Practical Fixture Design for Passive Intermodulation Tests for Flexible Metallic Contacts

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Abstract*—Passive intermodulation (PIM) commonly exists in non-ideal metallic contacts. Since PIM typically represents an extremely low level of nonlinearity, it has not drawn enough attention over the years except for extremely high-power applications such as base stations. However, in recent years, the study on PIM has become essential in universally used consumer electronics design because of the higher requirement on the radio frequency (RF) sensitivity of wireless communications. The metal contacts caused PIM can create the sideband spectrum to interfere with the receiving band in the frequency divide duplex (FDD) mode. Therefore, the study on PIM for the frequently used flexible metallic components is important in the industry. The PIM characterizations for the flexible components at least demand the compression variability and the capability to inject high-power signals while monitoring the sideband spectrum. It is preferred to have the access to measuring more relevant quantities. This paper aims to summarize the practical experience in designing a high-dynamic range and multi-purpose applicable test setup for characterizing PIM in the flexible components. Capabilities to precisely measure/control PIM, gap variability, tilted angle variability, and DC resistance (DCR) are presented with measurement examples.

Keywords*— *passive intermodulation, radio-frequency interference, spring component, fabric over foam, desense, two-tone test.

I. Introduction

Non-ideal metallic contacts due to oxidization, corrosion or material properties may cause nonlinear behaviors in electrical applications [1]. When there exist multiple frequencies on the non-ideal contacts, the nonlinearity can cause intermodulation on the frequencies and create new frequency components. This nonlinearity caused by passive components is called passive intermodulation (PIM). PIM has been studied for decades because the generated new frequencies may affect the performance in the high-power frequency divide duplex (FDD) applications such as base stations. In recent years, PIM has become more important driven by the rapid development of consumers' electronic devices. Modules need to have electrical connections to the chassis ground through flexible components. It has been found that the flexible components used for electrical contacts may also cause PIM to undermine the radio frequency (RF) antennas' receiving sensitivity (desense). The contacts between the flexible components to the aluminum alloy chassis can generate PIM because of the oxide on the aluminum alloy surface. In addition, variation in the manufacturing process increases the chance to make the contact quality worse.

There are some related works on studying the PIM generated by the flexible components such as springs. Using a controllable system to observe PIM and spring structure change during the movement, it has been found that the structure design affects PIM [2]. Besides, a measurement system with the capability to measure several related quantities such as contact force, gap, and DC resistance simultaneously, a sufficient amount of data can be obtained for statistical analysis to figure out the correlations between those quantities, even if PIM is very unstable [3]. Researchers have summarized several typical mechanisms for causing PIM and the dominant mechanism can be differentiated by measuring the regrowth rate of the output/input power [4], which requires a measurement setup capable of a large RF power range. As for the behavior model for PIM, a typical method is to use a physics-based equivalent circuit model to mimic the non-ideal contact area as non-contact, good contact, and PIM generation contact [5]. There are also some great efforts made on identifications or localization of the PIM sources [6][7].

However, due to the unstableness and poor repeatability properties of PIM, it is more difficult to accurately characterize a tiny metallic contact than the standard RF devices or accessories. Also, the PIM levels, using the third-order inter-product (IP3) under two-tone injections as the representation as an example, are typically more than 100 dBc to the carriers. In other words, the PIM signals are extremely weak, which makes the measurement even more challenging. Nowadays commercial PIM testers have the capability for high-power applications (>43 dBm) but lack the feasibility to enable a proper setup for testing tiny and flexible components. Thus, the PIM characterization system design should at least have control on the gap variability for compression movement to test the flexible contacts caused PIM. It is preferred to have high-precision controls to reduce the variations of contact PIM. There are optional capabilities such as the controls in tilted angle variability and the change of the contact locations. Also, monitoring necessary quantities besides PIM such as the contact force/pressure, the DC resistance (DCR), the gap, etc. is

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essential. Besides, having a high measurement dynamic range to correctly measure the weak signals is also important.

This paper focuses on the design of a practical PIM measurement setup for industrial flexible and small components. It is designed to be a duplexer-based two-tone test system. The RF signal paths are explained to help understand the design and why the improvements worked. Important experiences and details are summarized to help future researchers to build similar measurement setups more easily. The basic concepts of the two-tone test system and fixture design are explained. The performances of basic and add-on capabilities are shown with measured data.

