High-Dynamic-Range Measurement of 140-GHz Band Millimeter-wave Amplifier using Fundamental Mixing

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[Summary] We have studied and prototyped a 140-GHz fundamental mixing test system offering fewer multiple responses and higher dynamic range than conventional methods using a harmonic mixer. This paper describes measurements with a 20-dB or better dynamic range and excellent wideband suppression of multiple responses.

1 Introduction

Recently, millimeter-wave wireless systems in bands above 100 GHz are starting to be used more commonly in Wireless Personal Area Network (WPAN) applications. However, standards such as IEEE802.11ad have no recommendations about high-sensitivity and high-accuracy technologies for evaluating secondary harmonics of 60 to 70 GHz band wireless systems or wireless signals above 100 GHz, and spectrum analysis of signals in these frequency bands generally requires measurement by connecting an external harmonic mixer to the spectrum analyzer1), 2), 3) causing the following problems:

1) Mixing the harmonic wave of the LO signal and input signal in the harmonic mixer causes unnecessary frequency components (multiple responses3)) other than the original required frequency components in the output, making it difficult to monitor the original signal components.
2) Since the power of the LO signal generated in the harmonic mixer drops as the harmonic order increases, the mixer conversion efficiency becomes degraded. Consequently, the dynamic range is reduced greatly when monitoring frequencies above 100 GHz requiring a high harmonic order.

We have developed a 140-GHz fundamental mixing test system supporting measurement with fewer multiple responses as well as higher dynamic range than measurements using conventional harmonic mixers. To validate the performance of this system, we evaluated the third order intermodulation distortion (IM3)4) of a 140-GHz band millimeter-wave power amplifier, achieving measurement with a higher dynamic range of 20-dB or better than measurements using a conventional harmonic mixer.

2 140-GHz Fundamental Mixing Test System

The developed 140-GHz fundamental mixing test system is composed of devices for splitting the 100 to 140 GHz RF frequency band into two frequency bands of 108 to 128 GHz, and 122 to 140 GHz for monitoring. This system uses two fundamental mixers to convert these frequency bands into two IF frequencies of 4 to 24 GHz, and 6 to 24 GHz, respectively. The converted IF signals are then combined and observed to implement spectrum analysis of the 110 to 140 GHz band.

Figure 1 shows the block diagram of the 140-GHz fundamental mixing test system. The RF Signal Source is composed of dual signal generation systems to perform intermodulation distortion measurement and the two generated signals are combined for output using a magic-T. The LO Signal Source generates a LO signal of either 104 GHz or 116 GHz. The signals generated from the RF Signal Source and the LO Signal Source are adjusted to the best signal level using a variable attenuator (VATT) in each signal source before output. The Mixer is composed of mixers that support the analysis frequency band. Each mixer is connected to an isolator (→ in figure) at the LO and RF inputs. The IF signal that has been frequency converted by the Mixer is input to a Spectrum Analyzer for spectrum analysis. The Directional Coupler at the Mixer input section, and the Millimeter-Wave Power Meter and the Micro-wave Power Meter connected to the output of the directional coupler are used to calibrate the level of the test system explained below.

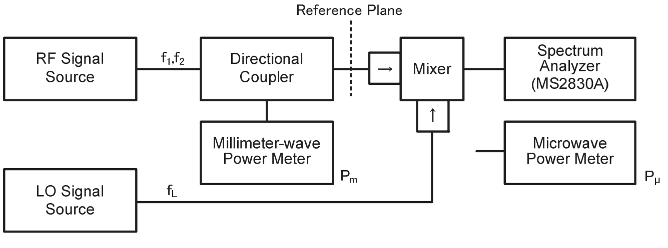


Figure 1 Block Diagram of 140-GHz Fundamental Mixing Test System

2.1 Level Calibration of Test System

To monitor the RF signal that has been frequency converted by the system Mixer using the spectrum analyzer, the frequency conversion loss from the isolator at the fundamental mixer input to the spectrum analyzer is calculated to obtain the required level calibration data. The conversion loss calculation is trialed based on the direct comparison measurement technique[3), 4)] used at power sensor calibration. In this method, the frequency conversion loss is calculated using P_m, the value measured by the Millimeter-wave Power Meter connected to the directional coupler, and P_μ, the value measured by the Micro-wave Power Meter connected to the mixer output.

