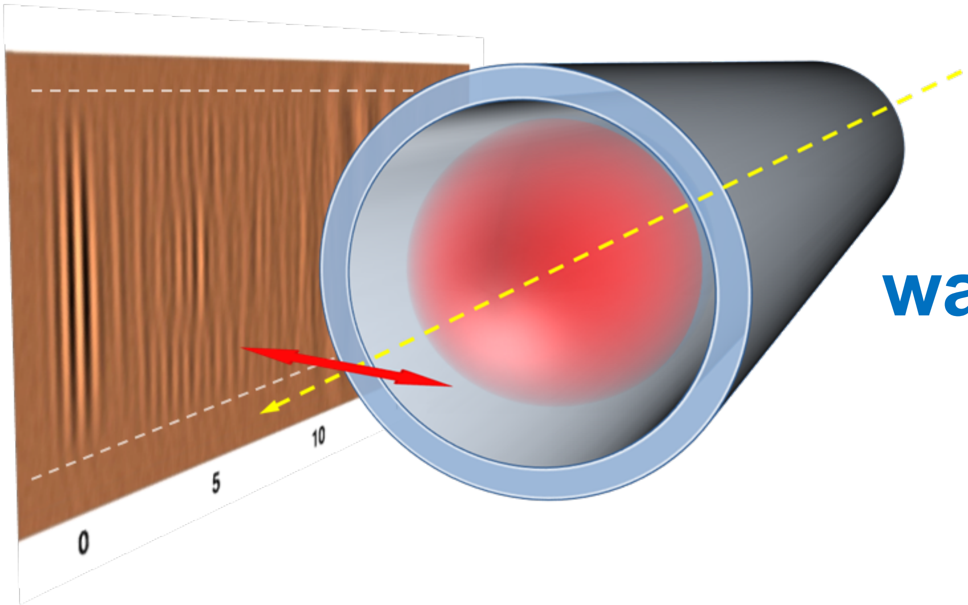


Terahertz waveguide and waveguide characterization technologies

Oleg Mitrofanov
University College London

THE ROYAL SOCIETY
EPSRC
Pioneering research and skills

Terahertz research at UCL

High spatial resolution THz imaging

O. Mitrofanov

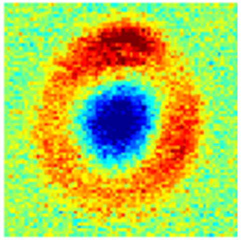
Optoelectronics for THz applications

A. Seeds, C. Renaud

Novel THz devices

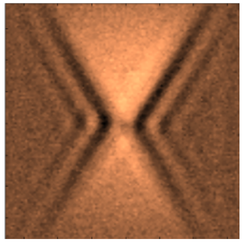
THz applications for scientific research

Sir M. Pepper



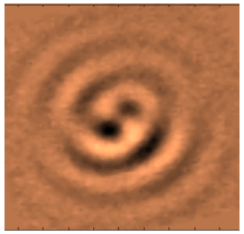
Waveguide mode mapping

Appl. Phys. Lett. 94, 171104 (2009
Opt. Express **18**, 1898 (2010)
JOSA B **1**, (2013)



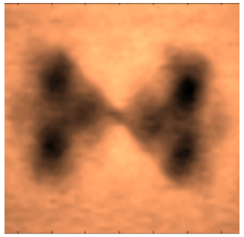
Surface wave excitation

J. Infrared Milli. Terahz Waves **32**, 1031 (2011)



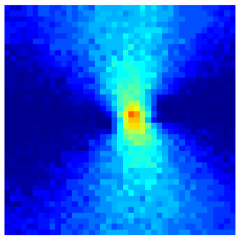
Surface wave imaging near strongly focused THz beams

Opt. Express **19**, 3212 (2011)



Antenna analysis

Opt. Express **20**, 16023 (2012)



THz spectroscopy on small scale

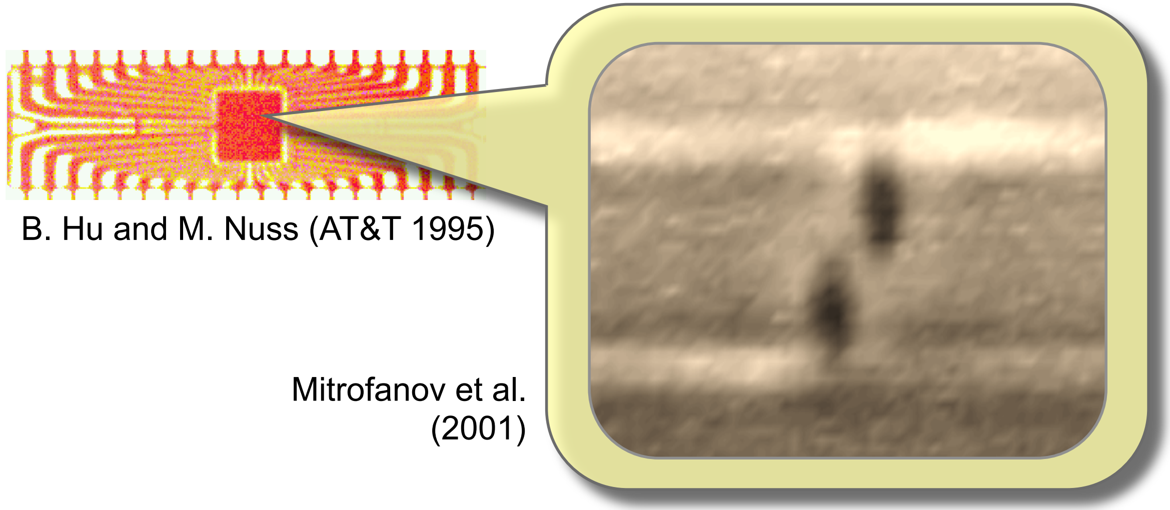
Opt. Express **20**, 6197 (2012)

THz high-resolution imaging – near-field microscopy

Spatial resolution

- better than diffraction limit

- 10 micron or better is can be achieved (0.1 – 3 THz)

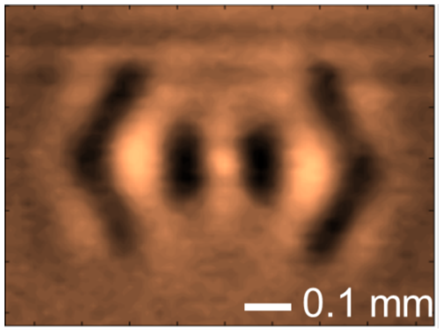


B. Hu and M. Nuss (AT&T 1995)

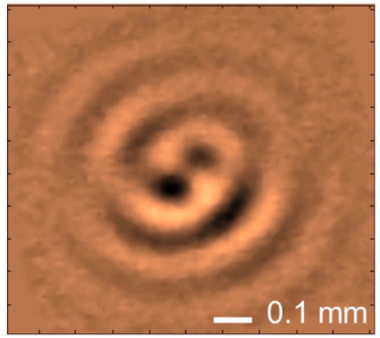
Mitrofanov et al. (2001)

Characterization of local fields

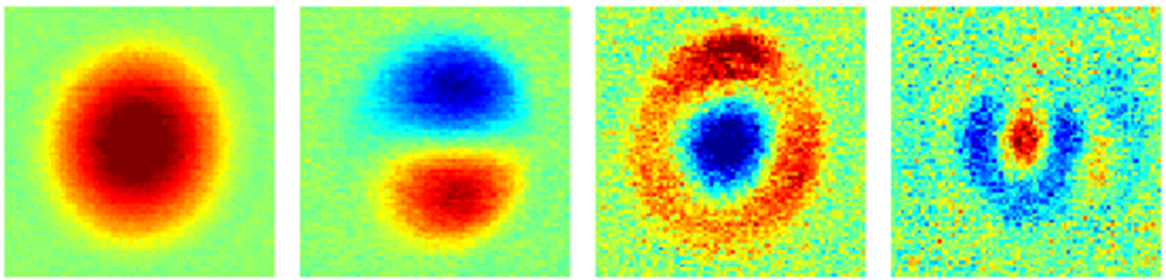
surface waves on a bow-tie antenna

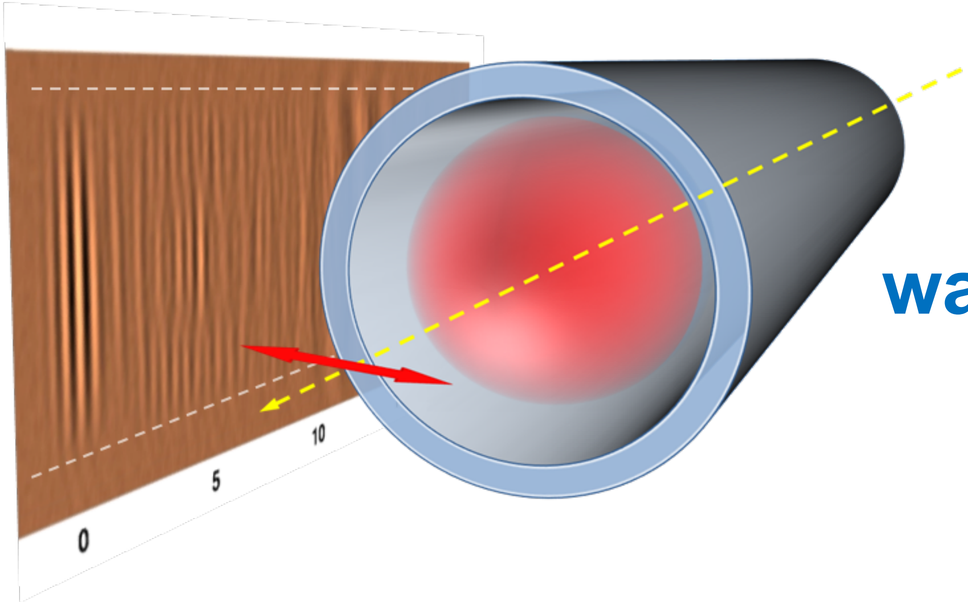


SPP near a focused beam



normal modes in dielectric –lined metallic WGs





Terahertz waveguide and waveguide characterization technologies

Overview of THz waveguide challenges and solutions

THz waveguide characterization:
near-field imaging, time-domain analysis

Dielectric-lined hollow metallic waveguides

Application and integration of THz waveguides

THz waveguide challenges

Transmission losses – absorption in dielectrics, Ohmic losses

Fabrication – material challenges

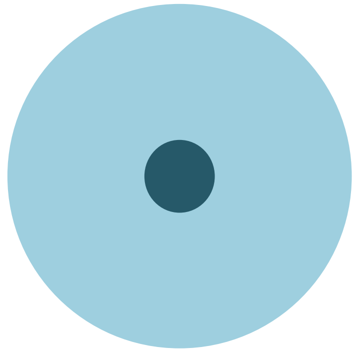
Characterization – THz sources, THz detection and imaging systems

Integration into THz systems – efficient coupling

Transmission Losses at THz frequencies

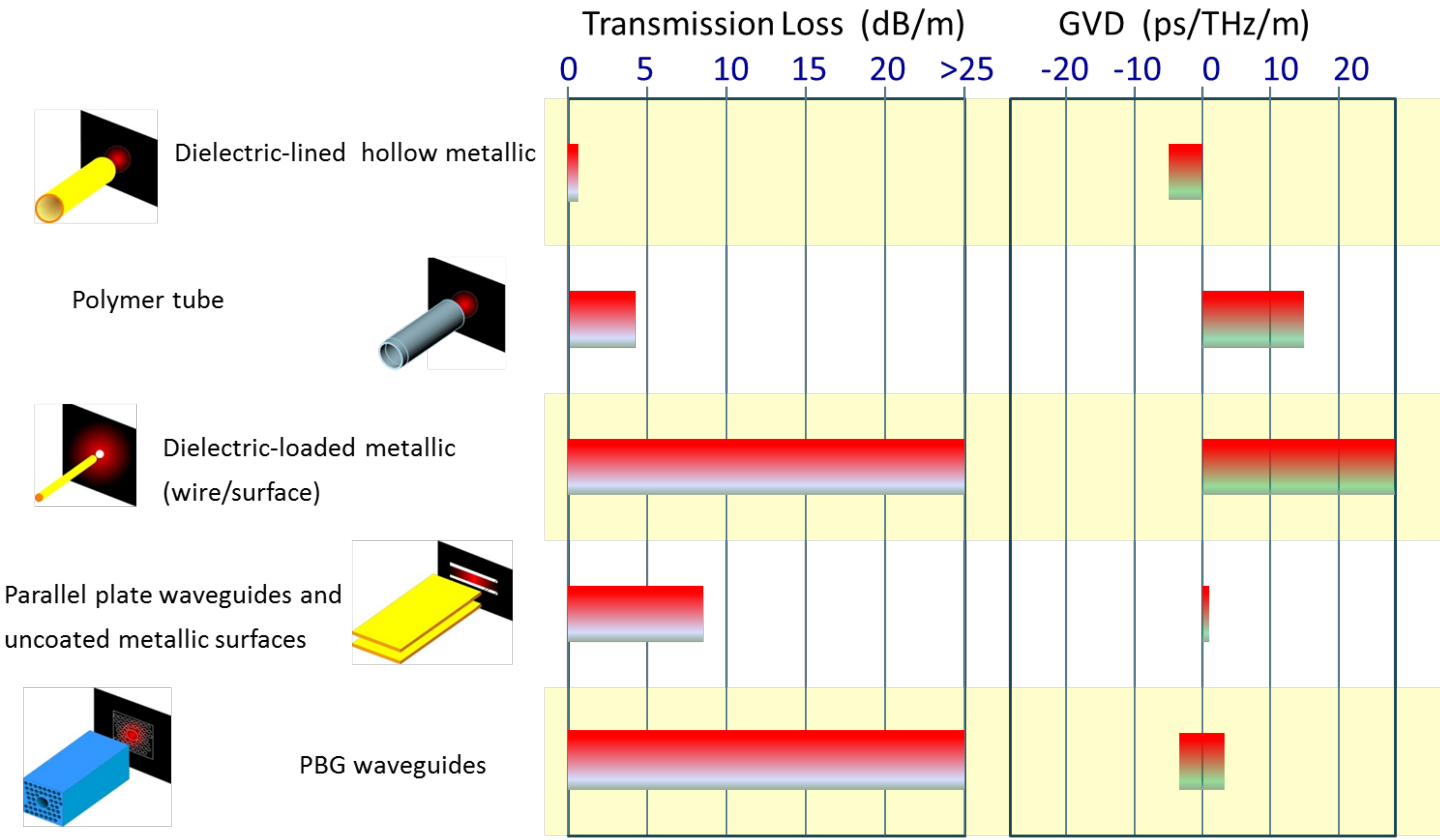
coaxial waveguide

optical fiber



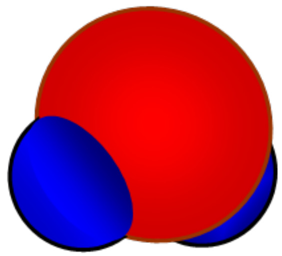
high loss (10-100 dB/m) at THz frequencies

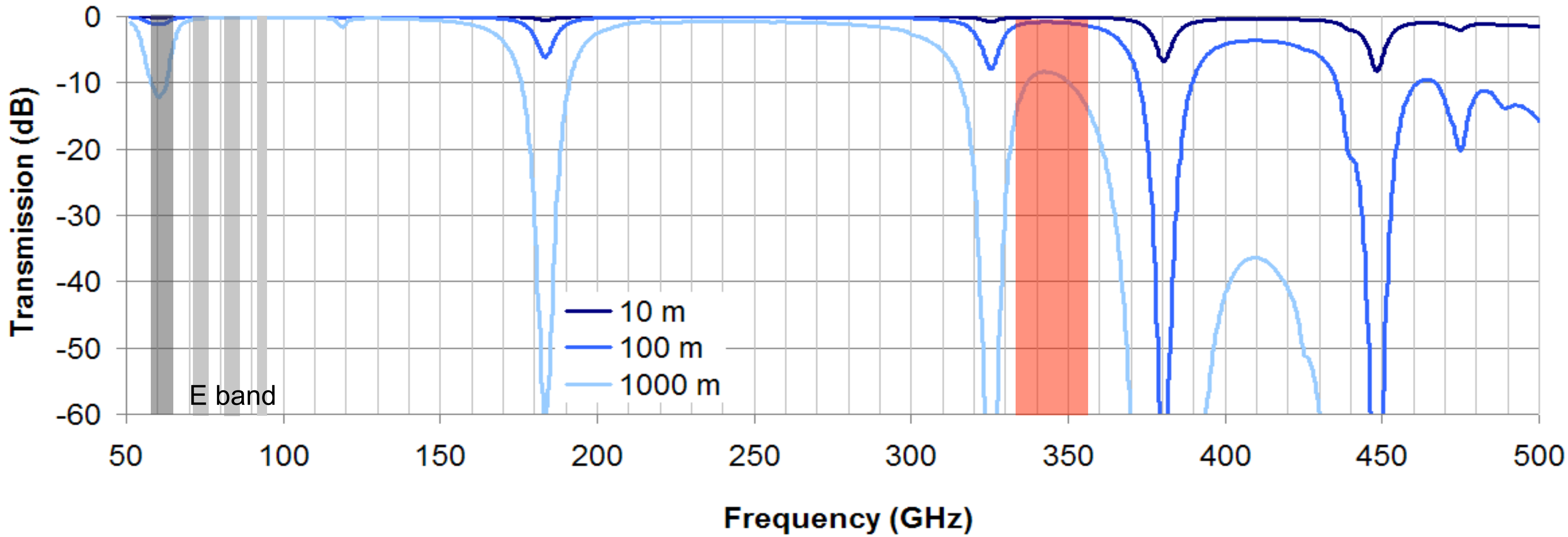
THz waveguides – transmission loss and dispersion



IEEE Transactions on THz Science and Technology, **1**, 124 (2011)

Terahertz absorption in air due to water vapour

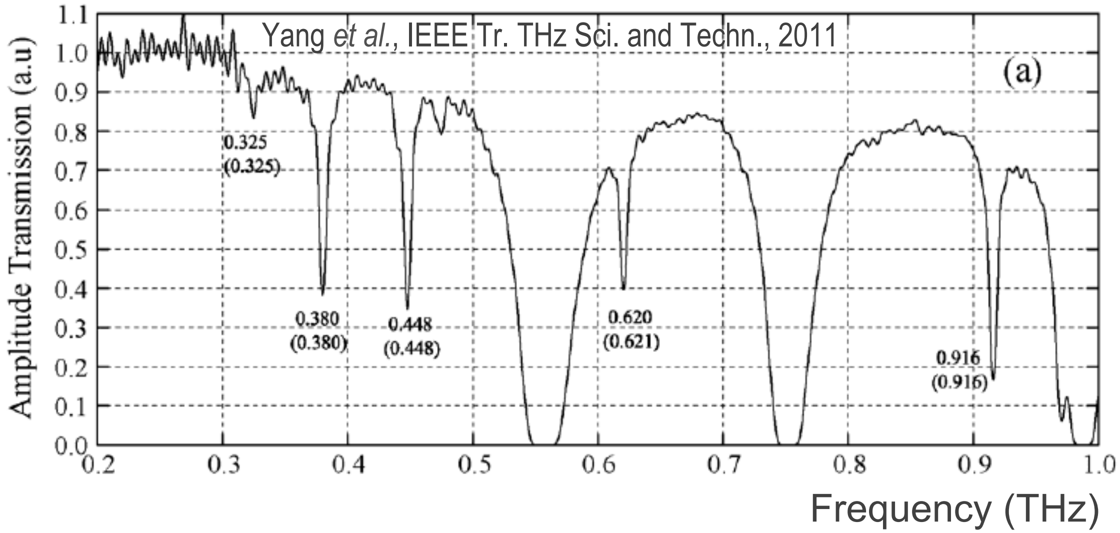


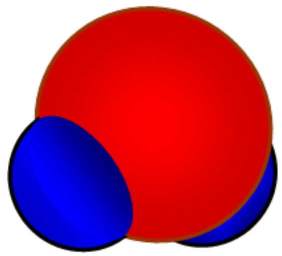


[Transmission spectra obtained from spectra.iao.ru/en/en/home/ for 2.59% H_2O.]

