

New Method for Millimeter-Wave Signal High Sensitivity Receiving and Testing in Range

X. Chen and J. Z. Xu

Abstract—Based on the actual demand of the weak signal (low to -128 dBm) detection in millimeter-wave range test, and through the analysis of signal-to-noise ratio, the W-band receiver system of -128 dBm sensitivity is achieved by using the technology of super-heterodyne broadband multi-channel fast swept-frequency composite channelization. With the designed millimeter-wave calibration source and the spatial attenuation theory, a new test method of the high sensitivity (-128 dBm) in W-band is put forward. Theoretical analysis shows that the minimum power of the millimeter-wave signal source can reach -128 dBm in W-band when the test distance is 290 m and the corresponding attenuation value is about -121.5 dB. The practical measurements using the calibrated millimeter-wave signal source demonstrate the feasibility of the proposed test method.

Index Terms—Range test, high sensitivity, millimeter-wave source, spatial attenuation, weak signal, W-band, signal to noise interference ratio.

I. INTRODUCTION

With the rapid development of millimeter-wave weapons, the research on the millimeter-wave test equipments and the technology of range is vigorously promoted to realize the range millimeter-wave signal monitoring and qualification test of weapons systems [1]-[4]. Due to the measured target in the range test often in motion and some missile-borne millimeter-wave measurement systems working in passive state, the weak millimeter-wave signal requires high sensitivity receiver in the testing system. The advanced level for W-band test system in the world can achieve -128 dBm [5]. But as a result of technical blockade and equipment embargo in the high-end research field, the range millimeter-wave testing technique gap between our country and the western countries is still big, we only reach the sensitivity of -120 dBm W-band high sensitivity in the receiver system [6]. Meanwhile, for the lack of the millimeter-wave band (especially W-band) test instrument, there is no testing standards and conditions for more than 40 GHz system performance [7], and there exist no performance test and calibration of the high-sensitivity W-band system in our country.

In order to make a breakthrough in W-band test field, this paper, by using weak signal detection technology of super-heterodyne broadband multi-channel fast swept-frequency composite channelization and the low noise amplifier good in W-band noise coefficient, develops a

W-band test system with the sensitivity to -128 dBm. And in the combination of the millimeter-wave calibration source with the spatial attenuation method, a minimum -128 dBm W-band millimeter-wave weak signal source is provided, realizing the test and calibration on the sensitivity of receiving system.

II. DETECTION OF MILLIMETER-WAVE WEAK SIGNAL

A. Detection Method

The key of weak signal detection is to eliminate the noise and improve the sensitivity of signal detection, namely to improve signal to noise interference ratio (SNIR) of the detection system. Noise is the basic reason for the sensitivity limit of the receiver. For the receiver noise coefficient, the primary design is very important, so in order to effectively improve the receiving sensitivity, the low noise amplifier (LNA) is placed in the front of the receiver. According to the current millimeter-wave components level, the noise coefficient of a single W-band millimeter-wave LNA is 6-9 dB, the gain is 20 dB. And the noise coefficient of the W-band mixer is 6-8 dB [8]. Take the two stage cascade of LNA and a single stage of the mixer into consideration, the total noise coefficient is [9]:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} \quad (1)$$

where F_1 is the noise coefficient for radio frequency transmission loss (take 2 dB); G_1 is the gain caused by the radio frequency loss in the transmission line (take -5 dB), F_2 is the noise coefficient of the first stage LNA (take 7 dB), G_2 is the gain of the first stage LNA (take 20 dB), F_3 is the noise coefficient of the second stage LNA (take 8 dB), G_3 is the gain of the second stage LNA (take 20 dB), F_4 is the noise coefficient of the first stage mixer (take 7 dB). As shown in (1), the total noise coefficient is 11.6 dB. We can see that the system noise coefficient is mainly influenced by the radio frequency transmission loss and the millimeter-wave LNA, so in order to effectively reduce the noise coefficient, the W-band LNA with the current international leading noise coefficient index is used.

The concept of sensitivity originates from the minimum detectable signal power in the radar equation, namely the least input signal power when the signal to noise ratio is equal to 1. The higher the receiver sensitivity, the stronger the weak signal reception ability is. The system sensitivity of the receiver can be calculated in the formula as follows [10]:

$$P_{S \min} = kT_o B_{RI} F \quad (2)$$

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where k is Boltzmann constant (1.38×10^{-23} J/k), T_o is the receiver's operating temperature (take 290 K), B_{RI} is the linear pass-band of the receiver (the total pass-band of high frequency and intermediate frequency part of receiver). If the measured signal is very weak, we can reduce the pass-band bandwidth of the receiver to improve the sensitivity of the system. Therefore according to the calculation as shown in (2), the pass-band bandwidth of the receiver should be smaller than 3 kHz to meet the requirements of receiving the -128 dBm minimum signal.

