CURRENT PROGRESS IN PHENOMENOLOGY AND EXPERIMENTAL CHARACTERISATION OF PASSIVE INTERMODULATION IN PRINTED CIRCUITS

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ABSTRACT

The development of phenomenology, simulation tools and techniques for experimental characterisation of passive intermodulation (PIM) generation in printed circuits is at the forefront of current academic research and development by leading manufacturers of high-performance microwave laminates and printed circuits. This paper presents a brief review of the current status of the research and the major advances made to date in understanding of PIM phenomena in printed lines. The main aspects of the distributed PIM production and experimental characterisation of printed circuits are revisited and illustrated by the recent findings. Designer guidelines for low-PIM printed circuit solutions are suggested.

1. INTRODUCTION

Passive intermodulation (PIM) generation in printed circuits presents one of the major challenges for the manufacturers of high-performance microwave laminates and printed circuit components for wireless communications. Whenever an excessive level of PIM products, interspersed into the transmitting signals, emerges at the receiver input it degrades the receiver performance, particularly, dynamic range, and might even jam the channel. This is a common situation in the GSM base stations, where the third-order PIM (PIM3) products of the transmitting multi-carrier signals are generated by weak nonlinearities in the cable assemblies, filters, diplexers and reflectors and appear as undesired signal in the receiver band [1]. In multi-band systems this effect is further aggravated by the inter-band interference [2-3].

The PIM production in printed circuits and packaged devices has recently become a critical issue for the advances in wireless telecommunications, including frequency-hopping spread spectrum signal transmission and ultra-wide-band communication equipment, co-located antennas and antennas in complex changing environment, e.g., multi-band spacecraft and avionic antennas. The problems of electromagnetic interference in printed circuits are an integral part of the design routing for densely-packed electronic sub-systems and front-ends, e.g., for micro- and nano-satellites.

Despite the apparent ubiquity of the PIM appearance, its far-reaching effect and grave impact upon the high-speed data transmission, the complexity of PIM phenomena has long been hindering the development of the engineering techniques for prediction and modelling of PIM effects. Suffice it to mention here that even though the low-PIM laminates are widely marketed by the major printed circuit board (PCB) manufacturers, there are still no commonly adopted cross-industry standards for PIM characterisation of microwave laminates and printed circuits. This deficiency often causes misinterpretation of the published PIM data and leave users confused over the laminate specifications.

In this paper, we present a brief review of the recent progress in the research of distributed PIM generation in commercial printed circuits. Section 2 summarises the phenomenology of distributed PIM production based upon the nonlinear transmission line model. Section 3 presents some recent advances in understanding of physical mechanisms of distributed PIM generation in printed circuits and means of its mitigation. The essential aspects of experimental PIM characterisation of printed lines are discussed in Section 4 and the future developments are outlined in Conclusion.

2. PHENOMENOLOGY OF DISTRIBUTED PASSIVE INTERMODULATION

The two-port measurements of the PIM response of the sections of microstrip transmission lines (MTL) of different length fabricated on commercial laminates were a precursor for the development of the phenomenology of distributed PIM production [4]. From the first results it has become evident that the pattern of PIM generation in printed lines is fundamentally different from the PIM generation by the nonlinear contact junctions at the end connectors of coaxial cable assemblies and terminations. It appears that the PIM level measured at the MTL output steadily grows with the line length. Similar phenomenon had been already reported for the sections of coaxial cables with nonlinear coatings [5] and superconducting transmission line [6].

A consistent interpretation of the observed PIM growth, so-called cumulative effect, has been given in terms of the distributed nonlinearity of the printed lines and the concept of phase matching in the four-wave mixing process [7]. It has been shown experimentally that a localised nonlinearity emanates PIM products with isotropic field distribution about the source, Fig. 1. The locally generated PIM products travelling in the forward direction (collinear with the carrier propagation) along a matched dispersionless nonlinear transmission line (NTL) are in-phase with the fundamental carriers and constructively interfere with the corresponding PIM products generated in the preceding line sections. On the contrary, the PIM products travelling in the reverse direction along the NTL have a phase mismatch with the corresponding products generated in the succeeding sections of the line. It causes variations (humps and troughs) of the reverse PIM level measured at the input of lines of different lengths. Therefore the pattern of PIM product distribution on a section of a straight uniform NTL exhibits undulations which are the result of superposition of the forward and reverse propagating PIM products, as illustrated in Fig. 2.

