Effects of Trace Dimensions and Substrate on Passive Intermodulation in Printed Lines

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***Abstract*— This paper reports the results of a comprehensive experimental study of passive intermodulation (PIM) generation on microstrip transmission lines. Effects of trace length and width, and substrate parameters on PIM performance of printed lines have been explored in GSM, DCS and UMTS frequency bands. Essential aspects of the experiment design, sample preparation and measurements are presented. Measurement results analysed on the basis of earlier developed phenomenology are discussed in detail.**

***Index Terms*—Passive Intermodulation (PIM), Printed Lines, Intermodulation Measurements, Nonlinearity.**

I. Introduction

Printed Circuit Boards (PCBs) constitute the backbone of most telecommunication equipment with increasingly stringent requirements being imposed on their performance. Signal integrity and electromagnetic compatibility pose particular challenges in high power PCB applications involving printed antennas, filters and interconnects [1].

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

Early studies [2]-[5] identified some correlations between the properties of PCB materials and measured PIM products. At the same time, they also showed that PIM performance of printed traces was extremely sensitive to the measurement procedures and fabrication processes. Moreover the reported PIM measurement results were often inconsistent, e.g. the correlation between carrier attenuation and PIM level observed in [2], was not seen in [3].

Nevertheless, certain relationships between laminate construction and PIM performance of processed PCB have been empirically established in [5]. In particular the impact of copper cladding finishing and dielectric composition on PIM performance has been confirmed experimentally. Additionally, the effect of the quality of the etched trace wall, discussed in [2], has also been observed in [4]. However, the roles of these factors in PIM production has so far received no consistent analysis which would allow for the identification of the origins and mechanisms of PIM generation in PCB materials.

In order to address these issues and develop the phenomenology of PIM generation on PCB material it is essential to first devise a means for reliable repeatable PIM measurement, data acquisition and analysis. The recently developed non-linear transmission line (NTL) model with distributed nonlinearity, [6] and [7], has proven to be instrumental for qualitative interpretation of the experimental results obtained for third-order PIM (PIM3) products.

However the basic assumptions of this physical model and its limitations still required experimental validation. Therefore an objective of our study was to set up targeted experiments for consistent measurements of PIM3 products on the printed microstrip lines, which could allow us to discriminate effects of the structure and laminate material parameters on PIM performance and mechanisms of PIM generation in PCB.

In this paper, we report the results of the first comprehensive experimental study of PIM3 generation on printed microstrip lines specially designed to identify contributions of the material and geometrical parameters to PIM performance of PCB. The main aspects of PIM measurement methodology, test setup and data analysis are presented in Section II. In Section III the results of PIM measurements of microstrip transmission lines are discussed in detail in order to elucidate the effects of the printed line parameters on PIM3 generation. The main findings are summarised in Conclusions.

II. Design of Experiments

A. Measurement setup

The test setup is based on the Summitek SI-900B, SI-1800B and SI-2000B (E) PIM analysers, [8], which supply two-tone signal (two CW carriers) to the device under test (DUT) and monitor forward (signals travelling in the same direction as the carriers) and reverse (signal flowing in the direction opposite to the carriers) power at the intermodulation frequencies which fall within the reception band of the

Manuscript received …. This work is supported by the UK Engineering and Physical Science Research Council under Grant EP/C00065X/1.

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instrument. Magnitudes of the forward and reverse PIM3 products are measured either at a spot frequency (versus time) or in a frequency sweep of one tone at a time. In the latter case the PIM3 frequency equal to $f_{PIM3}=2f_1-f_2$ ($f_1<f_2$) is varied in one of the following two ways:

(i) The carrier frequency f_1 is fixed at its lowest value while f_2 is swept downward from its maximum value (referred to as 'DOWN').

(ii) The carrier frequency f_2 is fixed at its maximum value and f_1 is swept upward from its lowest value (referred to as 'UP').

In order to ensure a meaningful comparison between test specimens the full test setup is first calibrated for the residual PIM3 level without a DUT being present. This provides the reference PIM3 level of the test instrument with its cable assemblies. Additionally the uncertainty of the test setup is monitored through repetitive measurement cycles (up to five) of disconnecting and reconnecting the DUT.

The results of the measurements have been averaged over the swept frequency band (910-915MHz in GSM 900 band) and the series of reconnections. This allowed us to alleviate the effect of intrinsic noise of the test setup itself, which could be commensurate with PIM3 level in high quality (low PIM) PCB laminates. Thus throughout the rest of this paper the mean values of the PIM3 products are adopted as representative quantities for consistent evaluation of specimen performance. The validity of such an analysis of the measurement data has been confirmed by the following observations:

(i)PIM3 products at spot frequencies demonstrated noticeable time variations while their median consistently remained within narrow uncertainty margins.