However, the actual pass-band bandwidth of the received signal in W-band is 6 GHz. To improve the sensitivity of the system receiver, the channel processing technology is used. And by taking the margins into account, the minimum resolution bandwidth of the channelized receiver is designed to 1 kHz. But the amount of 6×10^6 channels is needed when the 6 GHz bandwidth is transformed into the 1 kHz, which is quite difficult in engineering realization. Taking it into account that the measured signals have a certain dwell time, the time for space approach is used, which means to use the heterodyne method to shift the broadband signal into the intermediate frequency band, and then mix the measured signal with the swept-frequency synthesizer and divide the wider broadband into a set of sub-band with narrow bandwidth in time. By doing so, the number of channels can be greatly reduced and still achieve 1 kHz channel bandwidth after the two stages processing.

Due to the dynamic test speed requirements and the large signal dispersion bandwidth, the direct digital frequency synthesizer (DDS) swept-frequency and channelization receiving are combined in the treatment. The processes are as follows: divide 1 GHz dispersion bandwidth of the measured signal into 200 MHz sub-band by using the swept-frequency synthesizer, and each 200 MHz sub-band is divided into 10 parallel 20 MHz channels through channelization, each of which, by the phase-locked loop (PLL) frequency synthesizer, is frequency-swept, by step with 1 MHz, to achieve parallel 20 point/channel frequency sweeping. In order to improve the channelization processing speed further, each 1 MHz frequency point is tested with 1 kHz/step by the method of fast swept-frequency of DDS and the crystal filter group is used to complete fine narrow-band filtering to reduce the bandwidth of the intermediate frequency receiver to 1 kHz, ensuring the detection sensitivity. With the rapid feature of DDS, the swept-frequency time for each 1 kHz within 1 MHz is reduced to less than 1 μ s, making the response speed of the channelized receiver better than 50 ms/200 MHz.

B. Analysis of Signal to Noise Interference Ratio

The signal to noise interference ratio of the weak signal detection system is equivalent to the ratio of input noise bandwidth to the system noise equivalent bandwidth. The larger the SNIR, the stronger the noise processing ability and the higher the weak signal detection level.

When the radiation resistance of the antenna and the input resistance of the receiver matches, the total input noise power can be calculated according to the corresponding relation between the power and the temperature:

$$P_n = k(T_e + T_o)B = kT_oFB \quad (3)$$

where $T_e = (F - 1)T_o$ is equivalent noise temperature. The minimum input signal level $P_{in} = -128$ dBm, so the input SNR of the receiver is,

$$I_{SNR_in} \geq P_{in} / P_n = -63.4\text{dB} \quad (4)$$

Considering the back-end signal processing (such as the radio frequency measurement in passive monitoring), we take $I_{SNR_out} = 4$ dB, according the definition, SNIR of the whole system should satisfy $I_{SNIR} \geq 67.4$ dB.

It is assumed that the receiver noise obeys the normal distribution (Gaussian white noise), according to the analysis of section A, the input noise bandwidth is approximate as the radio frequency bandwidth $B=6$ GHz, and the minimum resolution of the channelized receiver is 1 kHz bandwidth, so the maximum SNIR provided by the channelized receiver can be expressed as:

$$I_{SNIR_max} = \frac{B}{\Delta f_{min}} = 67.8\text{dB} \quad (5)$$

From (5), we can see that it can improve SNR by 67.8 dB through the weak signal detection method of super-heterodyne broadband multi-channel fast swept-frequency composite channelization, realizing the reliability of the W-band weak signal (-128 dBm) detection and the demodulation of the corresponding parameters.

III. THE SYSTEM SENSITIVITY TEST METHOD

A. Test Principle

The system receiver sensitivity is a comprehensive index. If the system meets the demands of the receiver sensitivity index, it is implied that other indicators of the system also meet the index requirements. At present, the system sensitivity test method is to add the known standard power source of the precise attenuation to the receiver input for a test in the laboratory environment [11], [12]. But the high-precision attenuators and the good performance isolators are lacked in W-band, so the leakage power of the signal source is larger, which is close to or even larger than the output energy of the attenuator. Besides, according to the experience from the indoor measurement, the attenuation effect is decreased obviously when the attenuation value is more than 90 dB, namely the millimeter-wave signal will be no longer weakened with the increase of the attenuation value. Therefore, to test the sensitivity index of -128 dBm of the W-band receiver system, the key is to provide a W-band millimeter-wave weak signal source with its minimum power of -128 dBm.

