Intracavity-pumped, terahertz parametric oscillators and their applications

Dr Nils Hempler, Business Development Manager, M Squared Lasers

Presentation Outline

- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - Security / Defense
- Open Innovation

Presentation Outline

- **Introduction to M Squared Lasers**
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - Security / Defense
- Open Innovation

M Squared Lasers

History

- Founded in 2006
- Focus: Next-generation lasers and photonic systems
- Dependable Innovation
- Experience: spans CW to fs, DUV to THz
- Headquarters: Glasgow, Scotland
- State of the art facility: 15,000sqft
- Core Team of 50 Employees
- Fastest Growing Company in Scotland in 2012

M Squared Lasers

The Team

Delivering dependable innovation...

Expertise

- R&D
- Manufacturing
- Control systems
- Service and Support

Mr. Calum Brown
Construction and Installation

Mr. Kevin Shao
Processor Board Design

Mr. Bill Miller
Electronic Design

Dr. Graeme Malcolm
Photonic Design

Mr. Bill Handyside
Construction and Installation

Mr. Richard Western
PCB Design

Mr. Trevor Patterson
Software Design

Dr. Gareth Maker
Photonic Design

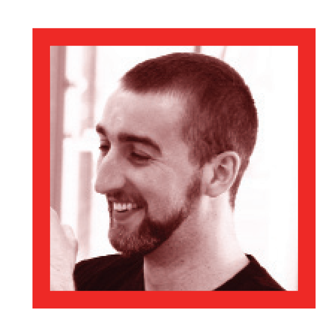
Mr. Daniel Aitken
Construction and Installation

Mr. Simon Roper
DSP Software Development

Dr. Simon Munroe
Mechanical Design

Miss Yvonne Samson
Customer Liaison

Dr. David Armstrong
Marketing



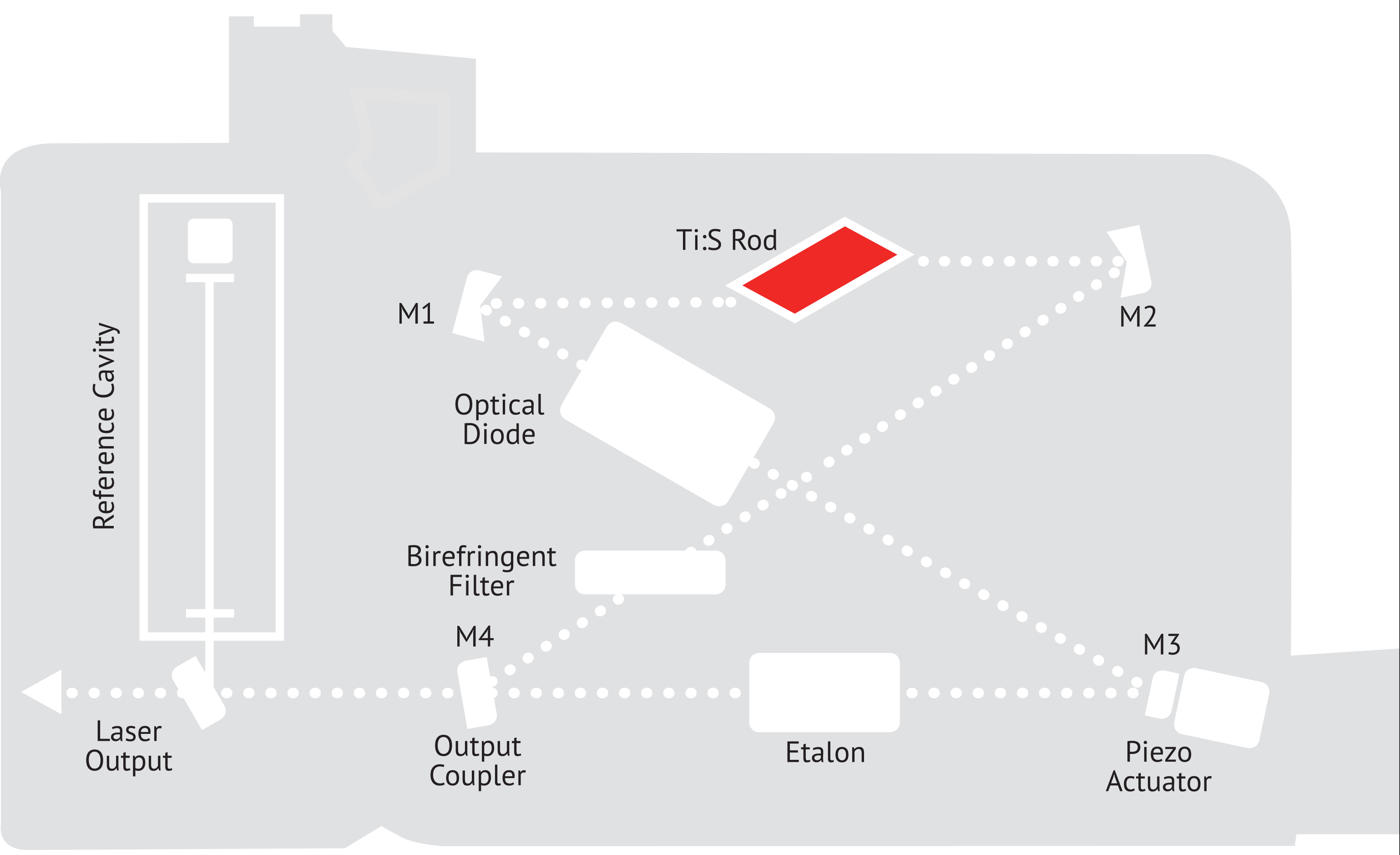
Mr. Euan Cochrane
User Interface Design

Dependable Innovation

It’s in our Design

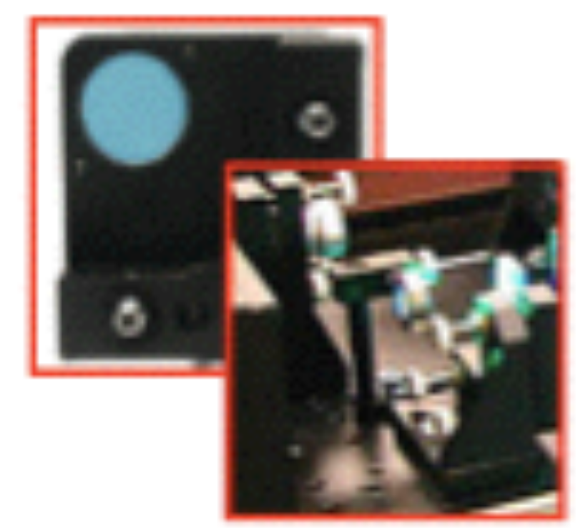
Ultra-compact, turnkey, reliable laser designs, with industry-leading performance

- ‘InvarianT™’ alignment-free, drift-free opto-mechanical technology
- Novel sealed monolithic housing
- Active and passive temperature stabilization
- ICE-BLOC photonic control modules



"InvarianT" brings stable drift-free alignment

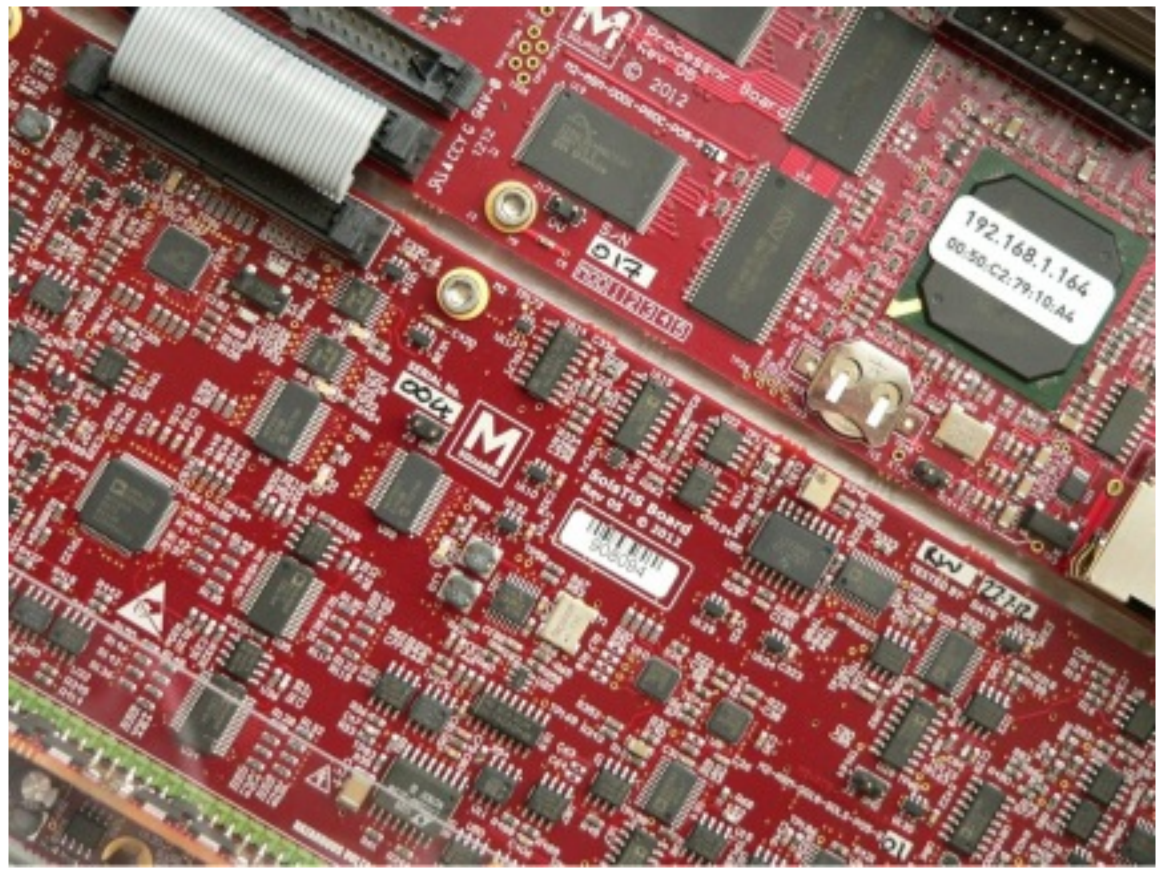
InvarianT
InvarianT optical mount 
Alignment free, no-tweak design (factory 'set & forget')
Drift free, low thermal sensitivity (proprietary design, materials)
Low-stress optic retention User focuses on experiment, not laser maintenance

Traditional 'Ball+Spring'
 Example 'ball & spring' mounts typical of competing Ti:S designs.
Requires periodic realignment by user
Spring constant ages, temperature sensitive ⇨ drift
Optics typically retained via point pressure ⇨ strain
User must realign periodically ⇨ maintenance time

Foundations

ICE brings state of the art electronics

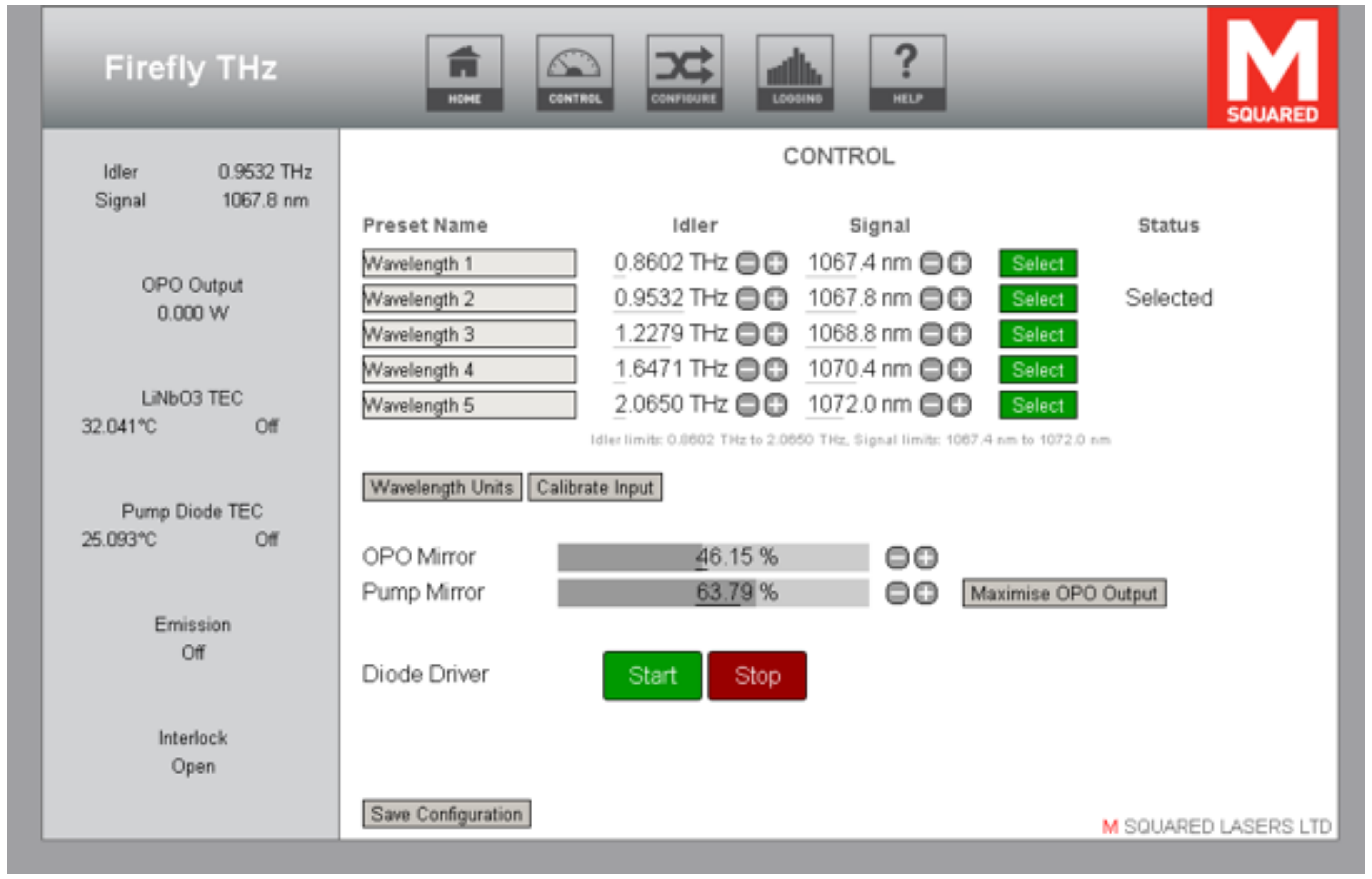
- Instrument Control by Ethernet
- Higher bandwidth, lower noise
- Easy interfacing through IP
- Remote control and monitoring
- Easy upgrade



Firefly THz

ICE brings superior simple control

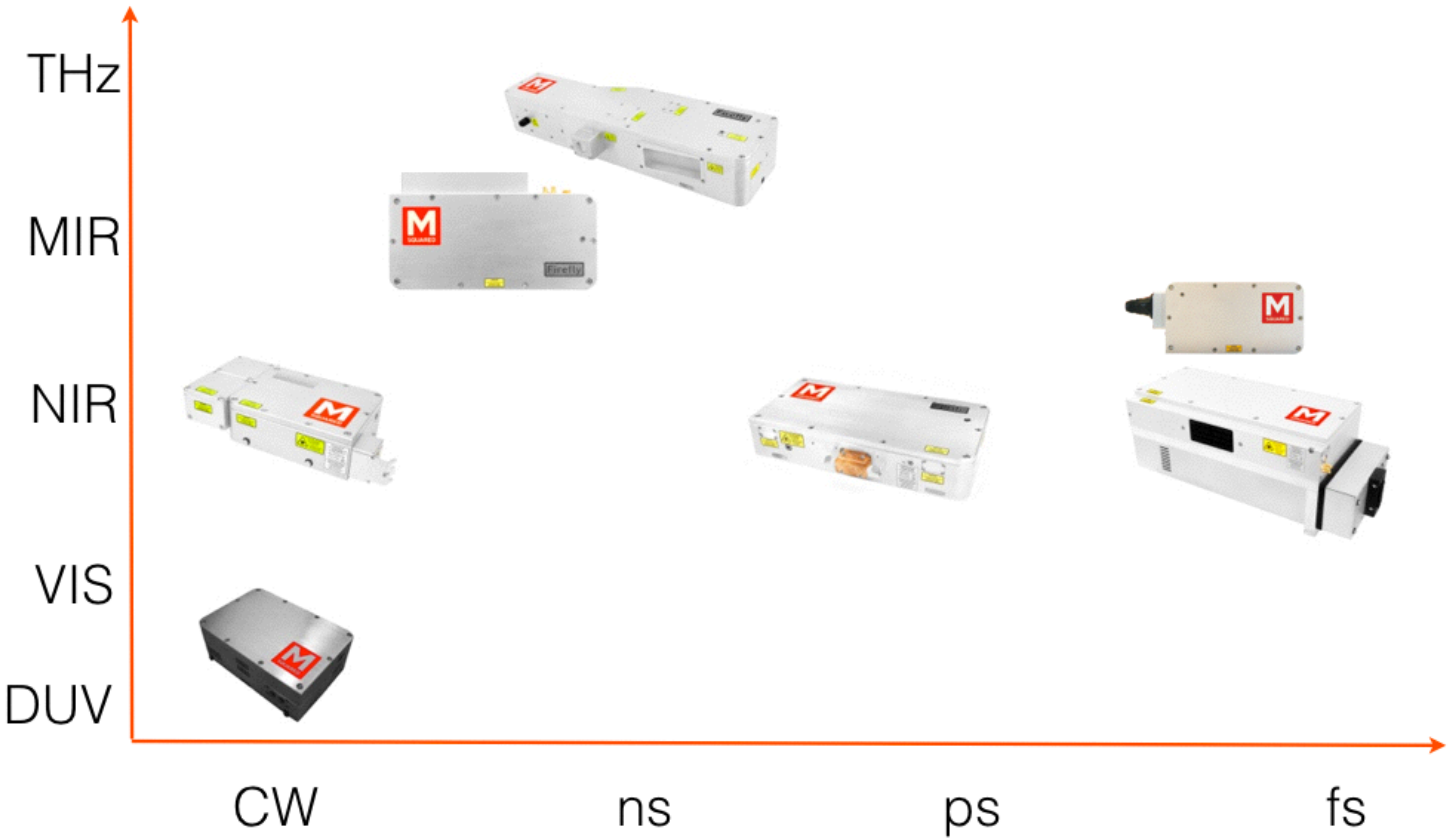
- Simple User Interface
- Control through web-browser
- No more drivers!
- Software, UI and netbook included
- Control across the lab or across the World!



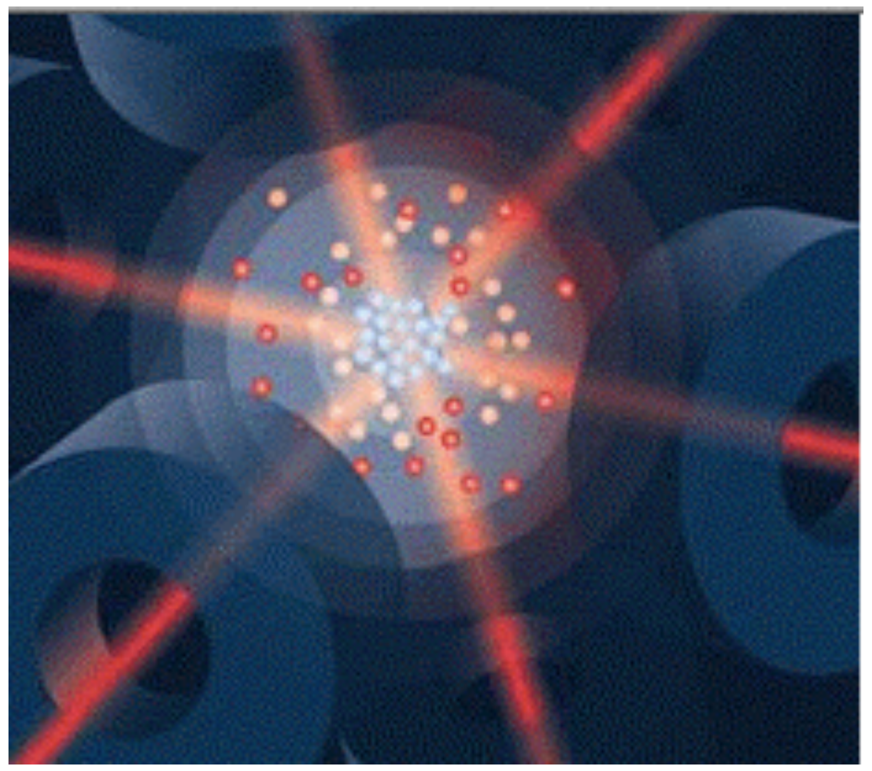
M
SQUARED

Product Range

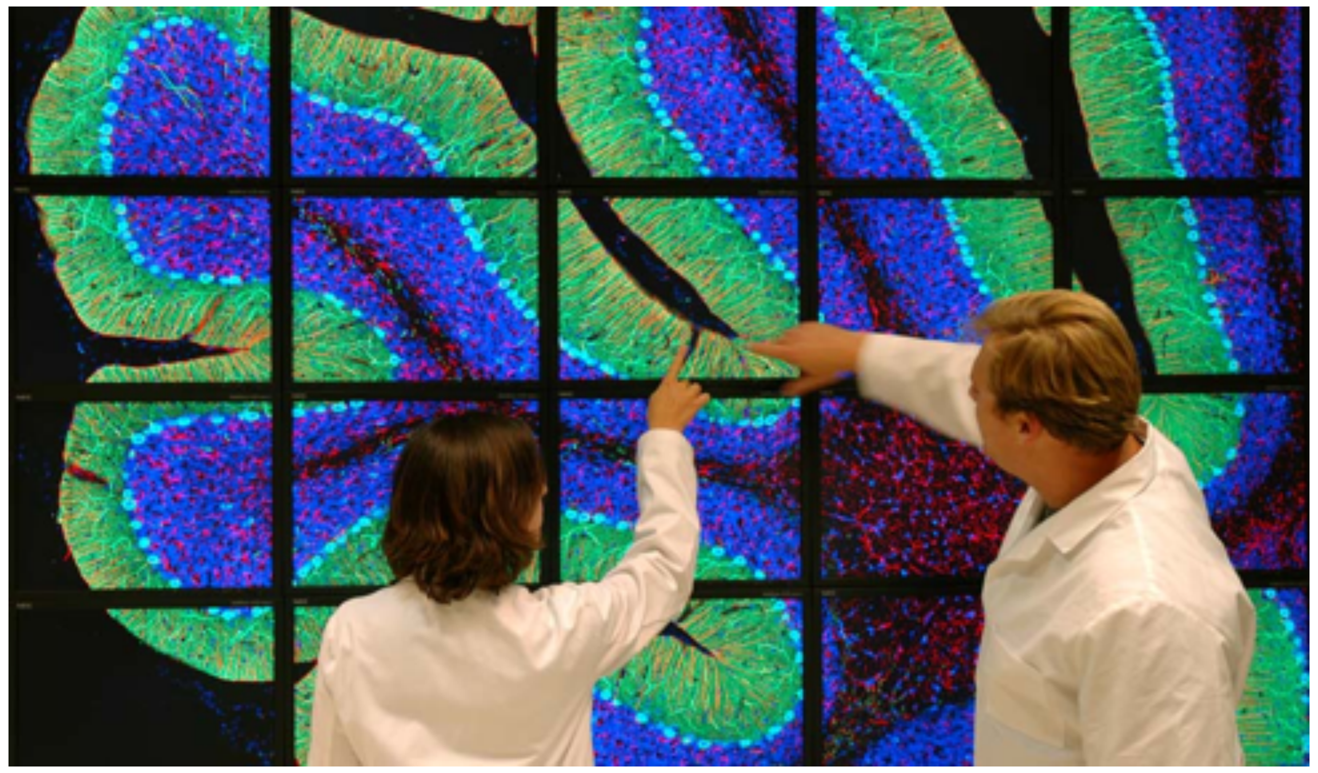
Covering the Spectrum



Exploring Diverse Sectors



Atom Optics



Biomedical

Threat Detection

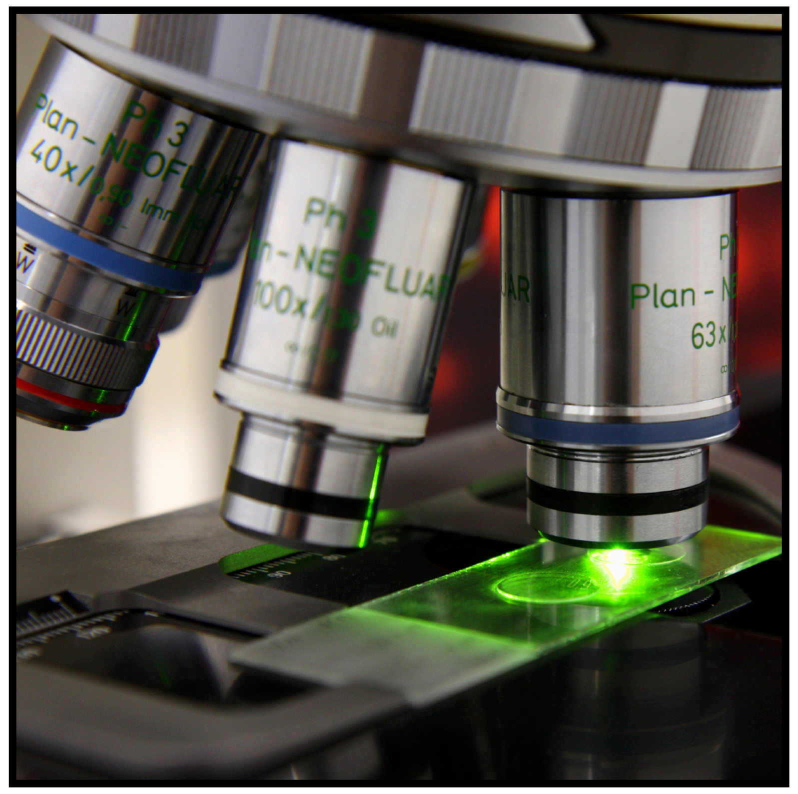
Industrial Monitoring

Presentation Outline

- Introduction to M Squared Lasers
- **Pulsed Terahertz Parametric Oscillator**
  - **Theory and System Design**
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - Security / Defense
- Open Innovation