II. PIM Measurement Setup Design

A. The Duplexer-based Two-tone Test System

The nonlinear distortion due to PIM is typically too small to be captured in the time domain but can be resolved in the frequency domain in a proper measurement setup. The key point in the study of PIM is to quantify the nonlinear level of the contact and the third-order inter-product (IP3) in a two-tone injection test is the most used quantity to represent nonlinearity because it has the highest amplitude except for the carriers. Therefore, PIM measurement setup usually adopts the method of injecting two-tone signals into the device under test (DUT) and observing the IP3.

As Fig. 1 (a) shows, this diagram describes the wirings between the instruments, devices, and DUT. The two sinusoidal waves are within the TX frequency range of the duplexer and the generated IP3 will be within the RX range of the duplexer so it can be measured by the spectrum analyzer. Fig. 1 (b) shows the actual setup. The test fixture movement, measured data recording, and instrument settings can all be automatically controlled by the PC. It needs to be emphasized that automation is important for PIM measurement due to its high sensitivity to vibrations. To obtain a better resolution in measured data, high precision mechanical control is also needed. Besides, massive repeatability tests are required because PIM sometimes has large variations due to the unstable behavior, thus it can only be analyzed statistically which requires a great amount of data. All the factors mentioned above urge that automation is strongly suggested in PIM measurement.

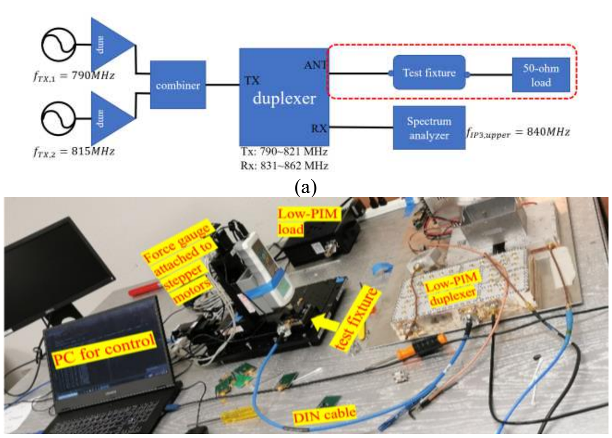


Fig. 1. The duplexer-based PIM measurement system: (a) connection diagram (b) the actual setup

The reason to use a duplexer in the system is to avoid saturation in spectrum measurement. Even if the IP3 has the highest magnitude among all the inter-products, it is still too weak compared to the high-power carriers. The spectrum analyzer won't be able to measure the IP3 when it co-exists with the two-tone because of the saturation of the instrument. By introducing a duplexer, the high-power signals and the weak sideband will be separated as Fig. 2 shows. The high-power two sinusoidal waves under 790 MHz and 815 MHz will inject into (already amplified and combined) the "TX" port of the duplexer, then go out from the "ANT" port to the test fixture (with DUT assembled), and eventually consumed by the dummy load. Therefore, the two-tone signals can hardly propagate from the "RX" port to the spectrum analyzer and thus the saturation problem can be avoided. The test fixture marked in the red dashed rectangle is the PIM source under investigation. More accurately, PIM is generated at the contact point between the flexible component (here the example is a spring clip) and the landing pad marked as the dashed blue rectangle shows. Generated PIM power will propagate equally in both left-going and right-going directions [8] as the red arrows indicate. The right-going IP3 power will be terminated by the load while the left-going wave will go to the spectrum analyzer and be measured.

