Invited Paper

A 330 GHz active terahertz imaging system for hidden objects detection

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Abstract: A 330-*GHz* terahertz active imaging system has been designed for personal concealed objects detection. The study concerns both the optimization of a terahertz transceiver and the development of an optomechanical system. Unlike passive imaging systems, active imaging systems will emit a strong enough illumination source (generally approximating to 1 *mW*) to penetrate through thick clothes, and to generate a high signal-to-noise ratio (SNR) to overcome large signal clutter and speckle caused by a scene with a diversity of angles of incidence, surface roughness, and clothes layers. On the other hand, active imaging systems are insensitive to temperature change, and thus it is not easily impacted by ambient environment. Therefore the detector performance requirement is extremely lowered. In our active imaging systems, a heterodyne coherent detection technology as applied in others groups and a frequency-modulated continuous wave (FMCW) technology adopted from the radar field have been utilized to achieve a mm-scale resolution. In the emission end, the emission chain generates a fast chirp source of 20-21.25 *GHz* which is then doubled, amplified, 3 *times* passively doubled, and transmitted at 320-340 *GHz* by the horn antenna. The emission bandwidth of 20 *GHz* ensures sub-cm range resolution. In the receiving end, the reflected signal of 320-340 *GHz* plus a shift frequency proportional to the target range (for example 40 *MHz*) is mixed via a sub-harmonic mixer with a 160.48-170.48 *GHz* multiplier chain. In the sub-harmonic mixer end, an intermediate frequency (IF) signal of 960 *MHz*±40 *MHz* is generated and transmitted to in-phase and quadrature (I/Q) module. After frequency downconversion, a 40 *MHz* signal including phase and amplitude information of the detected objects is digitized. To obtain a scan area of 2.0 *m* (L) x 1.0 *m* (W) with about 7.5 *mm* resolution within 5 *seconds*, the tilt angle is designed as 2.875 degree with a rotation speed of 3768 *rpm* and a vibration speed of 5.675^0/s. Both the rotation and tilt axes of the scanner are controlled by commercial motor drivers. About 26667 Image data are collected continuously during the scanning with the transceiver triggered by an optical encoder on the rotational axis. Using the Delaunay algorithm, a THz-image with gray or color maps is finally obtained. In short, the active terahertz imaging system can be applied in personal concealed weapon and contraband surveillance in the airport and customs.

Keywords: Terahertz imaging, Transceiver, Optomechanical scanning system, Multiplier chain

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1. Introduction

Terahertz (THz) science has attracted more and more scientists to investigate it due to its some unknown physical properties. Light in terahertz frequency domain interacting with matter will yield which new physical phenomena maybe is the vital problem to be revealed. Though THz science still is not understood clearly, THz technology has been extremely active in various application fields such as nondestructive testing, terahertz time-domain spectrum, and terahertz communications etc. THz imaging has been almost the most potential one among all THz technology applications because of its unique properties of security, penetration and high resolution. Compared to the passive THz imaging system, active THz imaging system has higher signal to noise ratio (SNR) to overcome the full dependence on receiver sensitivity. Furthermore, active THz imaging effect is not easy to be influenced by ambient environment changes. In the past years, PNNL has achieved numerous research fruits from 9 *GHz* to 1000 *GHz* for personal imaging [1-4], and some research results have been successfully transformed into commercial products (http://www.safe-view.com/advancedimaging/provision-at.htm). They used 27-33 *GHz* transceiver array with rotary motor to scan rapidly the whole person, and utilized holographic algorithm to quickly obtain high resolution imaging. At present, their imaging rate approaches to 1.5 second/person and the imaging resolution approximates to 5 *mm*. For short-range personal imaging (generally less than 2 *meters* distance between person and imager), it is sufficient to realize the aim using millimeter wave. Considering the cost of the imager, usually around 30 *GHz* active imaging system is the best candidate for short-range personal imaging. However, for long-range personal imaging (more than 5 *meters* distance), terahertz waveband active imaging system is the optimal choice due to a smaller range resolution ($c/2B$, where c is light speed, and B is the bandwidth). For THz imager, the bandwidth B can easily reach on the level of 10-30 *GHz*, which ensures the range resolution to be 5 *mm*-15 *mm*, while it is extremely difficult to achieve the bandwidth level for millimeter wave. On the other hand, it is easier to penetrate thick clothes to detect concealed weapon and contraband using terahertz wave.

