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A Comprehensive Test Approach on High-Power Low-Noise Intermodulation Distortion

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Abstract

With the shortage of wireless communication bandwidth resource, the radio interferences occur so frequently. Currently, effcient frequency allocation algorithm designing and Intermoduation Distortion (IMD) suppression are two means to rationally improve the bandwidth resource. Therefore, four comprehensive approaches named stimulus isolation, channel crosstalk isolation; spectrum slight offset and Auto Level Control (ALC) leak control are proposed respectively to avoid the restriction of the periphery system's noise and dynamic range of measurement instruments. Moreover, the high power and low noise detection approach, the auxiliary components amelioration and the measurement system improvement are analyzed. Finally, utilizing Silicon-On-Insulator (SOI) Radio Frequency (RF) switch as the carrier to do the experiment based on Advantest 93K tester. Experiment results show that the comprehensive optimized approaches can keep the whole system to less than -150 dBm (nearly 170 dBc) low noise range under the large signal cases. The actual intermodulation distortion signal could be rejected and sampled in precise accuracy which is nearly 20% improved. What's more, the approaches are also beneficial to the expansion of the industrial multi-site test.

***Keywords**: intermoduation distortion, crosstalk, low noise*

1. Introduction

With the fast development of the social informatization, the studies of wireless communication technology are corresponding under the strong spotlight. Due to the limitation of bandwidth resource, wireless communication should take full and rational advantage of the bandwidth [1-3]. Meanwhile, IMD (Intermoduation Distortion) verification methods attract people's more attention and hence more researches are involved [4, 6]. At present, high power and low noise detection of intermodulation distortion is largely restricted to the periphery system's noise and dynamic range of measurement instruments [7, 8]. Large signal and low noise IMD is easily drowned in the noise floor of the whole system. It is shown in most reported experimental results that around -100 dBm could be controlled at high power stimulus. Therefore, the comprehensive optimized approaches research and selection is a very important subject as to enhance IMD signal detection accuracy of the actual device.

Based on the study and analysis of measurement method, auxiliary devices and test system, this paper proposes the comprehensive optimized approaches which could be separated to four parts. The first approach is defined as stimulus isolation. The second approach is channel crosstalk isolation. The third approach is called spectrum slight offset and ALC (Auto Level Control) leak control is involved in the fourth approach. Finally, the paper utilizes the SOI RF switch as carrier to do the experiment on Advantest 93K tester. As a result, the floor noise is reduced to less than 150 dBm (nearly 170 dBc), and the actual accuracy is also increased by over 20%. What's more, it also provides the certain theoretical support on the high power and low noise intermodulation distortion measurement.

2. IMD Theoretical Analysis

IMD signal is defined as that when two or more different frequency signals go through a nonlinear system, much more harmonic and combined frequency components are produced due to the nonlinear factors. One of the signals is modulated with another one, and product the

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mixed spurious signals. Consequently it affects the identification of the useful signal as shown in Figure 1.

