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Pulse time-domain holography for terahertz wavefront metrology

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Dec 04 2019 NTNU Taiwan-Russia WIP

Outline

- **Introduction**
- **Terahertz Time-Domain Holography**
  - Basic Principles
  - Essence of the Technique
  - Important Improvements
- **Applications of broadband wavefront metrology**
  - Propagation in Linear Media
  - Sustainability to Obstacles

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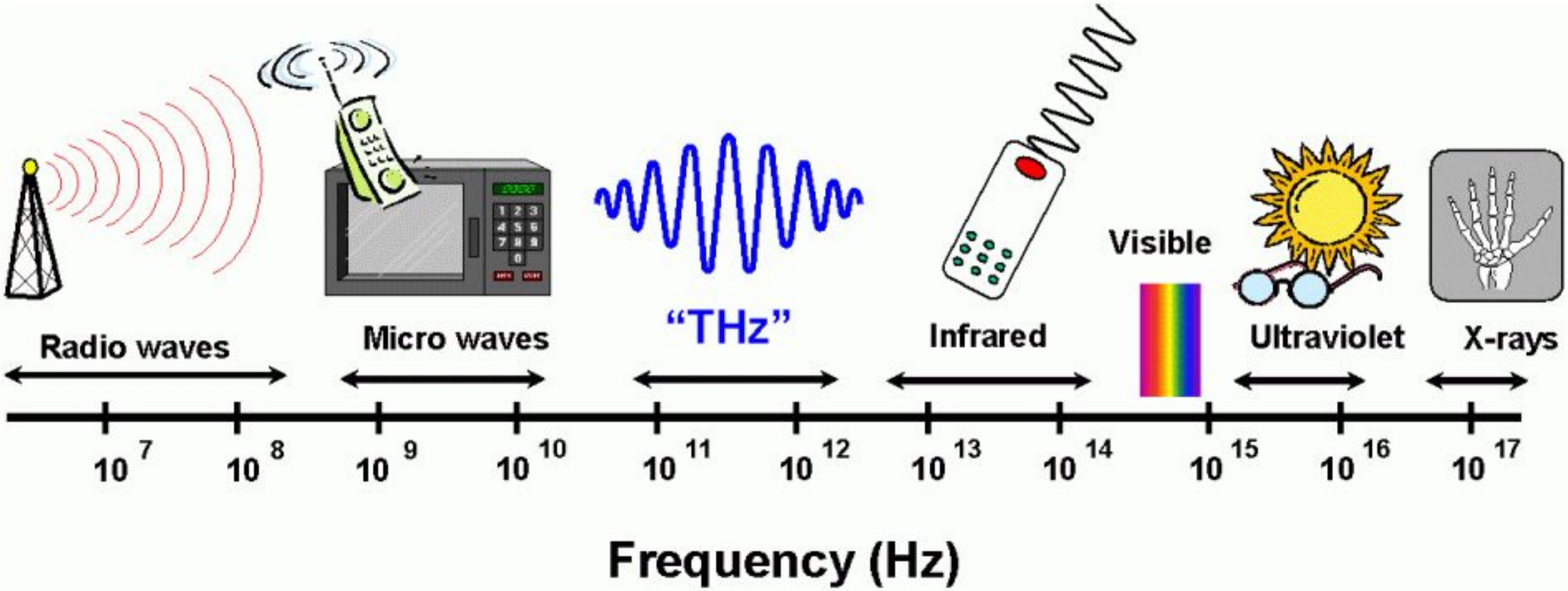
THz Frequency Range

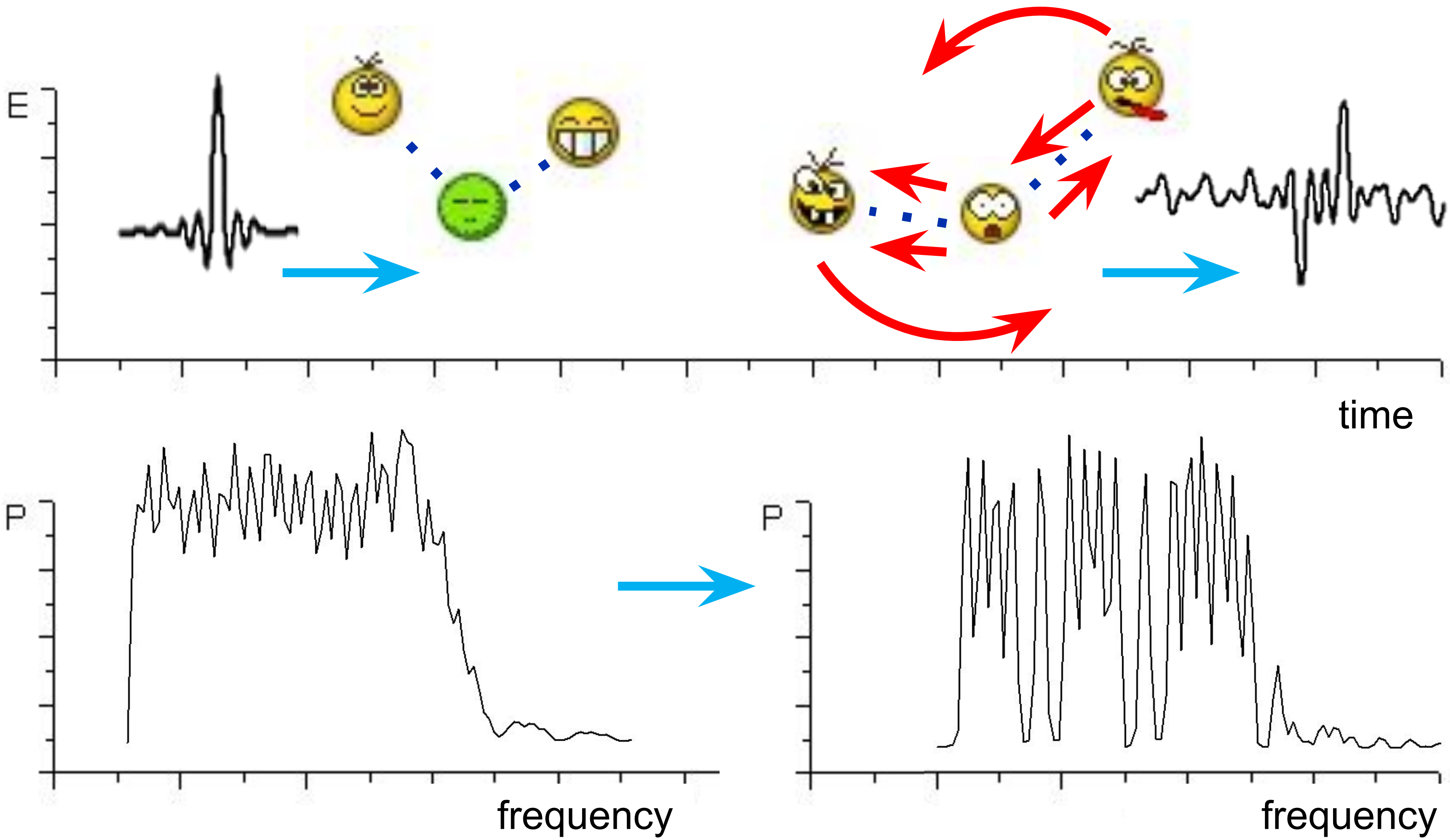


Wavelengths: 3 mm — 30 um

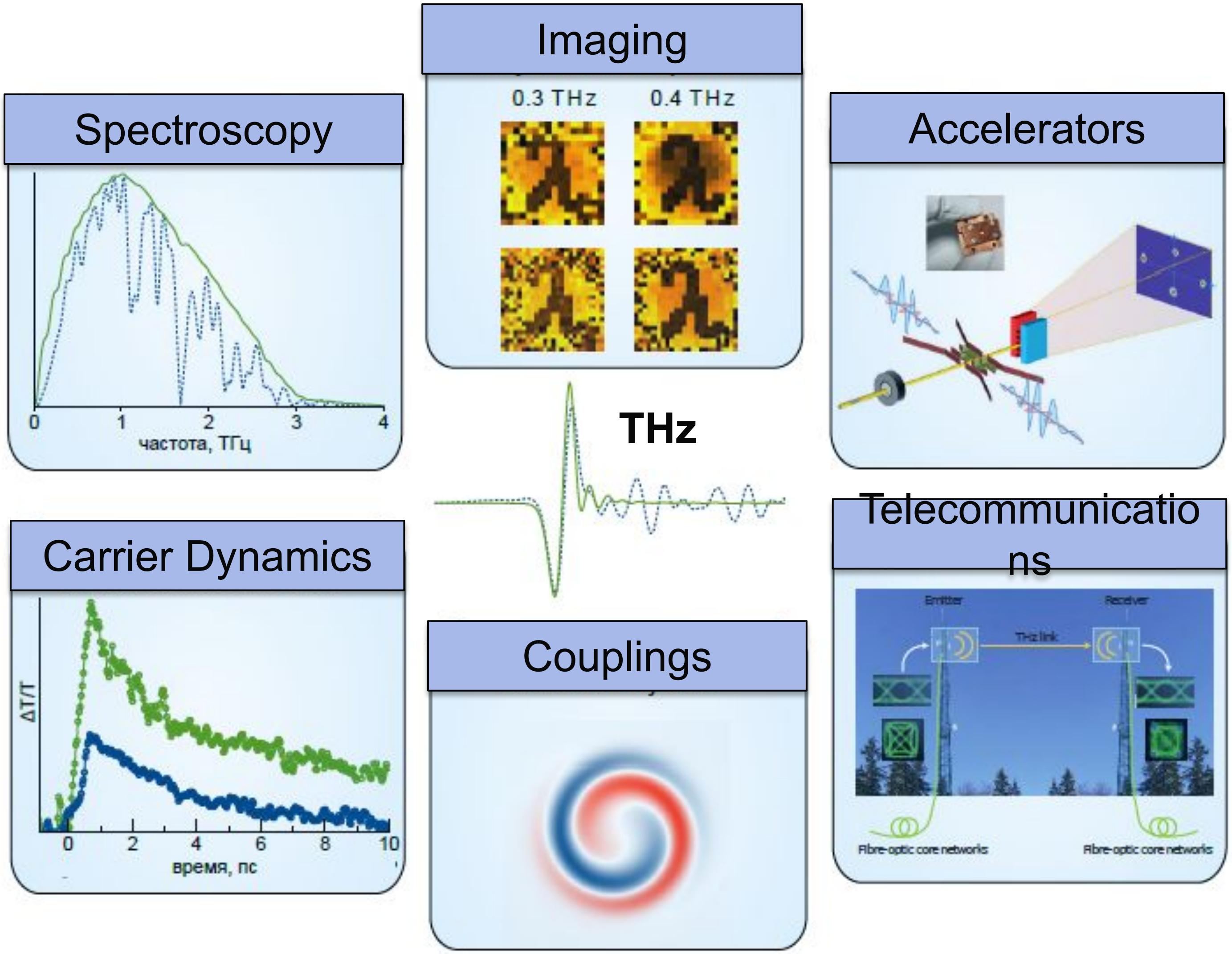
Frequencies: $0{,}1 \cdot 10^{12}$ — $10 \cdot 10^{12}$ Hz

1 THz ↔ 1 ps ↔ 300 um ↔ 33.3 cm^{-1} ↔ 4.1 meV ↔ 47.6 K.

Interaction between broadband THz radiation and matter



Main Applications of THz Radiation

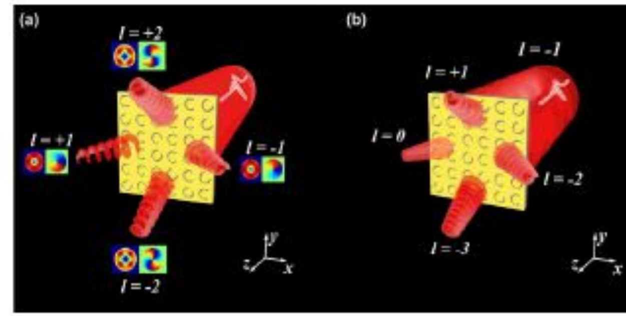


A. Gorodetsky, Thesis for Dr. Sci. in Phys., ITMO University (2019)

Pulsed THz radiation is a promising for following applications:

- Communications
  due to the following:
  - high carrier frequencies,
  - broad spectral bandwidth,
  - high pulse repetition rate.

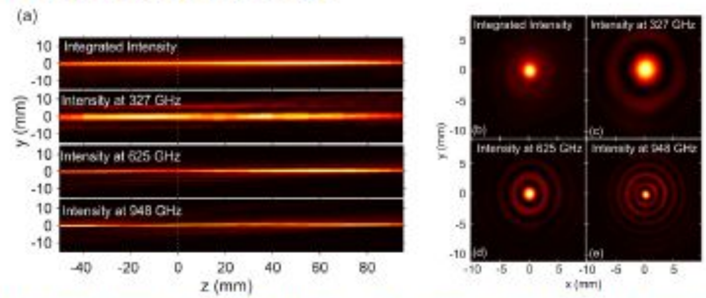
H. Zhao, B. Quan, X. Wang, C. Gu, J. Li, Y. Zhang *ACS Photonics* **5**, 17261732 (2018).



Schematics of (a) OAM multiplexing and (b) OAM demultiplexing.