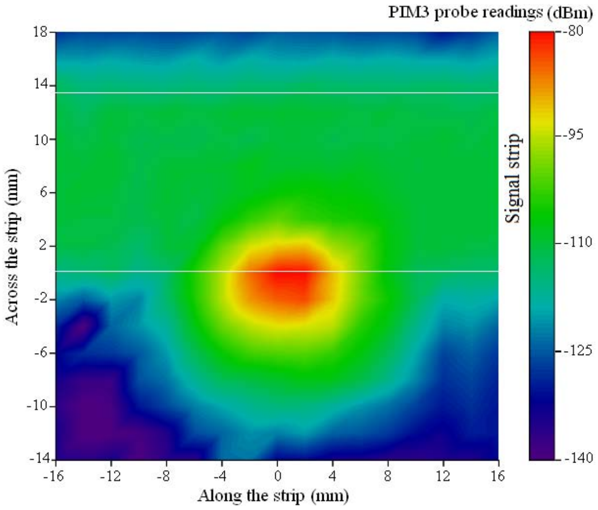

Figure 1. Near-field distribution of the third-order PIM (PIM3) products about the lumped PIM source (a pencil mark of 3.5×1 mm^2 centred in the origin) measured with a vertical open-ended coaxial probe at 910 MHz and 2×43 dBm carriers

It is noteworthy that, as distinct from the PIM generation by a localised source, the forward PIM level measured at the output of long MTL with distributed nonlinearity significantly exceeds the reverse PIM level measured at the line input.

Another important feature of the distributed PIM production is the generation of multiple spatial modes in the NTL. Even a single fundamental mode carrier can produce multiple travelling modes at the PIM frequency if they are supported by the line geometry. For example, Fig. 3 shows the cross-sectional distribution of the PIM3 products formed by the superposition of the odd and even modes in a coplanar waveguide (CPW). Moreover, spectrum of the local PIM generation contains bounded (guided), radiating and evanescent modes. Therefore, the PIM products in CPW are deemed to be less confined to the guiding structure and thus exhibit stronger attenuation and cross-coupling.

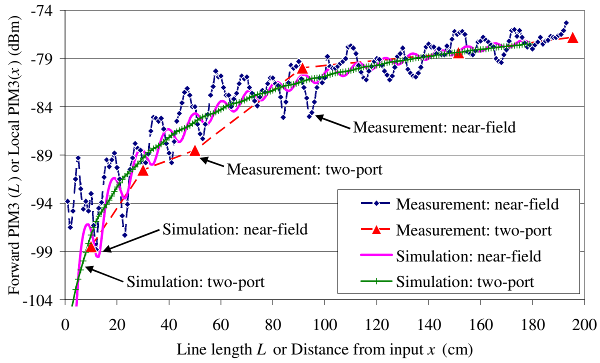

Figure 2. Forward third-order PIM (PIM3) level at the line output of the samples of different length as compared with the PIM3 magnitude distribution along the longest sample (normalised results); measurements were performed with a vertical open-ended coaxial probe at 910 MHz and 2×43 dBm carriers [8]

Two main types of the distributed PIM sources should be distinguished in printed NTL, namely, conductor (current-driven) and substrate (voltage-driven) nonlinearities. It was shown in [9] that in MTL with dominant conductor nonlinearity the signal strip has major impact on the PIM production, whereas the contribution of the return current on the ground plane is practically negligible despite both conductors are made of the same copper foils. It has also been shown that the MTL strip edges considerably stronger contribute to the distributed PIM generation than the strip centre, owing to the current bunching at the strip edges.

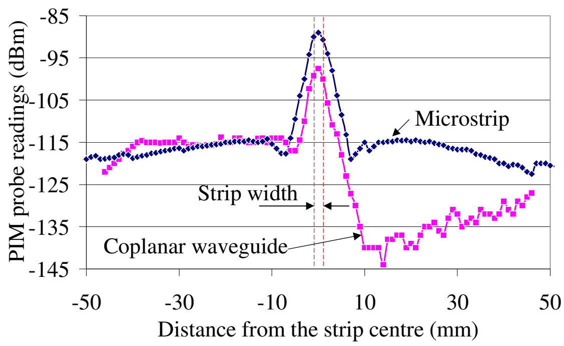

Figure 3. Near-field PIM distributions across MTL and CPW measured with a vertical open-ended coaxial probe at 910 MHz and 2×43 dBm carriers (NB: the laminates under test had the same grade of copper cladding and finish coating but nonlinearity of the MTL substrate is higher than that of the CPW substrate)

The strip edges also play the major role in PIM generation in the lines with dominant substrate nonlinearity. In this case, fringing field causes PIM generation of not only bounded mode but also leaky wave guided by the dielectric substrate. This effect is illustrated in Fig. 4 where the retrieved distribution of the PIM3 products measured across a microstrip line is plotted beside the respective field pattern of the fundamental guided mode in linear regime. The higher level of the PIM3 products than that of the guided wave away from the strip indicates the presence of the leaky mode generated by the fringing fields of the carriers.