(ii)PIM3 frequency dependencies sometimes exhibited random kinks, especially in reverse PIM3 response. Occasionally a peak appeared in the place of dip after minor changes in the sample assembly or as the result of drift of instantaneous residual PIM3 level. These adverse effects of the instrumental instabilities are grossly suppressed the results of averaging.

Finally it is important to note that instrument uncertainties strongly affect measurements at the level close to the residual PIM level [8]. However, our extensive study has shown that even in this situation when the instantaneous PIM3 products had greater variations, the averaged PIM3 characteristics consistently display the distinctive trends of PIM generation in the test specimens.

B. *Sample design and preparation*

Sample microstrip lines (Fig. 1) have been specially designed to explore the effects of trace geometry and substrate material composition on PIM3 generation. In order to evaluate the impact of manufacturing factors and tolerances, two or three replicas of the traces were fabricated for each test. The following specimens of microstrip lines were manufactured and tested:

(i) Doublets of uniform meandered 50Ω lines of different *lengths* on woven glass reinforced PTFE substrate (thickness 1.58mm, dielectric constant DK=2.5 and dissipation factor Df=0.0019). The conductor traces of width 4.32mm had lengths 917mm, 1828mm, and 2736mm (Fig. 1a, Boards 1, 2).

(ii) Triplets of 917mm long straight lines of different *widths* matched to 50Ω input/output (Fig. 1b, Boards 3, 4) were made of the same material as the Boards 1, 2: the uniform central sections of length 522mm had widths 13.46mm, 9.14mm, 2.29mm, and 4.32mm (straight uniform 50Ω microstrip line).

(iii) Triplets of straight uniform 50Ω lines of length 915mm on the substrates of thickness 0.76mm with different *laminate compositions* as specified in Table 1 (Fig. 1c, Boards 5-10).

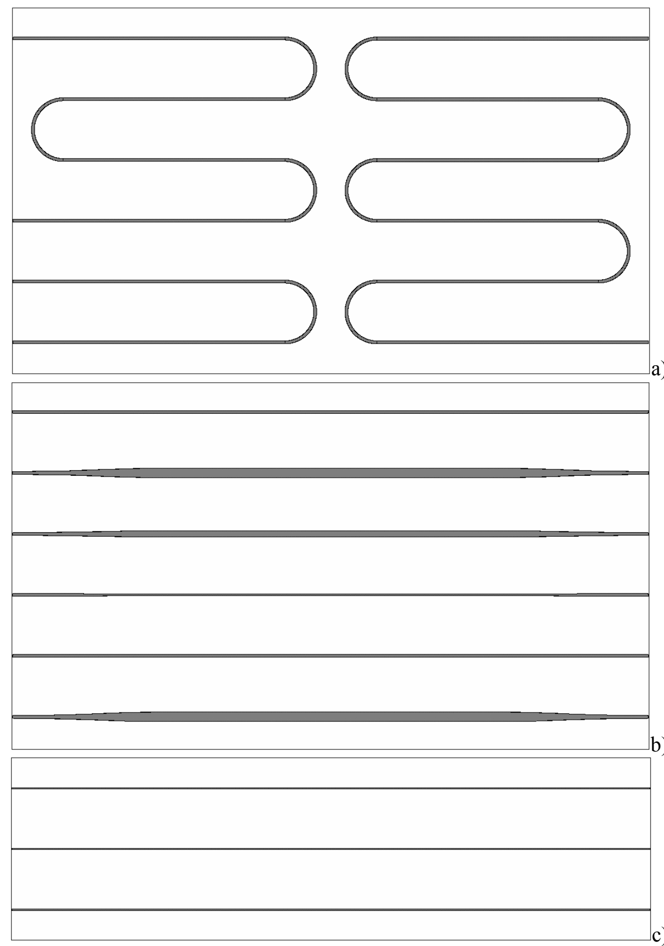


Fig. 1. Plan view of the board with printed microstrip traces: a) uniform meandered lines (Boards 1, 2); b) traces with different width (Boards 3, 4); c) straight uniform lines for PIM3 characterisation of different PCB laminate compositions (Boards 5 - 10).

In order to prevent environmental oxidation of the copper foils, all conductors were coated by applying a 1um thick layer of immersion tin plating which according to [9] should provide good PIM3 performance.

Earlier studies often showed significant variations of PIM3 performance of printed lines on substrates with identical specifications but made of different raw materials and in different fabrication processes, e.g. [4]. To minimise such uncertainties, our test samples were produced in the controlled manufacturing processes. Namely, the same laminate composition and copper cladding were used for all Boards 1-4. All laminates except Board 5 used the same grade of low profile reverse treated copper foil of thickness 35μm with metallic zinc-free anti-tarnish coating. The foil used for Board 5 had the same thickness but came from different supplier. Etching and plating were performed by the same commercial PCB processing house. Boards 5-10 (substrate thickness 0.76mm) were processed in one batch, while Boards 1-4 (substrate thickness 1.58mm) were made in another batch.

