Invited Paper

Research progress of THz measurement technology based on rectangular waveguide

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Abstract: In this paper, in order to meet the testing requirements of terahertz scientific researches and engineering applications, we have introduced the relevant international standards of terahertz transmission lines, as well as the precise manufacturing and process realizations of complex three-dimensional guided wave structures such as terahertz rectangular metal waveguides, multilayer guided wave structures and double directional coupling structures. Then, the research progress on active devices and circuits such as terahertz Schottky diodes, high-efficiency frequency multiplication, harmonic mixing, power detection, etc. are presented. On the basis of the research progress, four common measuring instruments including terahertz vector network analyser, signal generator, spectrum analyser and power meter are developed. Furthermore, three measuring systems consisting of material, radar cross section (RCS) and antenna are developed. The developed measuring instruments and systems can cover the frequencies ranging from 50 *GHz* to 750 *GHz*. The whole industry chain including the core devices, components, measuring instruments and systems are independently controllable, which is able to provide a complete set of measuring solution for terahertz scientific research and engineering applications.

Keywords: Millimeter wave; Terahertz; Measuring instruments; Measuring systems.

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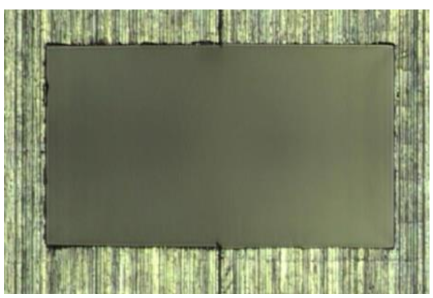
1. Introduction

With the rapid development of electronic systems such as radar, mobile communication, satellite communication, satellite navigation, remote sensing telemetry, space exploration, electronic reconnaissance and electronic countermeasures, and precision guidance, etc., the electromagnetic signals in the microwave and millimeter wave bands are getting denser and denser, and the electromagnetic spectrum resources are getting tighter and tighter. The development and utilization of terahertz (THz) spectrum resources have risen to the major strategic need of the developed countries in the world. The comprehensive utilization of terahertz spectrum resources has already become a hot research topic [1-5]. The measuring instruments, which is the guarantee for researches and engineering applications, are inseparable from the terahertz scientific research and engineering applications. Based on waveguide transmission lines, the 41st Research Institute of China Electronics Technology Group (CETC) has developed terahertz measuring instruments and systems to support terahertz technology researches and engineering applications.

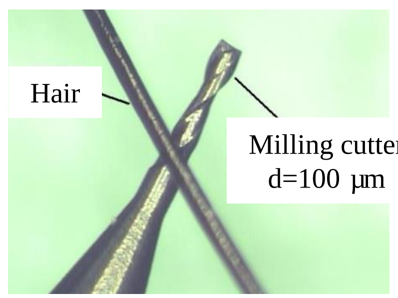
This paper mainly focuses on the development of terahertz measuring instruments that are based on waveguide transmission lines, as well as key technologies such as the forming processes of terahertz waveguide transmission lines and complex guided-wave structure, terahertz devices, terahertz signal generation, terahertz signal detection and analysis, terahertz power detection, etc. Then, the terahertz measuring modules are developed upon microwave measuring instruments. Four terahertz instruments (vector network analyzer, signal generator, spectrum analyzer and power meter) and three measuring systems (materials, antennas and radar cross section) are developed to provide basic measurement tools for the terahertz scientific research and engineering applications.

2. Forming process of the terahertz three-dimensional complex guided-wave structure

The terahertz transmission lines are generally realized by rectangular metal waveguide. Terahertz active and passive circuits such as directional couplers, matched loads, filters, frequency multipliers, mixers, and amplifiers, etc. are all implemented in long and narrow rectangular metal waveguides. Thus, the forming process of rectangular waveguide and complex three-dimensional structure inside the waveguide are the key difficulties for the fabrication.



