

## Track 2: Terahertz and Millimeter Waves

Sep. 18, Room 105B	
Presider: Zhiming Huang, Shanghai Institute of Technical Physics, CAS	
14:00-14:30 (Keynote)	<b>Terahertz semiconductor quantum devices and their applications</b> Juncheng Cao, Shanghai Institute of Microsystem and Information Technology, CAS
14:30-14:50 (Invited)	<b>Broadband continuous frequency tuning of terahertz quantum cascade lasers</b> Gangyi Xu, Shanghai Institute of Technical Physics, CAS
14:50-15:10 (Invited)	<b>Development of 1-THz high-harmonic gyrotron oscillator at Peking University</b> Chao'ai Du, Peking University
15:10-15:30 (Invited)	<b>THz s-SNOM technique and its study on the detection of polaritons</b> Shu Chen, Yiming Zhu, University of Shanghai for Science and Technology
15:30-15:45	Coffee break
Presider: Juncheng Cao, Shanghai Institute of Microsystem and Information Technology, CAS	
15:45-16:05 (Invited)	<b>Effect of THz spectra of L-Arginine molecules by the combination of water molecules</b> Wei Shi, Xi'an University of Technology
16:05-16:25 (Invited)	<b>Millimeter wave and terahertz traveling wave tubes for wireless communication</b> Jinjun Feng, Beijing Vacuum Electronics Research Institute
16:25-16:45 (Invited)	<b>Performance enhanced terahertz electromagnetic shielding and absorbing material based on mxene</b> Qiye Wen, University of Electronic Science and Technology of China
16:45-16:55 (Invited)	<b>High-efficiency frequency conversion of near IR pulses down to 0.03 THz in oxide nonlinear crystals</b> Yury Andreev, Institute of Monitoring of Climatic and Ecological Systems RAS
16:55-17:05	ESIT2022-0803-1 <b>Terahertz wave generation and detection using liquid water</b> Liangliang Zhang, Capital Normal University

17:05-17:15	ESIT2022-0812-1 <b>Experimental and simulation study on terahertz absorption spectra of organic aqueous solution</b> Lei Hou, Xi'an University of Technology
17:15-17:25	ESIT2022-0815-14 <b>The Application of the silicon micromachining technique in terahertz radio astronomy and planetary science</b> Haotian Zhu, National Space Science Center
17:25-17:35	ESIT2022-0806-13 <b>Fabrication of bendable low-loss terahertz hollow waveguides based on plastic tubes</b> Sheng Liu, East China Normal University
17:35-18:30	Poster Session
18:30-20:30	Banquet
<b>Sep. 19, Room 105B</b>	
Presider: Ning Dai, Shanghai Institute of Technical Physics, CAS	
8:30-9:00 (Keynote)	<b>Research Progress of Terahertz Measurement Technology</b> Fushun Nian, Ceyear Technologies Co.Ltd
9:00-9:20 (Invited)	<b>Principle of terahertz near field optical microscopy and its applications</b> Min Hu, University of Electronic Science and Technology of China
9:20-9:40 (Invited)	<b>THz schottky diode modeling for IC design</b> Jianjun Gao, East China Normal University
9:40-10:00 (Invited)	<b>Programmable metasurfaces for intelligent terahertz wave control</b> Jingbo Wu, Nanjing University
10:00-10:15	Coffee break
Presider: Jianjun Gao, East China Normal University	
10:15-10:35 (Invited)	<b>TBA</b> Ning Dai, Shanghai Institute of Technical Physics, CAS
10:35-10:55 (Invited)	<b>CMOS terahertz detectors and image sensors</b> Liyuan Liu, Institute of Semiconductors, CAS

EARTH & SPACE: FROM INFRARED TO TERAHERTZ INTERNATIONAL CONFERENCE

10:55-11:15 (Invited)	<b>Terahertz topological photonic structure based on Kagome lattice</b> Yun Shen, Nanchang University
11:15-11:35 (Invited)	<b>Diffractive metasurfaces for terahertz beam manipulation</b> Jierong Chen, Nankai University
11:35-11:55 (Invited)	<b>Compact terahertz laser based on quantum cascade laser and its application</b> Zhiyong Tan, Shanghai Institute of Microsystems and Information Technology, CAS
11:55-12:05	ESIT2022-0820-15 <b>Identification of moldy wheat in terahertz images based on Broad Learning System</b> Yuying Jiang, Henan University of Technology
Presider: Zhiyong Tan, Shanghai Institute of Microsystems and Information Technology, CAS	
13:30-13:50 (Invited)	<b>A new route to realize high-sensitive long wavelength infrared to terahertz photoelectric detection beyond cut-off wavelength</b> Wei Zhou, Shanghai Institute of Technical Physics, CAS
13:50-14:10 (Invited)	<b>Spintronic based ultrabroadband terahertz emitters: from fundamentals to applications</b> Zuanming Jin, University of Shanghai for Science and Technology
14:10-14:30 (Invited)	<b>High performance terahertz quantum cascade lasers, transmission waveguides and their biomedical applications</b> Chongzhao Wu, Shanghai Jiao Tong University
14:30-14:50 (Invited)	<b>High speed THz modulation technology and communication system</b> Lan Wang, Yaxin Zhang, University of Electronic Science and Technology of China
14:50-15:00	ESIT2022-0814-12 <b>Terahertz near-field nanoscopy of edge fringes in the material interface</b> Fucheng Qiu, Chongqing Institute of Green and Intelligent Technology, CAS
15:00-15:10	ESIT2022-0814-3 <b>Study of low temperature induced hydrate formation in alkali halide solutions by terahertz time-domain spectroscopy</b> Ligang Chen, Chongqing Institute of Green and Intelligent Technology, CAS
15:10-15:25	Coffee break
Presider: Wei Zhou, Shanghai Institute of Technical Physics, CAS	

15:25-15:45 (Invited)	<b>High-sensitivity graphene-based terahertz detectors with Johnson noise readout</b> Wei Miao, Purple Mountain Observatory, CAS
15:45-16:05 (Invited)	<b>Terahertz Spectral Imaging of Biological Samples from far-field to near-field</b> Huabin Wang, Chongqing Institute of Green and Intelligent Technology, CAS
16:05-16:25 (Invited)	<b>Terahertz target scattering characteristics and radar technology</b> Qi Yang, National University of Defense Technology
16:25-16:35	ESIT2022-0821-6 <b>Rice freshness recognition method based on improved VGG network and THz image</b> Hongyi Ge, Henan University of Technology
16:35-16:45	ESIT2022-0814-9 <b>Study of long-pulse high-power 170GHz gyrotron for fusion plasma ECRH</b> Bentian Liu, Institute of Energy, Hefei Comprehensive National Science Center
16:45-16:55	ESIT2022-0806-8 <b>Microwave kinetic inductance detectors for terahertz imaging</b> Runfeng Su, Nanjing University
16:55-17:05	ESIT2022-0819-4 <b>End-to-end design of metasurface-based complex-amplitude holograms by physics-driven deep neural networks</b> Wei Wei, Shanghai Jiao Tong University
17:05-17:15	ESIT2022-0806-10 <b>Versatile wavefront manipulations based on active transmissive metasurface</b> Chaohui Wang, Air Force Engineering University
17:15-17:25	ESIT2022-0822-7 <b>Encryption and decryption applications on conductive films using THz near-field real-time imaging system</b> Wei Zhang, Nanjing University

## Terahertz semiconductor quantum devices and their applications

Juncheng Cao

Shanghai Institute of Microsystem and Information Technology, CAS

Terahertz (THz) wave refers to the electromagnetic spectrum region between millimeter wave and infrared light with frequency from 300 GHz to 10 THz, corresponding wavelength from 1 mm to 30 microns. THz technologies have significant application prospects in physics, material science, biology, astronomy, information science and national security. THz radiation sources and detectors are the key devices for THz wave applications. In this report, we focus on the research progresses of the interaction physics between THz radiation and low dimensional semiconductors, the material growth and device fabrication of THz quantum cascade lasers and THz quantum well detectors, as well as the ultrafast wireless communication, high resolution imaging and other applications based on these THz quantum devices.