TABLE I
PCB LAMINATES FOR THE COMPARATIVE STUDY

Board No.	Composition	DK	Df	Moisture Absorption %	Copper Cladding
5*	Cured resin-impregnated woven glass	3.00 (a)	0.0034 (a)	0.8	35um*
6	PTFE/ woven glass	3.00 (a)	0.0030 (a)	<0.02	35um
7	BT epoxy/ ceramic/ woven glass	3.00 (a)	0.0026 (a)	<0.16	35um
8	PTFE/ceramic/ woven glass	3.00 (b)	0.0014 (b)	<0.02	35um
9	PTFE/ woven glass	2.17 (a)	0.0009 (a)	<0.02	35um
10	PTFE/ woven glass	2.5 (a)	0.0019 (a)	<0.02	35um

(a) as measured at 10GHz;
(b) as measured at 1.9GHz;
* different supplier of raw copper foil and laminate

C. *Microstrip Launchers*

Low-PIM launchers represent one of the critical elements of any test setup specifically designed for the study of PIM generation in PCB laminates. In [10] and in Section III-D below it was shown that input/output matching of the printed microstrip lines had significant impact on the PIM3 response of the transmission lines. Indeed high quality coaxial-to-microstrip transitions are expected to provide better test conditions and reduce inhomogeneity of power distribution along the traces caused by standing waves. Therefore launchers with Return Loss (RL) less than -20dB over a wide frequency range have been specially designed for our measurements (broadband matching was essential for measuring the same test samples in the different frequency bands).

In order to examine the impact of launchers on PIM3 generation, RL was measured first for the two types of coaxial-to-microstrip transitions fitted onto Boards 5-8 (Fig. 2):

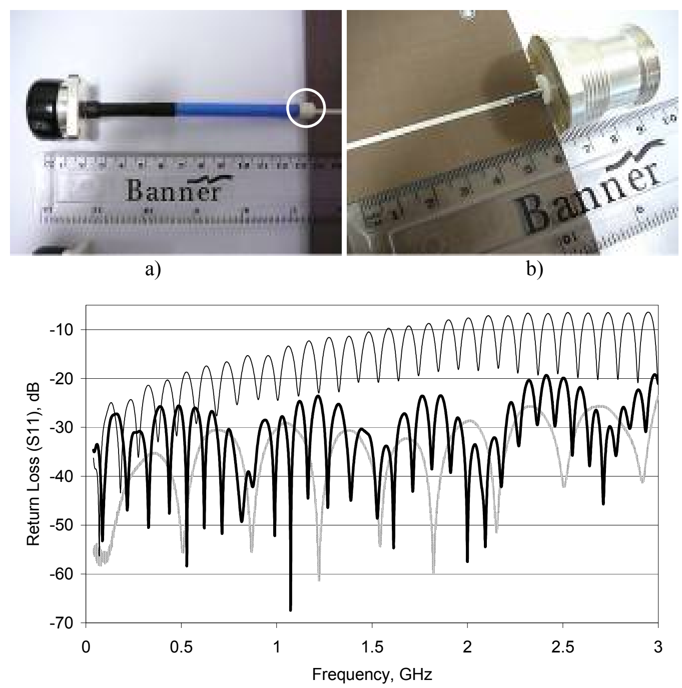
(i) Direct cable launchers (DCL), Fig. 2a, were made from the PIM3 certified Rosenberger cable assemblies comprised of 0.25″ semi-rigid cable of length 250mm with DIN 7/16 flange-mount connectors at the ends. The cable assemblies were cut in the middle and fitted at the PCB edges using the newly designed coaxial-to-microstrip transition units (see the encircled feature in Fig. 2a).

(ii) DIN 7/16 Edge-mount launchers (EML) fitted directly at the PCB edges, Fig. 2b (EML intended for 1.58mm boards were used on 0.76mm substrates).

The DCLs exhibited superior performance than the EMLs: RL less than -25dB in GSM 900 band (890-960MHz), and -20dB in DCS 1800 (1710-1880MHz) and UMTS (1920-2170MHz) frequency bands. Therefore DCLs were also used on Boards 1-4.

Finally it is necessary to mention that this study was carried out with high performance PCB materials certified by manufacturers as low-PIM laminates. Consequently PIM characterisation of such materials presents enormous challenges due to the limitations in the sensitivity of the available test instruments (typically better than -125dBm over 90% of intermodulation frequency band) and the complexity of discriminating PIM products generated by the printed traces, connectors and the test setup itself.

