190-GHz Band Spectrum Measurement System with Built-in Preselector for Implementing Low-Level Spurious

Yuji Sekine, Shigeo Arai, Takashi Kawamura, Shigenori Mattori

[Summary] Commercial rollout of both wireless communications terminals in the 60-GHz band defined by IEEE802.11ad, and automobile radar in the 76 to 81-GHz band is progressing steadily. The spread of these wireless devices requires development and evaluation to understand how occupied bandwidth and unwanted spurious impact suppression of interference, which in turn requires monitoring of the higher mmWave band. To monitor the spectrum from 140 to 190 GHz with high accuracy, we fabricated a spectrum measurement system with preselector for measuring spurious up to −60 dBc at a mixer input level of −15 dBm with a dynamic range of 155 dB. In addition, multiplier spectrum measurements confirmed the effective low unwanted-spurious response characteristics of this system.

1 Introduction

Development of 60-GHz band wireless terminals in compliance with the IEEE802.11ad standard is now underway to increase wireless transmission capacity. Additionally, automobile radar is being developed using the mmWave band of 76 to 81 GHz, which is mostly unaffected by weather conditions. Increasing the number of wireless devices using the mmWave band will result in future problems with unwanted emissions causing interference between devices. Consequently, development and evaluation of wireless devices with suppressed unwanted emissions requires high-accuracy precision instruments for measuring spurious and two-tone third-order intermodulation distortion. For example, the US Federal Communications Commission (FCC) stipulates measurement of unwanted emissions up to 231 GHz for 76 to 81-GHz band automobile radar[1].

Generally, conventional spectrum monitoring in the mmWave band uses an external down converter and harmonic mixer to convert the Radio Frequency (RF) signal to be measured to an Intermediate Frequency (IF) signal that can be monitored and analyzed with a regular spectrum analyzer. However, when measuring multiple RF signals with different frequencies, intermodulation distortion between the Local (LO) signal harmonic components and RF signal harmonic components causes a spurious response within the spectrum measurement system, resulting in a limited dynamic range due to overlap of the IF signal converted from the RF signal to be monitored and the spurious response.

We have previously reported an investigation into a spectrum measurement system for frequencies above 100 GHz and evaluated the distortion performance using non-linear devices such as mixers; a newly-developed Fabry-Perot preselector enabled development of a mmWave spectrum measurement system[2] with low spurious response. Moreover, we have also demonstrated the effectiveness of a filter-bank type preselector with better durability and insertion loss characteristics than the Fabry-Perot method in a 300-GHz band spectrum measurement system[3), 4)].

This article reports a 190-GHz band spectrum measurement system (this system hereafter) meeting the performance requirements for evaluating spurious in the mmWave band and explains the design procedure for achieving high dynamic range. In addition, we present measurement results for a multiplier output signal demonstrating the effectiveness of the reported system in suppressing spurious response.

2 Target Performance

Determining the target performance requires considering the measurement system conditions when evaluating the Occupied Band Width (OBW) and spurious as indices of the communication-system RF signal performance. As shown in Figure 1, the bandwidth of the monitored modulated signal is 5 GHz, assuming a 10-GHz frequency range of twice the analysis bandwidth at spectrum measurement. At OBW measurement with a 120-GHz band Field Pick-up Unit

(FPU), when considering the impact on total power with no margin from the Tx spectrum distribution to the measurement system noise level, the OBW can be thought of as the difference between the upper and lower frequency at a point 23 dB down from the maximum power excluding carrier leak, etc.[5]. When the RF signal power is distributed equally, this means the S/N ratio between the total power of the RF signal and the Display Average Noise Level (DANL) of the measurement system must be at least 23 dB.