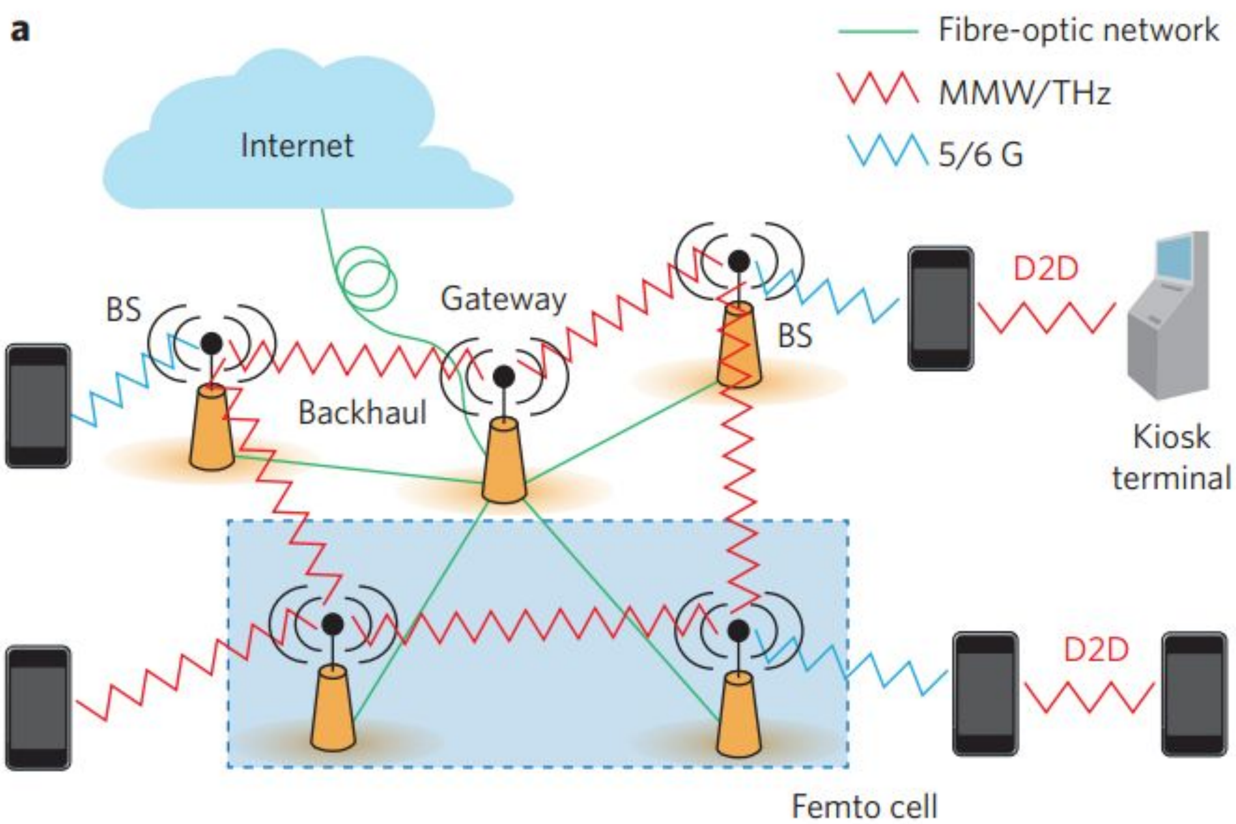
- Imaging
  due to the following:
  - spectral information,
  - multi-layered inspection,
  - low photons energy.

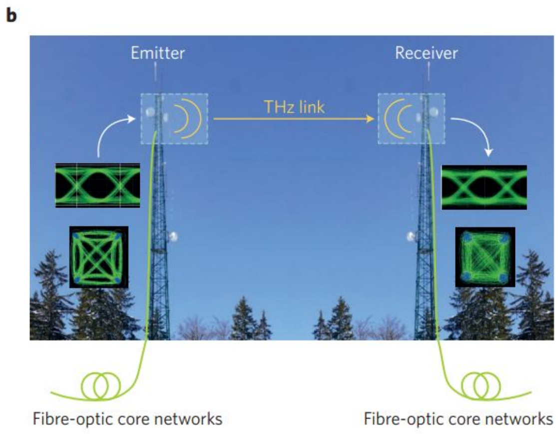
S. F. Busch, G. E. Town, M. Scheller, M. Koch *J. Infrared Millim. Terahertz Waves* **36**, 318-326, (2015).



Measured intensities of the axicon beam: axial (a) transversal and (b-e) overall and at the selected frequencies.

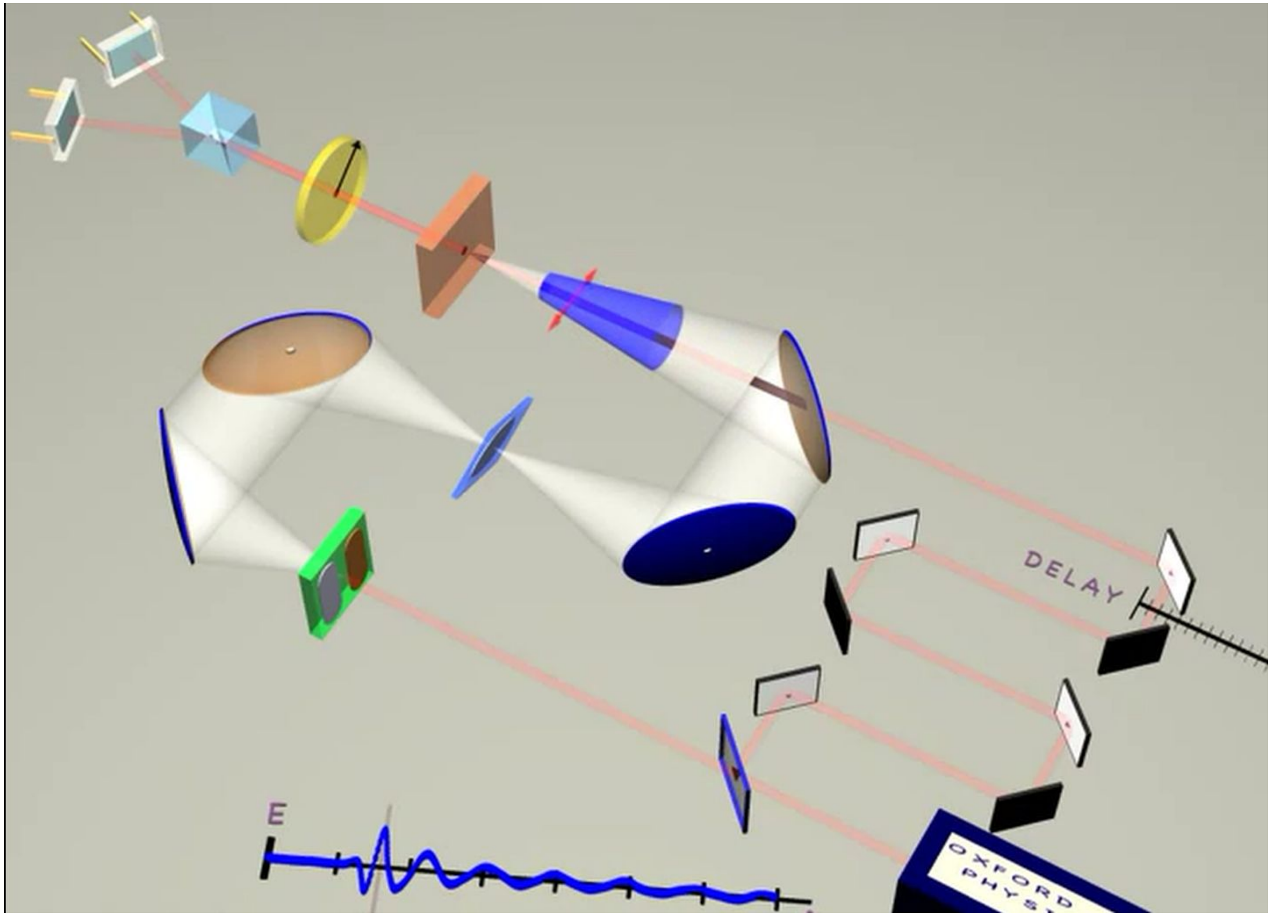
Application of THz links in networks





Nature Photonics, **10**, 371.

Electro-Optical Detection of THz radiation



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THz TDS vs PTDH Setup

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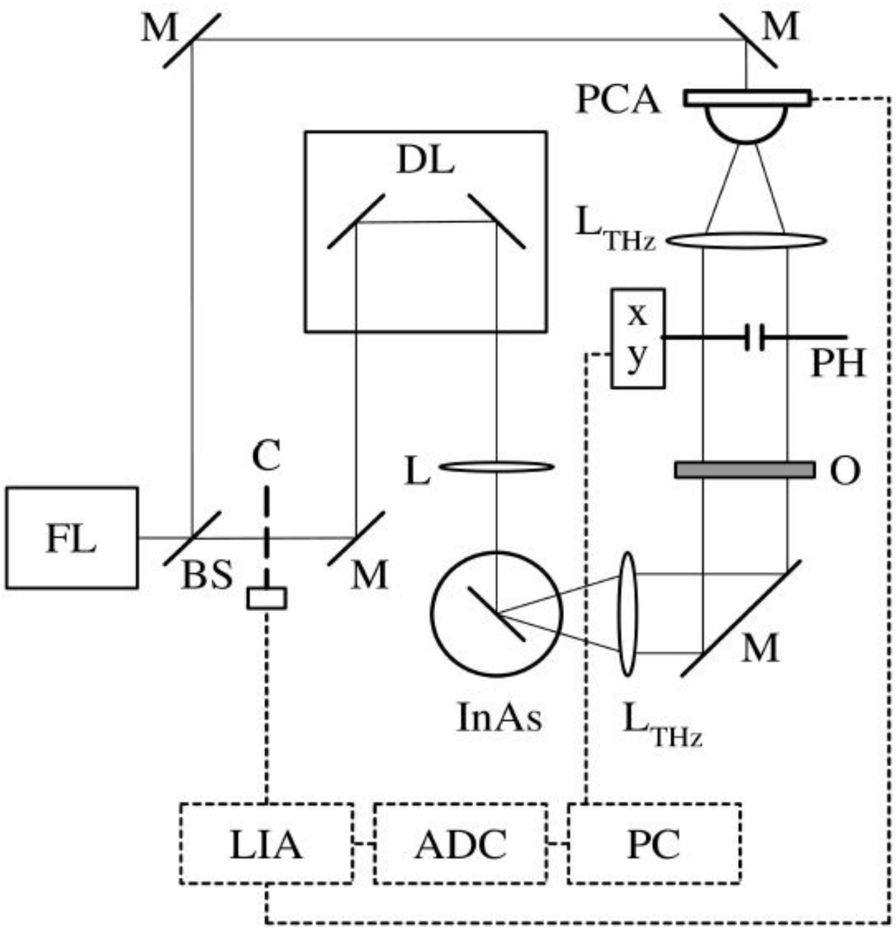
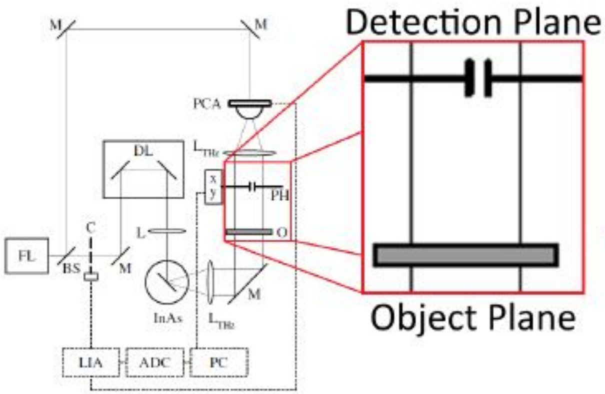
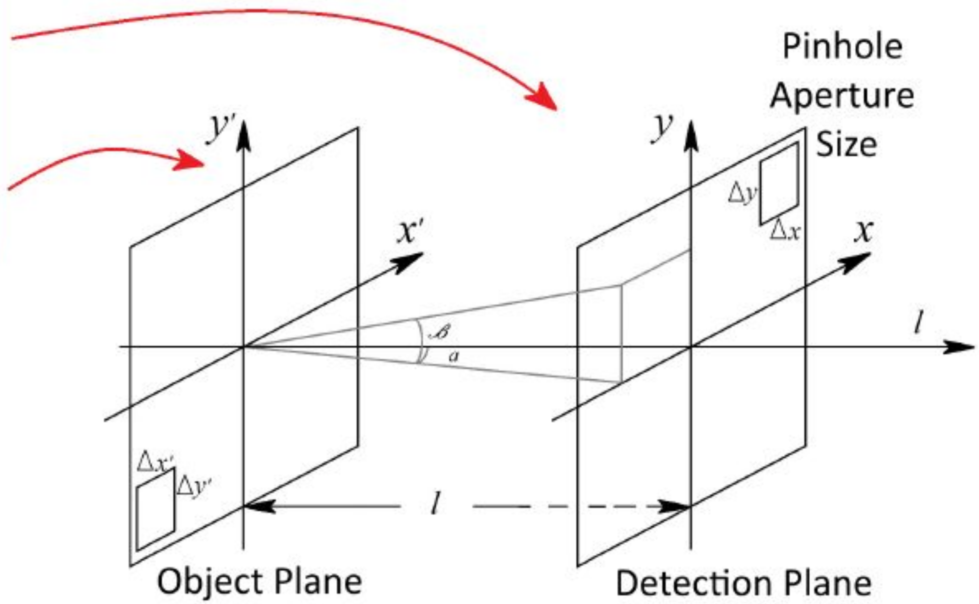


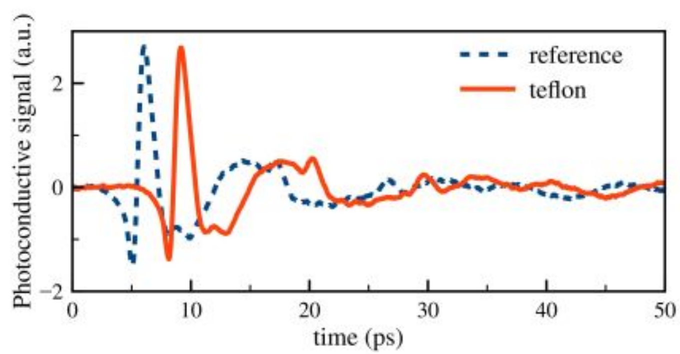
FL	-	femtosecond laser
BS	-	beam splitter,
C	-	mechanical chopper,
DL	-	delay line,
InAs	-	THz generator,
M	-	mirrors,
L	-	lens,
O	-	object,
(x-y)	-	2D scan stage,
L_{THz}	-	lens for THz radiation,
PCA	-	photoconductive antenna,
LIA	-	lock-in amplifier,
ADC	-	digitizer