In the next Section, we demonstrate that thorough design of the experiment and analysis of the measurement data permits the consistent evaluation of PIM products in such high quality PCB materials.



c)

Fig. 2. Comparison of two types of board launchers: (a) – direct cable launcher, (b) – edge-mount DIN7/16 launcher; and (c) - typical RL measured on Board 7 (bold solid line – direct cable launcher, thin solid line – edge-mount connector, dotted line – the original cable assembly).

III. EXPERIMENTAL RESULTS AND DISCUSSION

The test specimens described in Section II have been designed for the experiments targeted at the identification of the principal mechanisms responsible for PIM generation on microstrip printed lines and to distinguish the contributions of the line structure and the material parameters to PIM performance of PCB. In this section the results of PIM3 measurements are discussed in the context of these aims.

All measurements were carried out in an anechoic chamber.

A tap test was performed after each reassembly to ensure that no mechanical faults (e.g. loose connectors, dry joints, etc.) would cause excessive PIM generation. Sometimes during the measurements we observed carrier(s) power drift ±0.5dB, whereupon the PIM3 products of the DUT fell 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.

A. Cumulative Effect

Distributed weak nonlinearity has been perceived as a primary cause of PIM generation on printed lines. Based on this concept, the theoretical model developed in [7] has predicted cumulative growth of PIM3 products with line length. In order to verify this conjecture, the effect of *length* of the uniform 50Ω microstrip line on PIM3 response was studied first. Forward 'UP' PIM3 products measured on the two "identical" boards with the same trace geometries (Fig. 1a) are shown in Fig. 3 with quantities averaged over the frequency band and over a series of 3-5 reconnections. The values at zero line length correspond to the residual PIM3 level of the test setup, calibrated before the measurements of each board as described earlier. Error bars delimit deviations in each series of reconnections.

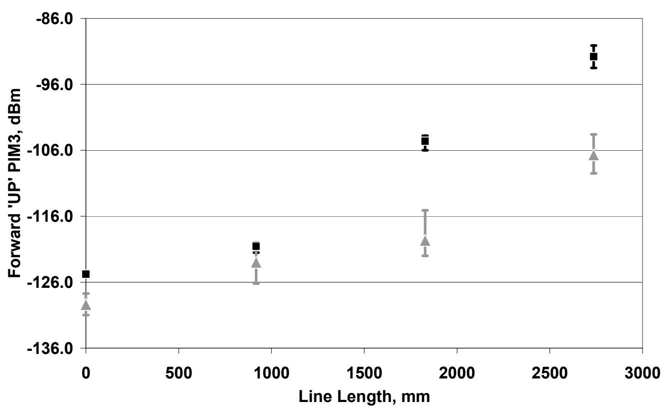


Fig. 3. Forward PIM3 vs. line length at 2×43dBm carrier power in GSM 900 band averaged over the swept frequency band 910-915MHz: black squares – samples on the Board 1; grey triangles – samples on the Board 2.

The results in Fig. 3 demonstrate several important features of the measured PIM3 products:

(i) The magnitude of the forward PIM3 monotonically increases on the longer traces, thus providing evidence of the cumulative growth of PIM3 products along the line.

(ii) The rate of PIM3 growth differs for the two boards.

(iii) The difference between PIM3 products measured on the 917mm long lines is nearly equal to the difference between the residual levels in the two tests; however it noticeably increases on the longer traces.

Even though much care was taken to make the test specimens identical (the same raw materials and processing batch), their PIM3 responses were dissimilar. Indeed, while intensification of PIM3 products with trace length is evident in Fig. 3 for both boards, their growth rates were noticeably different. This discrepancy can hardly be attributed to effect of launchers because it was consistently observed for all line lengths, and each trace had its own set of launchers. Thus, these results indicate that minor imperfections of the PCB board itself, board processing and assembly may affect PIM3 performance, and these defects can be detected by simple comparative tests.

Forward PIM3 products in the 'DOWN' frequency sweep exhibited the same qualitative dependence on the line length, while their magnitudes were slightly different. This discrepancy can be attributed to dissimilar matching conditions at the different carrier frequencies in "UP" and "DOWN" sweeps (cf. RL in Fig. 2) that generate PIM3 products at the same frequency.

Reverse PIM3 products in these tests showed no visible intensification with the line length and were below the forward PIM3 level. This suggests that reverse PIM3 products are predominantly generated nearby the input of the matched line.

It is noteworthy that despite a steady increase of forward PIM3 magnitude with line length in Fig. 3, PIM3 does not grow indefinitely. On sufficiently long lines attenuation of the carriers may exceed the rate of PIM3 generation. This results in decrease of forward PIM3 products. This fundamental limitation has been known in the theory of travelling-wave harmonic generators, cf. [11], and is also consistent with the predictions of the NTL model with distributed nonlinearity [7].