(a)



(b)

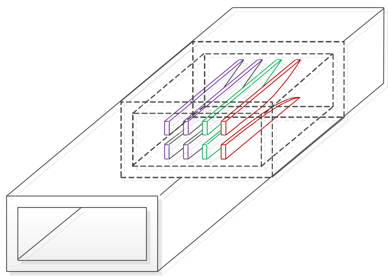
Fig. 1 Waveguide fabrication (a) Cross-section of waveguide operating from 500 *GHz* to 750 *GHz* (b) Comparison of milling cutter and hair.

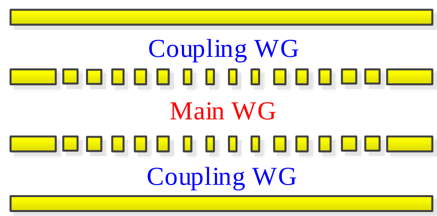
2.1. Forming process of the terahertz rectangular waveguide

As the operating frequency increases, the cross-sectional dimensions of terahertz rectangular metal waveguides become smaller and smaller, making the processing more and more difficult. Taking the frequencies ranging from 500 *GHz* to 750 *GHz* as an example, the cross-sectional dimension of the rectangular metal waveguide is only 0.380 *mm* × 0.190 *mm*. To fabricate the rectangular metal waveguide as shown in Figure 1(a), the forming process is critical. A solid carbide coated milling cutter, which is presented in Figure 1(b), is chosen as the machining tool after repeated experiments. The cutting and burr processing method of the micro-diameter milling cutter are optimized to realize the exact fabrication of rectangular metal waveguides

2.2. Molding process of the multilayer terahertz waveguide

For the long and complex multilayer waveguides, the one-shot molding of the precision machining process is adopted after hundreds of tests and process exploration. Figure 2(a) indicates the realized multilayer structures in a small elongated rectangular metal waveguide. The waveguide structure has a length of 50 *mm* and a dimensional tolerance of ±1.5 μm. The precise assembly of the multi-layer complex waveguide structures are realized by micro stress clamping and secondary positioning, leading to a high positioning accuracy (±1.5μm) between the multilayer structures.





(a) (b)

Fig. 2 Multilayer waveguide fabrication (a) Multilayer structures in a small elongated rectangular metal waveguide (b) Stacked placement of the dual orientation coupling scheme.

2.3. Molding process of the terahertz double directional coupling structure

Terahertz directional couplers are the key component of vector network analyzers to separate incident, reflected and transmitted waves. Figure 2(b) shows the stacked placement of the dual orientation coupling scheme. The excitation signal injects into the main waveguide, and the upper and lower sub-waveguides respectively couple the incident wave and the reflected wave (or transmission wave). Pre-drilling of the micro-diameter drill and spiral cutting of the micro-diameter milling cutter are the main process of the coupling hole forming, which can form dozens of coupling holes with different sizes and positions at one time. The minimum hole diameter is only 0.1 *mm* and the accuracy of the hole diameter is ±2 μm.

3. Design and manufacturing technology of the terahertz active circuit

Active components， such as terahertz frequency multipliers, harmonic mixers and wideband detectors， are the crucial components of terahertz measurement instruments. Multi-stage frequency multipliers translate the microwave signal to the terahertz signal. Analogically, harmonic mixers perform the opposite transformation process. Meanwhile, the terahertz signal can also be converted into the DC signal by wideband detectors to measure the power.

3.1. Terahertz schottky diode

As shown in Figure 3, the 13th Institute of China Electronics Technology Group Corporation developed a quasi-whisker contacted anode structure to consumedly reduce the parasitic capacitance. Multi-layer metal air bridge manufacturing processes are adopted to enhance the support strength of the suspended air bridge. Flexible ultra-thin wafer cutting methods are employed to overcome the fragile problem of ultra-thin GaAs substrates. Then, a 5 μm ultra-thin GaAs Schottky diode is successfully developed with a cutoff frequency of 10 *THz* and localized the terahertz chips [6].

