Passive intermodulation in printed lines: effects of trace dimensions and substrate

A.P. Shitov D.E. Zelenchuk A.G. Schuchinsky V.F. Fusco

The Institute of Electronics, Communications and Information Technology (ECIT), Northern Ireland Science Park, Queen’s University of Belfast, Queen’s Road, Queen’s Island, BT3 9DT Belfast, Northern Ireland, UK
E-mail: a.schuchinsky@qub.ac.uk

Abstract: A comprehensive experimental study was performed to identify and discriminate mechanisms contributing to passive intermodulation (PIM) in microstrip transmission lines. The effects of strip length and width, and substrate materials on PIM performance of printed lines were investigated in the GSM900, DCS1800 and UMTS frequency bands. The major features of the experiment design, sample preparation and test setup are discussed in detail. The measurement results have demonstrated that the PIM level cumulatively grows on the longer microstrip lines and decreases on wider strips and, thus, indicated that the distributed resistive nonlinearity of the printed traces represents the dominant mechanism of intermodulation generation in the printed lines on PTFE-based substrates.

1 Introduction

Printed circuit boards (PCBs) constitute the backbone of most telecommunication equipment. The signal integrity and electromagnetic compatibility of the PCB-based devices impose increasingly stringent requirements to PCB performance and pose particular challenges in high-power applications such as printed antennas, filters and interconnects [1].

Passive intermodulation (PIM) in printed circuits has major detrimental effects leading to deleterious electromagnetic interference in wireless communications systems. Despite the growing demand for effective means of mitigating PIM generation in PCBs, the mechanisms underlying this phenomenon are still barely understood and are scarcely addressed in the technical literature.

Recent studies [2–5] have revealed some correlation between the properties of PCB materials and measured PIM products. At the same time, they have also demonstrated that the PIM performance of printed traces was extremely sensitive to the measurement techniques and fabrication processes. Moreover, the results of the PIM measurements presented in the literature were often inconsistent, for example, the correlation between carrier attenuation and the PIM level reported in [2] was not observed in [3].

Nevertheless, certain interrelations between laminate construction and the PIM performance of processed PCB have been empirically identified [5]. In particular, the effect of the copper cladding and the surface bonding layer on PIM performance has been observed along with the effect of walls of etched traces [2, 4]. However, the role of the trace shape and laminate composition in PIM production has received no consistent interpretation so far, mostly because of lack of the pertinent experimental data on PIM generation in PCB materials.

To address these issues and gain insight into the origins of PIM production in PCB materials, it is essential to perform systematic and repeatable PIM measurements on the canonical printed structures, which are adequately described by the predictive phenomenological models. Therefore the objective of this study was to set up the targeted experiments, which could allow us to measure PIM products on the microstrip lines and juxtapose the obtained experimental data with the characteristics inferred from the nonlinear transmission line (NTL) model [6, 7].
In this paper, we present the results of the first comprehensive experimental study of third-order PIM (PIM3) generation on microstrip lines specially designed and manufactured in order to identify and separate the individual contributions of the material and geometrical parameters to PIM performance of PCB. The main features of the PIM characterisation of PCB materials, the test setup and data analysis are presented in Section 2. In Section 3, the results of the PIM measurements are discussed, and the main findings are summarised in the Conclusions. The principal aspects of the NTL model used for interpretation of the PIM measurements are summarised in Appendix.

2 Design of experiments

2.1 Measurement setup

The test setup is based on a commercial Summitek Instruments PIM analyser [8]. Three different models: SI-900B, SI-1800B and SI-2000B(E), have been used for the measurements in the GSM900, DCS1800 and UMTS frequency bands as detailed in Table 1. The analyser feeds a two-tone signal (two continuous wave carriers) into the device under test (DUT), and monitors levels of the forward PIM products at the DUT output port and the reverse PIM products at the DUT input port in the respective bands of the instrument receiver. Magnitude of the forward and reverse PIM3 products (PIM3) is measured either at a spot frequency or in a frequency sweep of one tone at a time. In the latter case, the PIM3 frequency fIM3 = 2f1 − f2 (f1 < f2) is swept in the bands specified in Table 1 as follows:

1. The carrier frequency f1 is fixed at its lowest value, and f2 is swept downward from its maximum value (referred to as ‘DOWN’ sweep).