The cumulative effect has been observed in the DCS 1800 frequency band for forward PIM3 products measured on Board 1. Again, PIM3 products grew nearly linear with line length but a slope of the linear regression ~5.2dB/m was smaller than that obtained in GSM 900 band (~15.8dB/m) at 2×43dBm carriers being averaged over the frequency band 910-915MHz. Thus the same qualitative trends of monotonic growth of forward PIM3 products on the longer lines have been consistently observed in both cases. The discrepancy between PIM3 response in the GSM and DCS bands is attributed to the use of dissimilar direct cable launchers with different RL (see subsection D below).

Thus the measurements of PIM3 products versus line length provide clear evidence for the cumulative intensification of PIM3 products on printed lines [13] and support the phenomenology of NTL-model with distributed nonlinearity.

B. Effect of Line Width

Effect of line width variation on PIM3 product generation is difficult to evaluate independently because it is accompanied by impedance change and subsequent line mismatch. Two options had been considered to address this issue:

(i) Modification of the substrate parameters to compensate the line width variations and maintain 50Ω impedance [3], or

(ii) Use of tapered impedance transformers to match 50Ω input and output ports to the central segment of a uniform line with modified width.

The latter approach has been adopted in this work because it allowed lines of different widths to be fabricated and measured on the same board (Fig. 1b) thus excluding the effect of dissimilar substrates on PIM generation. The drawback of this approach was that the matching transformers could introduce additional uncertainty into the PIM3 measurements.

The results of the PIM3 measurements in the GSM 900 frequency band are shown in Fig. 4 for the matched traces on Boards 3 and 4 (see layout in Fig. 1b). The data points in Fig. 4 represent quantities averaged over frequency and sample line triplets (residual forward and reverse PIM3 levels were below -120.4 dBm and -121.6dBm, respectively in these tests). Error bars delimit deviations of the measurement data in each group of specimens with the same strip width.

The average magnitudes of forward PIM3 products in Fig. 4 exhibit monotonic decrease with line width. This observation correlates well with the prediction of the NTL model based on the assumption of a current-driven distributed nonlinearity [7]. Indeed, assuming the smaller current density on wider strips, it is reasonable to expect lower PIM3 level to be generated by the nonlinear resistance of the printed traces. Such a mechanism has also been discussed in [3] on the basis of experimental results for microstrip lines with different substrate materials.

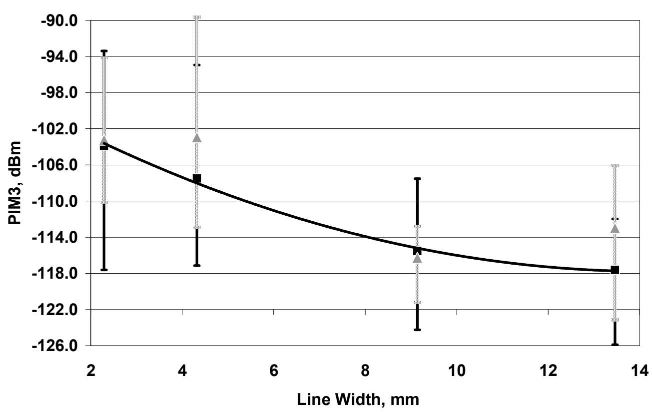


Fig. 4. Forward ‘UP’ (black squares) and reverse ‘UP’ (grey triangles) PIM3 vs. the microstrip line width in GSM 900 frequency band.

The reverse PIM3 products in Fig. 4 show little correlation with line width. Such behaviour is attributed to the impact of the weakly reflecting matching transformers. However, as shown in [7] and [10], even small reflection can noticeably change the reverse PIM3 response and therefore completely obscure the effect of line width.

Finally, it is necessary to remark that PIM3 measurements on the lines of different widths proved to be more sensitive to tolerances and constructional workmanship, and exhibit higher uncertainty. Nevertheless, the obtained results have consistently demonstrated the qualitative trend that forward PIM3 products are lower on microstrip lines with wider strips. This provides further evidence in support of the conjecture that the PIM generation mechanism is based upon a current-driven distributed nonlinearity.

C. *Effect of Dielectric Substrate*

The effect of the laminate composition on PIM3 performance of the printed lines has been examined using straight uniform 50Ω microstrip lines fabricated on Boards 5-10 (cf. Table I). The measurement results for the GSM 900, DCS 1800 and UMTS 1900 frequency bands are presented in Fig. 5 for forward ‘DOWN’ PIM3 response averaged over frequency sweeps and the sample triplets. Since effect of substrate losses on PIM3 generation has been of particular interest, the data is plotted versus Df, as specified by the PCB manufacturers for the respective substrate materials (Df=0 corresponds to the residual PIM3 level of the test instrument).

