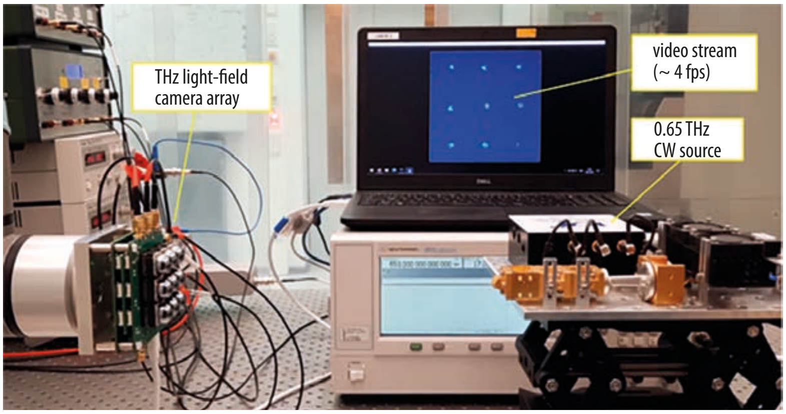
Enabling terahertz light-field imaging

Using fully integrated silicon components enables the development of a modular terahertz light-field camera.

Vishal Jagtap and Ullrich Pfeiffer

Light-field imaging is a highly versatile computational technique for three-dimensional scene reconstruction, depth estimation, and content editing. Combining light-field with terahertz detectors to perform real-time see-through imaging will lead to novel applications in security, medical science and industry.



The THz light-field camera array maps the radiation pattern of a 650 GHz source.

All Images: Uni Wuppertal

The terahertz frequency range is defined between 300 GHz and 3 THz corresponding to wavelengths from 0.1 to 1 mm. It offers unique advantages for imaging and sensing applications. Compared to microwaves or millimeter-waves (mm-wave) with lower frequency, terahertz waves permit a finer image resolution on the sub-mm scale comparable to the human eye. This resolution enables the shapes of most common objects in everyday life to be identified.

Terahertz waves are strongly absorbed by water molecules, reflected by metals, and transparent to the dielectric materials such as daily use plastics – they behave very similar to X-rays. However, X-ray photons have a high energy and can therefore lead to the ionization of biomolecules such as human gene structures. Therefore, X-ray doses must be limited and shielded to prevent unintentional exposure. Terahertz waves, on the other hand, have no such side effects and can therefore be operated freely. As a result, terahertz imaging exhibits a strong potential in security screening, quality control, and biomedical diagnosis as well as in the inspection of packaging and the conservation of art. Due to the limitations of terahertz hardware components, the attention was focused on traditional two-dimensional imaging. State-of-the-art terahertz transmitters and receivers either perform weakly or lack a sufficient integrability to be implemented in sophisticated computational imaging techniques such as light-field imaging.

Light-field imaging is a robust computational technique based on ray-tracing geometry for the three-dimensional scene reconstruction, depth estimation, and content editing. Using this method, the light flowing into and out of the object is considered as a vector field composed of some bundles of rays which are quantified in terms of the energy density along a specified direction and position in three-dimensional space. If the position and the flow direction of individual light rays are known, it is possible to apply either back-propagation from the sensor or forward-propagation from the source to reconstruct a three-dimensional volume source of the field disturbance. The light-field method works with incoherent radiation but it requires spatio-directional sources and detectors. These components can synthesize and sample the light along multiple angles across different spatial locations. Isotropic, incoherent sources generate excellent spatio-directional light-fields which can be readily sampled by a camera. Light-field techniques have become popular for visible-light imaging due to the ubiquitous availability of such sources and inexpensive cameras.