2. The carrier frequency f2 is fixed at its maximum value, and f1 is swept upward from its lowest value (referred to as ‘UP’ sweep).

To ensure a meaningful comparison of test specimens, the full test setup is first calibrated for the residual PIM3 level without a DUT. This provides a reference PIM3 level of the test instrument together with the cable assemblies. The measurement uncertainty has been assessed by repeating the tests after disconnecting and reconnecting the DUT three to five times and then averaging the measurement results over the swept frequency band and a series of reconnections. This allows us to reduce the effect of intrinsic noise in the test setup itself, which could be commensurate with the measured PIM3 level in high-quality (low PIM) PCB laminates. Therefore the mean values of the measured PIM3 are adopted in this paper as the representative quantities for characterisation of specimen performance. The viability of such an approach is supported by the following observations:

i. The PIM3 levels at spot frequencies demonstrated time variations whereas their median consistently remained within narrow margins.

ii. Frequency dependencies of PIM3 magnitude exhibited random kinks, especially, the reverse PIM3 response. These could be caused by occasional minor changes in the sample assembly or drift of the instantaneous residual PIM3 level. Such adverse effects of the instrumental instabilities were grossly eliminated by averaging.

Finally, it is important to note that the instrument uncertainties strongly affect measurement data at the level close to the residual PIM level [8]. However, our extensive tests have shown that even near the analyser sensitivity floor, where the instantaneous PIM3 level has greater variations, the PIM3 median consistently demonstrates the distinctive signatures of PIM products in the test specimens.

2.2 Sample design and preparation

The board layouts with the microstrip line specimens used in the experiments are shown in Fig. 1, and the parameters of the respective PCB materials are listed in Table 2. The test samples were specially designed to explore the effects of trace geometry and substrate material composition on PIM3 generation. To reduce sensitivity of the test results to manufacturing factors and tolerances, two to three replicas of each board were fabricated simultaneously. The following microstrip line specimens were manufactured and tested:

<table>
<thead>
<tr>
<th>Table 1 Frequency bands of carriers and PIM3 products</th>
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<tbody>
<tr>
<td>PIM analyser</td>
</tr>
<tr>
<td>SI-900B</td>
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<tr>
<td></td>
</tr>
<tr>
<td>SI-1800B</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>SI-2000B(E)</td>
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</table>
i. Uniform straight and meandered 50 Ω lines of several lengths (Board 1 with the layout shown in Fig. 1a).

ii. Straight lines of different widths combined with the six-section Klopfenstein tapered transformers providing the impedance matching between the central sections and 50 Ω input/output ports (Boards 2 and 3 with the layout shown in Fig. 1b).

iii. Straight uniform 50 Ω microstrip lines on the substrates with different laminate compositions (Boards 4–9 specified in Table 2 with the trace layouts shown in Fig. 1c).

Note that the Boards 1–3 are made of the same laminate material, see Table 2.

The PIM measurement data available from the PCB manufacturers and end-users often showed significant variations of PIM3 performance of printed lines despite their substrate materials having identical specifications, [4, 5]. To minimise uncertainties caused by the different raw materials in PCB laminates and fabrication techniques, our specimens were produced in strictly controlled manufacturing processes. Namely, Boards 1–3 and 9 have the same laminate composition and copper cladding but different thickness. The same grade of low-profile reverse-treated copper foil of thickness 35 μm with metallic zinc-free anti-tarnish coating was used for copper cladding of all laminates except Board 4. The foil used in Board 4 had the same thickness but came from a different supplier. To prevent environmental contamination of the exposed copper surfaces, all conductors were coated by a 1 μm thick immersion tin. According to [9], such a protective layer provides low PIM finishing of the printed traces. The specimens were manufactured by the same commercial PCB processing house and produced in three separate batches: (i) Boards 1 (ii) Boards 2 and 3 and (iii) Boards 4–9.