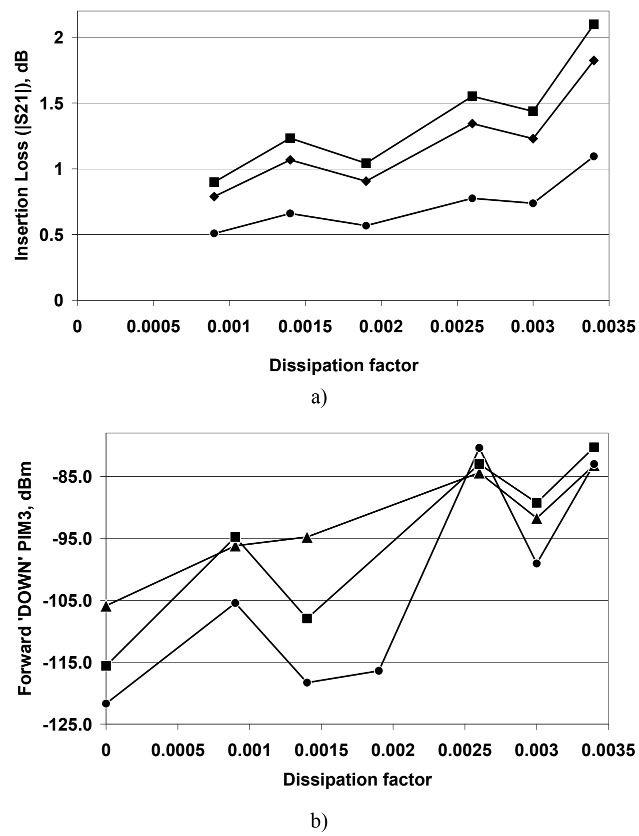


Fig. 5. Insertion loss (|S21|) (a) and forward ‘DOWN’ PIM3 (b) at 2×43 input power in GSM 900 (dots), DCS 1800 (squares) and UMTS 1900 (triangles) bands vs. dielectric dissipation factors of the substrates specified in Table 1.

Although a general trend of the increased PIM3 level on the boards with higher Df and DK can be inferred from Fig. 5, no direct correlation between PIM3 magnitude and the substrate Df has been observed. Apparently, various ingredients of the laminate compositions such as glass reinforcement, bonding layers, impregnation, etc. have both direct and indirect impact on PIM3 products. The former is inflicted by nonlinearity of substrate itself, while the latter is essentially a linear effect of carrier attenuation due to dielectric losses. However, contributions of particular ingredients of the laminates into these mechanisms are difficult to discriminate in measurements of the scattering parameters only. Nevertheless, it is interesting to note that Boards 5 and 7, which contain cured resin impregnation and BT epoxy, respectively, have higher moisture absorption rate and exhibit higher PIM3 level than the boards with PTFE impregnation.

It is noteworthy that both nonlinearity and losses of dielectric substrate affect PIM3 generation on microstrip lines. However comparison of linear Insertion Loss (IL) in Fig. 5a and PIM3 products in Fig. 5b shows that while IL steadily increase with Df, PIM3 products do not follow this trend. This implies that for the tested laminates, dielectric losses represent a secondary effect on PIM3 generation. A more detailed account of the laminate composition contribution to PIM3 performance of printed lines involves further material studies and model refinement, both of which are beyond the scope of this paper.

TABLE II
MEASURED EFFECT OF THE DIELECTRIC PARAMETERS AT 910MHZ WITH 2×43dBm CARRIERS

Board No.	DK	Df	Forward PIM3, dBm	Reverse PIM3, dBm
9	2.17	0.0009	-104.8	-122.3
10	2.5	0.0019	-115.7	-126.2
6	3.0	0.0030	-97.7	-126.5

The results of PIM3 measurements on Boards 6, 9 and 10 with a similar composition are summarised in Table II. In contrast to other substrates, these laminates do not contain any filler or epoxy, and their main differences consist in the grade of the glass reinforcement and bonding layers only. Despite the similarity in the substrates' construction and constituent materials, no explicit correlation was observed between variations of forward PIM3 and DK/Df, whilst reverse PIM3 level remained practically unchanged[1]. Again this suggests that weak intrinsic nonlinearity of the dielectric substrates is responsible for variations in PIM3 performance of the measured laminates.

D. *Effect of Line Matching*

Effect of matching on PIM3 generation by microstrip lines has been explored with the two different types of launchers shown in Fig. 2. The measurement results in UMTS band, summarised in Table III, demonstrate that the specimens with edge-mount connectors typically had reverse PIM3 products ~5-10dB higher than the samples with direct cable launchers. In the meantime, forward PIM3 products remained nearly the same for both types of launchers. Such impact of load mismatch on PIM3 products is fully consistent with the predictions of the NTL model and simulation results in [10].