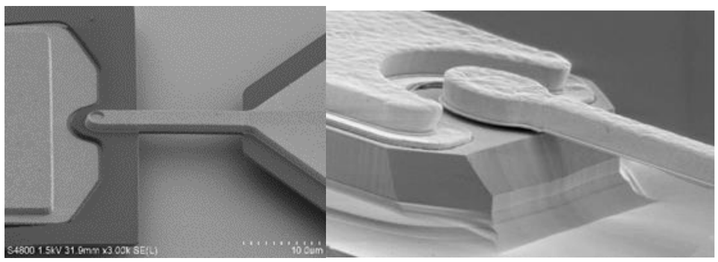


Fig. 3 THz GaAs Schottky diodes with point support air bridge structure.

3.2. High-Efficiency terahertz frequency multiplier

All-solid-state terahertz frequency multiplier links were developed by using the localization terahertz diodes [7-8]. Compared with InP materials and processes, the GaAs material process is more stable and has a higher yield [9]. The conventional terahertz frequency multiplier generally adopts the doubler scheme based on a dielectric substrate. Due to the dielectric loss and parasitic substrate mode, it is difficult to maintain high efficiency in an ultrawide frequency range [10]. A fully metal doubler structure is proposed to eliminate the dielectric loss and substrate parasitic for the enhanced efficiency with an extended bandwidth. Based on spatial power combining concept, as depicted in Figure 4, several planar diodes series structures are introduced to increase the power handling of the multiplier. As depicted in Figure 5, a multilayer multiplier scheme is proposed to eliminate the dielectric loss and shows good balancing characteristic, which enables the multiplier to realize good performances such as high-power handling, high-efficiency, excellent spectral purity, and so on.

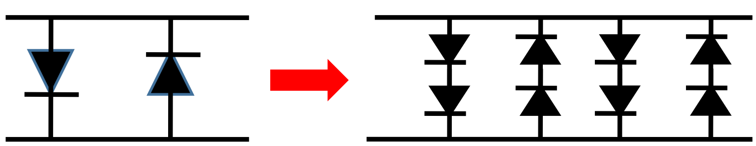


Fig. 4 Adopting several planar diodes series structure to enhance power handling.

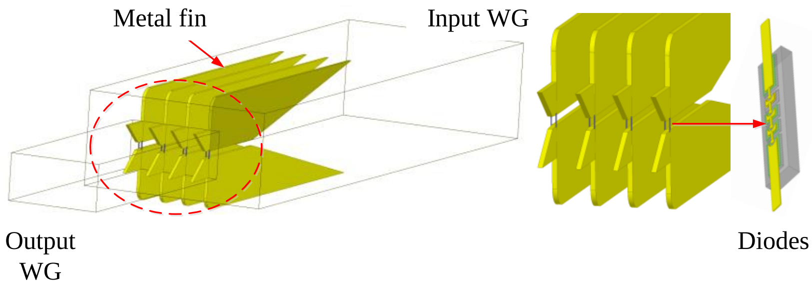


Fig. 5 Structure of the spatial power combined frequency multiplier.

3.3. Harmonic mixers with high local oscillator

As shown in Figure 6, harmonic mixer scheme with high local oscillator (LO) and integration is presented. It introduces the multiplier amplification chain and some filters are used in the LO chain and IF chain. The LO amplifier, the LO filter, the IF filter and the terahertz diode pairs are integrated in an 8 *mm* × 0.5 *mm* × 30 μm circuit. A better compromised design between broadband and high performance is realized with low intermodulation, less spurious response and high detection sensitivity [11].

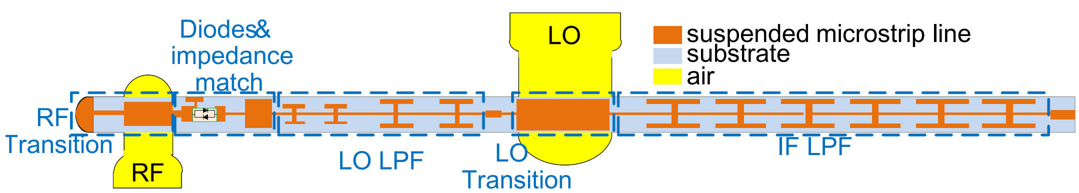


Fig. 6 Configuration of the harmonic mixer with high local oscillator.