2.3 Microstrip launchers

The low-PIM launchers represent the critical elements of the test setup employed for evaluation of PIM performance of PCB laminates. It was shown experimentally in [10] and is corroborated experimentally in Section 3.4 below that input/output matching of the printed microstrip lines has a significant impact on the measured PIM3 response of the transmission lines. Therefore high-quality coaxial-to-microstrip transitions are required to reduce the inhomogeneity of the power distribution along the traces, which is caused by standing waves in the mismatched lines. The board launchers have been specially designed for our experiments to provide the reflection coefficient less than −20 dB over a wide frequency range (broadband matching is necessary for testing the same specimens in the different frequency bands).

To examine the effect of the launchers on the PIM3 generation, the straight uniform microstrip lines on Boards 4–7 were equipped with two types of coaxial-to-microstrip transitions shown in Fig. 2:

i. Cable launchers, Fig. 2a, were made from the PIM3 certified connectorised cable assemblies, which comprised...
6.35 mm semi-rigid coaxial cable of length 250 mm and DIN 7/16 flange-mount connectors. The cable assemblies were cut in the middle and each half was fitted at the PCB edges using the newly designed coaxial-to-microstrip adaptors (see the encircled item in Fig. 2a).

ii. DIN 7/16 edge-mount connectors were attached directly at the PCB edges; see Fig. 2a. The measurement results in Fig. 2c demonstrate that the cable launchers exhibit a considerably lower reflection coefficient than the edge-mount connectors: less than 25 dB in the GSM900 frequency band and 20 dB in the DCS1800 and UMTS bands.

Finally, it is important to note that this study was carried out on high-performance PCB materials certified by manufacturers for low-PIM applications. Consequently, PIM characterisation of such materials poses an enormous challenge because of the limited sensitivity of the available PIM analysers (typically −125 dBm over 90% of the intermodulation frequency band), and the difficulties in separating PIM products generated by the printed traces and the test fixture including launchers/connectors. Nonetheless, the results presented in Section 3 demonstrate that the experimental approach described here provides a consistent and reliable means for evaluation of PIM performance of a broad range of PCB materials.

3 Experimental results and discussion

The test specimens described in Section 2 have been designed for the targeted experiments, which are aimed at identification of the PIM generation mechanisms in microstrip lines and discrimination of the effects of trace geometry and the substrate material on PIM performance of PCB laminates.

All measurements were performed in a screened anechoic chamber to exclude interference from external sources. After each reconnection of the specimen, the integrity of the whole assembly was checked by tapping the joints and the board to ensure that there were no mechanical faults or loose connectors, which could alter PIM response of the DUT. Occasionally during the tests, we observed a drift of carrier(s) power that led the PIM3 magnitude of the DUT to fall below the initial residual level. Such instances were treated as random errors of the instrument and were included in the estimations of the measurement uncertainty.

3.1 Cumulative effect

Distributed weak nonlinearity of the printed traces has been assumed as a primary source of PIM generation in microstrip
lines on low-loss substrates. The NTL model [7] with the current-driven nonlinear resistivity defined by (1) in Appendix predicted cumulative growth of the forward $P_{\text{IM3}}$ with line length. To investigate this phenomenon experimentally, $P_{\text{IM3}}$ level on the uniform 50 $\Omega$ microstrip lines of several different lengths was measured first. Magnitude of the forward $P_{\text{IM3}}$ on the microstrip traces of Board 1 (Fig. 1a) is shown in Fig. 3 for the 'DOWN' frequency sweep in the DCS1800 band. The plotted experimental points represent mean values in the swept frequency band (1730–1784 MHz), and the error bars delimit the maximum $P_{\text{IM3}}$ deviations in the series of reconnections.

Fig. 3 demonstrates that forward $P_{\text{IM3}}$ monotonically grows on the longer traces, and the measurement results correlate well with the NTL model prediction based on (2). The measurement results of the same lines for the GSM900 band were reported earlier in [11] and also exhibited a general trend of higher forward $P_{\text{IM3}}$ on longer traces. In the 'UP' frequency sweep, Table 1, the forward $P_{\text{IM3}}$ level exhibits the same qualitative trend, although its magnitude differs slightly. This discrepancy is attributed to dissimilar matching conditions in the 'UP' and 'DOWN' sweeps of the respective carrier frequencies (Fig. 2c). It is noteworthy that despite a steady increase of the forward $P_{\text{IM3}}$ with line length in Fig. 3, it does not grow indefinitely. According to the NTL model, when attenuation of the carriers on sufficiently long lines exceeds the rate of $P_{\text{IM3}}$ generation, forward $P_{\text{IM3}}$ starts to decay (2). This phenomenon was also observed in the theory of travelling-wave harmonic generators [12].