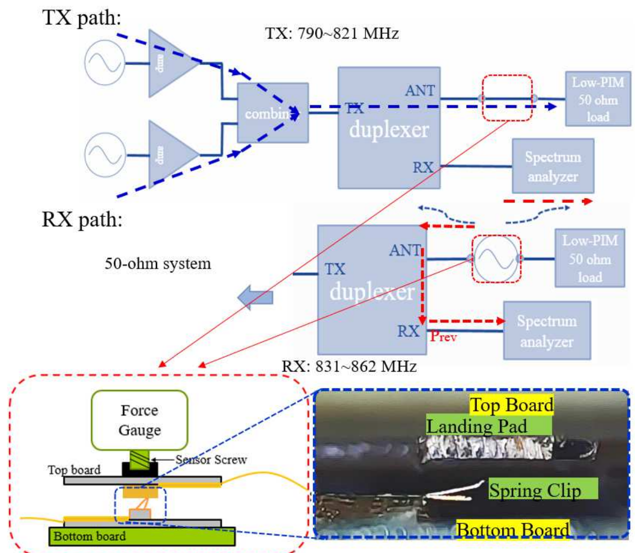


Fig. 2. RF signal flow paths and the zoomed-in design for the contacts

B. Test Fixture Design

As the targeting DUTs are flexible components used for electrical connections, movement is required for the test fixture to enable the compressions on the components. So, the fixture is designed to be two separate pieces facing each other as Fig. 3 (a) shows. The variable gap design between two PCBs originated from the study for harmonic generations [9]. The bottom one is fixed on a stationary platform while the top one is attached to a force gauge which is fixed on the vertical axis and controlled by a stepper motor. Thus, both the height/gap and the compression force can be monitored. Also, as discussed in Part A, the two-tone signals are intended to only propagate towards the dummy load and be terminated, so the test fixture should be a thru structure for RF signals. Therefore, as Fig. 3(b) shows, two microstrip printed circuit boards (PCBs) are used to guide the RF waves in the 50-ohm system.

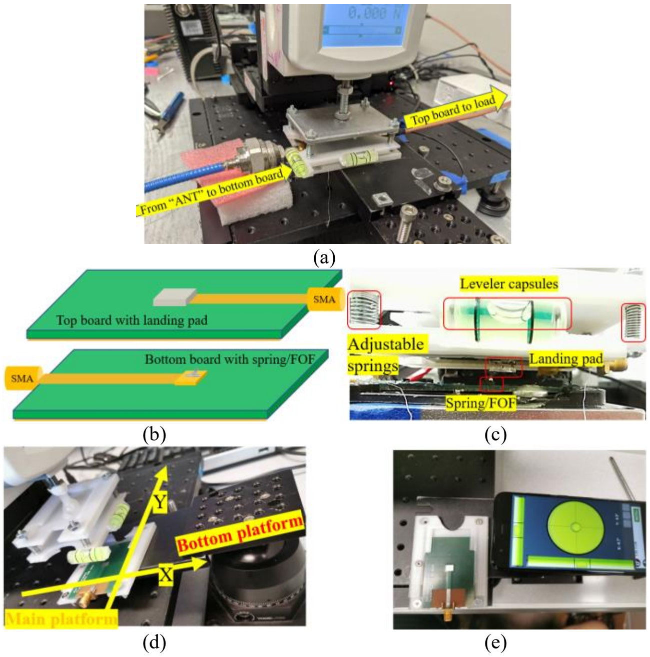


Fig. 3. Detailed test fixture design: (a) overview (b) test boards (c) sideview (d) decoupled platforms (e) level adjustment for the bottom platform.

According to our measurement experience, to achieve a more repeatable PIM measurement, the alignment for the level status is important. Therefore, some extra features have been added as Fig. 3 (c) (d) show. The top PCB is held by a 3D printed holder with two bubble leveler capsules attached perpendicularly and horizontally. There are four screw-spring-nut sets at the four corners of the holder to adjust the level status of the top PCB. The bottom board is held on a separate platform. The other platform is mechanically decoupled to the main platform and will also need to calibrate the level status. As Fig. 3 (e) shows, a mobile app is adopted to use the cellphone sensors for calibrating the level status. Section III Part D will explain the reason for the usage of a separate platform. It is optional to make the bottom PCB stationary on the main platform if a certain test purpose is not required.

Although both PCB microstrip lines are good RF paths for the interested frequency range, when the spring-to-pad contact is made, the RF signals do not necessarily have a good enough path because the two PCBs don't have a shared return plane. In this design, the RF current will find a return path through displacement current. In other words, the "shared" ground is achieved by capacitive coupling between the two face-to-face PCBs. Therefore, a reasonably large size of the PCBs will provide a sufficiently good return path for the RF current. The performance of the two-PCB fixture was checked in both full-wave simulation and measurement. As Fig. 4 (a) shows, the actual geometry was simulated in CST and both measurement (with the add-on features for 4-wire connection, has not mentioned so far but will be discussed in Section III) and simulation results are shown in Fig. 4 (b). The ripples in the measurement are due to the common-mode current because the two PCBs do not have a physically connected ground. Except for that, the insertion loss of this fixture is suitable for the PIM test in the 1 GHz range.