Assuming the total power of the modulated signal is −15 dBm, the required measurement system DANL is found as follows:

$$\begin{aligned}\text{DANL} &= -15\ [\text{dBm}] - 10\log(5\ [\text{GHz}]) - (\text{S/N})\\ &= -15\ [\text{dBm}] - 97\ [\text{dB/Hz}] - 23\ [\text{dB}]\\ &= -135\ \text{dBm/Hz}\end{aligned}$$

Next, we considered the required spurious measurement conditions. In many standards, since measurement is performed with the Resolution Band Width (RBW) set to 1 MHz max., the previously described DANL becomes −75 dBm/MHz at RBW conversion for 1 MHz. Here, the spurious response generated by the measurement system must be less than the DANL so as not to mis-identify small signals within the measured RF signal. Consequently, monitoring a signal with a total power of −15 dBm requires a maximum DANL of −75 dBm/MHz if the spurious response of the measurement system is −60 dBc max. Generally, two-tone signal third-order intermodulation distortion is the main cause of spurious. When the signal input level is −15 dBm, the input Third-Order Intercept point (TOI) must be at least +15 dBm since the two-tone signal third-order intermodulation distortion is −60 dBc max. Table 1 lists the target performance required by this system based on these required conditions.

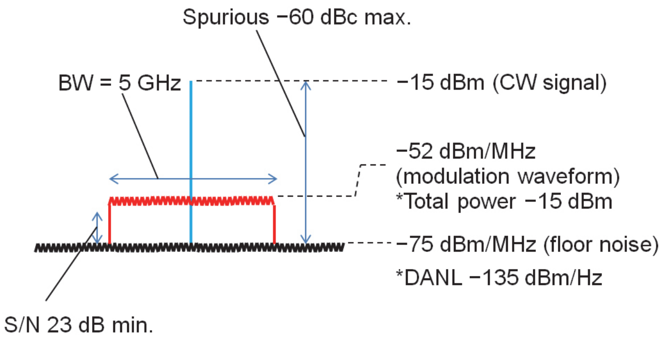

Figure 1 Signal Levels at Modulated Signal Measurement

Table 1 Target Performance of 190-GHz Band Spectrum Measurement System

Item	Specification	Remarks
Frequency Range	140 to 190 GHz	
DANL	<−135 dBm/Hz	Dynamic Range 150 dB
TOI	>+15 dBm	
Spurious Response	<−60 dBc	Input Level −15 dBm

3 Construction of 190-GHz Band Spectrum Measurement System

3.1 Sub-harmonic Mixer Operation Principle

Achieving the target spurious response performance requires designing the frequency for the mixer LO signal and IF signal. Generally, mmWave spectrum measurement systems use harmonic mixers but for high-accuracy measurement, either a fundamental mixer or a sub-harmonic mixer with small conversion loss is desirable. Here, we estimate the generated spurious response based on the sub-harmonic mixer operation principle when using a sub-harmonic mixer of about one-half the frequency of the measured RF signal in the LO signal[6].

Figure 2 shows the operation principle for a sub-harmonic mixer using an Anti Parallel Diode Pair (APDP). The APDP voltage versus current characteristics are an odd-number function with symmetry about the origin, expressed as:

$f(X) = a_1 X + a_3 X^3 + a_5 X^5 + \cdots$

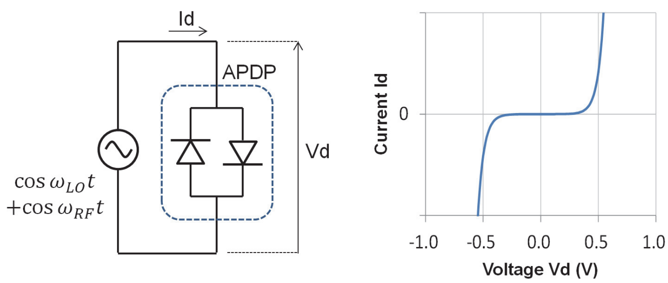

Figure 2 Principle of Sub-harmonic Mixer

Here, the third-order item X^3 of the function f(X) when the RF signal is added to the LO signal $(\cos\omega_{LO}t + \cos\omega_{RF}t)$ is expressed by Eq. (1).

$$\begin{aligned}X^3 &= (\cos\omega_{LO}t + \cos\omega_{RF}t)^3\\ &= \cos^3\omega_{LO}t + 3\cos^2\omega_{LO}t\cdot\cos\omega_{RF}t + 3\cos\omega_{LO}t\cdot\cos^2\omega_{RF}t +\\ &\quad \cos^3\omega_{RF}t \quad \cdots\cdots \quad (1)\end{aligned}$$

The first item on the right side of Eq. (1) is expressed as shown in Eq. (2) by a triple-angle formula.