N. V. Petrov, et al. *IEEE Trans. Terahertz Sci. Technol.* **6**, 464, (2016).

Measurement Details

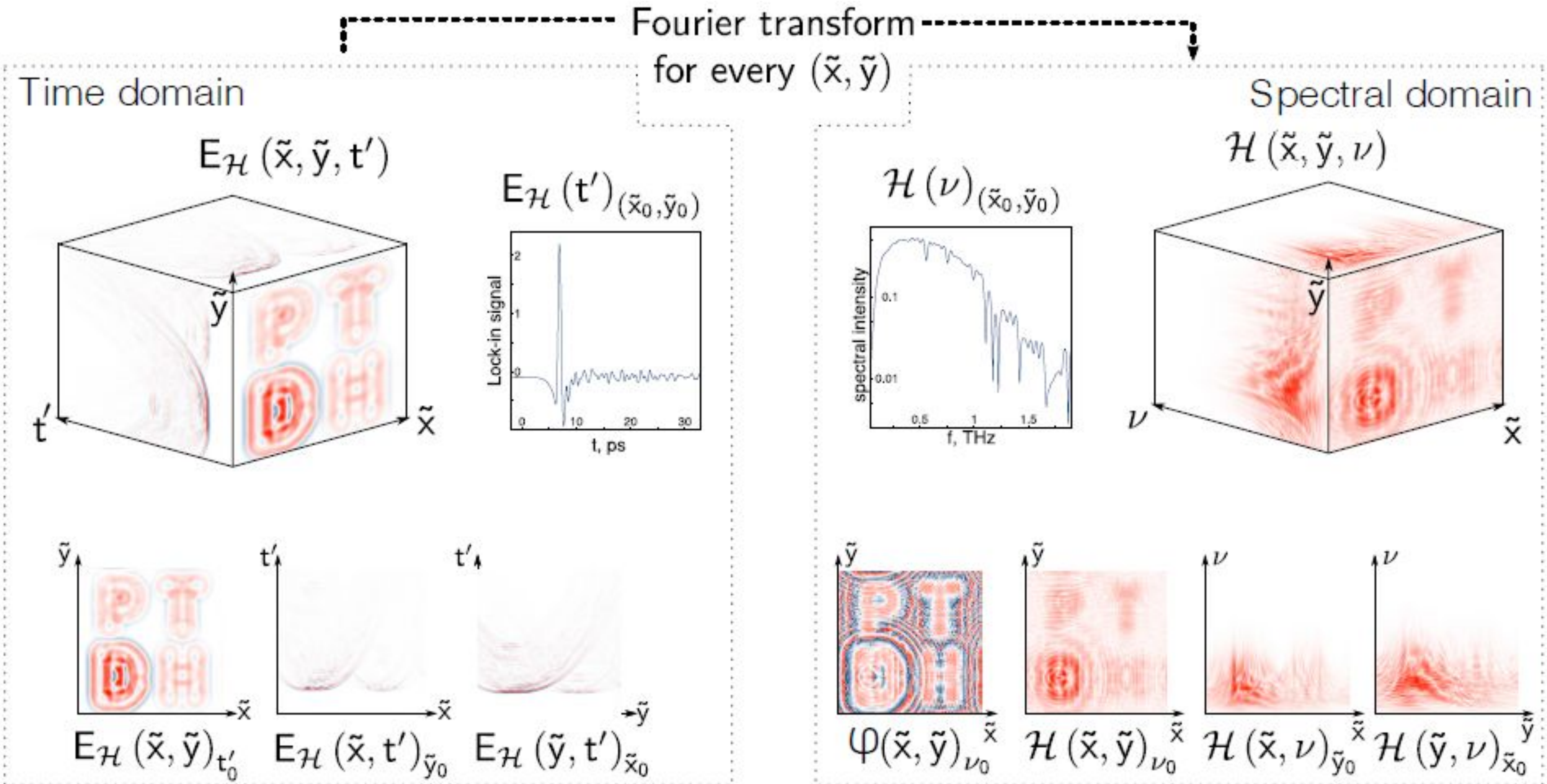






Petrov N. V. et al. // IEEE Trans. Terahertz Sci. Technol. 2016. Vol. 6 P. 464.

THz Pulse Time-Domain Holography



N.S. Balbekin, M.S. Kulya, A.V., A.A. Gorodetsky, N.V. Petrov
Increasing the resolution of the reconstructed image in terahertz pulse time-domain holography. // Sci. Rep. 2019. Vol. 9, P. 180.

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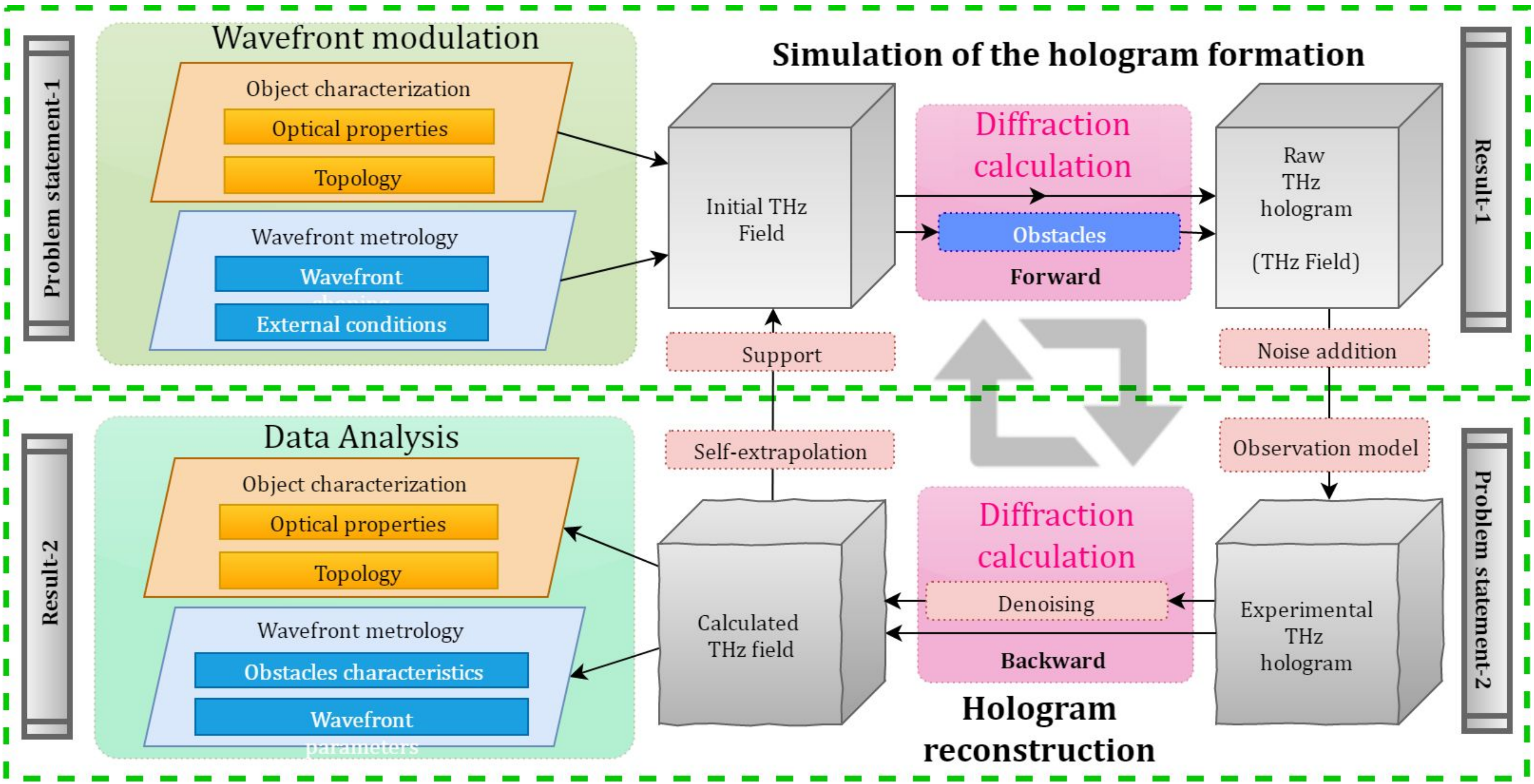
Essence of the Technique

- **Experimental setup schemes for the registration of collimated THz wavefront in the form of spatio-temporal profiles:**
- Raster scanning
- THz field detection on a wide electro-optical crystal conjugated with matrix photodetector
- **Numerical techniques for data processing:**
- Digital signal processing (signal extraction, denoising)
- Iterative algorithms for field of view expansion and resolution increasing
- **Mathematical methods for calculation of the diffraction of monochromatic spectral components of broadband radiation aimed for:**
- Analysis of the propagation dynamics of distribution of complex-structured fields
- Object image formation
- **Software tools for data representation and analysis**
- Representation of complex-valued fields in spatial, angular, temporal and spectral coordinates
- Specialized modules for extraction of data required to solve various tasks.

THz-PTDH Conceptual Diagram



THz PTDH Research Directions

- **Methodology Development**
  - Denoising — *Opt. Express.* 2019. **27**, 18456; *Appl. Opt.* 2019. **34**. G61
  - Increasing of field of view and resolution — *Sci. Rep.* 2019. **9**, 180
- **Measurement of Objects' Amplitude-Phase Characteristics**
  - with complex gradient-step relief — *IEEE Trans. Terahertz Sci. Technol.* 2016. **6**, 464
  - in dispersive media — *J. Mod. Opt.* 2017. **64**. 1283
- **Spatio-Temporal Metrology of Broadband THz Wavevronts**
  - THz Gauss-Bessel beam propagation dynamics — *Sci. Rep.* 2018. **8**, 1390
  - broadband uniformly topologically charged beams self-healing — *Appl. Opt.* 2019. **58**. A90

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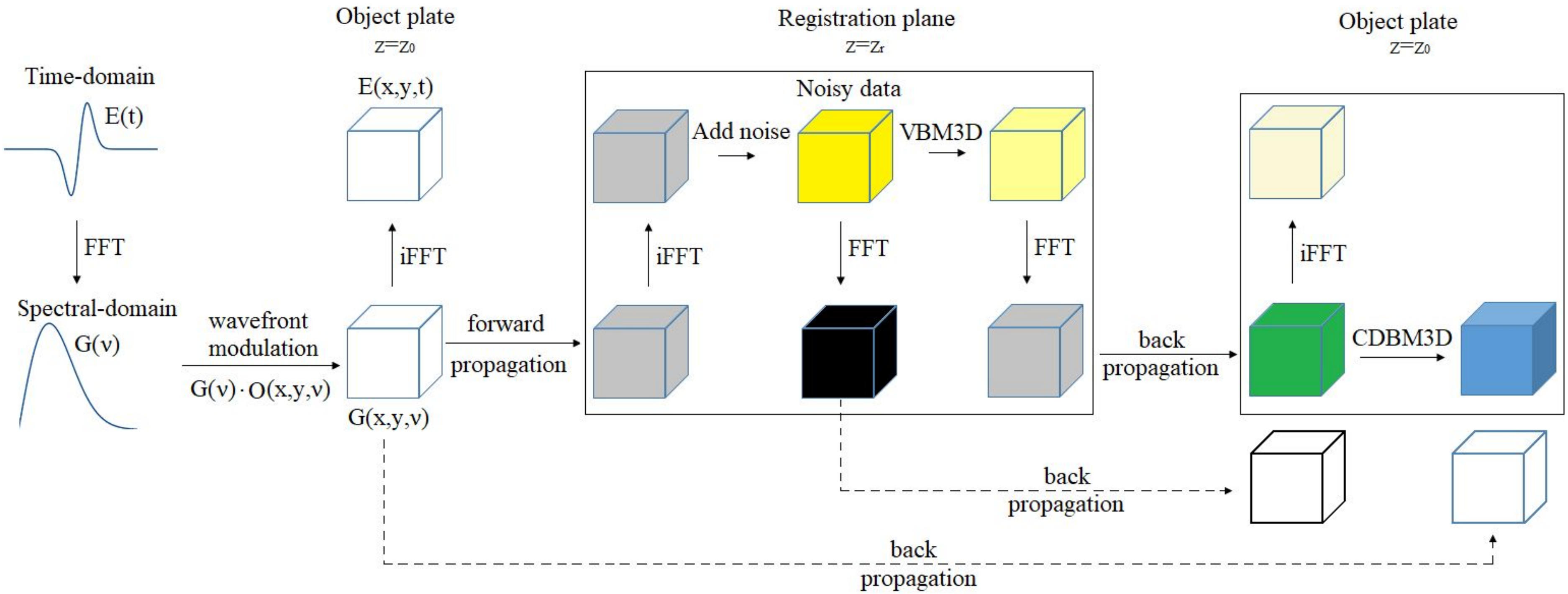
Hyperspectral Data Denoising

Opt. Express. 2019. **27**, 18456



Block-Matching Three Dimensional (BM3D) Denoising:

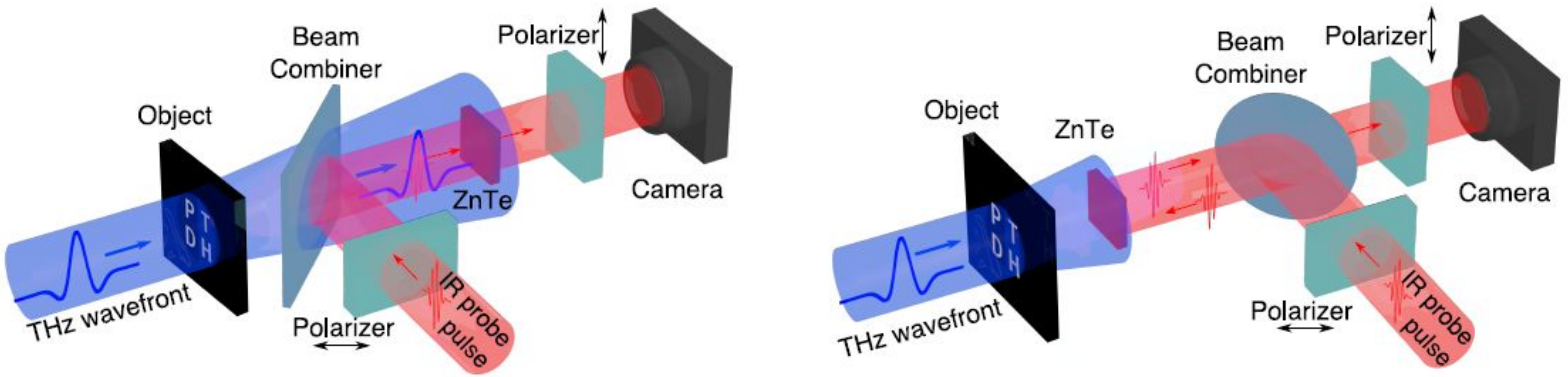
Video-filtering (VBM3D)