3.4. Fast detection of the terahertz signal

The balanced detector with schottky diodes converts the terahertz signal into DC signal and they are positively correlated. As shown in Figure 7, the reduced waveguide pumps the terahertz signal to schottky diode and realizes an excellent impedance matching. It enhances the isolation between the terahertz signal and the 50 *MHz* calibration signal and improves the detection sensitivity of the terahertz signal.

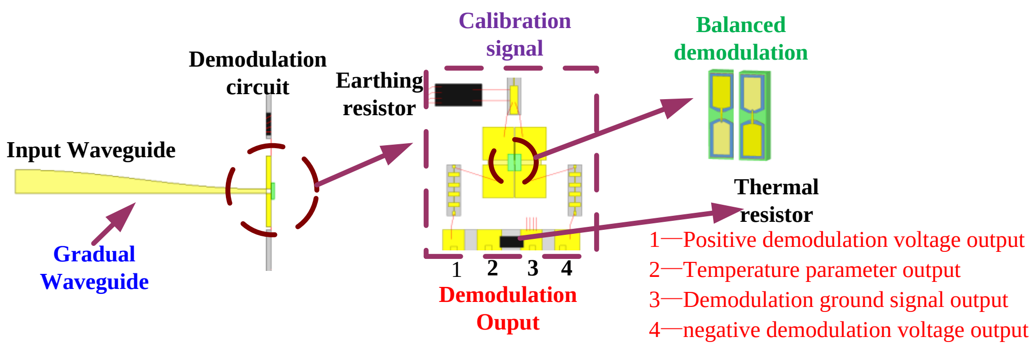


Fig. 7 Configuration of the Terahertz detector.

4. Terahertz measuring instruments and systems

Via breaking through THz common technologies of core devices and key components, several commonly used THz measuring instruments and systems are designed by making use of the microwave measuring instruments, such as Vector Network Analyzer (VNA), signal generator, spectrum analyzer, power meter (PM), and the materials, antennas and radar cross section (RCS) testing system in the range of 50 *GHz*-750 *GHz*, which can provide a perfect testing solution.

4.1. Terahertz signal generator

Terahertz signal generator is composed of a microwave signal generator and a terahertz multiplier module, which can satisfy the testing requirements in different frequencies via using corresponding modules. The multi-stage multiplier method is used to generate terahertz signals from microwave frequency band to terahertz frequency band. Figure 8 shows the terahertz multiplier link, and Table I presents the required different multiplication factors for different waveguide frequency bands. Both the multiplier and the power amplifier are the key to the terahertz multiplier link, which together determine the output power of the terahertz signal, as shown in Figure 9. Until now, the output power of the terahertz signal generator is limited due to the missing of the high-frequency driving power amplifier. The output power of the terahertz signal can be significantly improved when the high-frequency driving power amplifier is developed.

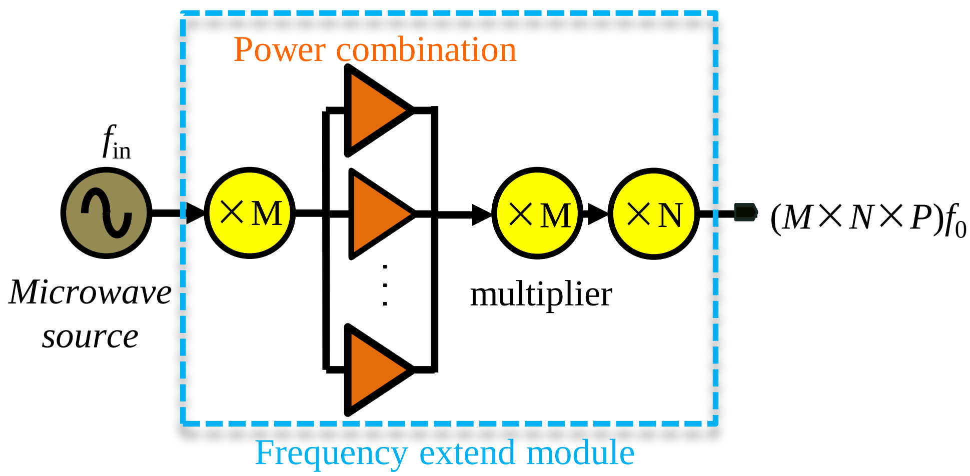


Fig. 8 Topology of the terahertz signal generator.