How light-field imaging works

The fundamental idea behind light-field imaging is to map the space between two planes to observe the vector fields. One of these planes is classified as the source plane while the other one, the sensor plane, is based on the direction of the ener-

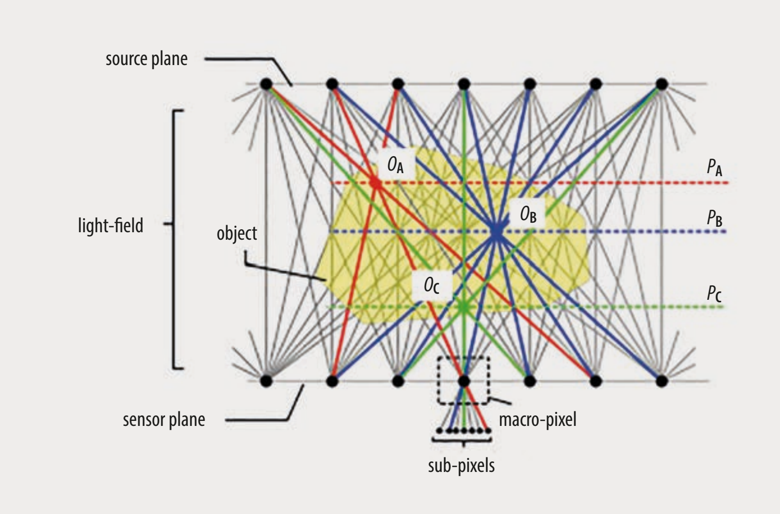
© 2024 Wiley-VCH GmbH

gy flow. Such a representation may encompass one subspace of a full light-field system which might also consist of other components such as lenses and mirrors. It is assumed that the sources and sensors work isotropically, i. e. they radiate and capture energy along all directions in a similar manner. Assuming that there are no effects like diffraction and interference of the waves, the straight lines joining the sources and the sensors form the light-rays. An object placed between the two planes will partially transmit the light-field and partially reflect and thus perturb it. If the sensor plane samples all the spatio-directional light-rays, ray-tracing and – in post-processing – the integrated intensity of the light along different sets of rays allow focusing on different parts of the object including its depth axis. Extending the basic concept to multiple sets of rays enables the compilation of two-dimensional images corresponding to single planes. If different planes in the scene provide cross-sections along the object depth, a three-dimensional reconstruction is allowed for.

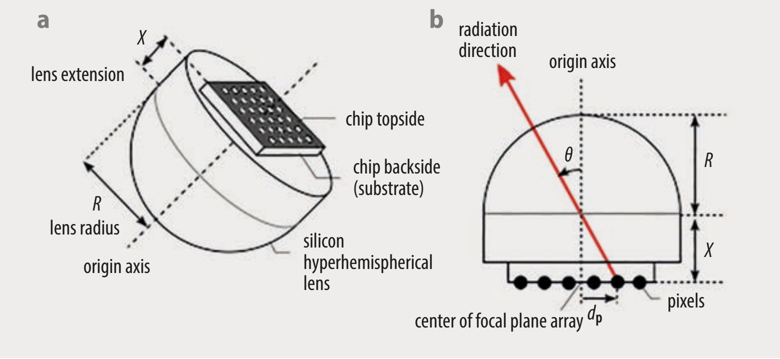
Sampling the light-field

If each point on the sensor plane consists of a single pixel, the intensity of all the light rays captured within this pixel is integrated. Therefore, the spatio-directional information is irrevocably lost. Instead, multiple sub-pixels are required at each sensor position. These so-called macro-pixels sample the incident light along different directions. Such a macro-pixel is the key building block for any light-field imaging system. The object sampling density corresponds to the discretization of the light-field which is associated with the spatial and angular arrangement of the sub-pixels and the macro-pixels.

The first demonstrations were based on scanning a scene by moving a single camera. Applications included the modeling of a three-dimensional illumination source, a virtual imaging illustration, the preparation of a digital archive of art sculptures from the renaissance, and the production of interactive city panoramas. Compact light-field camera designs have been demonstrated, consisting of a two-dimensional array of micro-lenslets arranged across a digital camera sensor. This technology is now commercialized for three-dimensional imaging and computational aperture synthesis in photography and three-dimensional microscopy. Some of these advancements have led to the multi-camera setups available in modern smartphones.



Spatio-directional light-fields are established between the source and the sensor plane containing a macro-pixel and sub-pixel arrangement.