Item 1

$$= \cos^3\omega_{LO}t = \frac{1}{4}\cos 3\omega_{LO}t + \frac{3}{4}\cos\omega_{LO}t \quad \cdots\cdots \quad (2)$$

The second item on the right side of Eq. (1) is expressed as shown in Eq. (3) by a double-angle formula.

Item 2

$$= 3\cos^2\omega_{LO}t \cdot \cos\omega_{RF}t$$
$$= \frac{3}{2}\cos\omega_{RF}t + \frac{3}{4}\cos(\omega_{RF} + 2\omega_{LO})t + \frac{3}{4}\cos(\omega_{RF} - 2\omega_{LO})t \quad \cdots\cdots\cdots (3)$$

Since the third and fourth items on the right side of Eq. (1) can be substituted by ω_{LO} and ω_{RF} of items 1 and 2, respectively (1), each of the frequency components generated by X^3 of the function f(X) is represented by $3\omega_{LO}$, $3\omega_{RF}$, $\omega_{RF}\pm2\omega_{LO}$, $\omega_{LO}\pm2\omega_{RF}$, ω_{LO}, and ω_{RF}. Here, if ω_{RF} is about twice ω_{LO}, $3\omega_{LO}$, $3\omega_{RF}$, $\omega_{RF}+2\omega_{LO}$, $\omega_{LO}\pm2\omega_{RF}$, and ω_{LO} are filtered by the Low Pass Filter (LPF) in the IF circuit and the remaining $\omega_{RF}-2\omega_{LO}$ is extracted as the IF signal generated by the sub-harmonic mixer.

Next, when considering item X^5 of the function f(X), the frequency components generated by the sub-harmonic mixer are likewise demonstrated to be $5\omega_{LO}$, $5\omega_{RF}$, $4\omega_{LO}\pm\omega_{RF}$, $4\omega_{RF}\pm\omega_{LO}$, $3\omega_{LO}\pm2\omega_{RF}$, $3\omega_{RF}\pm2\omega_{LO}$, $3\omega_{LO}$, $3\omega_{RF}$, $2\omega_{LO}\pm\omega_{RF}$, $2\omega_{RF}\pm\omega_{LO}$, ω_{LO}, and ω_{RF}.

For this type of ideal sub-harmonic mixer, when m is the harmonic order of the RF signal, and n is the harmonic order of the LO signal, the sum of m and n in the frequency components expressed by $|m\times\omega RF + n\times\omega LO|$ generates only an odd-number spurious response. In fact, since the diode-pair characteristics of the sub-harmonic mixer APDP are not completely symmetrical, an even-number spurious response is also generated. However, the spurious response amplitude is determined by the non-linearity characteristics of the diodes and the frequency characteristics of the peripheral circuits, making accurate estimation difficult. As a consequence, the preselector specifications were determined as described below based on spurious response measurement results for the sub-harmonic mixer actually used.

3.2 190-GHz Band Spectrum Measurement System Configuration

Figure 3 shows an external view of this system, which is composed of a front end, spectrum analyzer, signal generator, and PC controller; Figure 4 shows the block diagram.

The RF signal to be measured is input to the mixer after passing via the front-end isolator and preselector. The LO signal supplied to the mixer is created by doubling the signal from the external signal generator. The mixer frequency-converts the RF signal to be measured to an IF signal and the spectrum finally detected by the spectrum analyzer is displayed on the PC controller screen.

Next, the required filter specifications for suppressing the spurious response of this system were examined. The input level of the RF signal to be measured was set to −15 dBm by measuring the spurious response of the mixer actually used. Figure 5 shows the measured spurious response results with a system spectrum observed frequency f_{DSP} of 140 to 190 GHz, and an IF of 20 to 22 GHz. The spurious response generated by the m-order component of the RF signal and n-order component of the LO signal are represented in this figure as IM(m,n). In addition to odd-number order components IM(m,n) = IM(−2,3), IM(2,−3), etc., produced by the sum of m and n, even-number order components IM(−2,4), IM(2,−4), etc., were also measured.