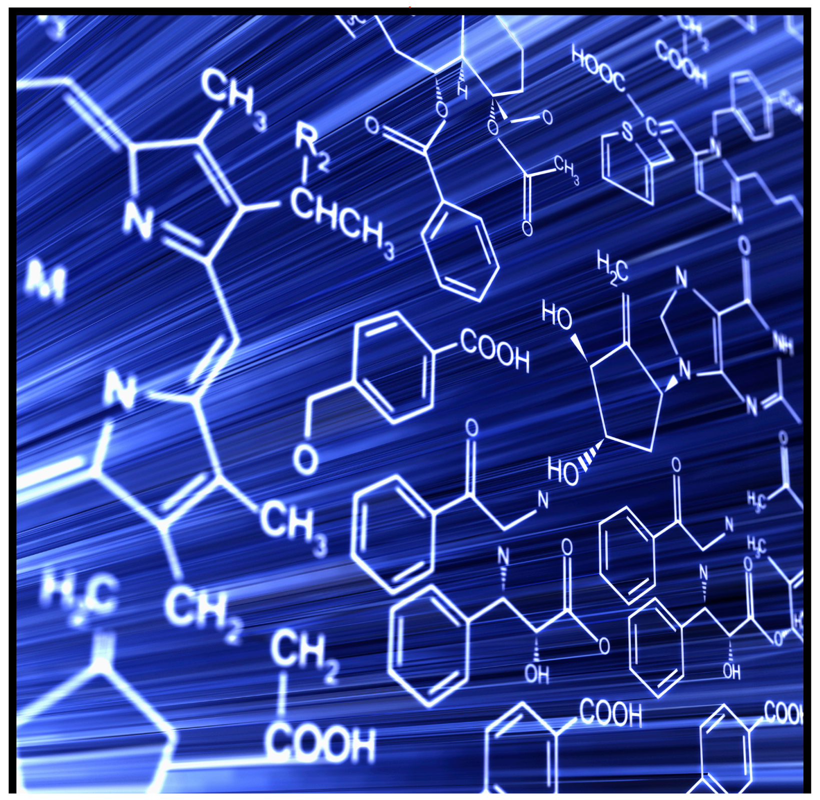
Exploring THz Applications

Security



Bio-Photonics

NDT / Quality Control



Spectroscopy

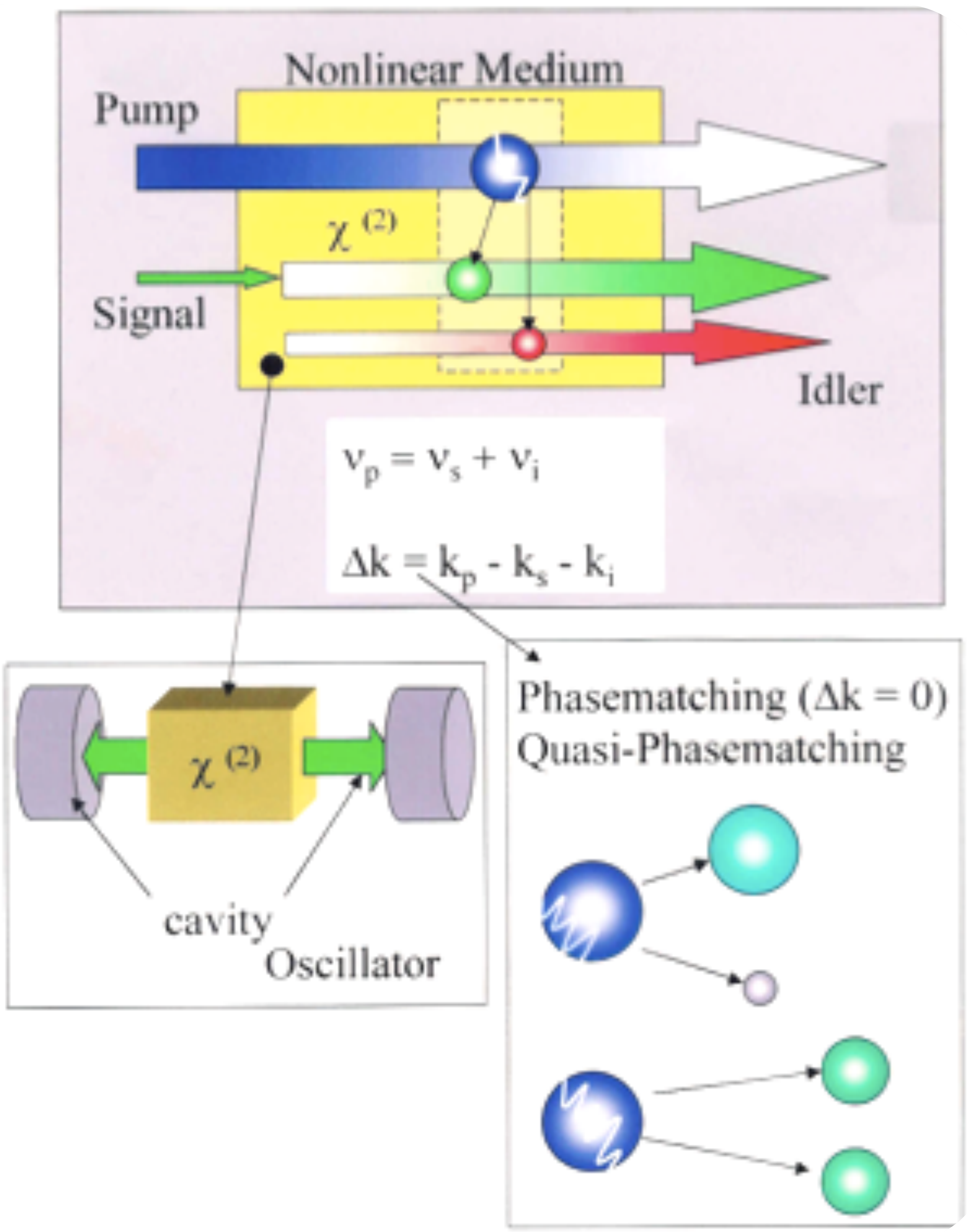
Pharmaceutics

Motivation

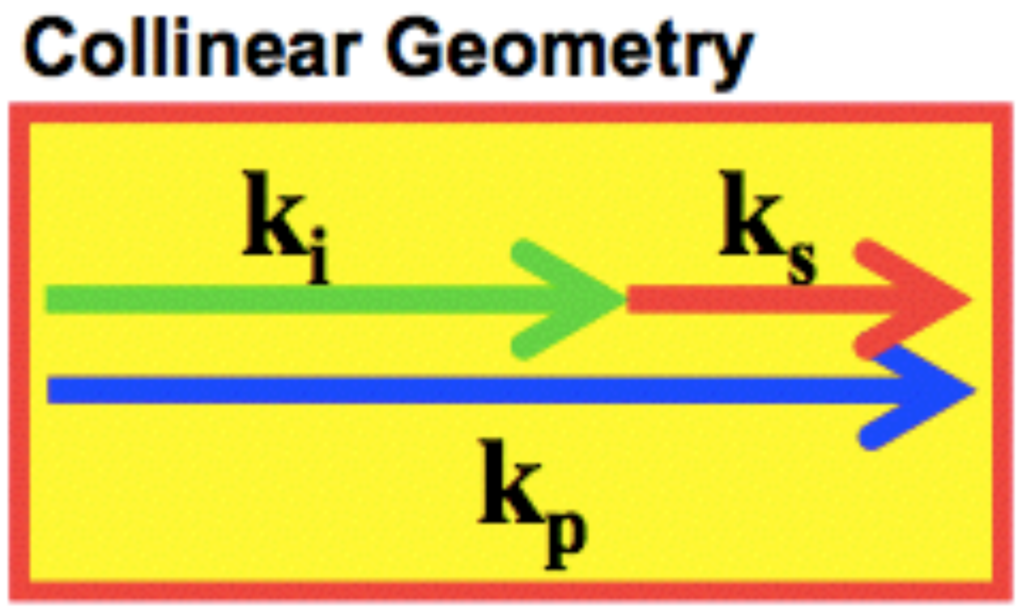
	THz OPO	Diode laser DFG	CO_2-pumped FIR gas	fs laser + Auston switch
High peak power?	Yes (ns pulses)	No (CW)	No (CW)	Yes, but low power/ nm
High average power?	Yes (with efficient NLO conversion)	No (>10nW typ.)	Yes (>50mW typ.)	No (>1µW typ.)
Wide tuning?	Yes (>1-3THz typ.)	Yes (>1-3THz typ.)	No (many discrete lines)	Broadband (>2THz typ.)
Narrow linewidth?	Yes (<50GHz typ.)	Yes (few 100MHz)	Yes	No: broad pulse
Easy to use?	Yes: compact, air-cooled, stable	No: turnkey systems not available	No: large, water-cooled, can drift	No: fs laser, delay line, FFT required)

Parametric Generation

Collinear



$$P = \varepsilon_0 \chi^{(2)} E^2$$

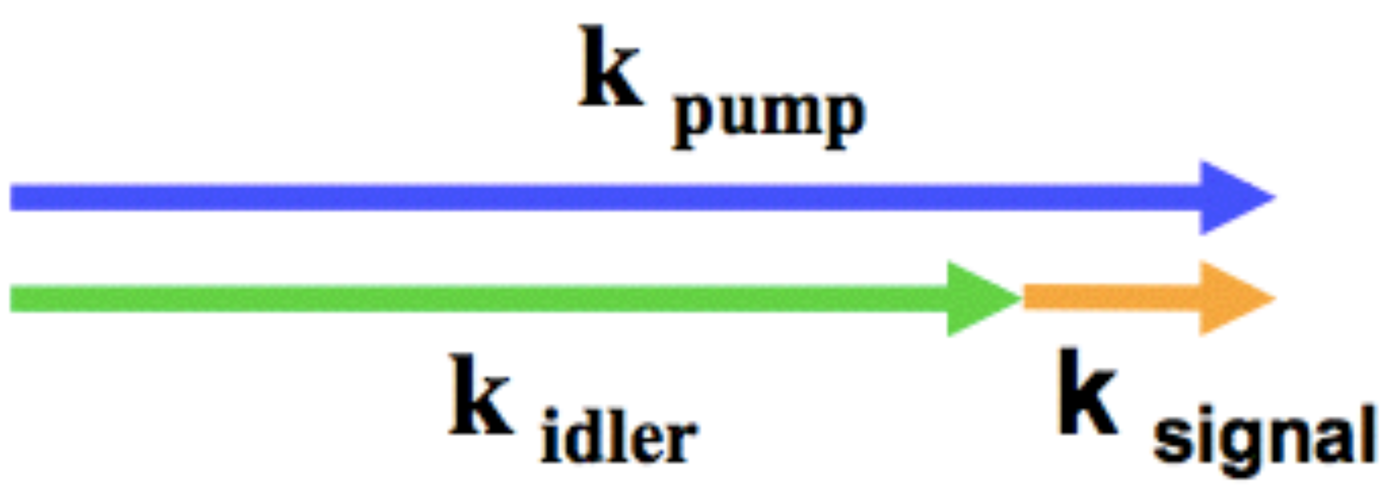


Parametric Generation

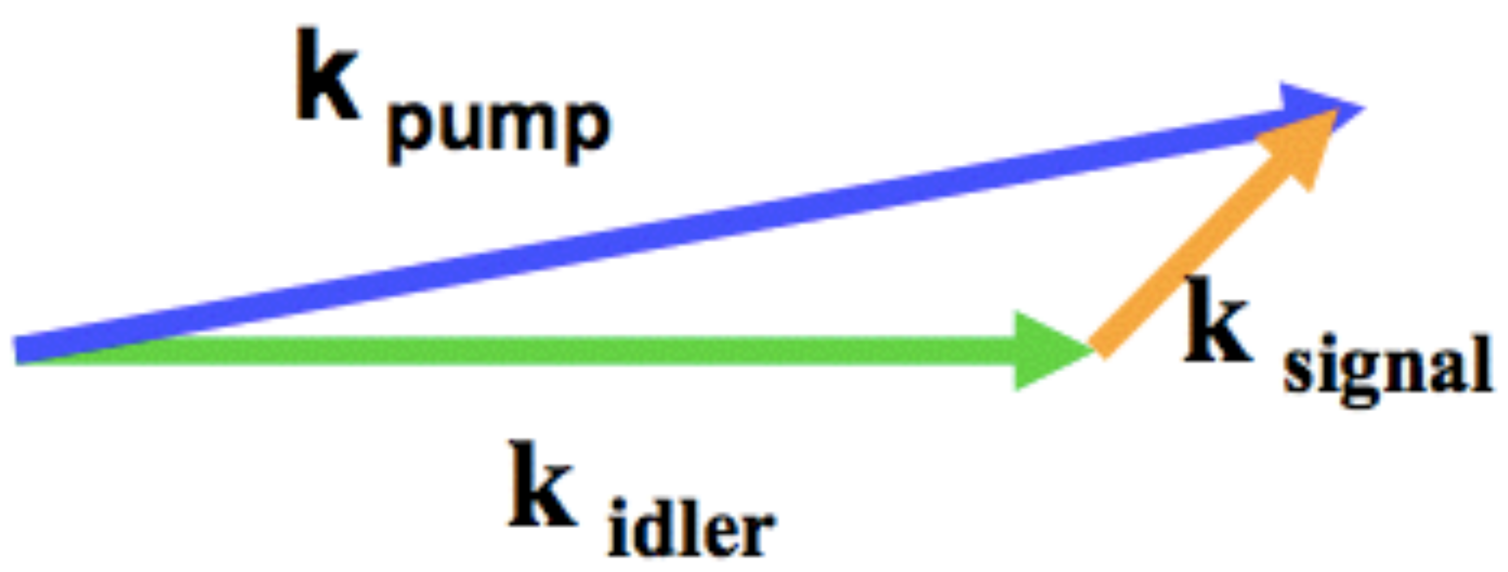
Non-collinear

Highly non-collinear phase-matching allows direct THz generation

$$k_{pump} = k_{idler} + k_{signal}$$



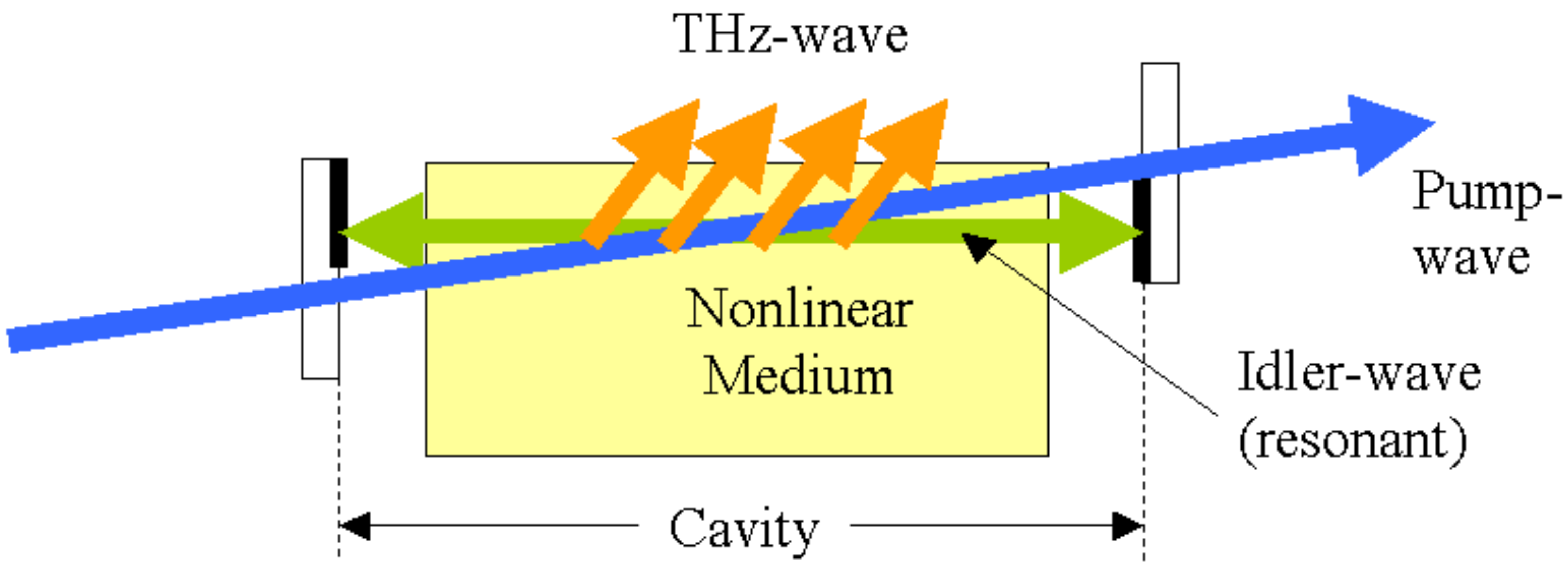
$$\underline{k}_{pump} = \underline{k}_{idler} + \underline{k}_{signal}$$

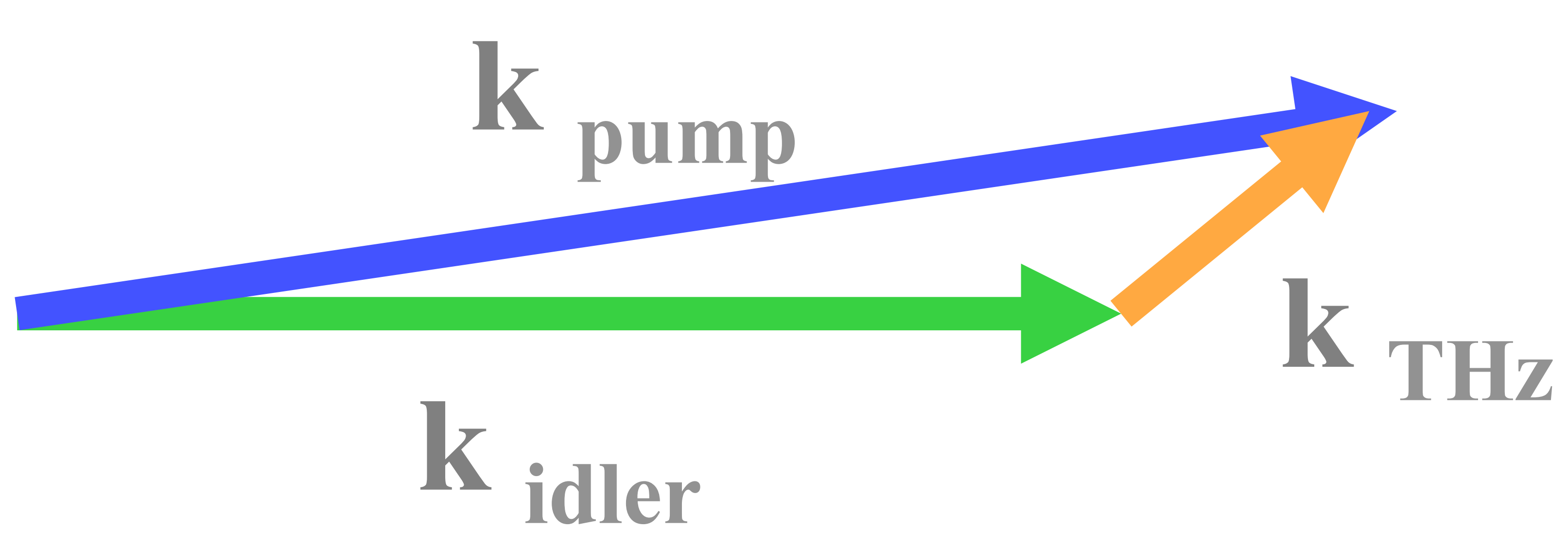


Parametric Generation

Non-collinear

Highly non-collinear phase-matching allows direct THz generation





THz Parametric Oscillator

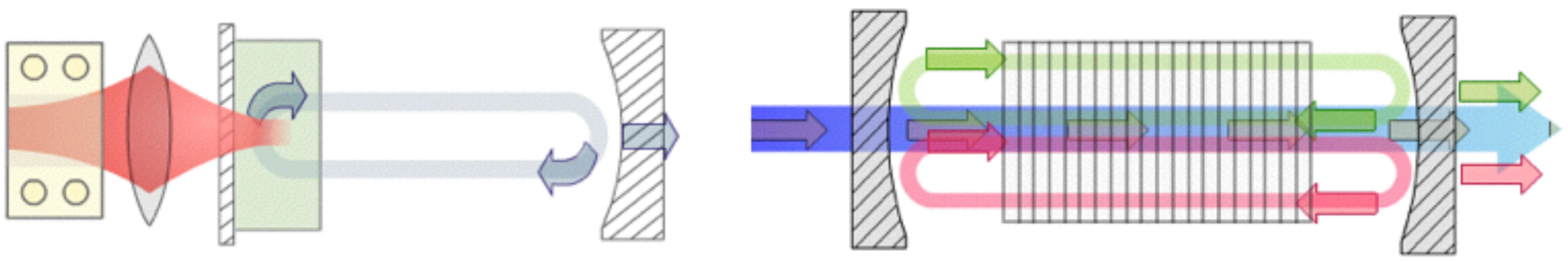
Compact high peak power terahertz source

- Low quantum efficiency: η_{signal} / η_{pump} x 100 ~ 1%
- Available nonlinear media (e.g. LiNbO3) highly absorbing for THz waves
- THz must exit medium rapidly to minimise absorption
- Rapid exit reduces parametric gain
- Need gain medium with high nonlinear coefficient (deff)
- LiNbO3 suitable candidate, but has polariton resonance; deff: 125pm/V (18pm/V)

THz Parametric Oscillator

Pump Geometry

Extracavity Pumping Requires High Primary Pump Power



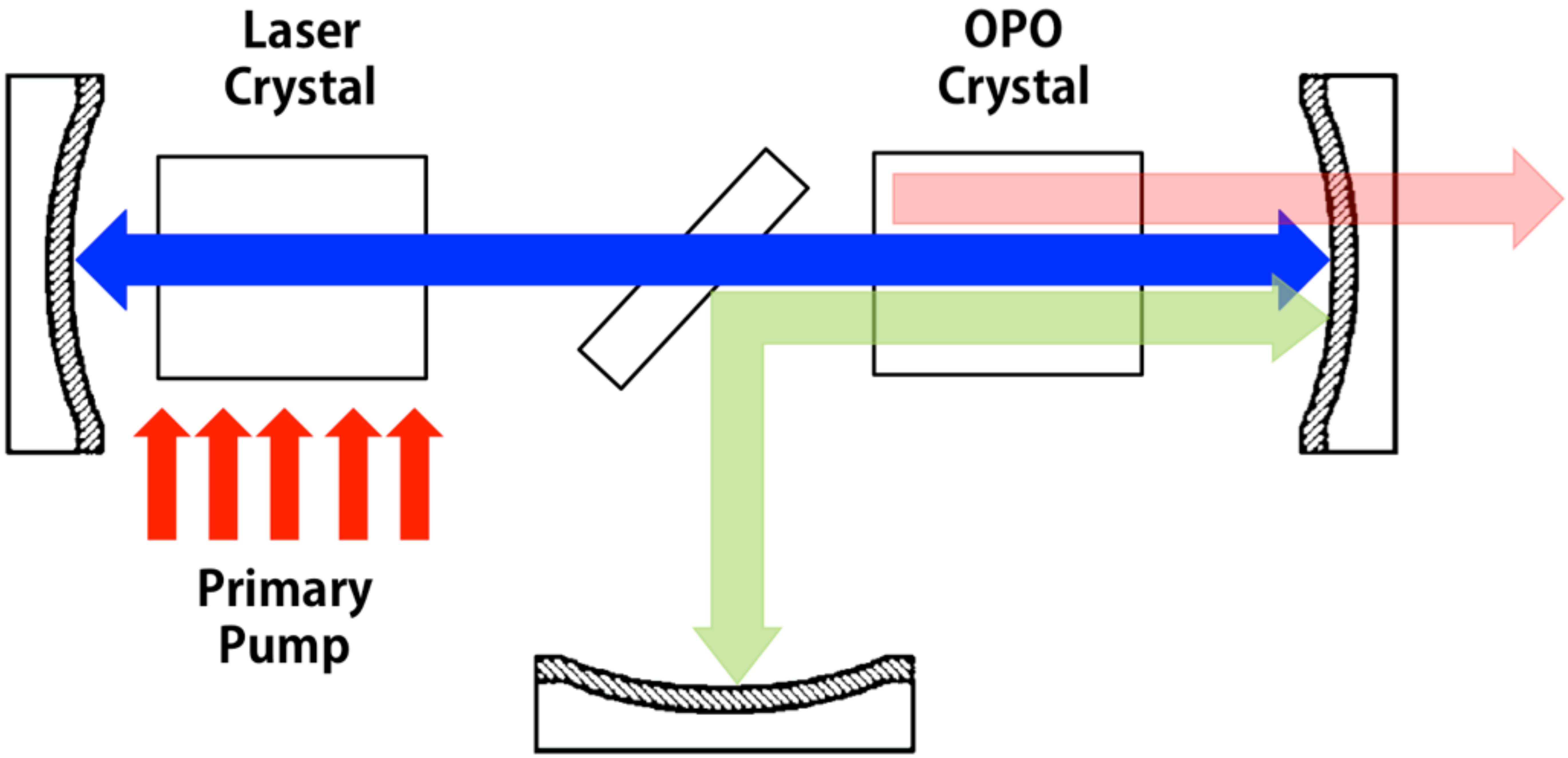
Parent Pump Laser
(Plenty of Power but at Wrong Wavelength)

Wavelength Converter
(Optical Parametric Oscillator)