In contrast to the forward $P_{\text{IM3}}$, the reverse $P_{\text{IM3}}$ level showed no consistent increase on longer lines, and its level remained below the forward $P_{\text{IM3}}$. These observations are consistent with the NTL model predictions and suggest that the reverse PIM products are predominantly formed near the input port of the matched microstrip line. This effect can also be attributed to the phase matching in a nonlinear mixing process [13].

Thus, the presented results of $P_{\text{IM3}}$ measurements on microstrip lines of different lengths provide conclusive evidences of the cumulative growth of PIM3 products on printed lines [2, 14] and support the phenomenology of the NTL model with distributed nonlinearity.

### 3.2 Effect of strip width

The effect of strip width on PIM3 product generation is difficult to assess independently because it is accompanied by the line mismatch, which is caused by the change of the line impedance. Two approaches have been used to investigate this effect:

i. Substrates with modified parameters to compensate for the strip width variations and maintain the line impedance at the 50 $\Omega$ [3].

ii. Impedance transformers integrated with lines of different widths on the same substrate to provide matching to 50 $\Omega$ input and output ports (Fig. 1b).

The latter configuration has been adopted in this work because it allows the direct comparison of the lines of several different widths on a single board (Fig. 1b) and, thus, excludes additional uncertainty incurred by dissimilar substrates. The shortcoming of this arrangement is that the matching transformers may also contribute to PIM3 generation and somewhat obscure the effect of the line width as detailed below.

The results of forward $P_{\text{IM3}}$ measurements in the GSM900 frequency band are shown in Fig. 4 for the matched microstrip lines of several widths fabricated on
Boards 2 and 3 (see the layout in Fig. 1b). The data points in Fig. 4 represent quantities averaged over the frequency band, the sample line triplets and a series of reconnections (the residual forward $P_{IM3}$ level was below $-120.4 \, \text{dBm}$). Error bars delimit the maximum $P_{IM3}$ deviations within each group of specimens with the same strip width.

The $P_{IM3}$ magnitude in Fig. 4 exhibits a monotonic decrease with strip width that can be attributed to lower current density on wider traces with nonlinear resistivity defined by (1). A similar effect was also observed in [3] for microstrip lines with different substrates. These experimental results are consistent with NTL model predictions and, hence, provide an independent confirmation that the current-driven distributed nonlinear resistivity of printed traces represents the dominant mechanism of PIM3 generation in microstrip lines on PTFE/woven glass substrates.

It is noteworthy that the forward $P_{IM3}$ magnitude measured on 917 mm long uniform microstrip lines on Boards 2 and 3 is higher than on Board 1, Figs. 3 and 4. The only difference between these two groups of specimens is that they were manufactured in separate batches. This fact demonstrates once again that PIM performance of printed lines is highly sensitive to the laminate materials and fabrication process.

The reverse $P_{IM3}$ level has shown little correlation with the strip width. Apparently, this implies that weakly reflecting matching transformers make a dominant contribution to the reverse $P_{IM3}$. This conclusion is consistent with the observations in Section 3.1 that the reverse $P_{IM3}$ level is predominantly determined by the line section near the input port of the matched microstrip line, and that even small reflections can noticeably affect the reverse $P_{IM3}$ [11]. This is why impedance matching transformers may completely disguise the effect of the trace width on the reverse $P_{IM3}$ level.

It is necessary to note that $P_{IM3}$ measurements on the traces of different widths have shown higher sensitivity to fabrication tolerances and workmanship, which cause higher measurement uncertainties, Fig. 3. Nevertheless, the obtained experimental results consistently demonstrate the qualitative trend of a lower forward $P_{IM3}$ on microstrip lines with wider traces. These results provide further evidence of PIM generation on Boards 1–3 by the current-driven distributed nonlinearity of printed traces (Appendix).

