Experimental study on the practical mitigation of passive intermodulation for time and temperature in cavity duplexer

Byungchang Choi

The 1st R&D Institute-2, Agency for Defense Development, Yuseong-gu, Daejeon, Republic of Korea

Practical methods to mitigate level and variation of passive intermodulation with respect to time and temperature of coaxial cavity type duplexer are proposed through a variety of experimental results. From the findings derived in this study, a stable passive intermodulation response with less than 1 dB variation was shown in the environment temperature range of −10 to 85 °C. The duplexer with time-stable PIM response at room temperature had a stable PIM value even in the environment temperature range.

Introduction: Passive intermodulation (PIM) refers to generation of spurious or interference frequencies in the output signal when two or more RF signals are impressed onto a passive non-linear component [1]. Third-order PIM level must be kept low particularly so that they do not disturb neighbour service performance since frequency bands for different applications are very close. This unwanted PIM can be generated by a variety of sources such as metal-metal (MM), metal-insulator-metal (MIM) contact, materials, plating, roughness, and resonator structure etc. [2–4]. Many of them have been identified and modelled along the years, yet the physical descriptions of the different sources are quite obscure. It is also difficult to evaluate which of the all possible sources causes the measured PIM level, as well as to isolate one of them to perform an experimental study because of mutual entanglement.

PIM is a very heuristic problem and it greatly depends on the manufacturing skills and experimental results. This letter aims to propose practical ways to improve PIM (i.e. mitigation of power and variation for time and environment temperature) during the filter design and development stage and to establish the mass production guidelines.

Duplexer design: The coaxial cavity duplexer was designed to meet the given mechanical and electrical specifications (i.e. sizes, passband, insertion loss, attenuation rate etc.). Its transmitter (Tx) filter consists of nine resonators with two inductive nested structures [5], which provides four transmission-zeros at upper stopband for sufficiently suppress the other application band or PIM band. In fact, the duplexer also has a receiver filter consisting of six resonators, low pass filter to suppress high order harmonics of the resonator, and coupler for Tx power monitoring, but they are not involved in PIM generation.

In order to minimize the potential PIM source regarding MM and MIM contacts, housing integrated cavity resonators, tuning screw-free structure, and capacitive disc excitation feeding rather than direct tap should be used [6], but it is very impractical for mass production. In reality, focusing on the cavity resonator structure is the only way to reduce PIM in a design stage. Figure 1 shows the possible configuration of resonator structures. As is well known, the Figure 1(b) or 1(c) providing a more stable grounding than the Figure 1(a) because of minimization of contact resistance. The resonator should preferably be designed uniform impedance resonator rather than stepped impedance resonator to achieve higher unloaded quality factor. In this resonator design stage, peak power handling capability that depends on the distance between a resonator and tuning screw (or cover) must be considered [7].

The loop feeding structure is more suitable for the filter with 20 MHz bandwidth because of simplicity and controllability as shown in Figure 2. The optimum temperature compensation of the filter can be obtained by adjusting the dimensions of the resonators and bosses with different coefficients of thermal expansion. The modelled coaxial cavity type duplexer prototype is as shown in Figure 3. The housing and resonators are made of aluminium and free-cutting steel with silver plating, respectively. The feeding rod, loops, and tuning screws are machined from brass with silver plating. The silver plating thickness of all components was determined 5 μm which is about four times of skin depth (δs) at central frequency (1870 MHz) to stabilize the fields. Specifically, as a result of the reflection on the interface between the plating layer and conductors, the current concentrate more on the plating layer. To force the electromagnetic fields to propagate through only the silver plating layer, not aluminium or sum24l and to exclude the effect of plating on PIM generation, the thickness of the silver plating should be determined at least four times of δs [8].

PIM with respect to time: Because of the finite conductivity of metal including silver plating, RF energy loss and cyclic variations are inevitable in the metallic wall of cavity in a volume defined approximately by the δs. Since metallic conductivity depends linearly on temperature, it has also harmonic components which will produce wall currents at intermodulation frequencies. Thus PIM sources are typically variable with respect to time or local temperature [9].