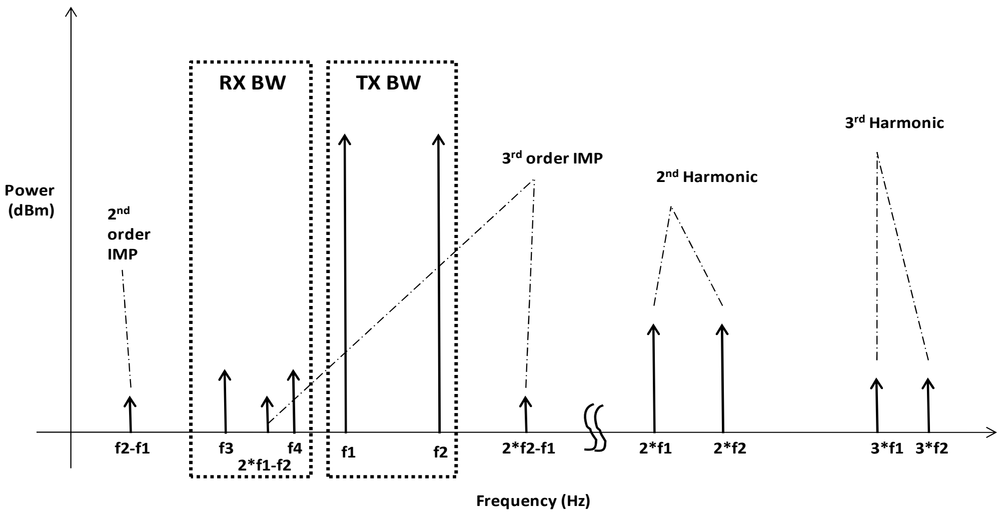


Figure 1. Intermodulation Distortion Production

The exact meaning is shown that a linear system contains the value of the nonlinear coefficient. The intermodulation production of nonlinear device consists of a series of signal with different frequencies. They include fundamental wave, second order harmonic and third order IMP (Intermodulation Distortion Production) and etc. Under the condition of small signal distortion model, Maclaurin expansion equation approximately equals to formula (1) usually:

$$V_o = \sum_{n=0}^{\infty} a_n \cdot V_i \quad (1)$$

In the formula, a_n is Maclaurin multinomial coefficient. Then two-tone signal is supposed to be stimulated,such as Equation (2):

$$V_i(t) = V_1 \cos \omega_1 t + V_2 \cos \omega_2 t \quad (2)$$

They are combined and processed by Prosthaphaeresis transform, and fundamental wave component ω_1 and $\omega_2$is calculated by simple and three cubed terms as formula 3:

$$i = \left(a_1 V_1 + \frac{3}{4} a_3 V_1^3 + \frac{3}{2} a_3 V_1 V_2^2\right) \cos \omega_1 t + \left(a_1 V_2 + \frac{3}{4} a_3 V_2^3 + \frac{3}{2} a_3 V_2 V_1^2\right) \cos \omega_2 t \quad (3)$$

Combined frequency components are generated by quadratic and three cubed terms and shown as formula (4-6):

$$a_2 V_1 V_2 \cos(\omega_1 + \omega_2) t + a_2 V_1 V_2 \cos(\omega_1 - \omega_2) t \quad (4)$$

$$\frac{3a_3 V_1^2 V_2}{4} \cos(2\omega_1 - \omega_2) t + \frac{3a_3 V_1^2 V_2}{4} \cos(2\omega_1 + \omega_2) t \quad (5)$$

$$\frac{3a_3 V_1 V_2^2}{4} \cos(2\omega_2 - \omega_1) t + \frac{3a_3 V_1 V_2^2}{4} \cos(2\omega_2 + \omega_1) t \quad (6)$$

According to the above available calculation results, different frequencies are caused by the cross terms. And they are likely to fall within the pass band of receiver. Especially when ω_1 and ω_2 are very closed to ω_0, the two sorts of difference frequency would be harmful to receiver seriously. And the kind of difference frequency is defined as IMD3 (3rd Order Intermodulation

Distortion). Relatively speaking, because the high-order term intermodulation signals are always far away to the pass band of receiver, it bring less influence. Therefore, following paper would mainly focus on the comprehensive optimization approaches' analysis based on IMD2(2nd Order Intermodulation Distortion) and IMD3. And verification model is also established on four methods such as stimulus isolation, channel crosstalk isolation, spectrum slight offset and ALC (Auto Level Control) leak control.

3. Study and Optimization on Test Approach

Because the root cause on intermodulation signal is complicated, the generation of intermodulation products couldn't be obtained accurately by theoretical analysis and calculation [9-12]. Therefore, the optimized test system's architecture is established based on the traditional test system. As demonstrated in Figure 2, four approaches are expanded on the core approach architecture both on periphery circuit and algorithm optimization. Detail algorithm and model on the four approaches would be introduced in the latter part of the paper.