K. Dabov, et al. *15 IEEE Euro Signal Process. Conf.,* **145** (2007)

Complex-domain denoising (CDBM3D)

V. Katkovnik, et al. *Signal Process*. **141**, 96 (2017)

Fast THz Holograms Detection

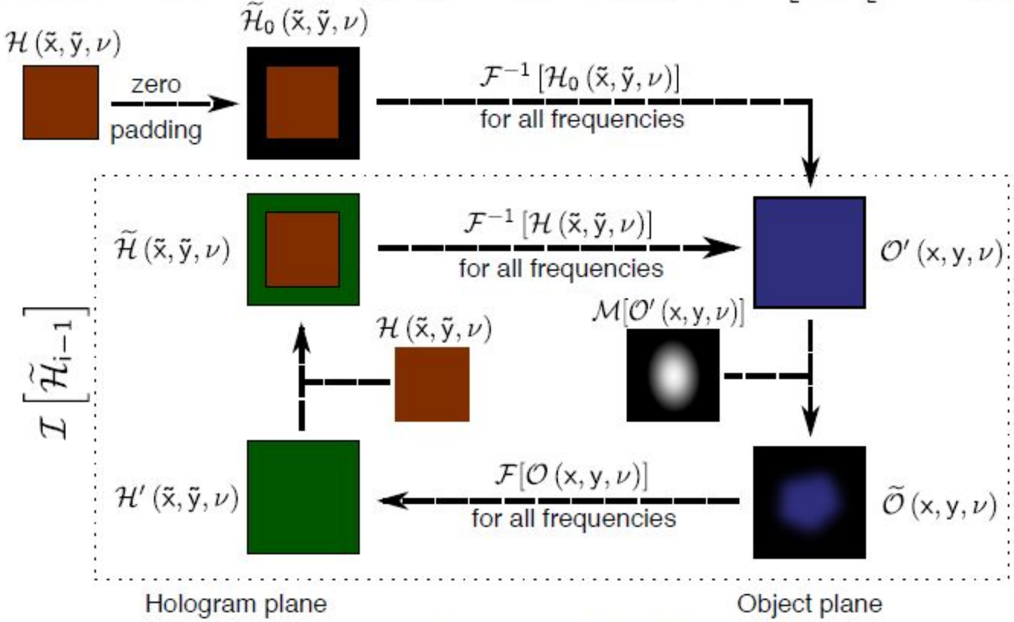


with codirectional (left) and retroreflected (right) probe IR beams

Sci. Rep. 2019. **9**, 180

Iterative self-extrapolation algorithm

Iteration operator: $\mathcal{I}(\mathbb{H}) \to \mathbb{H} : \mathcal{I}(\mathcal{H}) = \mathcal{F}\left[\mathcal{M}\left[\mathcal{F}^{-1}[\mathcal{H}]\right]\right]$



Extrapolation of THz spatial field distribution beyond the hologram registration area.

Backward wavefront propagation

$$\mathcal{O}'(x, y, \nu) = \mathcal{F}_{L,\nu}^{-1}\left[\mathcal{H}(\tilde{x}, \tilde{y}, \nu)\right]$$

Field masking

$$\widetilde{\mathcal{O}}(x, y, \nu) = \mathcal{M}_{x,y}\left[\mathcal{O}'(x, y, \nu)\right]$$

Forward wavefront propagation

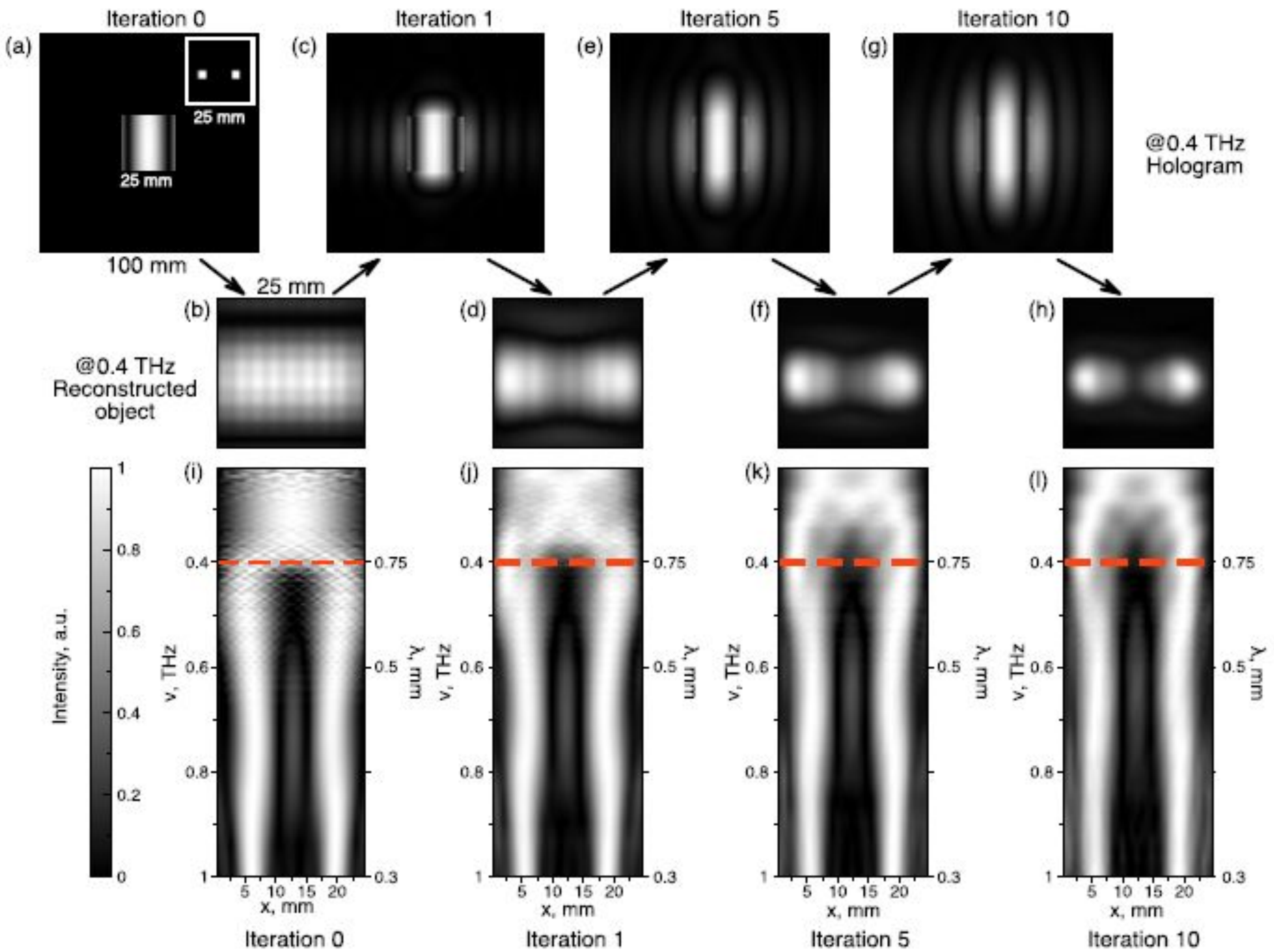
$$\mathcal{H}'(\tilde{x}, \tilde{y}, \nu) = \mathcal{F}_{L,\nu}\left[\widetilde{\mathcal{O}}(x, y, \nu)\right]$$

Central part replacement

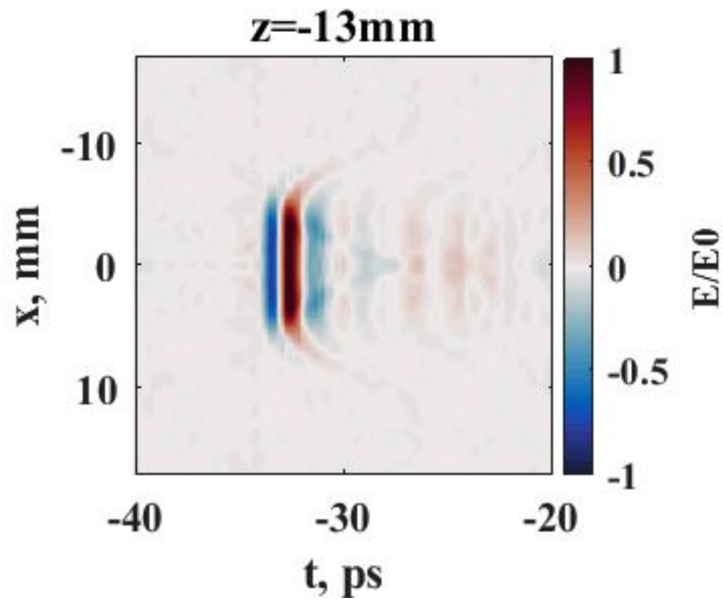
$$\widetilde{\mathcal{H}}_i(\tilde{x}, \tilde{y}, \nu) = \begin{cases} \mathcal{H}(\tilde{x}, \tilde{y}, \nu), & \mathrm{rect}\left(\frac{\tilde{x}}{N\Delta\tilde{x}}, \frac{\tilde{y}}{N\Delta\tilde{y}}\right) > 0 \\ \mathcal{I}\left[\widetilde{\mathcal{H}}_{i-1}(\tilde{x}, \tilde{y}, \nu)\right], & \mathrm{rect}\left(\frac{\tilde{x}}{N\Delta\tilde{x}}, \frac{\tilde{y}}{N\Delta\tilde{y}}\right) = 0 \quad \cap \quad i > 0 \\ 0, & \mathrm{rect}\left(\frac{\tilde{x}}{N\Delta\tilde{x}}, \frac{\tilde{y}}{N\Delta\tilde{y}}\right) = 0 \quad \cap \quad i = 0 \end{cases}$$

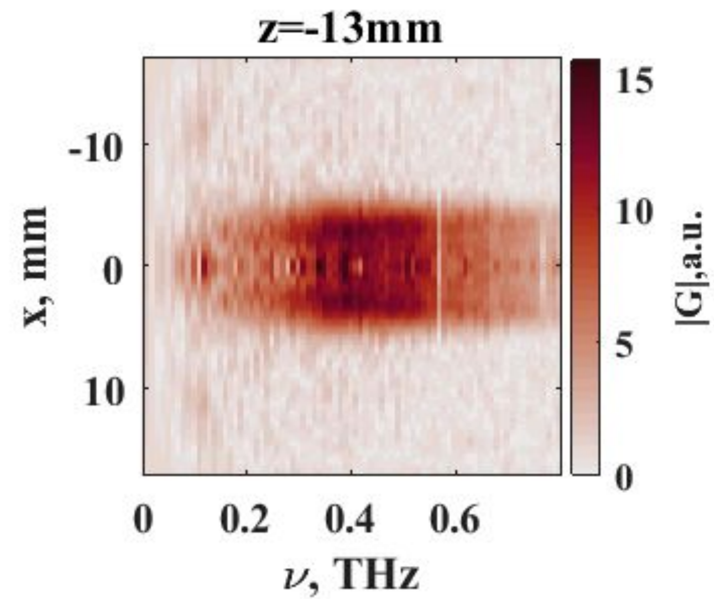
Sci. Rep. 2019. **9**, 180.

THz Pulse Time-Domain Holography



Broadband THz Wavefront Numerical Focusing



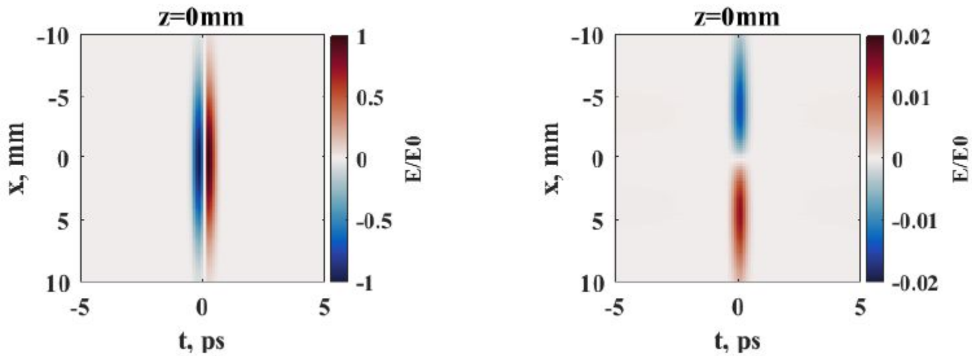


in spatio-temporal (left) and spatio-spectral (right) domains

Longitudinal Field Components Calculation

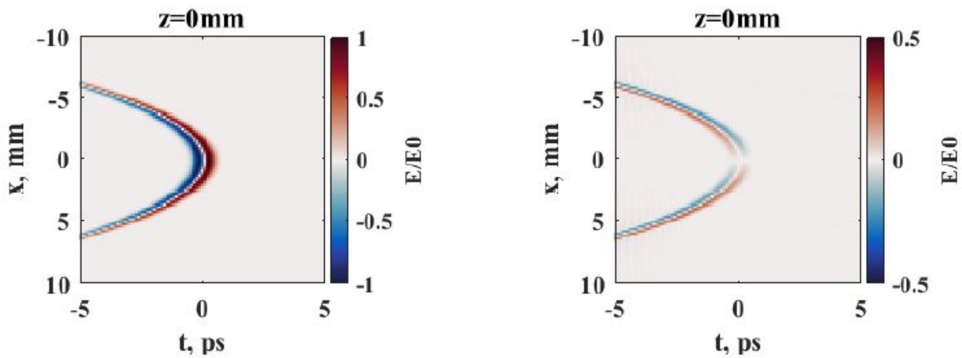
Initial THz Gaussian beam as a boundary conditions (distance z=0 mm):

Transverse component $Ex(x,y=y_0,t,z=0)$ Longitudinal component $Ez(x,y=y_0,t,z=0)$