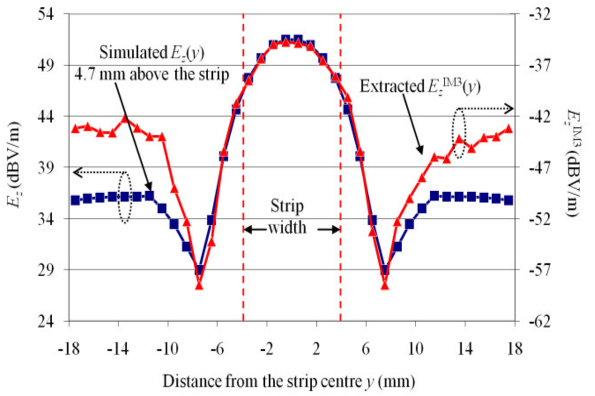

Figure 4. Retrieved distribution of the electric field magnitude E_z^{IM3} of the PIM3 products measured across the signal strip of a line with the dominant substrate nonlinearity. Measurements were made with a vertical open-ended coaxial probe at 910 MHz and 2×43 dBm carriers and are compared with the corresponding calculated E_z distribution of the fundamental mode of carrier in linear regime at 910 MHz [10]

In view of the fact that the level of the PIM products in commercial laminates and printed circuits is fairly low, typically below -100 dBc, the theory of distributed PIM generation in printed lines has been developed using the NTL-model with weakly nonlinear parameters of the conductors or/and dielectric substrate [7]. The closed-form expressions for the forward and reverse PIM3 products in finite sections of straight uniform microstrip lines have been obtained in [7] using the first order of perturbation technique. This model is inherently phenomenological and requires additional retrieval of the parameters of conductor/substrate nonlinearity from experimental measurements. It has been shown that the extracted nonlinear parameters are representative of the substrate material and can be employed to predict the PIM response of other printed structures fabricated of the same laminates.

The model of uniform NTL proved to accurately describe the effects of the cumulative growth of the forward PIM products and variations of the reverse PIM products, effects of the signal strip width, port mismatch [11] and weakly nonlinear terminations [12]. In particular, it has been experimentally observed that the forward PIM level grows with the strip width in the MTL with the dominant substrate nonlinearity and decreases in the lines with the dominant conductor nonlinearity. This effect has been thoroughly explored using the developed PIM phenomenology. Also the significant role of port matching in the two-port PIM characterisation of the printed lines was demonstrated theoretically. It has been suggested that the effects of microstrip discontinuities and line interconnects can be adequately modelled by cascading the uniform NTL sections with the nonlinear boundary conditions [12].

The present phenomenology of distributed PIM generation can account for the conductor and substrate nonlinearities of any nature, provided that the extrinsic nonlinear parameters are available for description of the specific nonlinear mechanisms. Alternatively, a holistic modelling approach would require multi-physics analysis that dramatically complicates the mathematical problem. For instance, a rigorous self-consistent formulation of the thermo-electrical mechanism of distributed PIM generation would contain the nonlinear system of Maxwell and heat transfer equations with the corresponding constitutive relations. However, the NTL phenomenology with its assumptions enables one to reduce the simulation complexity by means of the successive solution of the problems of heating resistive conductors by the high power carriers and subsequent generation of the PIM products due to the change in the resistance associated with the temperature variations at the envelope frequency [13]. Some of the physical mechanisms of the nonlinearities in printed lines are further discussed in the next section.