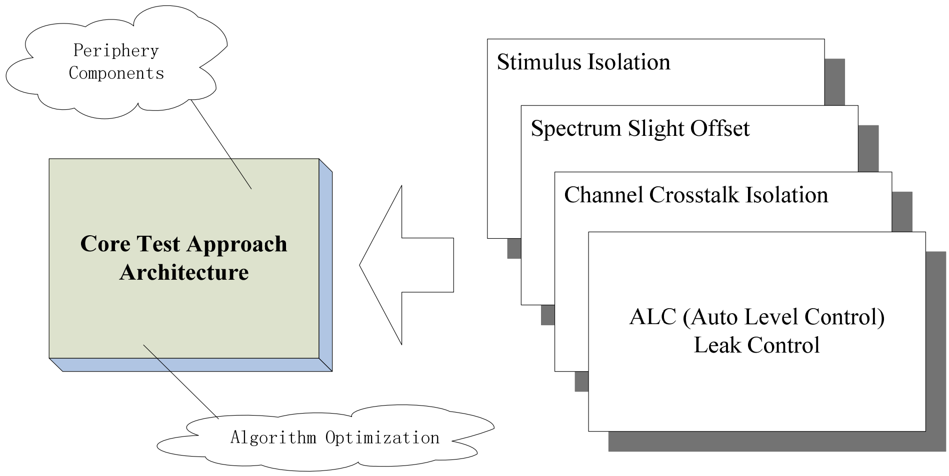


Figure 2. Test System Architecture Optimization

On stimulus isolation, the whole optimized test system is established as shown in Figure 3. The splitter is added to capture the two-tone signal stimulated to assure the completion of the DUT (Device Under Test)'s input power. DC block is used to avoid the DC signal involved in the system. BPF (Band Pass Filter) and LPF (Low Pass Filter) in the system are used to do IMD3 and IMD2 measurement excluded large stimulus signal effect. In traditional way, two single-tone signals are combined as a two-tone signal through the low pass filter. As formula (1) describes, the test system could be expanded to cascaded non-linear affect. Equation (7) and Equation (8) show details:

$$\mathrm{V_{o(n)}(t)} = a_1\mathrm{V_i(t)} + a_2\mathrm{V_i^2(t)} + a_3\mathrm{V_i^3(t)} + \cdots \quad (7)$$

$$\mathrm{V_{o(n+1)}(t)} = \mathrm{b_1V_{o(n)}(t)} + \mathrm{b_2V_{o(n)}^2(t)} + \mathrm{b_3V_{o(n)}^3(t)} + \cdots \quad (8)$$

And the isolator is substituted for the low pass filter in this way in order to avoid the return wave and leak of the adjacent source and reflect as $\mathrm{V_R} = \rho_\mathrm{L}\mathrm{V_i}/\sqrt{\mathrm{K}}$, ρ_L present standing-waveratio and K present attenuation factor. Meanwhile, it's proved that if little signal leak or reflect between the stimulus sources exist, serious intermodulation distortion would be generated due to the cascaded effect. Thus, two isolators are necessary to be input after the high power stimulus source and it's effective to avoid effect on return wave and adjacent source leak.