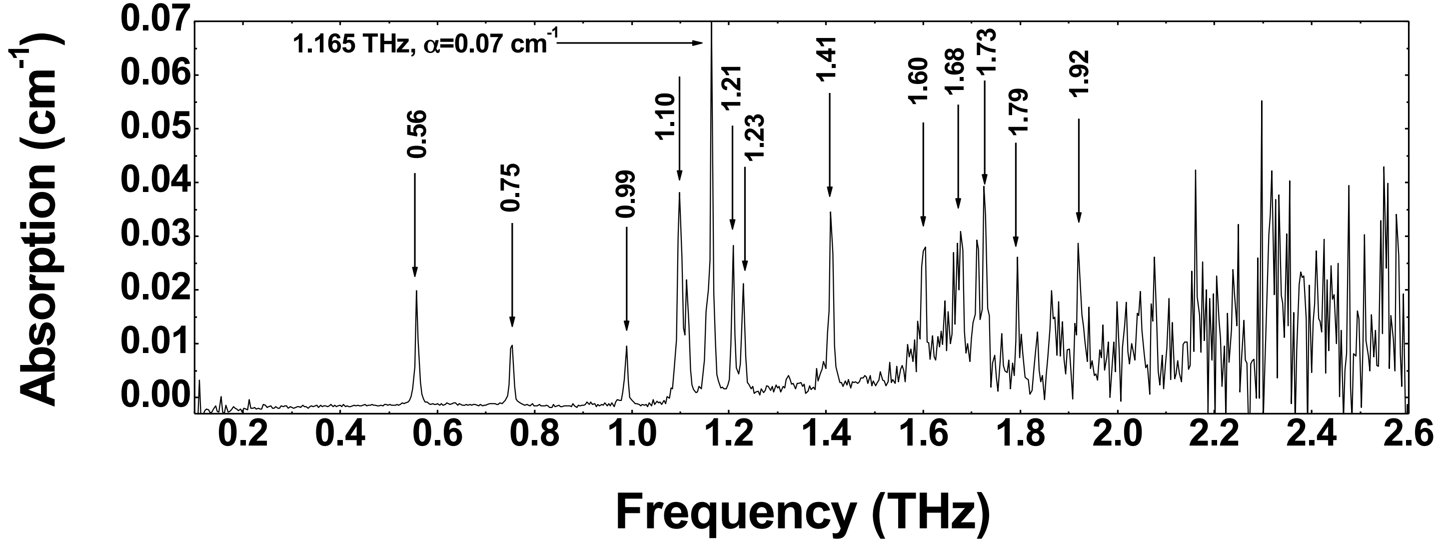
Terahertz absorption in air

167 m, RH 7%





RH 50%



Low-loss THz waveguide strategy

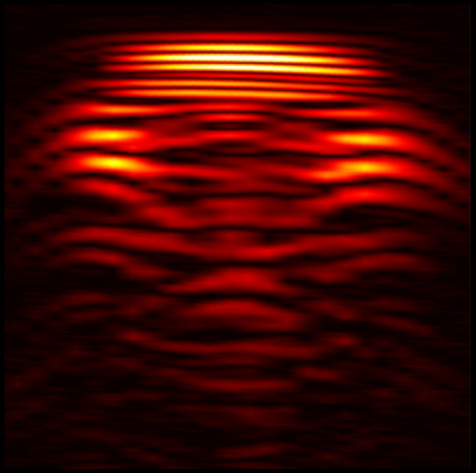
Waveguides with hollow regions

Closed walls – for dry air purging

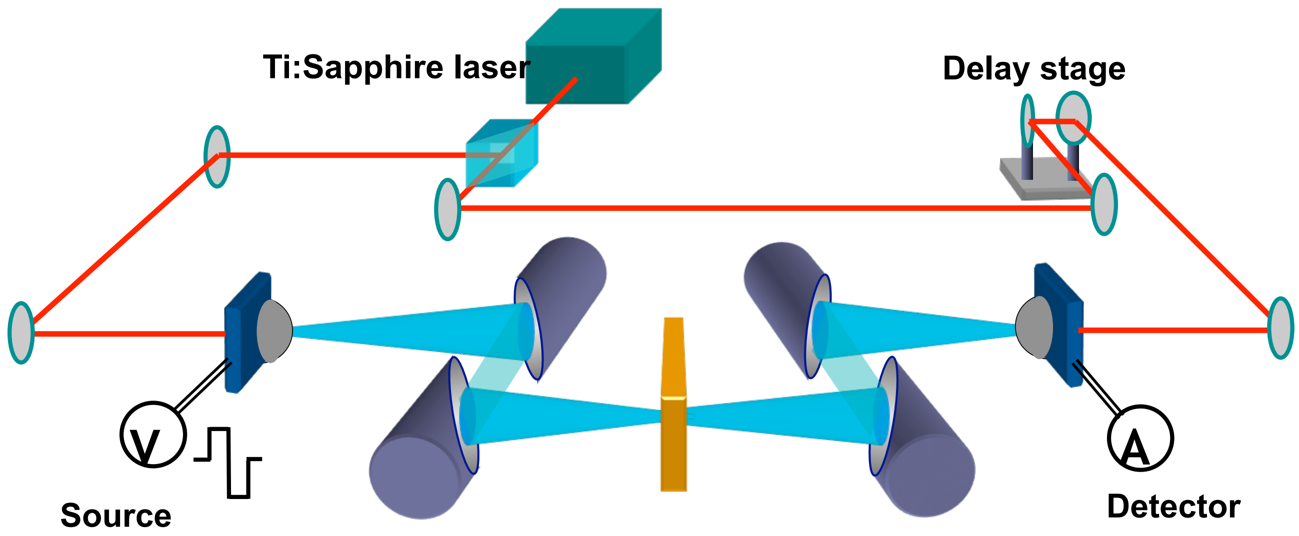
Minimal interaction with waveguides walls – large core

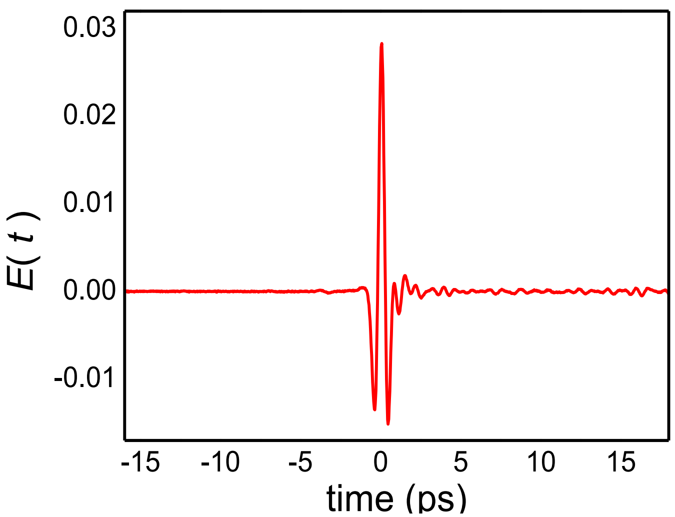
Multimode waveguides – mode management, efficient coupling

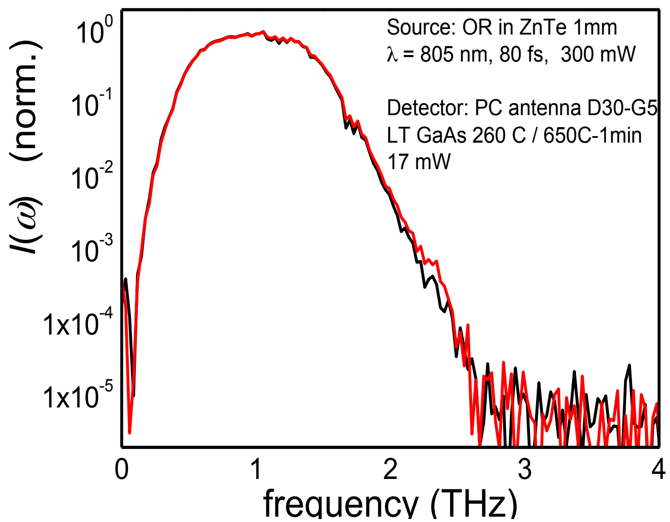
Characterization of THz waveguides



THz time-domain spectroscopy system



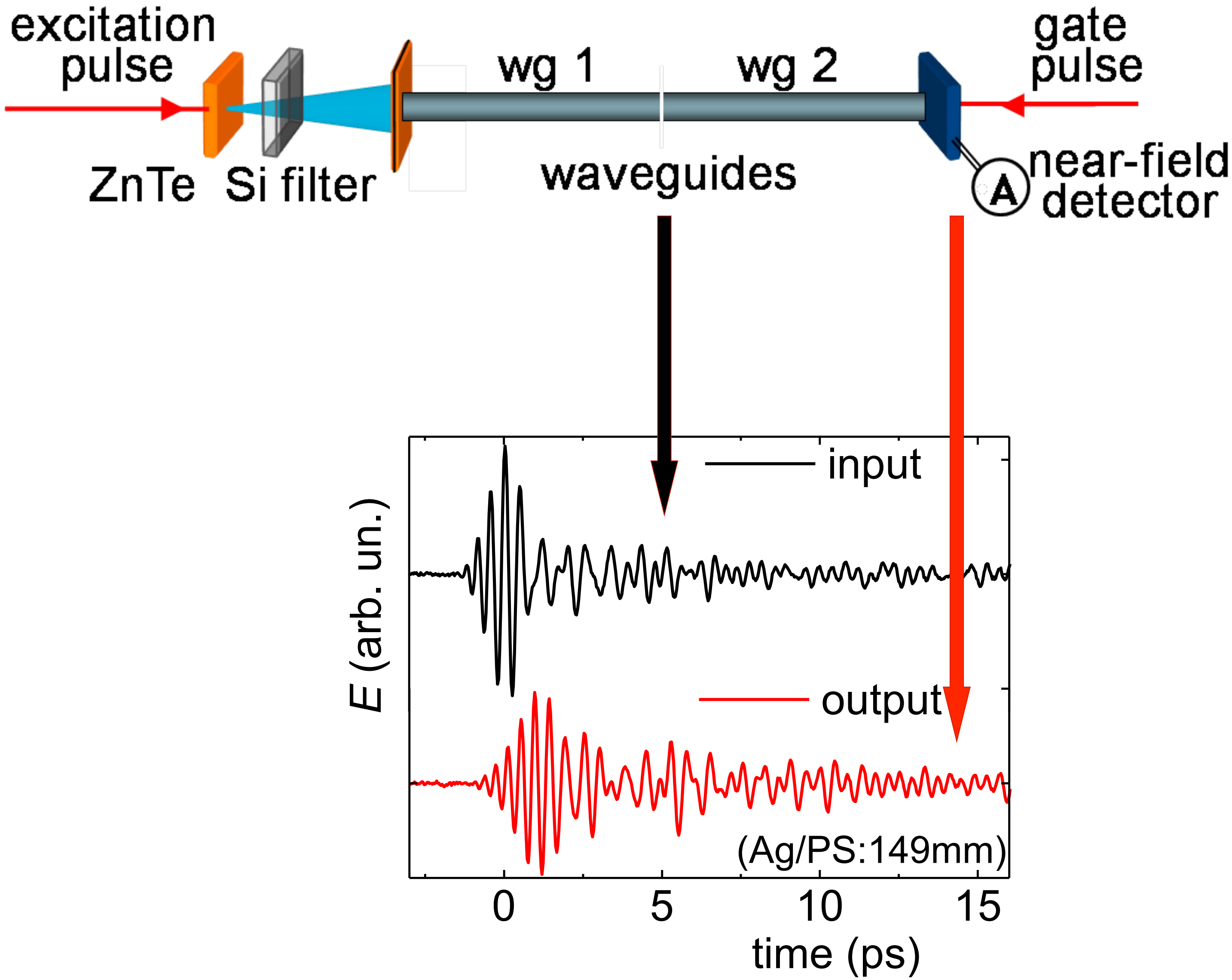




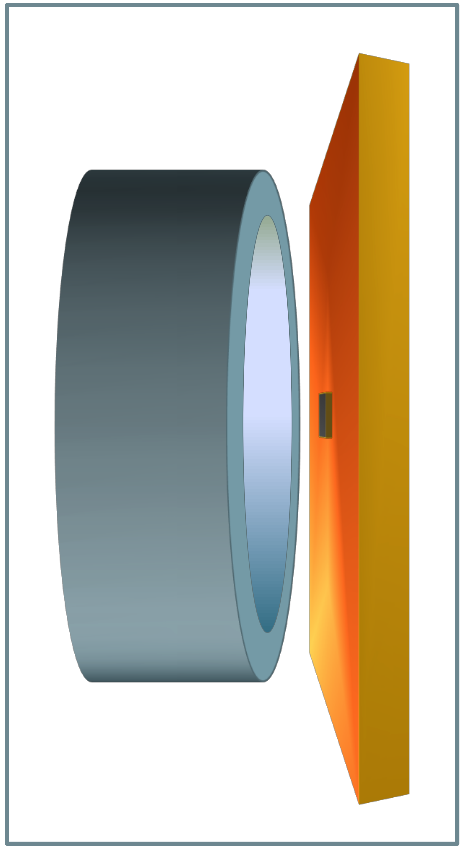
Required:
Modified THz-TDS for WG studies

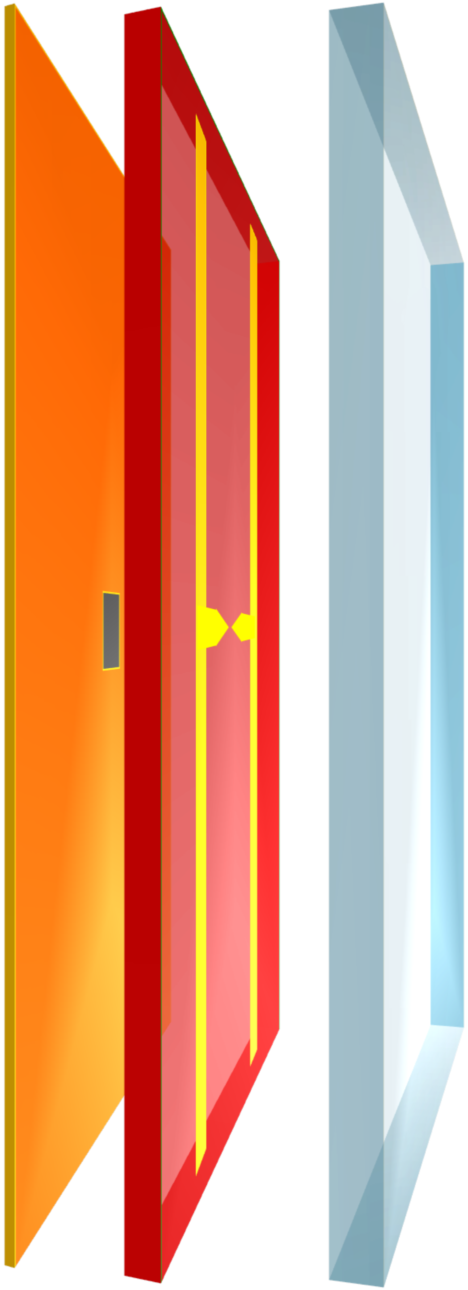
- long wg samples (10-100cm)
- mode interference
- mode-dependent coupling

Time-resolved characterization with THz pulses



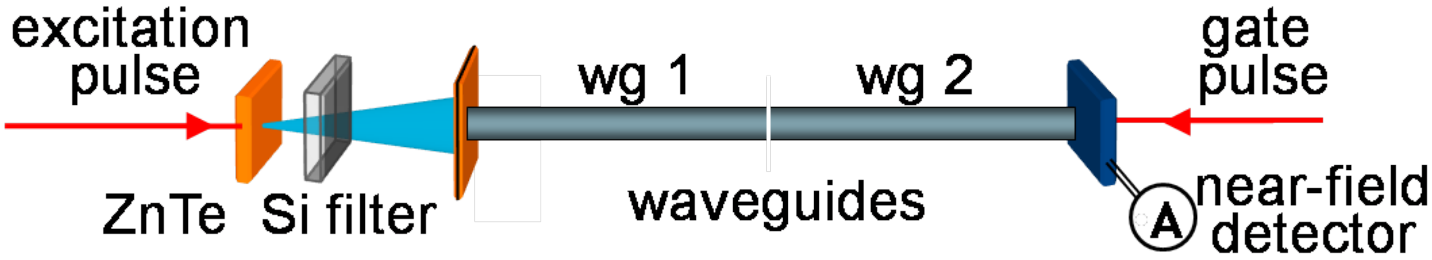
Wave mapping – near-field probe

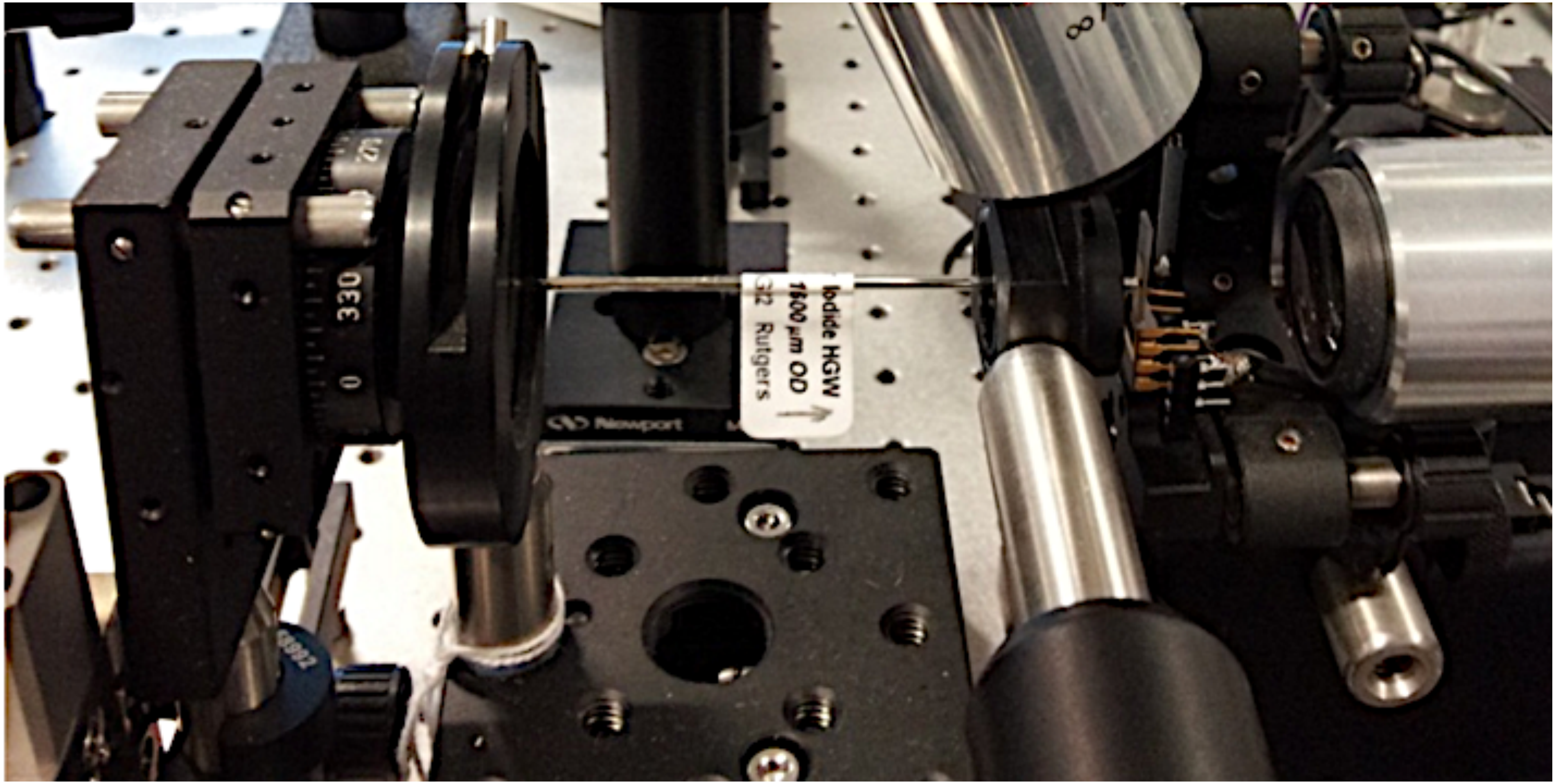




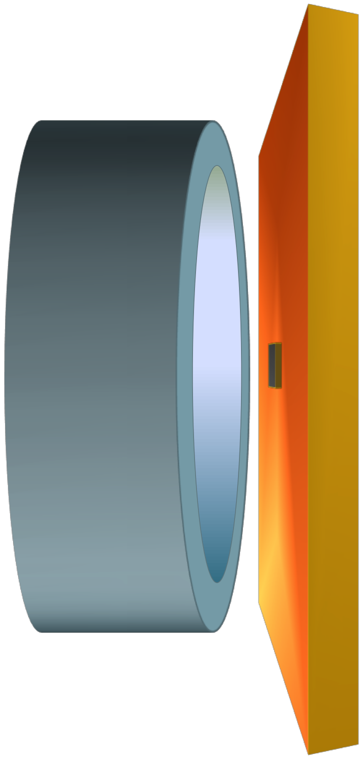
APL. **77**, 3496 (2000)

Time-resolved characterization with THz pulses





Near-field waveform detection

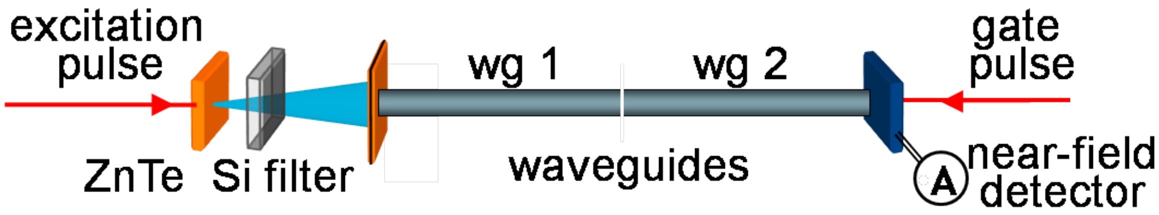


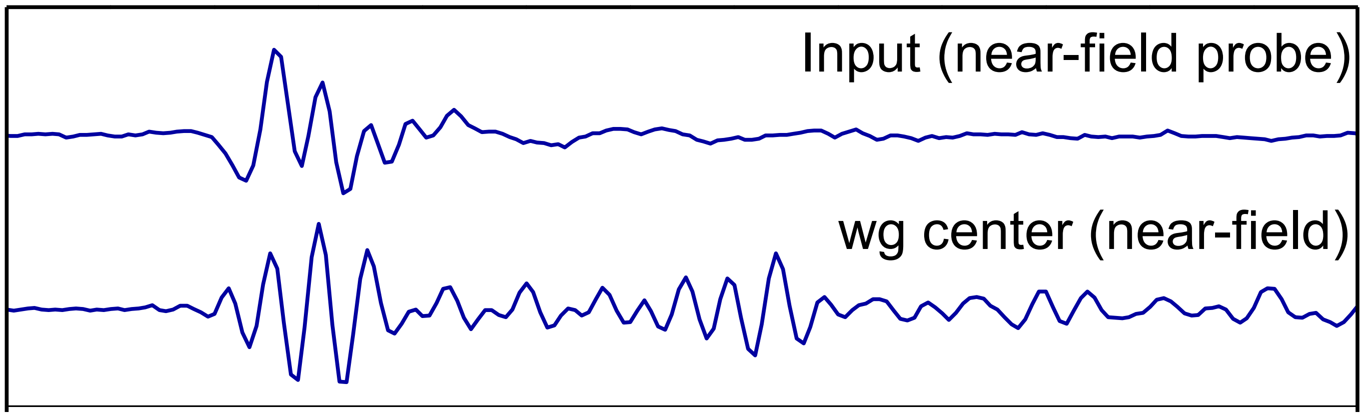
Near-field Probe:

subwavelength aperture

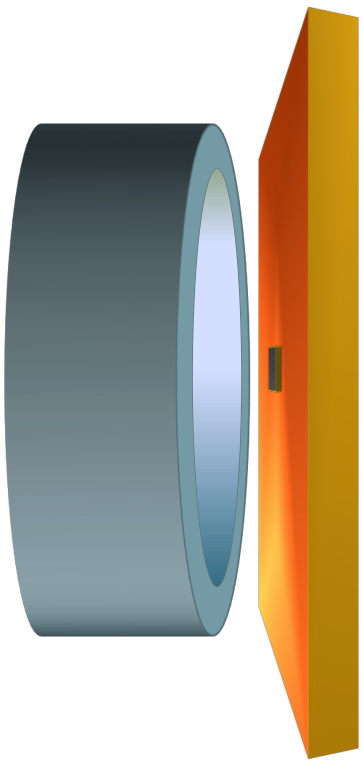
integrated PC probe

APL. **77**, 3496 (2000)





Waveguide field mapping



Near-field Probe:

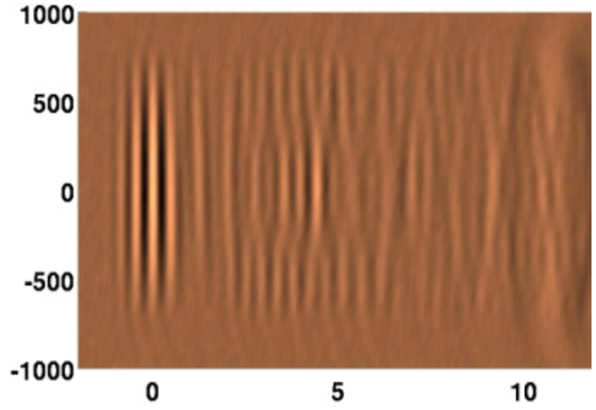
subwavelength aperture

integrated PC probe

APL. **77**, 3496 (2000)

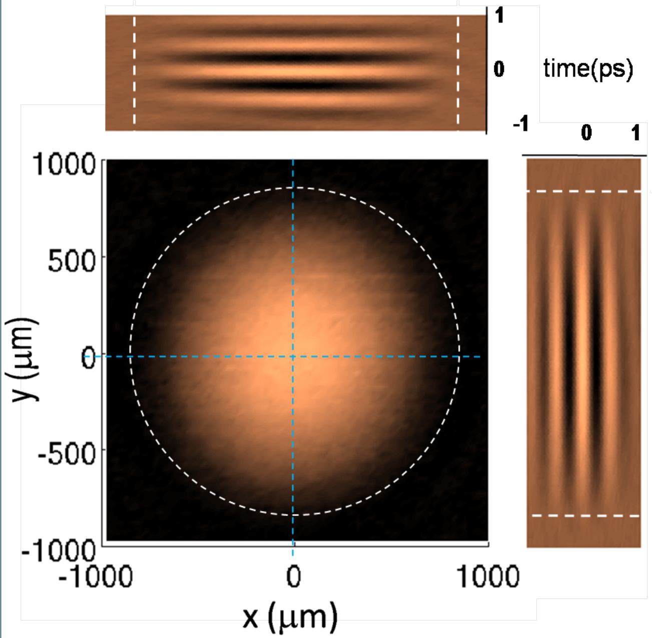
Space-time mapping

- *near-field time-resolved waveform detection*



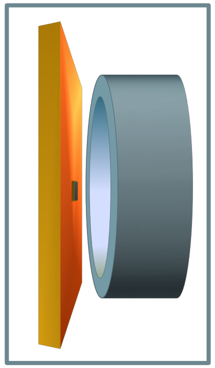
Spatial mode mapping

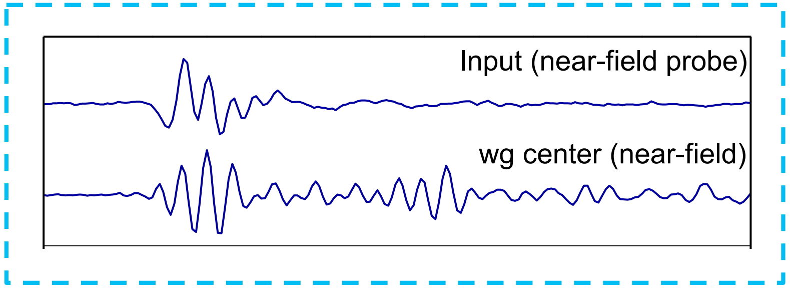
- *near-field imaging of the waveguide output end*

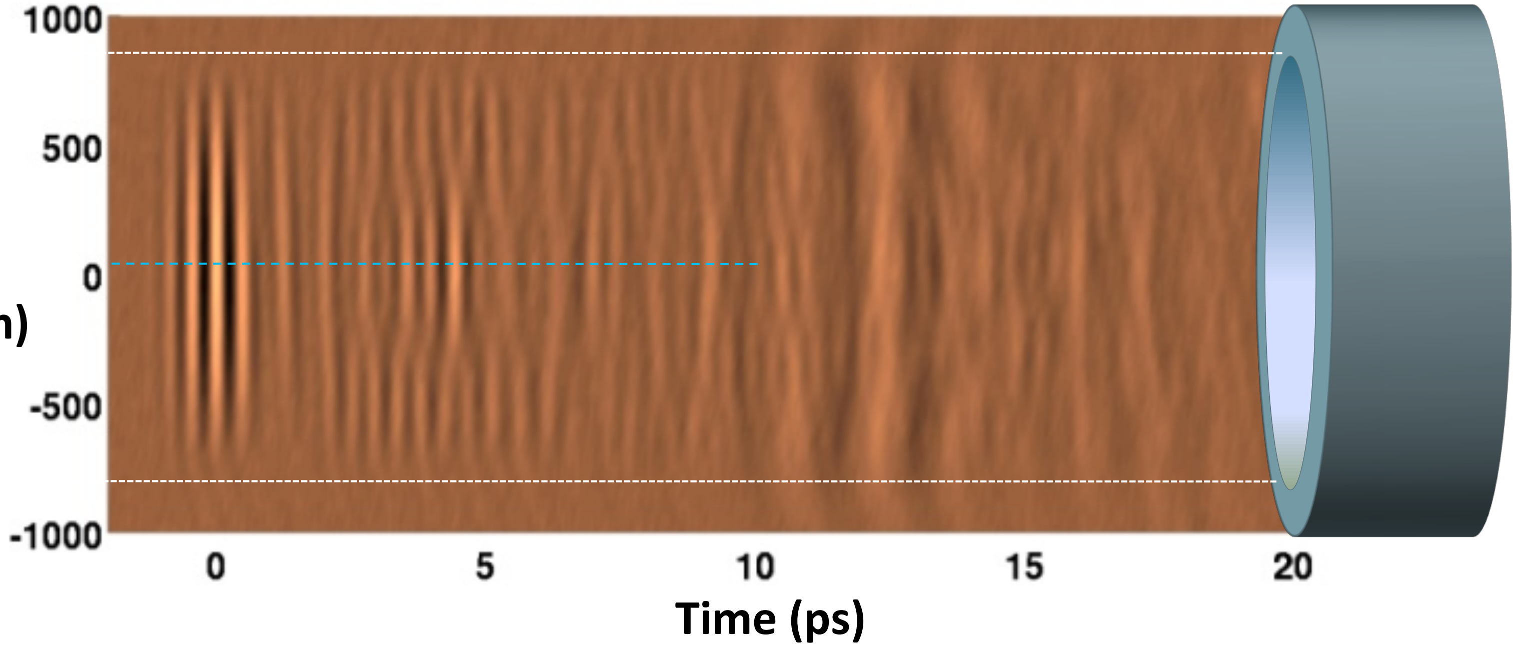


Appl. Phys. Lett. 94, 171104 (2009)

Space-time mapping



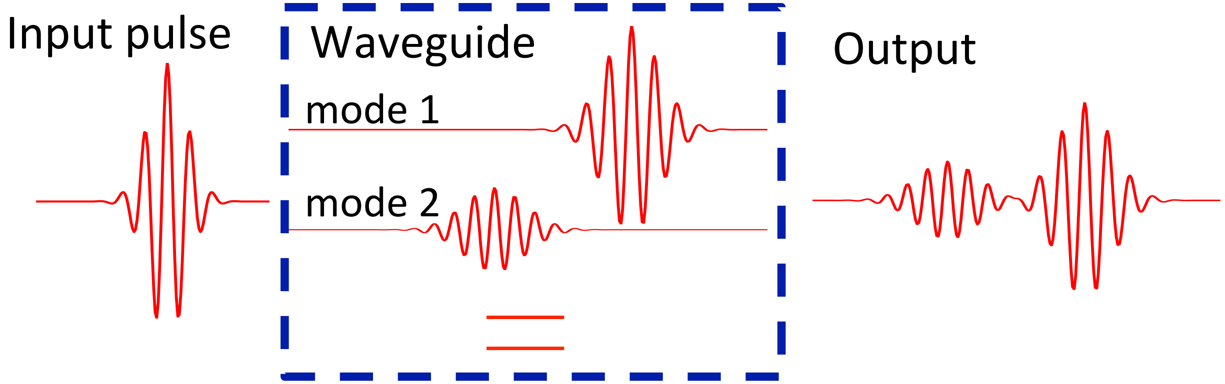


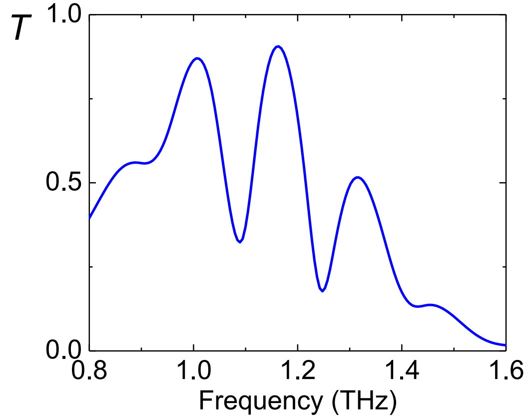


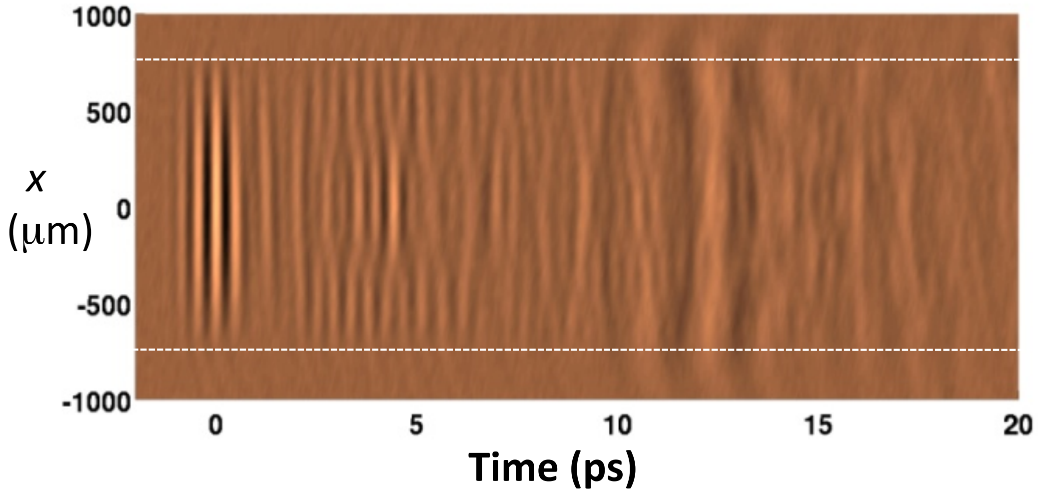
Appl. Phys. Lett. ***94***, 171104 (2009)

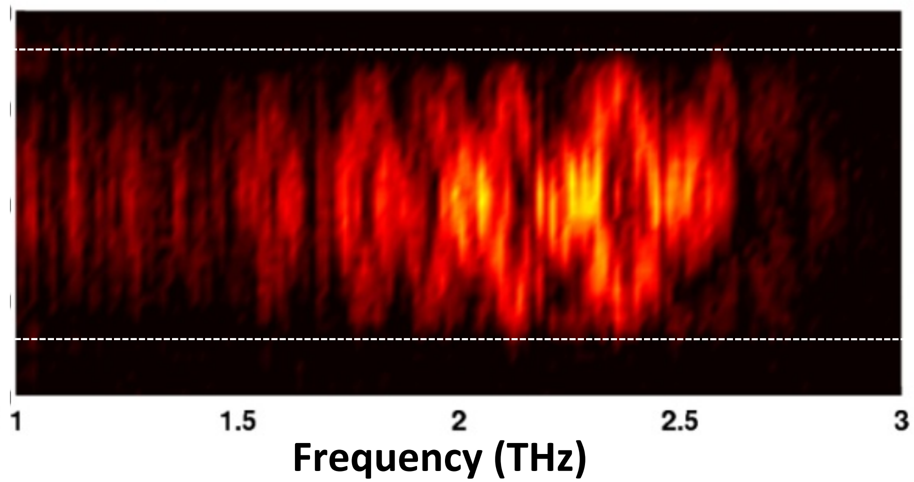
Mode interference

produces periodic variations in the THz-TDS spectrum



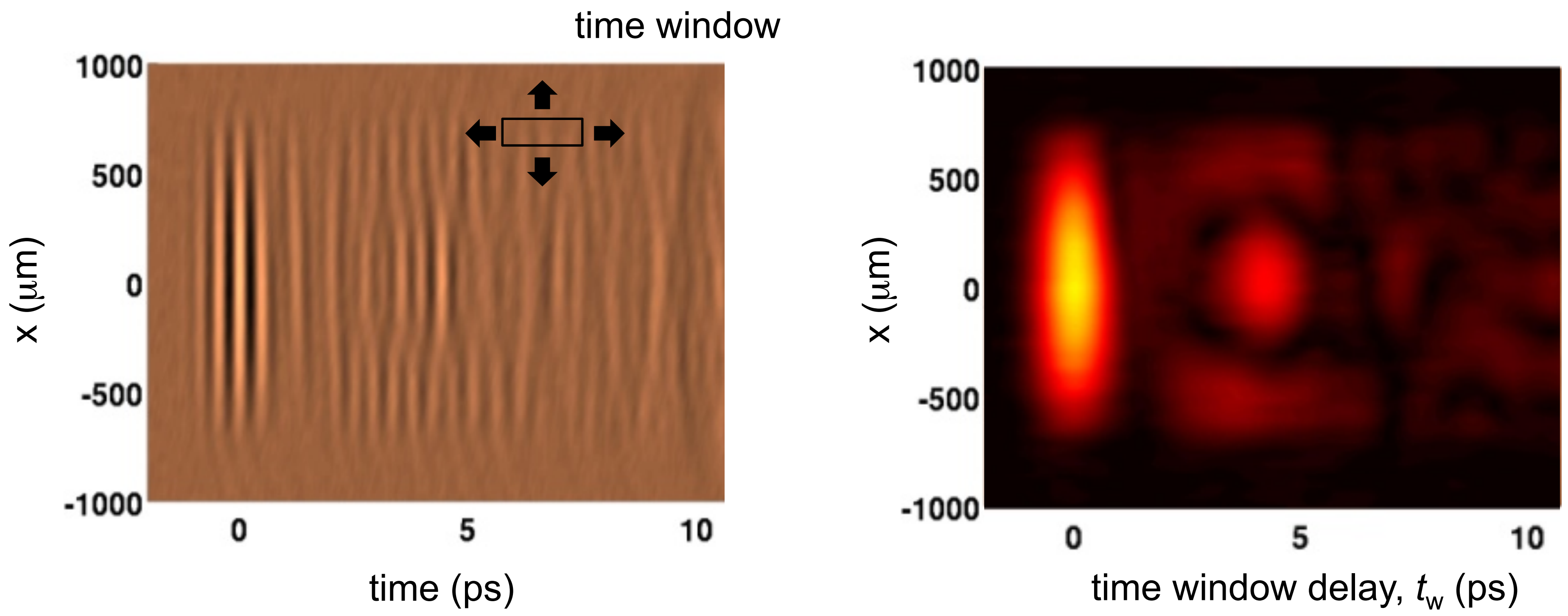




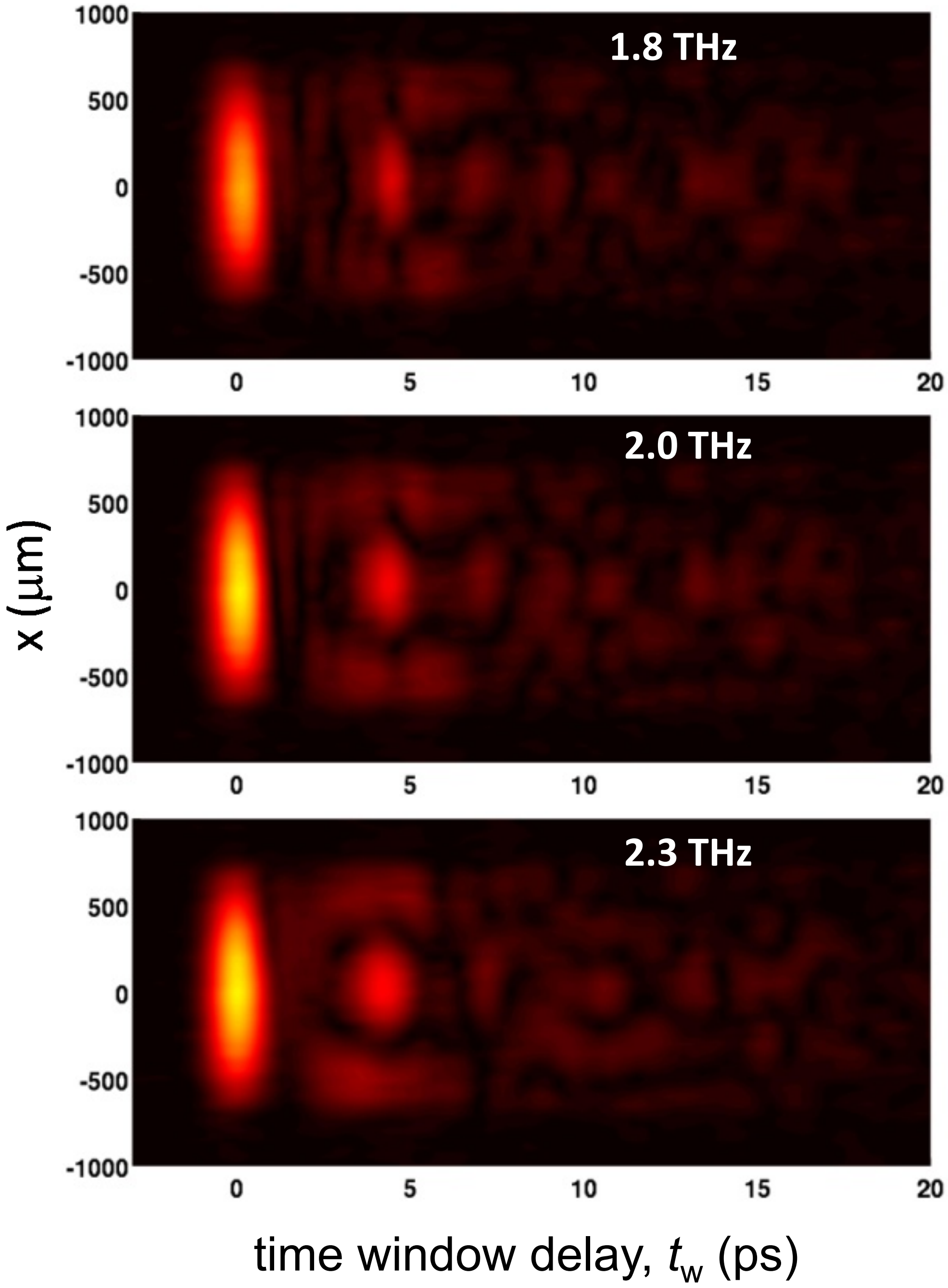


Mitrofanov et al. *Appl. Phys. Lett*. **94**, 171104 (2009)