Unfortunately, millimeter-wave’s good performance is very luxurious for THz imager. For 350 *GHz* terahertz imaging system, the imaging rate can be only reached on the level of 10 seconds per frame and the imaging resolution is 1-2 *cm* [4]. To improve imaging rate, JPL team has been devoting themselves to optimize chirp source, data acquisition device, optomechanical scanning structure, and driver speed [5-8] of above 600 *GHz* imagers. Though the imaging time is shortened to 1 second with a range resolution of 1 *cm*, the field of view still was confined to below 50x50 *cm*.

In this paper, we design a 330 *GHz* active terahertz imaging system for hidden objects detection. A heterodyne coherent detection technology [9] and a frequency-modulated continuous wave (FMCW) technology adopted from the radar field have been utilized to achieve a mm-scale resolution [10]. Using the two techniques, a 330 *GHz* THz wave with a 20 *GHz* bandwidth is emitted out of a horn antenna. Through an optomechanical scanning system, the reflected THz wave off the objects underclothes is collected by receiving antenna. After frequency downconversion, baseband signal is demodulated and digitized via I/Q mixer and multi-channel FPGA. At last, a 5-second per frame active THz imager with a 7.5-*mm* range resolution will be developed to obtain a scanning area of 2.0 *m* (L) x 1.0 *m* (W).

2. System scheme and quasi-optical structure

The 330 *GHz* active THz imaging system as shown in figure 1 consists of transceiver unit, quasi-optical unit, driving motors, signal processing and saving unit, and imaging software. To realize standoff concealed weapon and contraband detection, the center frequency of the transmitter is selected as 330 *GHz* with a bandwidth of 20 *GHz* and an emission power of about 1 *mW*.