After focusing lens with focal length f=12.75 mm in z=0 mm:

Transverse component $Ex(x,y=y_0,t,z=0)$ Longitudinal component $Ez(x,y=y_0,t,z=0)$

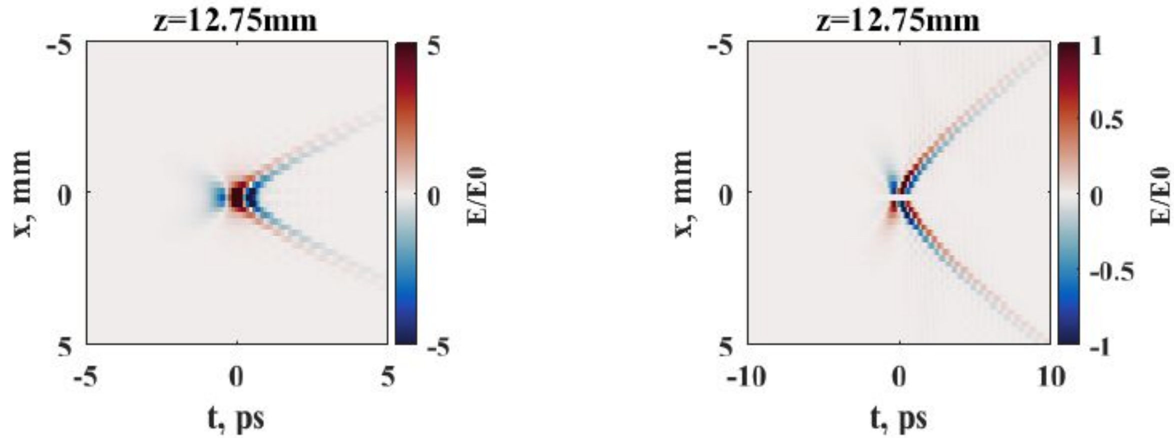


Longitudinal Field Components Calculation

Calculation of field propagation over a distance z=12.75 мм:

Non-paraxial calculation

Transverse component Ex(x,y=y_0,t,z=12.75) Longitudinal component Ez(x,y=y_0,t,z=12.75)



Calculation of the proportion of the longitudinal component to the transverse:

for intensity:

$$W = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|E_z(x,y,t)\right|^2 dxdydt}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|E_x(x,y,t)\right|^2 dxdydt} = 7.6\%$$

for spectral amplitude:

$$Q = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|G_z(x,y,\nu)\right| dxdyd\nu}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|G_x(x,y,\nu)\right| dxdyd\nu} = 62.2\%$$

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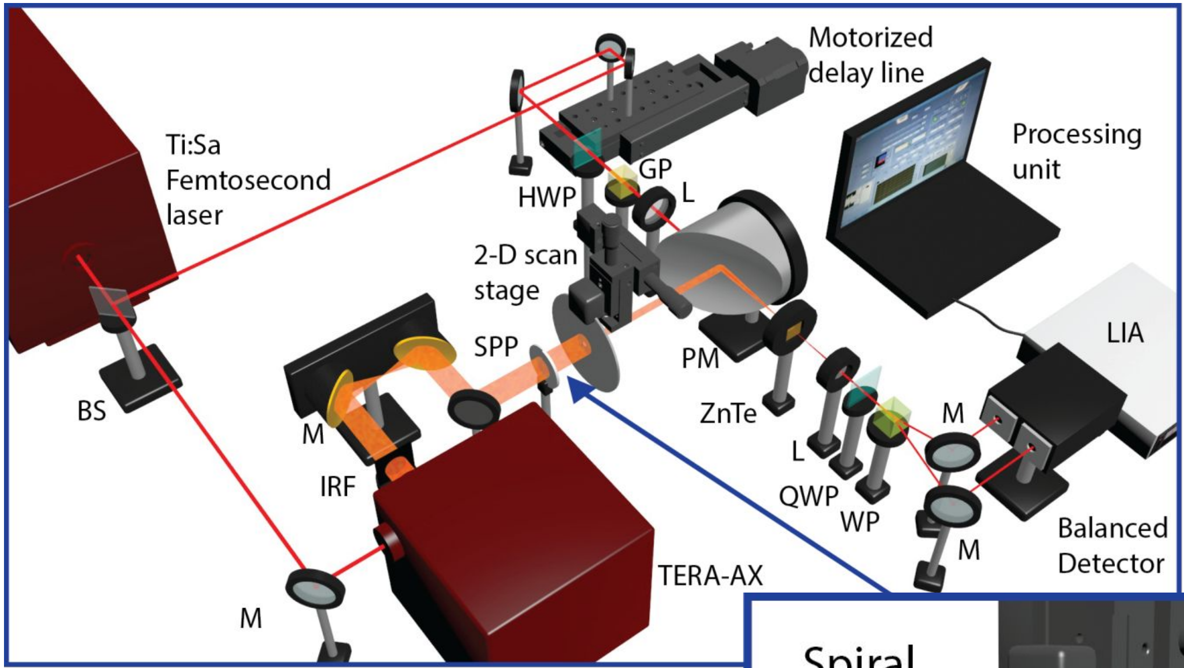
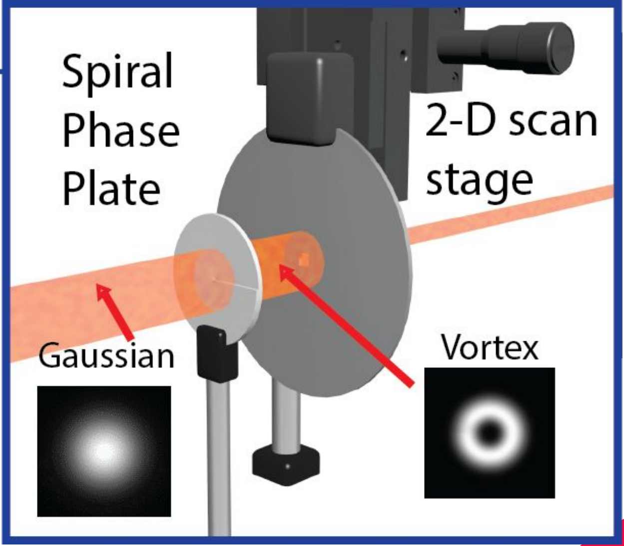
Applications. Wavefront Metrology

BS - beam splitter
TERA-AX - THz generator ($LiNbO_3$),
IRF – IR filter,
M - mirror,
SPP – spiral phase plate (Teflon, n = 1.46),
PM – parabolic mirror
L - lens,
GP – Glan prism
HWP – half-wave plate,
ZnTe – ZnTe crystal
QWP – quarter-wave plate,
GP – Wollaston prism
LIA - lock-in amplifier





Ti:Sa femtosecond laser system:
Central wavelength 790 nm
Average power 2 W
Pulse duration 30 fs
Repetition rate 1 kHz

Examination THz beams

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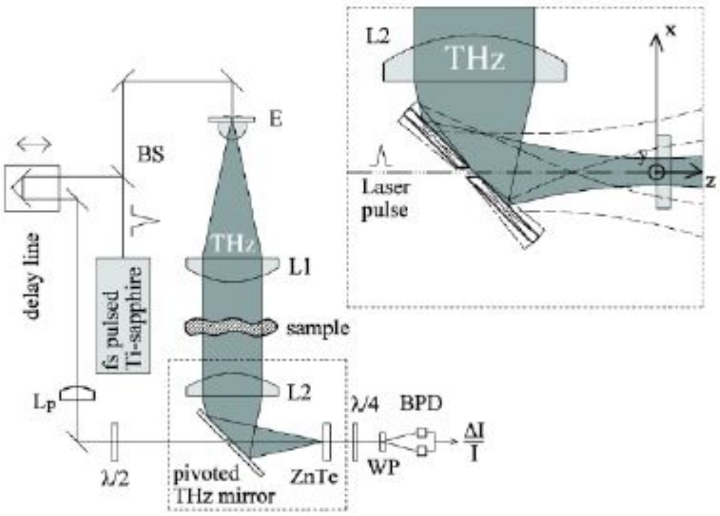
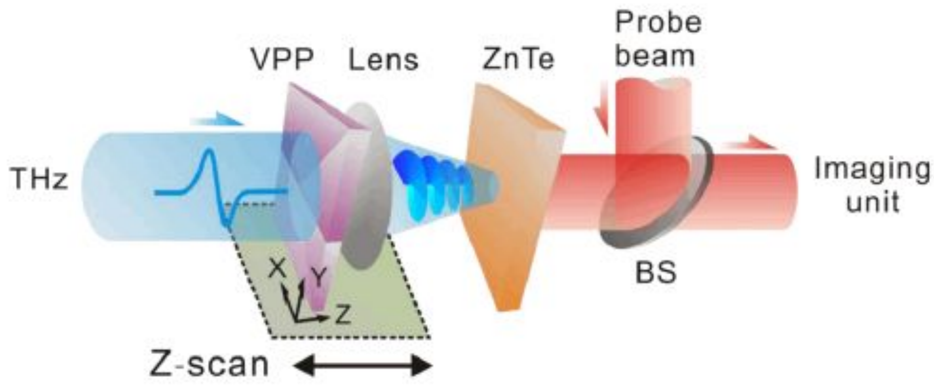
A. Bitzer, et al. *Appl. Phys. Lett.* **90**, 071112, (2007).

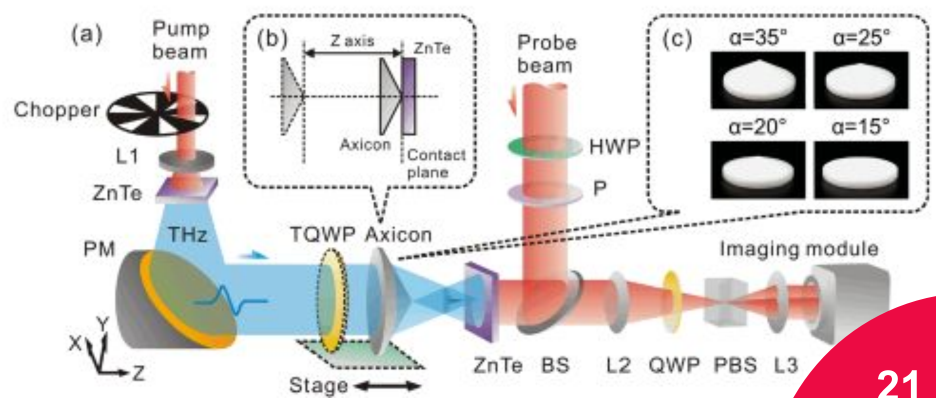


We propose another approach to investigate propagation dynamics of THz beams based on the measurement of the broadband wave front in one transverse plane and its numerical propagation along the optical axis by digital holography.

J. He, et al. *Opt. Express* **21**, 20230, (2013).



Z. Wu, et al. *Sci. Rep.* **7**, 13929, (2017).



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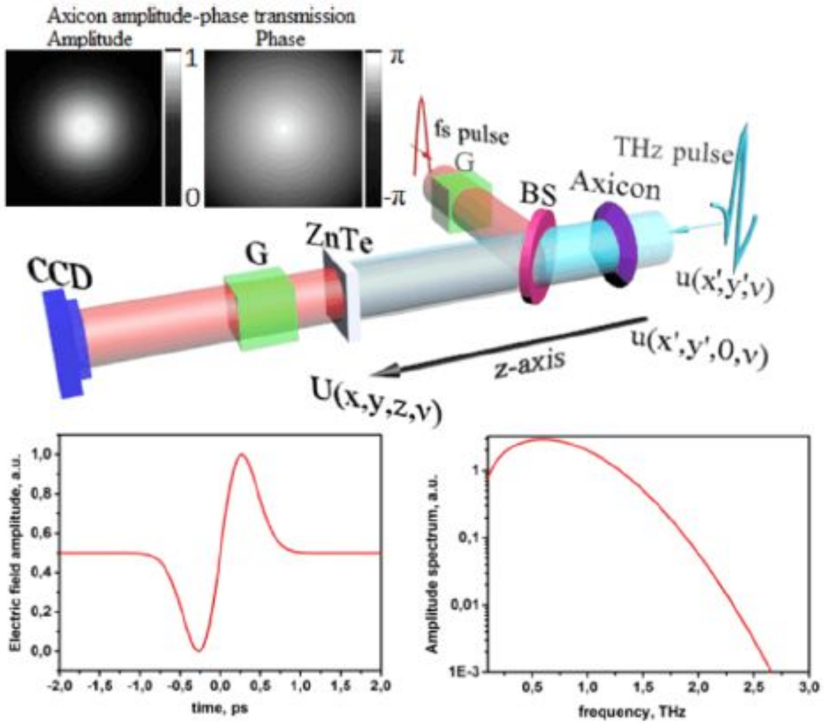
THz Gauss-Bessel beam



Pulse THz beam:

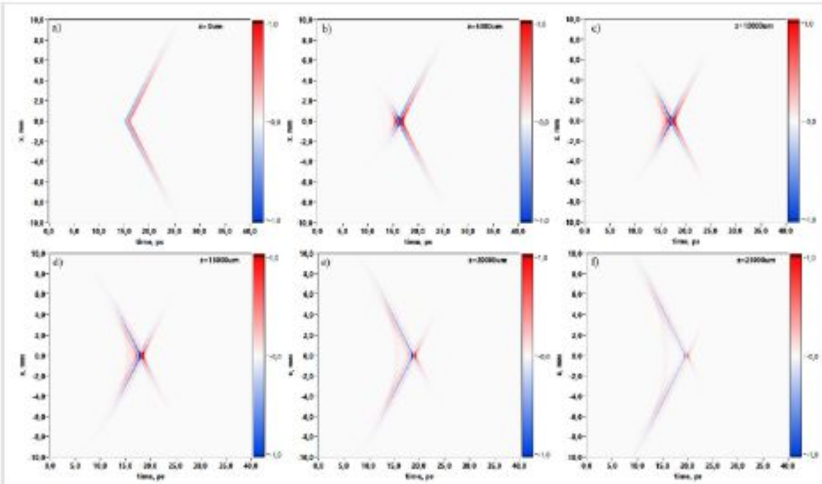
- Several oscillations of the electric field
- Broad spectrum 0.1-2.0 THz
- Pulse duration ≈ 2 ps
- Beam size:
  Transverse ≈ 20 mm,
  longitudinal ≈ 0.6 mm
- STCs effect
  (spatio-temporal couplings)