### Broadband continuous frequency tuning of terahertz quantum cascade lasers

Gangyi Xu

Shanghai Institute of Technical Physics, CAS

Terahertz quantum cascade lasers (THz-QCLs) hold great promise as solid-state sources of coherent THz radiation for their compactness, high reliability, high power, and high spectral purity. Broadband continuous frequency tuning of single mode emission THz-QCLs is highly demanded for many applications, but is still a big challenge nowadays because the conventional laser tuning methods are difficult to be implemented at terahertz frequencies. Up to now, broadband continuous tuning ( $> 100$  GHz) is only available in the system containing moving components. Moving-part-free, electrically controllable, reliable and predictable THz-QCLs that feature broadband continuous tuning of the single mode emission are highly desired but need to be realized.

Here, we demonstrate a novel tuning mechanism that qualitatively differs from all other methods. Our device consists of 1D non-uniform microlasers array, where the characteristic dimensions of each microlaser and the distance between the adjacent microlasers are all subwavelength sized, and each microlaser can be independently biased. By judiciously manipulating the eigen frequency and the loss/gain of each microlaser, as well as the coupling strength between the microlasers, continuous frequency tuning up to 80 GHz has been realized. Our results pave the way to the realization of high-power coherent THz source with broadband and fast frequency tuning.

### Development of 1-THz High-Harmonic Gyrotron Oscillator at Peking University

Chaohai Du

Peking University

Terahertz wave plays a turn-on-key role in the next generation wireless communication, high temperature plasma heating and diagnosis, biomedical diagnosis, spectroscopy, and so on. The design and development of a multi-mode high-harmonic gyrotron oscillator in Peking University will be reported here. This work is aimed at producing a high-power terahertz (THz) source with high peak power and ultra-wideband tuning capability ranging from the sub-millimeter to THz bands. The gyrotron can operate from first harmonic to forth harmonic in multiple discrete bands by varying the confining magnetic field strength, which includes 1st-harmonic TE<sub>1,2</sub> about 17-kW power around 185 GHz, 2nd-harmonic TE<sub>2,3</sub> about 11-kW around 345 GHz, 3rd-harmonic TE<sub>3,6</sub> about 5-kW power around 720 GHz and 4th-harmonic TE<sub>4,8</sub> about 1-kW power around 1000 GHz.

The interaction cavity is a classical three-segment structure following by a relatively long output terahertz tapering waveguide. The six modes will be driven by a magnetic-cusp axis-encircling electron gun. The gun can generate

axis-encircling electron beam with a nearly constant pitch factor in a wide range of magnetic field strength, which fully satisfies our demand in exciting the six modes. A regular water-cooled collector is adapted to support the short-pulse operation in the hot test. The output window is optimized to achieve a low reflection for the main operating mode. In the design and development of the THz gyrotron, a number of challenges, including the high ohmic loss in such a high frequency, the errors induced in fabrication, the misalignment correction during the hot test, and the measurement of power and frequency, will be systematically addressed. This gyrotron oscillator aims to achieve the widest broadband capability in the terahertz band currently reported.

## THz s-SNOM technique and its study on the detection of polaritons

Shu Chen, Yiming Zhu

University of Shanghai for Science and Technology

Invited

Terahertz (THz) spectroscopy owns great advantages in the studies of electron, phonon and chemical information of molecules and materials. Because of the limitation of diffraction, however, the conventional THz techniques don't allow the spectral and imaging studies at the nanoscale, significantly limiting the wide applications of THz spectroscopy and imaging. The emergence of THz scattering type scanning near-field optical microscopy (THz s-SNOM) provides the solution to this issue, benefiting from the capabilities of breaking through the diffraction limitation and achieving a nanometer spatial resolution, the latter of which is mainly determined by the tip radius. In recent years, our team settle down to the development of the domestic THz s-SNOM systems, including THz sources, THz detectors, tip engineering and THz background-free techniques (for example, THz pseudoheterodyne interference technique that allows simultaneously amplitude and phase signals). Finally, we achieved the THz s-SNOM systems with the performance of spatial resolution  $< 20$  nm, signal to noise  $> 30$  dB, tunable frequencies in range of 0.1- 5 THz and compatibility of a variety of THz sources, arriving at the international advanced level.

THz s-SNOM has shown promising applications and advantages in a variety of fields, such as, polaritons photonics, materials science, biochemical nanoimaging, semiconductor technology. Very recently, by using THz s-SNOM, we detected the THz polaritons in one of the typical topological insulators, that is,  $\text{Bi}_2\text{Se}_3$ , which has attracted great attentions owing to its topological surface states. Besides, the unavoidable bulk doping during the growth and the existence of optical phonons make the origins of the THz polaritons in  $\text{Bi}_2\text{Se}_3$  complicated and controversial. Moreover, the reported works were based on the characterizations of far-field spectroscopy, which does not allow to real-space image the polaritons. We thus anticipate to real-space detect the polaritons and explore the origins of the polaritons in  $\text{Bi}_2\text{Se}_3$  by introducing the THz s-SNOM technique. By utilizing the THz s-SNOM, we achieved the first THz polaritons image in  $\text{Bi}_2\text{Se}_3$ . We extracted the polariton momenta, which is 12 times as compared with that of free space, from a polariton wave with a propagation length less than one wavelength through our newly proposed complex analysis. By further imaging the  $\text{Bi}_2\text{Se}_3$  films with different thicknesses, we concluded that the polaritons in  $\text{Bi}_2\text{Se}_3$  is originated from the hybridization of optical phonons, bulk free carriers and surface free carriers. Our work (1) demonstrated the feasibility of imaging THz polaritons in thin layered materials by THz s-SNOM; (2) established the methodology for the imaging of THz polaritons; (3) provided new insights for the understanding the nature of polaritonic origins in topological insulators.

## Effect of THz spectra of L-Arginine molecules by the combination of water molecules

Wei Shi  
Xi'an University of Technology

Most biomolecules are biologically active only in water; hence, it is worth investigating whether THz spectra of biomolecules are affected by the combination of water molecules and biomolecules. In this report, by combining the sample cell with the THz-TDS system, the THz spectra of L-Arginine crystal as well as its hydrate and aqueous solution are measured. The experimental results show that L-Arginine crystal and its hydrate share the same three absorption peaks at 0.99, 1.46, and 1.7 THz, respectively. But the trend of characteristic absorption spectrum of L-arginine solution is almost identical to that of free water. Because the contents of free water and hydrated water are different in many diseased and normal tissues, the diseased tissues can be detected according to the difference in THz spectral information. The proposed approach provides a reliable means for the detection of pathological changes of active molecules and tissues.

## Millimeter Wave and Terahertz Traveling Wave Tubes for Wireless Communication

Jinjun Feng  
Beijing Vacuum Electronics Research Institute

Folded waveguide (FWG) slow wave structures (SWS) have been widely studied for its properties of all-metal, compatible fabrication with MEMS technologies and easily coupling to rectangular waveguide etc in the research and development of high frequency TWTs. In this paper, the design and experiments of TWTs with hundreds watts power level at E/W band, tens watts power level at G band and watts-level power at frequencies over 300GHz will be introduced, which have potential applications in high data-rate wireless communication. The latest progress of the theoretical and experiment research of these high frequency TWTs will be given.

## Performance Enhanced Terahertz Electromagnetic Shielding and Absorbing Material based on Mxene

Qiye Wen  
University of Electronic Science and Technology of China

Terahertz (THz) wave with frequency between 0.1 THz to 10 THz is becoming a powerful tool, for a wide range of applications: from security imaging, non-destructive detection, material identification<sup>3</sup>, biomedical sensing, to the emerging sixth generation (6G) communications, in which THz absorbers with high absorption intensity in a large qualified bandwidth are urgently demanded, either for THz emitting/detecting antennas to reduce the sidelobe radiation or for the whole THz systems to suppress the electromagnetic interference (EMI). Another potential use is for radar cross section (RCS) reduction, which can reduce radar echo to achieve a greater element of stealth. Overall, there is being a huge demand of high-intensity absorption, broadband, and low-cost THz absorber in both military and civilian aspects. In this talk, we show how to achieve broadband THz absorption or shielding materials with new kind of two-dimensional nanomaterials, the 2D transition metal carbide/nitride (typically Mxene). We first report on a flexible and thin  $Ti_3C_2T_x$  sponge composite working as broadband THz absorber.  $Ti_3C_2T_x$ , as one of the most studied MXenes, has been attracting great attentions due to its unique physical and chemical prop-