Tab. I Configurations of the multiplier and mixer links in 50 *GHz* -750 *GHz.*

Frequency extend module	**THz signal generator**		**THz spectrum analyzer**			
***f* (GHz)**	K=M×N× P	f_{in} (GHz)	h^{th} harmonic mixer	J=m×n× p	f_{LO} (GHz)	f_{IF} (MHz)
50-75	2×2	12.5-18.8	1	2×2	12.5-18.8	425MHz
60-90	2×3	10-15	6	×2	5-7.5	
75-110	2×3	12.5-18.3	7	×2	5.4-7.9	
90-140	2×3	15-23.3	1	2×3	15-23.3	
110-170	2×2×3	9.2-14.2	9	×2	6.1-9.4	
140-220	2×3×2	11.7-18.3	2	2×3	11.7-18.3	
170-220	2×3×2	14.2-18.3	7	×4	6.1-7.9	
170-260	2×3×2	14.2-21.7	2	2×3	14.2-21.7	
220-325	2×3×3	12.2-18.1	9	×4	6.1-9.0	
260-400	2×3×3	14.4-22.2	2	2×3×2	10.8-16.7	
325-500	2×2×3×3	9.0-13.9	4	2×3	13.5-20.8	
500-750	2×3×3×3	9.3-13.9	4	2×2×3	10.4-15.6	

4.2. Terahertz spectrum analyzer

Terahertz spectrum analyzer is composed of a microwave spectrum analyzer and a terahertz harmonic mixing module, which can meet the testing requirements in different frequencies via using corresponding modules. As shown in Figure 10, a high frequency LO multiplier link is integrated in the terahertz harmonic mixing module, which can improve the sensitivity of the harmonic mixer by reducing the mixing order and the conversion loss at the expense of increased costs. As shown in Table I, the configuration information indicates that the terahertz harmonic mixer at different frequency bands require different LO multiplying factors and harmonic mixing orders. The sensitivities of the terahertz spectrum analyzers are presented in Figure 11.

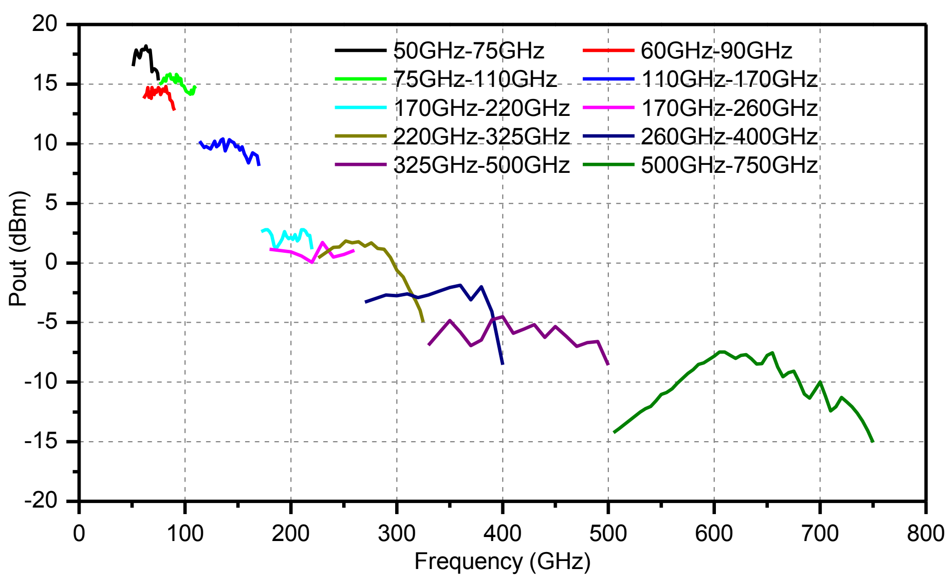


Fig. 9 Output power of the terahertz signal generator at different frequency bands.