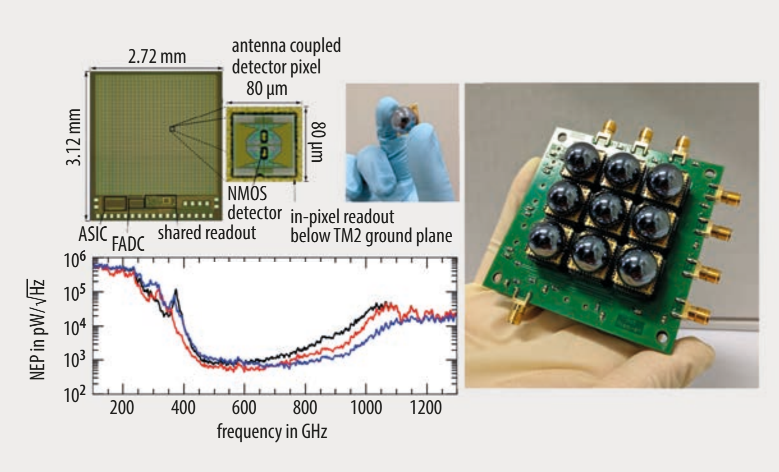


Macro-pixels are realized by silicon-lenses (a) while the sub-pixels consist of a THz focal plane array of direct detectors (b).

Visible versus THz wavelengths

There are many similarities between systems using visible light and the incoherent terahertz light-field systems. Both require spatio-directional sensors and diffused illumination. The plenoptic function for both explores a co-domain of real numbers and the intensity of the light drops corresponding to $1/r^2$ if r is the distance a spherical wavefront in the far-field has travelled from a point source. However, there are also significant differences

© 2024 Wiley-VCH GmbH



Fully integrated THz digital camera with 32 × 32 pixels – micrograph (top left), individual antenna-coupled detector (middle), and packaged view (right) – and its broadband spectral characteristics of selected antenna-coupled detectors (bottom left)

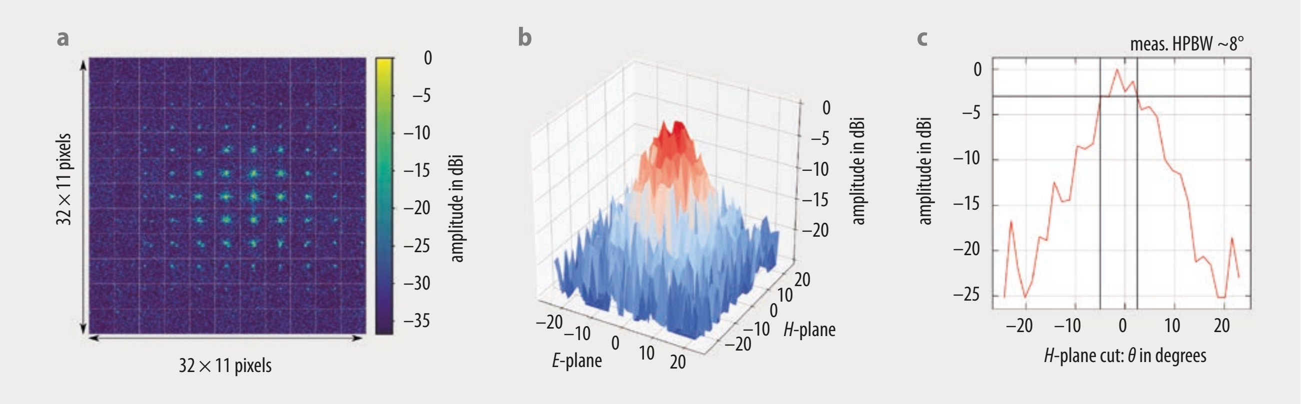
between terahertz and visible light presenting unique challenges for terahertz light-field systems.

First of all, the wavelength of terahertz light is nearly three orders of magnitude larger than the one of visible light. This fact severely limits the dense packaging of the sensing pixels due to an enlarged scale diffraction limit. In addition, high intensity isotropic incoherent terahertz sources do not exist so far – and it is impossible to perform computational light-field imaging in the absence of an appropriate illumination. The same applies to sensors for terahertz wavelenghts. The low integration density poses another particularly important challenge: only a few hundreds of terahertz sensors can be integrated within a focal-plane array while millions of pixels are available for sensors of visible light. This limitation directly restricts the light-field density and the accessible image resolution. Furthermore, arrays of lenses which are required to capture the spatio-directional light-field in compact cameras are not available at terahertz frequencies.