erties, such as metallic conductivity (up to  $10000 \text{ S cm}^{-1}$ ), and good dispersity in various solvents.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene sponge foam (MSF) was fabricated by filling  $\text{Ti}_3\text{C}_2\text{T}_x$  flakes into commonly used polyurethane (PU) sponge foam via a dip-coating approach. The PU sponge is deliberately selected to have pore size over hundreds of micrometers (e.g.  $650 \mu\text{m}$ ). Without further post-treatment, MSF can be directly used as THz absorber, realizing an efficient and cost-effective fabrication process. With the large-pore sponge based open architecture, the surface of MSF can easily meet the impedance matching to the free space and greatly reduce the THz reflection so that almost all of THz waves could enter into the MSF. Then, the co-existence of three states of  $\text{Ti}_3\text{C}_2\text{T}_x$  flakes in the composite realizes the multiple reflection of the THz waves inside the composite, finally absorbing and transforming THz waves to heat through electric loss. As a result, the optimal average absorption in the effective range of THz frequency (0.3-1.65 THz) can reach above 99.99% with less than 22.5% weight percentage of  $\text{Ti}_3\text{C}_2\text{T}_x$  filling in the composite. We further studied a superhydrophobic  $\text{Ti}_3\text{C}_2\text{T}_x$ -based THz absorbing foam. By spraying silane coupling agent (SCA) and silica particles on the surface of the sample, we have successfully prepared a superhydrophobic absorbing material with a hydrophobic angle of  $150.5^\circ$  and a rolling angle of  $7.6^\circ$ , which enable the potential application in rainy, icy, and humid environments. Moreover, an ultra-high absorption rate of 99.98% and an extremely low reflectivity of 0.0007% are achieved in the frequency range of 0.3 THz-1.65 THz. Therefore, we successfully prepared a THz absorbing foam with super-hydrophobic properties and ultra-high absorption efficiency, which has extremely practical value. We further provided a versatile method to transform diverse substrates into THz EMI shielding functional substrate. While coating/patterning onto various substrates, traditional EMI shielding materials suffer from limited interaction with the substrate surface of variable chemistries, limiting their universal application. Using the copolymer polyacrylic latex (PAL), which is full of high-polarity  $-\text{C}=\text{N}$  functional group, we fabricated a new class of high-viscosity, high-adhesion and fast film-forming MXene waterborne paint (MWP) and demonstrated its broadband THz EMI absorption and shielding on various substrates even with irregular shape. The existence of various functional groups in copolymer PAL helps regulate the viscosity of MXene suspension by tuning the colloidal and viscous forces. And the  $-\text{C}=\text{N}$  group from PAL provides strong intermolecular polar interaction between MWP and substrate. High-filled polymer consists of conductive filler and high-polarity group can be a general strategy to overcome the poor wettability and inadequate adhesive interaction between most EMI paint and substrates. As a result, a  $38.3\text{-}\mu\text{m}$ -thick MWP on quartz exhibits EMI shielding value of 64.9 dB, while excellent reflection-loss of 32.8 dB is obtained on MWP coated sponge foam. This substrate-independent MWP pave a simple but efficient way to achieve high performance THz shielding/absorption efficiency.

### High-efficiency frequency conversion of near IR pulses down to 0.03 THz in oxide nonlinear crystals

Yury Andreev

Institute of Monitoring of Climatic and Ecological Systems RAS

Former time France-Russia team has been demonstrated top (360 J) third harmonic pulse energy by using nonlinear LBO crystal of 8 mm in length and 65 mm in diameter, as well as 10-ns Nd:YAG pump pulses. In this study high efficiency of the THz wave generation is demonstrated in a number of oxide nonlinear crystals under the pump by fs Nd:YAG laser. The highest efficiency is achieved by using high quality LBO crystal possessing minimal nonlinear susceptibility coefficient of  $0.47 \text{ pm/V}$  but as measured, top damage threshold among nonlinear crystals and as low absorption coefficient as below  $10^{-3} \text{ cm}^{-1}$ . Other details on optical properties, experiment carried will be discussed.

## Research Progress of Terahertz Measurement Technology

Fushun Nian  
Ceyear Technologies Co.,Ltd

Focusing on the measurement needs of terahertz scientific research and engineering applications, this report sorts out the product system of terahertz measurement instruments based on electronics and photonics. Then, the research progress of terahertz measurement instruments and key technologies are introduced, as well as the engineering application of measurement technology. Finally, the future development direction and focus of terahertz measurement technology are proposed.

## Principle of terahertz near field optical microscopy and its applications

Min Hu  
University of Electronic Science and Technology of China

Terahertz has become the focus of biomedical research because of its unique properties. However, terahertz has particular limitations in biomedical imaging because of its longer wavelength than X-ray visible light. Terahertz scattering near-field optical microscope based on atomic force microscope can break through the terahertz diffraction limit and achieve nano spatial resolution. In this report, we will introduce the working principle of the system, discuss relevant physical problems, and show our independently developed domestic system. At the same time, we will show the preliminary applications of the system, including micro nano materials and biomedical samples.

## THz Schottky Diode Modeling for IC design

Jianjun Gao  
East China Normal University

Terahertz modeling and parameter extraction of the anti-parallel air-bridged GaAs Schottky diode are presented. The simulated data agree well with the measured data up to 325GHz. The large signal model of anti-parallel air-bridged GaAs Schottky diode has been used to design a 220GHz sub-harmonic mixer terahertz monolithic integrated circuit.

## Programmable Metasurfaces for Intelligent Terahertz Wave Control

Jingbo Wu  
Nanjing University

Towards the applications of THz technology in wireless communication, radar, imaging, and other fields, the devices that can control the THz wave intelligently are highly demanded. The programmable THz metasurfaces provide an excellent choice to reconfigure the THz environment intelligently and process the information. This paper reports our recent progress on THz programmable metasurfaces based on liquid crystal and phase change material. We developed a liquid crystal metasurface-based spatial light modulator and realized dual color compressive imaging. Utilizing the hysteresis effect of phase change materials, we developed an electrically addressable metasurface with non-volatile memory. Our work may find applications in many fields, such as THz beamforming, holographic plates, and compressive imaging.

## Material Growth and Device Fabrication of InAsSb Medium-wave Infrared Detectors at RT

Hao Xie, Hongyu Lin, Shuhong Hu, Ning Dai  
State Key Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, CAS

High quality InAsSb has been grown by liquid phase epitaxy (LPE). The adopted step-cooling method slows down the growth speed, leading to the significant improvement in material qualities. The materials present smooth surface morphology, high crystallinity, and few interface composite defects. The pBin-structured infrared detectors have been designed and fabricated. Inserting a barrier layer in the device structure showed substantial improvement of device performance with the reduction of leakage current. By further improving the device processing, InAsSb devices with good photoelectric response performance have been successfully fabricated, the detectivity ( $D^*$ ) reaching  $2.0 \times 10^9$  cm-Hz<sup>1/2</sup>W<sup>-1</sup>@4μm at room temperature (RT). The device passivation process was preliminarily explored, which shows further improvement of the optical response.

## CMOS Terahertz Detectors and Image Sensors

Liyuan Liu  
Institute of Semiconductors, CAS

Imaging with terahertz is promising and has potential applications in non-invasive detection, security check, material analysis et.al. Available detectors using micro-bolometer, golery cells provide satisfactory responsivity, but they suffer from bulky volume and are not suitable for large array. In this talk we report CMOS terahertz detectors and imaging sensors. Detectors are all implemented with commercial CMOS technology which offers low cost and high yielding. This talk first introduce the principle of terahertz detection using CMOS. Then we talk about design of terahertz detector, including design of antenna, matching network, notch filter. Since the detector output is very small DC voltage, to readout the signal, low noise amplification and analog-to-digital conversion circuit is required. To make an array sensor, architecture should be carefully chosen according to design constrains such as frame rate, dynamic range and chip complexity. We show several silicon implementation of detectors and image sensors with different resolution. The talk ends with perspective on future trends in development of CMOS terahertz sensors.