3. PHYSICAL MECHANISMS OF NONLINEARITY IN PRINTED LINES

Several experimental observations of the distributed PIM generation in commercial printed circuits can provide an insight into the physical mechanisms and sources of the distributed nonlinearity. At first, the effect of conductor-to-substrate interface, particularly roughness of the copper cladding underside [14], has been a subject of the detailed studies. Extensive testing revealed strong correlation between the cladding roughness and generated PIM, [14-15]. Although it is generally accepted now that rougher copper underside generally causes the higher PIM level, the physical mechanisms of this correlation are still obscure. It has been suggested that higher dissipation loss at rough surface might facilitate the intrinsic self-heating and thus boost the distributed PIM production due to the nonlinear thermo-electric phenomena. Another speculation is that the rough surface is prone to trapping various contaminants and developing structural defects, such as microscopic voids and broken dendrites. Such imperfections might create microscopic sources of nonlinear mixing of the high-power carriers causing the distributed PIM generation.

The effect of the surface bonding layer is demonstrated in Fig. 5. The absence of bonding layer results in the higher level of PIM generation, which might be due to the weaker copper adhesion to the substrate and thus inferior interface quality. These factors affect both the quality of the strip etching and contamination of the interface by chemical residuals that may cause PIM production through different nonlinear mechanisms.

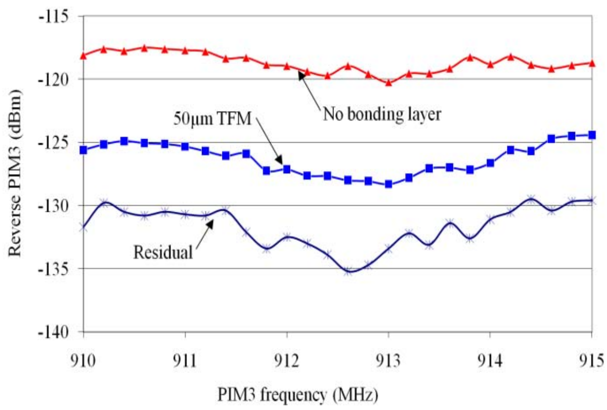

Figure 5. The effect of surface bonding on PIM3 response of microstrip lines with 50 µm TFM bonding film and with rearranged structure (embedded bonding layers) measured at 2×43 dBm carrier power [16]

Similarly, the internal structure of copper foils appeared to influence PIM generation. The finer crystalline structure is more resilient to the mechanical stresses and fracturing, and also provides finer surface of the copper matte side. These factors contribute to the lower PIM.

The effect of the finish coating on distributed PIM generation is currently an active area of research [17]. There are two aspects of the finish coating which affect the distributed PIM generation, namely, finish material and its structural properties. The material effect is usually associated with hysteresis nonlinearity of the ferroics. It has been found that some hysteresis mechanisms display unique features. In particular, it was demonstrated that in contrast to the memoryless PIM response, the even-order hysteresis nonlinearity produces the odd-order PIM products, and their growth rate with the carrier power does not follow the "classic" rates [18]. It has been shown that the ferromagnetic response of the nickel coating can be efficiently suppressed by the proper addition of phosphorus content [19]. The study [20] argues that the electroless nickel/immersion gold (ENIG) demonstrates considerably lower nonlinearity as compared with the immersion tin coating. This might be attributed to the proper phosphorus content in the test coating which enabled effective suppression of the nickel ferromagnetic response. The amount of the phosphorus additives corresponding to the minimum PIM production seems to be determined by the electronic properties and crystallisation phase of the nickel-phosphorus deposit.

The comparison of non-ferroic coatings [17], such as immersion silver, organic solder preservative (OSP), lead-free hot air solder levelling (HASL) and immersion tin, has revealed that the latter coating demonstrates superior performance in terms of low-PIM generation. This result might be attributed to the special properties of the immersion tin as a finish layer, namely: good wetability, coplanarity and adhesion. It was suggested that the immersion silver coating might cause the higher rate of PIM production due to its granular structure. In contrast to the aforementioned coatings, the recently introduced autocatalytic silver coating [19] provides significantly lower PIM production rate as compared with the immersion tin, presumably due to its finer internal structure.

One of the fundamental mechanisms of distributed PIM generation in printed lines, which has been recently addressed in [13], is thermo-resistance of the conductor electrodes. The phenomenon itself has been a focus of extensive investigation for decades, specifically, in respect to the coaxial waveguides [21-22] and microwave interconnections [23]. Electromagnetic power dissipation in the conductors inflicts variation of the intrinsic temperature in the strip which in turn gives raise to the nonlinear resistance associated with the conductors. Apparently, the associated PIM generation depends on the conductor loss and heat transfer in the conductors and substrate.