THz Parametric Oscillator

Pump Geometry

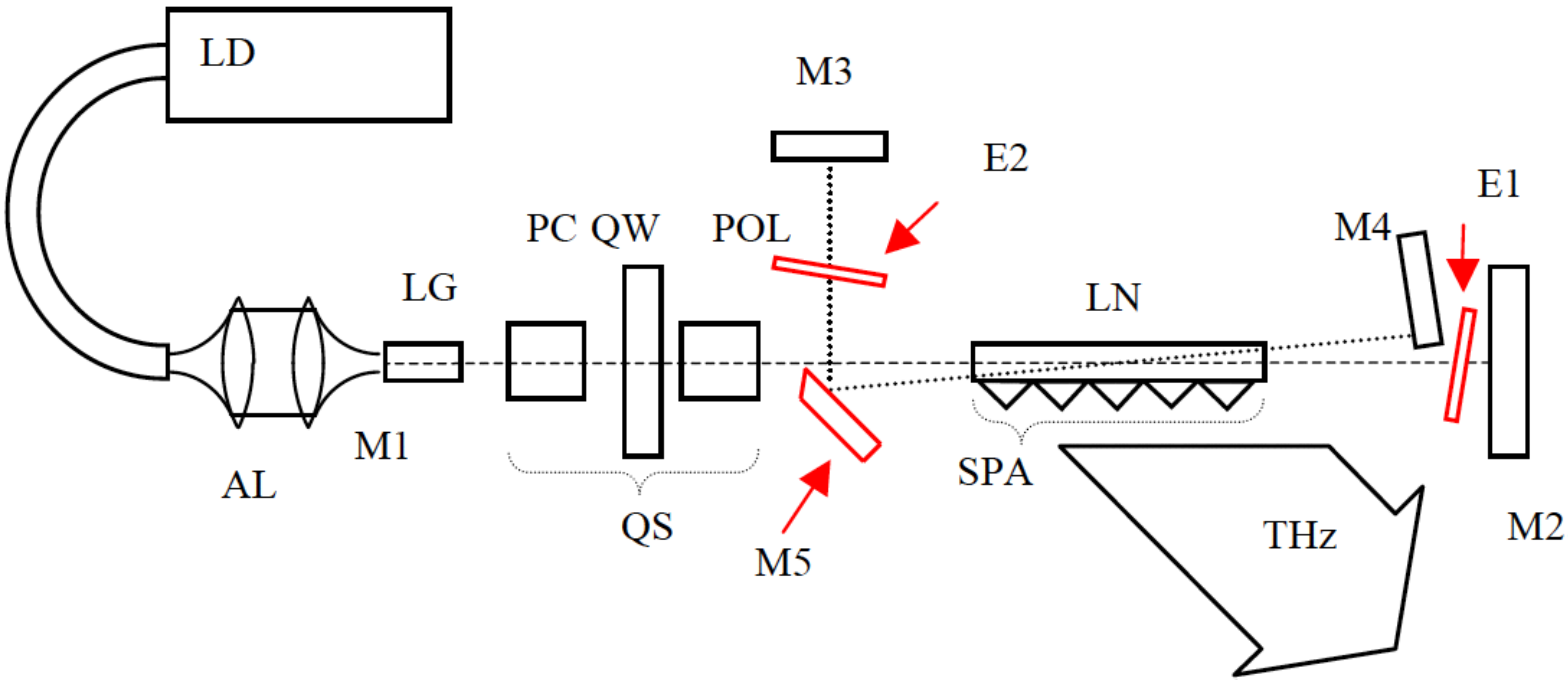
Intracavity Pumping - Reduced pump power and form factor



Intracavity THz OPO

System Design

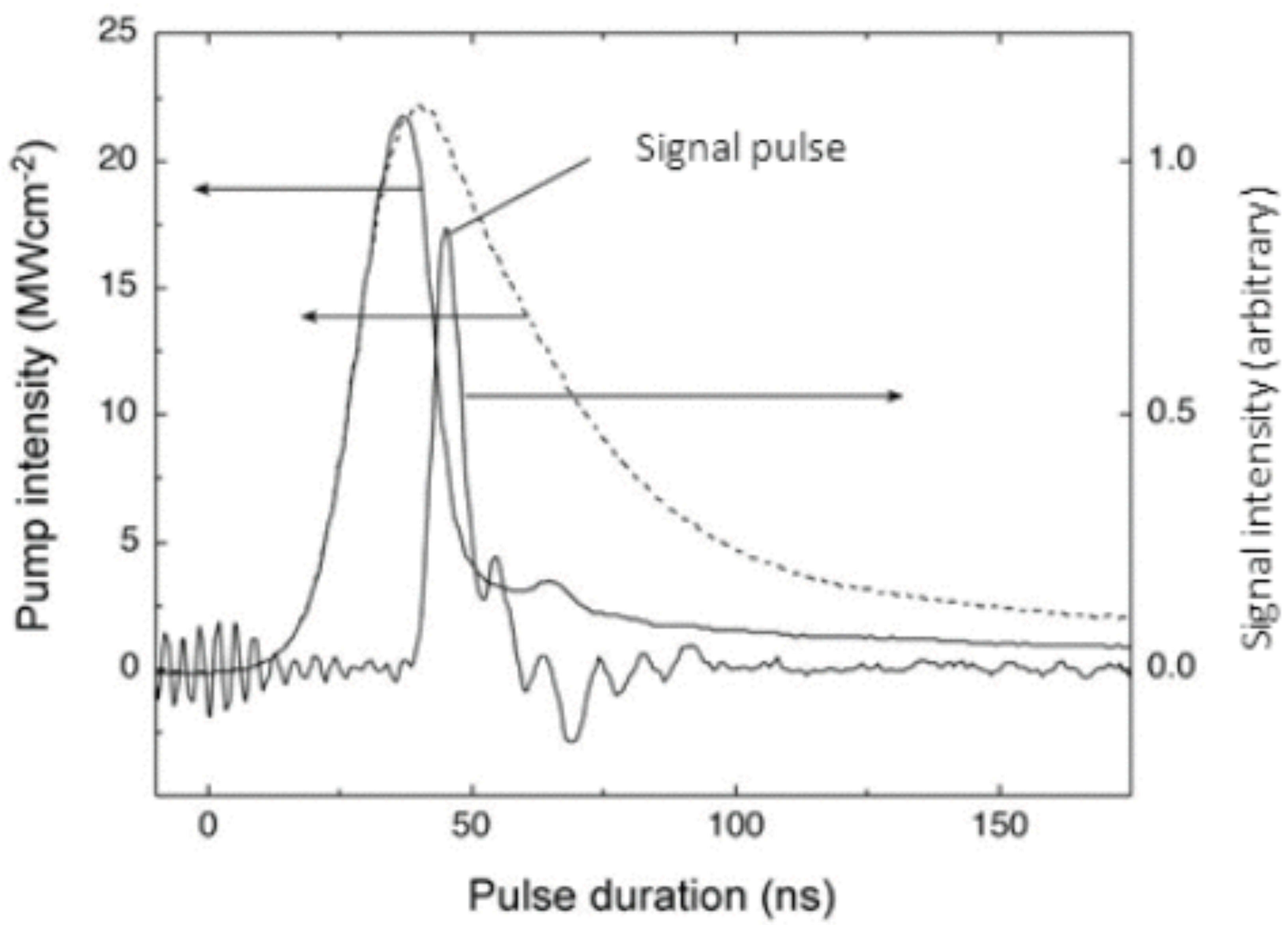
System Configuration

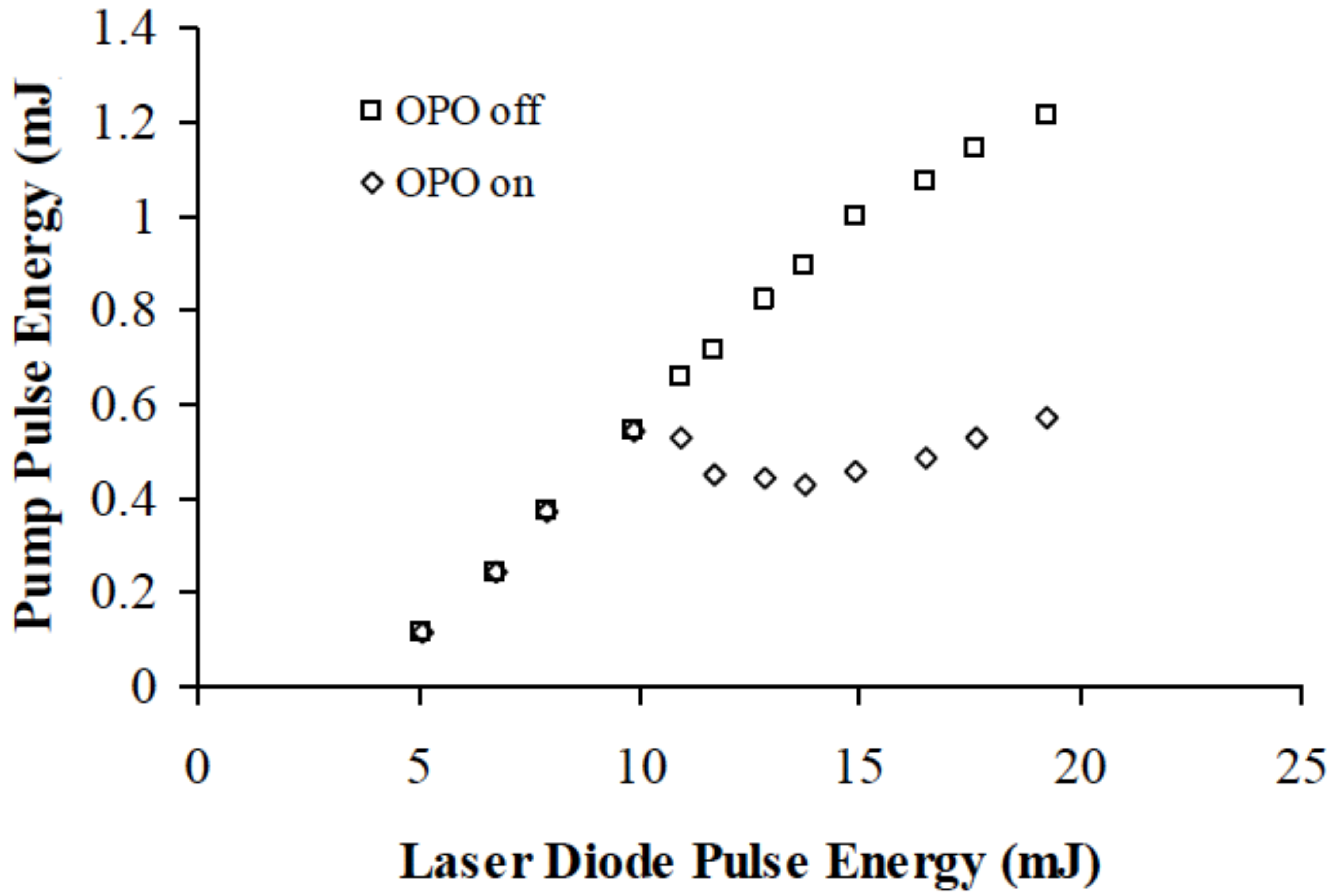


Intracavity THz OPO

In Operation

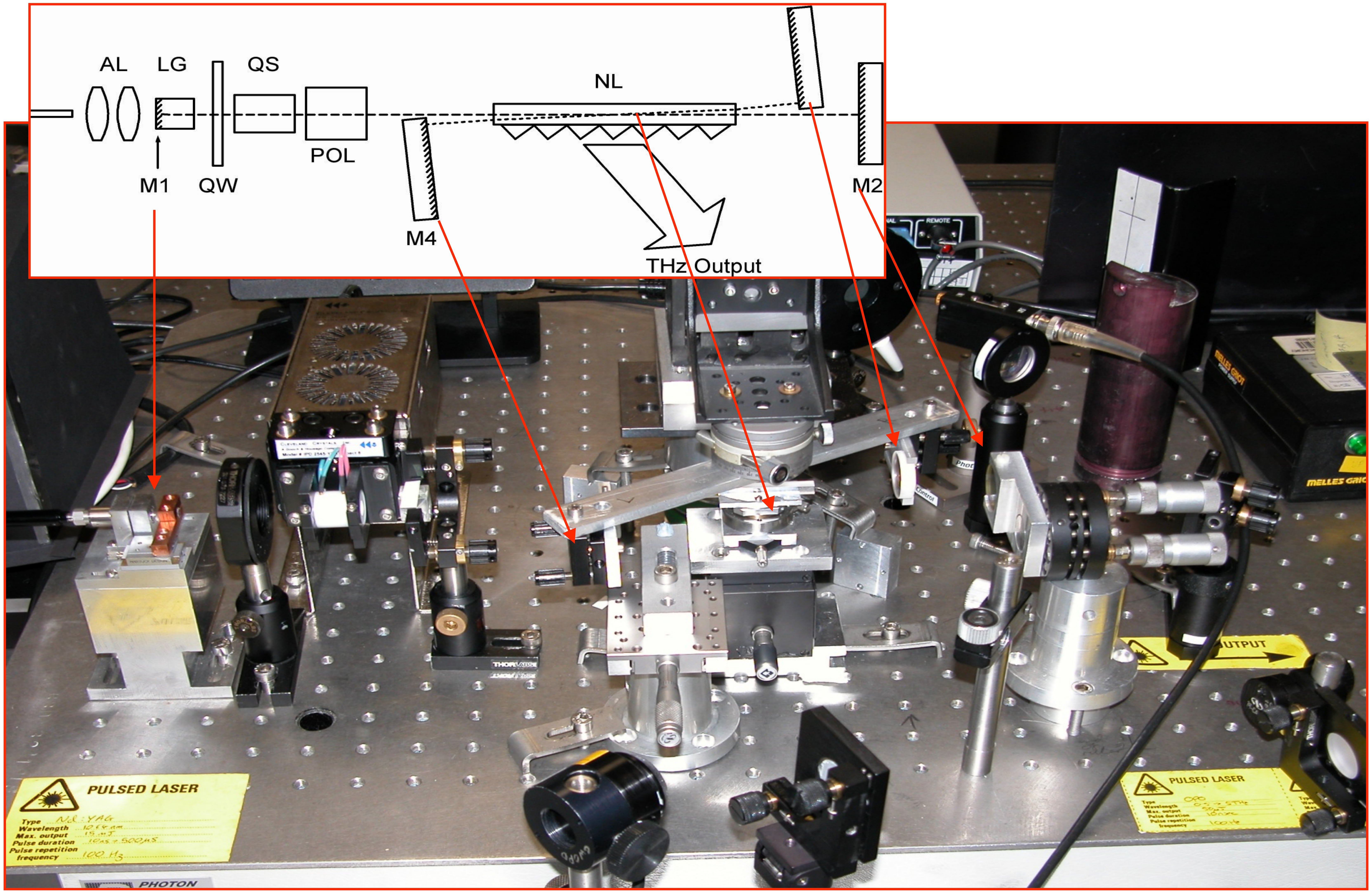
Energy Conversion from NIR to THz





Intracavity THz OPO

System Design



Intracavity THz OPO

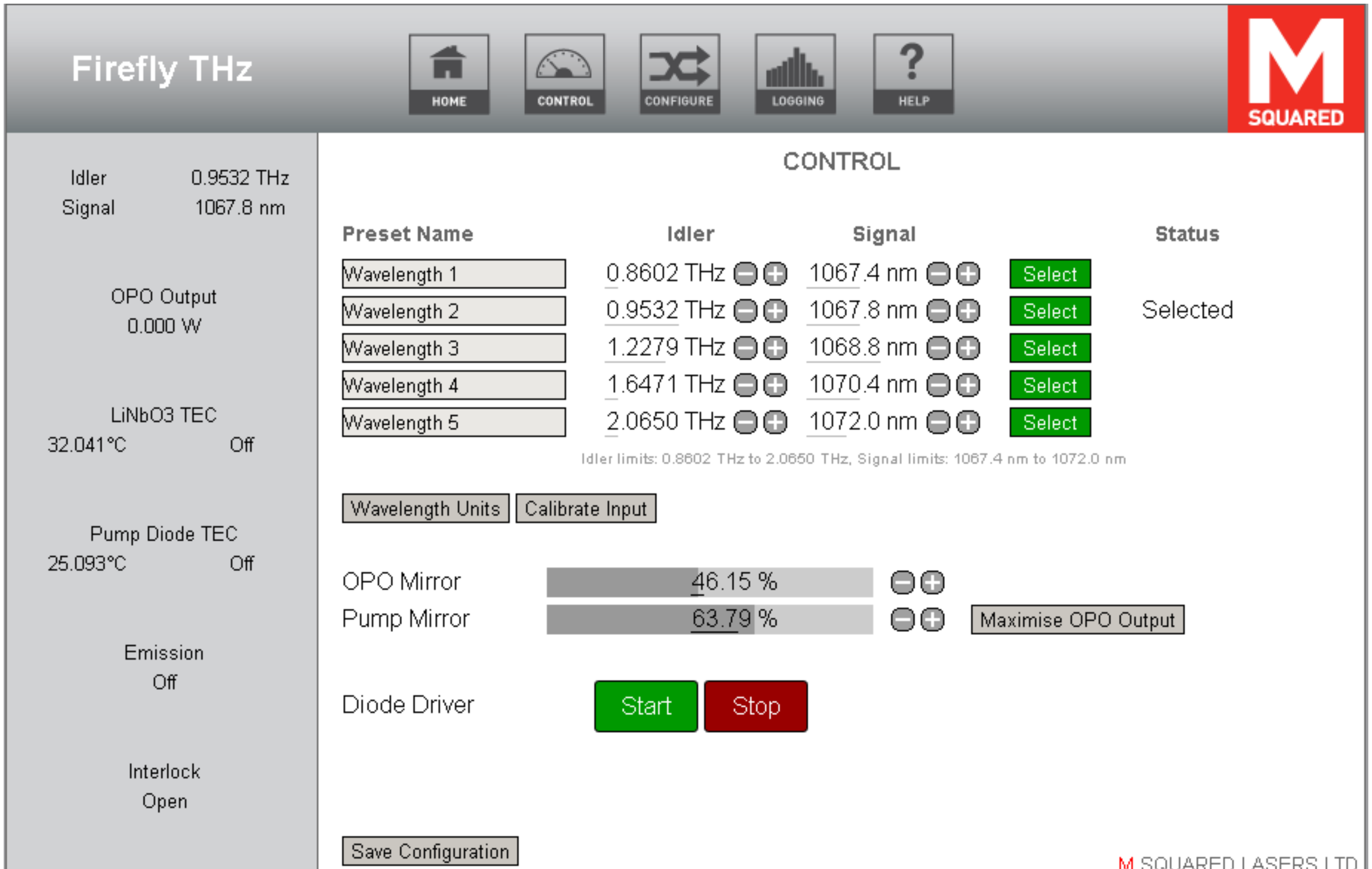
Firefly THz

High Peak Power and Broad Tunability

- Repetition rate: 50 Hz
- Peak power: 1 W
- Average power: 500 nW
- Pulse energy: 10 nJ
- 50GHz / 1GHz linewidth
- Tuning range: 0.6 - 2.5 THz

Firefly THz

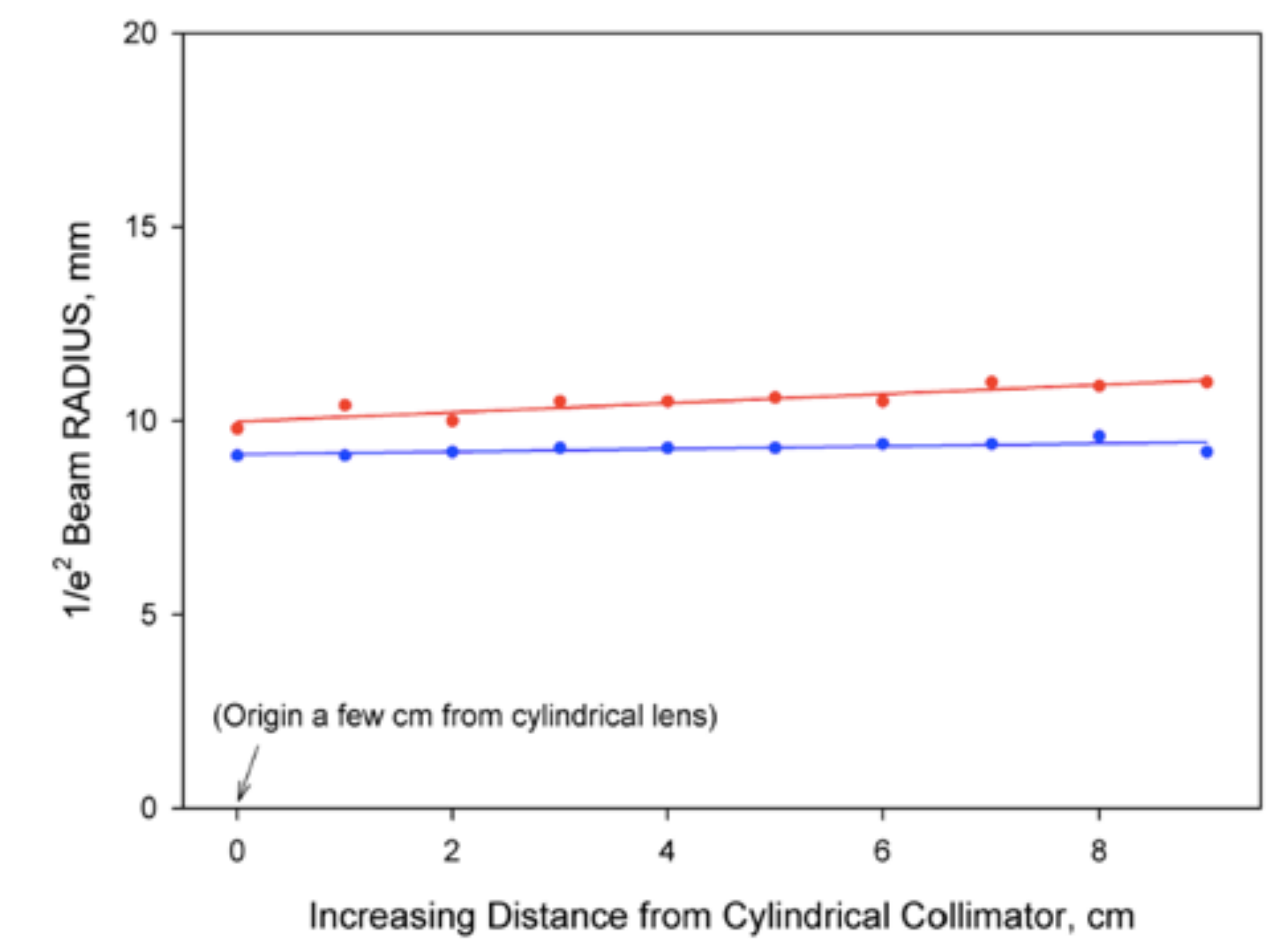
Firefly THz User Interface

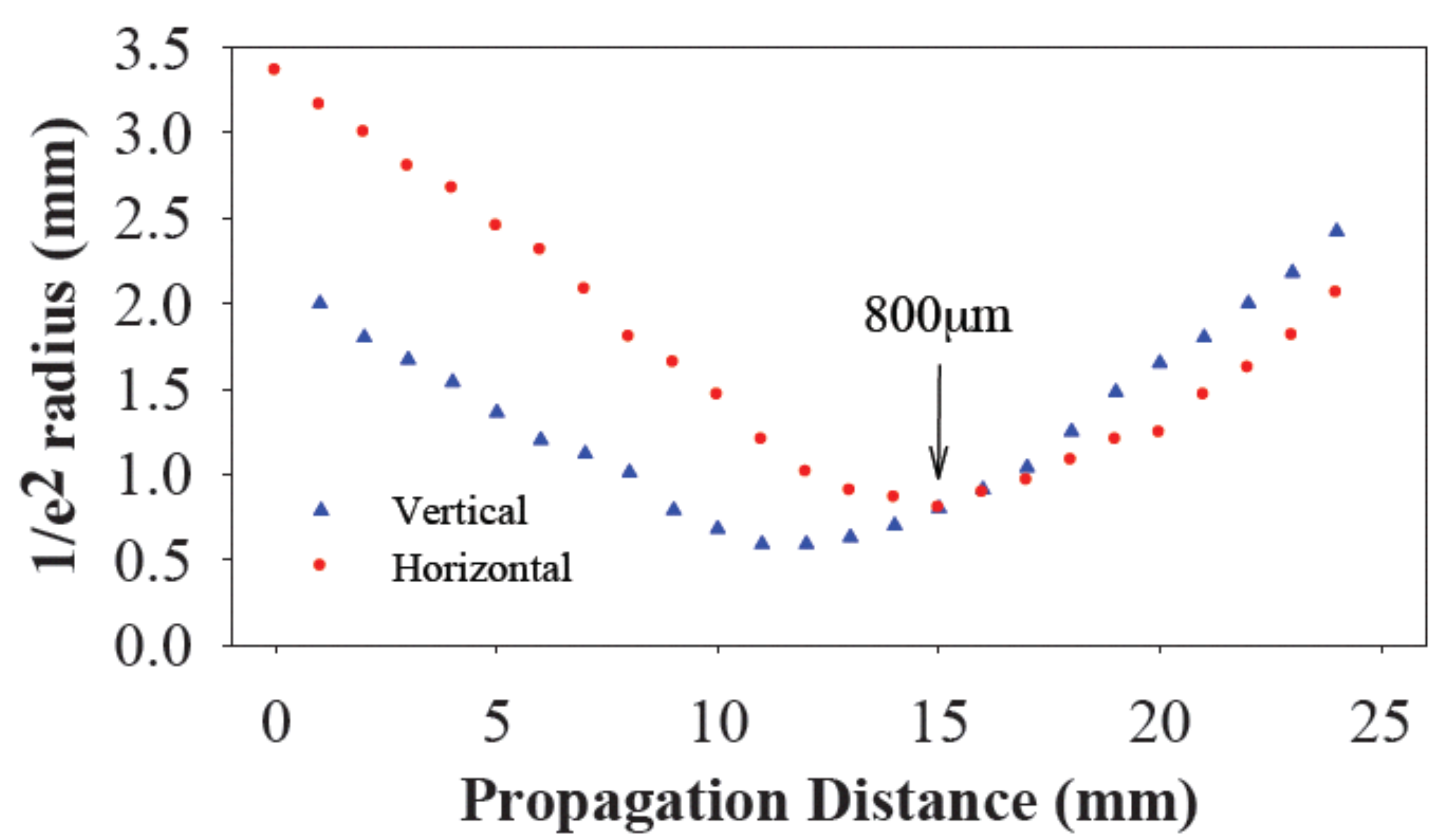


Intracavity THz OPO Performance

Beam Quality and Propagation

- Collimated with cylindrical HDPE lens
- Collimated beam diameter of ~20 mm
- Spot size ~2.3 times diffraction limited
- M^2 in the horizontal ~6.7
- M^2 in the vertical ~2.3