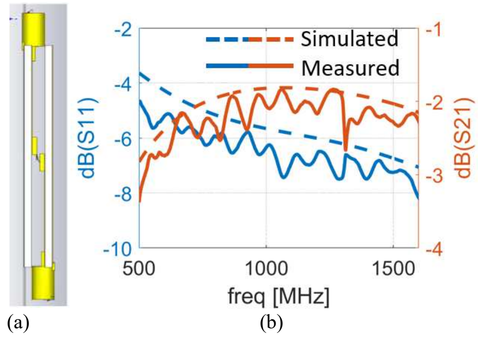


Fig. 4. RF performance of the two-board test fixture: (a). CST simulation model; (b). S-parameters (measurement case with inductors)

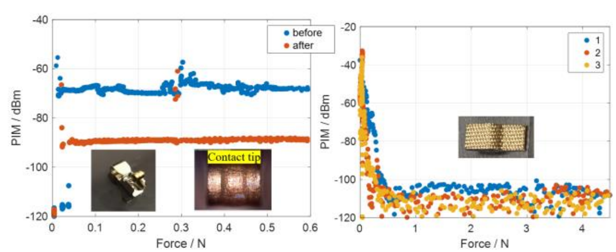
C. *Measurement Dynamic Range Improvement*

The measurement dynamic range is one of the most important specifications for the PIM measurement setup. As PIM has large variations and is extremely weak, some subtle behaviors of PIM can only be captured in a careful design system. The dominant factor that undermines the PIM measurement sensitivity is the unwanted PIM source(s). When the system generated PIM overwhelms the DUT generated PIM, then what is measured in the spectrum analyzer cannot represent the nonlinearity of the DUT. However, due to the expensive price, poor flexibility, heavy weight and large size of the low-PIM cables or accessories, it is costly to replace all RF paths to be low-PIM. Fortunately, not all locations need to be low-PIM. There may exist some nonlinear sources before the two-tone injected into the duplexer, but due to the duplexer's band passing property, any new spectrum created out of the TX band will be blocked. Also, in the "RX" port to spectrum analyzer path, the ordinary SMA cable and connectors may be PIM sources and generate more frequency components, but 840 MHz is the only frequency point to be observed and none of the newly generated frequencies are at 840 MHz. As it has been discussed in Part A, the intended PIM source locates in the contact point of the test fixture, so only the RF path between the "ANT" port of the duplexer and the low-PIM load needs to be taken care of, as Fig. 1(a) red dashed rectangle marked. It can also be noticed that there is an important detail in the setup is that the connection cable between the "ANT" port and the front side of the test fixture is a low-PIM DIN cable as Fig. 1(b) shows.

However, the size of the PCBs (FR-4 substrate) cannot support the DIN connector (due to the large gap between the inner and outer conductors) designs. Also, to maintain the flexibility for the movement of the top board, heavy and rigid DIN cables and connectors are not suitable for mechanical concerns. Furthermore, as discussed in Part B, the capacitive coupled ground will make the PCBs more susceptible to the surrounding environment any nonlinear source nearby may interfere with the RF current flowing capacitively on the boards and generate PIM. To summarize, the unwanted PIM sources in the "ANT" path can be dominantly caused by: a) SMA connection right after the DIN port near the bottom board; b) SMA connection at the top board; c) the flexible coaxial cable from the top board to the load; and d) any non-linear component in the environment.

The selection of the connectors, adaptors, and cables can be done through experiments. A step-by-step "open" load test can be used to quickly check the PIM generation level of the selected item. Namely, the two-tone sources are turned on but to begin with, there is nothing attached at the "ANT" port. Note that when the "ANT" port is left to be open without a load attached, the TX power will be mostly bounced back to the duplexer and then back to the output ports of the combiner and amplifiers. Thus, it is important to limit the injected power level to prevent any damage to the devices. Then connect cables/adaptors/connectors step-by-step and keep watching the measured IP3 level in the spectrum analyzer. Occasionally, the same type of connectors can have more than 10 dB difference in the aspect of PIM generation. To summarize the experience: a) a rule of thumb, for PIM, DIN<N-type<SMA; b) use brass-color SMA rather than steel-color SMA; c) try different surroundings. All the items were selected as the step-by-step "open" tests. It is worth mentioning that we found the force gauge sensor screw attached to the top board was a significant PIM source, so extra spacing has been added between the force gauge and the top board. Similar issues may occur when other researchers want to build a PIM measurement system.