Based on the design and development of the millimeter-wave calibration source, the sensitivity test experiment plan of the receiver is designed under the existing condition according to the spatial distance attenuation principle. The test principle is shown in Fig.1. The method uses the

millimeter-wave calibration source after spatial distance attenuation assisted by the absorbing materials with a certain attenuation value to realize the -128 dBm weak millimeter-wave power signal, which is required by the measurement of millimeter-wave signal monitoring system.

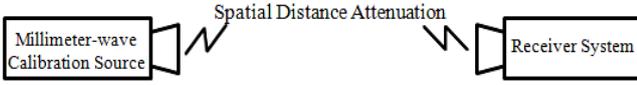


Fig. 1. Sensitivity testing principle

Provided the power of the emission source is P_t , the gain of the antenna is G_t , then the power intensity at a distance of R to the emission source along the wave beam axis is,

$$I_s = P_t G_t / 4\pi R^2 \quad (\text{W/m}^2) \quad (6)$$

When the signal is received by the isotropic antenna, and the effective aperture area of which is $A_e = \lambda^2 / 4\pi \quad (\text{m}^2)$, the power received is as follows,

$$P_r = P_t G_t \lambda^2 / (4\pi R^2) \quad (\text{W}) \quad (7)$$

where λ is the operating wavelength.

We can see that the spatial distance attenuation L_R caused by distance R is:

$$L_R = \lambda^2 / (4\pi R^2) \quad (8)$$

When the operating wavelength $\lambda=3\text{mm}$ (in W-band), the influence of atmosphere attenuation is ignored, the relationship between the spatial distance attenuation L_R and the distance R is showed in Fig. 2.

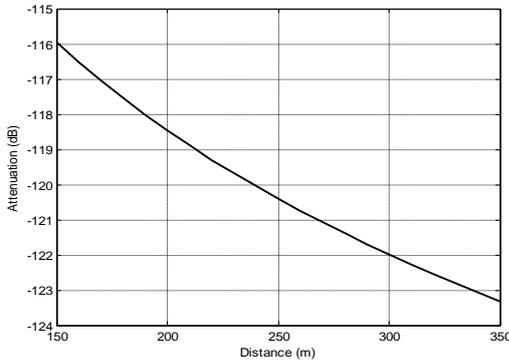


Fig. 2. Relationship between spatial attenuation and distance

From Fig. 2, we can see that the value of spatial distance attenuation in W-band probably range from -116 to -123 dB when the distance range from 150 to 350 m, which satisfy the condition of far less than -90 dB.

B. Millimeter-Wave Calibration Source

The calibration source consists of the millimeter-wave power source, the standard antenna, the fixed attenuator, the multilayer absorbing materials and the power supply. Its simplified structure is shows in Fig.3. The import W-band standard source is used as the millimeter-wave power source, and its operating frequency is selected in the middle of

receiver band of the measured millimeter-wave signal monitoring system with its power magnitude P_t ranging from 0-20 dBm. The millimeter-wave antenna is a standard horn antenna, the gain is $G_t \approx 20\text{dB}$. The fixed attenuator is the standard broadband fixed attenuator usually with the value of attenuation $L_D = 30 - 40\text{dB}$. The millimeter-wave power source signal first radiates through the antenna radiation, then passes through absorbing material and distance attenuation, and finally arrives at the receiver antenna aperture of the millimeter-wave signal monitoring system. We can adjust the attenuation value L_M to meet the requirements of the test sensitivity in the tested system by using the absorbing plate, and increasing or decreasing the thickness or number of the absorbing plate.

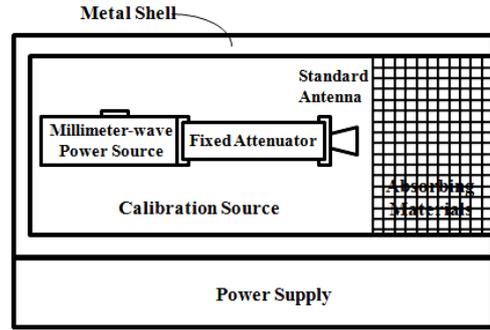


Fig. 3. Structure diagram of the millimeter-wave calibration source

IV. EXPERIMENT AND RESULT

Based on the above method, the concrete steps of the receiving sensitivity test of the millimeter-wave signal monitoring system are as follows:

1) The millimeter-wave calibration source should be calibrated in the laboratory environment. Specifically, the millimeter-wave frequency meter and the power meter are respectively used to measure the frequency f_0 and the power P_t of the millimeter-wave power source. The attenuation value L_M of the absorbing material is measured by the actual power source and the power meter in the anechoic chamber. The gain G_t of the millimeter-wave standard antenna and the attenuation L_D of the fixed attenuator are provided by the suppliers, which are determined according to actual operating frequency. The parameters of the millimeter-wave calibration source after the first calibration are showed in Table I.