The electrical nonlinearity of the dielectric substrate is another important factor of the distributed PIM generation in printed lines [24]. A dielectric substrate is complex composite material. It is typically formed as a multilayer structure comprised of base thermoset or/and thermoplastic dielectric material, glass reinforcement (woven glass fabric or random cut glass fibres), surface bonding layers (e.g., skived PTFE film) and ceramic filler additives used to adjust the mechanical and thermal properties of the substrate. Although the research in this subject has yielded rather limited data to date, it is evident that the glass grade and purity, fibre coating, and ceramic filler material affect PIM performance of substrates[1].

Other mechanisms of substrate nonlinearity can be suggested, including electrostriction of the open-porous PTFE and nonlinearity of ferroelectric ceramic particles (e.g., $SrTiO_3$ commonly used as the filler to increase dielectric permittivity of materials and improve their mechanical and thermal properties). It has also been suggested that the crystallinity rate of PTFE film might affect its behaviour. In particular, the correlation has been observed between the PIM response of processed

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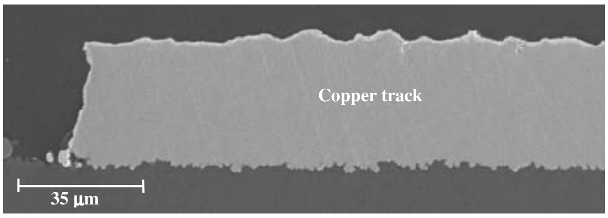
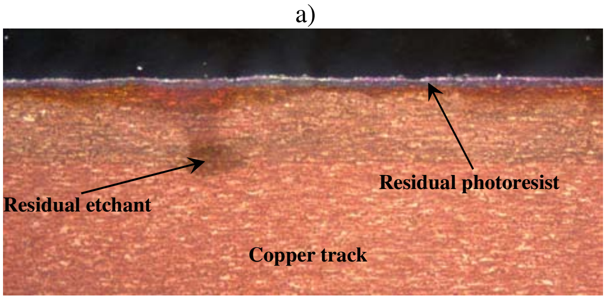
printed circuits and change of PTFE laminate colour, presumably caused by PTFE recrystallisation. However, all these conjectures still require further corroboration.



a)



b)

Figure 6. Typical conditions at the strip edges of the processed printed line [16, 25]: a) cross-sectional SEM image of the fractured strip edge; b) high-resolution optical microscopy of the contaminated edge of the copper track underside

Processing of the printed boards with low PIM response presents another challenge. Comprehensive evidence has been collected that quality of etching of the copper tracks strongly affects the PIM performance of printed boards [4]. The fractured edges of the copper track are prone to delamination and contamination, Fig. 6, and degrade the quality of the finish coating, especially at strip edges. Indeed, when these fractures are plated over they might produce numerous microscopic voids and bridges with high constriction resistance. Similar observation has been made with respect to undercutting the strip edge [26]. Exposed to the high power, these defects burn out and cause the bursts of PIM response.

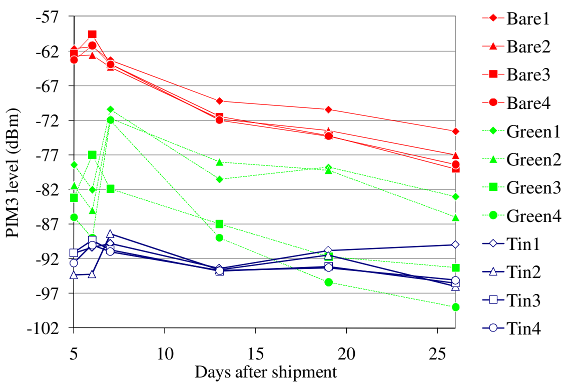


Figure 7. Forward PIM3 response of a commercial microwave laminate with different strip finishing (bare copper, OSP “green-mask” and 1um immersion tin) measured over an extended period of time [16]

A new dimension has recently been added to the study of PIM generation in printed circuits. The PIM tests of the commercial printed lines with different finishing carried out in office environment over a period of time have revealed considerable self-improvement of the PIM performance, Fig. 7 [16, 27]. It has been observed that the printed lines with immersion-tin finishing demonstrate better stability and lower levels of PIM production. Understanding of this phenomenon still requires further investigations, yet the existing experimental evidence suggests that viscoelastic stress relaxation mechanism is involved.