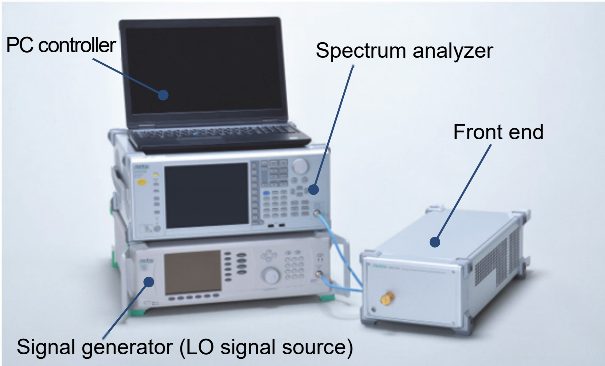

Figure 3 External View of 190-GHz Band Spectrum Measurement System

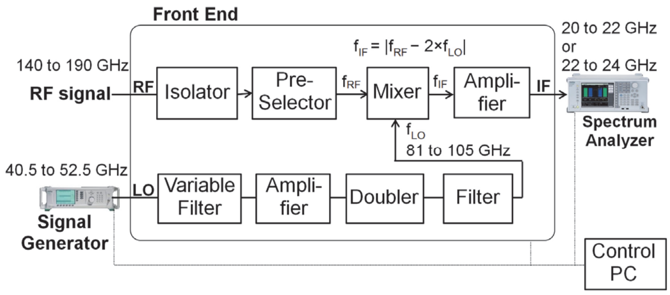

Figure 4 Block Diagram of 190-GHz Band Spectrum Measurement System

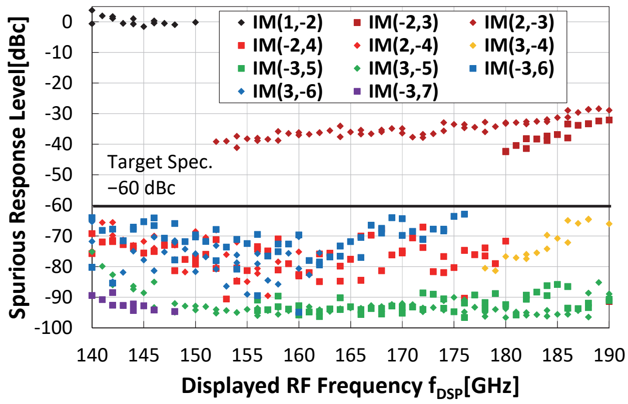

Figure 5 Measured Spurious Response at IF

From Figure 5, achieving a target spurious level of −60 dBc or less and considering a filter margin of 10 dB requires attenuation of the IM(−2,3) and IM(2,−3) components by at least 40 dB. Additionally, the IM(3,−4), IM(−3,6), and IM(3,−6) components must also be attenuated by at least 10 dB. Moreover, with an ideal sub-harmonic mixer, although the even-number order component IM(−2,4) is not generated, the IM(2,−4) is generated with a level of about −70 dBc, so consideration was given to attenuating this component.

4 Preselector

In this system, the LO signal frequency is set stepwise when the displayed frequency increases by 2-GHz, setting the frequency relationship so the IF becomes 20 to 22 GHz (22 to 24 GHz for some parts). Figure 6 shows the spurious response generated by the sub-harmonic mixer in this system. The horizontal axis indicates the system displayed spectrum frequency (f_{DSP}) and the vertical axis indicates the frequency (f_{RF}) of the measured RF signal input to this system. IM(−1,2) indicates the wanted signal to be monitored and all other parameters indicate unwanted spurious response. Even-number order components IM(3,−5), IM(−3,5), and IM(−3,7) below the target level in Figure 5 are filtered out.