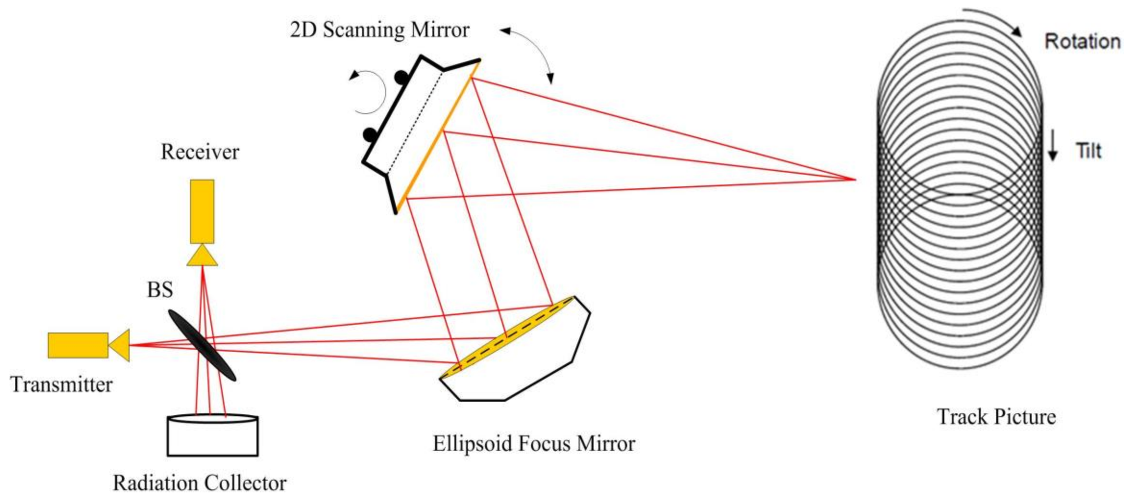

Fig. 1 330 *GHz* active terahertz imaging system diagram. The center frequency of transmitter and receiver is 330 *GHz* with a 20 *GHz* bandwidth. The transmitter power is about 1 *mW*. BS is a high-resistivity silicon beam splitter. Radiation collector gathers the remaining THz wave. Ellipsoid focus mirror with a 50 *cm* diameter has two focuses: one is 1 *m* and the other is 6 *m*. 2D scanning mirror with a 50 *cm* diameter is mounted on an rotation axis which exists a 2.875^0 tilt angle with normal direction. Using advanced motor driver the rotation rate and the vibration speed is expected to reach the level of 3768 *rpm* and 5.675^0/s, respectively. Focused beam penetrates through the thick clothes and scans concealed objects with some ellipse tracks within an area of 2.0 *m* (L)X1.0 *m* (W).

According to Rayleigh criterion ($c/2B$, where c is light speed, and B is the bandwidth), a range resolution of 7.5 *mm* should be obtained. A portion of the emitted THz wave transmits through high-resistivity silicon beam splitter (BS), and the other portion is reflected into radiation collector. Ellipsoid focus mirror with a diameter of 50 *cm* receives THz radiation from emission antenna placed at the position of 1 *m* short focus length, meanwhile reflects conical beam onto the object at the position of 6 *m* long focus length through the 2D scanning mirror. The scanning process is accomplished by rotating two perpendicular axes. The 2D scanning mirror is mounted on a rotation axis with a spinning speed of 3768 *rpm*. The rotation axis has a 2.875^0 tilt angle with the normal direction of the mirror surface (see figure 2). The tilt angle θ causes an ellipse shaped scanning path of the focal spot in the object plane. A rotary stage with a speed of 5.675^0/s drives the spinning axis perpendicular to it, which leads to a linear movement of the scanning ellipse in the Y direction. After a 13.5^0 vibration of the 2D scanning mirror in the Y direction, the initial ellipse and the ending ellipse have a common touching point. The whole scanning area is

2.0 *m* (L) x 1.0 *m* (W) and is covered by about 26,667 pixels. To improve the operation performance of the optomechanical scanner, a very light honeycomb sandwich panel applied in aircraft industry is used for 2D scanning mirror. THz radiation reflected off the concealed object is collected by the receiving antenna. After frequency downconversion via sub-harmonic mixer, an intermediate frequency (IF) of 960 *MHz*±40 *MH* is processed, then a baseband signal of 40 *MHz* including object amplitude and phase is filtered and digitized. Where the 40 *MHz* value indicates phase difference through the detected object.