As shown in [10], load mismatch stronger affects reverse PIM3 response, whilst its level is always lower than forward PIM3 products. This is exactly what was observed in our measurements and it is consistent with other experimental results discussed above.

TABLE III
EFFECT OF THE BOARD LAUNCHERS IN UMTS BAND

Board No.	Direct Cable Launchers		Edge-Mount 7/16 Launchers	
	Forward 'DOWN' PIM3, dBm	Reverse 'DOWN' PIM3, dBm	Forward 'DOWN' PIM3, dBm	Reverse 'DOWN' PIM3, dBm
5	-83.2	-98	-82.1	-86.1
6	-91.8	-108.7	-90.2	-95
7	-84.4	-104.4	-85.8	-99.1
8	-94.8	-102.5	-89.9	-91.5

Nevertheless, it is necessary to mention that on several occasions we did observe reverse PIM3 higher than forward PIM3 products. In these cases, the measurement results were found to be erratic and unrepeatable. Therefore we have attributed such performance of the "odd" test specimens to detrimental effects of trace defects, poor assembly or damaged launchers, which could act as the localised PIM sources.

Thus on the basis of our observations, we can conclude that good matching is a prerequisite for reliable and consistent characterisation of PIM3 performance. More detailed study of matching effect on PIM3 generation would require PIM3 certified tuneable high-power loads, but the design of such terminations is a challenge in its own right.

E. *Effect of Carrier Power*

The dependence of PIM3 products on the carrier power following from the basic NTL model [7] is represented by a straight line with a slope 3:1 (3rd order nonlinearity), irrespectively of the line length, width and substrate parameters. However, in practical measurements we have observed that this dependence significantly deviates from the ideal case as illustrated in Fig. 6, Fig. 7. In particular, saturation of the power curves at the higher input power occurs, as shown in Fig. 6. This type of power curves is known and associated with the higher-order nonlinearities [14].

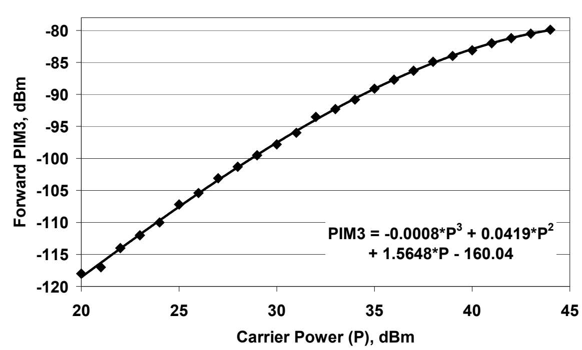


Fig. 6. Forward PIM3 dependence on the carrier power for a microstrip line on the Board 7 at 910MHz PIM3 frequency (PIM3 measurements in time)

Fig. 7 illustrates forward PIM3 products versus carrier power for the lines on Boards 1, 2. The curve slopes here are less than 3:1 for Board 1 and greater than 3:1 for Board 2. These slopes also differ for the "identical" traces on the two

[1] Very low level and small variations of reverse PIM3 products in Table II indicate that they are commensurate with the background PIM3 level of the entire test setup. This sensitivity floor is determined not only by the reverse residual PIM3 level of the instrument itself (measured at -132dBm), but also by launches and connectors used.

boards and for traces of several lengths on each board. Such variations of the power curve slopes suggest that the parameter of nonlinearity varies from the specimen to specimen. This implies that the growth rate of PIM3 products with line length may also alter with carrier power that could lead even to lower PIM3 level on longer traces when measured at different levels of input power. It is important to emphasise that such results do not contradict to the cumulative effect described in Section III.A, but rather indicate that PIM3 characteristics retrieved from the measurements of lines of several different lengths may not represent the actual PIM3 distribution on a single long transmission line.