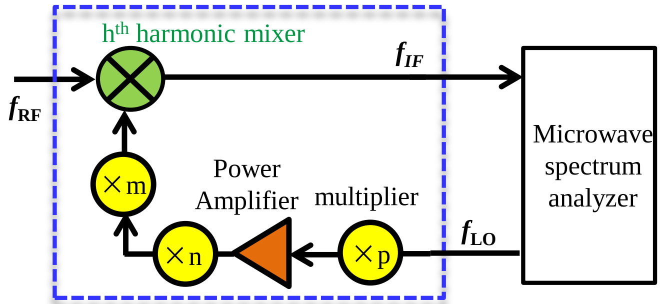


Fig. 10 Topology of the terahertz spectrum analyzer.

4.3. Terahertz vector network analyzer

As shown in Figure 12, the terahertz VNA is composed of terahertz spread spectrum module and S-parameter testing module based on the microwave VNA, which can meet the testing requirements in different frequencies via adopting corresponding S modules. The terahertz excitation signal is generated via a multiplier link. Terahertz signal is down-converted to the intermediate frequency by a harmonic mixer. The configuration of the multiplier link and the harmonic mixer presented in Table I is adopted in the development of the THz VNA. Two-port terahertz network S-parameter can be acquired by employing a dual directional coupler to extract the incident, reflected and transmitted waves. In addition, the phase-locking problem caused by the high-order multiplier and harmonic mixer has to be resolved while testing S-parameter. The phase noise of the terahertz signal can be decreased and the phase can be accurately locked through the multi-ring phase-locking method. Both the amplitude and phase of terahertz signal can be acquired via utilizing the digital synchronous detection technology based on the quadrature demodulation with a high accuracy. Figure 13 shows the dynamic range of the THz VNA.

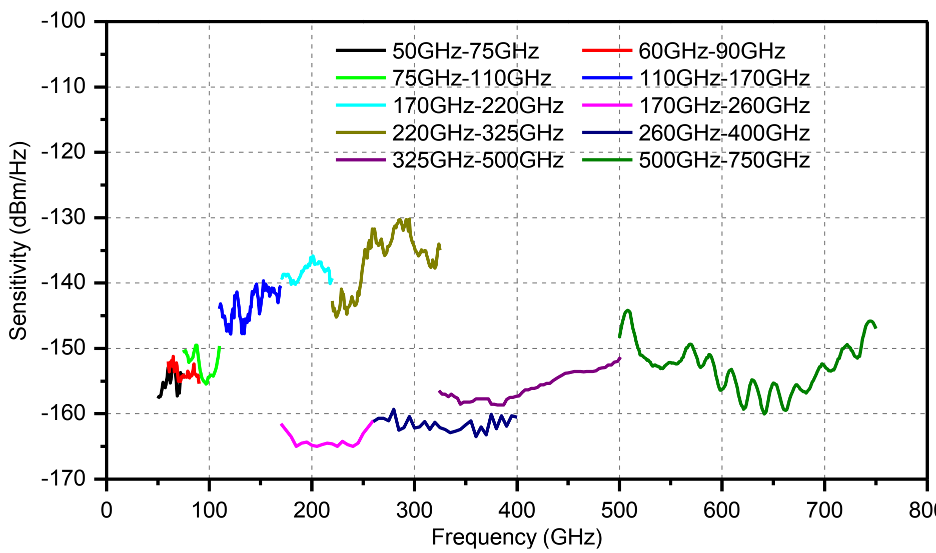


Fig. 11 Sensitivities of the terahertz spectrum analyzer at different frequency bands.