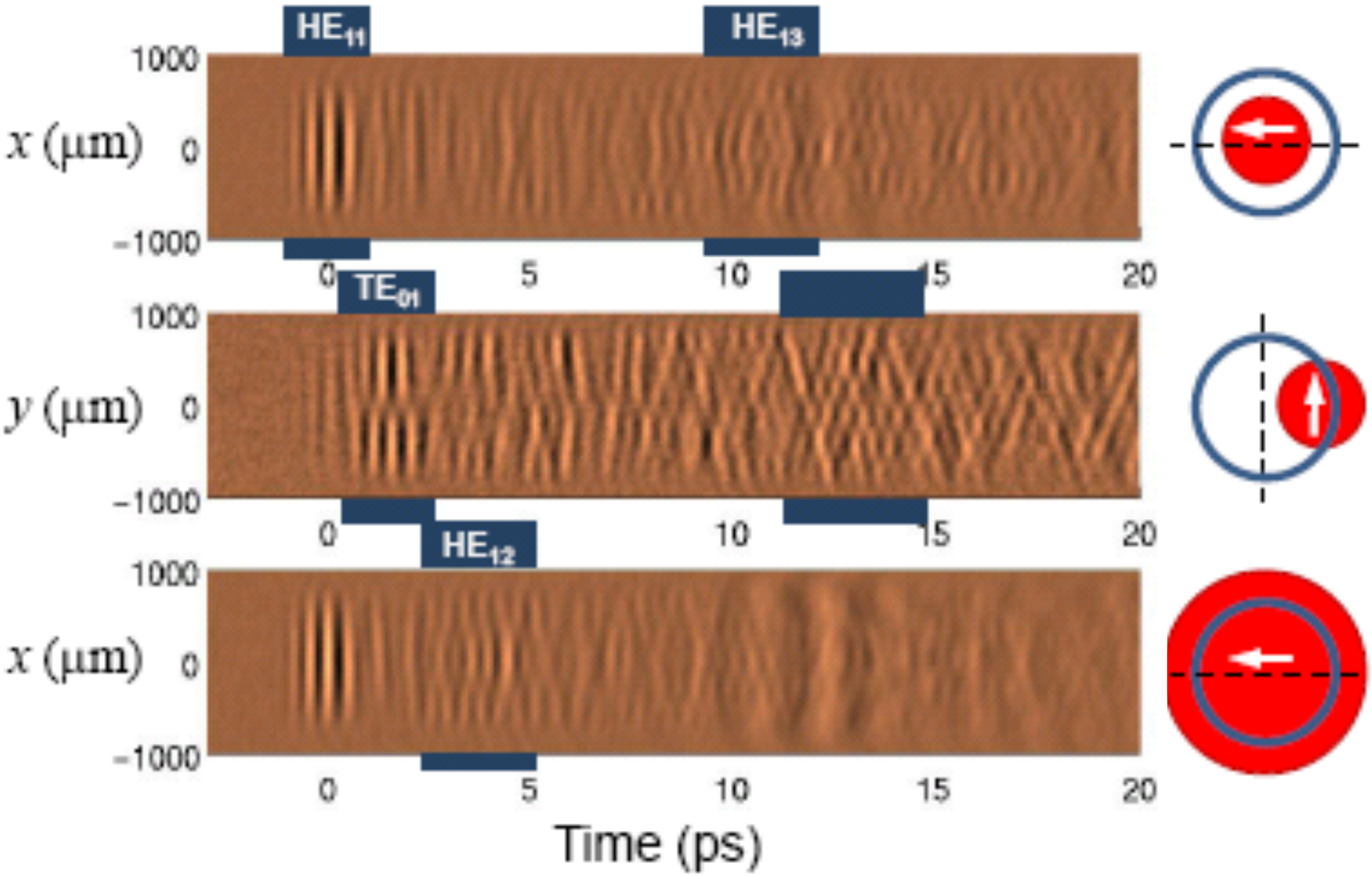
Fourier transform of space-time maps



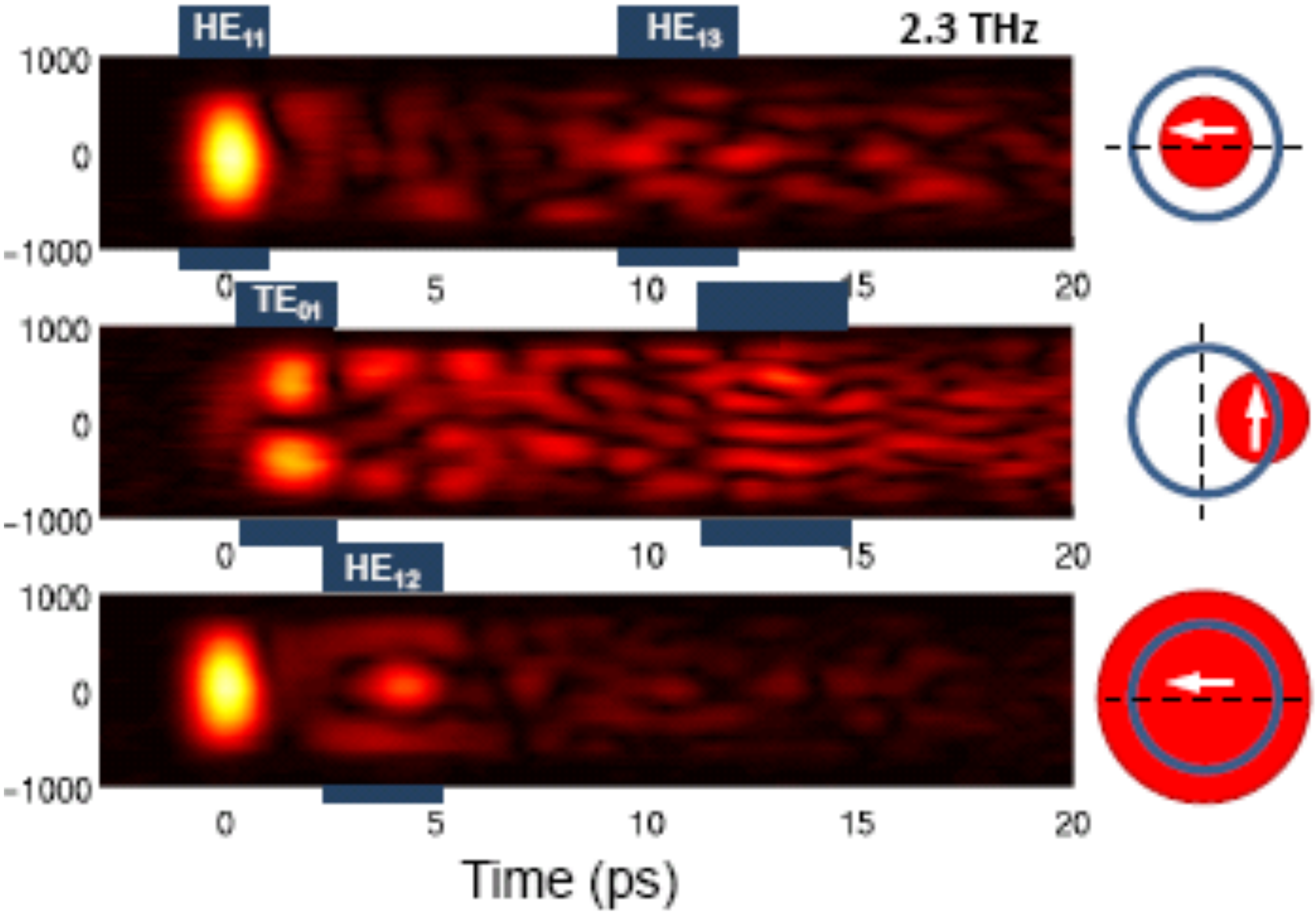
Space-time mapping



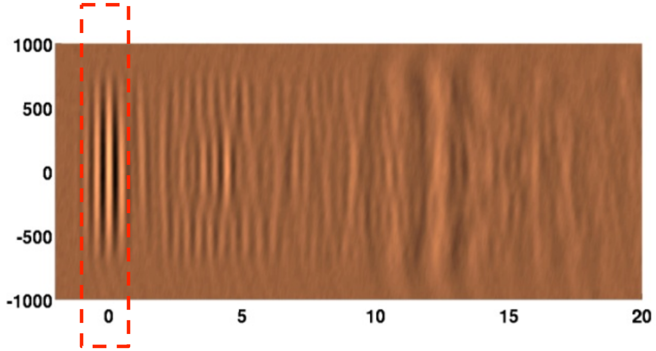
Mode composition analysis

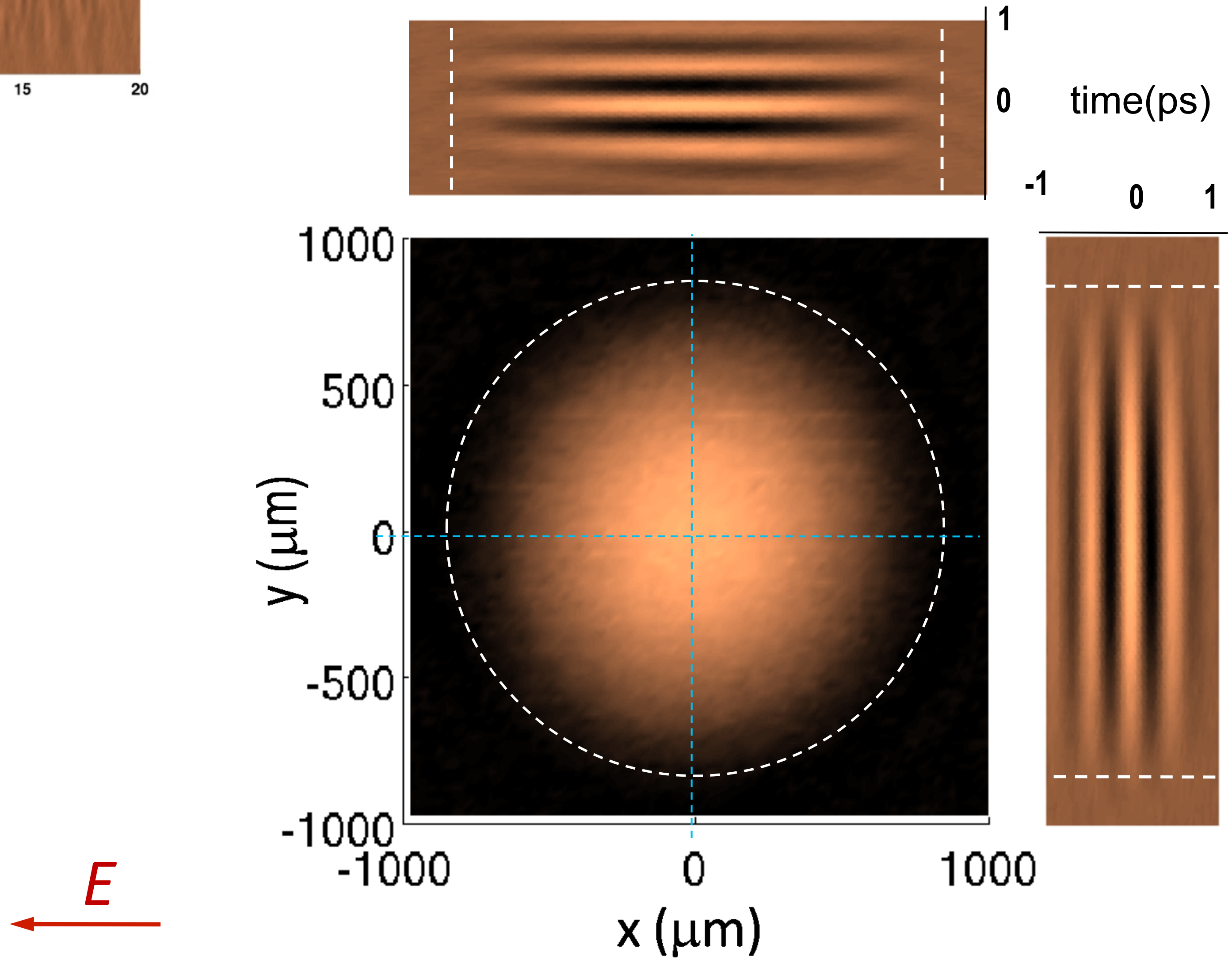


Mode composition analysis

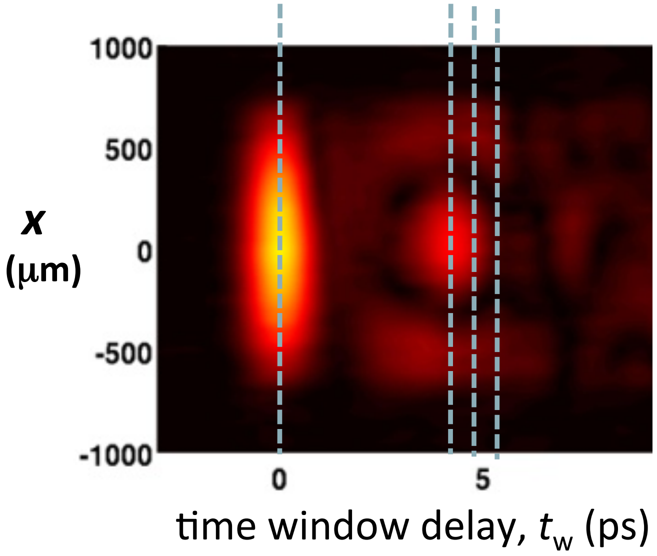


Mode profile mapping



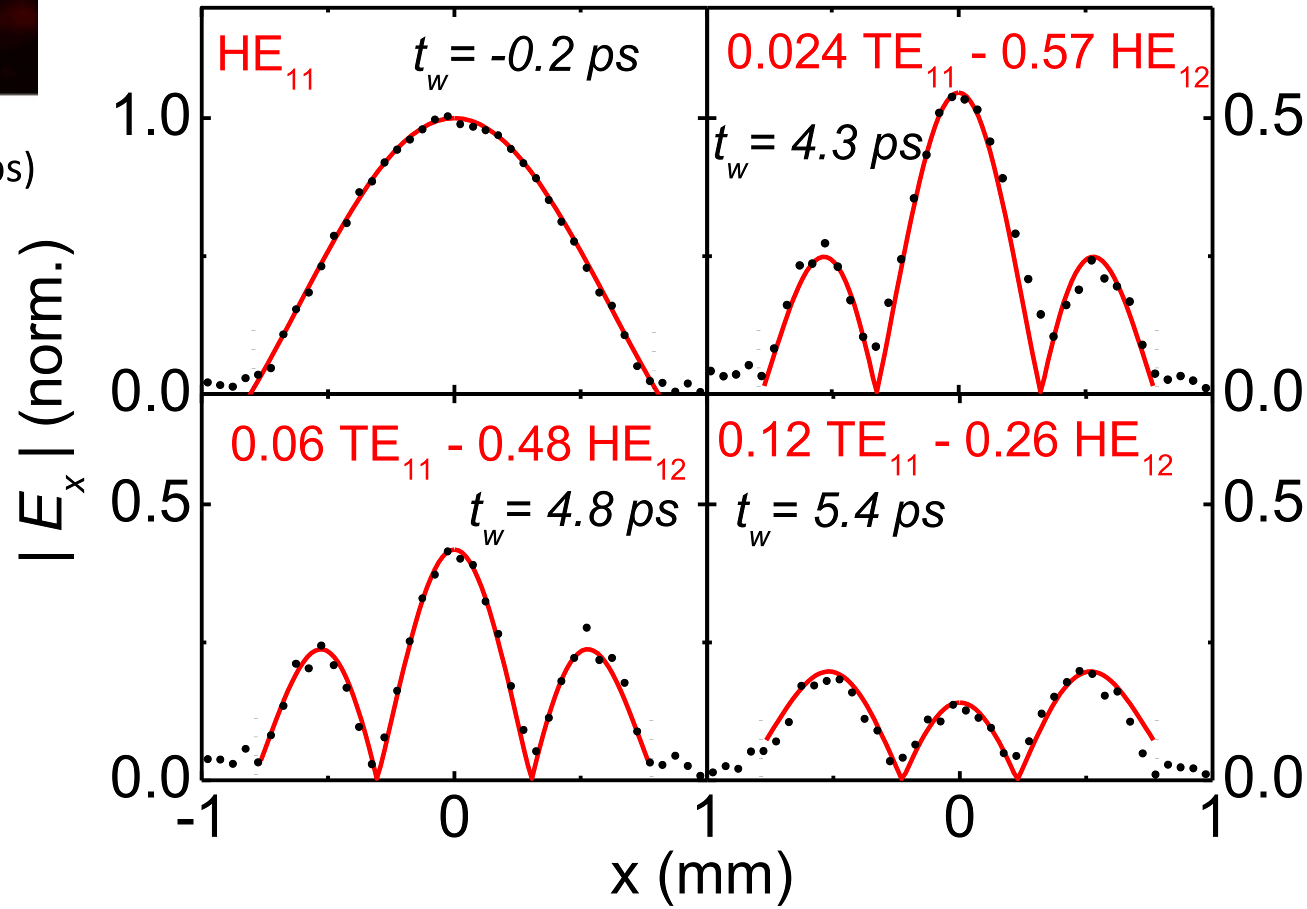


Mode profile mapping – temporal mode overlap

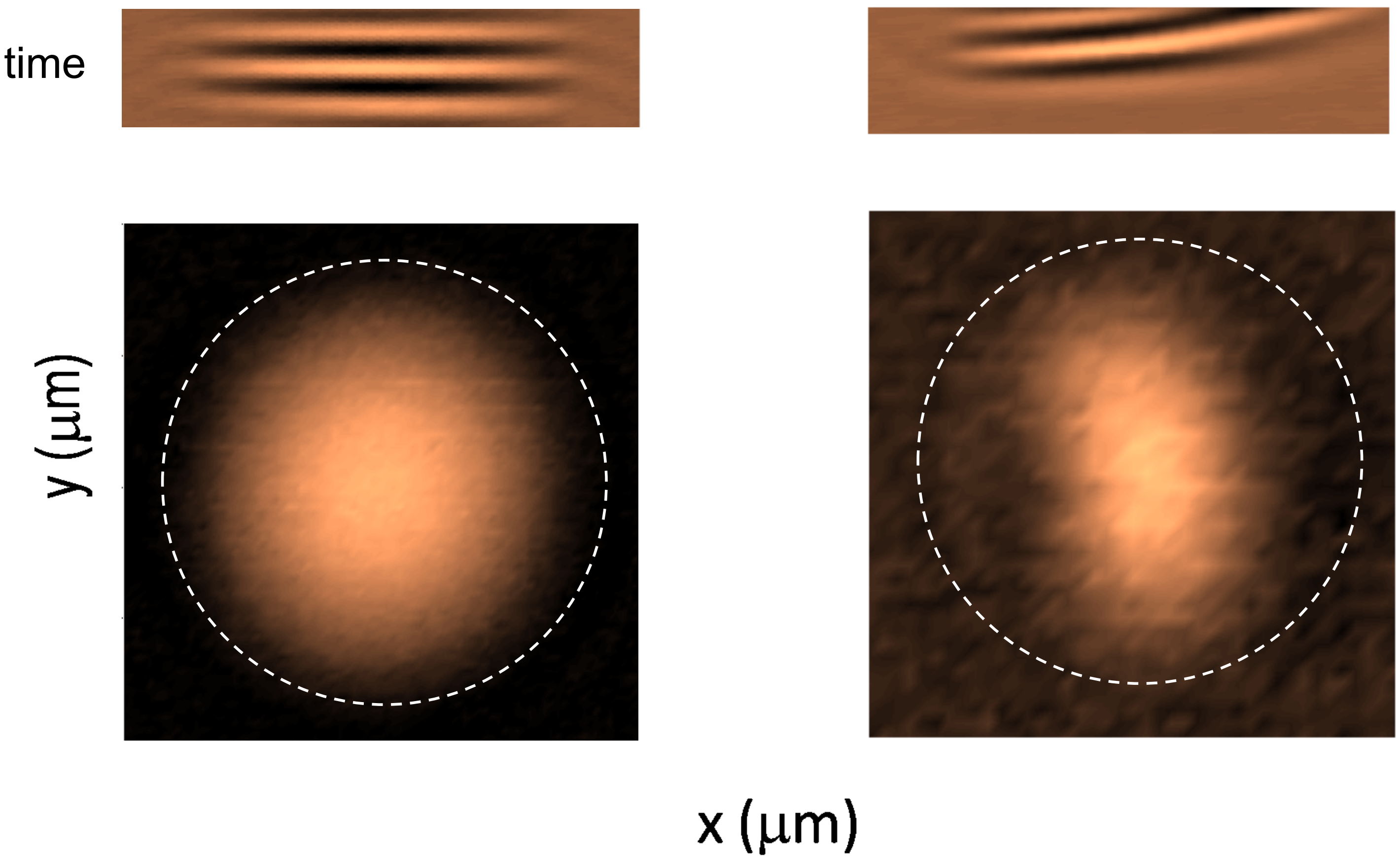


Distribution of the 2.3THz component.

Time-window Fourier analysis allows to identify modes by their spatial profiles



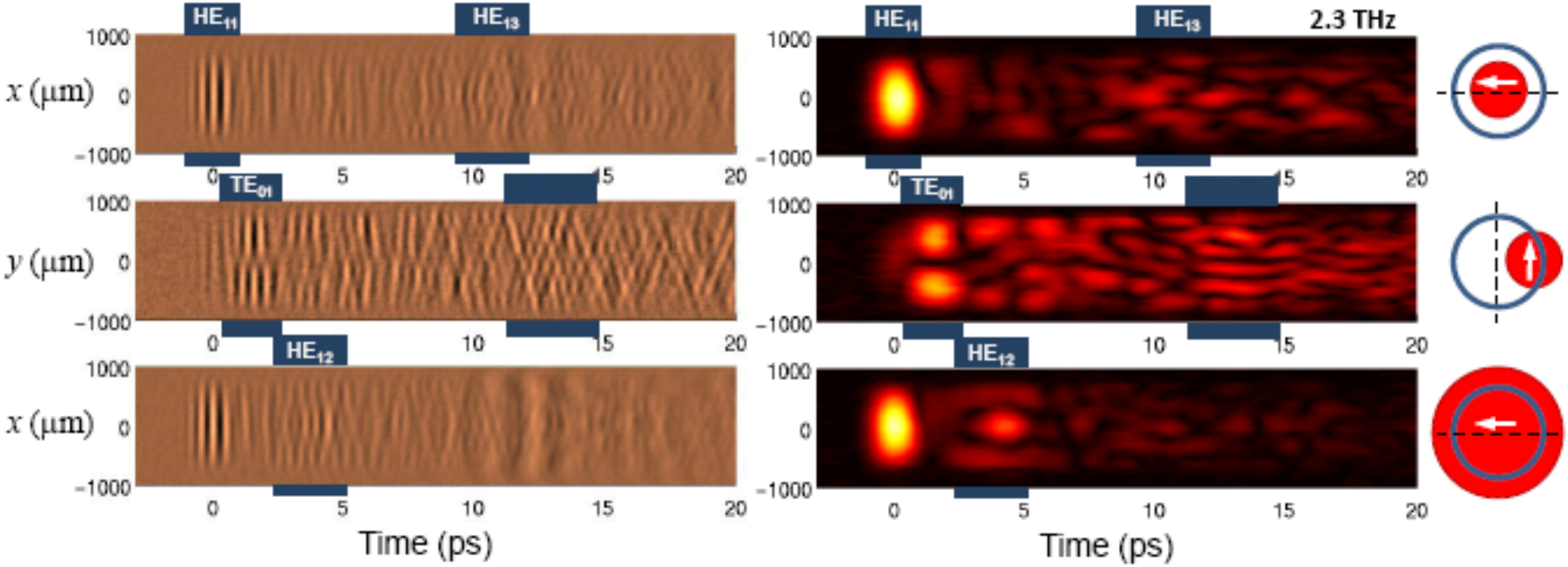
Waveguide alignment



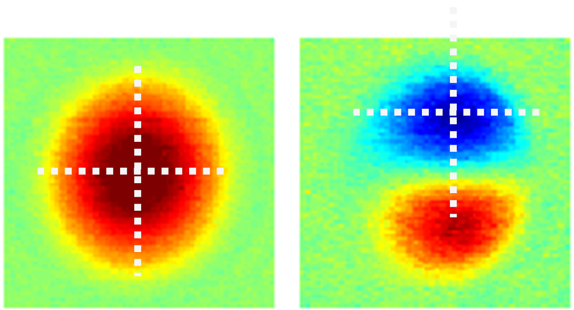
Appl. Phys. Lett. **94**, 171104 (2009)