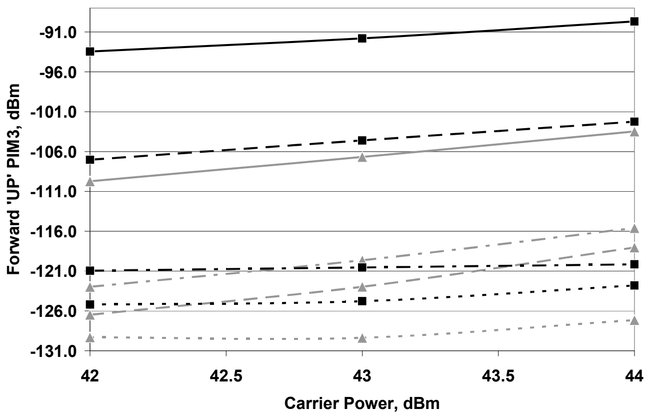


Fig. 7. Forward 'UP' PIM3 dependence on carrier power in GSM 900 band. Black squares – Board 1: dotted line – residual PIM3 (SLOPE=1.19:1); dash – 917mm (SLOPE=0.40:1); dash-dot – 1828mm (SLOPE=2.39:1); solid – 2736mm (SLOPE=1.89:1). Grey triangles – Board 2: dotted line – residual PIM3 (SLOPE=1.08:1); dash – 917mm (SLOPE=4.22:1); dash-dot – 1828mm (SLOPE=3.13:1); solid – 2736mm (SLOPE=3.69:1).

It is interesting to note that the slope of the *residual* PIM3 in Fig. 7 is close to 1:1, and thus PIM3 response of the test setup itself cannot be described by a simple model of an "ideal" lumped nonlinearity of the third order. Moreover it is necessary to note that any weak intrinsic nonlinearity of DUT may significantly differ from the nonlinearity of the test setup, so that in actual measurements of the former can be obscured by the latter.

IV. Conclusions

The targeted experiments have been devised to identify mechanisms of PIM generation on printed microstrip lines and elucidate effects of the structure and material parameters on PIM3 performance. Due to high susceptibility of the measurements to sample quality and fabrication workmanship, several replicas of each line have been fabricated in the same batch of the controlled manufacturing processes. Study of the effect of dielectric substrate proved to be laborious, because it required representative sampling of the specially selected laminates. Special launchers with low RL (below -20dB) over a broad frequency range have been designed to provide the high quality matching of the specimens with the test instruments.

In the series of experimental measurements the effects of trace length and width, and substrate material on PIM3 generation in microstrip transmission lines have been explored. It has been shown that

(i) the magnitude of forward PIM3 monotonically increases with line length thus providing evidence of the cumulative growth of PIM3 products along the line that is caused by the distributed nonlinearity of printed traces;

(ii) reverse PIM3 products are normally below forward PIM3 level and show no visible intensification with line length, but they are stronger affected by input/output mismatch;

(iii) the average magnitudes of forward PIM3 products exhibit monotonic decrease with line width that is consistent with the prediction of the NTL model based on the current-driven distributed nonlinearity [7];

(iv) for the tested laminates no consistent correlation has been observed between PIM3 products and the parameters DK and Df of dielectric substrates; a more detailed material study is required in order to further explore the contribution of laminate composition to the PCB PIM3 performance;

(v) input/output matching significantly affects generation of reverse PIM3 products, viz. edge-mount connectors typically show reverse PIM3 levels that are ~5-10dB higher than direct cable launchers, whilst the level of forward PIM3 products remains nearly the same for both types of launchers.

The observed effects of trace dimensions on the PIM3 performance of the microstrip lines with low intrinsic PIM level are comprehensively described by the NTL-model with distributed current-driven nonlinearity [7]. While the NTL-model adequately predicts the effects of trace geometry and line mismatch on the PIM3 response, it employs an extrinsic parameter of nonlinearity which ideally should be determined from independent measurements (currently it is a single fitting parameter of the model).

In order to explore the type of nonlinearity on printed lines, the rate of PIM3 growth with carrier power has been measured. The measurement results presented have shown that PIM3 products significantly deviate from the 'ideal' cubic law and vary from sample to sample. These observations suggest that further study is necessary to determine the causes of such behaviour and to evaluate the combined effects of line geometry, dielectric substrate, localised discontinuities, material defects, and launchers on the type of nonlinearity responsible for PIM generation.

The presented study of PIM generation on printed lines has been based on indirect measurements (multiple samples of different length and shape). Alternatively, near-field probing can be employed to map PIM product distributions on the printed traces. This approach has recently been implemented [15] and fully confirmed the cumulative growth of forward PIM3 products on microstrip transmission lines. Nevertheless, it should be noted that near-field probing on low-PIM laminates and short transmission lines is limited by the sensitivity of the available PIM-analysers and the requirements of weak coupling of the probe (typically <-35dB). Thus, the approach of indirect PIM measurements presented in this paper currently provides the only practical way for investigation of PIM phenomena in the high performance PCB materials with low nonlinearity.

ACKNOWLEDGMENTS

Authors are grateful to Taconic Advanced Dielectric Division Ltd, Trackwise Designs Ltd, Racal Antennas Ltd, PCTEL Inc and Castle Microwave Ltd for their generous help with preparation of test samples and providing measurement facilities. Special thanks go to Mr. Jim Francey from Taconic for numerous discussions and support. The authors much appreciate helpful suggestions from Dr. David Linton, Queen's University of Belfast over the period of this work.

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