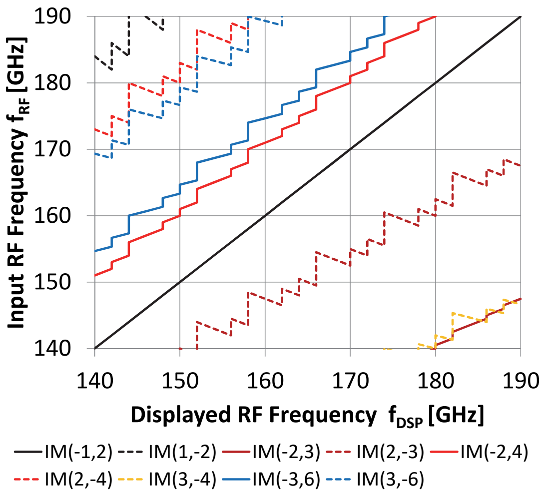

Figure 6 190-GHz Band Spectrum Measurement System Spurious Response

To extract only the IM(−1,2) wanted signal to be monitored, a preselector for selecting only the ideal filters corresponding to the monitored frequencies was provided to cut all other spurious responses and achieve the system target spurious response. We used a previously reported[7] filter-bank-type preselector composed of seven Band Pass Filters (BPF1 to BPF7) each with a different center frequency. Table 2 lists the specifications for each BPF. Figure 7 shows the relationship between the spurious response adjacent to BPF3 and the filter required performance. Within the monitored frequency f_{DSP} range of 152 to 158 GHz, the preselector is designed so the IM(−1,2) wanted signal is within the filter pass band and IM(2,−3), IM(−2,4), and IM(−3,6) unwanted signal components are outside each attenuation frequency for the filter high and low sides.

Figure 8 shows the S_{21} transmission coefficient for each actually fabricated filter. The measured value is about −4 dB compared to the required performance for each BPF of −5 dB and comes close to achieving the required performance including the attenuation.

Table 2 Preselector Filter Required Performance

	Passband (S_{21}>−5 dB) [GHz]	Low Side Attenuation Frequency (S_{21}<−50 dB) [GHz]	High Side Attenuation Frequency (S_{21}<−20 dB) [GHz]
BPF1	139 to 146	135.5	150.2
BPF2	146 to 152	141.9	156.3
BPF3	152 to 158	147.7	162.5
BPF4	158 to 166	153.6	170.7
BPF5	166 to 174	161.4	178.9
BPF6	174 to 182	169.2	187.1
BPF7	182 to 191	177.0	195.8

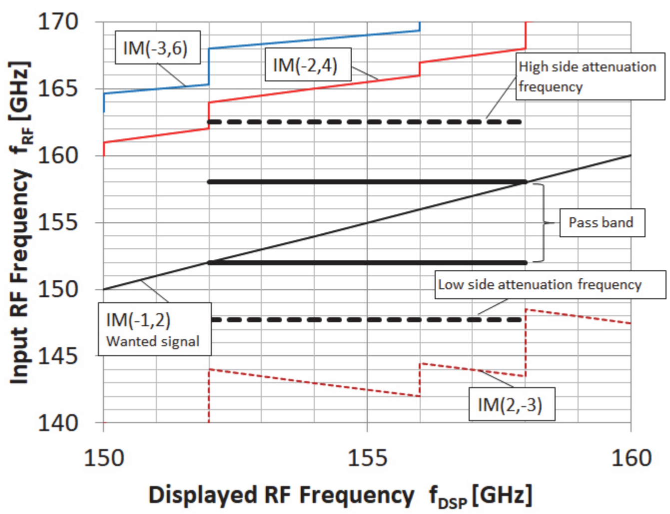

Figure 7 BPF3 Adjacent Spurious Response

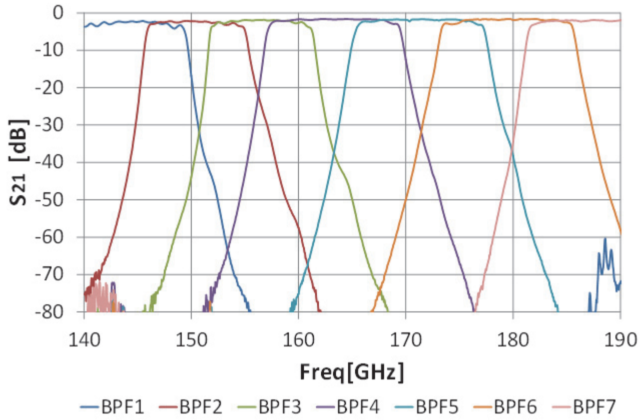

Figure 8 S_{21} Characteristics of Each Preselector BPF

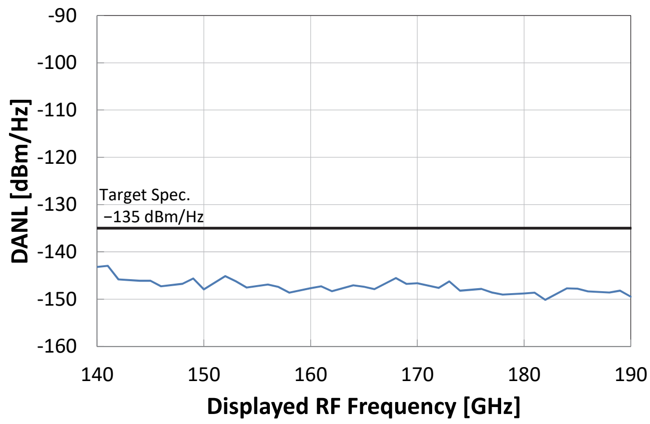

Figure 10 Display Average Noise Level (Detection Mode = Sample)