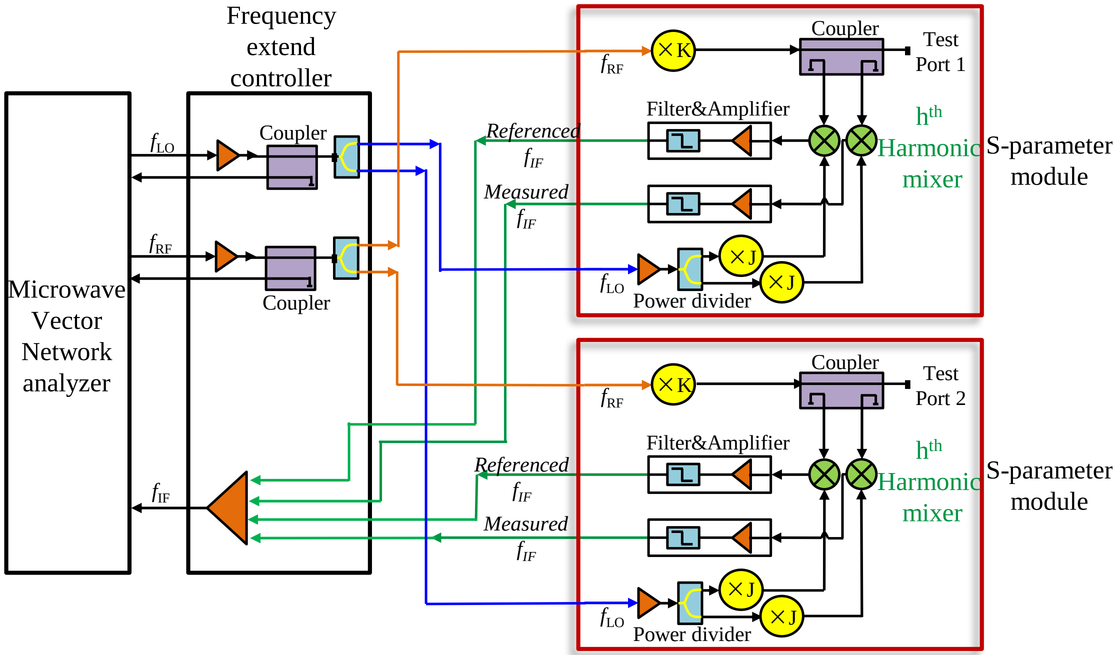


Fig. 12 Topology of the terahertz vector network analyzer.

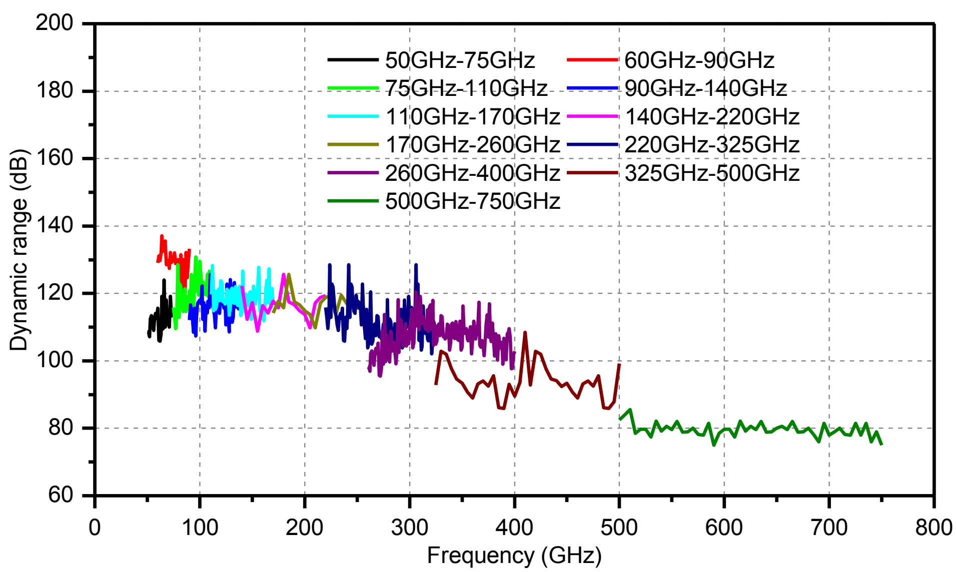


Fig. 13 Dynamic range of the terahertz vector network analyzer at different frequency bands.

4.4. Terahertz power meter

Based on microwave PM, terahertz PM is composed of a power probe and a terahertz power sensor for each standard waveguide frequency band. The sensitivity of power measurement is improved by using the balanced detection scheme. The 3-D (power, frequency and temperature) compensation method is used to improve the testing range of the schottky diode-based power sensor and the temperature stability of power measurement. The measurement speed is 1000 times that of the thermistor and thermocouple power sensors. Figure 14 indicates the sensitivity of the THz power meter at various bands.