## Terahertz topological photonic structure based on Kagome lattice

Yun Shen  
Nanchang University

Topological system is robust to disordered and continuous perturbations, which leads to non-dissipative edge states transportation of electrons in quantum solids and non-reflective propagation of light in photonic systems. In this paper, Kagome lattice, which has a new symmetric protective topological phase and exhibits extremely low berry curvature and nontrivial polarization, is studied. Theoretical and numerical analysis show that the structure can realize valley hall optical topological insulators with four edge states. Furthermore, fabricated topological waveguide are measured by THz-time-domain spectroscopy (THz-TDS). The results demonstrate that in range of 0.437-0.453thz, straight and Z domain walls have almost the same transmission, indicating the non-trivial topological edge state of the structure has a very strong ability to suppress backscattering. In particular, the THz-TDS measurements can provide time-domain information of waveguide modes that cannot be obtained from general measurements which only responds to power spectrum. Additionally, an open ring valley hall optical topology insulator based on Kagome lattice also is proposed. It shows that the C3V symmetry can be broken by overall rotation of split ring  $\alpha$  and individual rotation  $\theta$  to provide topological phase transition. The refraction effect of THz

signal propagating from the zigzag interface to the background space illustrates that the positive/negative refraction of the outgoing beam depends on the type of valley projected by the edge states ( $K$  or  $K'$ ).

THz waveguides have great potential in information and communication technology, including the sixth generation (6g) wireless communication, THz integrated circuits and interconnection of intra chip and inter chip communication. This work extends the topological insulator system to the THz band, provides a method for high time resolution THz-TDS measurement in topological photonic systems, and promotes its potential applications in directional collimation, beam splitting, negative refraction imaging, and so on.

### **Diffractive metasurfaces for terahertz beam manipulation**

Jierong Chen  
Nankai University

Metasurfaces have shown great potential to replace traditional bulky components for flexible control of the beam via tailoring the phase response of the subwavelength elements. The overall optical response of the metasurface is determined by both the refractive and the diffractive effects. Existing metasurfaces focus on the design of refractive phase gradient, while the diffraction effect is neglected. This report will emphasize on the role of diffraction effect in improving efficiency and increasing flexibility of beam manipulation. General diffractive theory for arbitrary wave front shaping is proposed. A variety of terahertz functional devices are designed and tested through the nonlocal diffraction control. The results might promote the study and application of high-efficiency, large-gradient and multi-functional terahertz functional devices.

### **Compact terahertz laser based on quantum cascade laser and its application**

Zhiyong Tan  
Shanghai Institute of Microsystems and Information Technology, CAS

Terahertz quantum-cascade laser (THz QCL) is one type of optoelectronic devices based on low dimensional compound semiconductor material, which is very important sources in terahertz region. It has the characteristics of compact configuration, mature fabrication process, stable performance, and easy integration. In this report, we first introduce the working principle and latest progress of THz QCL. Subsequently, a series of THz QCLs and their performance are introduced, and then we introduce the application of THz QCL in terahertz photoelectric characterization technology, fast scanning imaging system, compact real-time imaging system, near-field optical microscopy imaging system and super-resolution imaging, and finally look forward to the future development of compact THz laser source.

### **A new route to realize high-sensitive long wavelength infrared to terahertz photoelectric detection beyond cut-off wavelength**

Wei Zhou  
Shanghai Institute of Technical Physics, CAS

Space targets including lunar poles and asteroids have perpetually frozen surfaces, which radiate long-wavelength infrared waves. Many astronomical targets also radiate far infrared to millimeter waves. Therefore, long wavelength infrared to THz detection is of significant importance in remote sensing from moon to deep space. In this talk, we will present our research on a new phenomenon of electromagnetic induced potential well effect (EIW

effect), which achieves high performance detection from infrared to THz at room temperature. Subsequently, we have observed similar phenomenon and the resulting high-sensitive photo-conductance effect at room temperature in a variety of bulk and two-dimensional materials. This talk reviews our research works on the EIW effect in the past 8 years, including the study on the terahertz detection mechanism and a variety of far infrared detectors based on the EIW effect. A dozen materials including InSb, InGaAs, Si, Bi<sub>2</sub>O<sub>3</sub>Se, Bi<sub>2</sub>Te<sub>3</sub>, Ta<sub>2</sub>NiSe<sub>5</sub>, Te, NbSe<sub>2</sub> show excellent responsivity and NEP performance for IR and THz detection by constructing EIW detectors, which proves that the EIW effect is universal in these materials. Our works provide a new route to break through the high-sensitive long wavelength infrared photoelectric detection below the semiconductor bandgap width.

### Spintronic based ultrabroadband terahertz emitters: from fundamentals to applications

Zuanming Jin

University of Shanghai for Science and Technology

The development of efficient terahertz (THz) radiation sources is driven by the scientific and technological applications. To date, as far as the radiation of THz pulses is concerned, the widely used methods are biased semiconductor, electro-optical crystal and air plasma, which are excited by femtosecond laser pulses. The mechanisms involved are photo-carrier acceleration, second order nonlinear effect, and plasma oscillations, respectively. Here, we report the generation of coherent THz radiation in the designed ferromagnetic/non-magnetic metallic heterostructures, excited by ultrafast laser pulses. The origin of THz generation from FM heterostructures can be interpreted using two terms: the transient demagnetization and electric-dipole radiation resulting from the non-local spin current pulses. The THz emission is dominated by the photo-excited transient charge current, which is converted from the spin current with inverse spin Hall effect. Our results indicate that the peak-values of the THz radiation from W/CoFeB/Pt and Ta/CoFeB/Pt are stronger than that from 0.5 mm-thick ZnTe crystal covering the 0–2.5 THz range, under very similar excitation conditions. Furthermore, an efficient terahertz (THz) emission from Pt/CoFe/Ta trilayer fabricated on the flexible polyethylene terephthalate (PET) substrate is demonstrated. We show an efficient and practical approach to enhance and manipulate THz generation based on a cascaded PET/Pt/CoFe/Ta heterostructures. The cascaded spintronic THz emitters can not only be assembled with THz metasurfaces, but also be used to perform a THz spectroscopic measurement. These findings can be utilized for device-oriented opto-spintronics and also extend the established THz emitter to THz modulator.

### High performance terahertz quantum cascade lasers, transmission waveguides and their biomedical applications

Chongzhao Wu

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This talk will present our research on high performance terahertz quantum cascade lasers (THz QCLs) in terms of narrow beam pattern, frequency tunability, high output power and accurate predictions of resonant mode characteristics for THz QCLs with distributed feedback. Furthermore, I will discuss our recent developments of spatially, spectrally single-mode and mechanically flexible, stretchable 3D-Printed terahertz transmission waveguides of THz QCLs and their applications in biomedical sensing and imaging.

## High speed THz modulation technology and communication system

Lan Wang, Yaxin Zhang  
University of Electronic Science and Technology of China

## High-sensitivity Graphene-based Terahertz Detectors with Johnson Noise Readout

Wei Miao  
Purple Mountain Observatory, CAS

With a unique combination of small electronic heat capacity and weak electron phonon interaction, graphene has recently emerged as a promising material for sensitive detectors at terahertz (THz) frequencies. However, the resistance of graphene weakly depends on electron temperature, which reduces the detection performance of the graphene-based detector with a conventional resistive readout. Here we present the development of graphene-based THz detectors with Johnson noise readout, which probes the electron temperature by measuring the Johnson noise emitted by electrons at microwave frequency. This readout scheme can essentially provide wide bandwidth and sensitivity to resolve the fundamental thermal fluctuations. Using Johnson noise readout, we have demonstrated high-sensitivity and wide-dynamic-range graphene hot electron bolometers at THz frequencies.

## Terahertz Spectral Imaging of Biological Samples from far-field to near-field

Huabin Wang  
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In this presentation, I will introduce our recent work to demonstrate three different terahertz (THz) imaging techniques by which biological samples can be investigated with different spatial resolutions from millimeters, micrometers to nanometers. First, we employed a conventional far-field THz time-domain spectroscopy system with a spatial resolution on the millimeter scale to image mouse skin tissue with melanoma. It was found that the melanoma could be unambiguously identified from the normal tissue in the frequency region of 0.6 - 2.0 THz by exploiting the extracted refractive index and/or absorption coefficient. Second, we utilized a home-built photoconductive antenna microprobe-based THz near-field system with a calibrated spatial resolution of several microns to image mouse brain tissue slices, by which the corpus callosum region and the cerebrum region were detected clearly. In addition, individual watermelon pulp cells were successfully imaged using this technique and the drying process of the cell was observed and investigated. Finally, using a tip-scattering based THz near-field imaging technique, we realized to image individual biomolecules on the nanometer scale. Our results prove the capability of studying biological samples from different spatial resolution levels, which manifests that THz imaging techniques are holding a promising future in biomedical and biological fields.