Figure 2 shows the measurement blocks at calculation of the frequency conversion loss as a signal flow graph. Furthermore, in this graph, the S parameter of the directional coupler is represented as S_C, the S parameter of the Mixer section including the isolator as S_M, the Micro-wave Power Meter input reflection coefficient as Γ_μ, and the Millimeter-wave Power Meter input reflection coefficient as Γ_m. From figure 2, the relationship between the level of the input signal to the Mixer b_2, and the signal level at the input terminal of the Micro-wave Power Meter b_3, is expressed by Eq. (1).

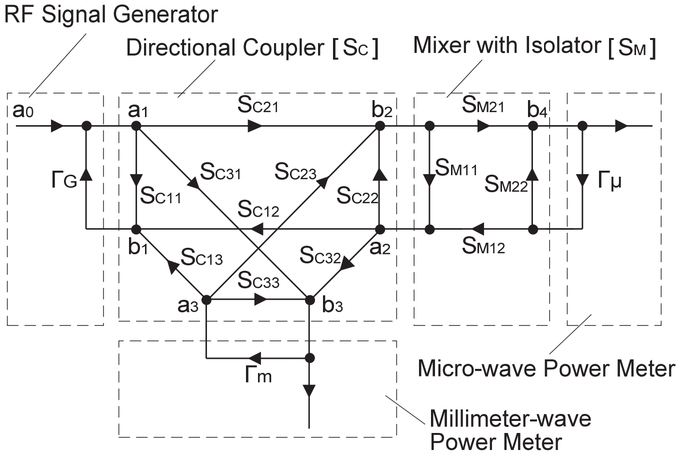


Figure 2 Signal Flow Graph

$$\frac{b_2}{b_3} = \frac{S_{C21}}{S_{C31}} \cdot \frac{1-\Gamma_m \cdot \Gamma_{ge3}}{1-\Gamma_A \cdot \Gamma_{ge2}} \qquad (1)$$

where, $\Gamma_A = \left\{ \Gamma_\mu \cdot \left(\frac{S_{M21} \cdot S_{M12}}{1 - S_{M22} \cdot \Gamma_\mu} \right) + S_{M11} \right\}$

$$\Gamma_{ge2} = \left(S_{C22} - \frac{S_{C21} \cdot S_{C32}}{S_{C31}} \right), \Gamma_{ge3} = \left(S_{C33} - \frac{S_{C31} \cdot S_{C23}}{S_{C21}} \right)$$

Similarly, the relationship between the level of the signal input to the Mixer b_2, and the level of the signal at the input terminal of the Micro-wave Power Meter b_4, is expressed by Eq. (2).

$$\frac{b_4}{b_2} = \frac{S_{M21}}{1 - S_{M22} \cdot \Gamma_\mu} \qquad (2)$$

Consequently, the frequency conversion loss (*C.L.*) can be calculated from Eq. (3) below.

$$C.L. = \left| \frac{S_{C21}}{S_{C31}} \right|^2 \cdot \left| \frac{b_3}{b_4} \right|^2 \cdot \frac{\left| 1-\Gamma_m \cdot \Gamma_{ge3} \right|^2}{\left| 1-\Gamma_A \cdot \Gamma_{ge2} \right|^2} \cdot \frac{1}{\left| 1 - S_{M22} \cdot \Gamma_\mu \right|^2} \qquad (3)$$

Terms 3 and 4 on the right side of Eq. (3) express the error due to mismatching of the measurement system, including the power meters. If the Mixer transmission characteristics due to the characteristics of the isolator at the Mixer input section are assumed to be $S_{M12} \cong 0$, and $S_{M11} \cong 0$, Γ_A in Eq. (3) can be approximated as $\Gamma_A \cong 0$. Table 1 shows the value of each reflection coefficient and S parameter in Eq. (3). The values in table 1 are the worst-case values in the respective measurement bands. Calculating from these values suggests that the effect of mismatching of the measurement system at frequency conversion loss measurement is within ±0.5 dB. Consequently, in this test, error due to measurement system mismatching can be ignored when calculating *C.L.*

Table 1 S-parameter and Reflection Coefficient of Measurement System

Γμ	0.11	Γge2	0.03	SM22	0.50
Γm	0.14	Γge3	0.04	-	-

Figure 3 shows the conversion loss measurement results for the two fundamental mixers used in the 140-GHz fundamental mixing test system. The same figure shows the conversion loss measurement results for two fundamental mixers with different LO frequencies. The respective LO frequencies are 104 GHz and 116 GHz. Even considering the effect of measurement system mismatching, the mixer frequency conversion loss was confirmed to be 10 dB or less. In addition, a difference of about 1 dB was confirmed at 121 to 127 GHz due to the use of mixers with different LO frequencies.