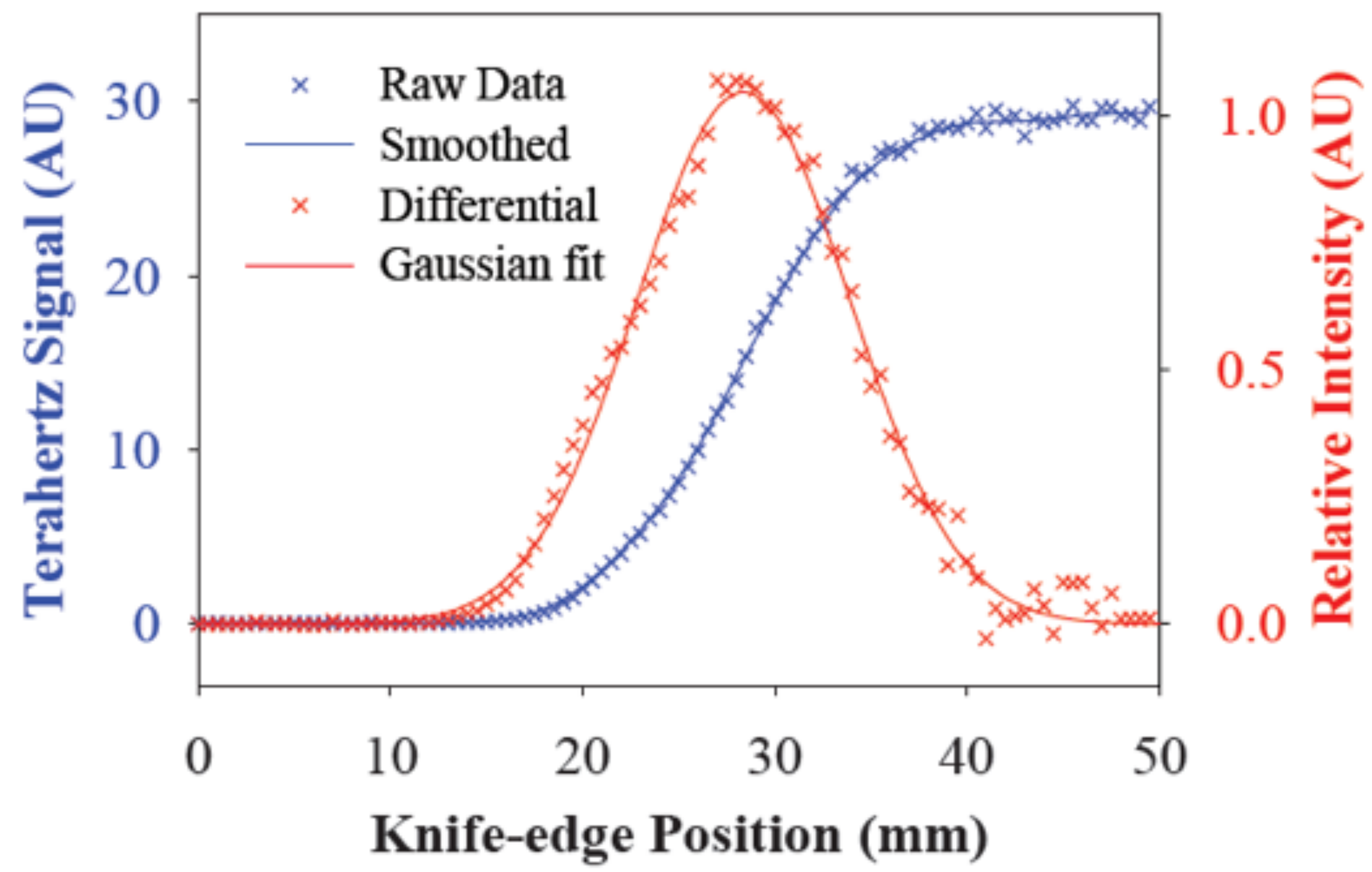


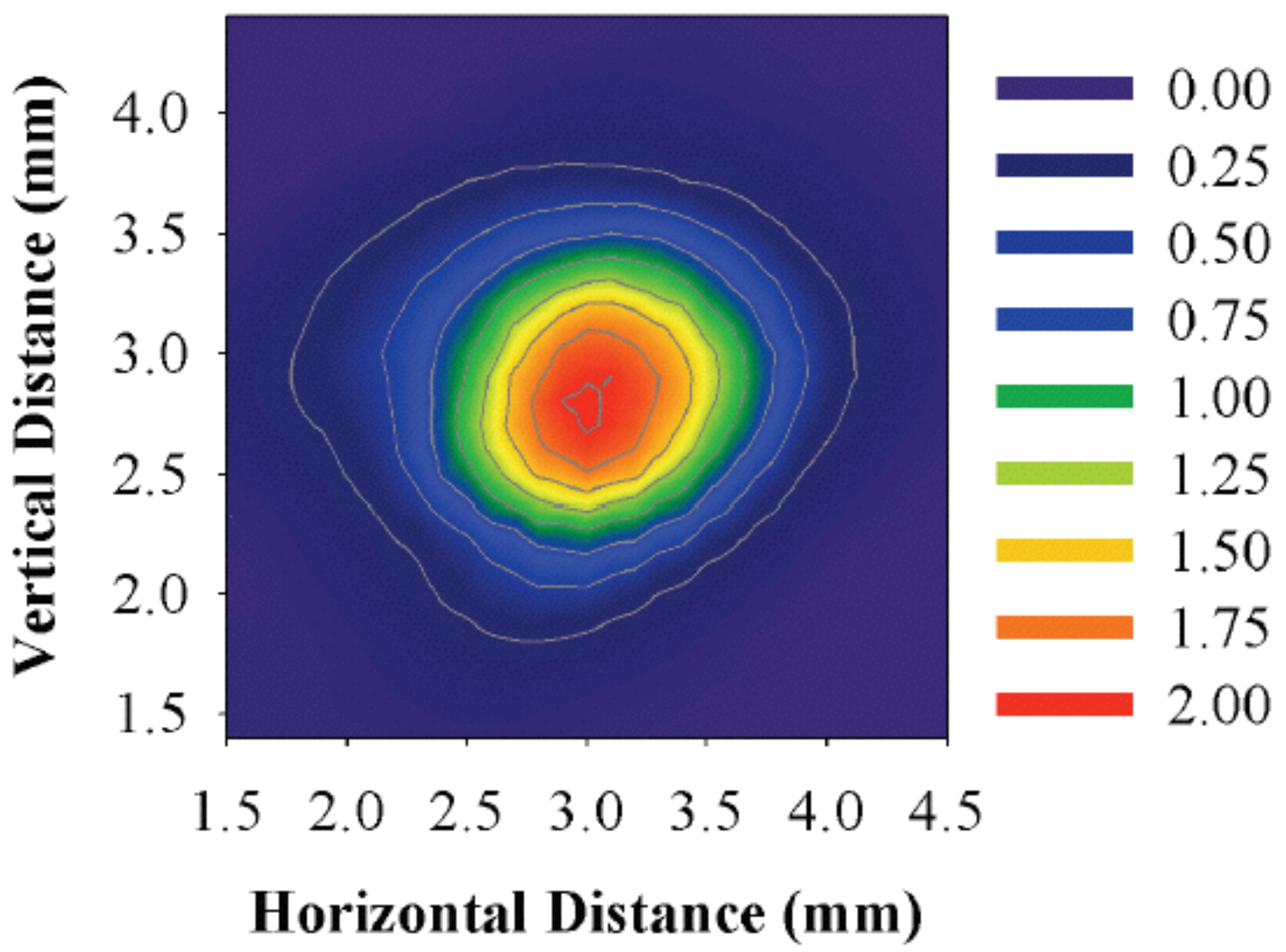


Intracavity THz OPO Performance

Beam Profile

- Gaussian and symmetrical THz output
- Advantageous in imaging systems
- Advantageous for spectroscopic applications with long optical path (e.g. for stand-off detection)

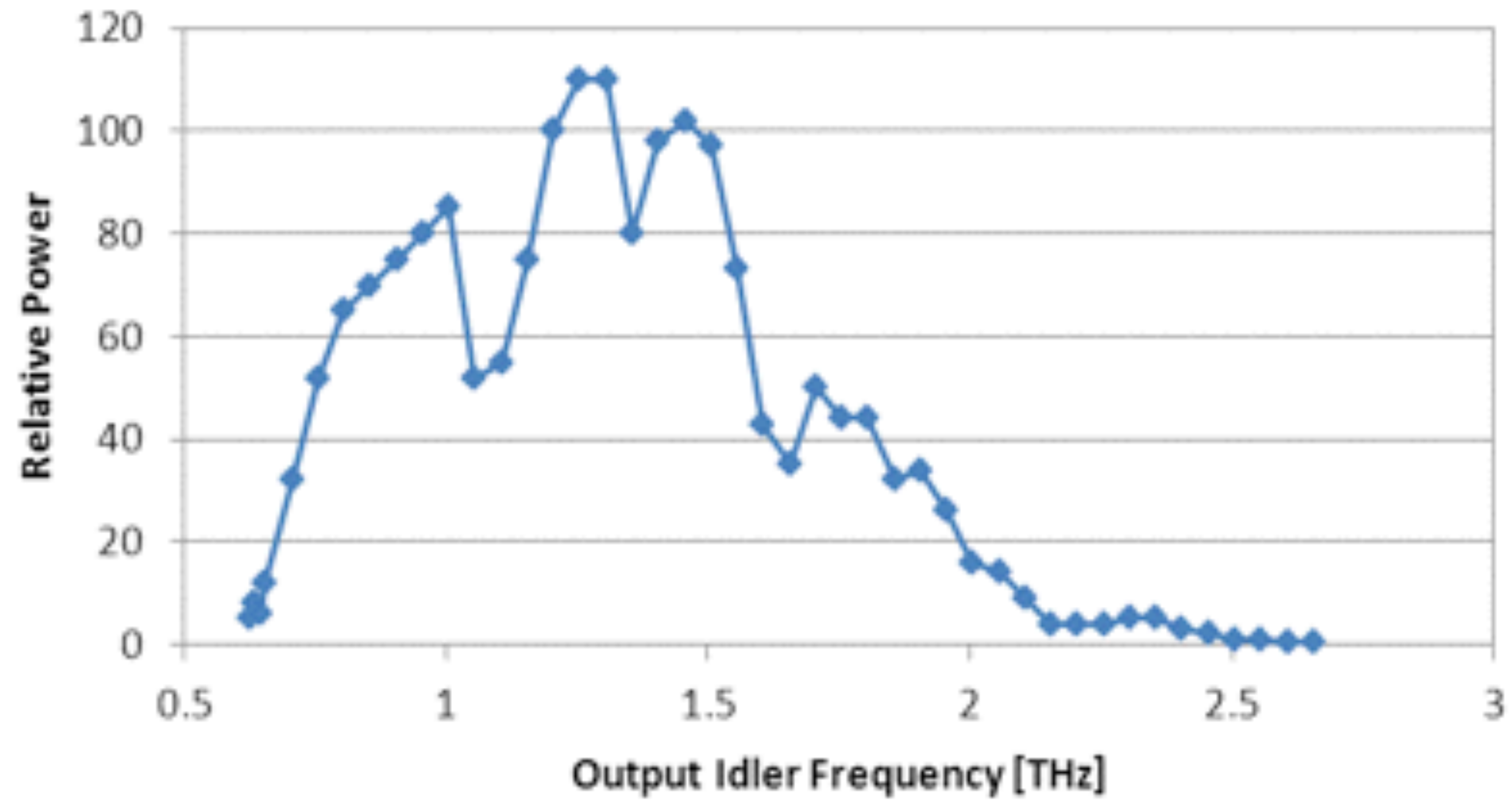


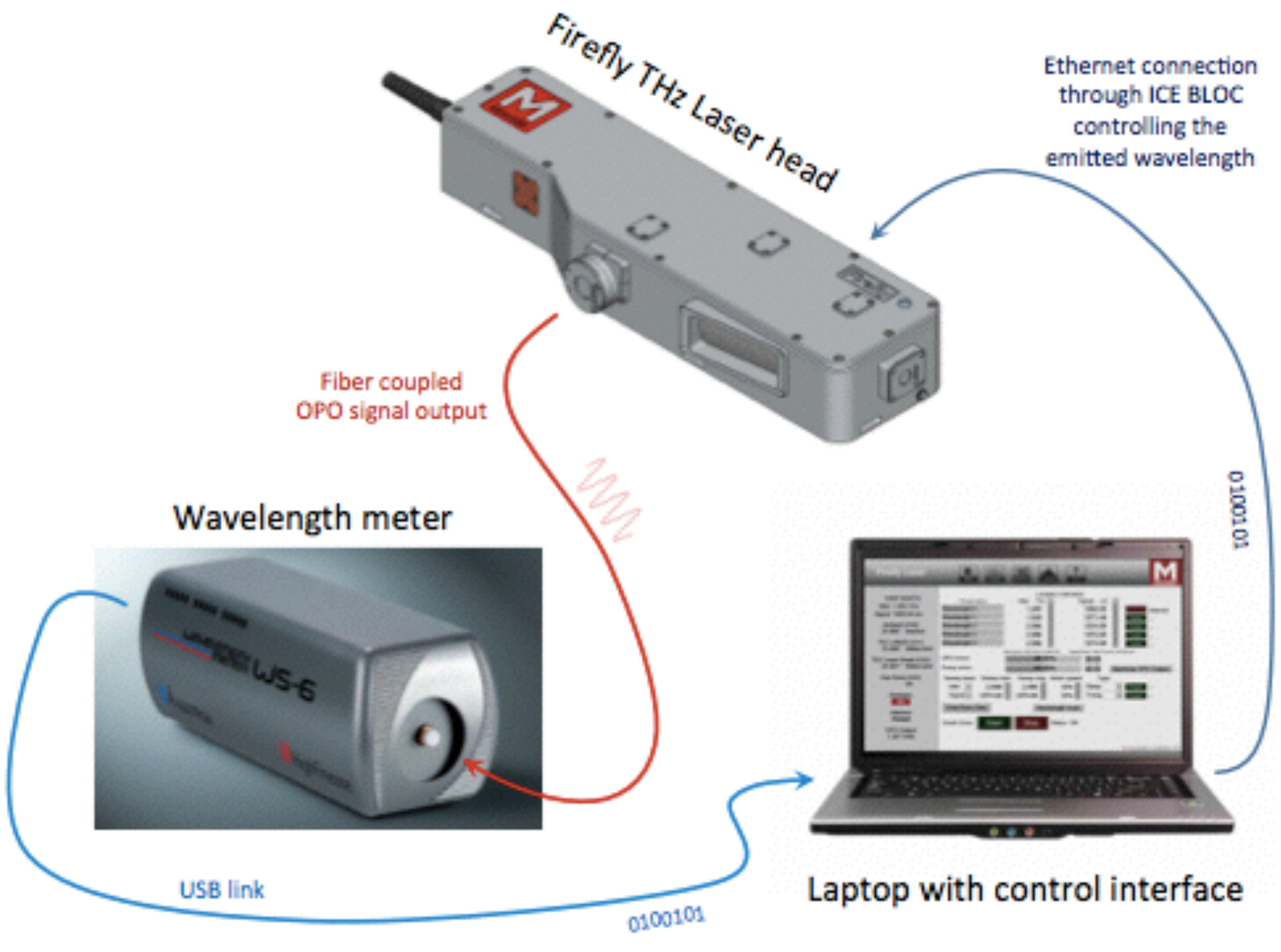


Intracavity THz OPO

Performance

Broad tenability and frequency control

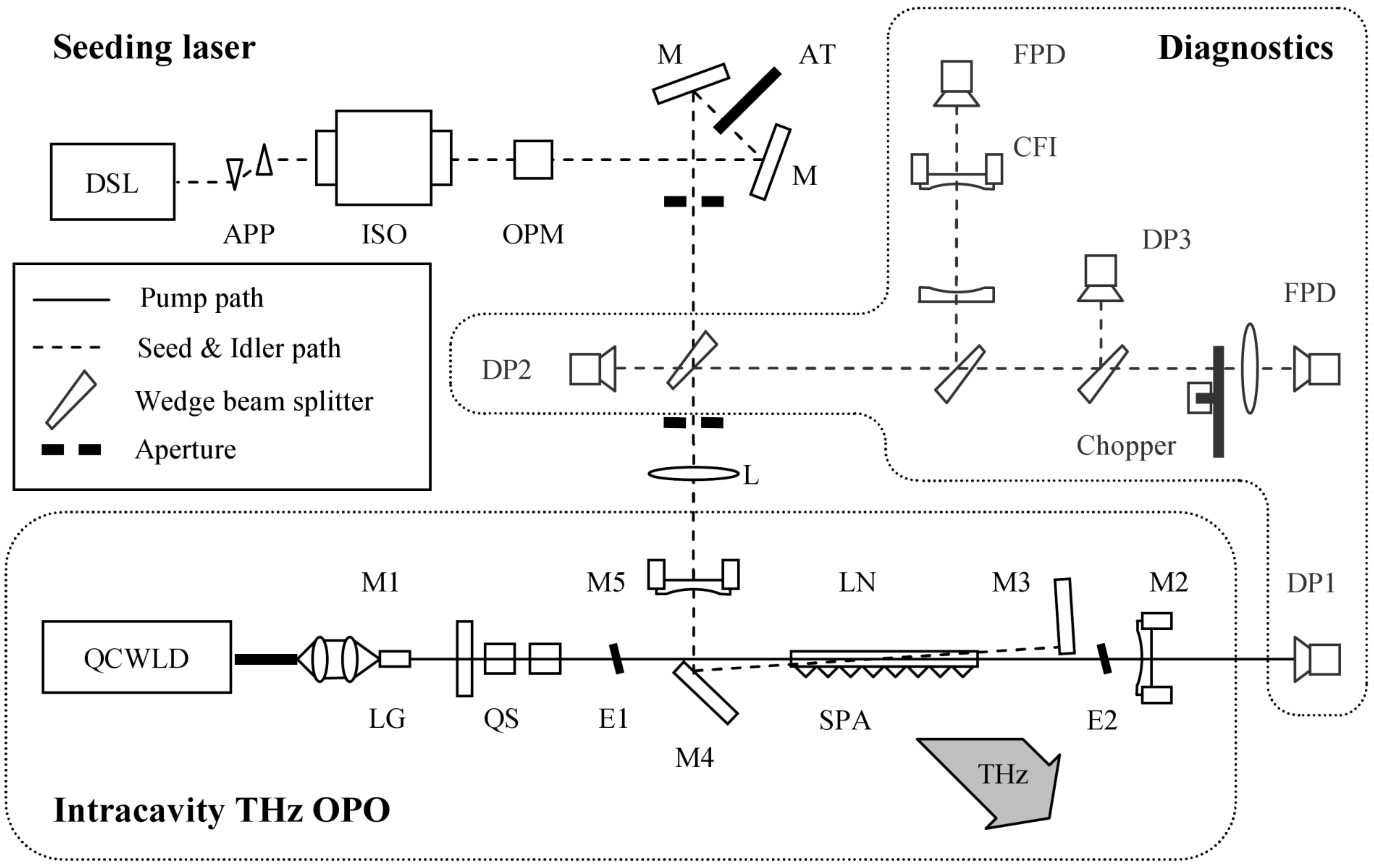


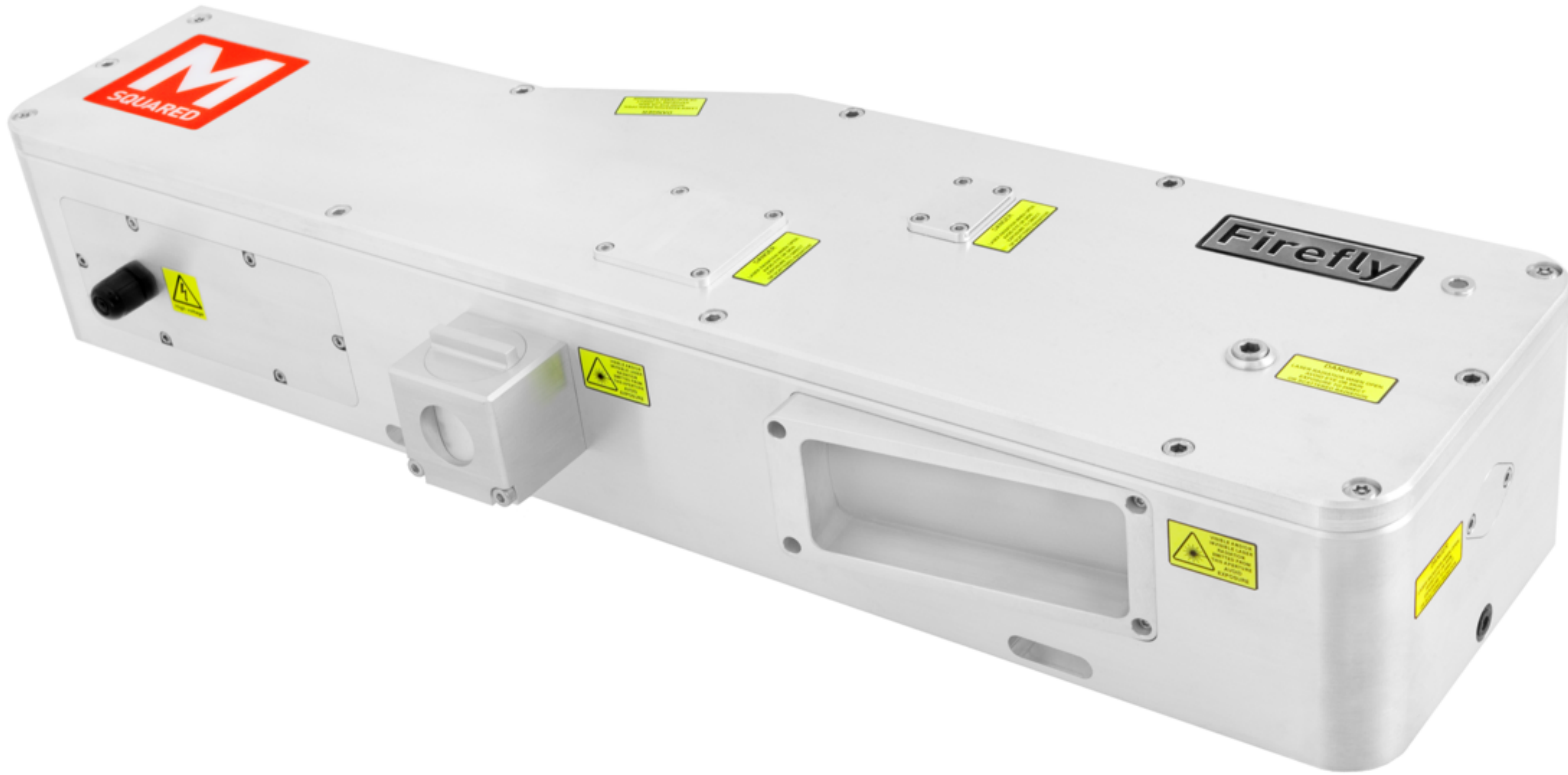


Intracavity THz OPO

Injection Seeding

Towards 100 MHz transform limited line width




M
SQUARED
Firefly


Power
LAN
Channel 1
Channel 2
Channel 3
Channel 4
M
SQUARED
ICE-BLOC
Instrument Control by Ethernet
TC-4 Temperature Controller
Power
www.m2lasers.com
M SQUARED LASERS LTD