Features of Gauss-Bessel beams:

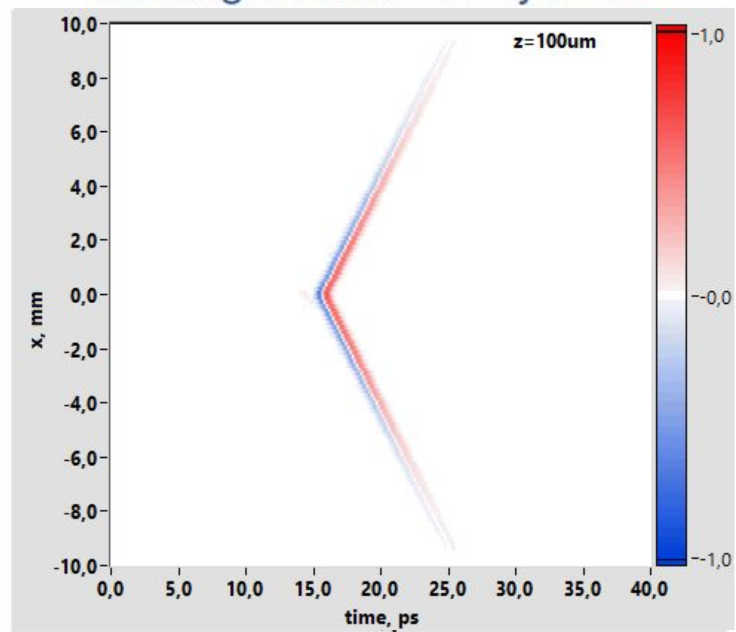
- High intensity in the near-axis region
- Small diffraction divergence of the central maximum

M. S. Kulya, V. A. Semenova, V. G. Bespalov, N. V. Petrov. *Sci. Rep.* **8**, 1390, (2018).

Spatio-Temporal Evolution



moving coordinate system



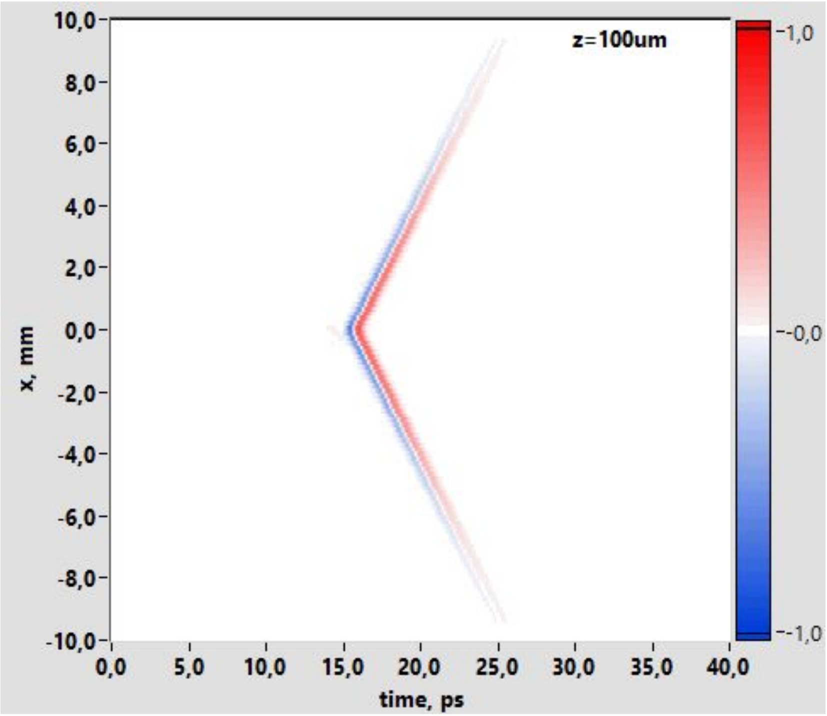
Features:

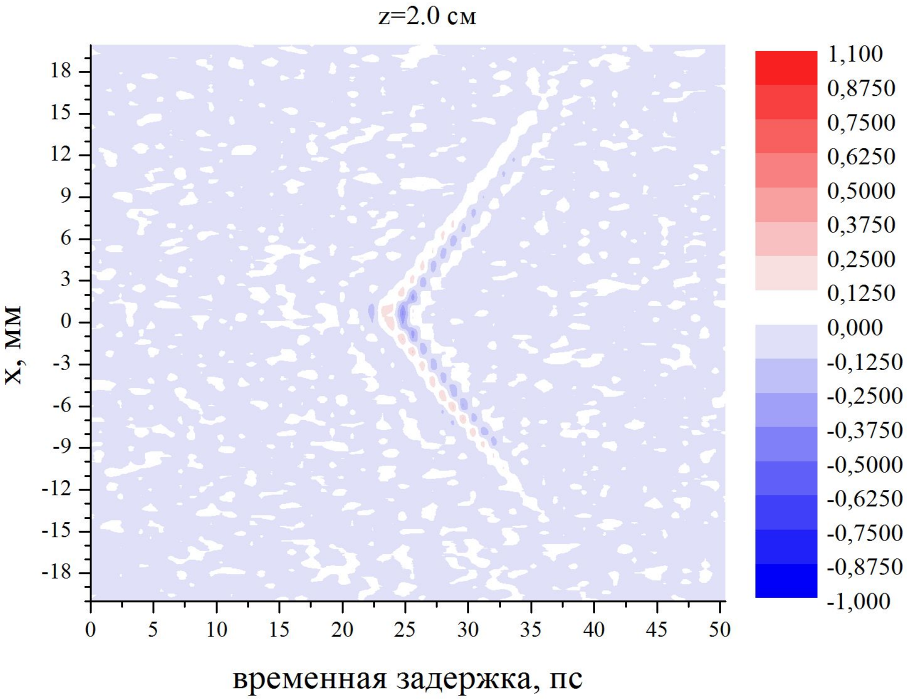
- STCs
- Pulse reshaping
- X-shape pulse

M. S. Kulya, V. A. Semenova, V. G. Bespalov, N. V. Petrov. *Sci. Rep.* **8**, 1390, (2018).

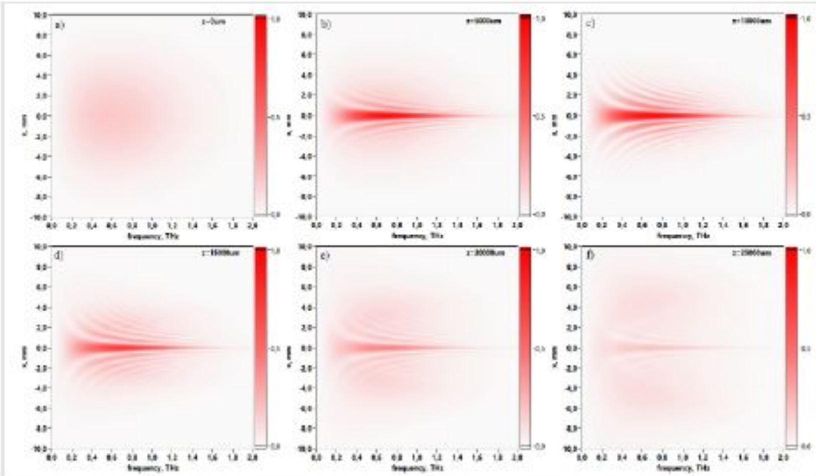
THz Gauss-Bessel Beam Evolution

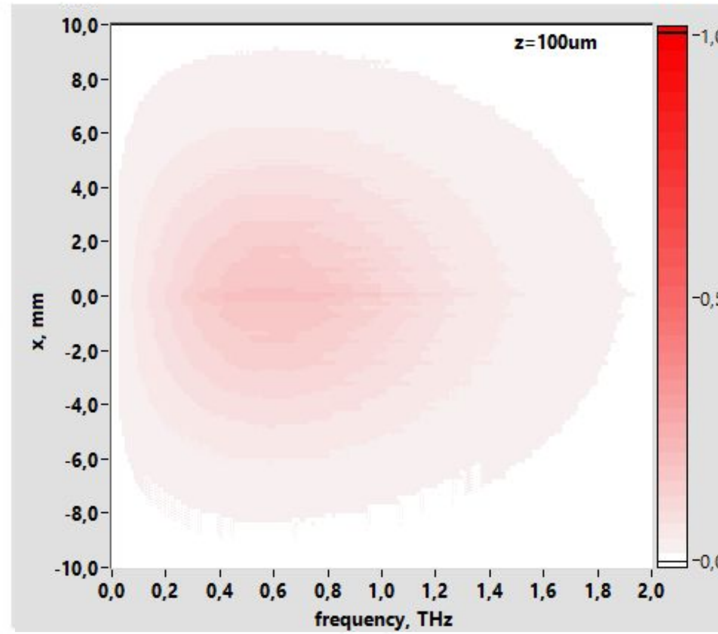
Simulation (left) and the experiment (right)





Spatio-Spectral Evolution





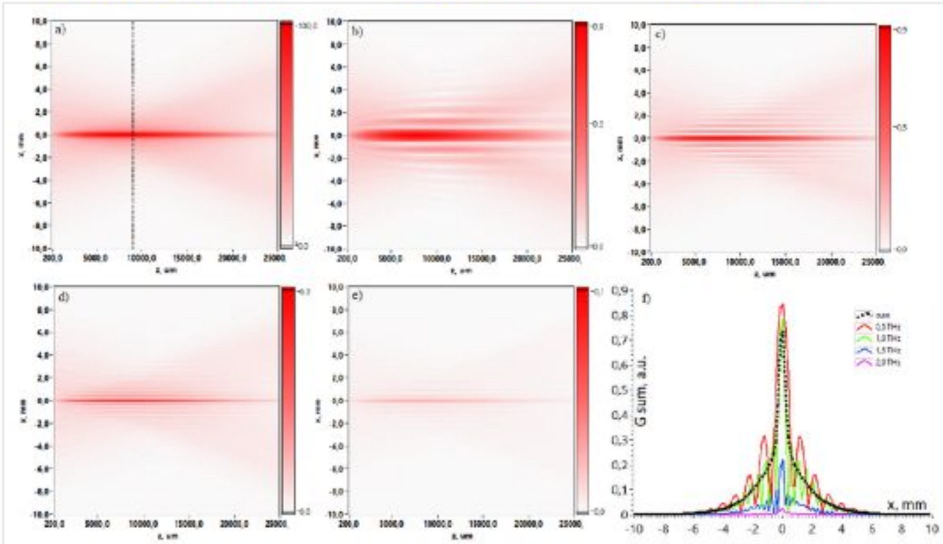
Features:

- Frequency-dependent scaling of the Bessel pattern as hyperbolic extrema;
- Decreasing intensity in far diffraction region.

M. S. Kulya, V. A. Semenova, V. G. Bespalov, N. V. Petrov. *Sci. Rep.* **8**, 1390, (2018).

Spatio-Spectral Evolution

ν = 0.05-2.0 THz   ν = 0.5 THz   ν = 1.0 THz



ν = 1.5 THz   ν = 2.0 THz $|U(x)|$ for z = 9.5 mm

Features:

The frequency summarized structure shows the narrow Gauss-Bessel non-diffractive beam in the integral form without interference rings.

- Radially symmetric waves formed after axicon propagated at some angle to the optical axis towards each other;
- Different frequency components provide different patterns of maximum and minimum of spectral amplitude due to the mutual interference of radially symmetric waves.

M. S. Kulya, V. A. Semenova, V. G. Bespalov, N. V. Petrov. *Sci. Rep.* **8**, 1390, (2018).

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Broadband THz beams Diversity

Optical setups for generation and measurements of:

broadband THz vortex beams.

J. He, et al.
Opt. Express **21**, 20230, (2013).

THz vortex beam with spectrally-homogeneous topological charge.

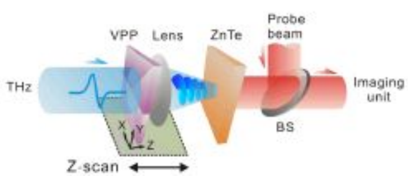
R. Imai et al.
Opt. Lett. **39**, 3714, (2014).

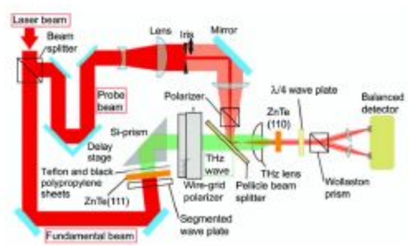
geometric phase matched THz vortex beams.

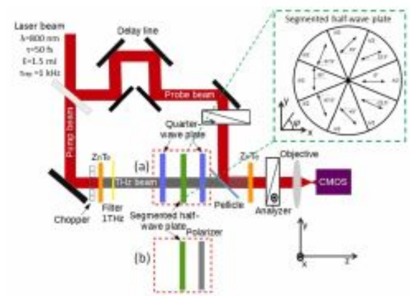
A. Minasyan, et al.
Opt. Lett. **42**, 41, (2017).

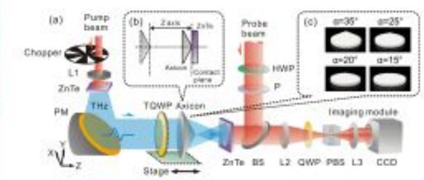
circularly polarized vector THz Bessel beams.

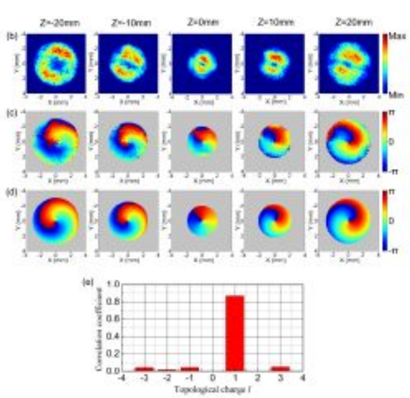
Z. Wu, et al.
Sci. Rep. **7**, 13929, (2017).