Space-time maps for selective excitation/probing

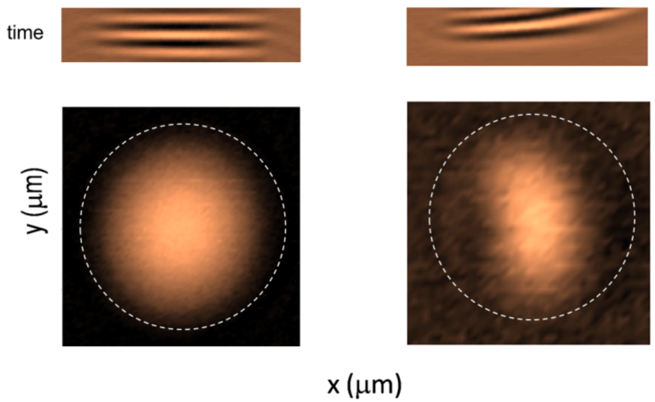
Selective excitation



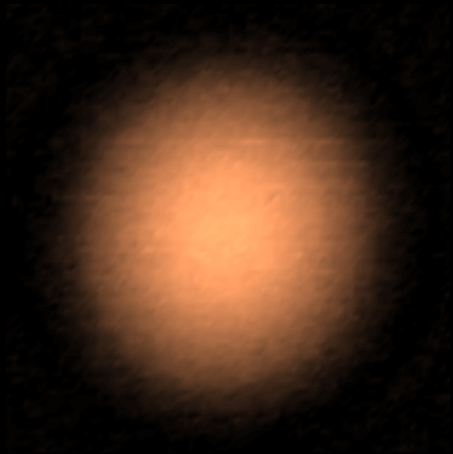
Selective probing



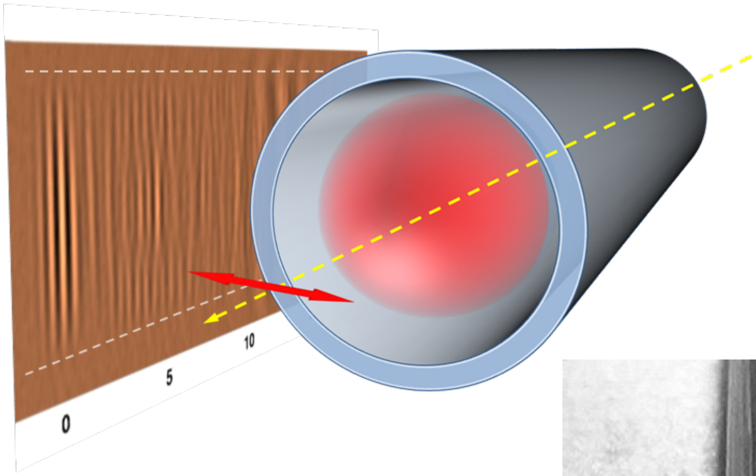
Alignment



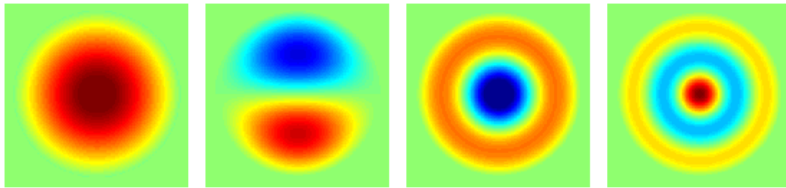
Dielectric-lined hollow metallic waveguides

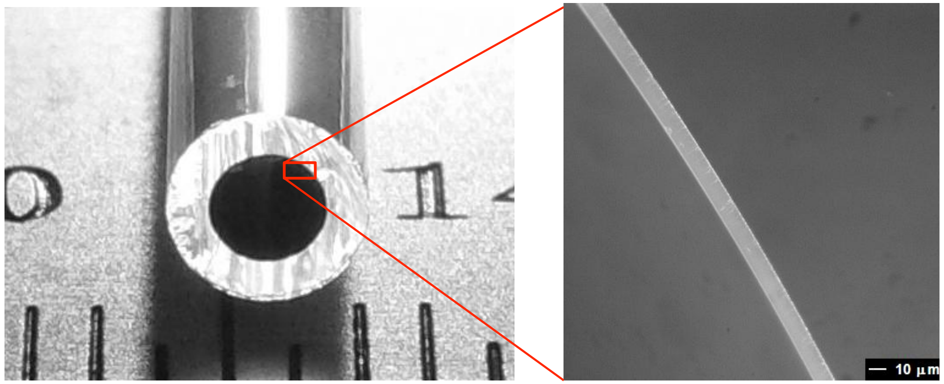


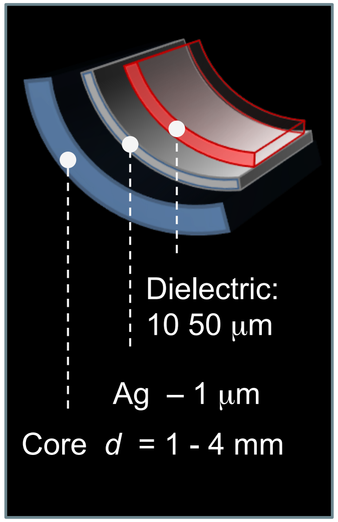
Dielectric-lined hollow cylindrical metallic waveguides

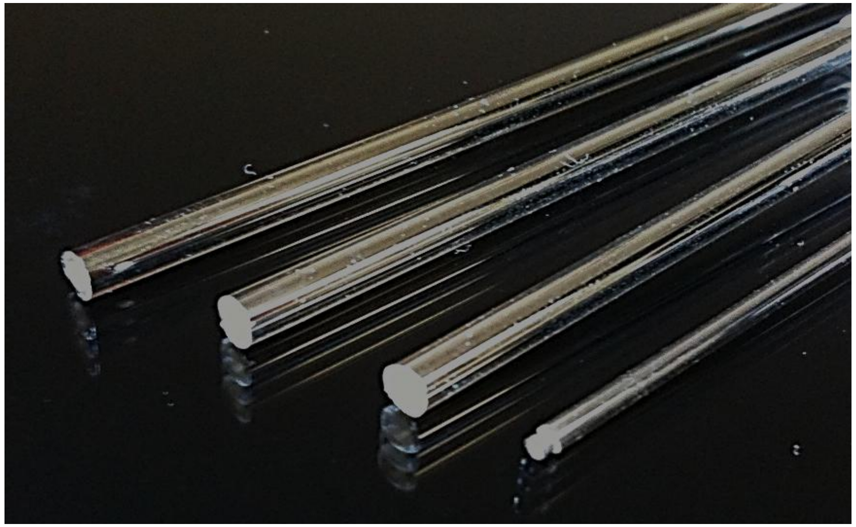


Miyagi and Kawakami, JLT (1984)



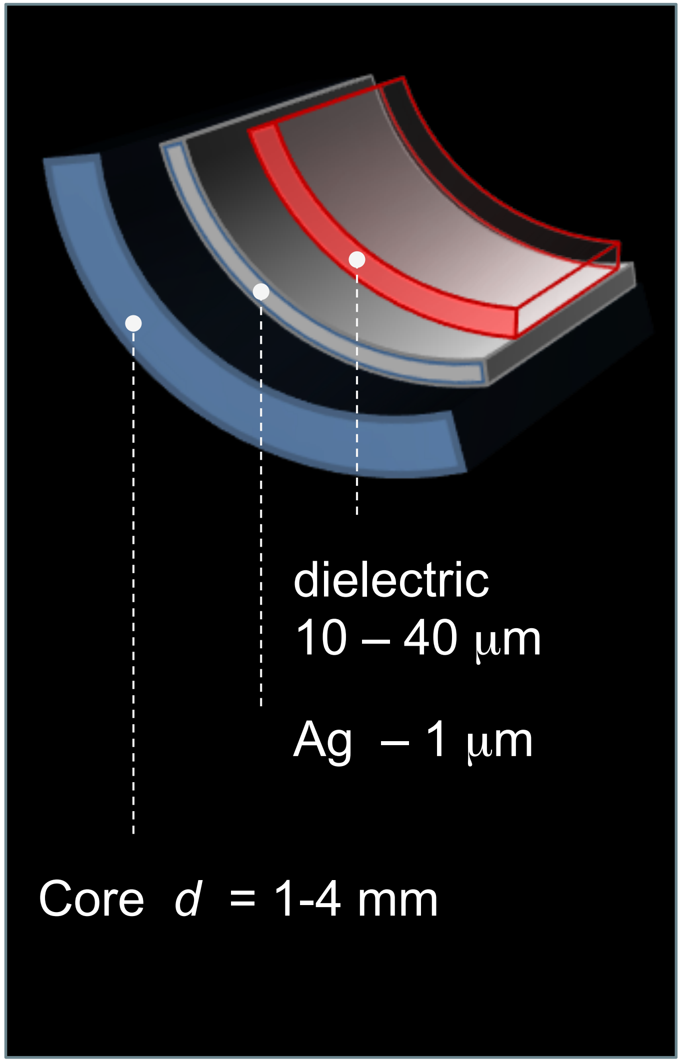


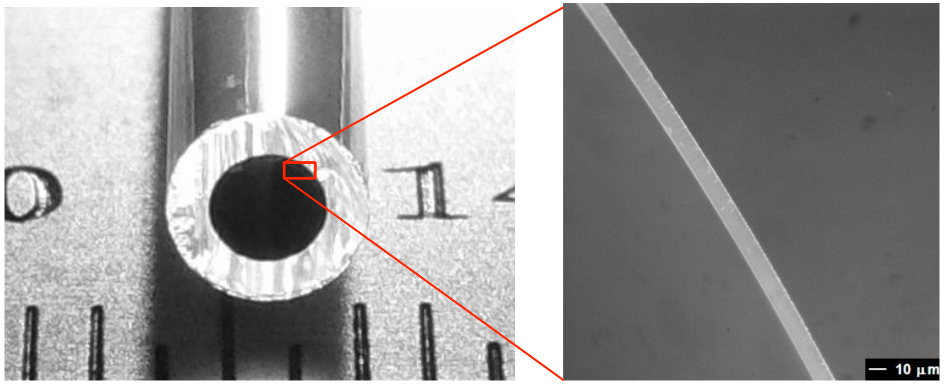


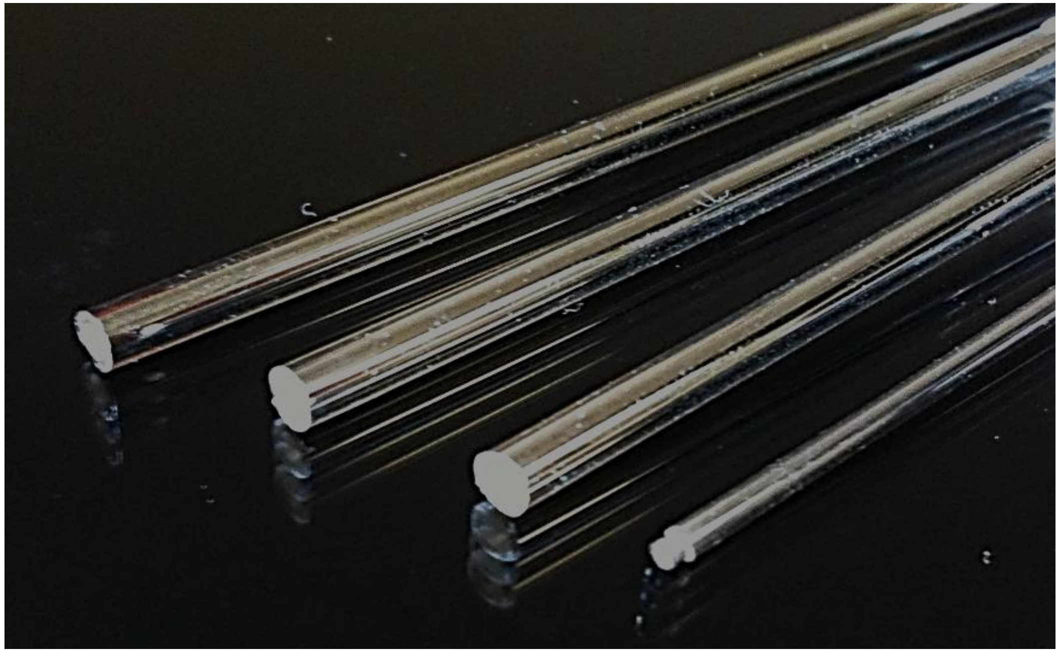


Opt. Lett. **32**, 2945-2947(2007)
Appl. Phys. Lett. **93**, 181104 (2008)
J. Appl. Phys. **104**, 093110 (2008)
Optics Express **18,** 1898 (2010)
JOSA B **1,** 134 (2013)

Dielectric-lined hollow cylindrical metallic waveguides

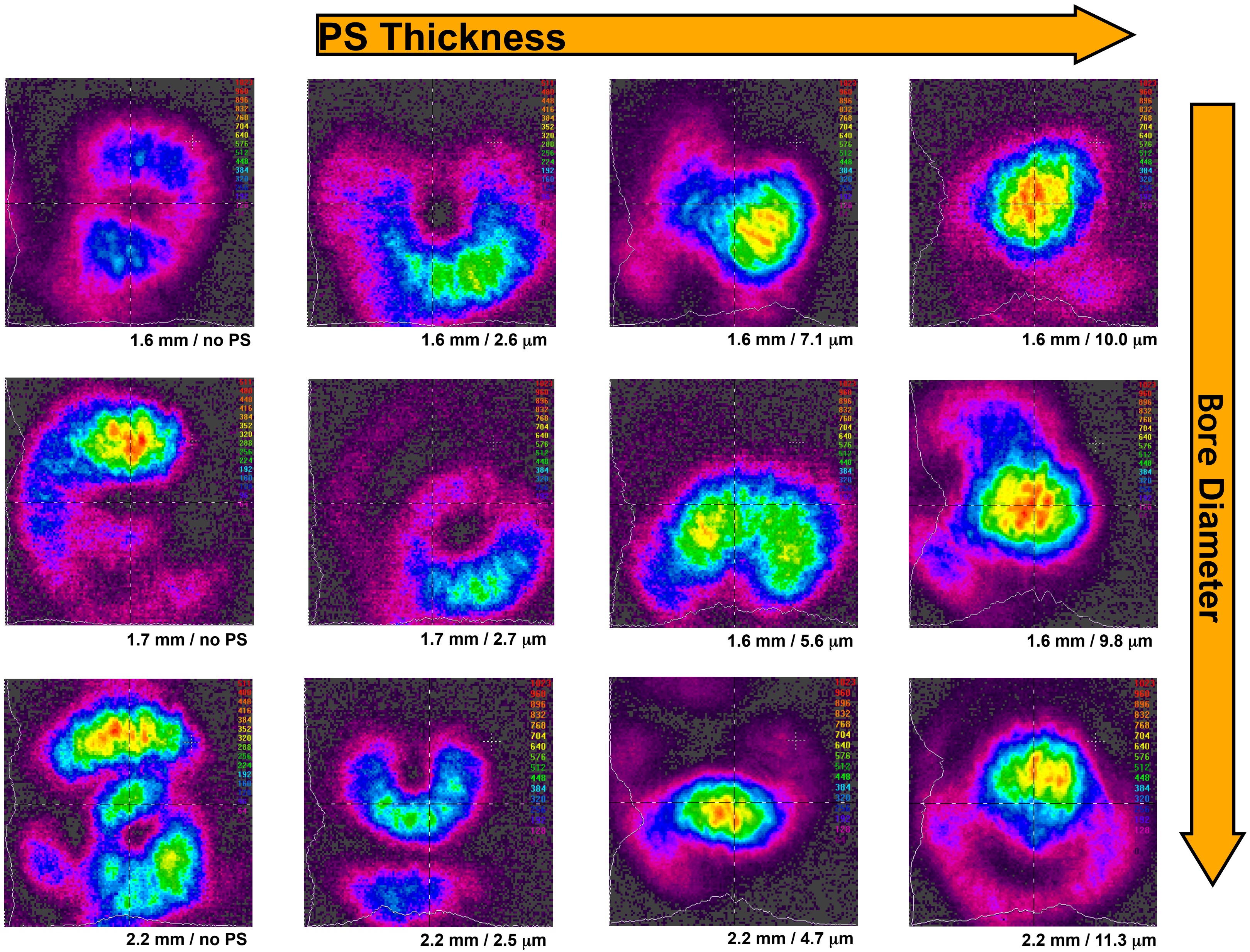






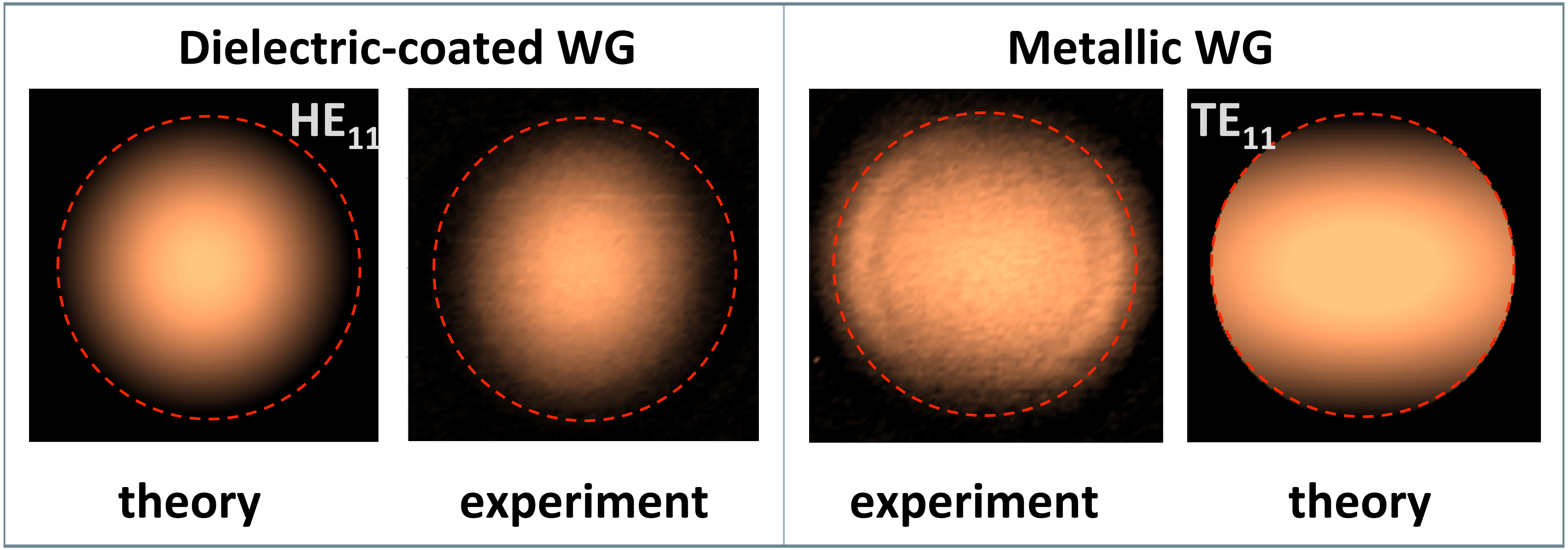
Opt. Lett. **32**, 2945-2947(2007)
Appl. Phys. Lett. **93**, 181104 (2008)
J. Appl. Phys. **104**, 093110 (2008)
Optics Express **18,** 1898 (2010)

CW (FIR laser, 2.5 THz) far-field mode imaging



Dielectric-lined hollow cylindrical metallic waveguides

Electric field, horizontal component.
(each image is 2mm x 2mm)



Transmission loss is reduced to ~1 dB/m   (from ~3dB/m in MWG)

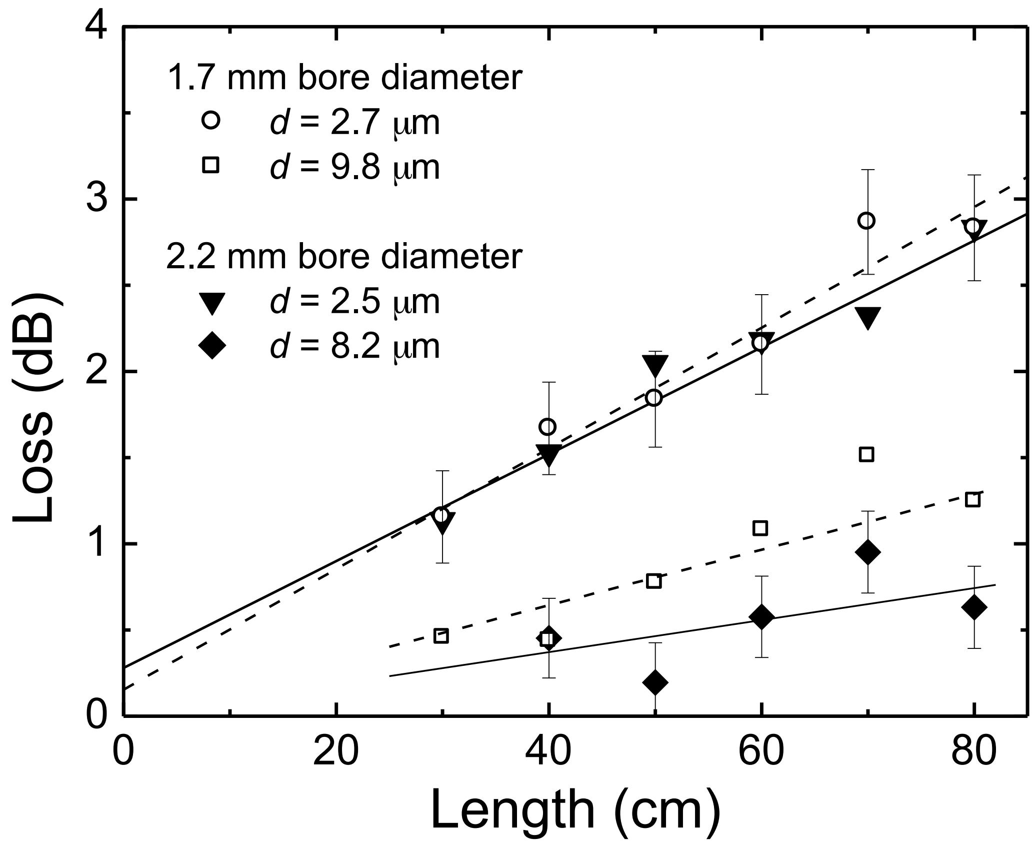
Linearly-polarized mode

Mode structure is ideal for free-space coupling: >80% (experiment)

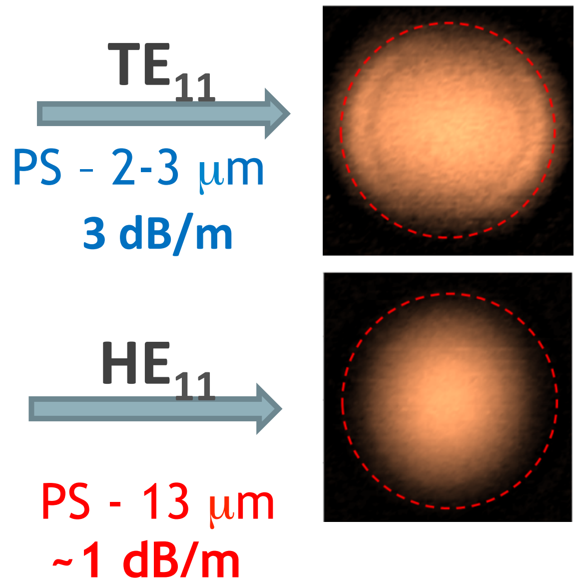
Appl. Phys. Lett. **94**, 171104   (2009)