A multi-chip THz camera

There is a preliminary requirement to perform light-field imaging: a large focal-plane array of detectors must be capable of detecting and resolving spatio-directional diverse light-fields. A solution might stem from a fully integrated terahertz digital camera comprising of two-dimensional arrays of antenna-coupled CMOS direct detectors which are themselves coupled to a high-resistivity hyper-hemispherical silicon lens.

The configuration of a silicon lens-integrated terahertz focal-plane array consists of antennas radiating from the backside, i. e. towards the substrate, of the chip. The extension length of this lens is selected such that the pixel-array is located at the focal point of an approximate ellipse formed by the hyper-hemispherical lens. Therefore, pixel-to-angle mapping becomes possible implying that the spatial location of a pixel on the array corresponds directly to the received beam angles. The mapping is deterministic and predictable to the first



Raw light-field image data (a), reconstructed source antenna pattern (b), and cross-section of light-field reconstructed antenna pattern (c)

© 2024 Wiley-VCH GmbH

order within a pinhole image formation mode. Actually, the silicon lens plays the role of a macro-pixel and the two-dimensional arrays of detector pixels act as sub-pixels providing directional diversity. A fully integrated terahertz light-field subpixel consists of 32 × 32 antenna-coupled CMOS terahertz power detectors. These detectors exhibit a broadband spectral characteristics with the best operating frequency at 600 GHz and a bandwidth of 3 dB or nearly 300 GHz. The detectors are activated in a rolling shutter mode through an on-chip row and a column selection logic. All detectors have some elements in common: the programmable gate array (PGA), the correlated double sampler (CDS) for offset cancellation, and the analog-to-digital converter (ADC).

A full-fledged terahertz light-field camera is realized by implementing large arrays of macro-pixels and routing the control logics on a common motherboard. This multi-chip scaling approach keeps the fabrication costs under control and retains the advanced functionality of fully integrated terahertz digital cameras. The modular design permits to flexibly scale the terahertz light-field imaging system. Furthermore, individual CMOS terahertz digital cameras can be replaced conveniently.

3D reconstruction – example

The described terahertz light-field camera already demonstrated real-time imaging. The camera was placed in front of a 650 GHz CW AMC source. The light-field image data was streamed out in form of a video with an overall framerate of 4 frames per second with each sub-camera streaming at 36 frames per second. The controlled implementation limited the imaging speed: individual commands were sent in sequence from a python interface to trigger the data acquisition of each camera. For pure demonstration purpose, the 3 × 3 array of the terahertz light-field camera was stepped in two-dimensional mode to capture the light-fields of a diverging source. The spatio-directional data collected is then computationally processed to reconstruct the radiation pattern of the AMC source.

*

This work received partial funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 101019972).

[1] *R. Jain* et al., IEEE ISSCC **64**, 484 (2021)
[2] *M. Levoy*, Computer **39**, 46 (2006)
[3] *R. Ng* et al., Stanford University Computer Science Tech Report (CSTR 2005-02), Stanford University (2005)
[4] *R. Jain* et al., IEEE Trans. Terahertz Sci. Technol. **6**, 649 (2016)

Authors

Dr. Vishal Jagtap, THz Imaging and Spectroscopy, **Prof. Dr. Ullrich Pfeiffer**, High-Frequency and Communication Technology, University of Wuppertal, +49 202 439 0

Light at Work: PhotonicsViews

The European industry magazine for optics, photonics, and laser technology

- 6 issues a year
- reports on optical systems and components
- research and development
- application reports and business news

Daily industry, research news, and magazine information at
www.wileyindustrynews.com/en
twitter.com/photonicsviews
www.linkedin.com/company/photonicsviews

WILEY

© shutterstock/ensuper

© 2024 Wiley-VCH GmbH