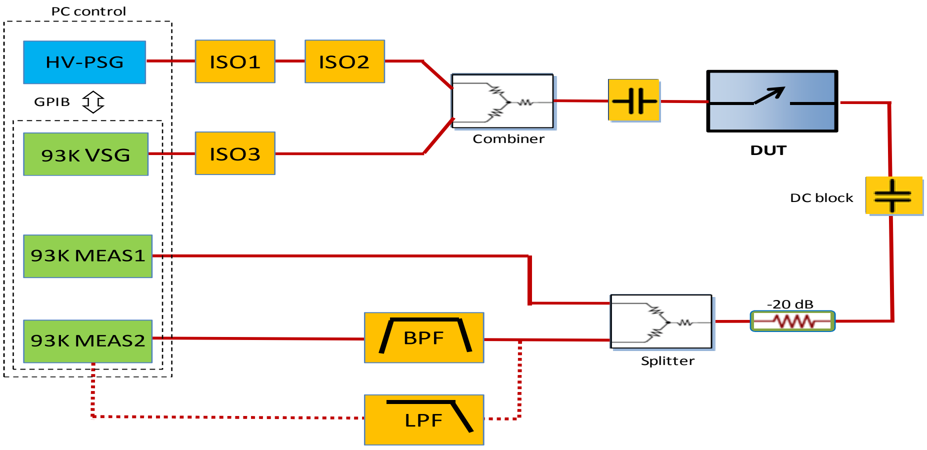


Figure 3. Test System Architecture

On channel crosstalk isolation, the wide spread tester Advantest 93K is selected as experiment instrument. Figure 4 shows the basic diagram on its RF instrument card which call PSRF (RF Pin Scale). There exists two measurement loop traces. While large signal loopback in the measurement unit which is the relatively trace pitch isn't large enough for the stimulus source, it would generate undesired crosstalk due to the nonlinear factors on the instrument card itself. The main concern regarding the ganged Mini-Coax connector and trace is isolation [13]. Isolation can be defined as electrical noise caused by mutual inductance and capacitance between adjacent signals due to their proximity. Crosstalk will mainly occur due to the small conductor pitch of the ganged connector or trace. Assuming the crosstalk depends mainly on mutual inductance, we can use the simple crosstalk estimation as it is shown in the equation (9) below, where D and H represent the centerline separation and trace height:

$$\text{Crosstalk[dB]} < 20\log\frac{1}{1+(\frac{D}{H})^2} \tag{9}$$

Therefore, channel crosstalk isolation approach is proposed to do the improvement. 93K MEAS1 trace is replaced to 93K MEAS2 trace to access the large signal thru in. And the 93K MEAS1 trace is changed to LNA(Low Noise Amplifier)mode to detect low power intermodulation distortion signal.

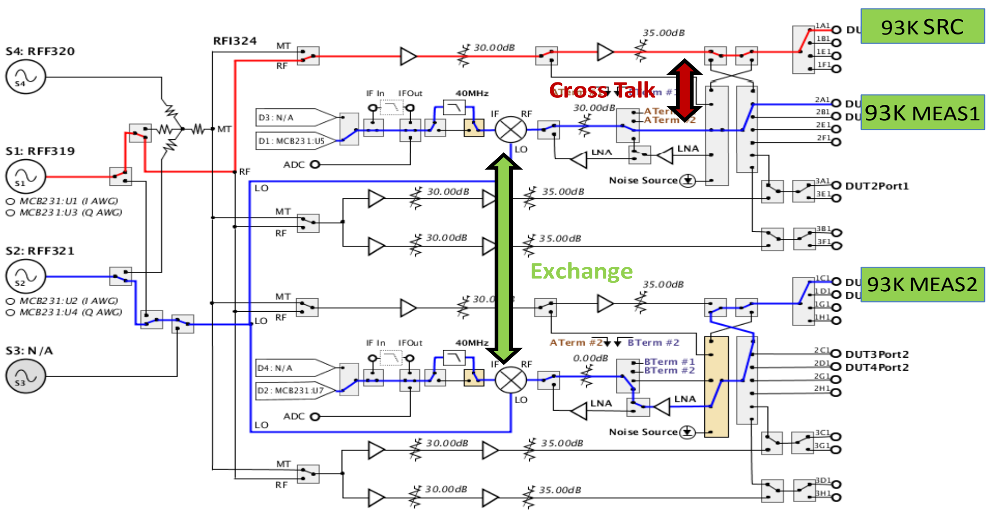


Figure 4. Channel Crosstalk Isolation

On spectrum slight offset, SFDR (spurious free dynamic Range) would also bring some effect in the low noise two-tone intermodulation signals product while doing spectrum testing [14-16]. Formula (10)-(11) describe the system dynamic range which caused by system non-linear characteristics. $\mathrm{F_t}$ represents floor noise, B represents bandwidth and SNR is signal noise ratio.

$$F_t(dBm) = k[T_a + (F-1)T_o]\left(\frac{dBm}{Hz}\right) + 10\,log\,B + (SNR)_{o,min}(dB) \qquad (10)$$

$$SFDR(dB) = \frac{1}{3}[2IIP_3(dBm) + F_t(dBm)] - [F_t(dBm) + (SNR)_{o,min}(dB)] \qquad (11)$$

On Advantest 93K, the spurious signal occurs in nearly 45MHz frequency point closed to fundamental frequency. As Figure 5 shows, the expected signal is covered by system noise floor. In consequence, frequency point slightly shift approach is involved in this paper. 1 KHz is shifted with the two-tone signal and the measure resolution is adjusted to 1 Hz to process narrowband sampling. In this way, the actual intermodulation distortion could be detected without exceeding the operation pass band in the meantime.