When all the system-introduced PIM sources were identified and suppressed, the sensitivity of the PIM measurement system has been significantly improved as the measured results shown in Fig. 5 (a). For the same spring component, the PIM floor got reduced obviously. In other words, the measured PIM floor before the fix was not the actual PIM generated by contact DUT but by the system. It can be concluded that PIM measurement sensitivity was improved by at least 20 dB since it was unknown that whether the -90 dBm PIM floor was caused dominantly by the system or by the DUT. For the PIM floor, the study provides important information that PIM can be further suppressed by enlarging the contact area [10]. Therefore, using a fabric-over-foam (FOF) component, which has a more than 100 times larger contact area than the spring tip, can help demonstrate the improvement of sensitivity in this case. As Fig. 5 (b) shows, when pressed firmly, the PIM floor is lower than -100 dBm for FOF, so the -90 dBm level in Fig. 5(a) was caused by the spring rather than the system residue PIM.



(a) (b)

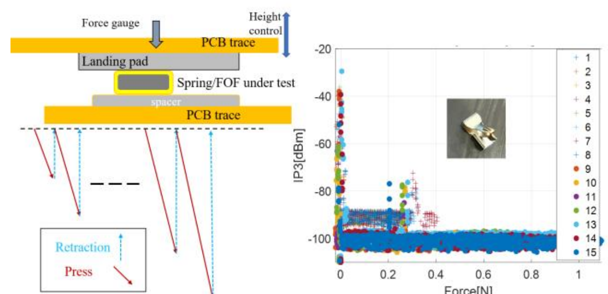
Fig. 5. Improved dynamic range: (a). same spring test data before and after the improvement; (b). FOF test data

III. Add-on Capabilities for Multi-Purpose PIM Measurement

The following sections introduce several add-on features and their applications in PIM measurement.

A. Subtle PIM Change Captured by Measurement

The automatic control has another advantage that the workflow of the tests can be modified accordingly. For example, a threshold can be set in force to stop the current press iteration and retract back to start the next press iteration. Or one can conduct the step-stress tests that the depth of the press will gradually increase over iterations as Fig. 6 (a) describes, so that some subtle changes may occur. An example showed the capability that by using the step-stress test workflow, the spring contact will plastically deform the landing pad metal surface at a force of 0.3N to scratch out the oxide layer and find fresh metal for contact. Then the PIM floor will have a sudden decrease as Fig. 6 (b) shows.

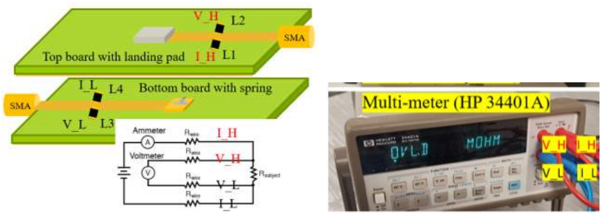


(a) (b)

Fig. 6. Subtle PIM change observed in the step-stress-test workflow: (a). step-stress flow for PIM tests; (b). PIM floor change captured in the measurement

B. Simultaneous PIM-Force-Height-DCR Test

Typically, flexible components caused PIM has a decaying trend under higher pressing force/smaller gap. DCR shows the same trend that with tighter contact, DCR tends to be lower and statistically has a correlation with PIM [3]. Therefore, one useful add-on is the DCR measurement capability. Since the DCR of a metallic contact is usually small in several ohms or milliohm range, 4-wire Kelvin connection is used as Fig. 7 shows. As described in Section II Part B, the height of the top PCB is controlled by the stepper motor. The contact force is monitored by the force gauge. Therefore, a PIM-Force-Height simultaneous measurement has already been enabled. The key point is that the add-on feature should not affect the original RF signal path while providing the access to DC current path. With the four inductors added, of course, the multi-meter has the DC path to the ports of the contact junction. At the same time, the S-parameters of the test fixture before and after the inductors were added should not change. Based on the inductance range and experimental results, the four inductors were selected to at least be able to block the RF signals running at 790~840 MHz range in this two-tone test.



(a) (b)

Fig. 7. 4-wire connection feature: (a). PCBs with 4 inductors for DC path; (b). optional connections: SMU or multi-meter

Give an example of the usage of simultaneously measured DCR as Fig. 8 shows. The measurement data are for a captured-structure spring. The previous study already demonstrated that the self-contact of the spring component can also cause PIM [2]. It can be observed in Fig. 8 (a) that the Force-Height curve has a slope changing point at 0.28 N and 230 um location. And PIM occurred at 0.28 N in Fig. 8(b), which is highly suspicious to be caused by self-contact. The simultaneously measured DCR in Fig. 8(c) can further support that conclusion because there is no DCR change near the 230 um height location. Furthermore, if the repeated tests are conducted and enough data are collected, then statistical analysis can be applied to investigate the feasibility of using DCR for PIM estimations [3].