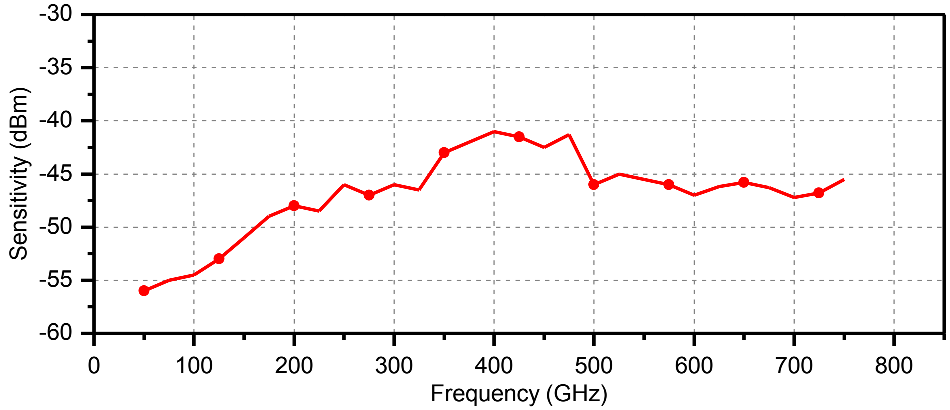


Fig. 14 Topology of the terahertz power meter at various bands

4.5. Terahertz measuring system

The universally used terahertz hardware testing platform is built on the basis of the terahertz spread-spectrum device, multiplier module, harmonic mixing module and the microwave VNA. Terahertz universal measuring software platform is constructed with Test Center software, which includes more than 200 instruments and equipment driver libraries for common instruments, turntables and scanning frames, etc. at home and abroad. Based on the universal measurement hardware and software platform, the measurement fixtures, methods and algorithms are also introduced. Through the novel integration, Figure 15 presents the developed three terahertz measuring systems including antenna, radar cross section (RCS) and materials, which can measure the parameters such as frequency, spectrum, S-parameter, antenna gain, antenna pattern, RCS, material dielectric constant and magnetic permeability. Compared with the foreign scalar measurement scheme [12], the proposed measuring systems can achieve amplitude and phase related information simultaneously.

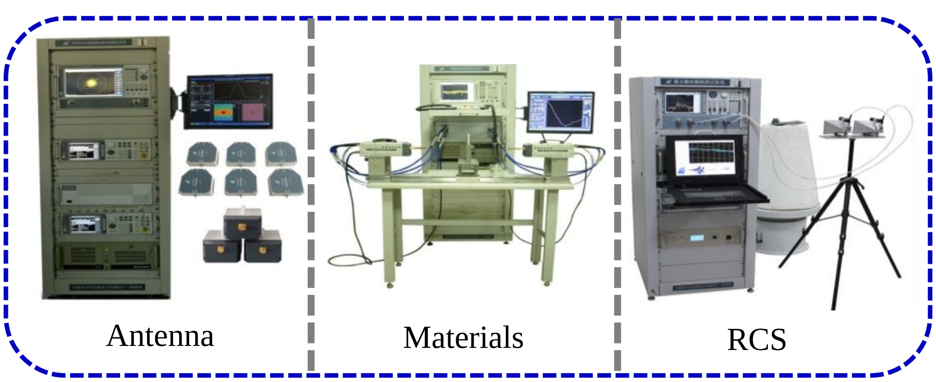


Fig. 15 Photographs of the developed three terahertz measuring systems.

5. Conclusions

The 41st research institute of CETC, together with the 13th and 55th research institutes of CETC, and the research institute of microelectronics of the Chinese Academy of Sciences, etc. have developed the terahertz integrated chips and built the industry chain, which includes the terahertz devices, components, measuring instruments and measurement systems. The large-scale batch production of the terahertz measuring industry chain has been realized and a complete set of test solutions is provided for terahertz scientific research and engineering applications.

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