4. EXPERIMENTAL CHARACTERISATION OF PASSIVE INTERMODULATION IN PRINTED LINES

Presently, most experimental techniques of PIM characterisation of printed circuits imply injection of a two-tone RF probe signal into the line under test and recording the magnitude of the corresponding in-band or inter-band PIM products generated within the TL-section. Two PIM recording approaches are widely adopted [8]:

- two-port PIM characterisation, which is the measurement of the PIM magnitude at the TL ports,
- near-field probing of the PIM product distribution on the TL.

The central issue in the experimental characterisation of PIM production is the design of a test bench and printed line specimens. Because the measured PIM levels are extremely low and often close to the residual PIM of the test instrument, much attention is paid to reducing the experimental uncertainties caused by mismatch of the MTL ports and other electrical discontinuities, and spurious PIM responses of the test cables, connectors, probes and test environment. The coaxial-to-microstrip transitions are the critical elements, and they can be implemented either as soldered joints or contactless couplers shown in Fig. 8, [8]. The former approach involves the edge-mount connector units Fig. 8a, or alternatively horizontal Fig. 8b [8] or vertical [15] direct cable launchers. The quality of soldering proved to be of utmost importance. In order to reduce the associated experimental uncertainty, several replicas of the test specimen are usually fabricated and, when necessary, the soldered joints are readjusted.

The contactless transitions can be implemented either as the capacitive coupling, commonly used in printed patch antenna feed networks [28], or broadside stripline couplers, Fig. 8c/d, [8]. In the latter design, the test fixture provides the ground plane and shielding of the test specimen, so that the accurate comparative PIM measurements can be performed on different substrates with different strip parameters and finish coating by using the same reference ground plane. Even though the total number of soldered joints in the measurement circuit with contactless coaxial-to-microstrip transitions is not less than in the cable launchers, the test specimens are free of the soldered joints. This advantage allows the contactless test fixture to be employed for inexpensive, fast and traceable PIM tests, which are of high interest for *in-situ* quality control for production line.

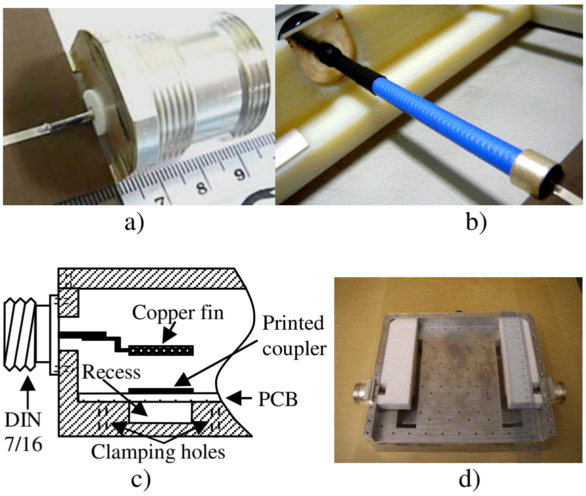


Figure 8. Microstrip launchers for PIM characterisation of printed circuits [8]: a) edge-mount 7/16 connector; b) custom-designed direct cable launcher; c) broadside stripline coupler and d) contactless test fixture

The near-field probing proved to be an efficient technique for experimental characterisation of the PIM generation in printed lines [8, 29-30]. The available probe designs enable imaging of the PIM product patterns generated by the distributed and lumped nonlinearities, and thus allow for accurate location of the PIM sources and identification of the nonlinearities. The two-port time-domain PIM reflectometry could provide an alternative means for location of the PIM sources, especially in shielded striplines and coaxial cables. However, the latter technique requires phase measurements of the PIM products but this capability is not supported in the commercial PIM analysers.

The central issues in the use of near-field probing for absolute PIM measurements are concerned with the probe design and calibration [29]. In addition to the basic requirements to the probes employed for the linear field mapping, the probes for PIM measurements must be highly linear and weakly perturb the high intensity fields of the carriers. Therefore, sharp features in the probe layout and nonlinear materials should be avoided in the probe design.

Generally, an accurate probe calibration requires full-wave electromagnetic analysis of the distributed PIM generation, which is still to be developed. Fortunately, for low PIM measurements, the probe readings allow an empirical normalisation based on the assumption that the scaling factor of the probe is independent of the nature of the measured field. So the probe scaling factor obtained at the PIM frequency in the linear regime can be applied to normalize the probe readings of PIM products at the same frequency [10].