5 Performance Measurement Results

The following section describes the performance evaluation results for this system with installed filter bank.

5.1 Spurious Response

Figure 9 shows the measured spurious response results.

Designing a filter bank with the margin to achieve the required system performance achieved a result of −85 dBc max., across the entire frequency band and greatly exceeding the target performance of −60 dBc. The deterioration of IM(1,−2) component around 146 GHz is due to poor attenuation of the BPF1 S_{21} characteristics around 190 GHz (Figure 8). It can be improved by tuning the design of BPF1.

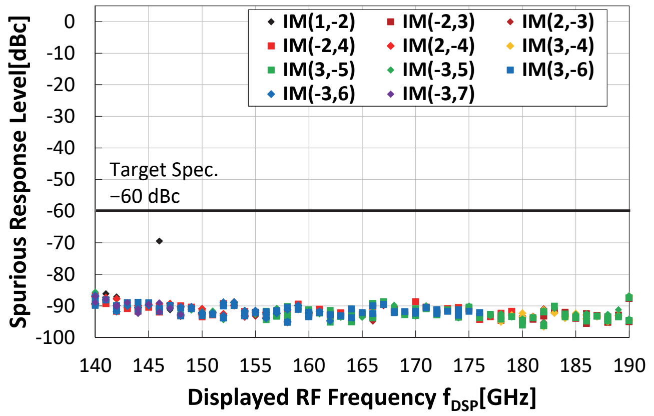

Figure 9 Measured Spurious Response Results (RBW = 100 Hz, Detection Mode = Positive, Input Level = −15 dBm)

5.2 Display Average Noise Level (DANL)

Figure 10 shows the DANL when the system RF connector is terminated. The displayed DANL value per Hz is converted from the measured results when the RBW is 300 Hz.

The worst value of −142 dBm/Hz still meets the target requirement of −135 dBm/Hz.

5.3 Third-Order Intercept Point (TOI)

Figure 11 shows the measured TOI results indicating the two-tone third-order intermodulation distortion performance. Assuming a difference in the TOI performance when the input two-tone frequency interval is inside and outside the preselector band, the frequency interval between the two-tone signal input was measured in two ways. When the frequency interval was 10 MHz, the TOI was +13 dBm or more; when the interval was 10 GHz, the TOI was +33 dBm or more. At the 10-MHz frequency interval, the +15 dBm target was not reached, but the dynamic range difference between the TOI and DANL was 155 dB, exceeding the target performance of 150 dB. Since the relationship between the TOI and DANL is a tradeoff depending on the design value for the input level to the sub-harmonic mixer, installing a fixed attenuator at the sub-harmonic mixer front end to tune the mixer input level seems likely to achieve the TOI target value.

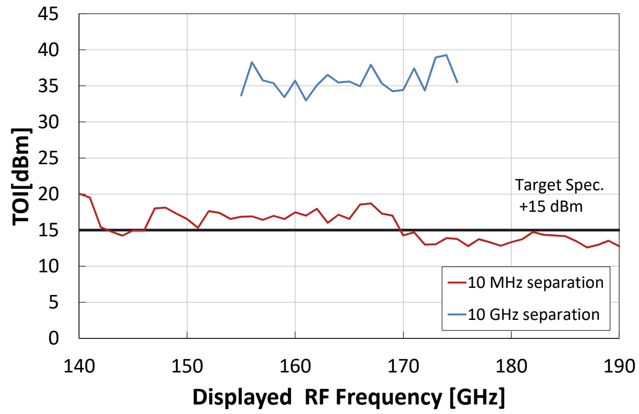

Figure 11 Third-Order Intercept Point Measurement Results (RBW = 100 Hz, Detection Mode = Positive, Input Level =−15 dBm/waveform)

6 Effect of Spurious Suppression

To demonstrate the effect of spurious suppression using the preselector, typical measurement results for the output spectrum from a ×12 multiplier are presented with and without the preselector. Figure 12 shows the measurement setup. The input level to the system was −13 dBm. As well as a ×12-multiplied 142-GHz signal for input of a continuous wave (CW) signal of about 11.83 GHz (142/12 GHz) to the ×12 multiplier, we also tested ×13 and ×14 multiplier signals (approx.. 153.83 GHz, and 165.66 GHz, respectively).