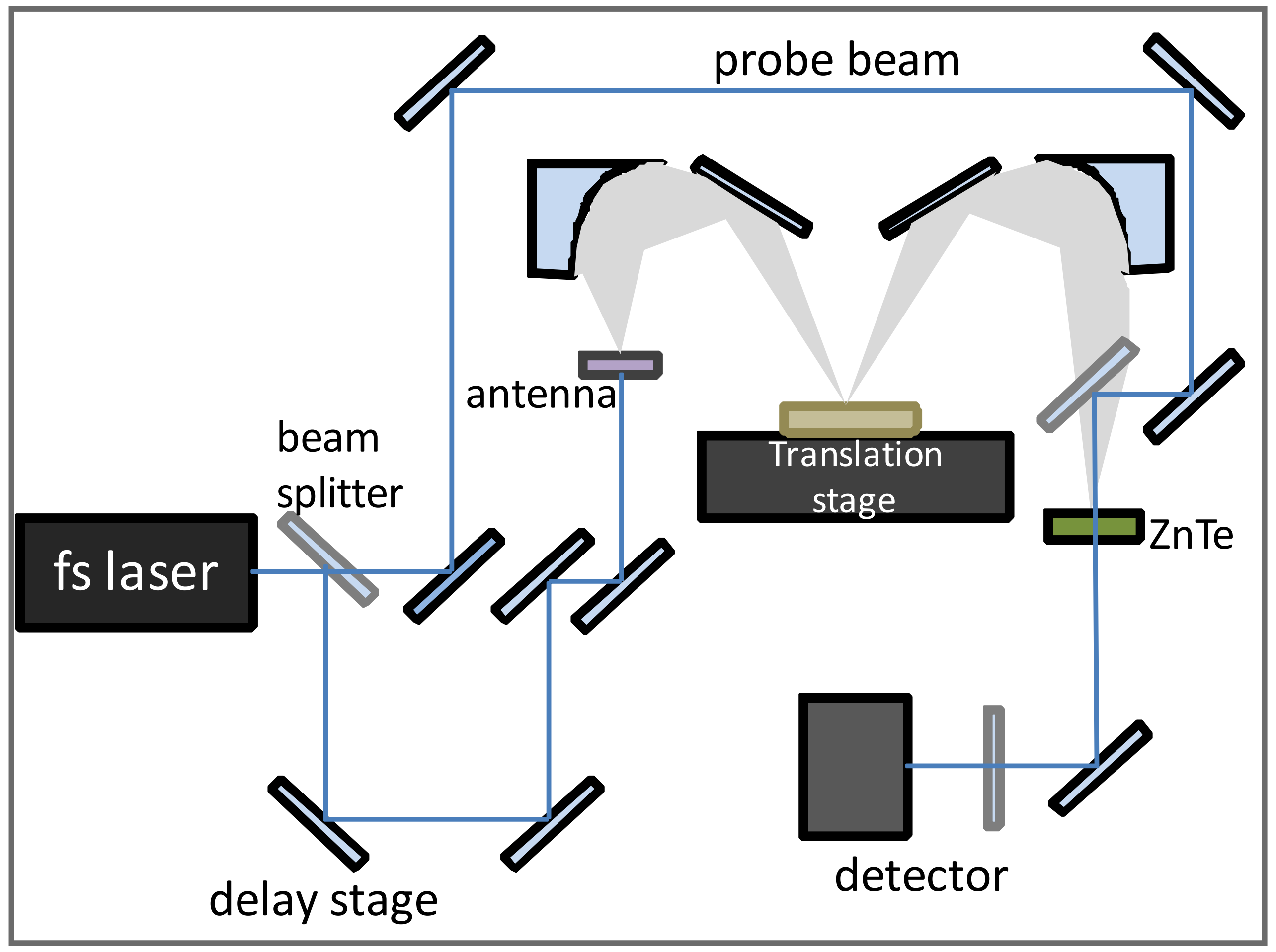
Presentation Outline

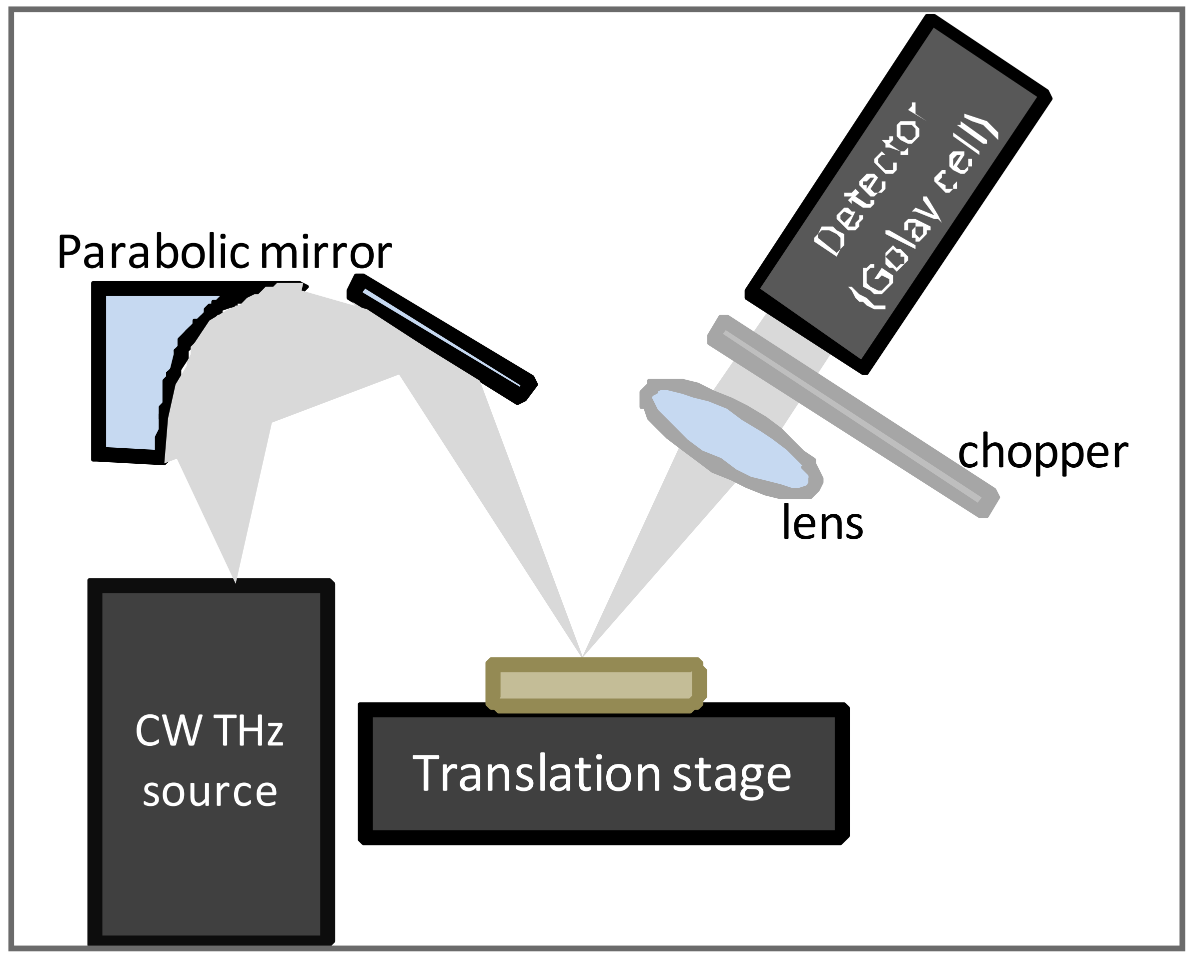
- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - **Towards Continuous-wave Operation**
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - Security / Defense
- Open Innovation

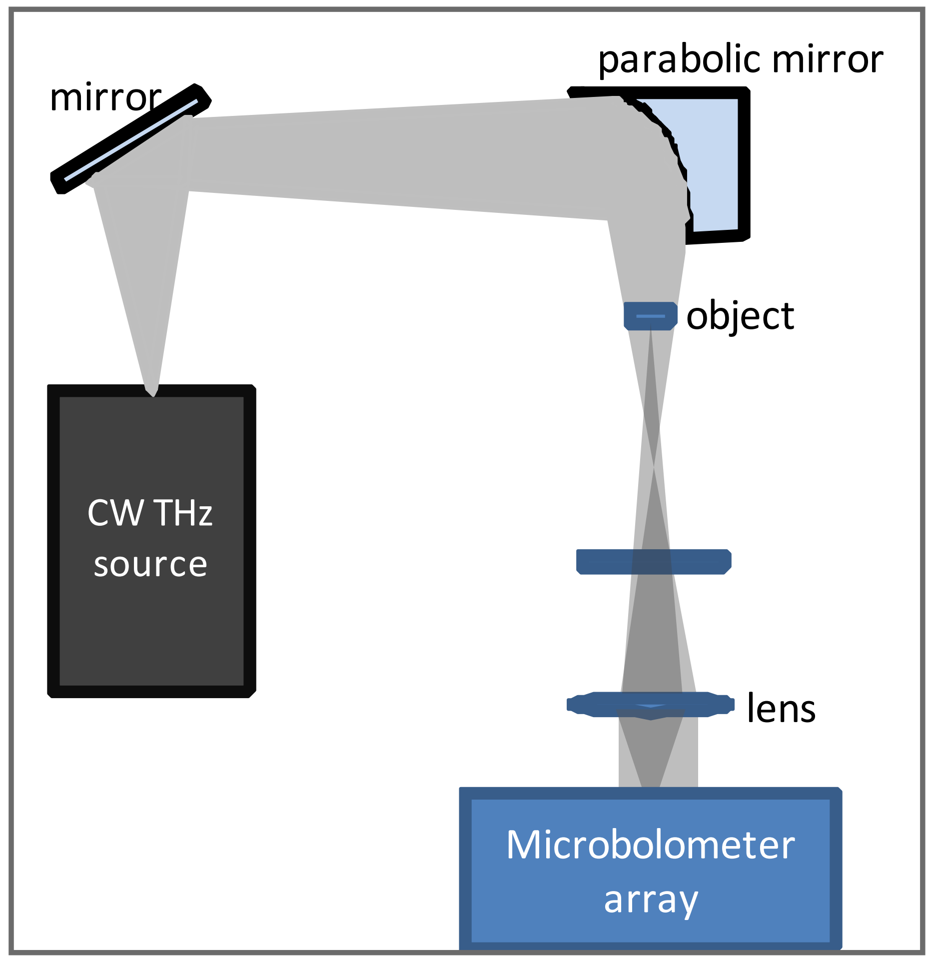
System Improvements

Continuous-Wave THz OPO

- CW allows narrower line width emission for high-resolution THz spectroscopy
- For imaging applications, CW radiation simplifies experimental arrangements

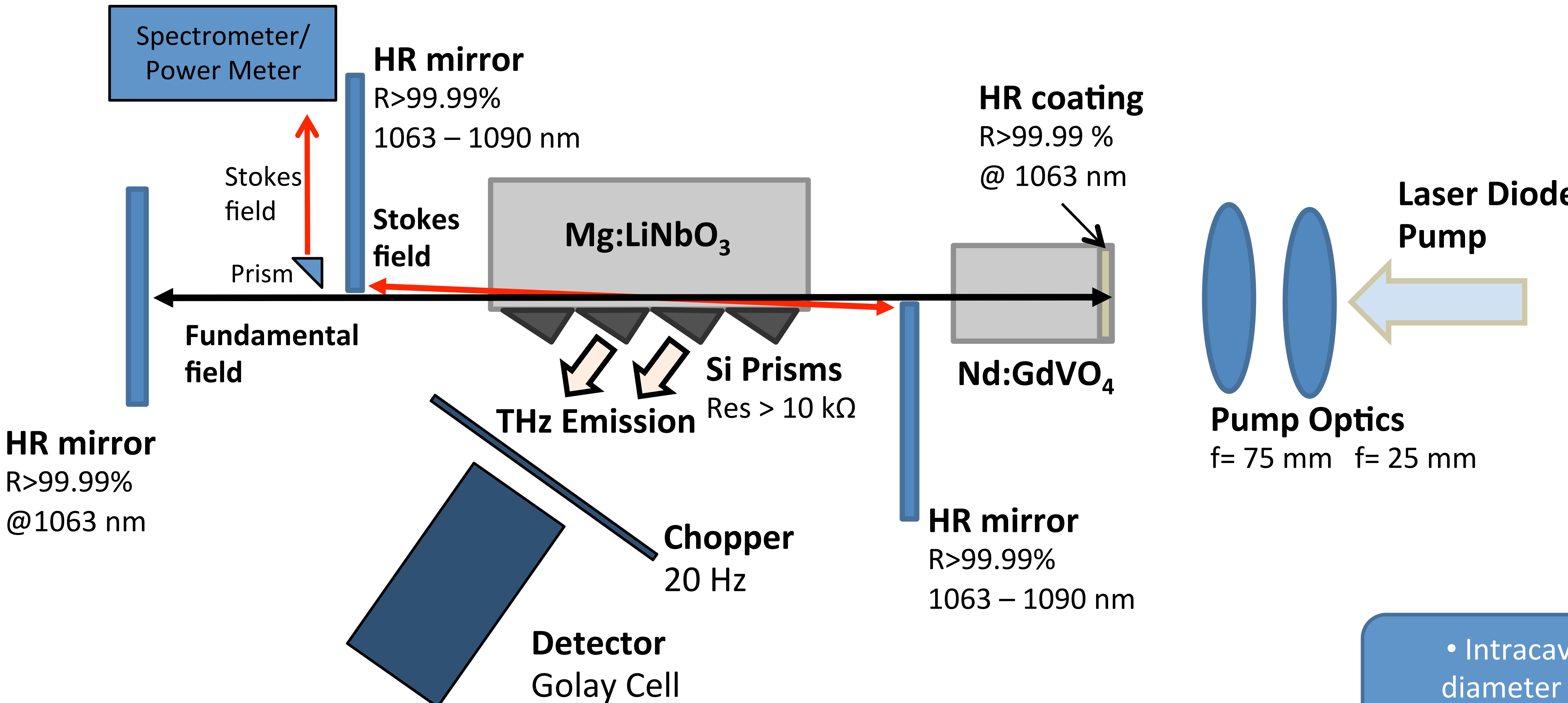






CW System Design

MACQUARIE UNIVERSITY



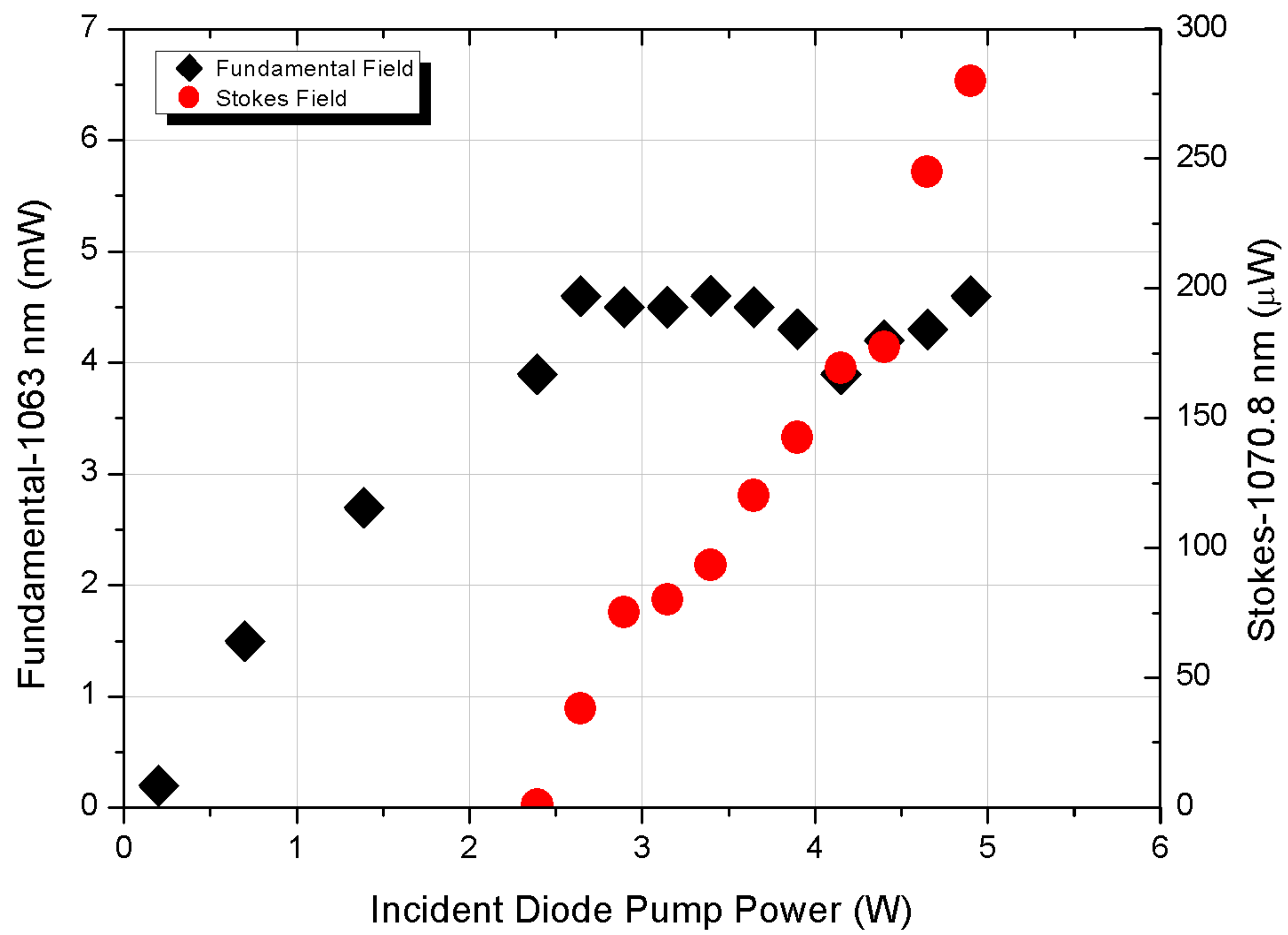
- Intracavity mode diameter ~ 300 µm
- Resonator length ~ 19 cm

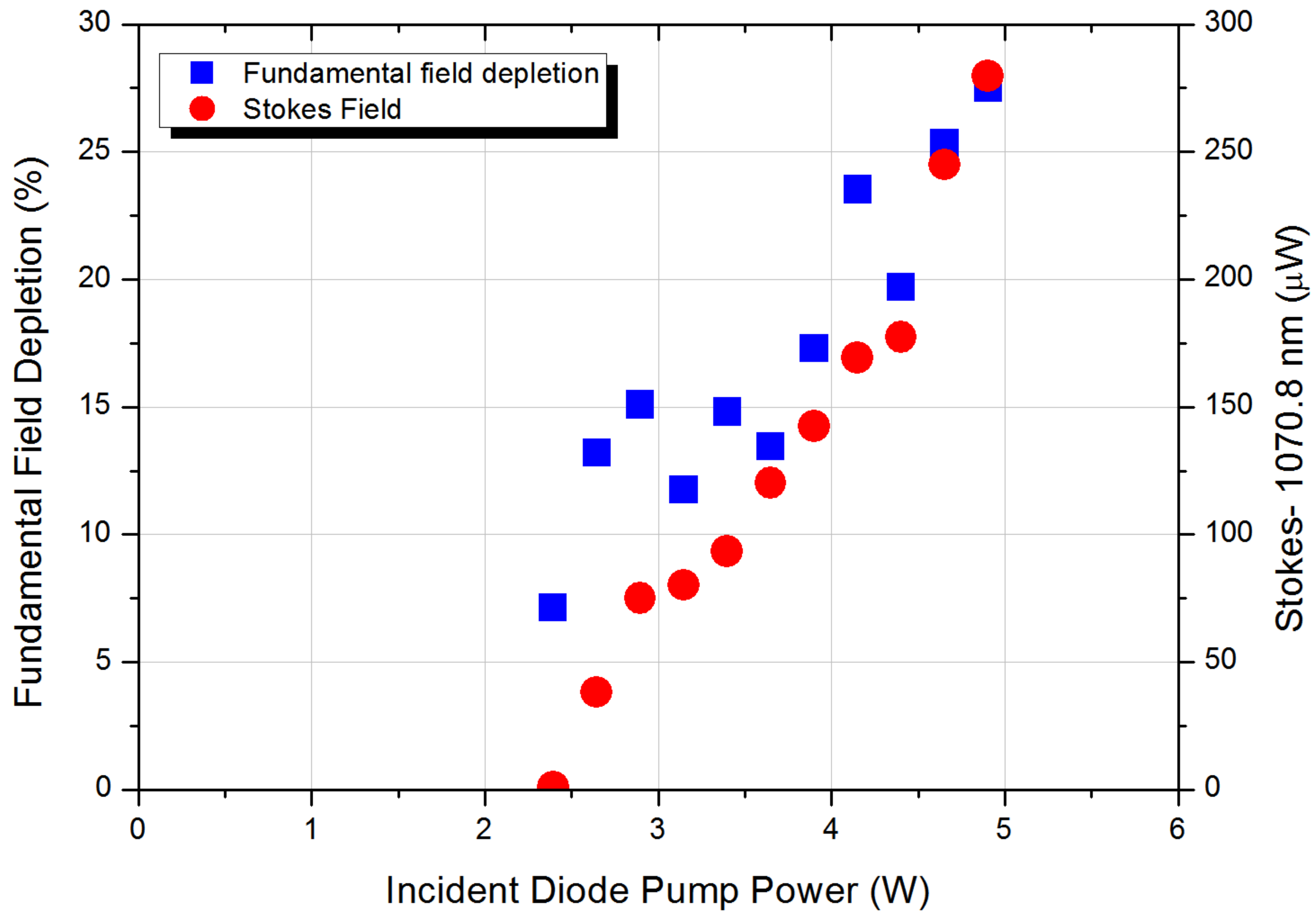
Component	Description
Laser Diode	879 nm, 30 W fibre-coupled laser diode, focussed spot size ~ 300 µm
Detector	Golay Cell (Tydex GC-1P)
Nd:GdVO$_4$	0.3 % Nd, a-cut (Castech); dimensions- 5×5×20 mm ; coatings- S1: HR coated, R>99.99 % @ 1063 nm S2: AR coated, R<0.02 % @ 1063 nm)
Mg:LiNbO$_3$	5 % Mg, x-cut congruent (HCPhotonics); dimensions- 5×5×25 mm; coatings- S1, S2: AR coated R<0. 05 % @ 1063 – 1085 nm).

CW System Performance

MACQUARIE UNIVERSITY

2.3μW THz Output for 5.9W Pump Power

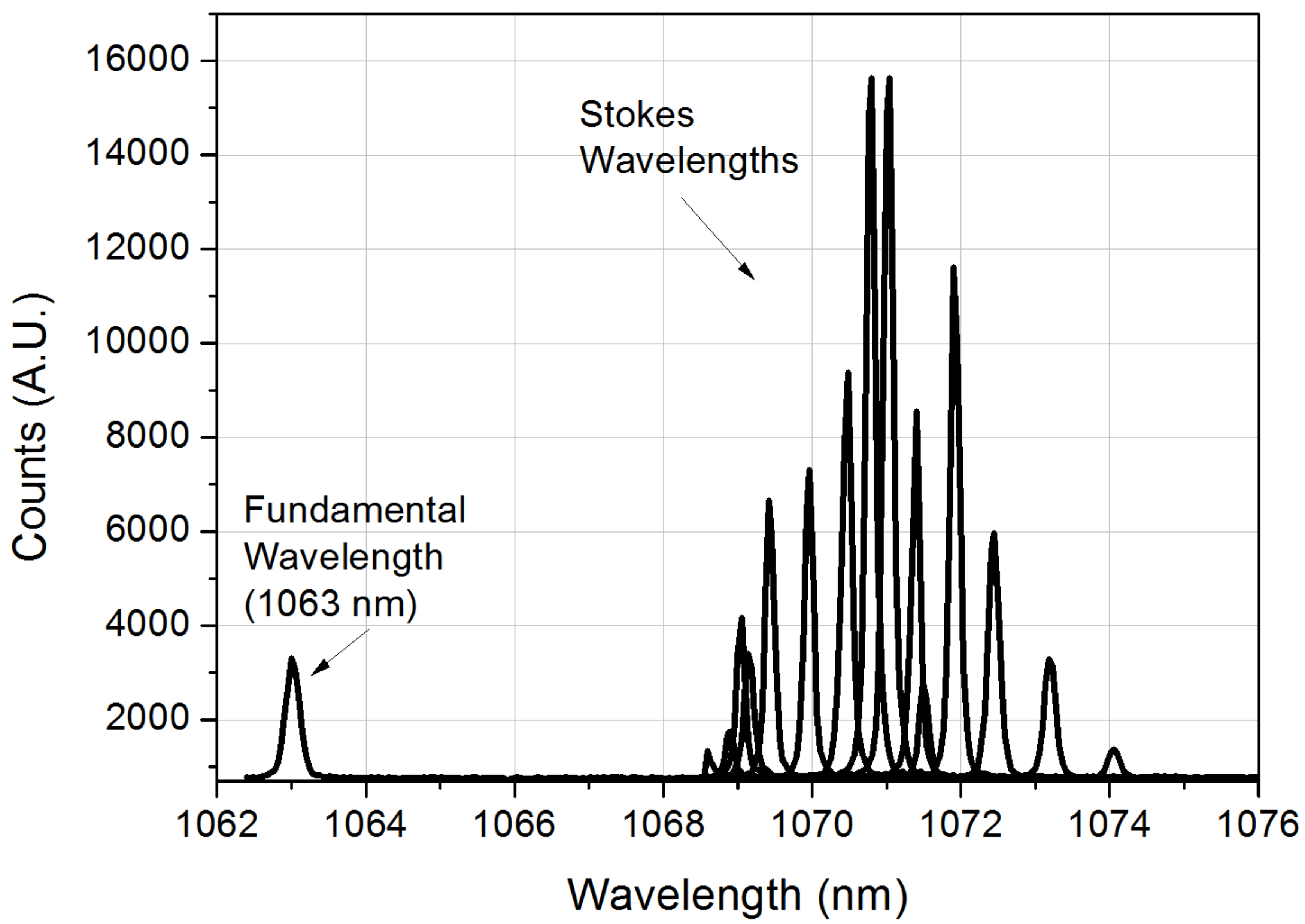


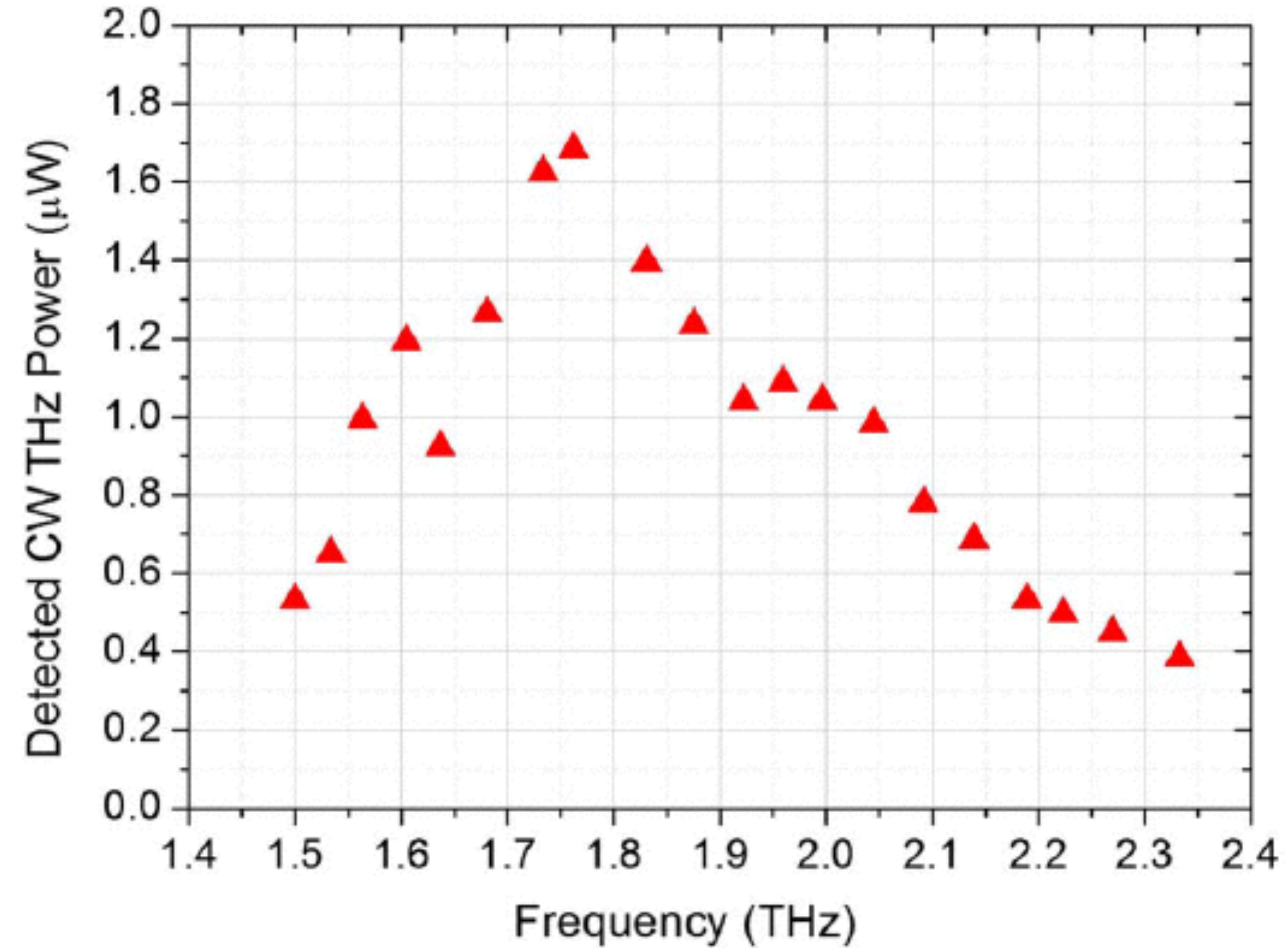


- Threshold for fundamental field (1063 nm): 0.2 W incident diode power
- Threshold for SPS- Stokes (1070.8 nm) /THz field (1.8 THz): 2.4 W incident diode power

CW Tuning Range

Tunability from 1.5 - 3.2 THz





Lee, A.J. and Pask, H.M., "Continuous wave, frequency-tunable terahertz laser radiation generated via stimulated polariton scattering," Optics Letters, 39 (3), pp. 442-445 (2014).