Other important aspects of the PIM measurements of printed circuits are concerned with

- the controlled test environment, including EM-screening and ambient conditions (humidity, temperature and air purity);
- preparation, cleaning and storage of the test specimens;
- fabrication tolerances of the samples produced in different batches.

These factors may cause noticeable variations of the PIM performance of the same laminates. Therefore, the test uncertainties must be evaluated on a statistical basis and taken into account to provide the reliable PIM evaluation of the PCB materials.

Although the PIM characterisation still needs further elaboration of the methodology, instrumentation and industrial standards, the existing techniques provide the basis for exploring the fundamental mechanisms of distributed PIM generation in printed circuits and empirical means for its mitigation.

5. PRINTED CIRCUIT TECHNOLOGY FOR LOW PASSIVE INTERMODULATION

Significant advances have been made recently in manufacturing low-PIM substrates for printed circuits. The use of new constitutive materials and circuit routing and finishing has dramatically improved the PIM performance of microwave laminates. It has been demonstrated experimentally that the low-profile copper foil provides lower PIM response, which consequently shifted the industry towards the low-profile reverse-treated copper foil. In the broader context, the quality of the conductor-to-substrate interface is considered to be a prerequisite of low-PIM generation.

Thicker copper cladding has been adopted for the low PIM circuits, mainly because the bulk copper provides better heat sink and thus facilitates heat distribution. However, thicker copper foil is often associated with greater roughness, which may have an opposite effect and aggravate the PIM production.

With the advent of lead-free soldering much attention has been given to the certification of lead-free alloys for low-PIM printed assemblies. It has been shown that the lead-free solder alloys produce different results depending on the printed board finishing. Overall, leaded solder alloys generally demonstrate lower PIM generation, albeit the lead-free alloys give comparable results on the immersion-tin plated boards.

It has been shown that the conductor track etching may cause undesirable edge fracturing and delamination. Since these defects usually cause increased PIM level, the quality of the etched tracks is a prerequisite for achieving the high performance of the printed circuits. The strip finishing also has significant impact on the PIM performance. Immersion-tin coating proved to suit best the low-PIM printed circuits and demonstrates superior performance as compared to immersion silver, ENIG and OSP coatings.

The dielectric substrates for low-PIM design currently include a number of commercial laminates based on woven-glass reinforced PTFE or/and epoxy. Apart from the substrate nonlinearity, low dielectric loss, low moisture absorption and high thermal conductivity should be considered. Although the substrate nonlinearity is a subject of specific testing, there are some obvious indicators to choose a low-PIM material, namely high-purity glass reinforcement and base dielectric.

The printed circuit layouts for low-PIM components should be thoroughly designed to avoid the electrical discontinuities that have strong impact on distributed PIM generation. The abrupt discontinuities also can act as sources of localised PIM generation associated with the high density currents and strong fringing fields. Port mismatch in the printed circuits results in standing-waves of the electric current and field which may boost the PIM production in the anti-nodes, so special consideration should be given to the circuit matching.

In open environment printed circuits generally tend to degrade. The degradation can be caused by mechanical stresses, vibrations, extreme temperatures, moisture absorption and chemical contamination, degradation of constitutive materials or dimensional instability. Such factors, either reversible or irreversible, have various manifestations, ranging from electrical mismatching to formation of nonlinear sources. In any scenario they have strong impact on the PIM performance of the printed circuits and should be carefully monitored.

6. CONCLUSION

Significant progress has been achieved in understanding of PIM phenomena in printed circuits. Modern PCB technology enables commercial manufacturing of the high-performance microwave laminates and printed boards with the PIM performance that meet the stringent requirements of 3G communications. However, there exists a large body of experimental results waiting for comprehensive interpretation and better understanding. They still puzzle the research community, and forewarn the PCB manufacturers and users.

Further developments are envisaged in the PIM phenomenology. The limitations of current NTL-modelling could be overcome with the aid of rigorous electromagnetic analysis of PIM phenomena. Efficient numeric simulation tools are still to be developed and implemented in commercial CAD and specialist software.

Progress is also envisaged in the methodology and instrumentation for experimental characterisation of nonlinearities in printed components. The urgent need for standardization of the PIM characterisation of printed circuits and microwave laminates has been identified. Cross-industry standardization of the PIM characterisation techniques and production testing require further coordination of the research activities run by the academic institutions, antenna manufacturers and network operators through appropriate committees.

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