In order to identify factors that influence PIM level and variation over time, dozens of prototypes with various independent factors were fabricated and measured in ambient temperature. Figure 4(a) shows the test results derived in this study, a stable passive intermodulation response with less than 1 dB variation was shown in the environment temperature range of −10 to 85 °C. The duplexer with time-stable PIM response at room temperature had a stable PIM value even in the environment temperature range.
bench for PIM measurement. The remote radio head (RRH) has four broadband waveforms of 43 dBm each at the central frequencies 1862.4, 1867.4, 1872.4, and 1877.4 MHz. Actually, measuring the PIM generated by broadband modulated signals is more realistic than the conventional two tone test [10].

Duplexer jig has sufficient Tx/Rx isolation and PIM value of $-110 \text{ dB}$ and $-135 \text{ dBm}$, respectively. PIM monitoring band is 1884.5–1900 MHz and peak value was measured at every sweep time (4 s) of spectrum analyser with a 300 Hz of resolution bandwidth and 3 Hz of video bandwidth. The requirement of PIM level of prototype is $-110 \text{ dBm}$ and noise floor is $-113.3 \text{ dBm}$ for the given setup.

The suggested independent factors are interface roughness between housing and cover (R_s), resonator grounding structure, material of feeding loop fastening screw, and excitation feeding structure. Figure 5 shows the PIM level for 60 s and influence of each factor on PIM level and variation over time can be inferred from the measured data.

As expected, the larger the roughness of the interface surface, the larger the PIM value and variation for time. Roughness 7 and 10 means that surface collapse or step difference occurred due to excessive brushes on the interface. For resonator grounding structures, the PIM level was not significantly affected, but the Figure 1(c) has the most stable responses.

The brass fastening screw with silver plating at loop is better at reducing the PIM level than using stainless steel (SS) screw. The applied tightening torques for M3 type brass and SS screws are 13 and 16 kgf.cm, respectively. In other words, the continuity between the component materials is more important than giving a strong torque to reduce contact resistance. For excitation feeding structure, the loop feeding scheme to avoid direct MM contact is better than direct tap feeding scheme to improve the PIM.

Recently, experimental studies on subsequent heat treatment (SHT) have been actively conducted to improve the conductivity of metallic materials [11, 12]. The SHT is a process of natural cooling at room temperature after storing all components in a 150 °C chamber for 24 h prior to assembly. A total of 40 samples were produced. The sample has the resonator structure shown in Figure 1(a) and a loop feeding structure with brass fastening screw. Twenty samples were assembled and filtered through the SHT process and the other were assembled after the SHT process. The PIM values of the SHT applied samples were distributed lower about 0.9 dBm on average than those non-applied samples and standard deviations are 0.32 and 0.49, respectively. Thus, it would be reasonable to add the SHT process before assembly in order to increase the yield for PIM during mass production.

PIM with respect to temperature: The environment temperature variations can lead to mechanical and electrical stresses due to the difference in the thermal expansion coefficient between the materials. The defined environment temperature of the duplexer is $-10–85 \degree \text{ C}$.

Figure 6 shows the PIM level with respect to the environment temperature for three particular samples with PIM value of $-110.5$, $-111.6$, and $-112.9 \text{ dBm}$ in room temperature. For convenience, they are defined ref. 1, ref. 2, and ref. 3 in order. The ref. 1 sample has the resonator structure shown in Figure 1(a) and a loop feeding structure with SS fastening screw, that is, the PIM level with respect to time is the most unstable and high through the previous section (i.e. Figure 5(b) red line with square symbol). Likewise, the ref. 1 had a severe fluctuation of PIM level approximately 6 dBm over the entire temperature range as shown in the solid red line in Figure 6.