### 3.3 Effect of dielectric substrate

The effect of the dielectric substrate on PIM3 generation in the GSM900 frequency band had been first considered in [11]. In this section, the study is substantially extended to include other frequency bands and different materials and to investigate, particularly, the relationship between the dielectric substrate loss and $P_{IM3}$ level.

To evaluate the effect of laminate composition on PIM3 performance of PCB, straight uniform 50 $\Omega$ microstrip lines were fabricated on Boards 4–9 (Fig. 1), whose parameters are given in Table 2 (manufacturers' specifications). The insertion loss in each line was measured first at frequencies 910, 1730 and 2050 MHz and is plotted against the substrate loss tangent in Fig. 5a (zero loss tangent corresponds to the typical cable assembly used for making the cable launchers). The results of forward $P_{IM3}$ measurements in the GSM900, DCS1800 and UMTS bands are shown in Fig. 5b. The experimental points represent mean values in the respective frequency bands averaged over the sample triplets. The value at 0 loss tangent corresponds to the residual forward $P_{IM3}$ of the PIM analyser with the test fixture.

Although a general trend of increased PIM production on the boards with higher permittivity and loss tangent can be inferred from Fig. 5, there is no consistent correlation between the $P_{IM3}$ level and the substrate loss has been observed. Indeed, comparison of the linear insertion loss in Fig. 5a and $P_{IM3}$ level in Fig. 5b shows that although insertion loss grows with loss tangent, $P_{IM3}$ magnitude does not follow the same trend. This implies that for tested laminates, dielectric loss represents a second-order effect on PIM3

![Figure 5 Insertion loss and forward $P_{IM3}$ against the substrate loss tangents specified in Table 2](image-url)
connectors; the measurement results for the UMTS band at carriers’ power $2^4$.

Table 4

<table>
<thead>
<tr>
<th>Board number</th>
<th>Loss tangent</th>
<th>Forward ‘UP’ $P_{IM3}$ dBm</th>
<th>Reverse ‘UP’ $P_{IM3}$ dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.17</td>
<td>$-104.8$</td>
<td>$-122.3$</td>
</tr>
<tr>
<td>9</td>
<td>2.5</td>
<td>$-115.7$</td>
<td>$-126.2$</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>$-97.7$</td>
<td>$-126.5$</td>
</tr>
</tbody>
</table>

The observed effect of impedance mismatch on $P_{IM3}$ is fully consistent with the simulation results [10] obtained from the NTL with distributed nonlinear resistivity.

Indeed, according to [10], the forward $P_{IM3}$ level is lower than the reverse $P_{IM3}$, whereas the reverse $P_{IM3}$ level remains lower than the forward $P_{IM3}$. This is exactly what has been observed in all our measurements, and it is also consistent with the measurement results discussed in Section 2.3. Thus, we can infer from these experimental observations that high quality matching is a prerequisite for reliable and consistent evaluation of PIM3 performance of printed circuits and PCB materials.

4 Conclusions

The targeted experiments have been carried out to identify the mechanisms of PIM generation on printed microstrip lines and to elucidate the effects of the trace geometry and material parameters on PIM3 performance of PCB laminates. To ensure the integrity of the measurements, the microstrip lines were thoroughly designed and fabricated using controlled manufacturing processes. Special cable launchers with a low reflection coefficient (less than $-20$ dB) over a broad frequency band have been designed to provide the high quality impedance matching of the specimens with the test instruments. In the measurement trials, the effects of strip length and width, substrate material and launchers on PIM3 generation in microstrip lines have been explored. The main findings can be summarised as follows:

i. The magnitude of the forward $P_{IM3}$ monotonically increases with line length, thus providing explicit evidences of the cumulative growth of the PIM3 products along the line caused by the distributed nonlinearity of the printed traces.
ii. The reverse $P_{IM3}$ level is lower than the forward $P_{IM3}$ on the matched lines and shows no direct correlation with line length; however, the reverse PIM3 is more strongly affected by the impedance mismatch.