Figure 13 shows multiplier spectrum screens using this system without the preselector. In this case, there is a lot of internally generated unwanted spurious response even with no signal input from the RF connector. Naturally, in addition to the approximately 165.66-GHz RF signal to be monitored, unwanted spurious signals are also observed at 167.0 GHz (−48 dBm level) and 167.33 GHz (−65 dBm level).

The generation of this unwanted spurious is explained below. In this system, the frequency of the RF signal to be measured is split into bands each of 2-GHz and a LO frequency is set stepwise for each band. In the unwanted spurious range of 166 to 168 GHz, the LO frequency f_{LO} is set to 95 GHz so the obtained IF f_{IF} signal of 24 to 22 GHz is displayed as the f_{RF} 166 to 168 GHz spectrum (calculated using the relation $f_{RF} = 2 \times f_{LO} - f_{IF}$).

On the other hand, multiple signals in the RF signal to be measured are output by the multiplier and multiple CW signals with a frequency interval of about 11.83 GHz are input simultaneously. Considering the ×13 multiplier approx. 153.83-GHz signal, high-order intermodulation distortion ($|m \times f_{RF} + n \times f_{LO}|$) is generated between the RF and LO signals in the front end. As an example, consider the IM(2,−3) resulting from the second-order component (m = 2) of the ×13 multiplied signal and the third-order component (n = −3) of the LO signal. From the equation $f_{IF} = 2 \times f_{RF} - 3 \times f_{LO}$, the approx. 153.83-GHz signal becomes an IF signal of about 22.66 GHz within the 24 to 22 GHz display range. Consequently, an unwanted spurious signal originally said not to exist is displayed at about 167.33 GHz.

Similarly, for the ×18 multiplied 213.00-GHz input signal, intermodulation distortion IM(1,−2) is generated between the RF signal first-order component (m = 1) and the LO signal second-order component (n = −2) resulting ($f_{IF} = f_{RF} - 2 \times f_{LO}$) in an IF signal of 23 GHz and displays unwanted spurious at 167.0 GHz. The top display in Figure 13 shows similar other unwanted spurious occurring as a result of inputting an RF signal existing outside the monitored band to the mixer, etc., internal circuits.

Last, Figure 14 shows the multiplier spectrum measured using this system with preselector installed. As described previously we can see that unwanted spurious is held below the system noise floor and only the RF signal to be monitored is observed.