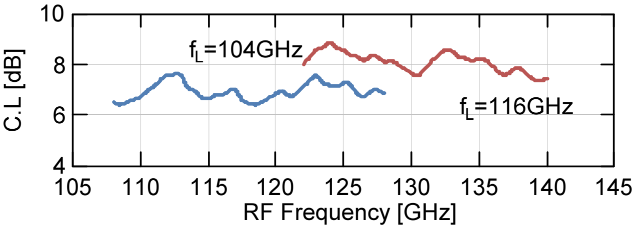


Figure 3 Conversion Loss Measurement Results

3 Millimeter-wave Amplifier Measurement

To validate the usefulness of this system for spectrum analysis, the 140-GHz fundamental mixing test system was used to measure IM3 of a commercial millimeter-wave amplifier (HPA).

3.1 Measurement System

Measurement was performed by connecting the HPA to be evaluated to the Reference Plane shown in figure 1. Moreover, to suppress distortion generated by the measurement system, a VATT was connected to the HPA output so the total gain of the HPA and VATT was about 0 dB. The spectrum analyzer was used to correct the level including the mixer conversion loss so that the mixer input level became the same as the spectrum analyzer displayed value. Figure 4 shows the 140-GHz fundamental mixing test system.

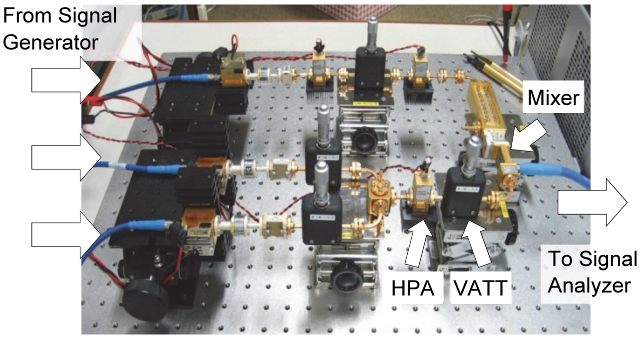


Figure 4 140-GHz Fundamental Mixing Test System

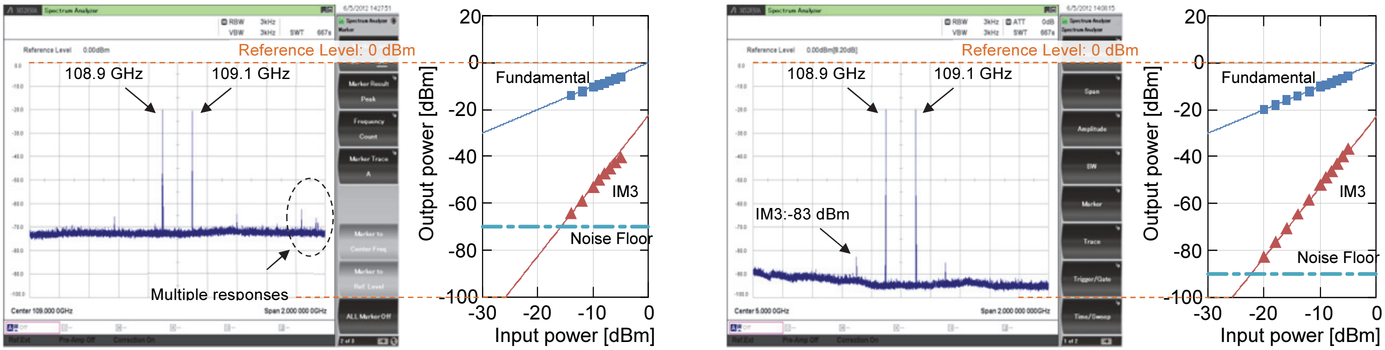
3.2 Measurement Results

To validate the dynamic range of this system, we ran comparative tests using a harmonic mixer and this system. Since the tested harmonic mixer supported the W-Band (75 to 110 GHz), we measured the IM3 of the HPA using a 2-tone signal of f1 = 108.9 GHz and f2 = 109.1 GHz approaching each upper frequency limit of the waveguide.

The results of the comparison are shown in figure 5; graph (a) shows the results using the harmonic mixer, and graph (b) shows the results using this system. Since evaluation of IM3 requires a measurement system with a very low noise floor, the resolution bandwidth (*RBW*) was set to 3 kHz for measurement. One measurement of a 2-GHz frequency analysis band required about 10 minutes.