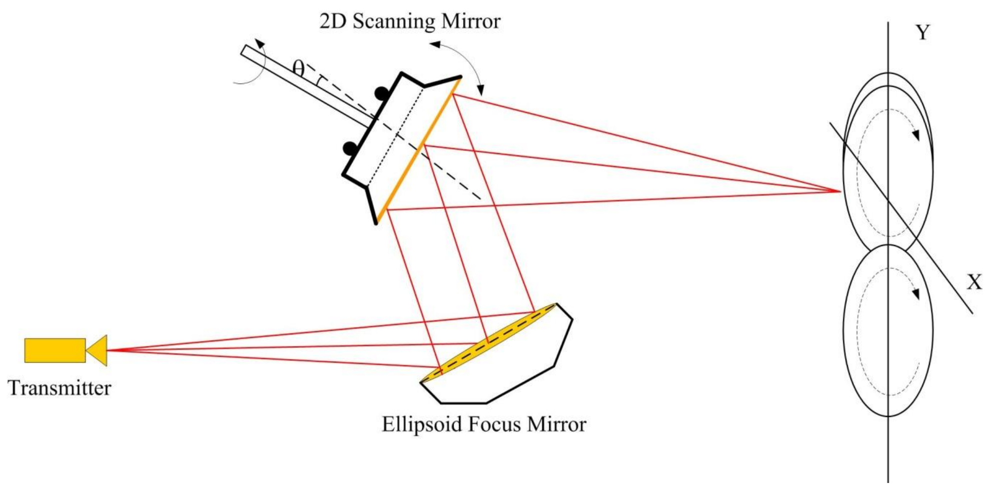

Fig. 2 Quasi-optical structure drawing. The scanning process is accomplished by rotating two perpendicular axes. The 2D scanning mirror is mounted on a rotation axis with a spinning speed of 3768 *rpm*. The rotation axis has a 2.875^0 tilt angle with the normal direction of the mirror surface. The tilt angle θ causes an ellipse shaped scanning path of the focal spot in the object plane. A rotary stage with a speed of 5.675^0/s drives the spinning axis perpendicular to it.

3. Transceiver system design and data processing

The THz imager's back-end electronics yields a fast sweep source of a frequency of 20-21.25 *GHz* which is then filtered, doubled, amplified, octupled, and transmitted at 320-340 *GHz* by the horn emission antenna. Therefore an initial center frequency of 20.625 *GHz* is multiplied by 16 to generate approximately 330 *GHz*. The 20 *GHz* bandwidth ensures the mm-scale range resolution, and the frequency band is chosen for good 3D imaging quality and clothes penetration in a low atmospheric absorbing window. The 20-21.25 *GHz* sweep source is obtained by loading the 0-1.25 *GHz* fast chirp source to a RF source of 20 *GHz*, and multiplied by a factor of 16 to 320-340 *GHz*. Simultaneously, in the receiving end, the chirp source is upconverted, and is then band pass filtered and amplified to drive the local oscillator (LO) chain of frequency multipliers. The receiver LO multiplier chain is similar with the RF multiplier chain, consisting of an active doubler followed by three passive doublers, and second harmonic mixer. In detail, the 20.06-21.31 *GHz* sweep source is yielded by loading the 0-1.25 *GHz* chirp source to the signal source with a center frequency of 20.06 *GHz*. After an octuple chain, a 160.48-170.48 *GHz* signal is mixed with the reflected wave of a frequency of 320-340 *GHz* plus a frequency of about 40 *MHz* including object information in the second-harmonic mixer. Meanwhile, two initial signal sources are mixed and then amplified, filtered and 16 *times* multiplied to generate 960 *MHz* reference frequency. After frequency downconversion, an IF signal is mixed with a 960 *MHz* reference frequency in the gain controlling unit and then sent to phase noise controlling unit. After I/Q demodulation and filtering, the 40 *MHz* baseband signal is data acquired using a multi-channel FPGA card, furthermore the formed data stream is processed by the Delaunay algorithm [11].

Using the Delaunay algorithm, all points in the object plane are connected with an optimized mesh consisting of numerous triangles, therefore the whole object plane is filled with triangles, and there is no any overlapping area among triangles. Finally a THz-image is displayed according to some gray or color maps.