TABLE I: PARAMETERS OF THE MILLIMETER-WAVE CALIBRATION SOURCE

Parameters	f_0 (GHz)	P_t (dBm)	L_D (dB)	G_t (dB)	L_M (dB)
W-band	94.53	10.0	-30.0	19.5	-32.9

2) According to the calibration value of the parameters of the millimeter-wave calibration source, the choice of the testing distance in field experiment can be obtained by the analysis and calculation. The known receiver power of the receiver system is equivalent to,

$$P_A \text{ (dBm)} = P_t + L_D + G_t + L_M + L_R + G_r \quad (9)$$

where, the receiving antenna gain $G_r = 26\text{dB}$ (average value of the measured data). In order to make the millimeter-wave signal power arriving at the antenna aperture of the measured millimeter-wave signal monitoring system satisfy the sensitivity requirement of -128 dBm , by putting the parameters in Table 1 into (9) and considering (8) or Fig.2, it can be obtained that when the testing distance is 290 m, the value of the spatial distance attenuation L_R is about to be -121.5 dB , then the received power of receiver is -128.9 dBm .

3) To master the free space test field. According to step 2), the measured millimeter-wave signal monitoring system and the millimeter-wave calibration source should be placed at the position apart from 290 m, and the actual test experiment is conducted at the stadium of Nanjing University of Science and Technology shown as Fig.4. The measured millimeter-wave signal monitoring system is placed in the second floor platform, and the millimeter-wave calibration source is placed in the round platform which is in the opposite of the second floor platform with the similar vertical height, or vice versa. The test distance is adjusted based on the actual measurement and satellite photos ranging. In order to guarantee the calibration accuracy, the testing environment is clear, no wind, 20°C with no metal objects, buildings, trees and other obstacles higher than the venue plane within the test distance range and 30 m at both sides.

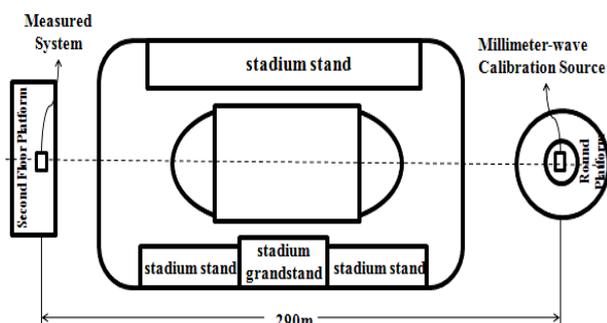


Fig. 4. Station diagram of system sensitivity test

4) According to step 1) to step 3), the system sensitivity is measured repeatedly under the test conditions. The measured results show that the average field intensity arriving at the antenna aperture of the receiver is -128 dBm .

V. CONCLUSION

Based on the actual needs of the millimeter-wave weapons test systems in the national shooting range, researches is made on the method of the reception and sensitivity measurement of the millimeter-wave weak signal (as low as -128 dBm). On the basis of the analysis on signal-to-noise ratio, the technology of super-heterodyne broadband multi-channel fast swept-frequency composite channelization is adopted, and the W-band receiver system of -128 dBm sensitivity is achieved, which, a breakthrough in the existing W-band test means in our country, can reliably detect the range millimeter-wave weak signals and

demodulate the corresponding parameters.

In terms of the problem that there is no condition of the sensitivity testing of the W-band system with high sensitivity, a new method of the high sensitivity testing is proposed. The core is to use the spatial attenuation theory and the self-developed millimeter-wave calibration source to provide a millimeter-wave standard signal source in W-band with the power as low as -128 dBm . The feasibility of the method is proved by the actual measurements in the free space test field, and the method serves as a new means for the range test equipments and technology.

But in order to the easy implementation of the high sensitivity receiver, the critical low-noise amplifier module in the front of the receiver is still used the imported devices, which is not conducive to reduce costs in engineering. So the design of W-band broadband low-noise amplifier will be conducted in further studies.

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