Transmission losses – HE$_{11}$ mode

Transmission Loss at 2.5THz



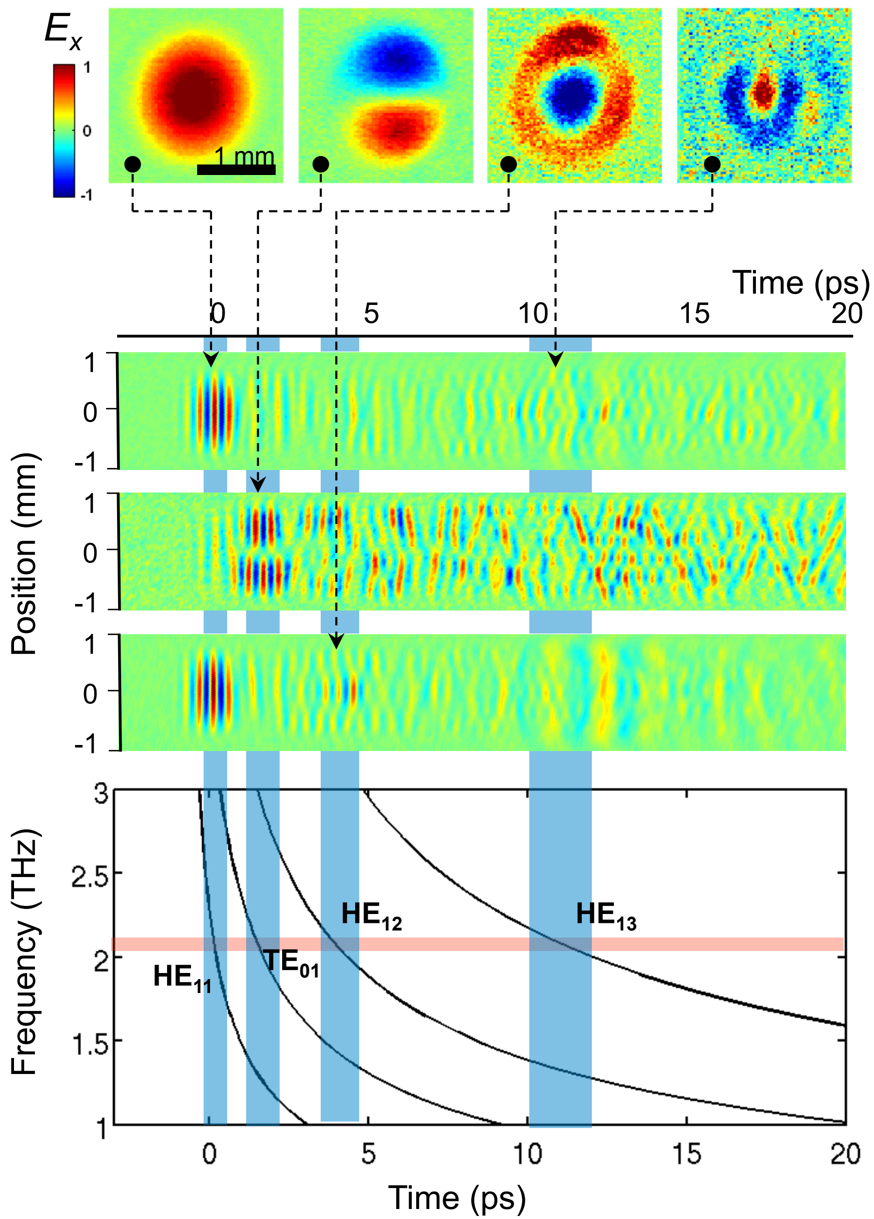
Correlation between transmission loss and the dominant mode profile



Opt. Lett. **32**, 2945-2947(2007)
Appl. Phys. Lett. **93**, 181104 (2008)

Appl. Phys. Lett. **94**, 171104 (2009)

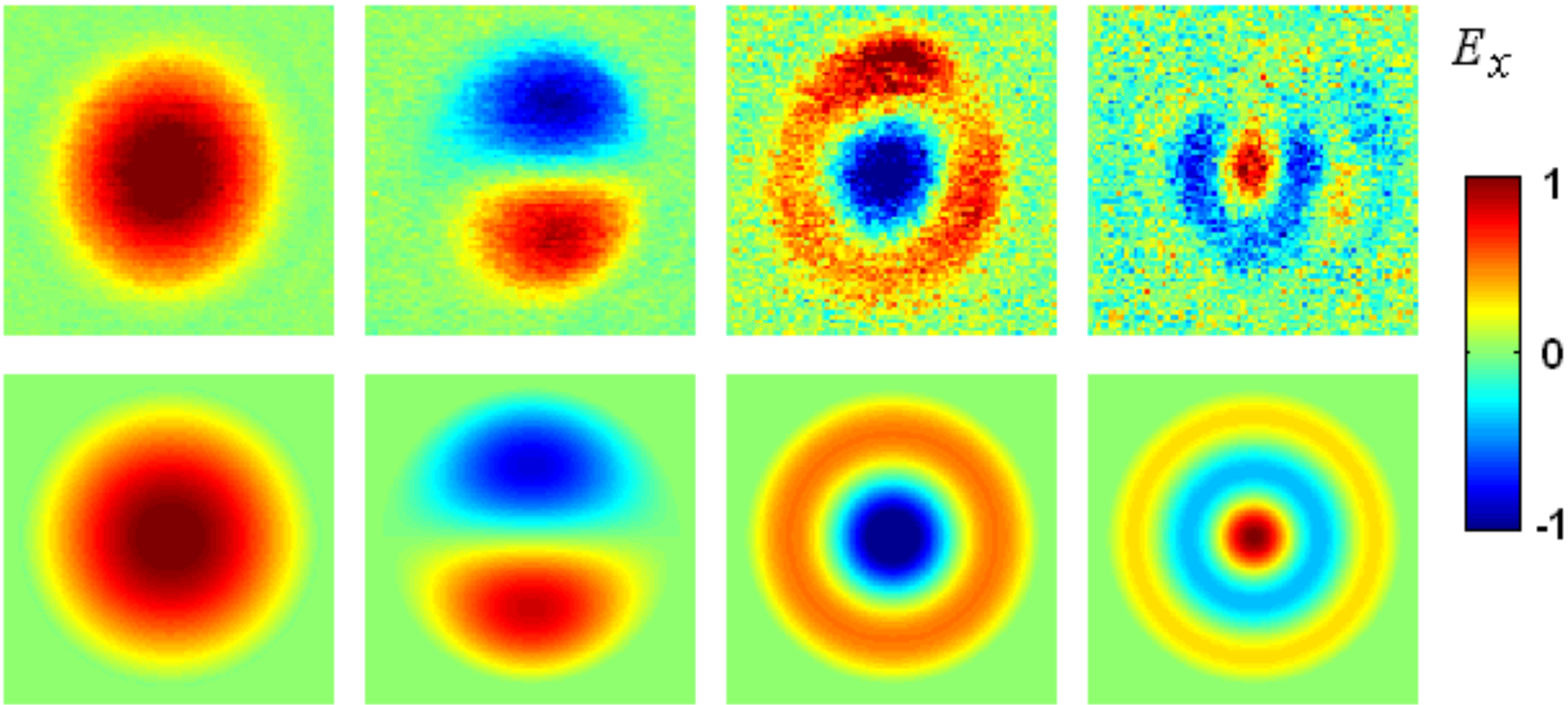
Time-resolved mode profile imaging



IEEE Trans THz Science and Technology, **1**, 124 (2011)

Time-resolved mode profile imaging

Experiment: Mitrofanov and Harrington, OpEx (2010)

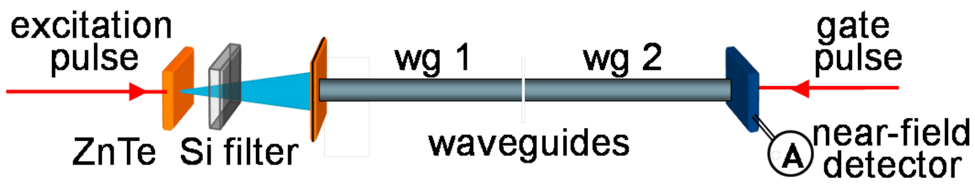


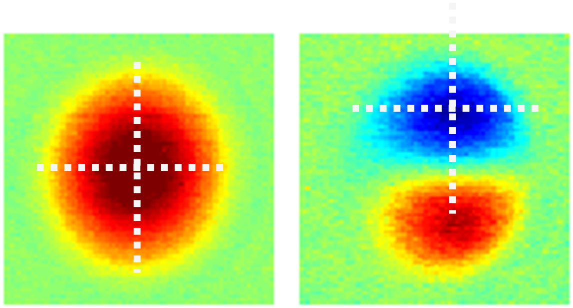
Theory: Miyagi and Kawakami, JLT (1984)

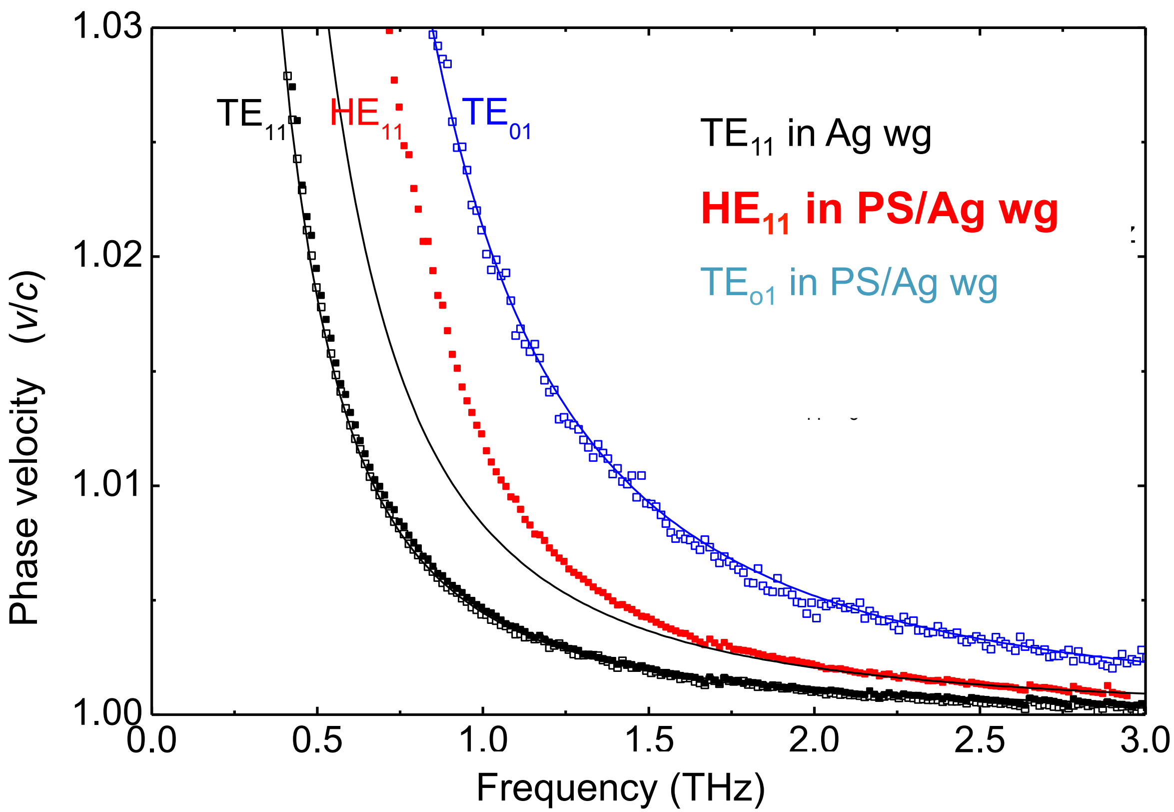
HE$_{11}$

$$E_x(r,\theta) = E_0 \cdot J_0(k_t r), \qquad E_y = 0$$

Dispersion measurements



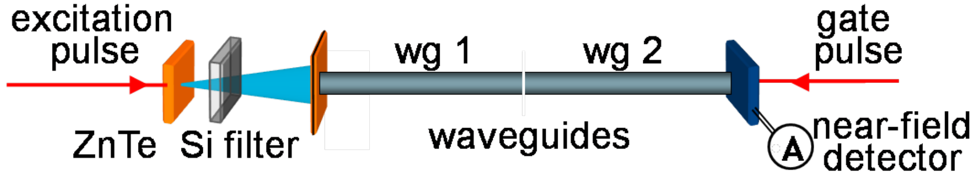


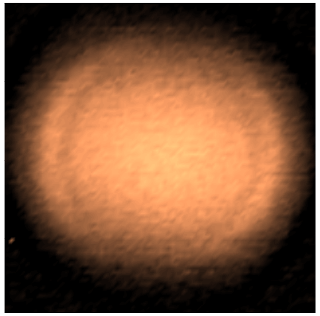


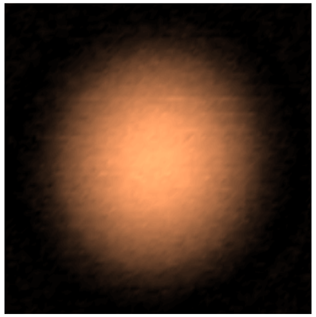
GVD:
< 6 ps/THz/m

Mitrofanov and Harrington, *Optics Express* (2010)

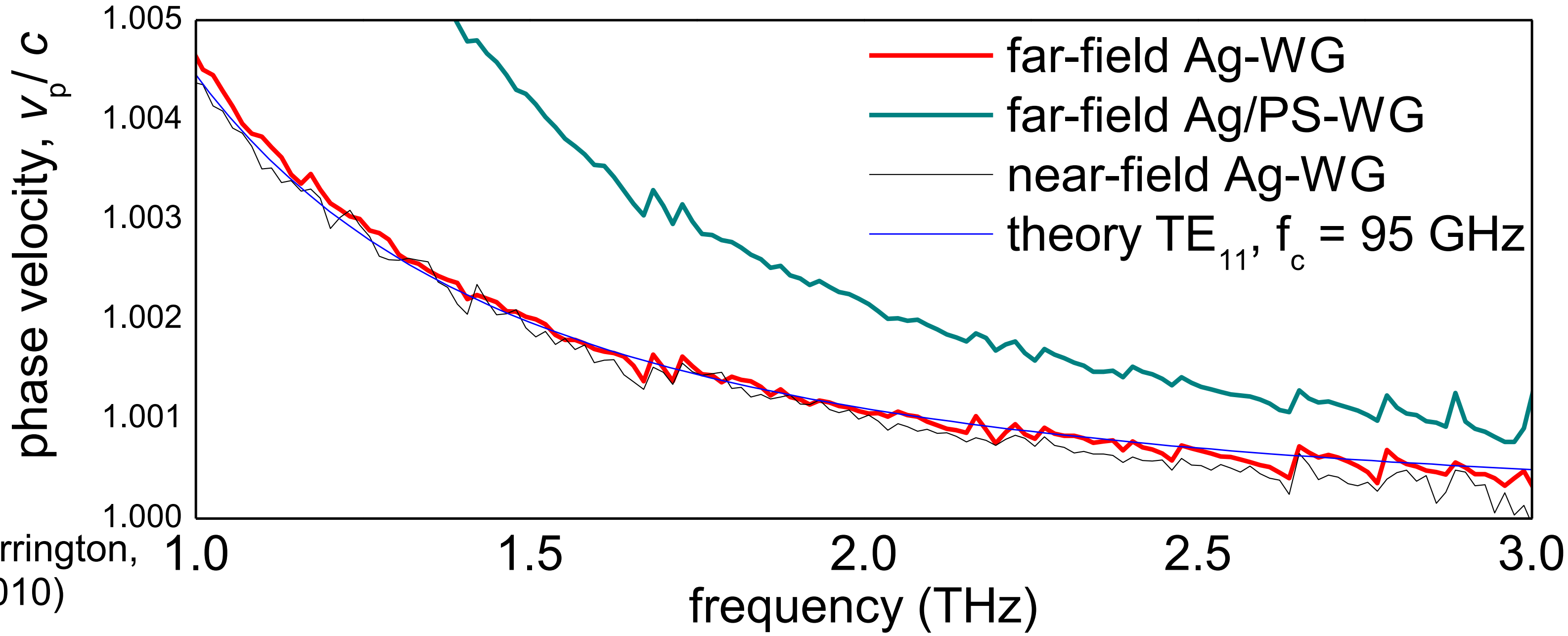
Dispersion measurements





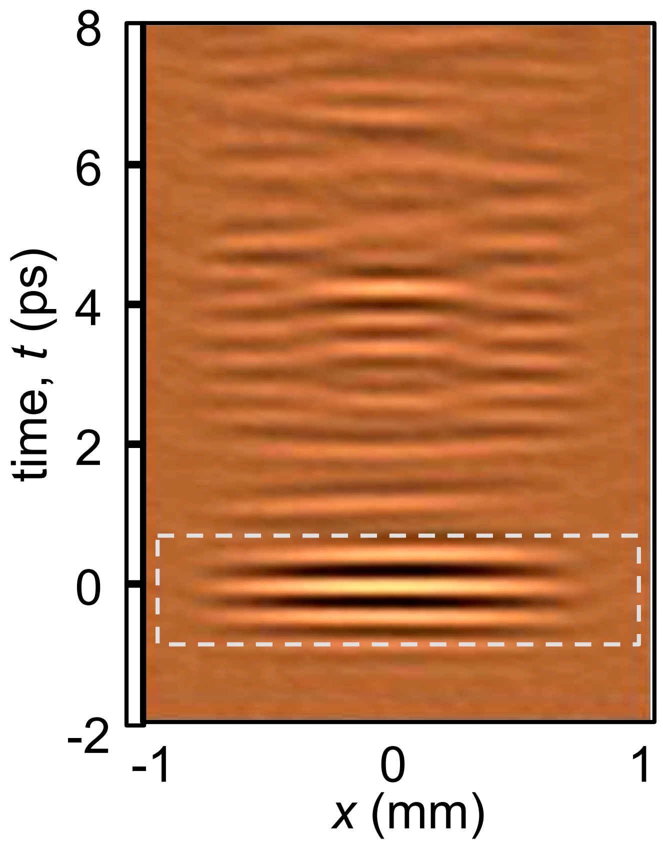


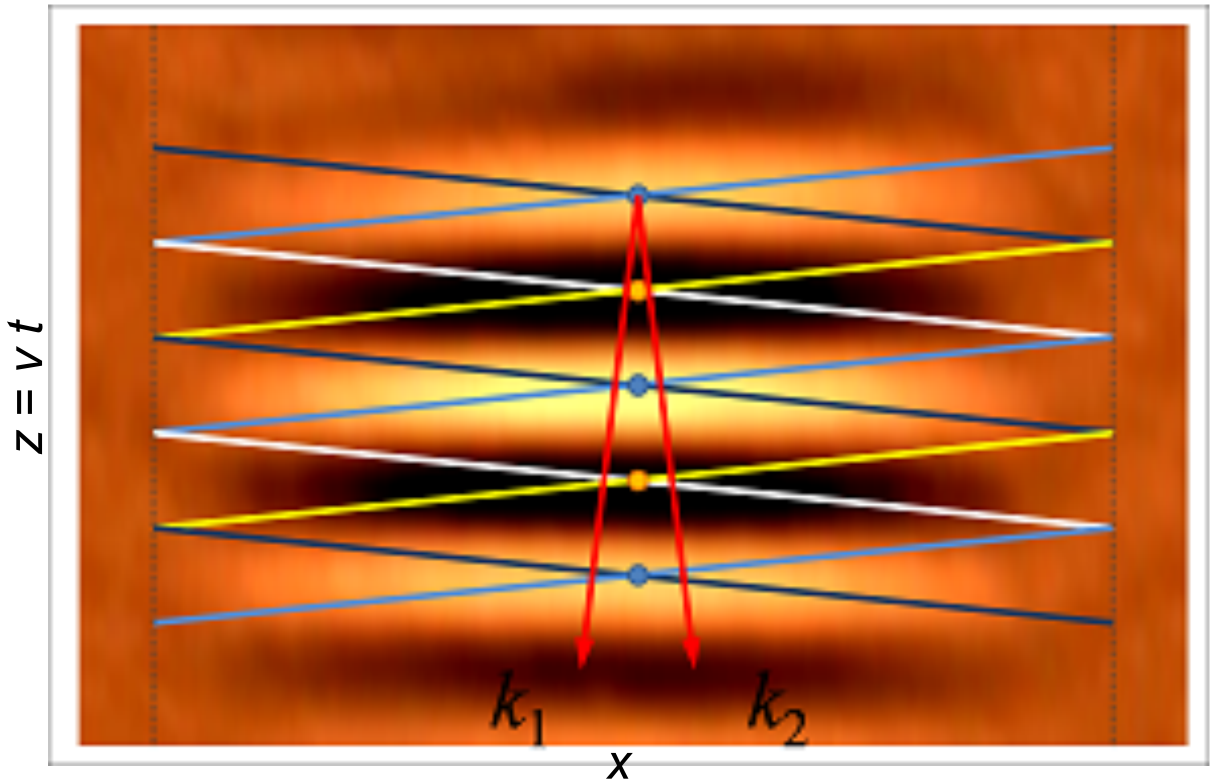
Au WG **TE_{11}** **HE_{11}** **Au/PS WG**



Mitrofanov and Harrington, *Optics Express* (2010)