## Terahertz target scattering characteristics and radar technology

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National University of Defense Technology

With the rapid development of terahertz devices, terahertz applications are coming out. Terahertz radar is a typical application in both military and civil fields. Based on the author's years of research in terahertz, this talk mainly deals with two problems: target scattering characteristics in terahertz band and terahertz radar technology. Target

scattering characteristic is the basis of terahertz radar application, and the special position of terahertz in the electromagnetic spectrum determines the particularity of its scattering characteristic. Terahertz radar is a synthesis of terahertz theory, devices, characteristics, technology and so on. It has a broad application prospect.

Invited

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## Terahertz wave generation and detection using liquid water

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In recent years, the study of terahertz (THz) wave has attracted extensive attention of researchers. As an emerging technology, THz time-domain spectroscopy (TDS) has broad application prospects in space detection, biomedical research, security inspection, broadband communication, etc. Solid-based electro-optic sampling, photoconductive antenna and laser induced air plasma are currently the most commonly used techniques for THz coherent detection.

Traditional optical methods use photoconductive antenna or electro-optic crystal as THz source, whereas the intensity of THz wave electric field radiated is only a few kV/cm, and the spectral range is below a few THz, which is not conducive to practical application. Air and liquid, as the generation medium of pulsed THz wave, have the advantages of no damage threshold, recyclable and so on. They can be pumped by high energy laser to obtain broadband strong THz radiation. In recent years, many researchers have paid attention to them. However, the mechanism of THz generation in air plasma has not yet been fully explained, and the generation efficiency needs to be further improved. Liquid (including water and other materials) as THz radiation source is rarely reported. Liquid usually has a higher density close to solid, a larger nonlinear susceptibility and a lower ionization threshold than gas, which means that the phenomena during filamentation in liquids accompanied by more abundant and strong physical effects. The fluidity of liquids greatly improves its damage threshold and self-healing ability. Therefore, the development of related application devices in the field of THz wave based on liquid water will have unique advantages.

THz wave generation and detection using liquid water has long been considered impossible due to its strong absorption in THz frequency range. A few very recent works reported THz generation from water, but the mechanism has not yet been well clarified and the efficiency demands to be further enhanced. At first, the THz wave generated by water film excited by 800 nm laser is several to or more than dozen times stronger than that generated by air plasma under the same conditions, and the influence of polarization and energy of pump laser on THz radiation generated by water film is explored. Furthermore, the THz radiation generated by water film is enhanced by long wavelength pump laser, and the influence of laser incidence angle on THz wave is studied. By using water line instead of water film, the radiation efficiency of THz wave is significantly improved. The intensity of THz wave is 100 times of that generated from air plasma excited by two-color fields. At the same time, the internal generation mechanism is analyzed. In order to find a better liquid medium, the THz waves radiated by different kinds and concentrations of liquid are studied. Compared with pure water, ethanol solution will produce more THz radiation. The results fill the gap of THz wave generated by liquid.

In general, the THz generation and detection are considered as /reversible/ theoretical analysis processes. Recently, Tan et al. proposed a coherent detection scheme of broadband THz pulses based on liquid water via four-wave mixing process for the first time. The spectral response reaches 0.1~18 THz, which can be extended to a wider range. It breaks through the bottleneck of limited spectrum in traditional solid-based detection methods. Meanwhile, the scheme brings a solution for polarization-sensitive detection of THz pulses. However, the understanding of plasma in liquid water is far from being sufficient. Therefore, it is necessary to conduct in-depth investigation on the THz coherent detection scheme based on liquids, particularly water. We plan to further explore other liquid medias, and preliminary studies have been carried out on organic solvents and inorganic salt solutions.

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## Experimental and Simulation Study on Terahertz Absorption Spectra of Organic Aqueous Solution

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Since terahertz (THz) waves can be strongly absorbed by water, the experimental research on the characteristics of water-containing samples by THz technique is developing slowly. With the development of computer technology, the application of quantum chemistry theory to analyze the characteristics of water-containing samples provides a new way for the research in this field. In this paper, The THz radiation was enhanced by using a high-multiplier photoconductive antenna in THz time-domain spectroscopy system, and the THz spectrum of lactose solution was measured by using a horn shaped tapered parallel plate waveguide. At the same time, the detection of THz spectrum of L-arginine solution was realized by using a sample cell. In order to investigate the relationship between THz spectra and molecular structure of the substances, the THz absorption spectra of  $\alpha$ -lactose monohydrate and L-arginine in aqueous solvent environment were investigated by combining density functional theory and SMD implicit water-solvent model, and they are in good agreement with the experimental results. To account for the generation of the THz characteristic absorption peaks, the potential energy distributions and the vibration modes of the two samples were analyzed and attributed in detail. Finally, the types of intramolecular interactions of the two substances were designated using the interaction region indicator. This paper provides a method for the investigation of the spectral properties of water-containing samples in the THz band.

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## The Application of the Silicon Micromachining Technique in Terahertz Radio Astronomy and Planetary Science

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To achieve more scientific outputs, the next generation of sub-millimeter heterodyne receivers for both space telescopes and ground-based telescopes requires higher frequency bands and high wide-field mapping speed and wider RF and IF bandwidth. To further improve the observing speed, multi-pixel radio astronomy receivers are favored. The observation speed will be increased by a factor of the pixel number of the receiver (as long as there is no degradation in the sensitivity of the individual pixel.). Therefore, high science throughput can be produced. For example, the observing speed of a 16-pixel focal plane array (FPA) is 16 times faster than a single pixel receiver. The first work is focused on the design, fabrication, assembly, and measurement of a 2\*2 LO array for a 1.37 THz HEB heterodyne array receiver. A HEB is an extremely sensitive THz mixer. The critical component of the 2\*2 LO array is a waveguide-based 2\*2 beam divider. The beam divider consists of a waveguide-based feeding network and four Pickett-Potter horns. The WR0.65 rectangular waveguide-based H-plane and E-plane junctions are used to construct the feeding network. The divider comprises two 400- $\mu$ m thick silicon wafers with multilayer deep reactive-ion etching (DRIE) micromachined circuits, and a Pickett-Potter horn array manufactured in aluminum using computer numerical control (CNC) machining. The two silicon plates and the aluminum plate were assembled with a special process using multilayer stacking technology to ensure an assembling misalignment lower than 10  $\mu$ m. Final, the beam divider was characterized by a LERMA ABnm Vector Network Analyzer (only  $S_{21}$  in the band of 1.3-1.4 THz. A measured normalized radiation patterns of the beam divider at 1.37 THz is done. A HDPE lens was set between the beam divider and the measurement plane. The distance between the beam divider and the HDPE lens is 32 mm, while the distance between the HDPE lens and the measurement plane is 190 mm. This is

the first prototype of the multilayer stacked waveguide-based 2\*2 beam divider at 1.37 THz ever fabricated [1].

To do the observation for planetary science, room temperature detectors are usually used. For measuring fine spectrum line of the planetary atmospheric molecule in sub-millimeter wave, the Schottky mixer is widely used. For example, the Microwave Instrument on Rosetta Orbiter project and the submillimeter-wave instrument (SWI) in Jupiter ICy moons Explorer (JUICE) project. For the earth atmosphere research and deep space mission, the low mass and small volume is the constraint of the satellite payload.

We design and fabricate a silicon block-based Schottky mixer, operating in 370-400 GHz. The upper layer of the silicon block is made of a ~420nm thick silicon wafer with two masks, while the bottom layer of the silicon block is made of a ~500nm thick silicon wafer with three masks. Both of the two silicon wafers are fabricated by the multilayer DRIE technology. A 3D vernier is used to improve the alignment accuracy of the mixer assembly. The measured SSB conversion loss of the silicon block-based Schottky mixer ~13 dB.

[1] H.-T. Zhu et al., "A 1.37 THz waveguide-based 2x2 beam divider fabricated by two microfabrication technologies," Proc. 31st International Symposium on Space Terahertz Technology, Tempe, AZ, pp. 1-1, Apr. 2020.

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### **Fabrication of bendable low-loss terahertz hollow waveguides based on plastic tubes**

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THz technology has developed rapidly in the past few decades due to its broad application prospects in many fields. The advancement of THz technology puts forward more stringent requirements on new THz waveguides. In previous studies, many THz waveguides have been developed, including metal-wire waveguide, hollow metal waveguide, photonic crystal waveguide, metamaterial clad hollow waveguide and metal/dielectric waveguide. Among these waveguides, the hollow waveguides attract the attention of researches due to the advantages of no end-reflections, high-damage threshold and low transmission loss. In our work, a variety of flexible terahertz hollow waveguides based on plastic tubes were developed, including plastic tube waveguide, metal-coated hollow waveguide, and metal/dielectric hollow waveguide.