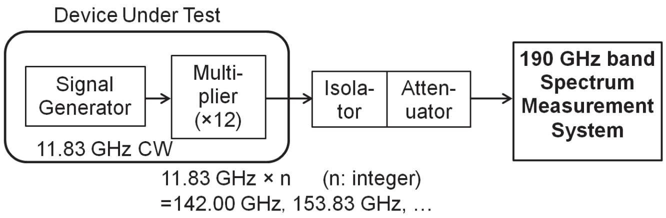

Figure 12 Multiplier Spectrum Measurement System

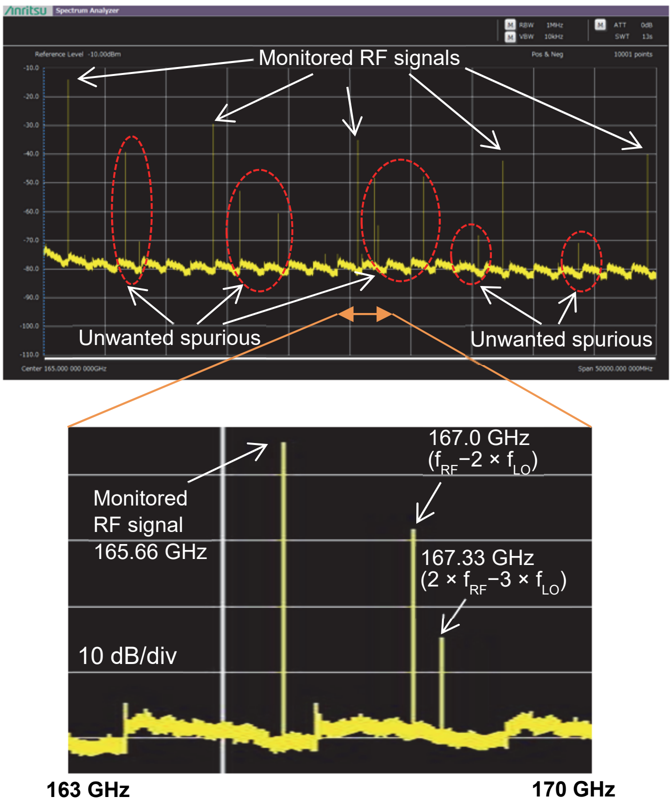

Figure 13 Multiplier Spectrum Without Preselector (Magnified Near Top: 140 to 190 GHz, Bottom: 163 to 170 GHz)

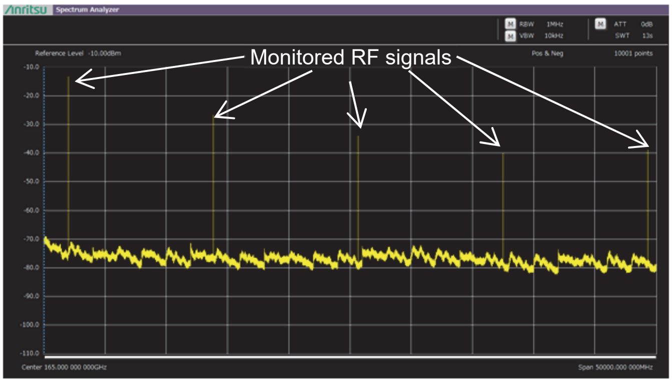

Figure 14 Multiplier Spectrum With Preselector (140 to 190 GHz)

7 Conclusions

We have successfully built a mmWave spectrum measurement system with filter-bank preselector to suppress spurious response of −60 dBc max. (at −15 dBm mixer input level) in the frequency range of 140 to 190 GHz with a dynamic range of 155 dB. Additionally, as one test example, results from monitoring the output of a multiplier confirmed that the preselector adequately suppresses unwanted spurious response generated by this system to enable easy monitoring of only wanted signals.

International Telecommunication Union Radiocommunication Sector (ITU-R) standard SM.329-12 recommends measurement of unwanted radiation up to 300 GHz and our future research targets construction of a spectrum measurement system covering 140 to 300 GHz by combining this reported 190-GHz band spectrum measurement system with a separately developed 300-GHz band system.

Acknowledgments

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References

1) FCC Part95 Subpart M—The 76-81 GHz Band Radar Service
2) M. Fuse, Y. Kimura, and A. Otani: "Over 100 GHz Millimeter-wave Spectrum Measurement System with Pre-selector", 2014 International Microwave Symposium (IMS), No. TH2D-1 (Jun. 2014)
3) Y. Sekine, S. Arai, T. Kawamura, M. Fuse, S. Mattori, H. Noda: "300-GHz Band Millimeter-wave Spectrum Measurement System with Pre-selector.", 2017 Asia Pacific Microwave Conference (APMC), No. WE1E2 (Nov. 2017)
4) Y. Sekine, S. Arai, T. Kawamura: "300-GHz Band Spectrum Measurment System with Preselector", Anritsu Technical Review No.26 (Sep. 2018)
5) Information and Communications Council: "Technical conditions of Field Pickup Unit (FPU) using 120 GHz band" (Jun. 2013) (in Japanese)
6) Hiroshi Tanimoto: "Mission Impossible? A Review of Mixers for Direct-Conversion Receivers", IEICE TRANSACTIONS on Electronics Vol.J84-C, No.5, pp 337-348 (May 2001) (in Japanese)
7) T. Kawamura, M. Fuse, S. Mattori: "Evaluation of >140-GHz Band Filter Bank Prototype", 2018 Asia Pacific Microwave Conference (APMC), No.WE1-B2-1 (Nov. 2018)

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