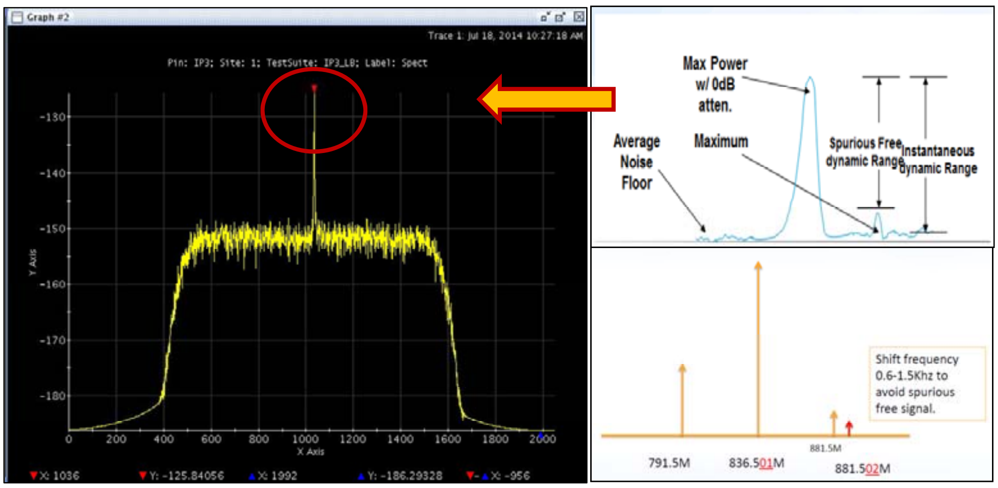


Figure 5. Spectrum Slight Offset

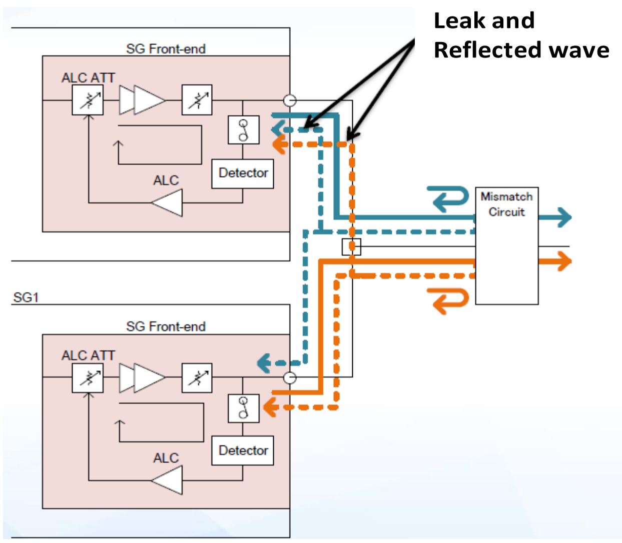


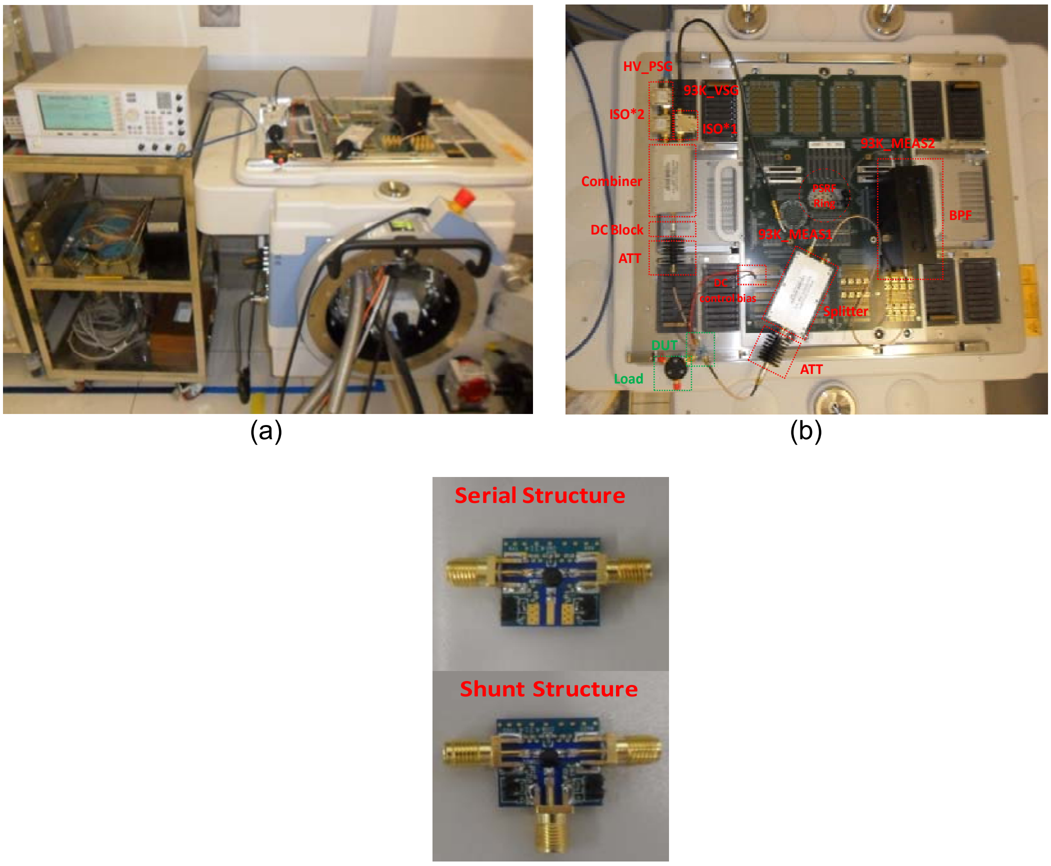
Figure 6. ALC Leak Control

On ALC(Auto Level Control) leak control, the approach is setup on the basis of the above three approaches. The front-end signal source contains auto level control unit as Figure 6 shows. Seen from the output, it could be approximately equivalent to a mixer [17, 18]. Due to the nonlinear factor, if signal leak from the other source or the mismatched return wave are impacted, the spurious intermodulation distortion would be easy to be generated inside of source card. To avoid the interference, the switch in front of the detector should be disconnected in following experience. Then, the pure signal would be assured.

If the above four approaches is embedded in the core test approach architecture, the detect accuracy on intermodulation distortion would be obviously improved to over 20%. And the actual devices' characteristic could be measured. Following paper would show the detail experiments and results.

4. Experiments and Results

Based on analysis of above four comprehensive optimized approaches, the testing system is established as shown in Figure 7(a)(b). And thru mode is selected to verify the system first. From the results as listed in Table 1, large signal trace with more isolators could reduce 20dB floor noise effectively and the accuracy is also increased nearly 20%. However, small signal trace with more isolators is in vain to the floor noise. Moreover, small signal trace without isolation would bring the other issue that higher order product of nonlinear system may shift the bias of the device during IMD2 test. Thereby, the result is illogical inverse changed as shown in Figure 8.



(a) (b)

(c)

Figure 7. (a) Overview of the test system (b) Detail auxiliary components Loop (c) SOI RF Switch as DUT

Table 1. Isolator influence on thru mode

No	Test loop	Two-tone (dBm)	IMD3 (dBm)	Compensated IMD3 (dBm)	Variation (%)
1	PSG+ISO1/VSG	22/-15	-126~-127	-104	18.1%
2	PSG+ISO1/VSG+ISO3	22/-15	-124.7~-127	-103	18.8%
3	PSG+ISO1+ISO2/VSG+ISO3	22/-15	-150	-127	0%
4	PSG+ISO1+ISO2/VSG	22/-15	-150	-127	0%