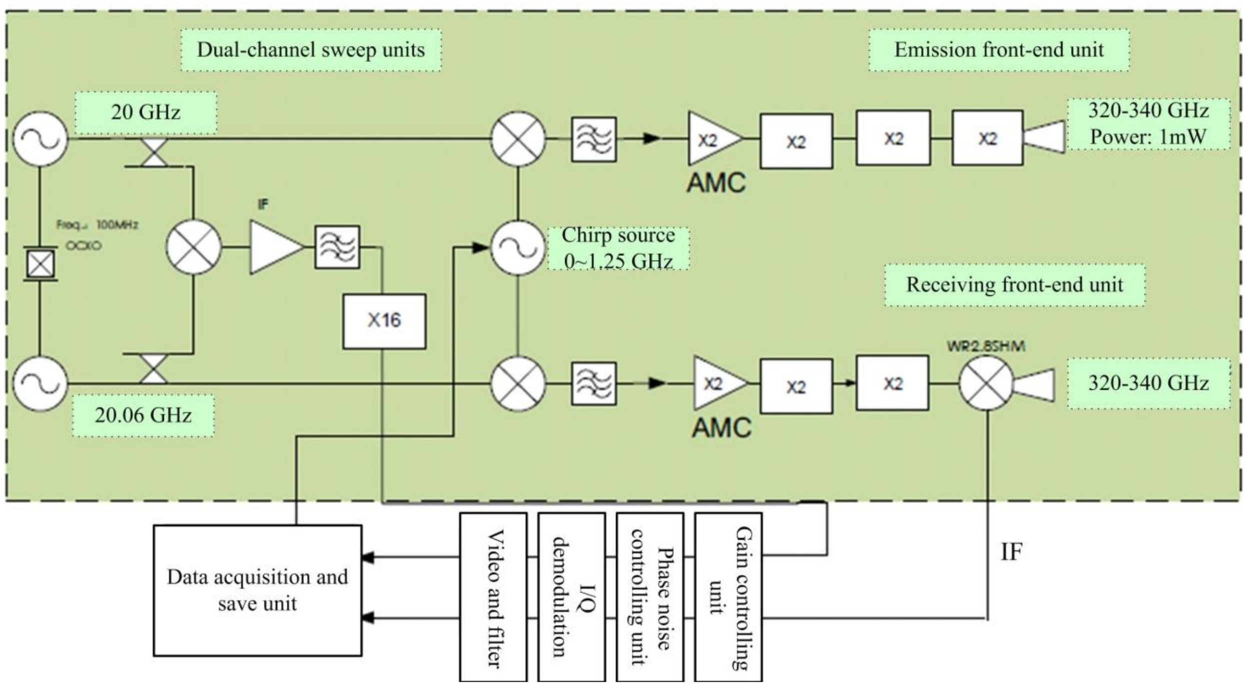

Fig. 3 Transceiver scheme diagram. A 320-340 *GHz* terahertz wave with a bandwidth of 20 *GHz* and a power of 1mW is generated by a 16 *times* multiplier chain and emitted via a horn antenna. A sweep source of 20-21.25 *GHz* is obtained by loading a 0-1.25 *GHz* fast chirp source to a RF source of 20 *GHz*, and multiplied by a factor of 16 to 320-340 *GHz*. In the receiving end, a 20.06-21.31 *GHz* sweep source is yielded by loading the 0-1.25 *GHz* chirp source to a local oscillator with a center frequency of 20.06 *GHz*. After an octuple chain, a 160.48-170.48 *GHz* signal is mixed with the reflected wave of a frequency of 320-340 *GHz* plus a frequency difference of about 40 *MHz* including object information in the sub-harmonic mixer. After frequency downconversion, an IF signal is mixed with a 960 *MHz* reference frequency in the gain controlling unit and then sent to phase noise controlling unit. After I/Q demodulation and filtering, the 40 *MHz* baseband signal is data acquired, furthermore the formed data stream is processed by the Delaunay algorithm. Finally a THz-image is displayed by the PC.

4. Conclusions

In short, a 330 *GHz* active terahertz imaging system for hidden objects detection has been designed. Using the heterodyne coherent detection and FMCW technologies, the transceiver electronics units with a center frequency of 330 *GHz* and a 20 *GHz* bandwidth is constructed. On the other hand, the optomechanical scanning system is developed. To shorten imaging time, a faster scanning rate is suggested. Surely the quick spin speed motor can't be found in recent commercial products, however it is possible to find it in the future. If so, a 5-*second* per frame active THz imager with a 7.5-*mm* range resolution will be realized to obtain a scanning area of 2.0 *m* (L) x 1.0 *m* (W).

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