinuities. The filter has been designed to be well-matched in the E-GSM band (880 - 960 MHz). The filter and test coupons of microstrip lines and step discontinuities were fabricated on the same PCB panel.



(a)



(b)

Fig. 5. (a) PCB layout of the low-pass filter and (b) measured and simulated PIM3 products vs. carrier power P_0 .

The effect of a step discontinuity was simulated as a moderate increase of the surface current density at the junction of the narrow and wide strip sections. Such a current bunching has a minor effect on the distributed PIM generation, thus suggesting that the step-in-width discontinuity can be modelled by a simple nonlinear T-network consisting of two series

nonlinear impedances connected through a shunt linear capacitor. Each nonlinear impedance is deduced from the model of the corresponding (i.e., same width) uniform transmission line. An alternative nonlinear characterisation can be based on the measured X-parameters of sample TL discontinuities, but this approach is not supported by the commercial PIM analysers.

Simulated and measured forward and reverse PIM3 products of the test filter versus input carrier power are shown in Fig. 5(b). The results are in good agreement. The magnitudes of the simulated and measured PIM3 products have ~ 3 dB offset, which is likely to be caused by fabrication tolerances leading to small dissimilarities of the printed filter and test microstrip lines used for the model estimation. Another reason could be the use of the uniform PIM model.

IV. CONCLUSION

The consistent semi-empirical approach has been presented for accurate nonlinear characterisation of microstrip circuits by means of conventional two-tone PIM measurements and efficient RF CAD simulations. The model estimation has been carried out using a representative set of microstrip lines, but in practice it will be difficult to ensure uniformity and repeatability of the PIM sources distributions. Nevertheless, the presented simulation results for the low-pass microstrip filter are in a good agreement with the experiment, which suggests feasibility of improved PIM control in the future. The proposed RF CAD assisted nonlinear characterisation can be a useful tool to get deeper insights on the mechanisms and sources of intrinsic nonlinearities in planar microwave circuits.

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