iii. The average magnitudes of the forward $P_{IM3}$, measured on Boards 2 and 3, exhibit a monotonic decrease with line width; this observation along with the cumulative growth of PIM products suggest that the current-driven distributed nonlinearity of microstrip traces represents the dominant mechanism of PIM generation on printed lines.

iv. For tested PCB laminates, no obvious correlation has been observed between the measured $P_{IM3}$ level and the permittivity, loss tangent and composition of the substrates; these results indicate that nonlinearity of the PTFE-based substrates represents a second-order effect when compared with nonlinear resistivity of the printed traces.

v. Input/output matching significantly affects the generation of the reverse $P_{IM3}$, namely, edge-mount connectors typically exhibit the reverse $P_{IM3}$ level of $\sim 5–10$ dB higher than cable launchers, whereas the level of forward $P_{IM3}$ remains nearly the same for both the types of launchers.

The study of PIM generation on printed lines presented in the paper is based on measurements, which involved multiple samples of different lengths and shapes. Alternatively, near-field probing can be employed to map PIM product distributions on printed traces. This approach has recently been implemented in [15] and has independently confirmed the cumulative growth of the forward $P_{IM3}$ level on microstrip lines. However, it is necessary to note that near-field probing on low-PIM laminates and short transmission lines is constrained by the sensitivity floor of the PIM analysers and the requirement of a weak coupling of the probe (typically less than $\sim 35$ dB). Thus, the two-port PIM measurements used in this paper currently represent the only practical way for characterisation of the high performance PCB materials with low intrinsic nonlinearity.

5 Acknowledgment

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6 References


7 Appendix

A phenomenological model of PIM3 generation in printed transmission lines with a weak distributed nonlinearity [6, 7] is used to interpret the measurement results. The current-driven per-unit-length nonlinear resistance is defined similar to [16, 17]

\[ R = R_0 + R_2 I^2 = \rho_0 \left( \int J^2 \, dl \right) + \rho_2 \left( \int J^4 \, dl \right) I^2; \]

\[ R_0 \gg R_2 I^2 \]  

where \( R_0 \) is the linear resistance and \( R_2 \) the nonlinear resistance; \( J \) is the surface current density on the infinitesimally thin imperfect conductors, [18]; \( \rho_0 \) and \( \rho_2 \) are the macroscopic linear and nonlinear resistivities, respectively. The macroscopic nonlinear resistivity \( \rho_2 \) is the model parameter, which is retrieved from the experimental data.

The solution of the nonlinear telegrapher’s equations for the perfectly matched segment of the transmission line of finite length \( l \) gives the following expression for the current distribution along the line at the PIM3 frequency \( f_{IM3} \) [7]

\[ I_{IM3}(x) = R_2 \xi \left\{ -(1 + \nu) \exp(-\gamma_{IM3} x) + \exp(-(2 \gamma_1 - \gamma_2) x) + \nu \exp(-\gamma_{IM3}(2l - x) - 2\alpha l) \right\} \]  

where \( \gamma_{1,2,IM3} = i \beta_{1,2,IM3} + \alpha \) are the complex wavenumbers at the frequencies of carriers \( f_{1,2} \) and of the intermodulation product \( f_{IM3} \); \( \xi = 3V_0^2 \beta_3 / (\omega Z_0^2(f_1)Z_0(f_2)Z_0(f_{IM3}) \times (\gamma_{IM3} + \alpha)) \), \( \nu = \alpha / \gamma_{IM3} \) and \( f_{1,2} \) are the source voltages at the frequencies \( f_{1,2} \) and \( Z_0(f) \) is the line characteristic impedance. Then, forward \( P_{IM3} \) magnitude is calculated as follows

\[ P_{IM3}(l) = \frac{1}{2} \text{Re} \left\{ I_{IM3}(l)U_{IM3}(l)^* \right\} \]  

where \( I_{IM3}(l) \) and \( U_{IM3}(l) \) are current and voltage at the transmission line output \( (x = l) \); \( ^* \) stands for complex conjugation and \( \text{Re} \) is the real part. Equations (1)–(3) are used for calculations of the \( P_{IM3} \) level on microstrip lines with the dominant current-driven nonlinearity.