For the plastic tube waveguide, we have successfully prepared the thin-wall cyclic olefin copolymer (COC) tube waveguide for the THz transmission using a well controllable dynamic coating method. The IR transmission spectra confirm that the wall thickness of COC tube waveguide is of high uniformity. The bandwidth can be broadened by decreasing the wall thickness of COC tube waveguide, and the low-loss transmission window will be moved from higher frequency range to lower frequency range when the wall thickness increases. The straight and bending (30°) transmission losses recorded on VDI systems reach 0.10–0.26 dB/cm and 0.18–0.31 dB/cm for the 58.6 μm wall thickness COC tube waveguide, 0.16–0.36 dB/cm and 0.20–0.41 dB/cm for the 51.6 μm wall thickness COC tube waveguide and 0.23–0.56 dB/cm and 0.29–0.58 dB/cm for the 33.0 μm wall thickness COC tube waveguide within 0.75–1.1 THz range, respectively.

In order to further reduce the transmission loss of the waveguides, several metal-coated hollow waveguides based on plastic structural tubes have been prepared, including ABS/Ag-coated hollow waveguide, ABS/Cu-coated hollow waveguide, and PEEK/Ag-coated hollow waveguide. The ABS/Ag-coated hollow waveguide can achieve low-loss and broadband (0.2-1.0 THz) transmission in the low-frequency range of THz waves. The 4.2-mm-bore hollow waveguide has the best straight transmission losses of 0.71 and 1.41 dB/m at 300 and 100 GHz, respectively. The bending transmission losses increase to 0.86 dB/m at 300 GHz (with a bending angle of 90° and a bending radius of 15 cm). The ABS/Cu-coated hollow waveguide was simple in design and inexpensive to fabricate. THz-

TDS attenuation spectra of the 5-mm-bore ABS/Cu-coated hollow waveguide showed that the prepared waveguide had relatively low attenuation at 0.32, 0.65, and 0.98 THz. The straight transmission loss was 0.85 dB/m at 0.98 THz, and the bending transmission loss increased to 1.12 dB/m at 180°. To further enhance the weather resistance of the waveguides based on plastic structural tubes, a robust PEEK/Ag-coated hollow waveguide was developed. The good thermal properties of the PEEK tube and the bonding performance between the silver film and the PEEK tube can meet the requirements of the stable transmission in high (150 °C) and low (-78.5 °C) temperature environments. In addition, the PEEK/Ag-coated hollow waveguide has extremely low transmission loss. For the 4.25-mm-bore waveguide, the straight transmission loss at 0.3 THz is 0.67 dB/m, the bending transmission loss rises to 1.02 dB/m upon a bending angle of 180° (bending radius: 15 cm).

On the basis of the metal-coated hollow waveguide, we also fabricated metal/dielectric hollow waveguide. The introduction of the dielectric layer can further reduce the transmission loss of the waveguide and adjust the low-loss transmission window of the waveguide. We fabricated successfully the Ag/PP hollow waveguide by optimizing the wall thickness of the PP tube and depositing a smooth and uniform silver reflective film onto its outer surface. From the loss spectra of THz-TDS, the prepared 5-mm-bore hollow waveguide has relatively low attenuation at around 300 GHz. The straight transmission loss is 1.05 dB/m at 300 GHz and the bending transmission loss has tiny increase up to 1.34 dB/m at 270°, as the bending angle varies from 0° to 270° (with the curvature radius of 15 cm).

In summary, these waveguides have the advantages of low transmission loss and excellent bending properties sheds light on the prospect of the waveguide transmission of low-THz frequency and the commercial applications in the future THz communication.

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### **Rice freshness recognition method based on improved VGG network and THz image**

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The freshness of rice can reflect the harvesting years and the degree of quality deterioration during storage. Therefore it is crucial to detect the freshness by using the THz image and improved VGG network.

Terahertz wave is an electromagnetic wave between microwave and infrared, the frequency range is 0.1THz-10THz. It has the advantages of non-destructive testing, molecular fingerprint, low energy. Terahertz imaging technology uses terahertz rays to irradiate the sample, and obtains a terahertz image of the sample by processing and analyzing the information of the transmission spectrum and reflection spectrum of the imaging sample. At present, terahertz imaging technology has been widely used in the fields of material identification, medical diagnosis, food detection and safety inspection. In this paper, The THz image of rice stored with different years were investigated by terahertz imaging system. Due to a large amount of data and inconspicuous shallow features of the terahertz image, the traditional VGG network cannot fully extract the deep feature information of the image. The Inception-ResNet-A asymmetric convolution module in the Inception-ResNet-V2 network is introduced based on the VGG19 network structure. According to the experimental findings, our improved network could increase identification accuracy up to 90 percent.

The results show that the proposed method of THz image combined with the improved VGG is efficient and feasible for identifying rice freshness and is a potential identification tool for ensuring food quality and safety.

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**Study of long-pulse high-power 170GHz gyrotron for fusion plasma ECRH**Bentian Liu<sup>1</sup>; Xiaojie Wang<sup>2</sup>1. Institute of Energy, Hefei Comprehensive National Science Center;  
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The MW gyrotrons are key devices in ECRH of magnetic confinement nuclear fusion systems. In order to achieve the high power and long pulse of the 170GHz gyrotron, which are adopted in the CFETR, a TE<sub>25,10</sub>-mode 170GHz gyrotron research are given in this paper. A single-anode magnetron injection gun (MIG) and the cylindrical resonant cavity operating are designed and optimized by PIC. The theoretical output power of the gyrotron with operating Voltage 75kV, electron current 45A is about 1.1MW, corresponding to electron efficiency of 32.6%. The gyrotron has been fabricated with the single-depressed collector and quasi-optical mode converter and will be tested in the future.

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**Identification of moldy wheat in terahertz images based on Broad Learning System**Fei Wang<sup>1,2,3</sup>; Yuying Jiang<sup>1,4,2\*</sup>; Hongyi Ge<sup>1,2,3\*</sup>; Xinyu Chen<sup>1,2,3</sup>; Li Li<sup>1,2,3</sup>

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The quality and safety of wheat are crucial components of food safety. The traditional methods for identification and detection of mildewed wheat grains require complex processing steps, take a long time, and have poor feature extraction ability, which easily leads to the loss of effective image information, resulting in ineffective identification and detection of mildewed wheat grains. Most of the algorithms do not have incremental learning characteristics and cannot be optimized for storage resources or model update time. This work suggests a Fast And Flexible Denoising Convolutional Neural Network-Convolutional Neural Network-Broad Learning System (F-C-BLS) network-based recognition algorithm of wheat mildew grain from terahertz (THz) spectral image address these issues. By including the Fast And Flexible Denoising Convolutional Neural Network (FFDNet) denoising module and the Convolutional Neural Network (CNN) feature extraction module and creating a F-C-BLS recognition model, the algorithm improves upon broad learning system (BLS). The algorithm improves the traditional BLS algorithm and constructs the F-C-BLS moldy wheat classification and recognition model by introducing FFDNet denoising network and CNN feature extraction network. To further improve the image processing capability of the F-C-BLS algorithm, a new convolutional network was proposed to enhance the image quality, improve the capability of network feature extraction, and increase the moldy wheat tera Hertzian spectral images of moldy wheat. Meanwhile, considering the possible gradient disappearance and overfitting caused by the depth of the network, we used parametric modified linear unit (PReLU) as the activation function. Finally the obtained feature matrix was converted into feature vectors and input to the BLS classification network for classification process.