Presentation Outline

- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- **THz Active Hyperspectral Imager**
- Applications
  - Pharmaceutical
  - Security / Defense
- Open Innovation

Firefly-IR

Capability

Broadly tunable infrared laser source

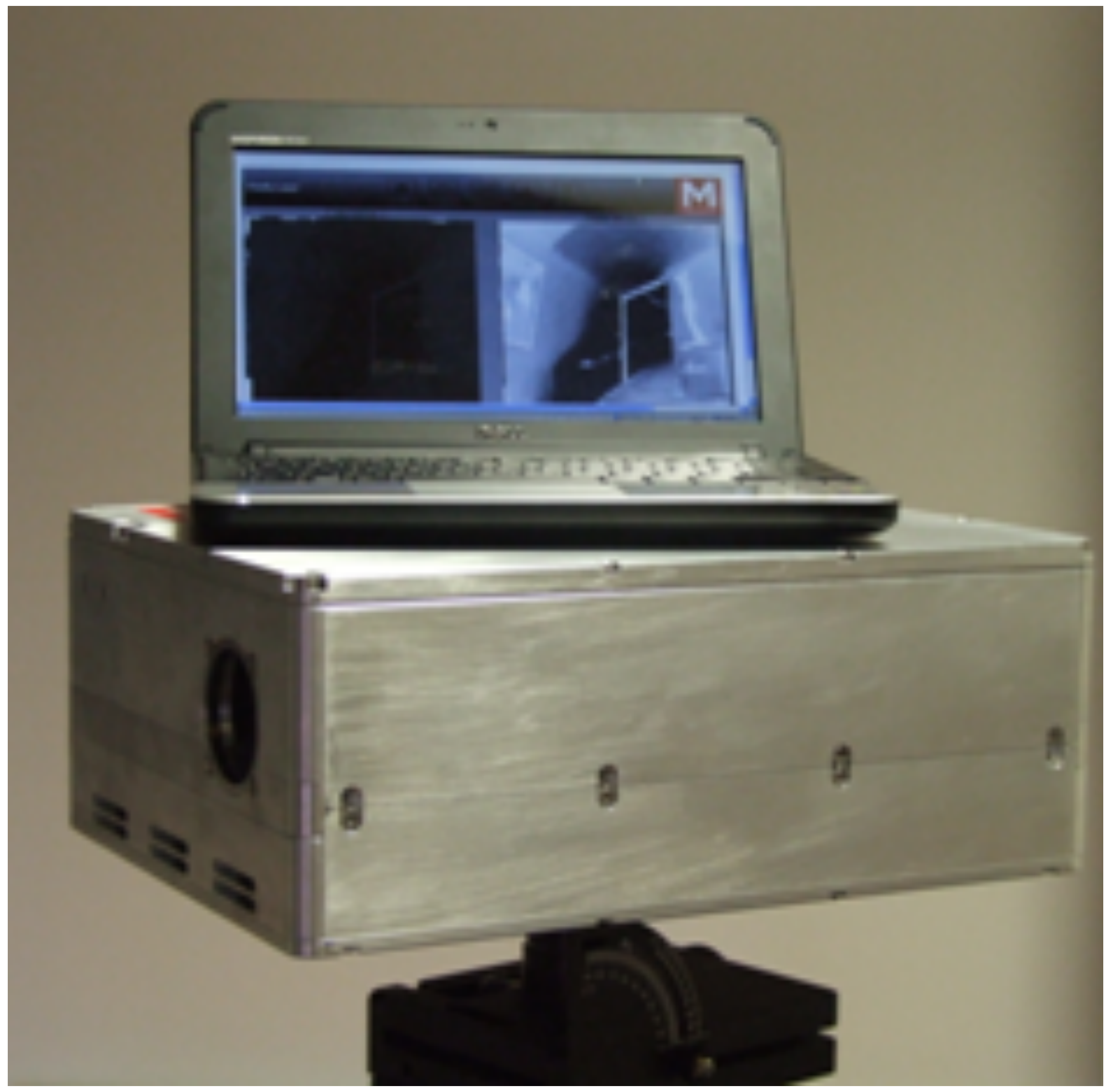
- 2.5 - 4.5 µm
- 1.1 - 1.9 µm
- >250 mW average power
- 150 kHz rep. rate

Firefly-Imager

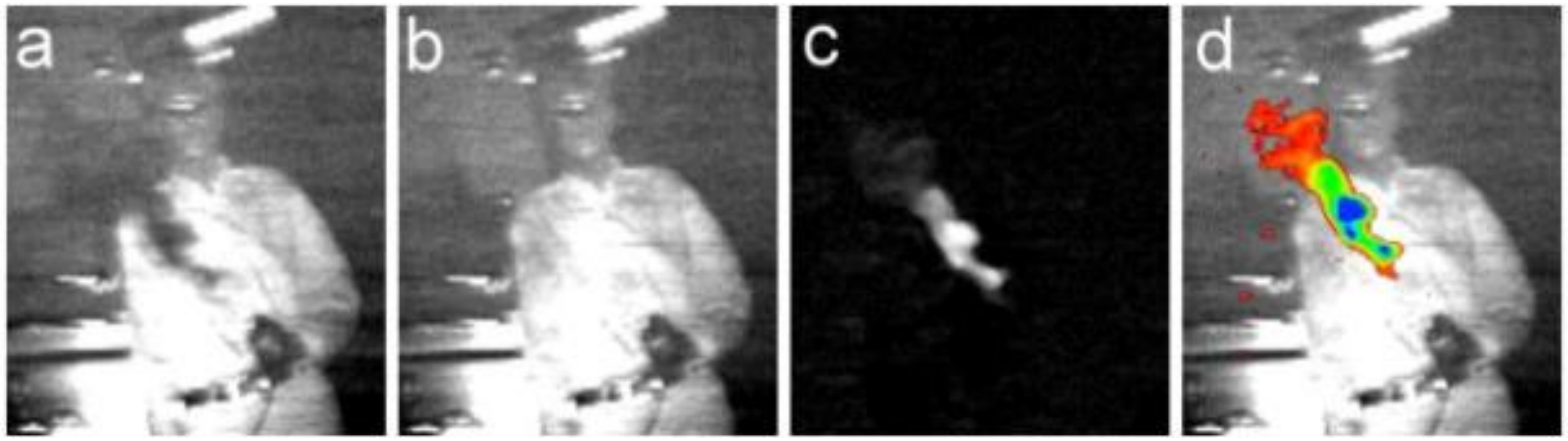
Specification

Real time imaging at 10m's, extendable to >100m

- Galvanometric mirror pair
- MCT and InGaAs point detectors
- Source, scanner, detector and electronics in a single package
- Portable and battery powered



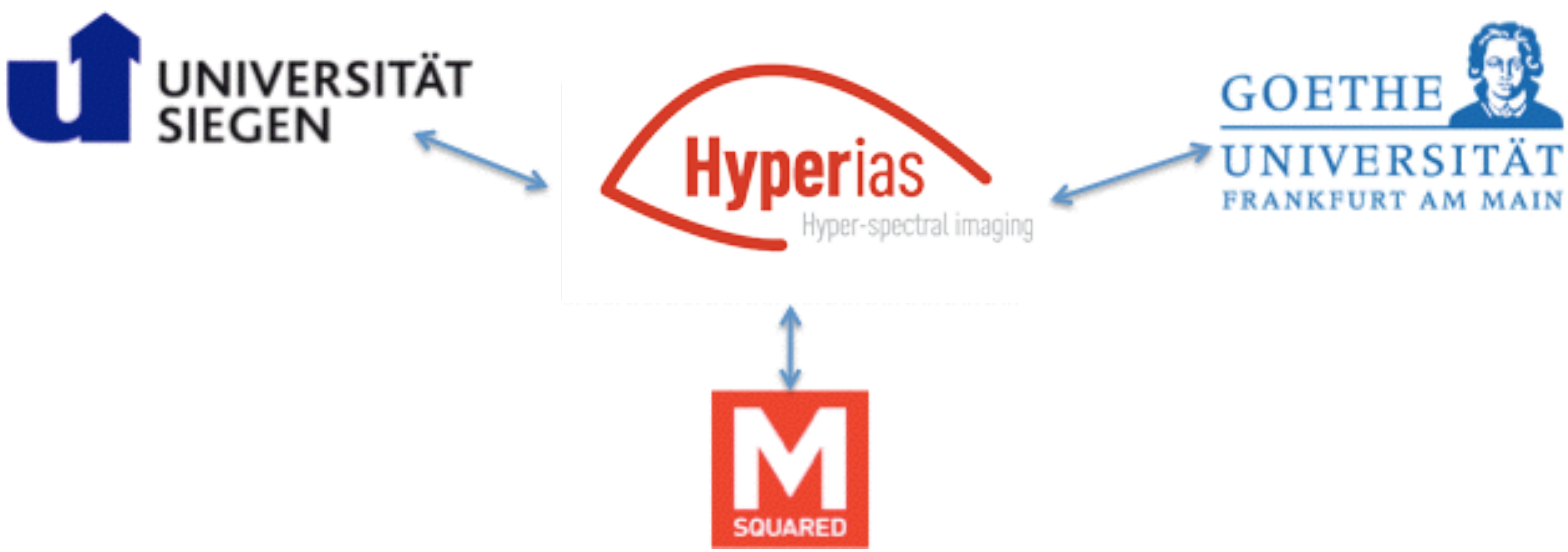
33.5 cm x 25 cm x 13 cm



European Project

Hyperias

Industry Accademic Partnerships and Pathways



SEVENTH FRAMEWORK PROGRAMME

The HYPERIAS project has received funding from the European Community's Seventh Framework Programme under Grant Agreement No. 324445

European Project Hyperias

Hyper-Spectral Imaging and Sensing in the THz Frequency Range

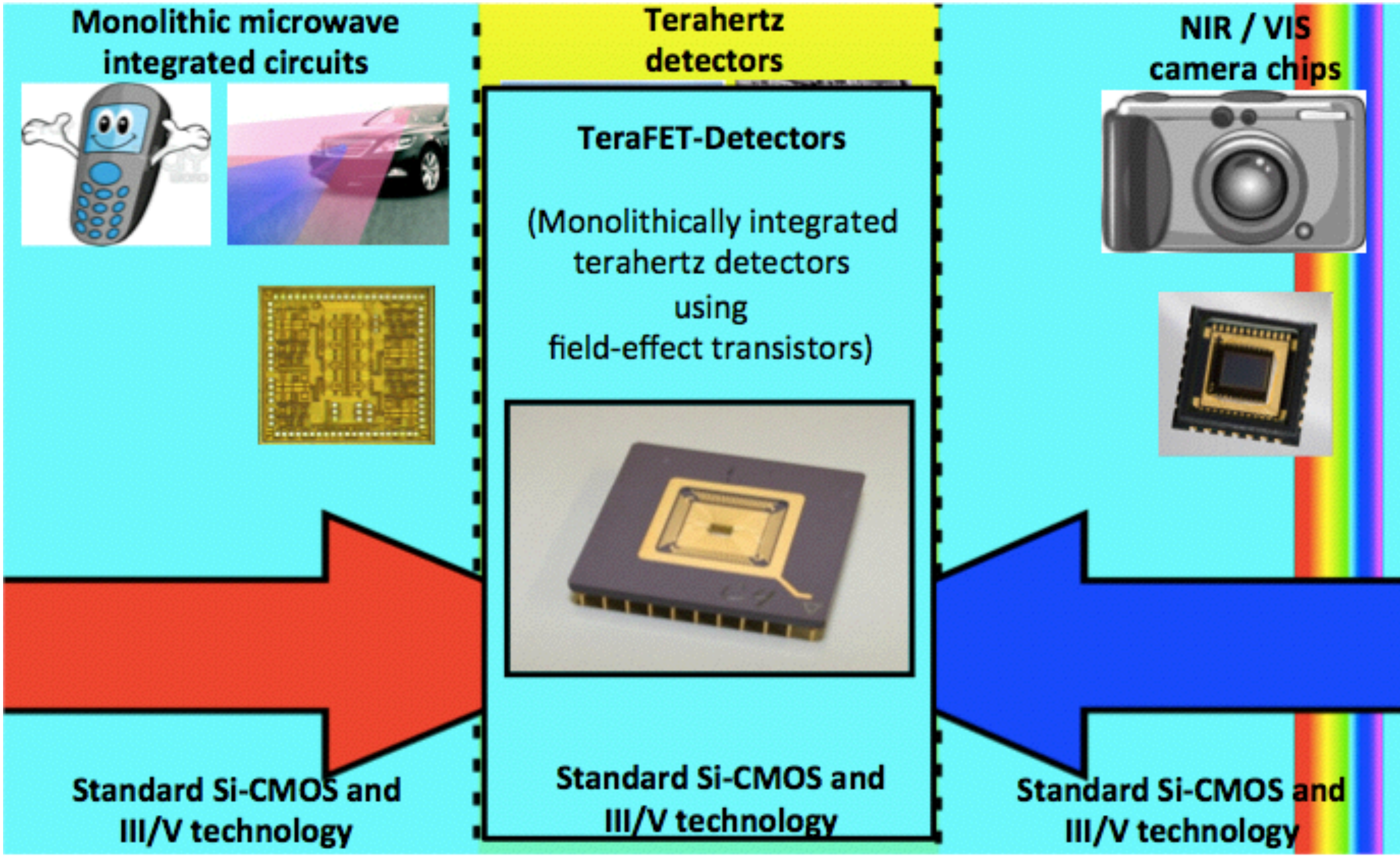
- Novel (CMOS) detectors
- Novel Source technology
- For the remote and proximity imaging
- Sensing of explosives and other relevant THz applications

SEVENTH FRAMEWORK PROGRAMME

The HYPERIAS project has received funding from the European Community's Seventh Framework Programme under Grant Agreement No. 324445

Goehte University

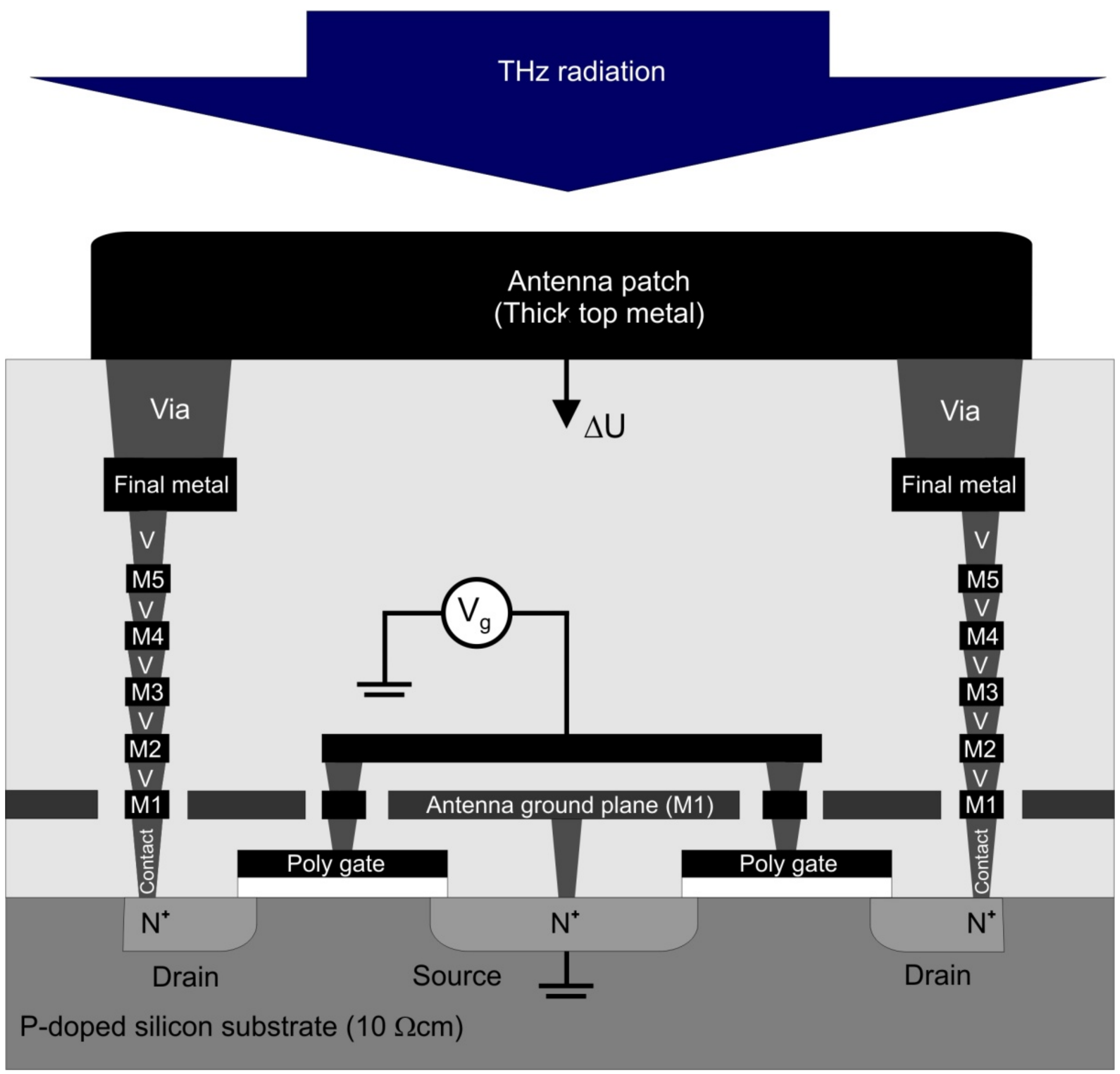
Detector Development

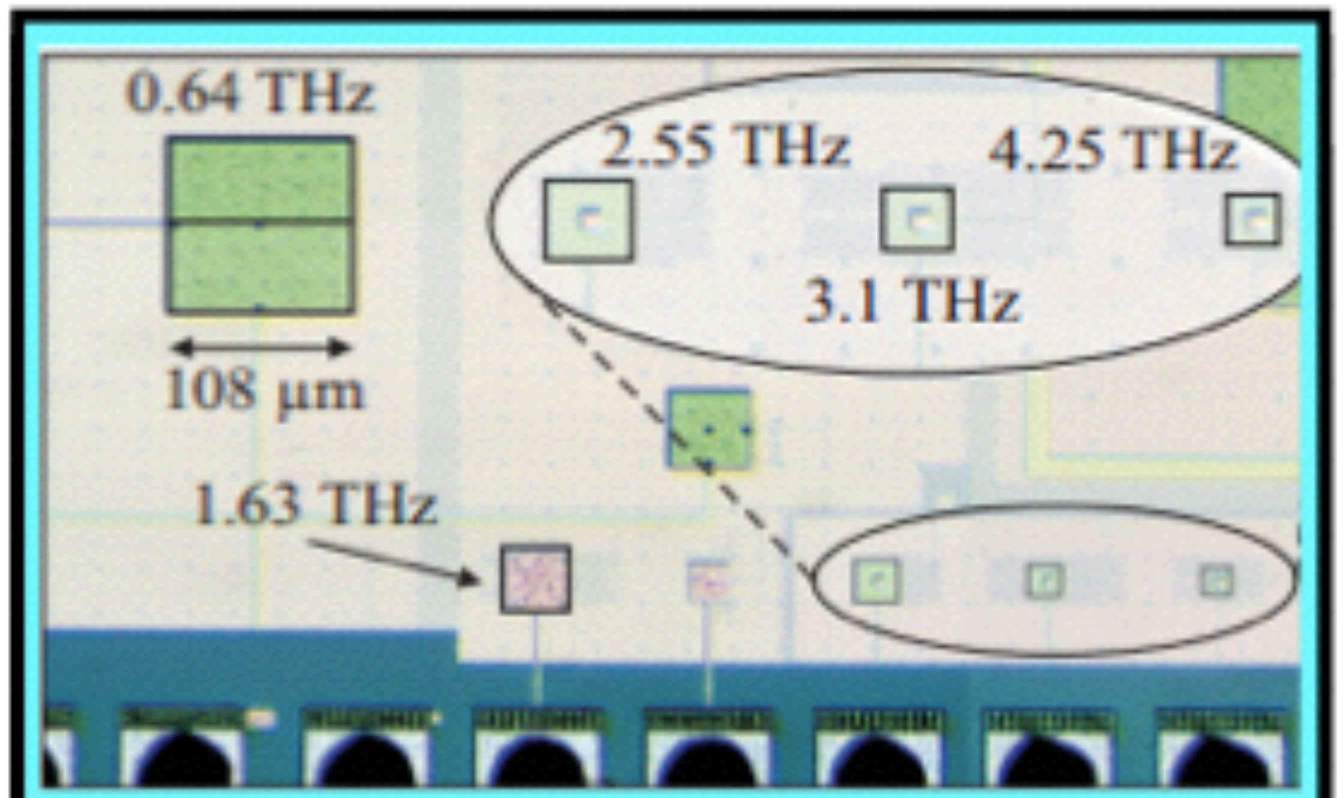


Goehte University

Detector Development

Implementations using cost-efficient commercial CMOS technology



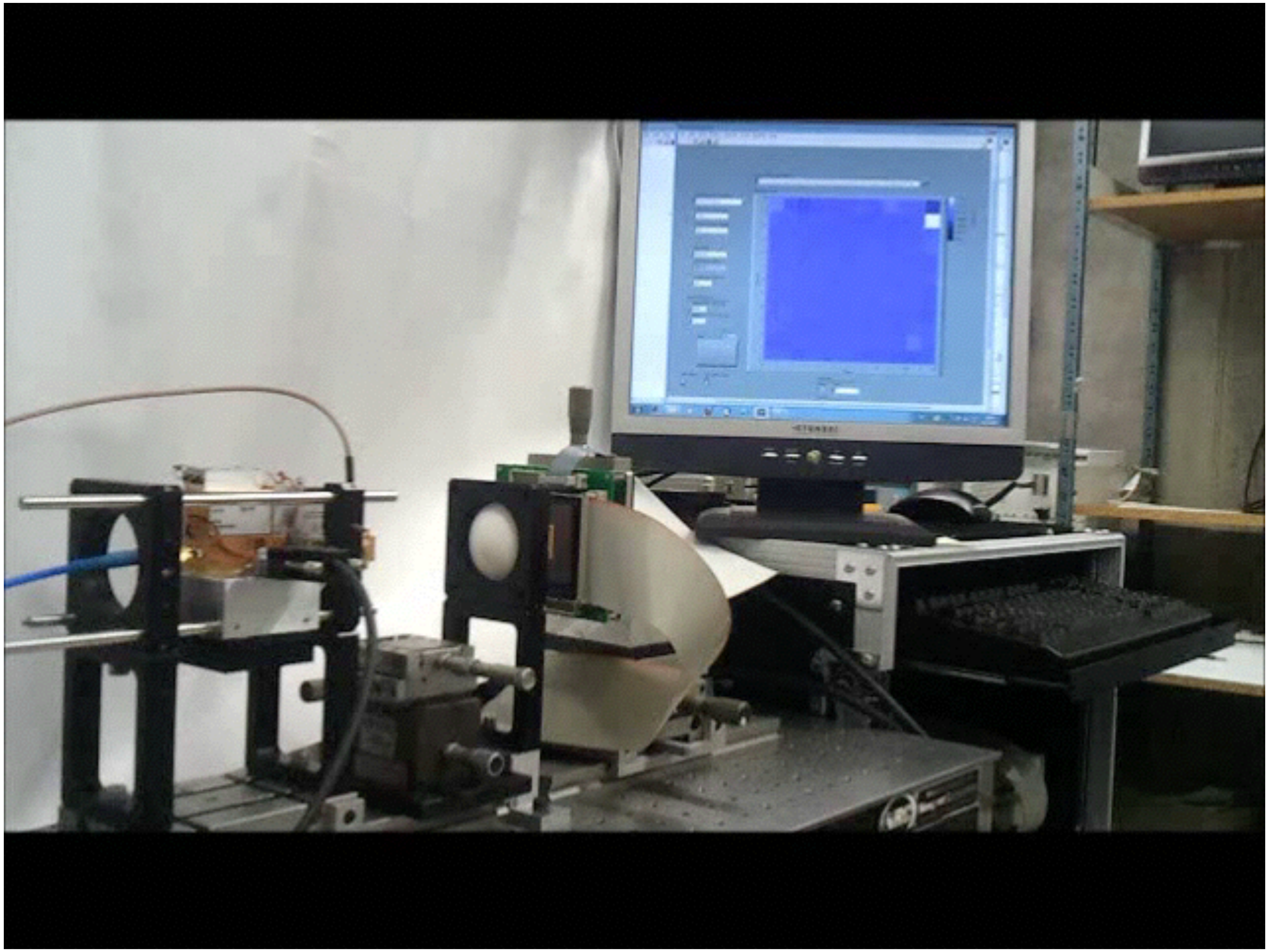


- **90-nm CMOS-Technology**
- **Operation demonstrated from 0.3 THz up to 9 THz**
- **Room temperature NEP: e.g. 63 pW/√Hz at 2.52 THz**
- **Competitive with commercial room-temperature detectors**