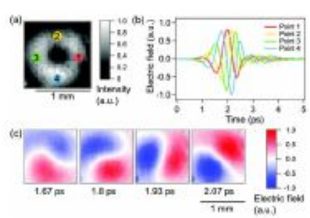


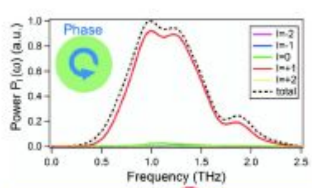


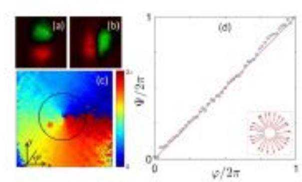


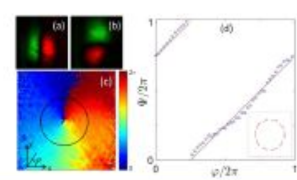


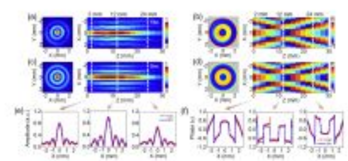


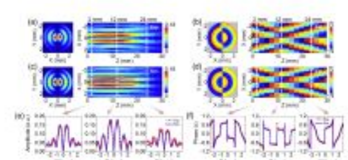






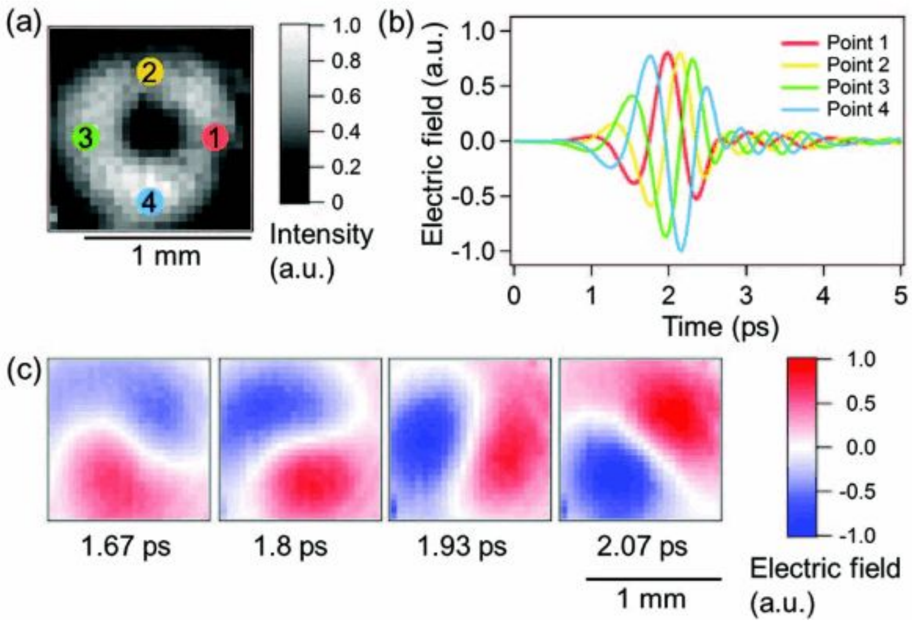




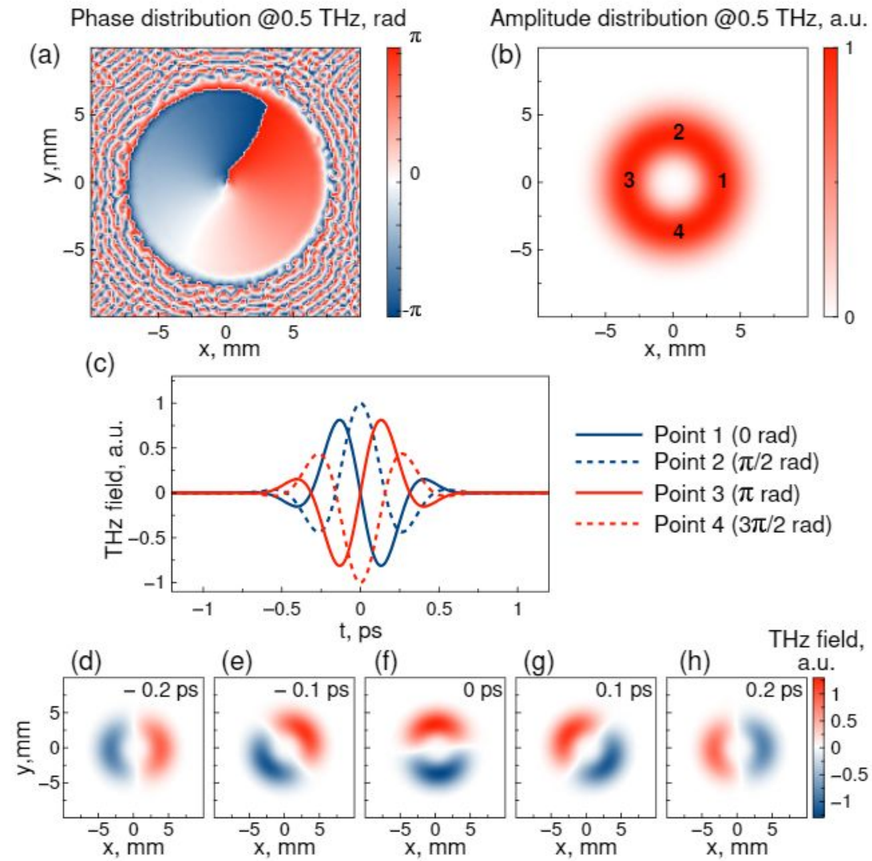


BUTCH Beam Self-Reconstruction

THz Broadband Uniformly Topologically Charged (BUTCH) vortex beam



R. Imai et al. Opt. Lett. **39,** 3714, (2014).



M. Kulya, V. Semenova, A. Gorodetsky, V.G. Bespalov N.V. Petrov
Spatio-temporal and spatio-spectral metrology of terahertz broadband uniformly topologically charged vortex beams // Applied Optics 2019. Vol. 58, № 5. P. A90.

BUTCH Beam Self-Reconstruction

Phase

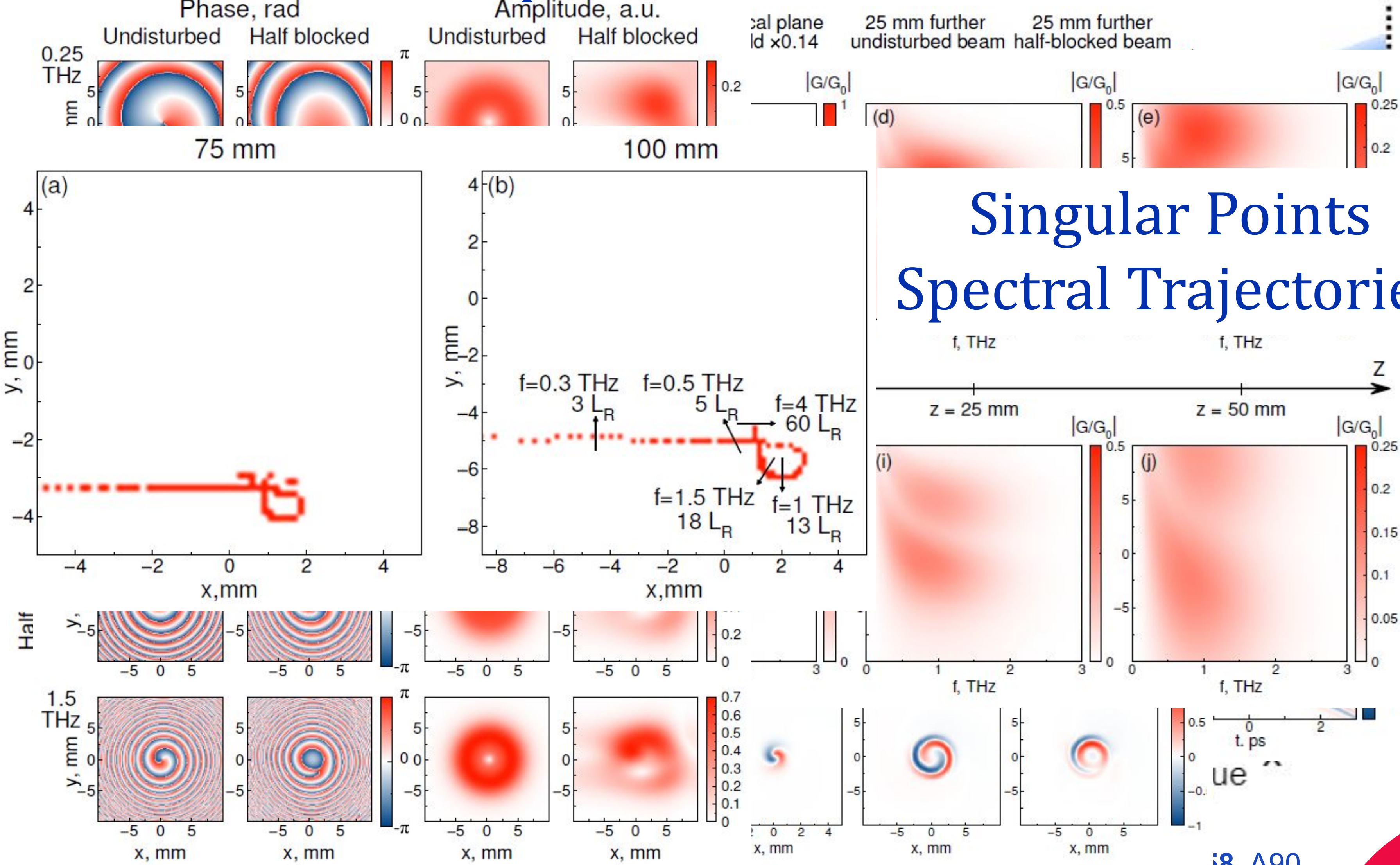
Amplitude

Time Sweep

Scheme of the Experiment

Singular Points

Spectral Trajectories



Appl. Opt. 2019. 58. A90.

Digital and Display Holography Laboratory

ITMO UNIVERSITY

Thank you for your attention!

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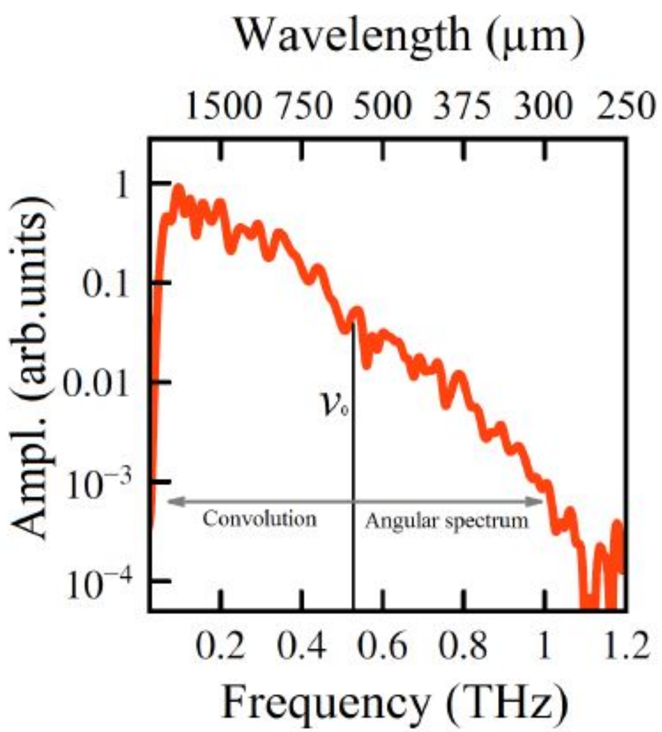
Methods of scalar diffraction theory used for wavefront propagation.

Sampling theorem makes possible to use two different methods in dependence from relation between frequencies and distances:

- Angular Spectrum (AS) method is possible for using if:

$$\nu \geqslant \nu_0 = \frac{c \cdot l}{N \cdot \Delta x^2}. \qquad (4)$$

- Rayleigh-Sommerfeld convolution (RSC) can be used if $\nu \leqslant \nu_0$.



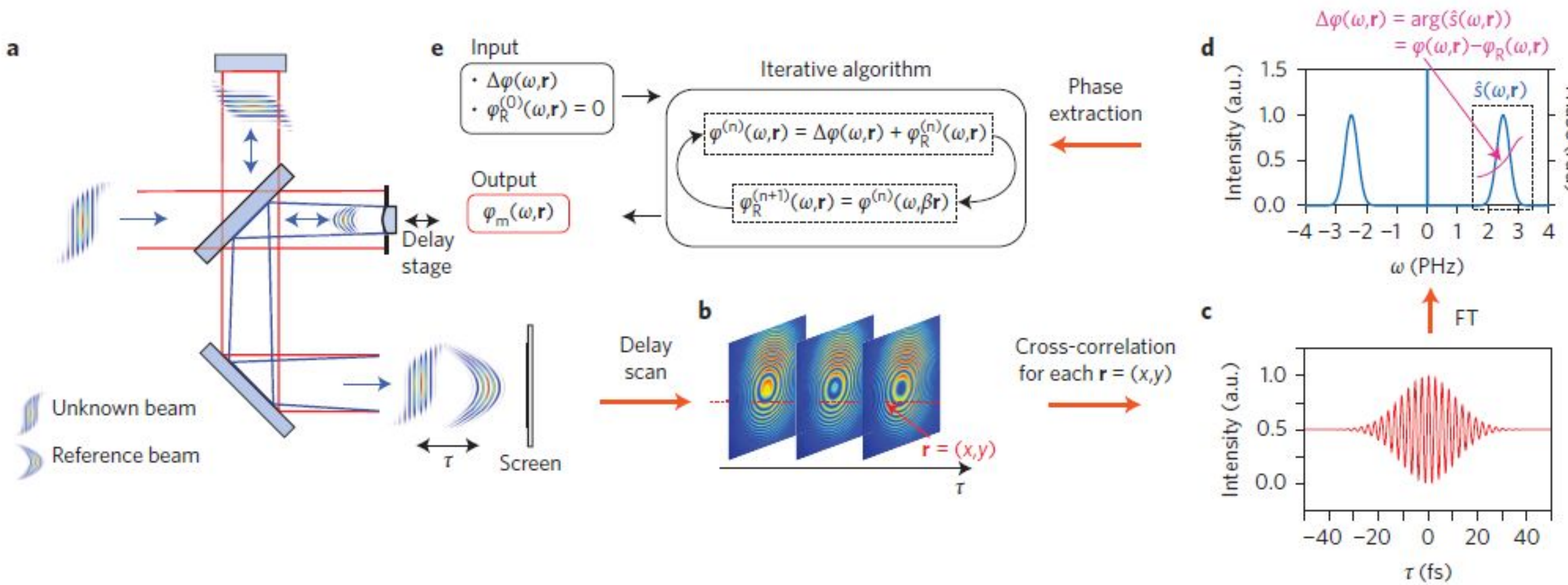
N.S. Balbekin, M.S. Kulya, P.Yu. Rogov, N.V. Petrov *Phys. Procedia* **73**, 49, (2015).