Experimental results show that the F-C-BLS algorithm effectively improved the image processing quality after denoising and convolutional extraction of features, significantly reduced detail loss, and improved the ability to retain fine features. The algorithm increases the recognition accuracy of wheat mildew grain terahertz-spectral image and outperforms the traditional BLS algorithm in the accuracy of recognition. In particular, the recognition accu-

racy reached 94.47%, the recognition accuracy of the BLS for seriously moldy wheat was only 68.32%, while the recognition accuracy of F-C-BLS reached 94.47%, and the accuracy of F-C-BLS increased by 36.27% compared with BLS. Meanwhile, the recognition accuracy of F-C-BLS increased 33.20% for normal wheat and 36.22% for lightly moldy wheat compared with BLS. At the same time, this paper uses Support Vector Machine (SVM) and Back Propagation Neural Network (BPNN) to compare with F-C-BLS. The classification accuracy of our F-C-BLS network is 14.26% and 7.84% higher than those of SVM and BPNN, respectively, and the training time of F-C-BLS reached 3278.8s, the training time of F-C-BLS was improved by 9.7% and 16.4%, compared to SVM and BPNN, respectively. Moreover, the algorithm has the advantage of convenience with low running hardware requirements. Therefore, the F-C-BLS algorithm proposed in this paper had obvious advantages in classification accuracy and processing time, which could effectively process the THz images of moldy wheat and rapidly and accurately identify the moldy wheat in different periods. Terahertz imaging combined with the bls algorithm provides a new technical means for wheat, opening up new possibilities for terahertz imaging applications.

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### Terahertz near-field nanoscopy of edge fringes in the material interface

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Oral

Terahertz (THz) imaging has attracted remarkable interest because of the distinct superiority in non-destructive examination, biomedical sensing, and security checking. However, due to the diffraction limit, the spatial resolution of conventional THz imaging systems is restricted to the sub-millimeter scale, which is not capable of nano-optical imaging of the fine structures. In recent years, the scattering-type scanning near-field optical microscopy (s-SNOM) has become an effective tool in the nanoscale research of the semiconductor, plasmonic, biology, and dielectric systems. Usually, a sharp scanning probe of atomic force microscopy (AFM) is placed in the vicinity of the sample surface to acquire high spatial frequency properties. Nanoscale resolution can be obtained by using an s-SNOM operating at frequencies from visible to microwave. We experimentally investigate some fringes which appear at the edge position of a material stripe in the THz near-field image. We pay special attention to the outside dark fringes and the bright fringes in the plateau of the edge. These fringes are different from those in the visible range, where gold supports plasmonic modes. Gold fringes in the THz range are not affected by the edge resonances. We theoretically interpret the formation of the fringes. The numerical simulation results of the edge fringes show that THz light is highly concentrated locally at the gap between the tip apex and the sample. The electric field strength between the tip and gold is stronger than that between the tip and the silicon substrate. When the tip scans the edge of the grating, two hot spots are formed: one right under the tip and one at the upper sharp edge of the sample. Because of these two hot spots, the THz near-field scattered signals can be increased and a bright fringe appears in the edge region. An extensive scanning of a gentle edge only shows the outside dark fringes. When the probe tip moves away from the plateau, the apex does not couple to the silicon substrate right beneath it due to the curved profile. The smaller refractive index environment reduces the effective polarizability of the tip and forms an outside dark fringe in the near-field image of the edge. To explain the absence of the dark fringes in normal THz near-field images, we compare the topography and the SNR of the step. The using of smaller tip, steeper interface, and larger scanning step potentially reduces the possibility of scanning the sharp step and the intensity of the signal change. On the other hand, the signal changes obscured by the noise will become more pronounced due to the increase of SNR.

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## Study of Low Temperature Induced Hydrate Formation in Alkali Halide Solutions by Terahertz Time-domain Spectroscopy

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Salt-water systems are ubiquitous in nature and play an important role in life activities. The terahertz spectroscopy technology has been used in the study of the systems because terahertz waves have a unique response to hydrogen bonds and molecular low-frequency vibrations. However, liquid water has strong absorption of terahertz waves, and its terahertz spectrum characteristics are not obvious, which limits the application of this technology. In this paper, the method of solution freezing is used to systematically study the terahertz spectrum characteristics of the salt solution in the frozen state by the terahertz time domain spectroscopy (THz-TDS) technology. And the intrinsic relationship between characteristic spectra and hydrates is ascertained, and the formation mechanism of salt hydrates is analyzed, which provides new ideas for the study of water-bearing systems and even biological tissues.

1. The lattice vibration mode of alkali halide crystals has been explored clearly. The terahertz spectral features of alkali halide crystals were studied with the combination of broadband THz-TDS. The results show that the characteristic terahertz absorption peaks were observed in each salt in the frequency region below 8.5 THz and the frequencies of these observed peaks are red-shifted with the increases of the mass and radius of the ions. These peaks could be assigned to the lattice vibration of the ionic crystals by the solid-state-based density functional theory (DFT) calculations. This correlation between the resonant frequency of the lattice vibration, the reduced atomic mass, and the equilibrium distance between the ions agrees well with the harmonic oscillator model.

2. The disadvantages in the study of terahertz spectroscopy of salt solutions has been avoided by freezing method. The cooling-induced formation of hydrate in aqueous NaCl solutions was probed using THz-TDS. It was found that the NaCl hydrate formation is accompanied with emergence of four new absorption peaks at 1.60, 2.43, 3.34 and 3.78 THz. Combining the X-ray diffraction (XRD) measurement with the DFT calculations, we assign the observed terahertz absorption peaks to the vibrational modes of the formed  $\text{NaCl} \cdot 2\text{H}_2\text{O}$  hydrate during cooling.

3. The ability of alkali brine solution to form hydrates in the frozen state has been identified, and the law of hydrate formation has been summarized. We systematically studied the ability of 20 alkali halides to form solid hydrates in the frozen state from their aqueous solutions by THz-TDS combined with DFT calculations. We experimentally observed the rise of new terahertz absorption peaks in the spectral range of 0.3-3.5 THz in frozen alkali halide solutions. The DFT calculations prove that the rise of observed new peaks in solutions containing  $\text{Li}^+$ ,  $\text{Na}^+$  or  $\text{F}^-$  ions indicate the formation of salt hydrates. As a simple empirical rule, the correlation between the terahertz signatures and the ability of alkali halides to form a hydrate has been established.

4. The influence of organic solvents on salt hydrate formation has been studied. The formation of salt hydrate in salt-organic solvent-water ternary system was probed using THz-TDS. In the methanol, ethanol, isopropanol and tert-butanol systems, the results show that the first three alcohols can all make the absorption peak of NaCl hydrate disappear. We consider that highly polar alcohols could affect the hydration layer of the central ion, which play a key role in the formation of hydrates. And this conclusion is proved by changing the type of salt or organic solvent in the ternary system.

Oral

## Microwave kinetic inductance detectors for terahertz imaging

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A large amount of information can be obtained in the far-infrared (FIR) or terahertz (THz) band (30-1000  $\mu\text{m}$ ) since distant, cold and dusty objects of the universe radiate energy invisible at other wavelength. Large arrays of ultra-sensitive direct detectors with background-limited performance have important applications in telescope imaging systems with a large field of view. The microwave kinetic inductance detectors (KIDs), which are a kind of superconducting pair-breaking detectors resonating at different microwave frequencies, represent a state-of-the-art detector for the next generation space based FIR/THz observatories. Photons with energy higher than the superconducting gap break Cooper pairs and create quasi-particle excitations in the film. The best sensitivities of KIDs are comparable to that of the transition edge sensor (TES) bolometers. Furthermore, it is relatively easy to implement KIDs arrays on larger scales. With intrinsic frequency-domain multiplexing allowing high multiplex factors, even kilo-pixel KID arrays can be read out through a single coaxial line which reduces system complexities.

We designed and fabricated a superconducting hybrid NbTiN-Al kinetic inductance detector (KID) over a broad band centered at 4.3 THz. The antenna-coupled KID consists of a hybrid NbTiN-Al half-wavelength coplanar waveguide resonator with two ends open, capacitively coupled to a microwave readout line. The length of the resonator is  $\sim 10.7$  mm, corresponding with a resonant frequency designed at  $\sim 4.6$  GHz. The NbTiN film is chosen as a part of the resonator mainly for reduction of two level system noise when using phase readout. An in-line X-slot antenna locates in the middle of the resonator to achieve peak responsivity and high THz absorption efficiency for the detector. Our hybrid KIDs are fabricated on a 500- $\mu\text{m}$ -thick high resistivity silicon wafer. NbTiN film with a thickness of 400 nm is deposited first by DC-magnetron sputtering. Then part of the resonator is formed by photolithography and reactive-ion etching. The central pattern of the resonator is defined using electron beam lithography overlay. Finally, a thin (65-nm thick) Al layer is evaporated using an electron beam evaporator followed by lift-off.