S. Boppel et al., IEEE Trans. Microw. Theory Techn. 60, 3834 (2012)
A. Lisauskas et al., J Infrared Milli mTeraherz Waves doi: 10.1007/s10762-013-0047-7(2014)

Goehte University

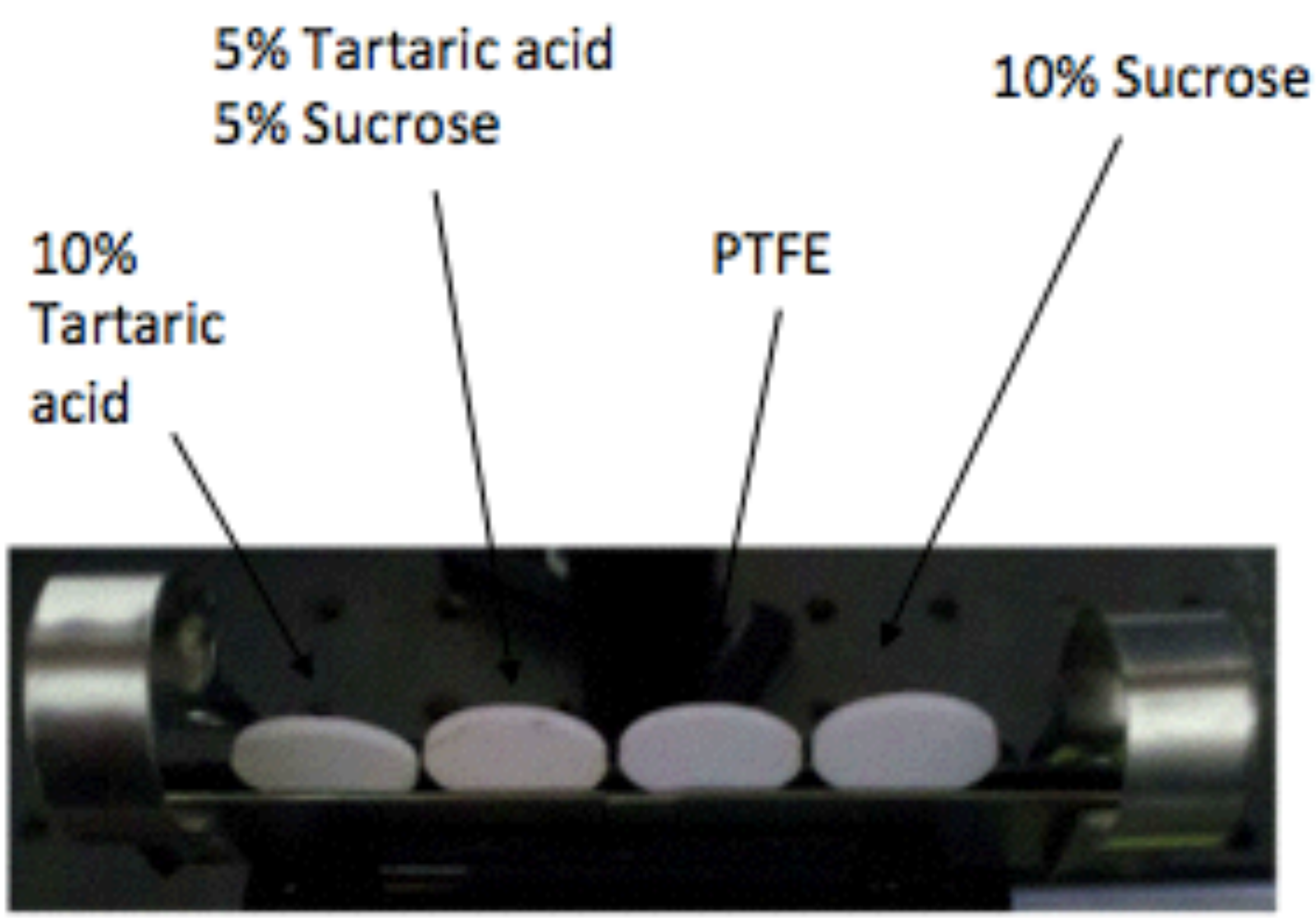
Detector Development



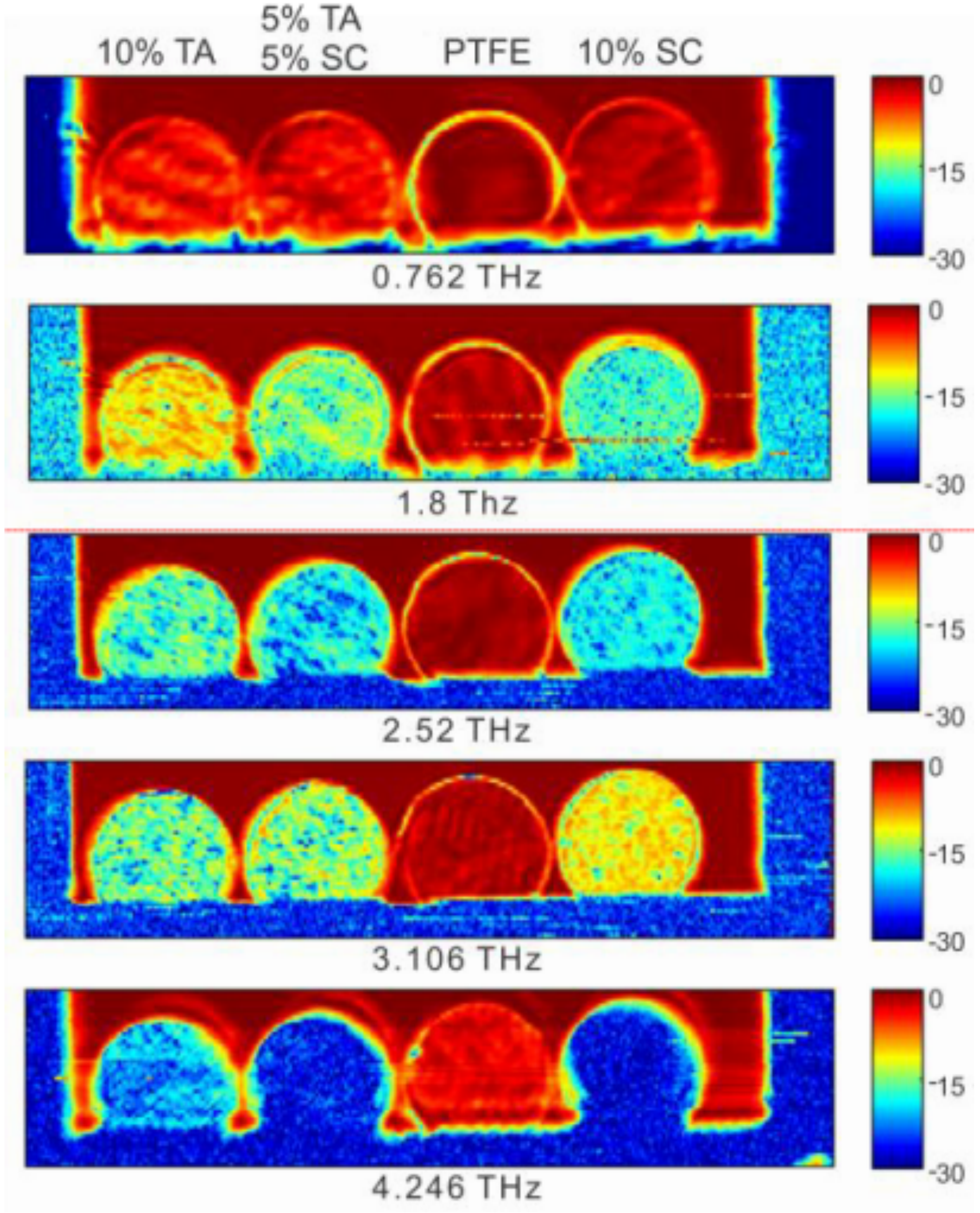
Goehte University

Detector Development

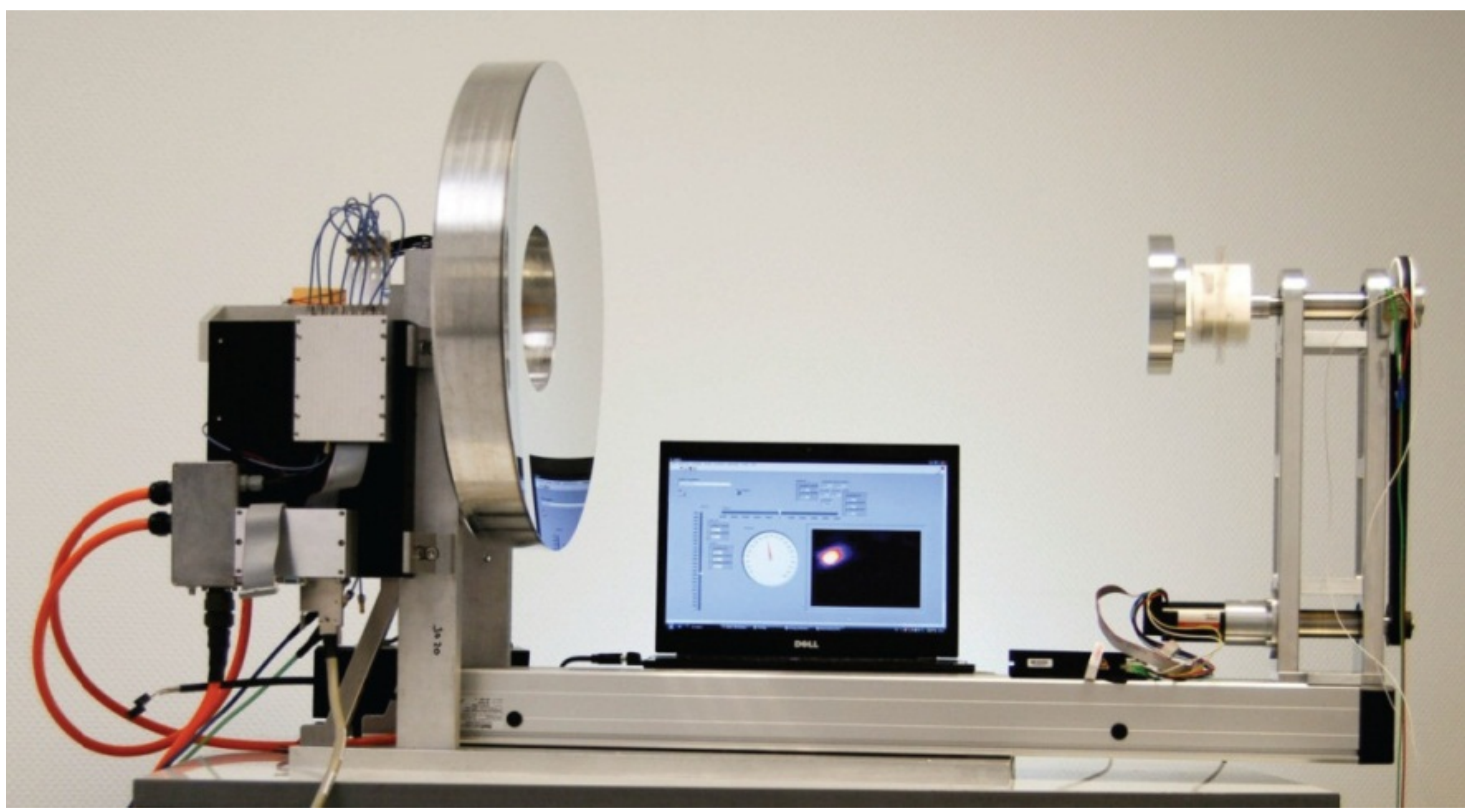
Imaging Examples using Point Detector

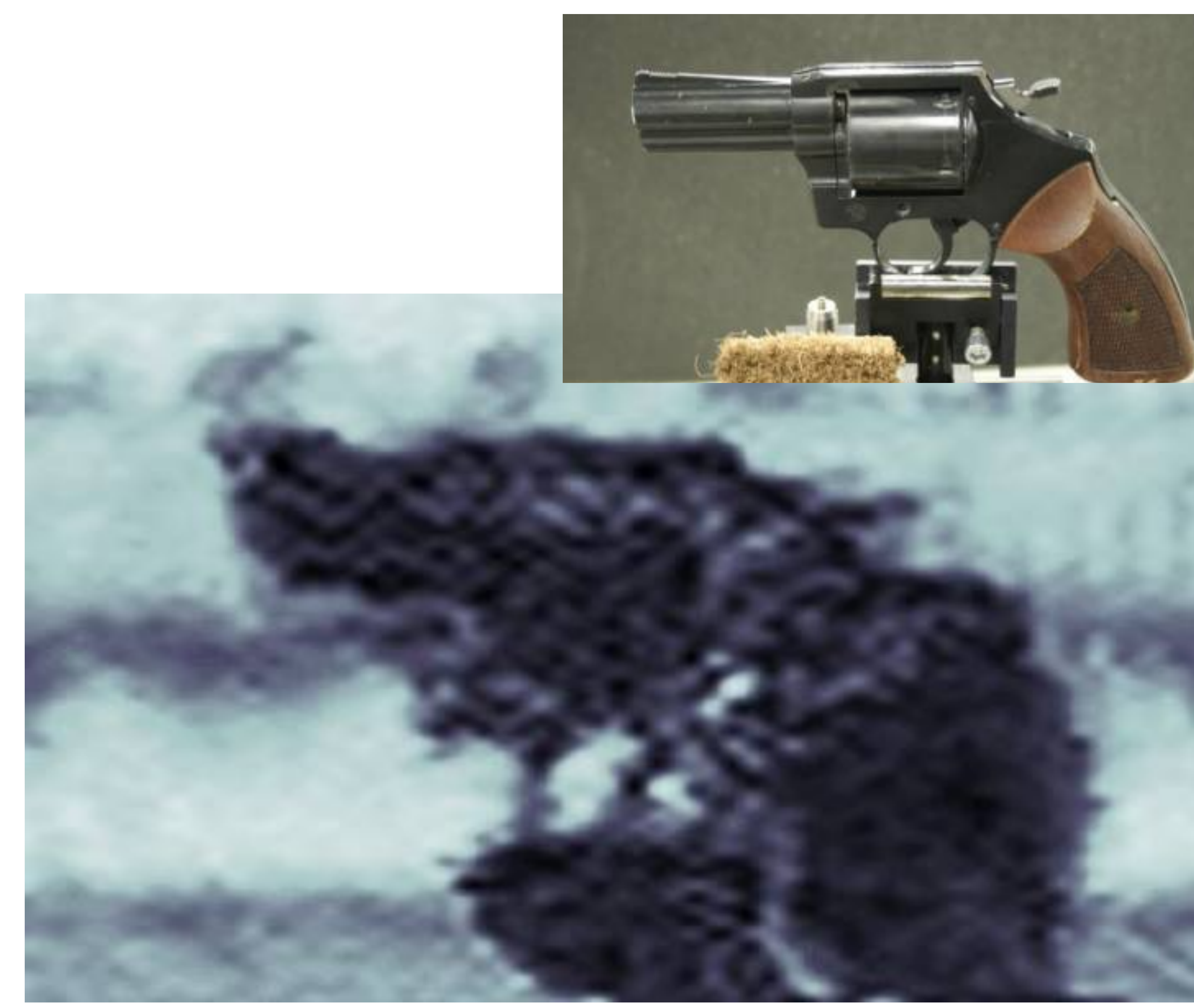


I. Kašalynas, R. Venckevičius, D. Seliuta, I. Grigelionis, and G. Valušis, *Journal of Applied Physics* 110, 114505 (2011).



Real-time THz Imaging for Security Applications



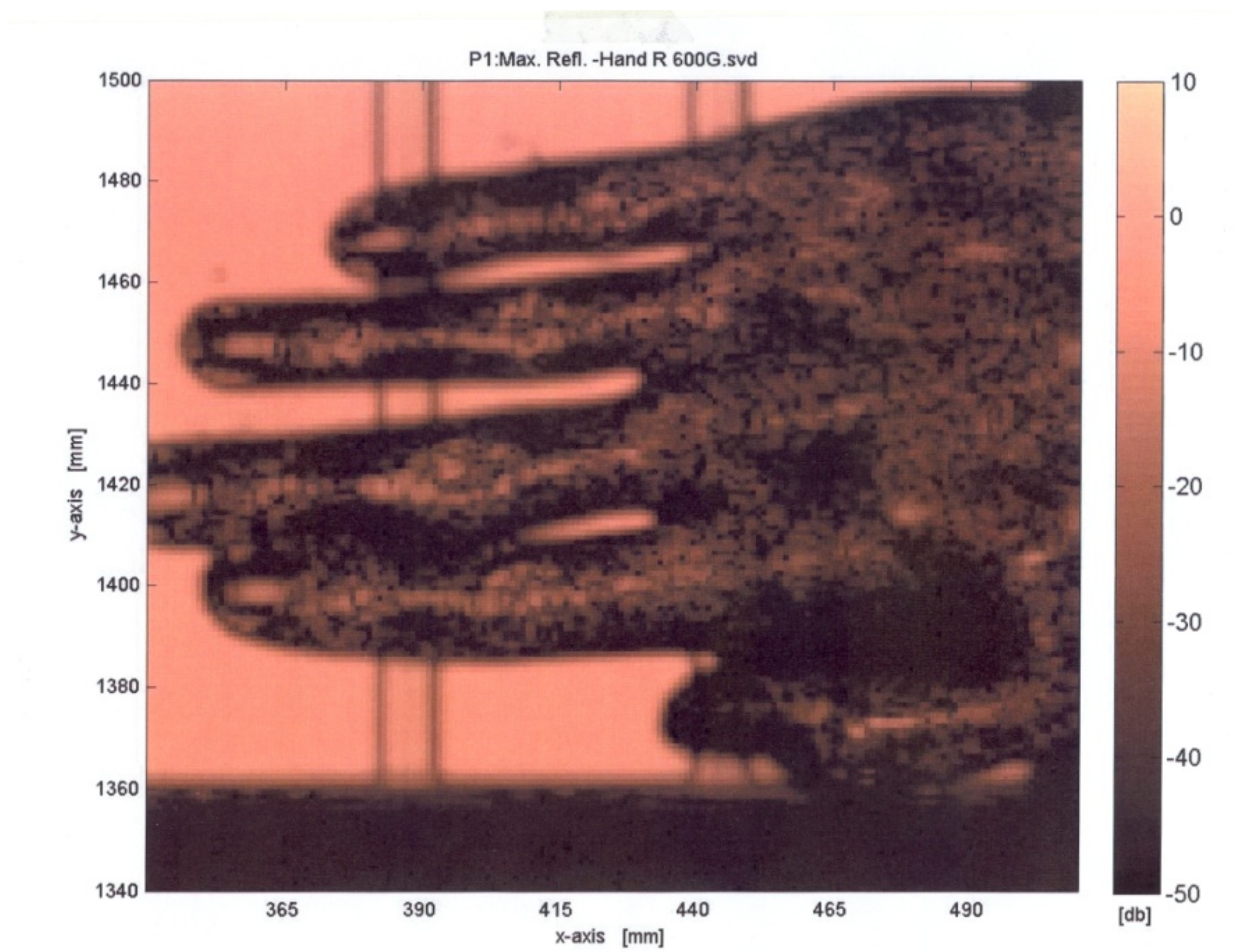


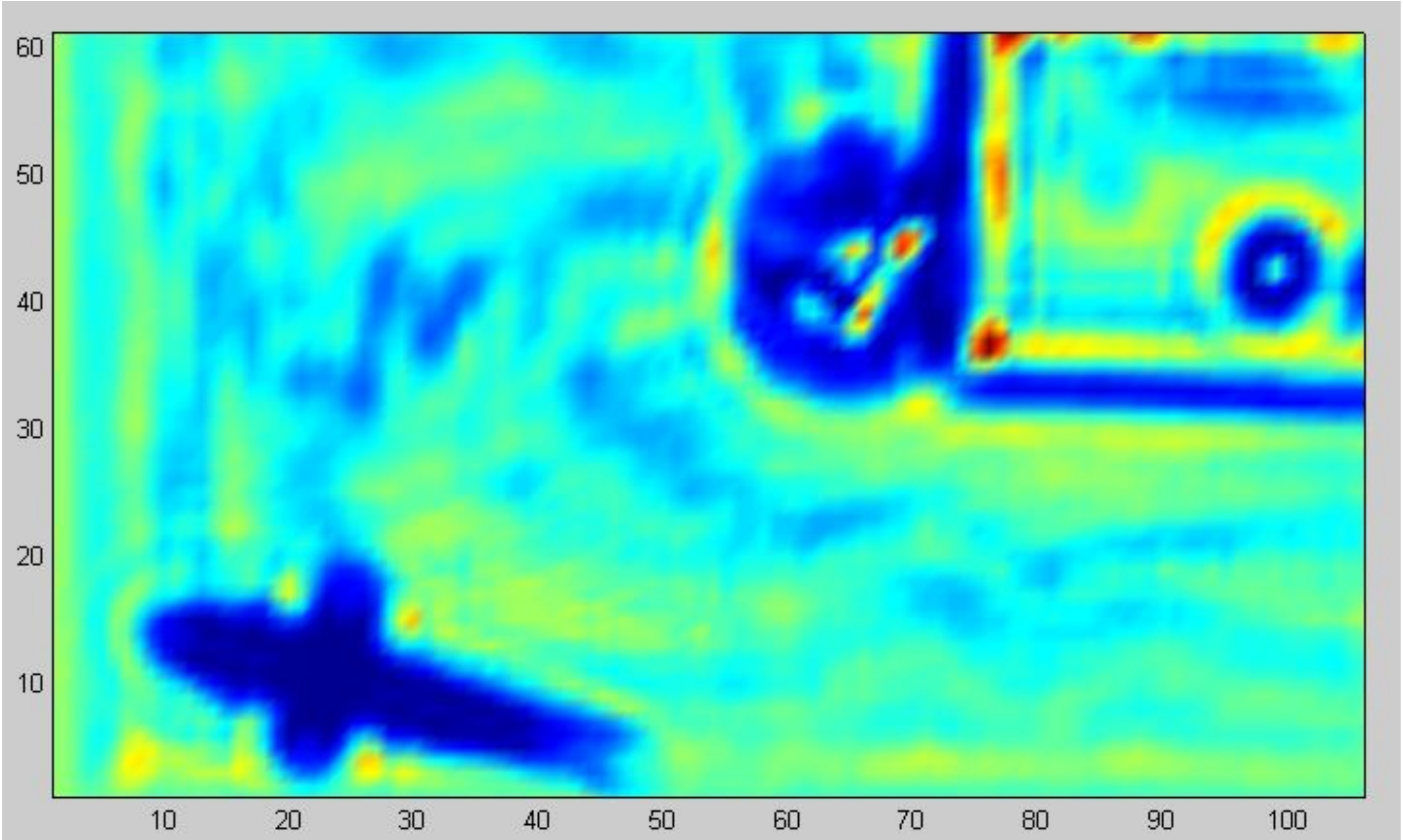
[F. Friederich, W. von Spiegel, M. Bauer, F. Meng, M. D. Thomson, S. Boppel, A. Lisauskas, B. Hils, V. Krozer, A. Keil, T. Löffler, R. Henneberger, A. K. Huhn, G. Spickermann, P. H. Bolívar, H. G. Roskos, THz Active Imaging Systems With Real-Time Capabilities, Appl. Phys. Lett., 103, 031106 (2013)]