The ref. 2 and ref. 3 have the Figure 1(c) resonator structure and loop feeding structure with brass fastening screw. Both samples showed generally similar trends and showed a maximum fluctuation of about 2 dB in the temperature range. Also, the PIM rapidly increased in the range of 55–70 °C. By changing the resonator material from sum24l to invar, frequency shift can be minimized from 900 to 100 kHz and it can be reduced to variation of about 1.5 dB, but the PIM value at room temperature does not change. As a result of sufficiently applying the amount of solder connecting the feeding rod and the SMA connector as shown in Figure 7(a), the PIM level was not only reduced absolutely, but also showed a stable response over the entire operating temperatures. Actually, there is a through hole in the feeding rod to identify sufficient soldering. In fact, PIM response at room temperature of the sample with
Conclusively, if the PIM shows a low and stable response with respect to time at room temperature, the PIM under environment temperature is also stable. Even after lots of fastening screws are tightened with a strong torque for stable response of PIM, the PIM level with respect to temperature did not significantly improve. In addition, it is not appropriate to treat the torque-related regulation as a factor for stabilizing PIM level because the fastening screws has a prescribed rated torque in mass production stage.

Conclusion: The presented experimental observations demonstrate the solutions about the MM contact interface for PIM mitigation over the operating time and temperature. In order to achieve a low PIM level in design stage, it is important to design a coaxial cavity resonator with a high unloaded quality factor and minimum frequency shift. In addition, the effect of the resonator grounding structure and excitation feeding structures on PIM level was examined. For time and temperature insensitive PIM response, the suggested solutions such as brass feeding loop fastening screw and ideal soldering process between feeding rod and connector should be actively utilized. It has been shown that the non-continuity contact between the component materials considerably increase the undesired PIM generation in cavity duplexer. Conclusively, if the PIM shows a low and stable response with respect to time at room temperature, the PIM under environment temperature is also stable.

References
1 Bi, L., et al.: Modelling of the passive intermodulation in coaxial connectors with broadband signal excitation. Electron. Lett. 55(15), 845–847 (2019)
2 Kozlov, D., et al.: Practical mitigation of passive intermodulation in microstrip circuits. IEEE Trans. on Electromag. Compait, 62(1), 163–172 (2020)
3 Duteil, G., et al.: Experimental studies of passive intermodulation in metal-to-metal contacts. Prog. In Electromag. Research M 60, 67–73 (2017)
4 Bai, C., et al.: Analysis and measurement of passive intermodulation in coaxial cavity filter. 48th European Microwave Conference, Madrid, Spain, pp. 902–904 (2018)
5 Brian Thomas, J.: Cross-coupling in coaxial cavity filters-A tutorial overview. IEEE Trans. Microw. Theory Tech. 51(4), 1368–1376 (2003)
6 Macchiarella, G., Stracca, G.B., Miglioli, L.: Experimental study of passive intermodulation in coaxial cavities for cellular base stations duplexers. 34th European Microwave Conference, Amsterdam, Netherlands, pp. 981–984 (2004)
7 Vanin, F.M., De Paolis, F., Schmitt, D.: Resonator voltage prediction in microwave bandpass filters. IEEE Trans. Microw. Theory Tech. 63(2), 397–402 (2015)
8 Deng, H.W., Zhao, Y.J.: Effective skin depth for multilayer coated conductor. Prog. In Electromag. Research M 9, 1–8 (2009)
9 Hienonen, S., Räisänen, A.V.: Effect of load impedance on passive intermodulation measurements. Electron. Lett. 40(4), 245–247 (2004)
10 Zhao, P., Zhang, X., Yang, D.: Analysis of passive intermodulation generated by broadband signals. Electron. Lett. 52(7), 564–566 (2016)
11 Pankade, S.B., Khedekar, D.S., Gogte, C.L.: The influence of heat treatments on electrical conductivity and corrosion performance of AA 7075-T6 aluminium alloy. Procedia Manuf. 20, 53–58 (2018)
12 Zhang, P., et al.: Analysis of the microhardness, mechanical properties and electrical conductivity of 7055 aluminium alloy. Vacuum 171, 1–7 (2019)