The detector sensitivity is characterized by changing the bath temperature in a dark environment. Both a vector network analyzer (VNA) and a homodyne detection setup are used in the KID measurements. The VNA is used to measure transmission coefficients from which resonant frequencies and quality factors can be determined. For homodyne detection, the signal from the generator splits into two branches via a directional coupler.  $-20$  dB of the signal as one branch are coupled to the cryostat as probe tone for the KID. The probe tone is heavily attenuated before arriving to the KID. The readout signal from the KID is amplified by the cryogenic low noise amplifier (LNA) with a gain of  $\sim 40$  dB across a broad bandwidth of 4 – 8 GHz and a noise temperature of  $\sim 1.5$  K. Then it is further amplified by a room temperature amplifier to a level appropriate for the IQ mixer. The other branch serves as a local oscillator signal for the IQ mixer. The demodulated in-phase (I) and quadrature (Q) signals are then sampled by an analog to digital converters (ADC). Both amplitude and phase readout are performed. The measured electrical noise equivalent power for phase readout is about  $2.6 \times 10^{-18} \text{ W} \cdot \text{Hz}^{-1} \sim 0.5$  at 200 mK. This ultra-sensitive KID, which enables frequency domain multiplexing readout intrinsically, is promising for kilo-pixel imaging instruments in future space based far-infrared observatories.

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## End-to-end Design of Metasurface-based Complex-amplitude Holograms by Physics-driven Deep Neural Networks

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Holograms which reconstruct the transverse profile of light with complex-amplitude information have demonstrated more excellent performances with an improved signal-to-noise ratio compared with those containing amplitude-only and phase-only information. Metasurfaces have been widely utilized for complex-amplitude holograms owing to its capability of arbitrary light modulation at a subwavelength scale which conventional holographic devices cannot achieve. Iterative Fourier-transform algorithms (IFTA), such as Gerchberg-Saxton (GS) algorithm, play a dominant role in existing metasurface-based hologram designs, but can only generate phase-only hologram. In the field of complex-amplitude holograms, existing methods employ single back-diffraction propagation and rely on the artificial blocks which are able to independently and completely control both amplitude and phase, resulting in difficulty seeking out a cluster of artificial blocks to meet the demand above. Here, we propose an unsupervised physics-driven deep neural network for the design of metasurface-based complex-amplitude holograms using artificial blocks with incomplete light modulation. This method, serving as a generative adversarial model, integrates a neural network module with a forward physical propagation module and directly maps geometric parameters of the blocks to holographic images for end-to-end design. In general, the neural network module operates as a generator to produce feasible solutions to geometric parameters corresponding to the target holographic images, and then the forward physical propagation module, which serves as the discriminator, models the forward process of holography and outputs real reconstructive images based on the feasible solutions. Loss between reconstructive images and target images is calculated to drive the training process. A Y-shape deep neural network, named Y-Net, is adopted as the neural network module. The Y-Net consists of one path as the encoder to capture the discriminative features of target images, and two paths as the decoders for precise retrieval of geometry parameters. Skip connections are employed between each of up- and down-sampling residual blocks to skip multi-scale spatial information from encoder to decoder and enhance the high-resolution reconstruction. The forward physical propagation module first formulates the phase and amplitude modulation as the function of geometric parameters and then reconstructs the holographic images using angular spectrum method. The proposed method can be treated as a general design framework to obtain an array of design parameters at different working wavelength. As an illustration, nanocylinders are chosen as the artificial blocks here, the height and diameter of which are adopted as design parameters. Peak signal-to-noise ratio (PSNR) and structural similarity (SSIM) are calculated for holographic images generated by finite difference time domain (FDTD) simulation, based on geometry parameter solutions obtained from the proposed method and GS algorithm, respectively. GS algorithm gets 12.7682 for PSNR and 0.1869 for SSIM, while the proposed method gets 18.1988 for PSNR and 0.4233 for SSIM, suggesting a better performance with higher signal-to-noise ratio of the proposed method. For reconstruction efficiency, 86.72% of electric-field energy in imaging plane is gathered to reconstruct the holographic image, compared with 39.41% by GS algorithm. The perfect reconstruction by the proposed method has demonstrated that compared with using complete blocks, an efficient utilization, association and cooperation of the limited artificial blocks can achieve outstanding holographic display as well. Furthermore, more restricted controls of the incident light are adopted for robustness test, indicating strong robustness of the method. The proposed method offers a real-time and robust way towards large-scale ideal holographic displays with subwavelength resolution.

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### Versatile wavefront manipulations based on active transmissive metasurface

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Recently, metasurfaces have attracted considerable interest in EM manipulation, which exhibits extraordinary potentials to design EM functional devices. However, most state-of-the-art multifunctional metadevices were designed based on passive metasurfaces, which only either work in reflection mode or single polarization channel. In fact, it is still very challenging to design reconfigurable metasurfaces in multi-polarization transmissive channels. Here, we propose and demonstrate a reconfigurable metasurface to achieve various EM functions by modulating transmitted phase in LP and CP channels, respectively. We employ active component PIN diodes inserted into cruciform metallic patterns to design the meta-atom. As a result, the transmitted phases can be manipulated by changing the bias voltages imposed on these diodes. By carefully engineering the input voltages, our reconfigurable metasurface achieves versatile EM functionalities under different polarizations, including anomalous deflections with steered beams, angular momentum generation, focusing lens, and even diffusive scattering for incident LP and CP wave. As a proof of concept, a prototype composed of 12 × 12 meta-atoms is fabricated and measured. Numerical results have a good agreement with experimental results, and demonstrate all predicted dynamically shifted functions in multi-polarization channel at 7.4 GHz. Our proposed reconfigurable strategy provides a way towards realizing reconfigurable metadevices in transmissive scheme, which promises potential applications in intelligent devices and integrated systems.

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### Encryption and decryption applications on conductive films using THz near-field real-time imaging system

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Terahertz (THz) imaging is one of the most important applications in the field of THz science and technology. Compared with other imaging methods, due to the characteristics of THz waves, THz imaging can nondestructively obtain rich information including the refractive index and electrical conductivity of the sample, which is of great significance in the fields of biological tissue differentiation, military security inspection, and nondestructive testing.

Traditional continuous-wave THz source imaging cannot obtain spectral information and the speed of point-by-point scanning pulsed THz source imaging is slow. To achieve high resolution and high imaging speed, traditional scanning imaging also cannot be applied to fields that require real-time performance such as biomedical imaging, which change fast.

In order to shorten the imaging time and achieve real-time THz spectra imaging, X. C. Zhang et al. proposed a QR (Quick Response) THz beam imaging system based on electro-optic sampling. Since this imaging method does not require point-by-point scanning, it greatly increases the speed of THz pulse imaging, making real-time THz pulse imaging possible. Thus, we built a real-time THz high-resolution spectral imaging system. And we use this system to realize many applications such as the detection of encrypted information in the THz band.

The system can quickly and accurately read the pencil writing in the paper clip, and can distinguish the mixed pencil coating pattern from the background under visible light. Compared with the traditional THz-TDS test method,

the results show the reliability and superiority of the THz imaging system.

We also designed three cases of encryption via our system. The first encryption case is that we use pencils with different conductivity to write different letters. The part written with 4B pencils is the content we need to encrypt, which cannot be recognized by the optical photo with other parts written with 4H pencils, but can be clearly decrypted by our system. The second case is that we use different conductivity pencils to write together without superposition. The part with low conductivity is the part we need to encrypt, which can be quickly and clearly decrypted in the THz image. As a final example, we designed a structure superimposed on each other. We used a QR code as a background and wrote the information that needed to be encrypted in a pencil with higher conductivity. Using our terahertz system for decryption, clear and quick results have been achieved.

Sometimes, due to environmental noise or system noise and other factors, our THz image SNR(signal-to-noise ratio) is low, so that the information detection is not accurate. So we used a new way to reduce noise -- using neural network architecture to reduce noise. We have comprehensively compared 7 mature network architectures, and the FFDNet (Fast and Flexible Denoising Convolutional Neural Network) is the most suitable network for our system. It has achieved the highest level of noise reduction and SSIM(Structural Similarity). In addition, due to the limitation of the resolution of THz CCD camera, we use the neural network model to improve the resolution of the original image. Compared with the traditional digital image processing method to improve the resolution, it can keep the original image look and feel as much as possible and obtain higher resolution.