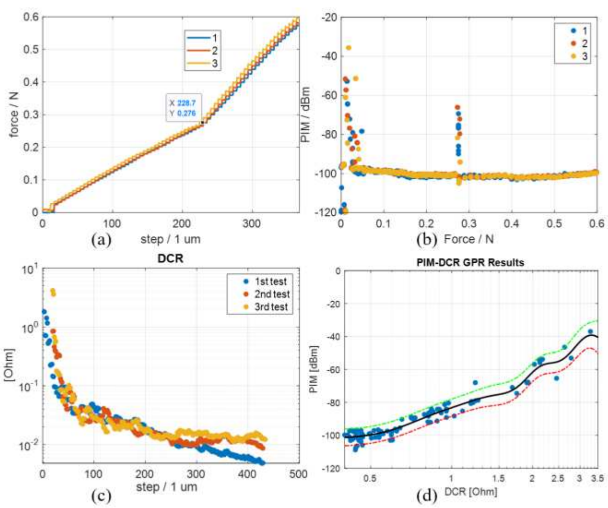


Fig. 8. Simultaneously measured data and analysis: (a). Force-Height; (b). PIM-Force; (c). DCR-Height; (d). Statistical analysis to PIM-DCR

C. Tilted Angle Effect on Contacts

In massive production and assembly process, the components may not be ideally placed flat to make the contacts to the landing pads. Therefore, it is beneficial to have the capability of investigating the effect of tilting.

The decoupled platform usage has been mentioned in Section II Part B. This add-on feature is for the capability of studying the tilted contacts between the springs and the landing pads. As Fig. 3 (e) shows, the mobile app will not only be able to calibrate the angles to be flat but will also help measure the tilted angle if one wants to have the tilting intentionally. Technically, the fine tuning of the tilted angle can be achieved by slightly loose the hexagon lock of the stage rotations and using a small rubber hammer to gradually change the angles until they meet the requirement. A set of measured results are shown in Fig. 10 to demonstrate that the tilted angle measurement has also been enabled in the PIM setup.

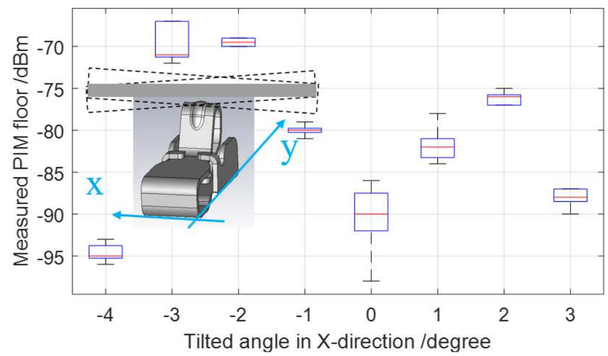


Fig. 9. Tilting contact angle test

IV. Conclusions and Discussions

A duplexer-based two-tone measurement system is introduced to measure PIM. The design of the test fixture is described in detail and the performance is shown. All the successful experience and lessons are summarized as a reference for future studies. Eventually, the finalized setup has a satisfying measurement dynamic range for the purpose of characterizing industrial components. More add-ons have been enabled to expand the capability of the test setup and showed the corresponding measurement results. The current PIM measurement setup has the following capabilities:

- A high-precision gap variability control system with a minimum of 0.3 micrometer step size.
- Accurate contact force monitoring with a 0.001 N resolution capability.
- Automations on the gap variability control, signal generators' power, frequencies, PIM measurement recordings etc. High flexibility to conduct tests with different workflows.
- Tilted angle variability control in horizontal directions.
- High dynamic range that a -100 dBm PIM can be captured (under 23 dBm two-tone injection condition)

However, the measurement setup may be further refined by having a better capacitive ground design. Instead of using microstrip, coplanar waveguide may be a better solution as the PCB ground-to-ground gap becomes smaller. Also, expanding the size may also help but this will affect the tilted angle study capability. Another aspect is that a cancellation method may further increase the measurement sensitivity: If the dominant system PIM sources are the two SMA connectors on the PCBs, try to use identical connectors and re-design the trace length carefully so that the generated PIM from the two connectors have approximately equal amplitude but out of phase in the interested frequency range.

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