Dispersion origin

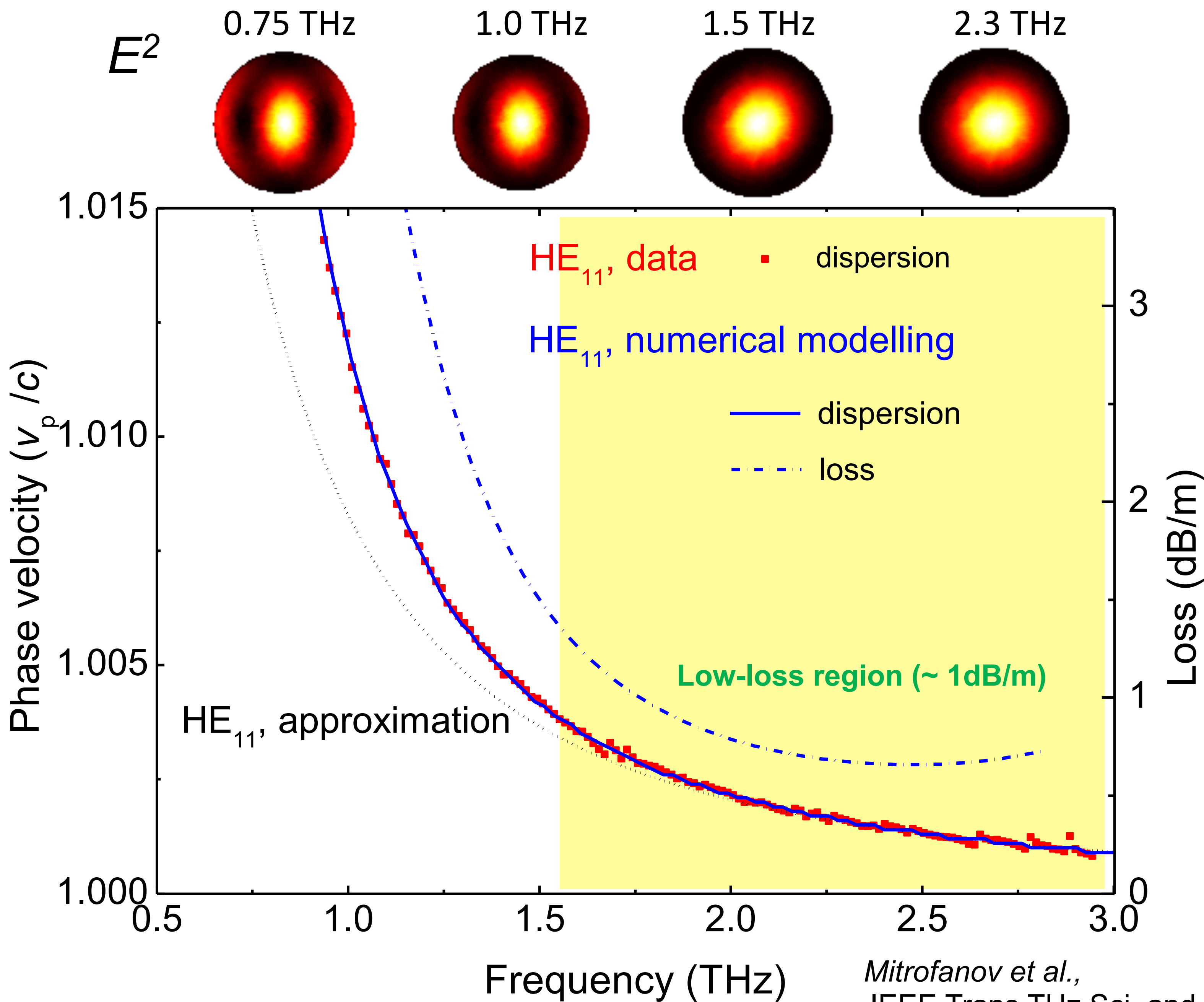




$$k_z = \sqrt{k_0^2 - k_t^2} = k_0 n_{eff}$$

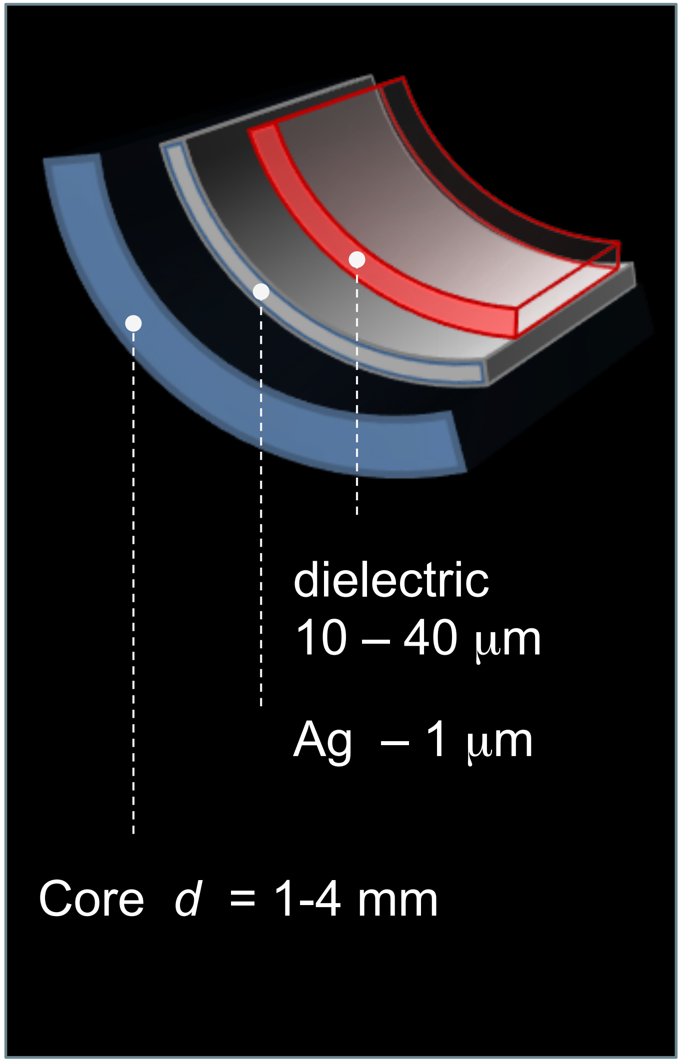
$$n_{eff}(\omega) = \sqrt{1 - \frac{\omega_c^2}{\omega^2}}$$

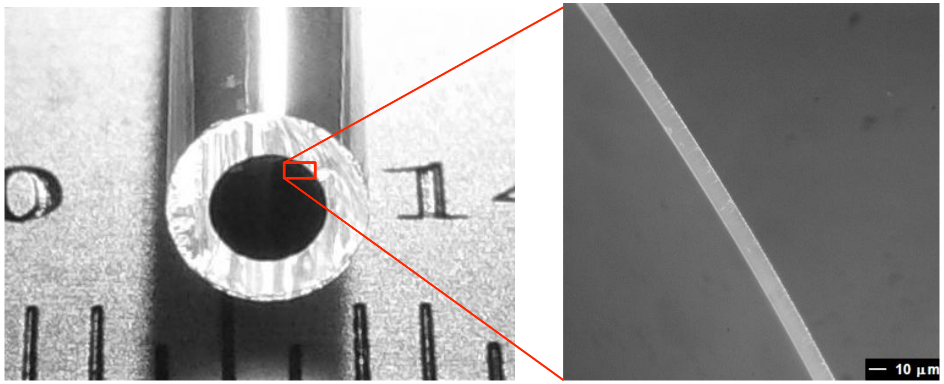
Loss in dielectric-lined waveguides

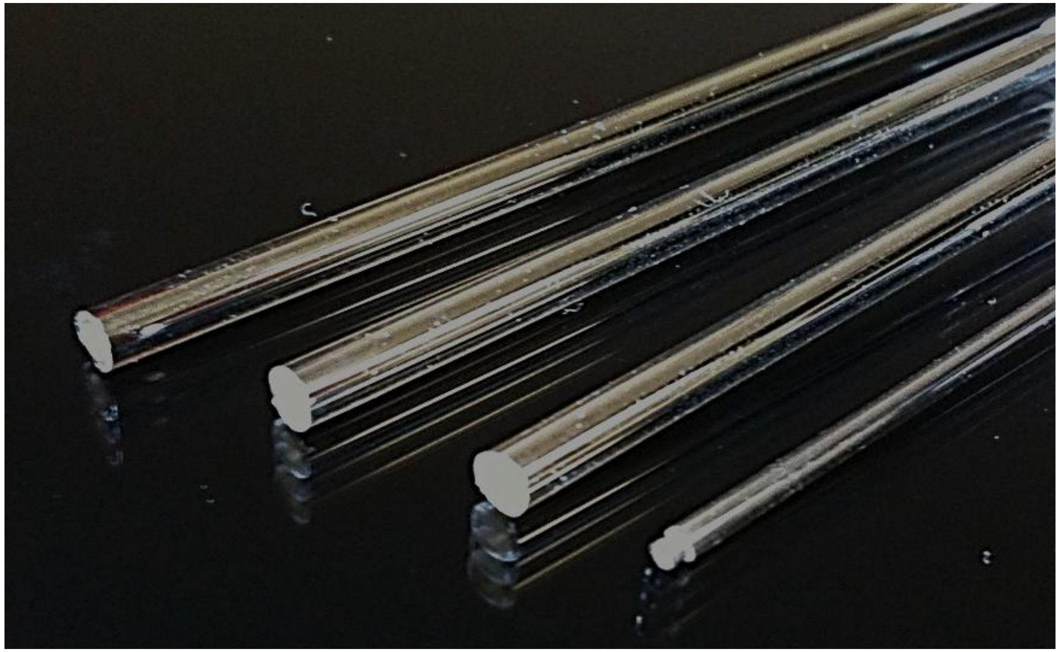


Mitrofanov et al.,
IEEE Trans THz Sci. and Techn. (2011)

Fabrication challenges: Dielectric-lined HMWG





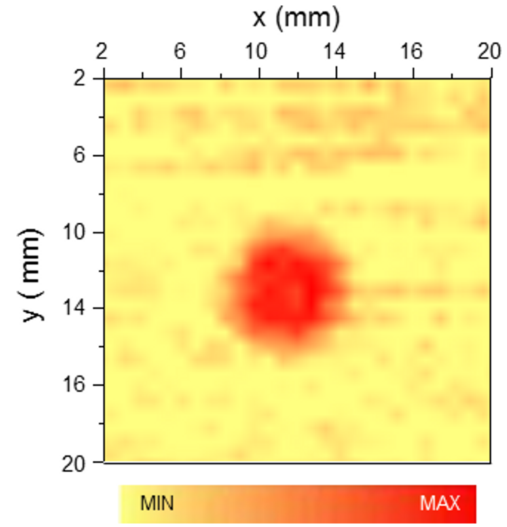


Opt. Lett. **32**, 2945-2947(2007)
Appl. Phys. Lett. **93**, 181104 (2008)
J. Appl. Phys. **104**, 093110 (2008)
Optics Express **18,** 1898 (2010)

Ag/AgI Waveguides - thin dielectric, dominant mode?

Flexible WGs made of 1 mm diam. thin glass tubes with Ag/AgI coatings (1micron):

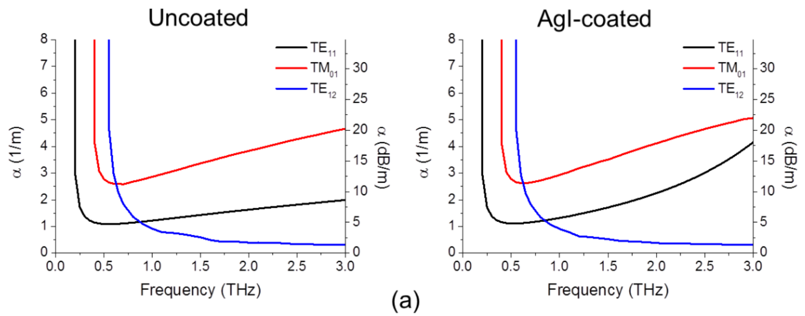
Far-field cw characterisation:
indicated that HE11 can exist in this waveguide at ~2.7THz

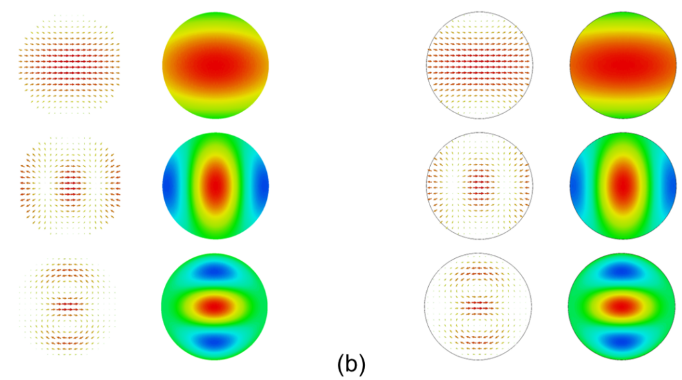


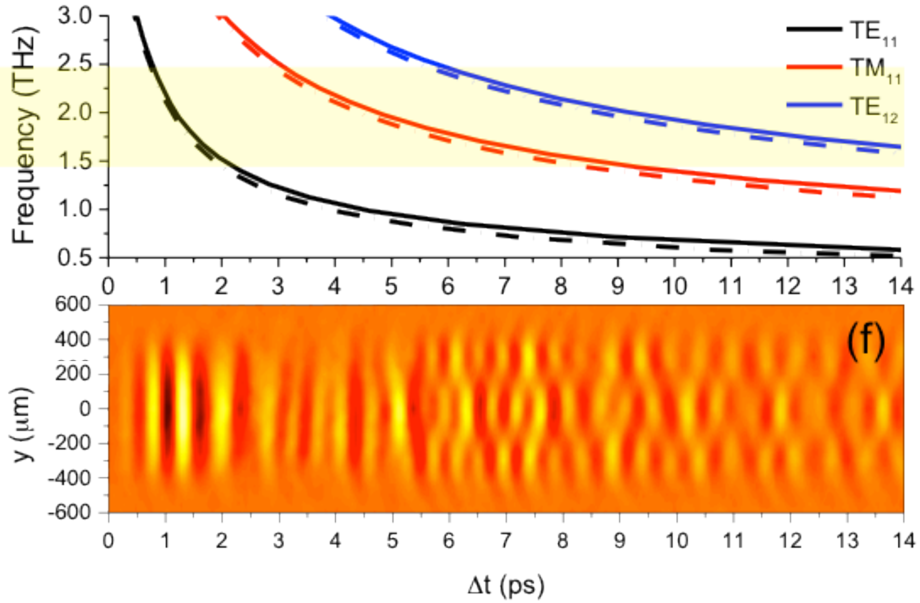
Near-field mode mapping and numerical modelling:

revealed that 1 micron AgI coating is not thick enough;

far-field mode profiles – obscured by mode interference.



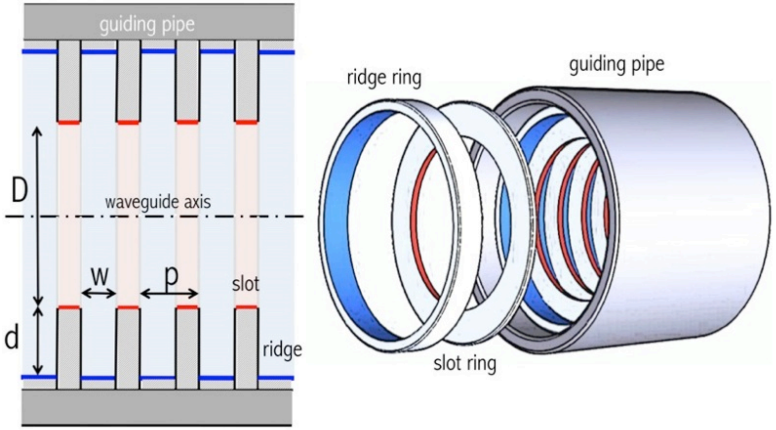




Navarro-Cia et al., JOSA B (2013)

Stacked-ring corrugated waveguides

- Stacked Rings: Overcome the limitations of conventional machining
- Propagate an HE_{11} mode
- Materials choice:
  Aluminum, Brass, Titanium, Stainless Steel, Copper, Molybdenum etc…



E. De Rijk, Rev. Sci. Instr. , Vol. 82, (2011)

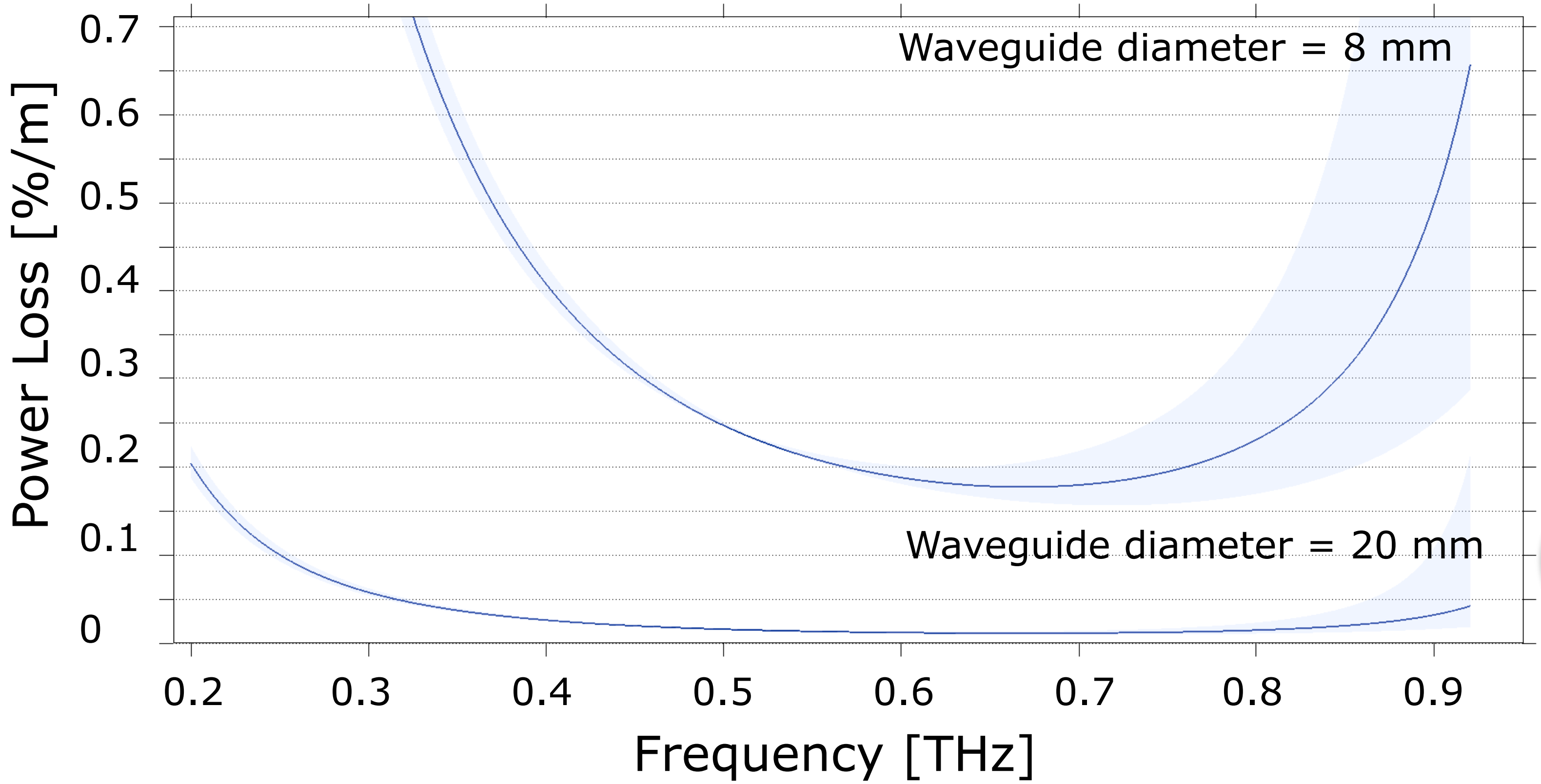
Swissto12
terahertz applications

Corrugated waveguide - Bandwidth tuning

UCL

Parameters:
- Choice of metal: Brass, Titanium, Stainless steel
- Waveguide Inner diameter
- Corrugation design

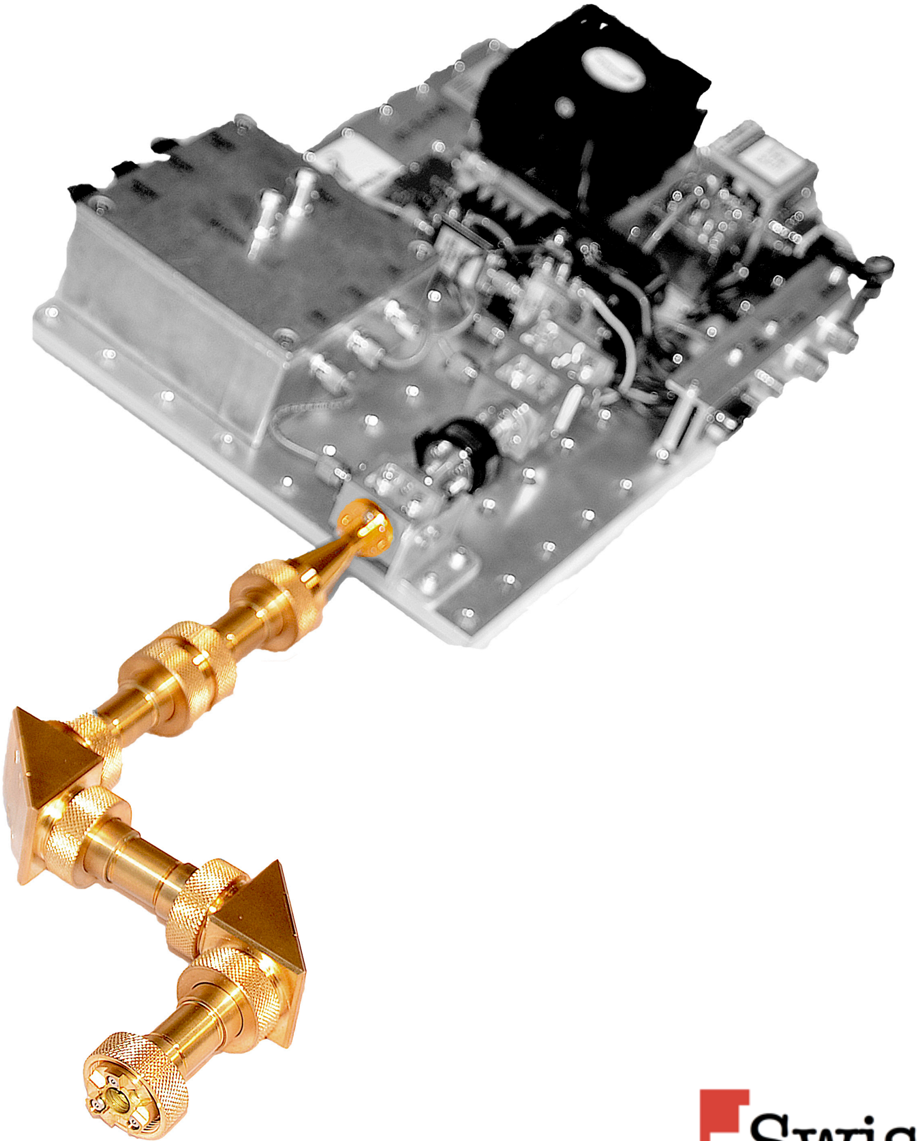
E.g. variation of inner diameter for given corrugation geometry



Swissto12 terahertz applications

Standard Transmission Lines Modules

UCL



Swissto12

terahertz applications

Multimode THz waveguides

Benefits of multimode waveguides:

- Low loss (< 1dB/m)
- Mode quality (linearly polarized, coupling >95% for HE_{11})
- Use of higher order modes (TE_{01})
- Reduced chromatic dispersion
- System simplicity

Applications:

- Imaging systems (beam quality, system simplicity)
- Communications/power delivery
  (low-loss, beam quality, dispersion, bandwidth)

Potential applications:

- Spectroscopy (challenges: mode suppression)
- Communication (challenges: modal dispersion, MIMO)