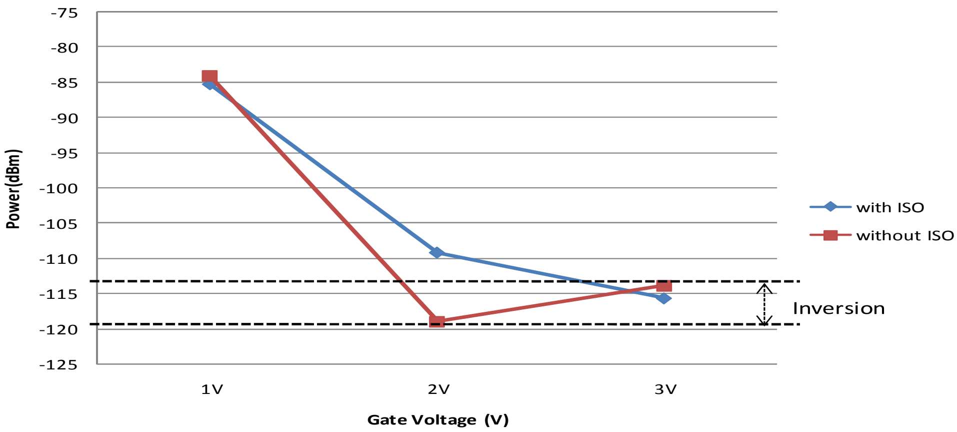


Figure 8. IMD2 with/without ISO comparison at different Vg

Finally, single structure of SOI RF switch as the carrier (See Figure 7(c)) is selected to do the optimized approach verification (See Table 2, 3). According to the test results analysis,the comprehensive optimized approaches which contain stimulus isolation, channel crosstalk isolation, spectrum slight offset and ALC (Auto Level Control) leak control could sample the intermodution distortion signal less than -150 dBm floor noise accurately. And the test system has high resolution ability even at large signal condition.

Table 2. IMD3 Results on SOI RF Switch

Vg	Two-tone signal input(output) power(dBm)	Serial Structure IMD3 (dBm)	Serial Structure Compensated IMD3 (dBm)	Shunt Structure IMD3 (dBm)	Shunt Structure Compensated IMD3 (dBm)
1V	22/-15(7/-27)	-83.2	-60.2	-94.3	-71.3
2V	22/-15(21.2/-15.7)	-117.8	-94.8	-127.2	-104.2
3V	22/-15(21.5/-15.5)	-145.3	-122.3	-150.0	-127.0

Table 3. IMD2 Results on SOI RF Switch

Vg	Two-tone signal input(output) power(dBm)	Serial Structure IMD2 (dBm)	Serial Structure Compensated IMD2 (dBm)	Shunt Structure IMD2 (dBm)	Shunt Structure Compensated IMD2 (dBm)
1V	22/-15(7/-27)	-108.3	-85.3	-120.1	-97.1
2V	22/-15(21.2/-15.7)	-132.2	-109.2	-145.7	-122.7
3V	22/-15(21.5/-15.5)	-138.7	-115.7	-150.0	-127.0

What's more, not only low noise IMD at high power stimulus is captured, but also actual SOI RF device characteristics are analyzed through the comprehensive optimization approaches. It is instructive and meaningful for device analysis and modeling development. What's more, it could lay a solid foundation on SOI front end module integration.

5. Conclusion

Through the above experiment, the increase of isolation between different stimulus sources can effectively reduce the interference on the return wave and adjacent leak. Channel crosstalk isolation could decrease the large signal effect from source to measurement to a large extent. Spectrum slight offset could avoid the spurious signal from SFDR. ALC leak control further prevents the intermodulaiton product which generated inside the source card. Meanwhile, in order to get accurate IMD sample, narrow band resolution of measurement is necessary as well. What's more, device also should be controlled to operate in linear region or operating bias shifted would bring illogical performance. Last but least, the optimized comprehensive approach could not only reach the better accuracy and more application, but also it could be extended to multi-site test for actual industrial engineering.

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