In the measurement using the harmonic mixer, since the mixer's own conversion loss is large at 40 dB or more, the noise floor observed at the spectrum analyzer is about –70 dBm. Consequently, when the input signal power was –15 dBm or less, the generated intermodulation distortion could not be observed because it was buried in the noise floor. Moreover, as shown by the dashed line in the figure, typical harmonic mixer multiple responses were observed near 109.9 GHz. Few multiple responses occurred with the fundamental mixer, and since these frequencies due to the relationship between the input signal frequency and the LO frequency[7)], measurement probably becomes even more difficult when approaching these frequencies.

On the other, at measurement using this system, the noise floor observed on the spectrum analyzer was about –90 dBm and few multiple responses were observed. Moreover, the results clearly confirm that it is possible to measure intermodulation distortion of –83 dBm generated at input of a –20 dBm signal.



(a) Using Harmonic Mixer (b) Using 140-GHz Fundamental Mixing Test System

Figure 5 IM3 Measurement Results f1 = 108.9 GHz, f2 = 109.1 GHz, RBW = 3 kHz, Span = 2 GHz

From this comparison of the results, we can say that this system can perform measurement with a 20 dB or higher dynamic range than when using a harmonic mixer. From the relationship[8] between *RBW* and sweep time T_{sweep} shown in Eq. (4), to obtain similar measurement results using a harmonic mixer, the value of *RBW* must be two orders of magnitude larger when *VBW* is set to the same value as *RBW*. In other words, the measurement time can be shortened by a factor of 1/10000 from 10 minutes to 60 ms, showing that this measurement system supports spectrum analysis of signals exceeding 100 GHz at a higher dynamic range, as well as faster analysis of spurious signals.

$$T_{sweep} = K \cdot \frac{SPAN}{RBW \cdot VBW} \qquad (4)$$
$$RBW \geq VBW, \quad K = 1, 2 \text{ or } 3$$

Figure 6 shows the HPA IM3 measurement results at f1 = 122.9 GHz and f2 = 123.1 GHz. Figure 7 shows the HPA IM3 measurement results at f1 = 138.9 GHz and f2 = 139.1 GHz, the upper measurement limit of this system. In figure 7, although we can see a drop in the reference wave level due to the HPA frequency characteristics, it is clearly possible to confirm the measurement result for the IM3 characteristics at frequencies near 140 Hz. Based on the above results, this measurement system can be used for analysis of signals in the 110 to 140 GHz band.

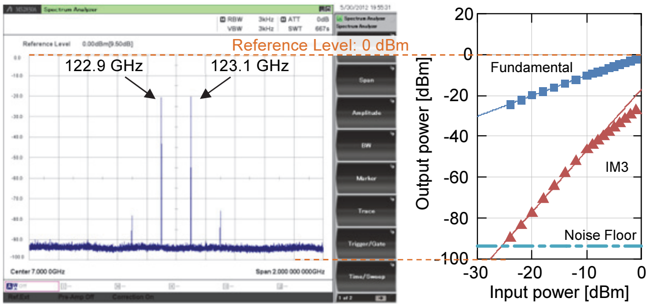


Figure 6 IM3 Measurement Result
f1 = 122.9 GHz, f2 = 123.1 GHz, RBW = 3 kHz, Span = 2 GHz

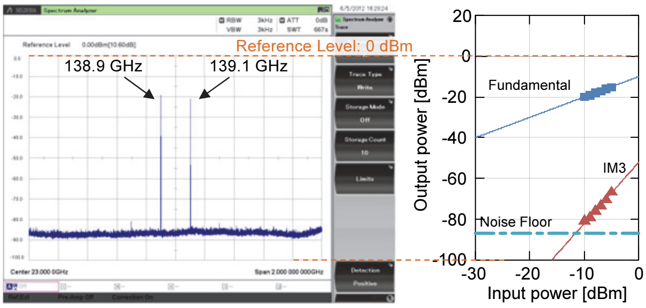


Figure 7 IM3 Measurement Result
f1 = 138.9 GHz, f2 = 139.1 GHz, RBW = 3 kHz, Span = 2 GHz

4 Summary

We have developed a 140-GHz fundamental mixing test system supporting higher dynamic range measurements than systems using conventional harmonic mixers and with few multiple responses. We used this test system to evaluate the IM3 of a 140-GHz millimeter-wave power amplifier and achieved measurements with a 20 dB or higher dynamic range than measurements using a conventional harmonic mixer. The typical multiple responses observed at measurements using harmonic mixers were not observed when using this system, which also supports high-dynamic-range measurement, confirming the possibility of using this system for spurious analysis of signals above 100 GHz.

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