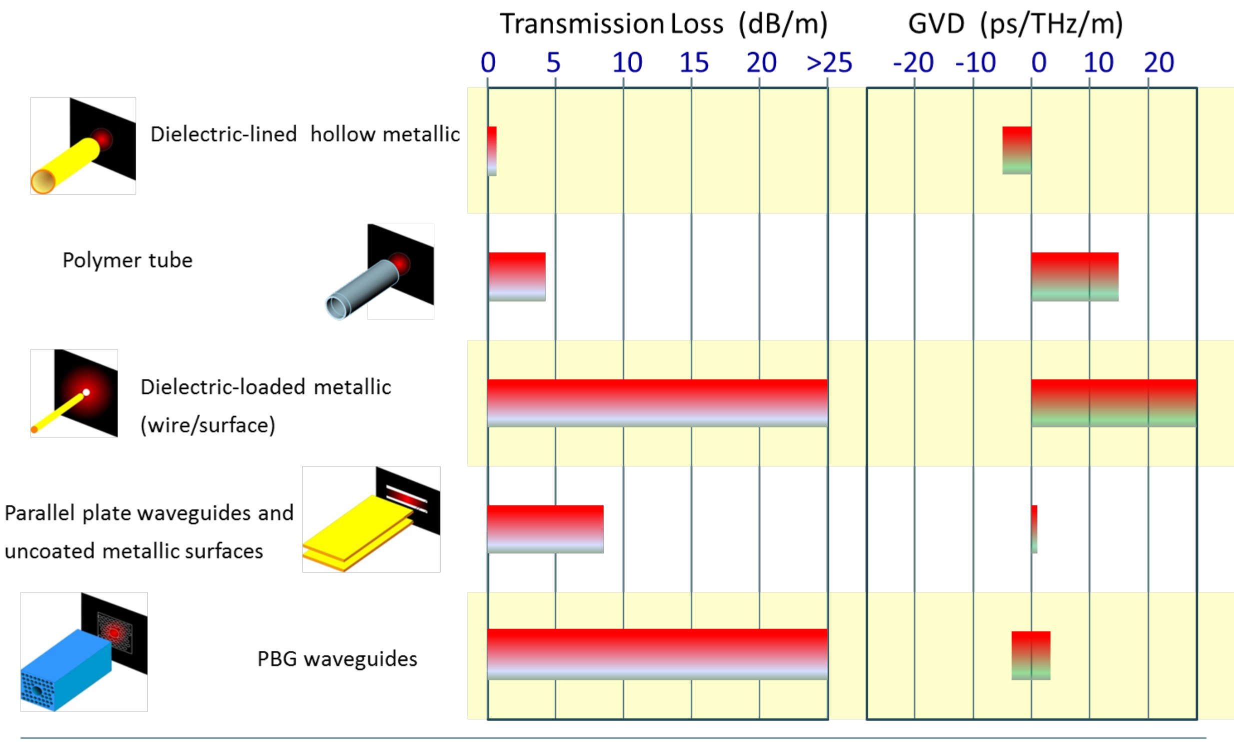
Dielectric-lined hollow metallic waveguides

Mode quality
(coupling >95%)

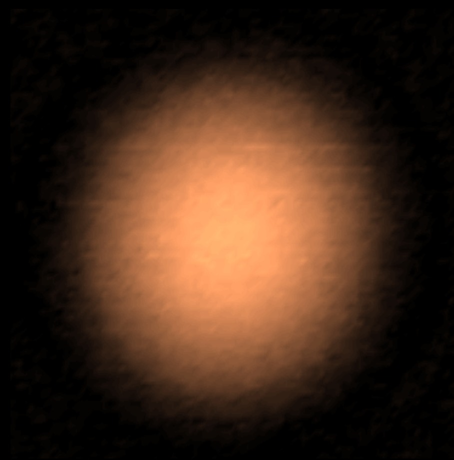
Low loss
(<1 dB/m)

Analytical approximation
(modelling)

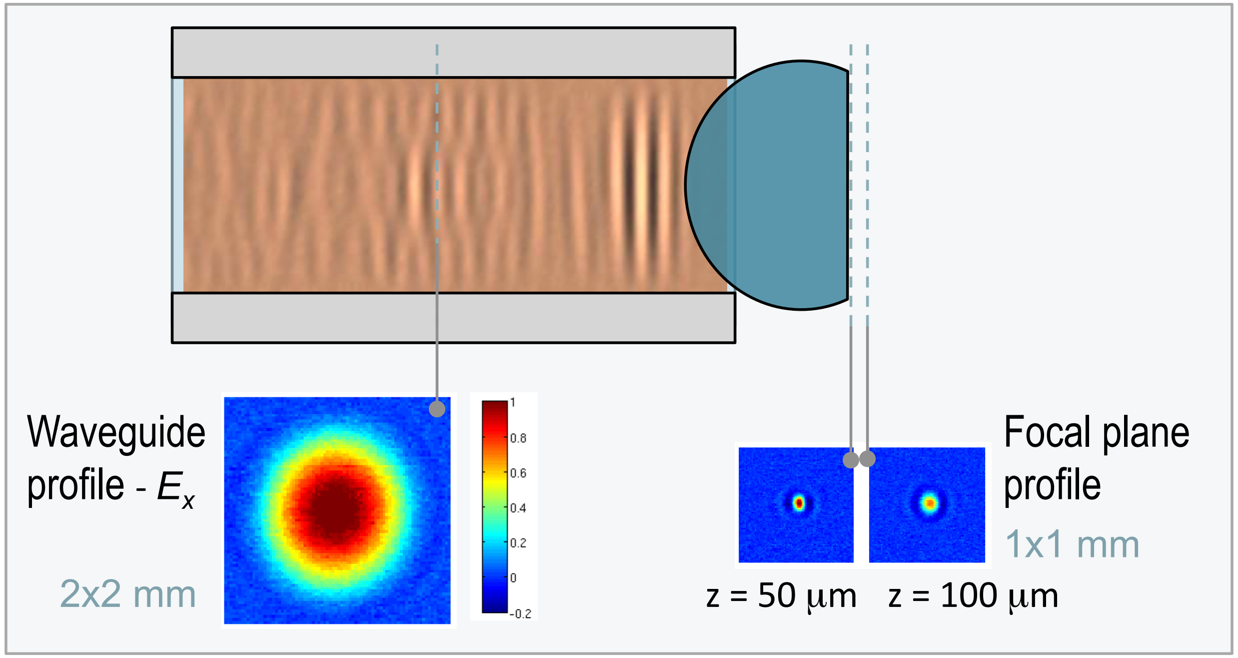
Bandwidth
(> 1THz)

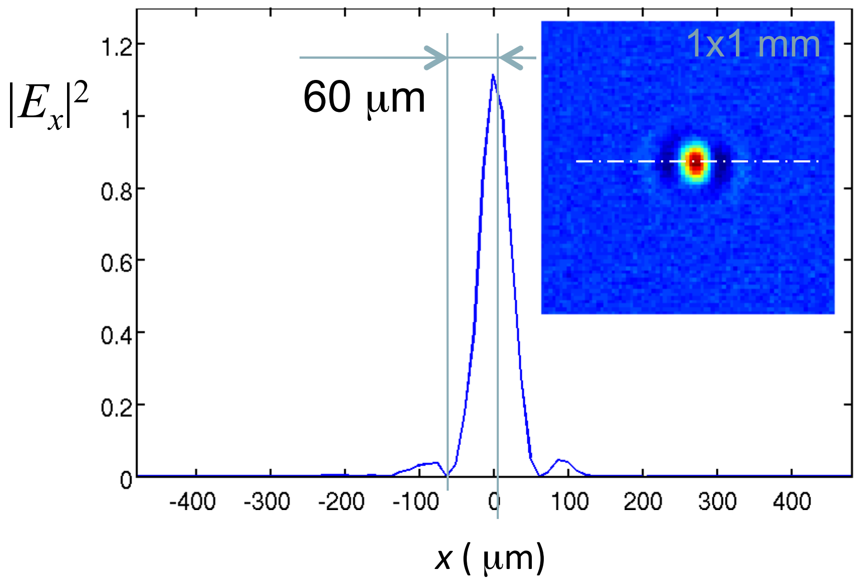


Waveguide applications and integration



Waveguides for imaging applications – beam quality



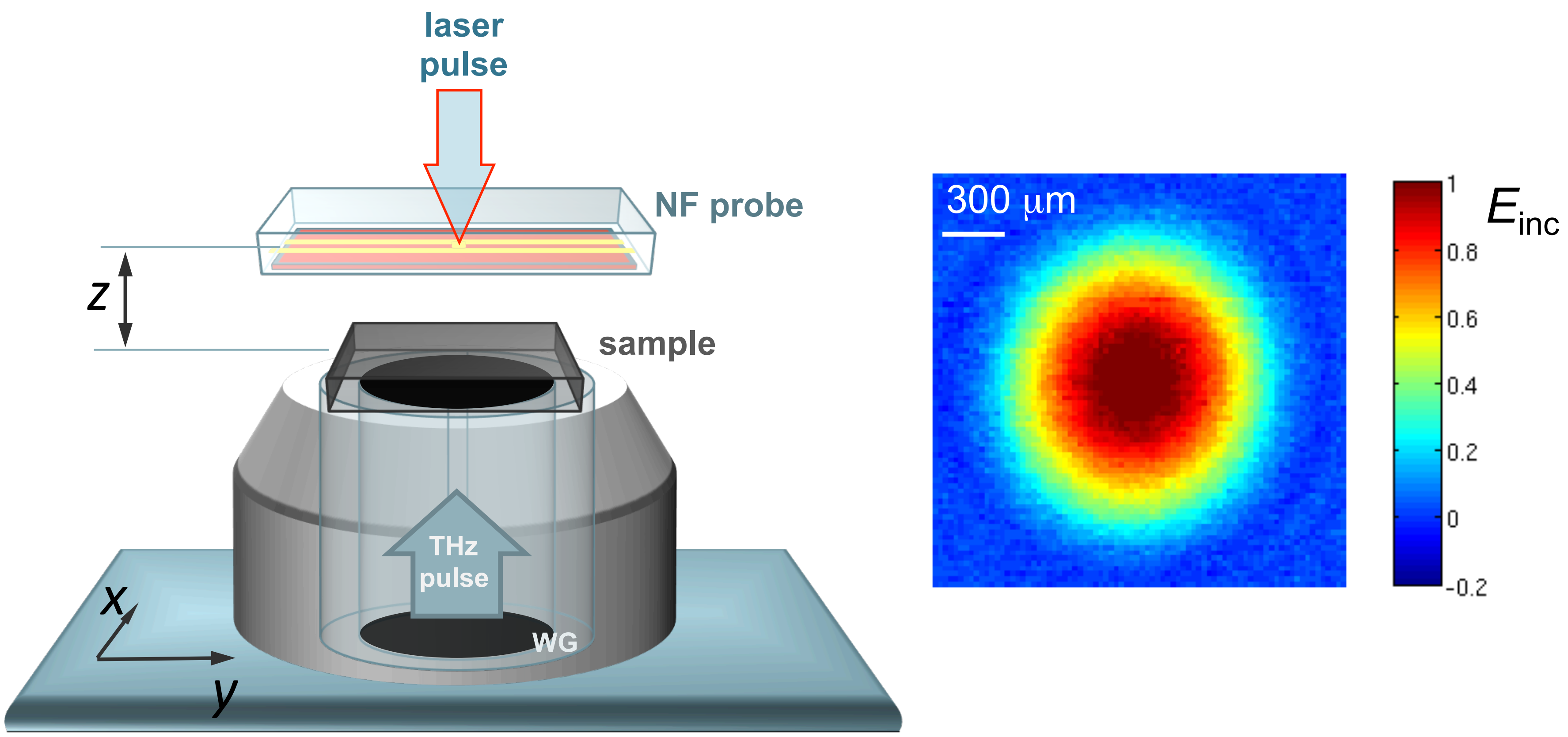


Point-spread function:

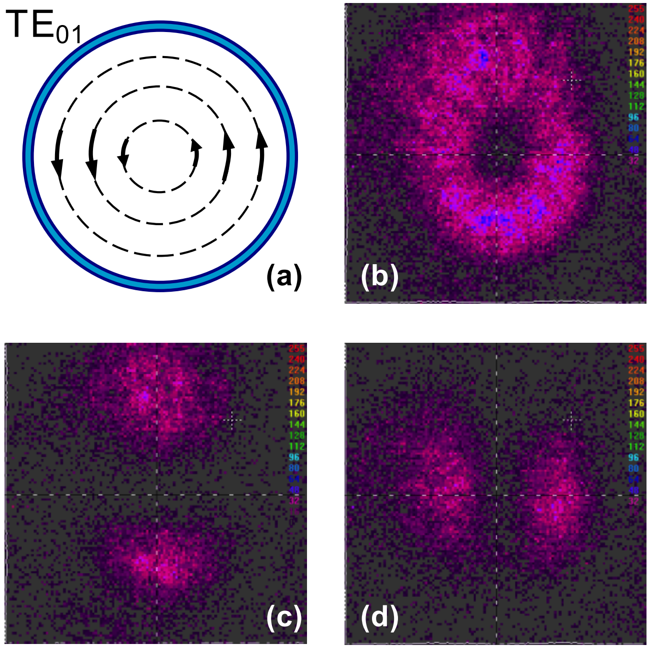
HE_{11} mode

λ_c = 140 μm

Waveguides for near-fild imaging applications

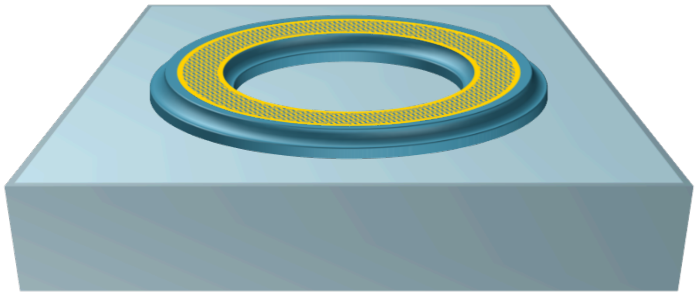


Waveguide integration

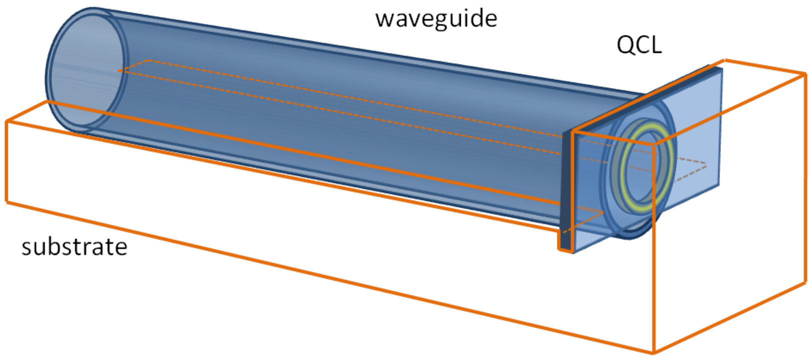


Mitrofanov et al., *APL.* **93**, 181104 (2008)

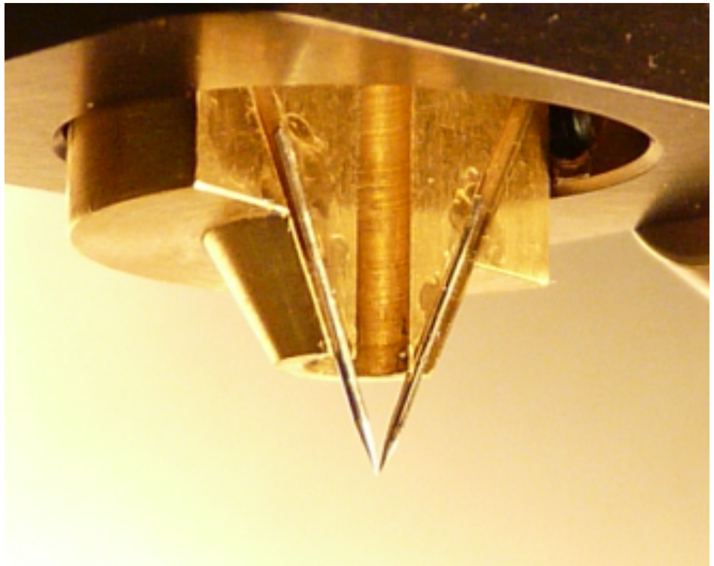
Micro-ring QCL

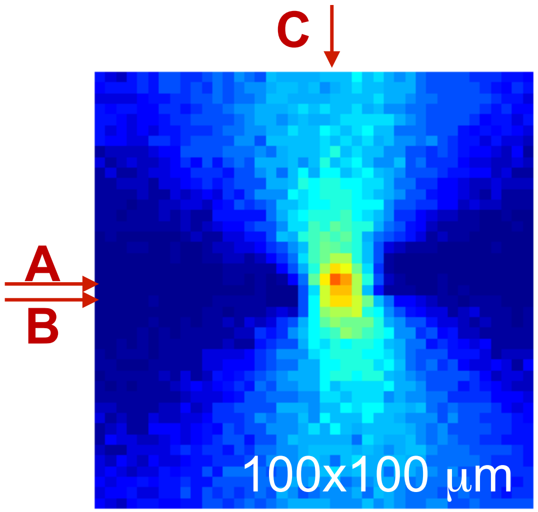


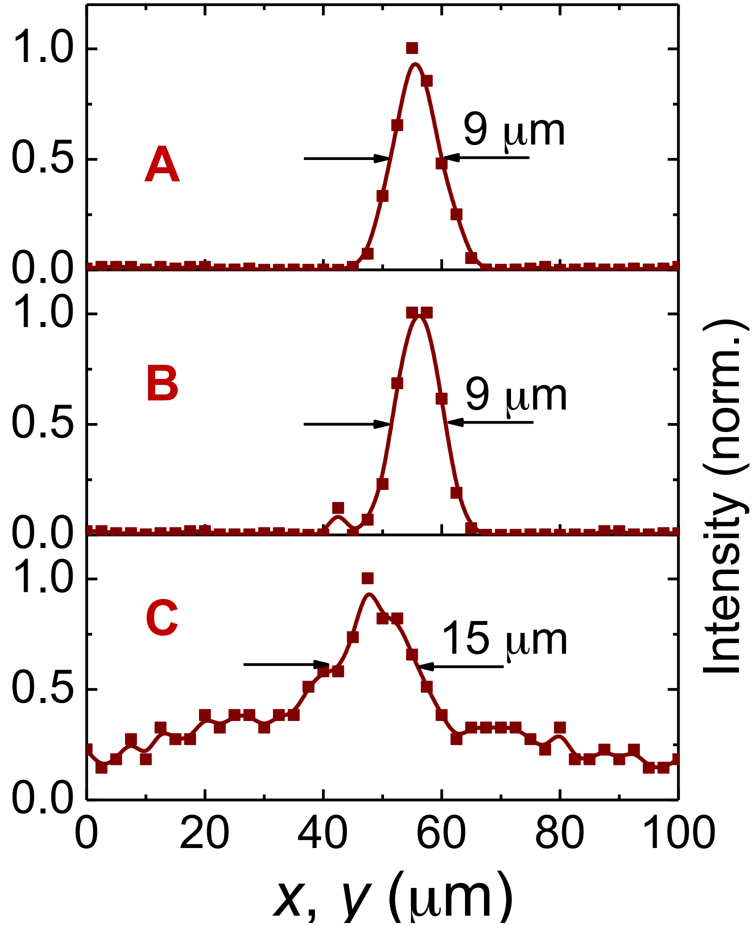
Vitiello *et al*., *Opt. Express* **19**, 1122 (2011)



Broadband THz confinement – surface waves

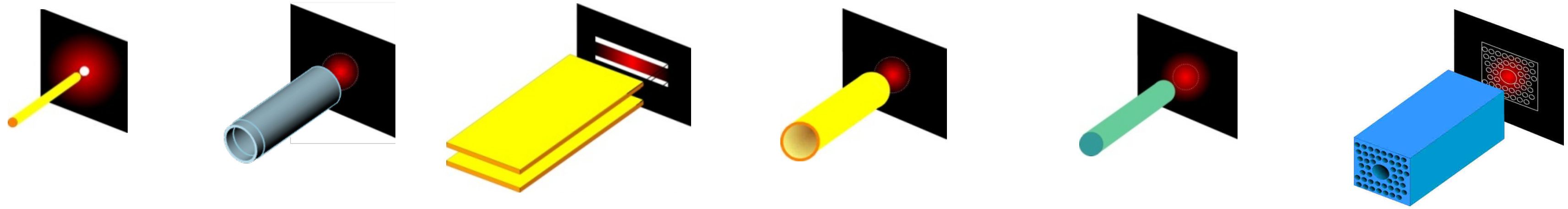




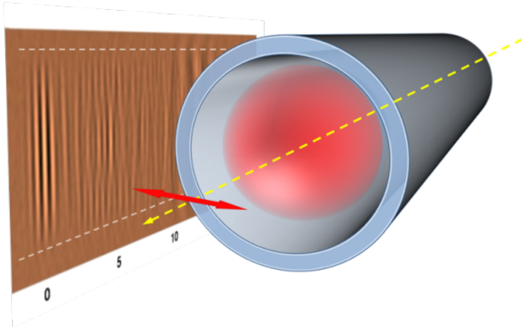


Mitrofanov *et al.*, Opt. Express **20**, 6197 (2012)

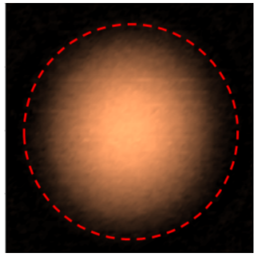
Conclusions – THz waveguide technologies



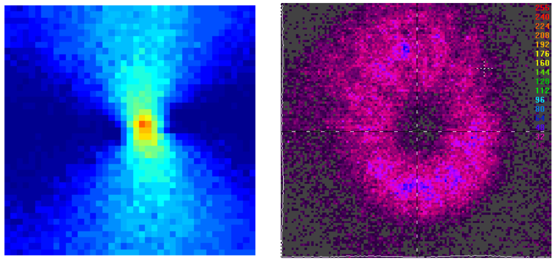
Waveguide probing:
near-field imaging
time-resolved characterization,



Dielectric-lined hollow metallic waveguides
Low losses, low dispersion, coupling



Application and integration of THz waveguides



Miguel Navarro-Cia, Richard James, Anibal Fernandez
UCL

James Harrington, Bradley Bowden, Carlos Bendt
Rutgers University

Miriam Vitiello, Alessandro Tredicucci
NEST, CNR

Harvey Beere, David Ritchie, Themis Mavrogordatos
Cambridge

Alessandro Macor, Emil De Rijk
SWISSto12

THE ROYAL SOCIETY

EPSRC
Pioneering research and skills