Spatio-Temporal Couplings

It is a fact though that none of these techniques has become widespread yet, probably due to their complexity and the difficulty of implementing them on advanced laser systems. A less obvious, yet major difficulty is that analyzing and understanding the structure of spatio-temporal/spectral fields (3D complex-valued matrices) provided by such techniques is far from trivial [25]- much more challenging for instance than getting insight into the temporal structure of a pulse. This has also significantly contributed to keep this advanced metrology so far accessible to specialists only.

Borot A., Quéré F. Spatio-spectral metrology at focus of ultrashort lasers: a phase-retrieval approach // Opt. Express. 2018. Vol. 26, № 20. P. 26444.

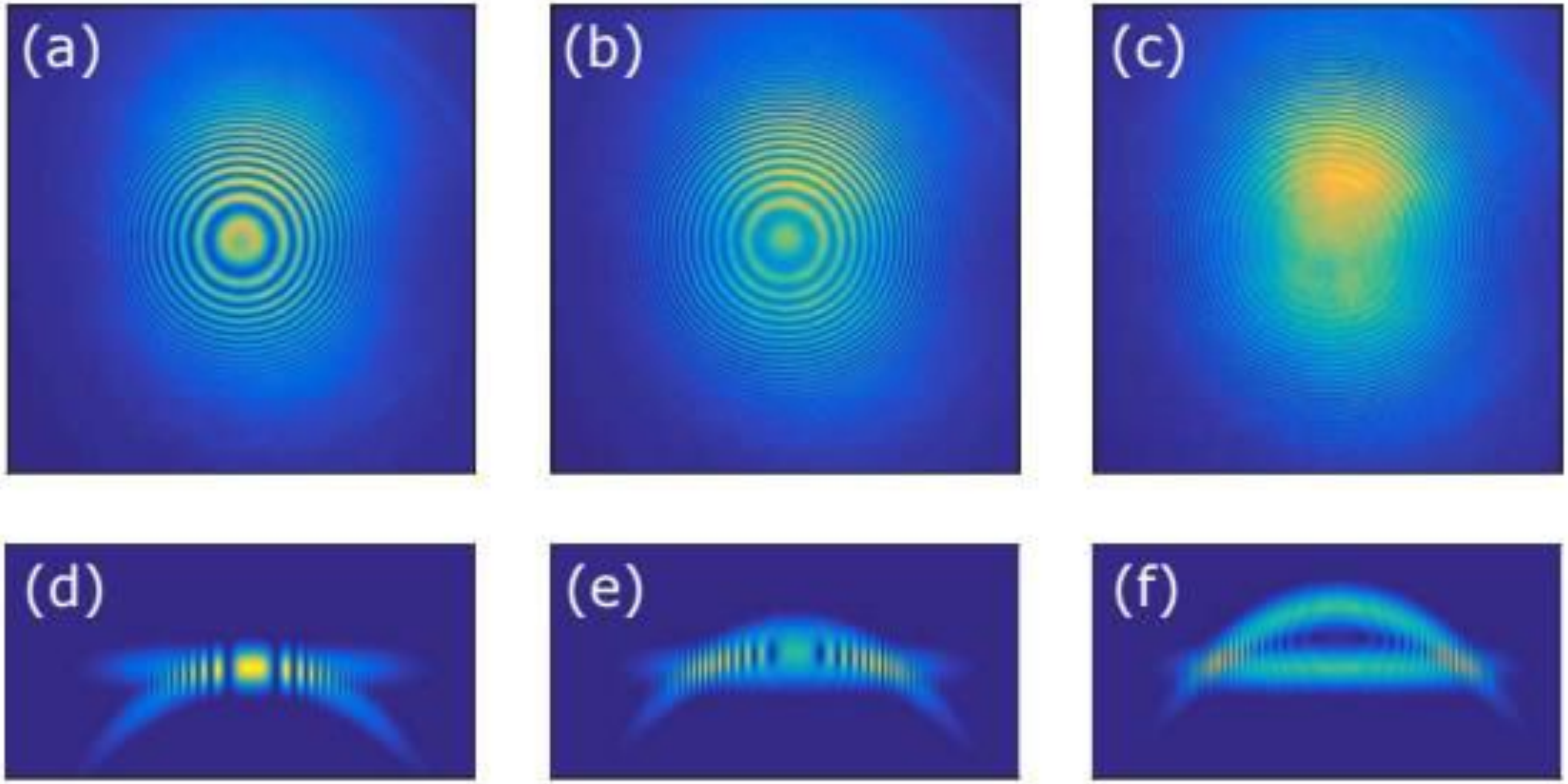
Total E-field Reconstruction Using a Michelson Interferometer Temporal Scan”,



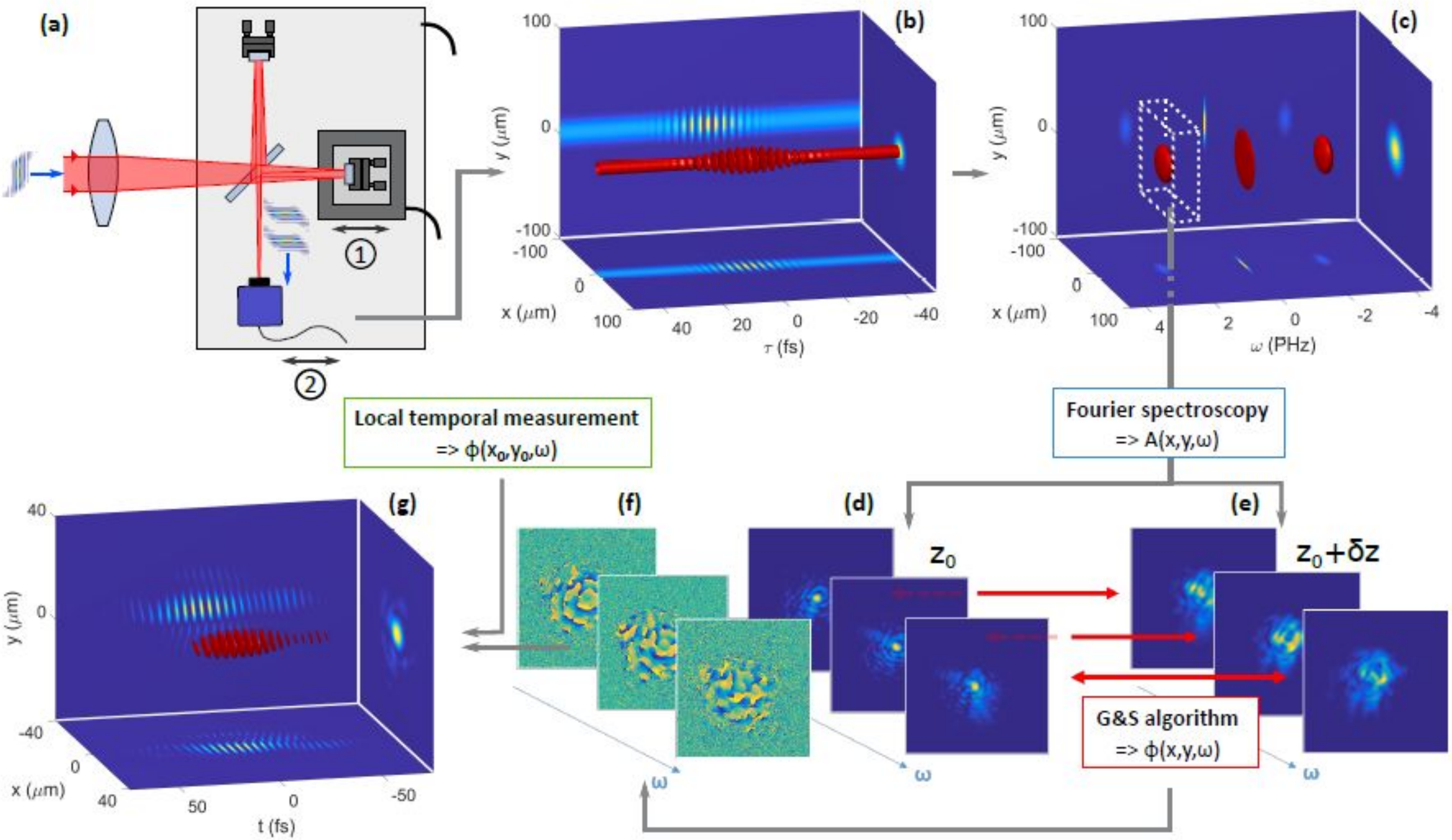
TERMITES Flowchart

G. Pariente et al. Nature Photonics. 2016. V. 10. P. 547

TERMITES



G. Pariente et al. Nature Photonics. 2016. V. 10. P. 547



INSIGHT Flowchart

Borot A., Quéré F. Opt. Express. 2018. Vol. 26, № 20. P. 26444.

State-of-the-Art

Current and future challenges

While many techniques have addressed the problem of measuring pulses in time and one spatial dimension, the main challenge currently facing the field of pulse measurement is the complete *spatiotemporal* measurement of pulses, yielding $E(x, y, t)$, especially on a single shot.

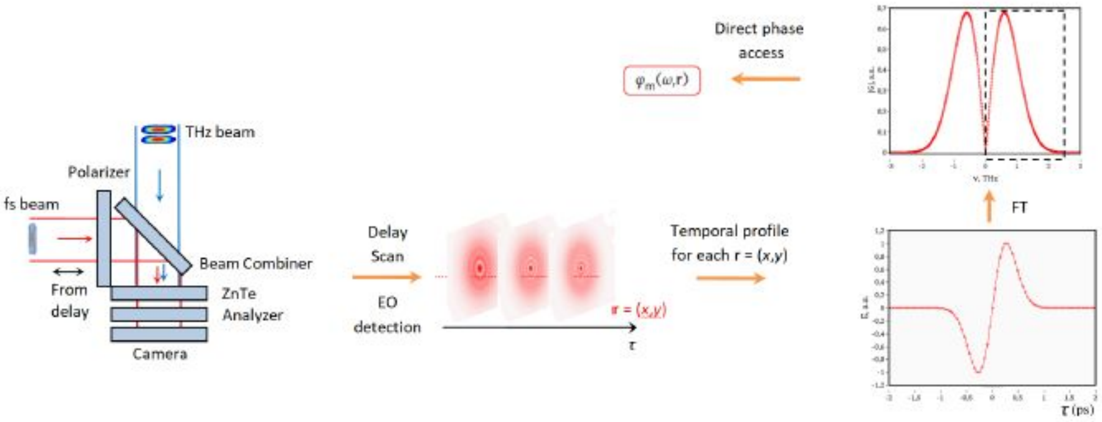
R. Trebino. Frontiers and issues in the measurement of ultrashort laser pulses @ D. T. Reid, et al. Roadmap on Ultrafast Optics // J. Opt. 18 (2016): 093006.

One can safely conclude at this stage that today complete pulse characterization variants exist which allow characterization of two-cycle pulses. However, let us now ask the question how far we can push techniques for reliable measurements of single-cycle or even sub-cycle pulses.

G. Steinmeyer. Optical pulse characterization at the single-cycle Limit @ D. T. Reid, et al. Roadmap on Ultrafast Optics // J. Opt. 18 (2016): 093006.

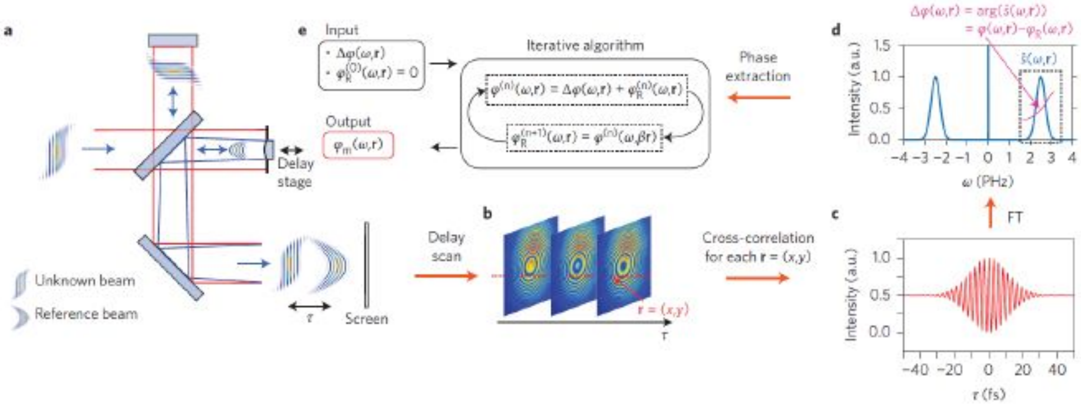
Pulsed wavefront sensing

THz PTDH: 'Terahertz Time-Domain Holography'



TERMITES:
'total E-field reconstruction using a Michelson interferometer temporal scan'

G. Pariente, et al. *Nat. Photonics* **10**, 547-553, (2016).



Techniques Comparison

	TERMITES	INSIGHT	PTDH
Frequency range	Visible		THz
Operation principle	Interferometry and phase retrieval		Coherent electro-optical sampling
Measured value	Cross-correlation function	Auto-correlation function	Real part of electric field vs. time
$\Delta\tau \cdot S$ product	No less than $8 \cdot 10^8$		$6{,}7 \cdot 10^7$

N.V. Petrov - Ultrafast Digital Holography and Spatio-Temporal Metrology @ Roadmap on Holography // Journal of Optics 2019 (submitted)