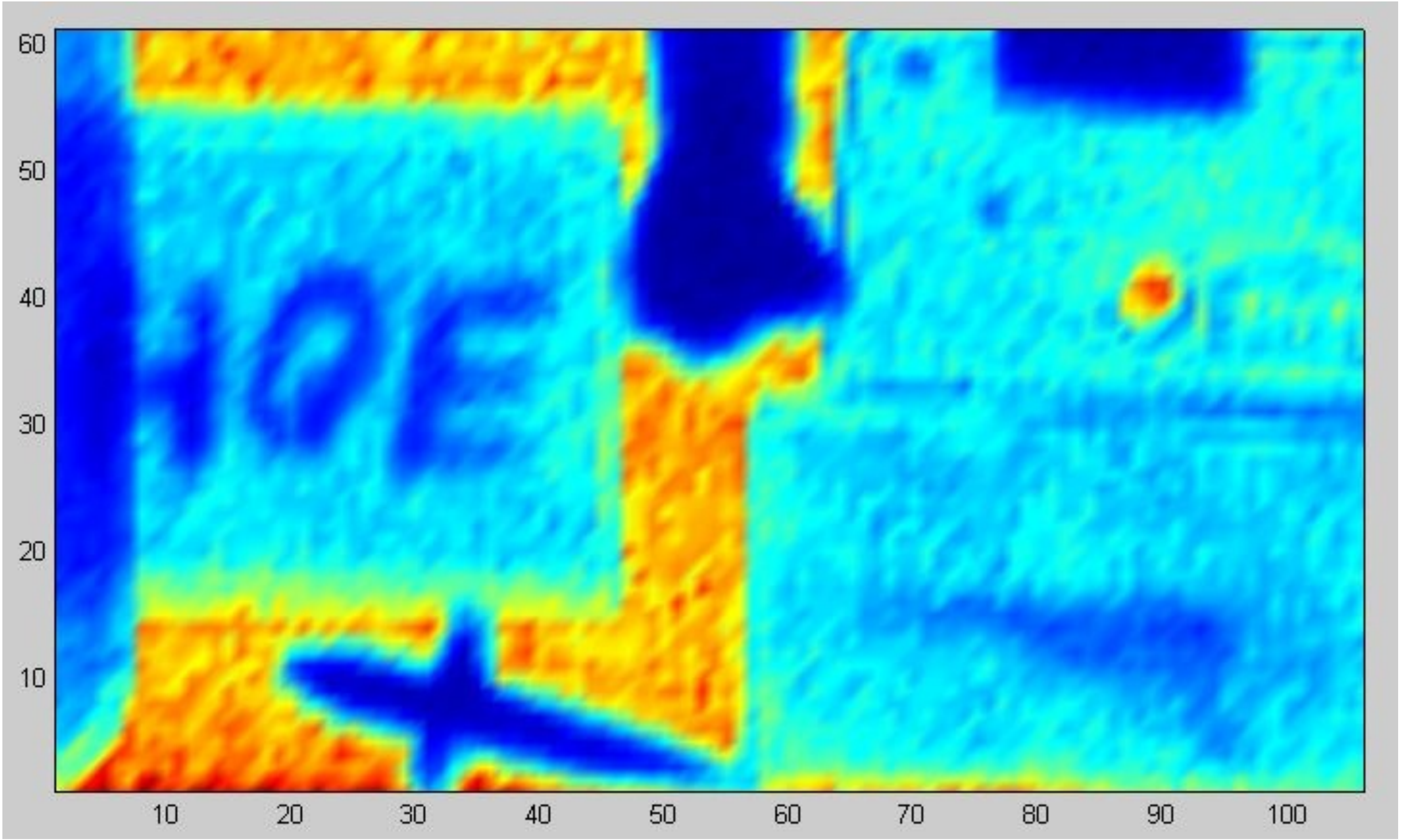
University of Siegen

Applications

THz Imaging at 140GHz, 600GHz, 2.5THz







Hyperias

Project Aims

System Development

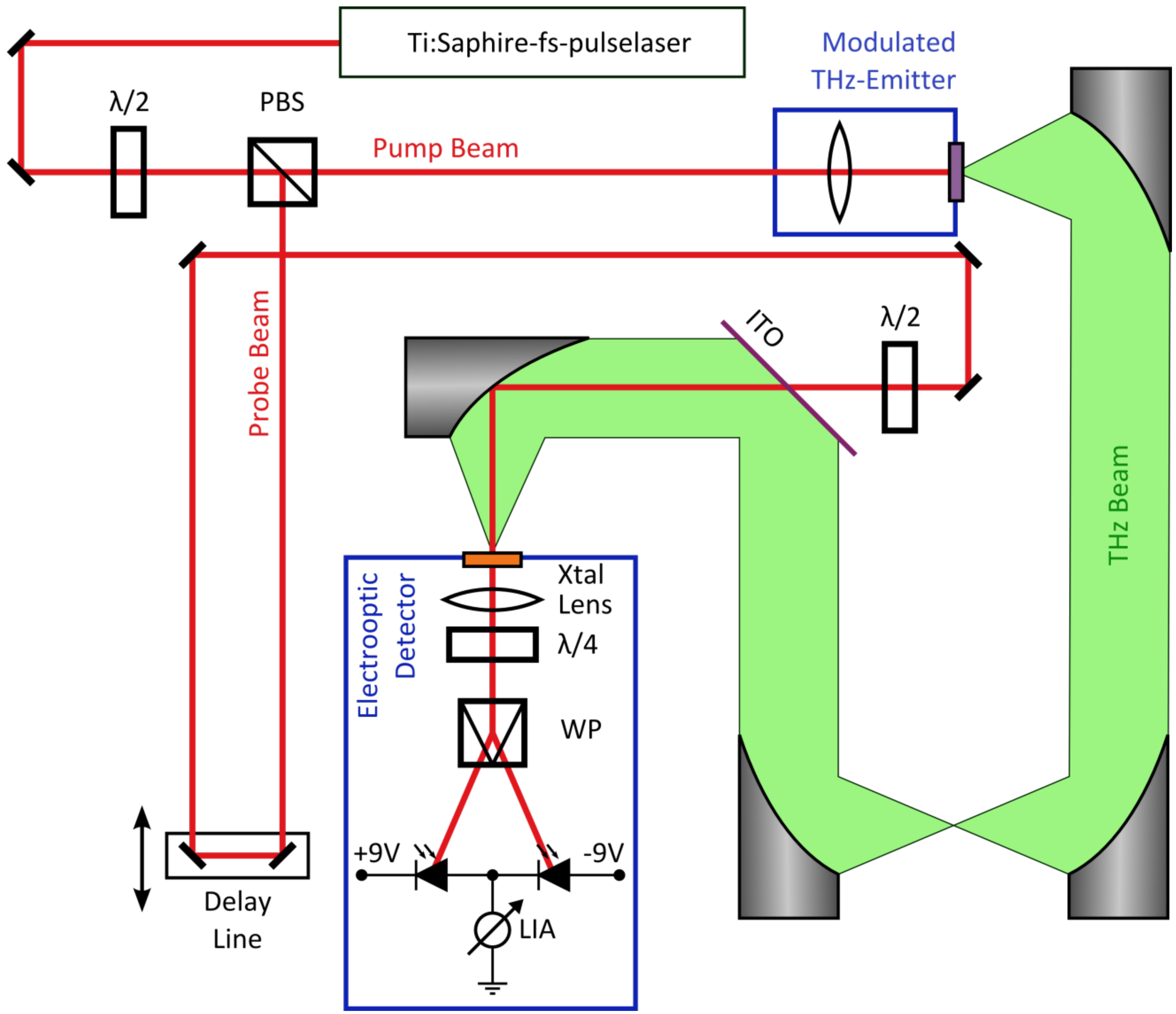
- Source Performance (power, frequency stability, linewidth narrowing)
- Optimised Detectors (proximity and stand-off detection)
- System concepts and data processing algorithms for active terahertz hyper-spectral sensing and imaging system
- Development of active hyper-spectral terahertz imaging system

Presentation Outline

- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- **Applications**
  - **Pharmaceutical**
  - Security / Defense
- Open Innovation

Ultrafast Laser

For TDS System



Sprite XT

Ultrafast Laser

Hands free, compact fs Ti:S for biological imaging

- Multiphoton Excitation Microscopy (MPE, MPI)
- CARS
- STED

Sprite XT

Ultrafast Laser

Ideal for THz generation

- 720 - 940 nm tuning range
- <180 fs pulse duration
- 80 MHz repetition rate
- > 1.3 W average output power

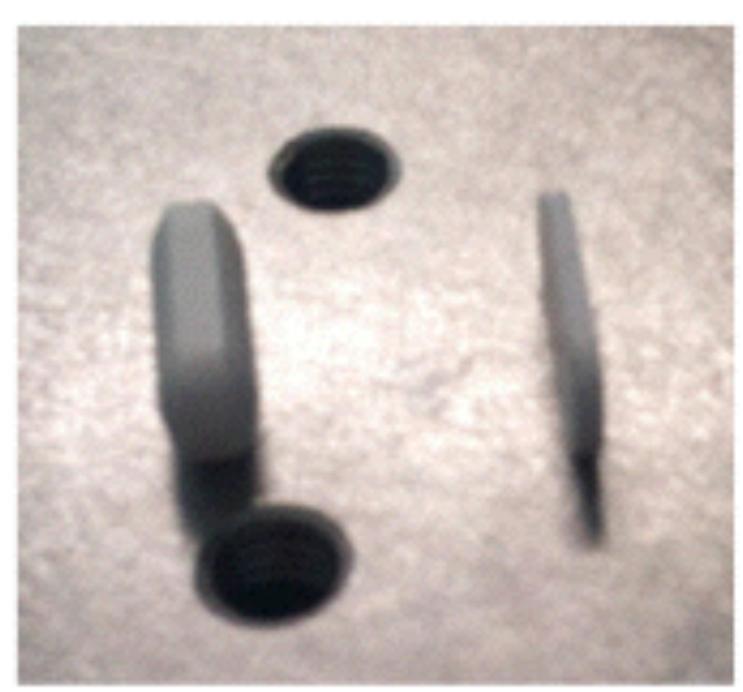
Pharmaceutical Application

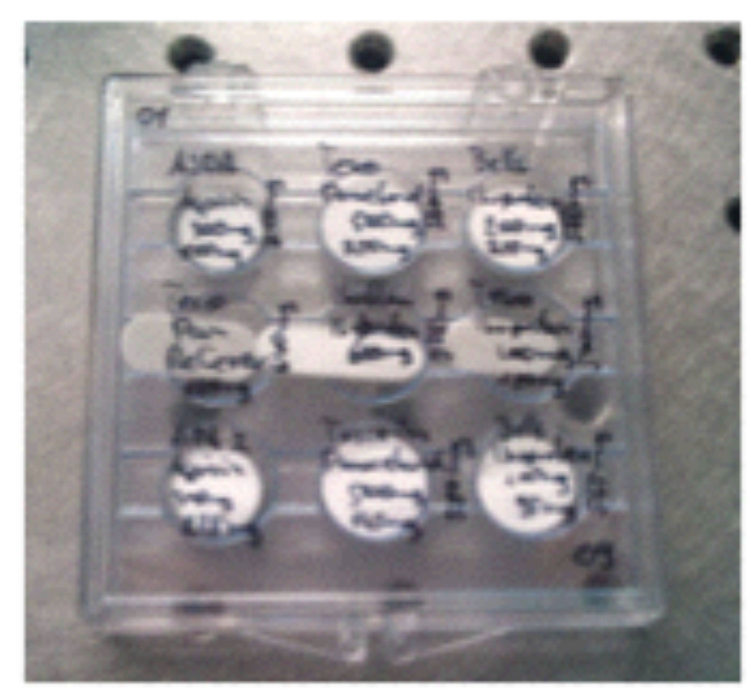
Measuring Drug Concentration

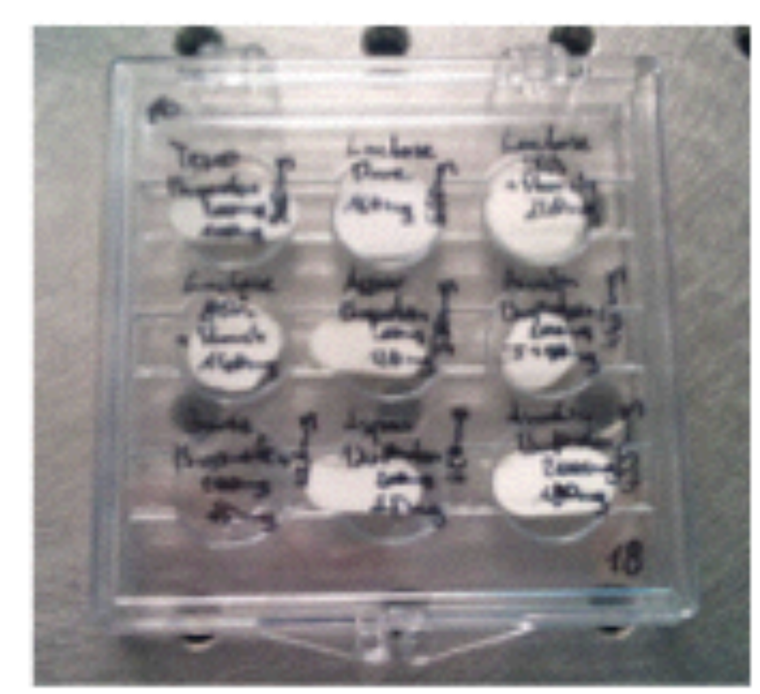
- Tablets flattened in sample preparation (avoid lensing effect)

  + Ratiopharm Ibu-Lysin 684mg

  + Ibuflam Ibuprofen 600mg



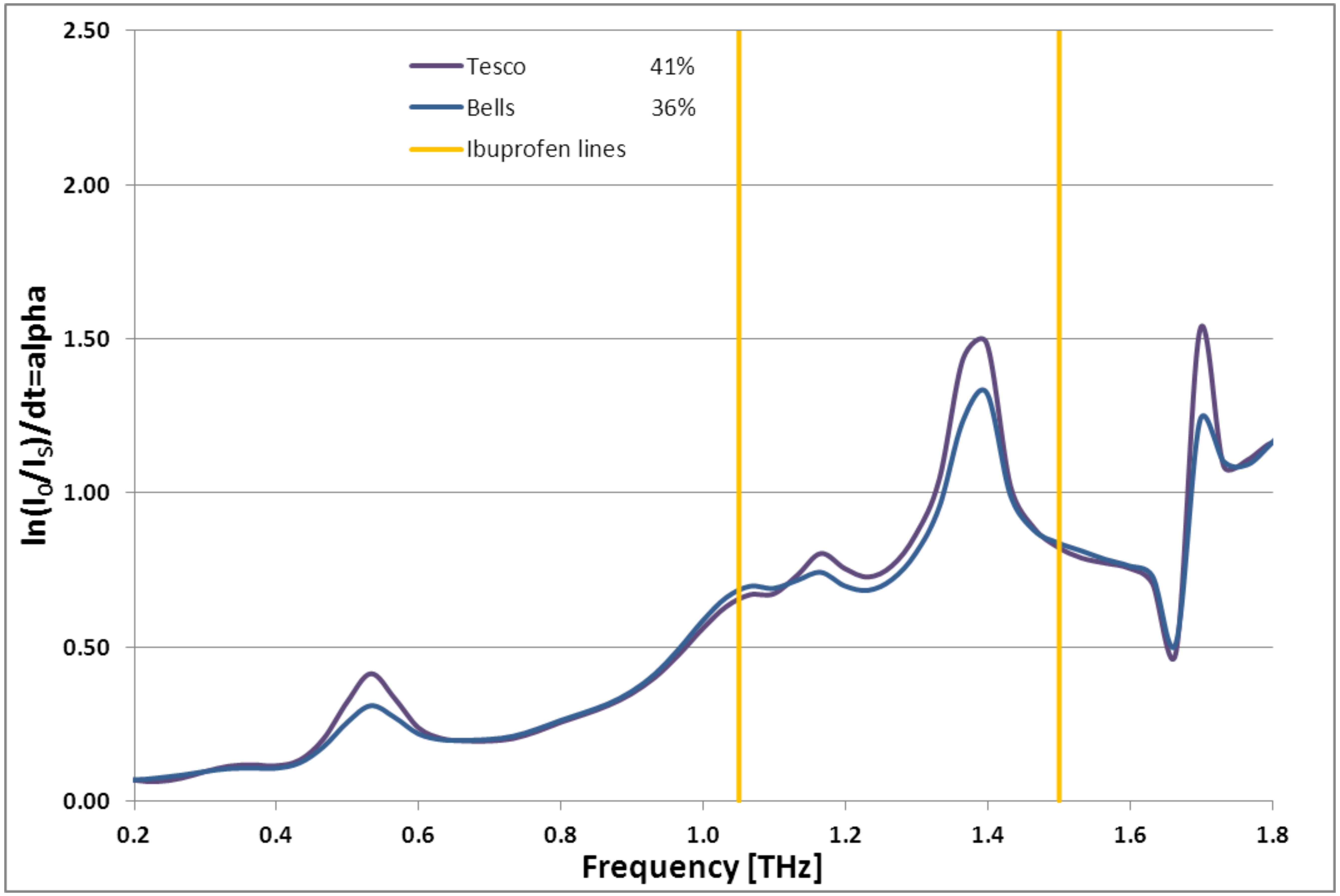




Hyperias

Pharmaceutical Application

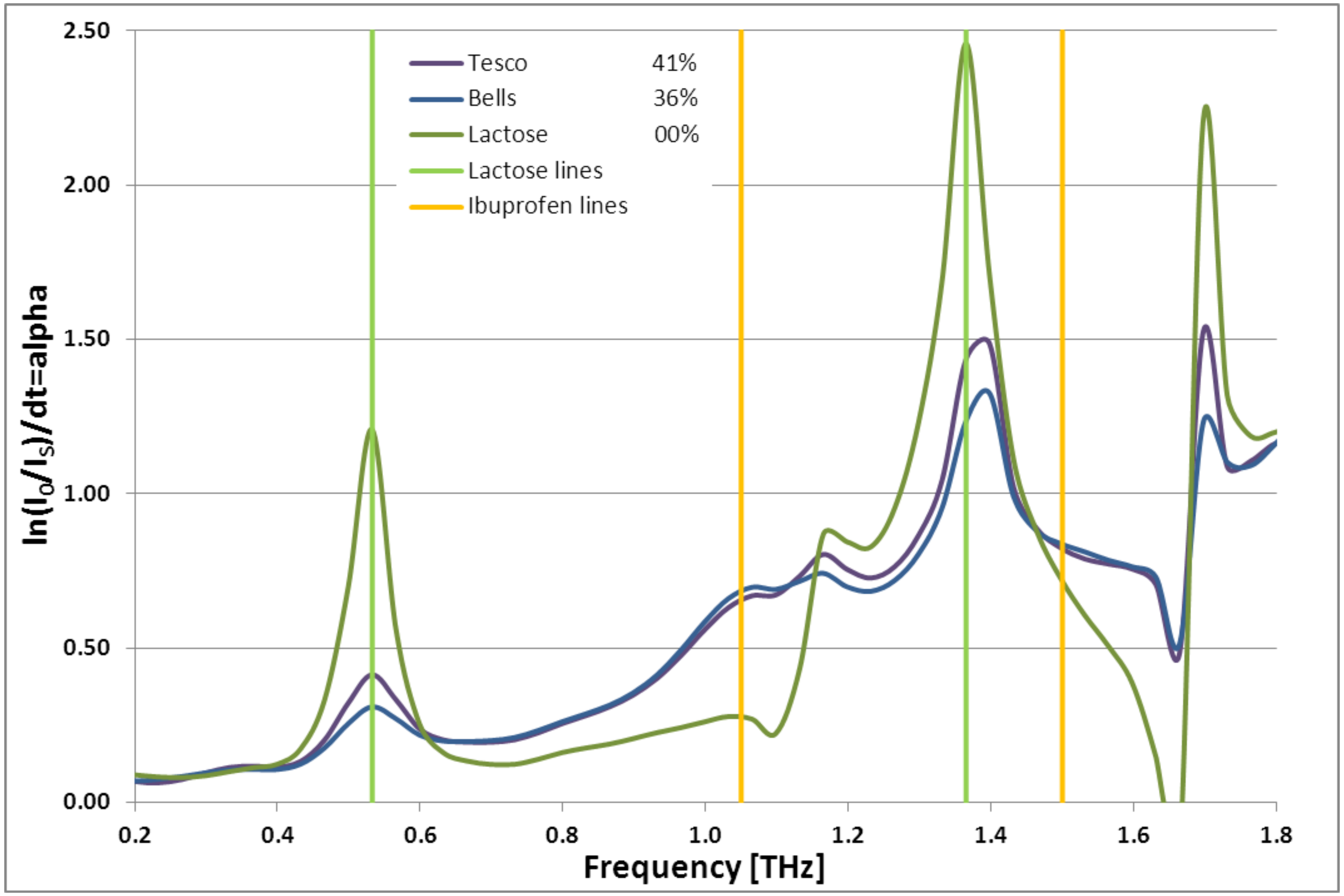
Ibuprofen Tablets



Hyperias
Hyper-spectral imaging

Hyperias Pharmaceutical Application

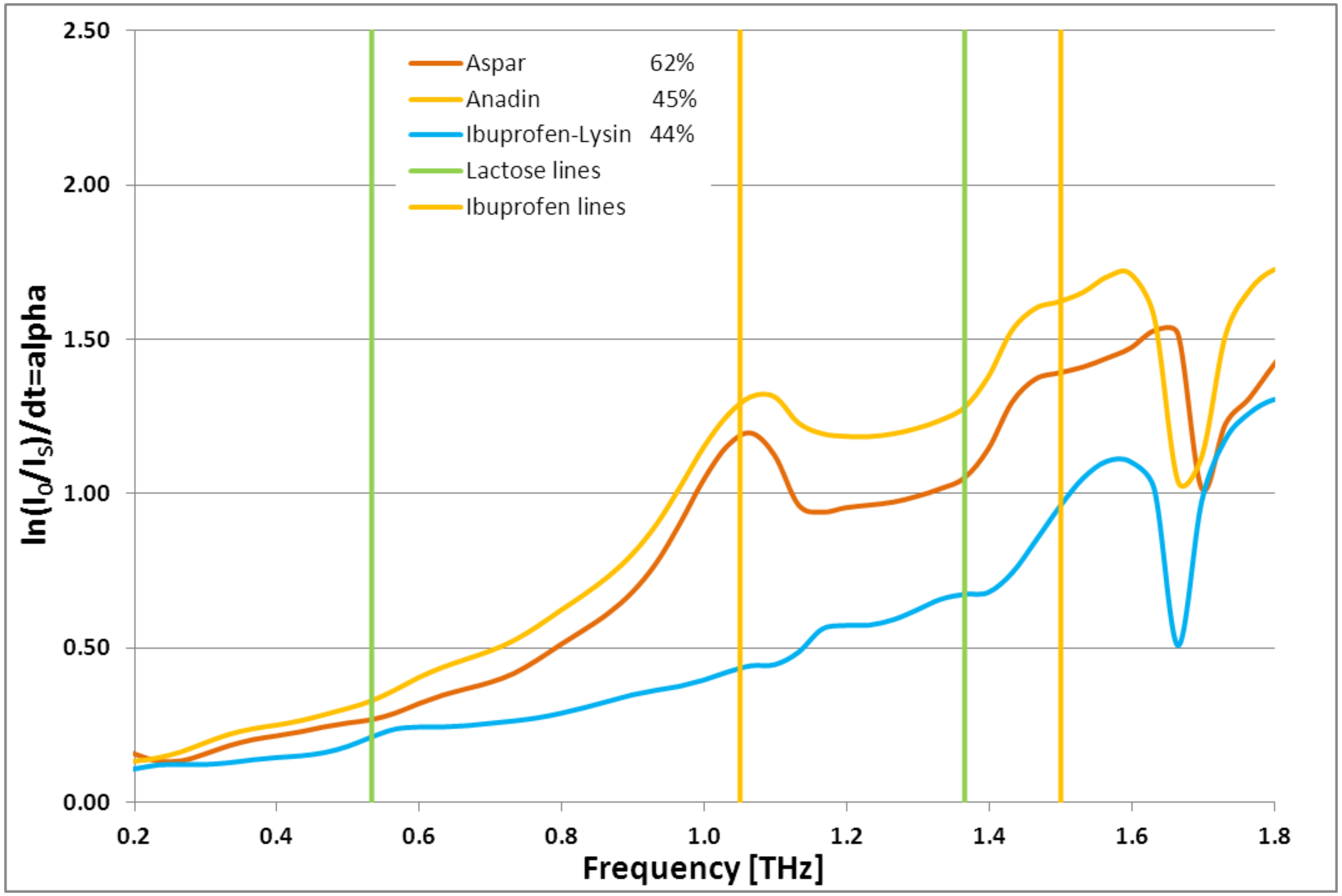
Lactose Filler



Hyperias

Pharmaceutical Application

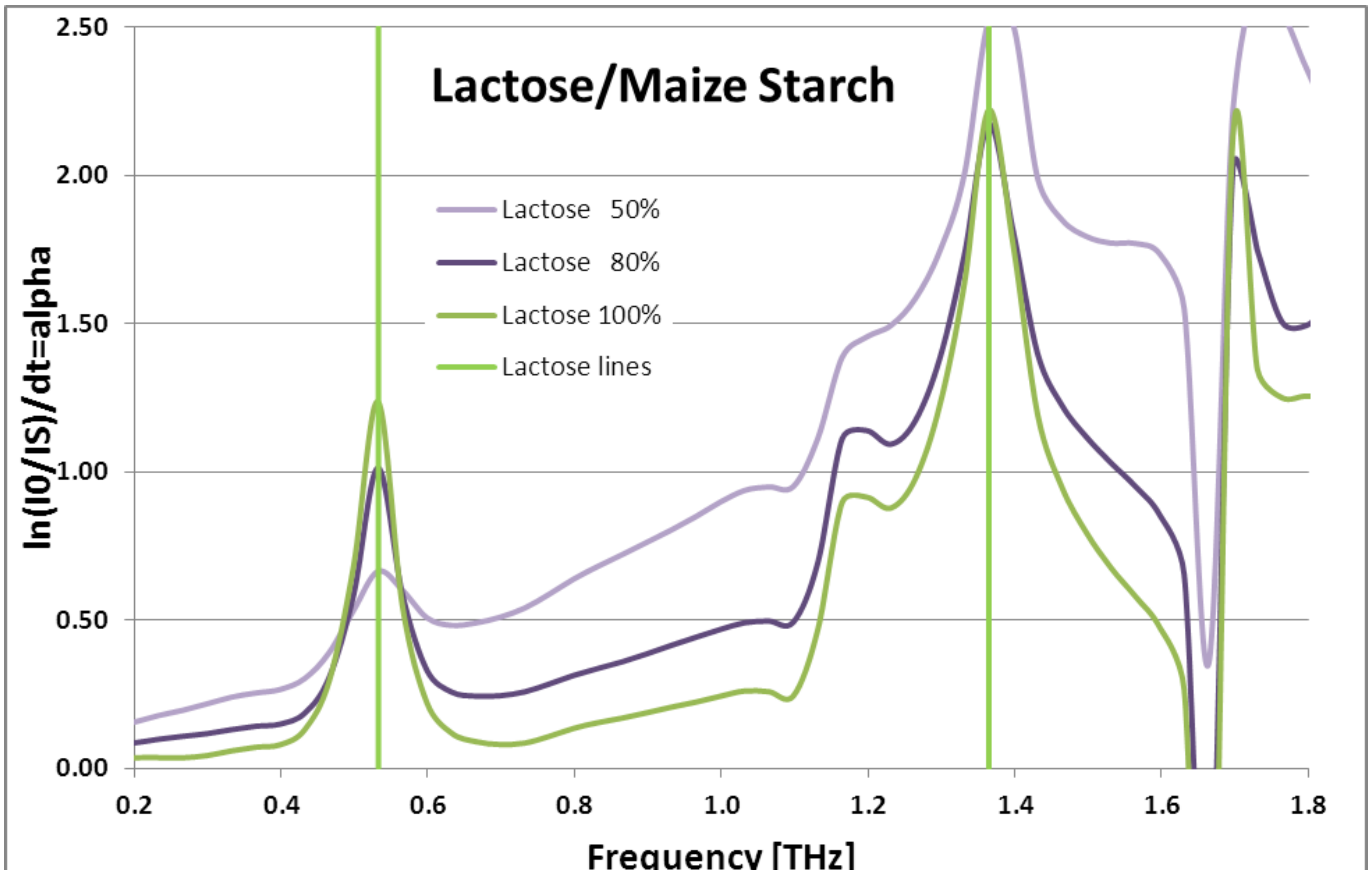
Ibuprofen without Lactose



Hyperias

Pharmaceutical Application

Maiz Starch as Filler

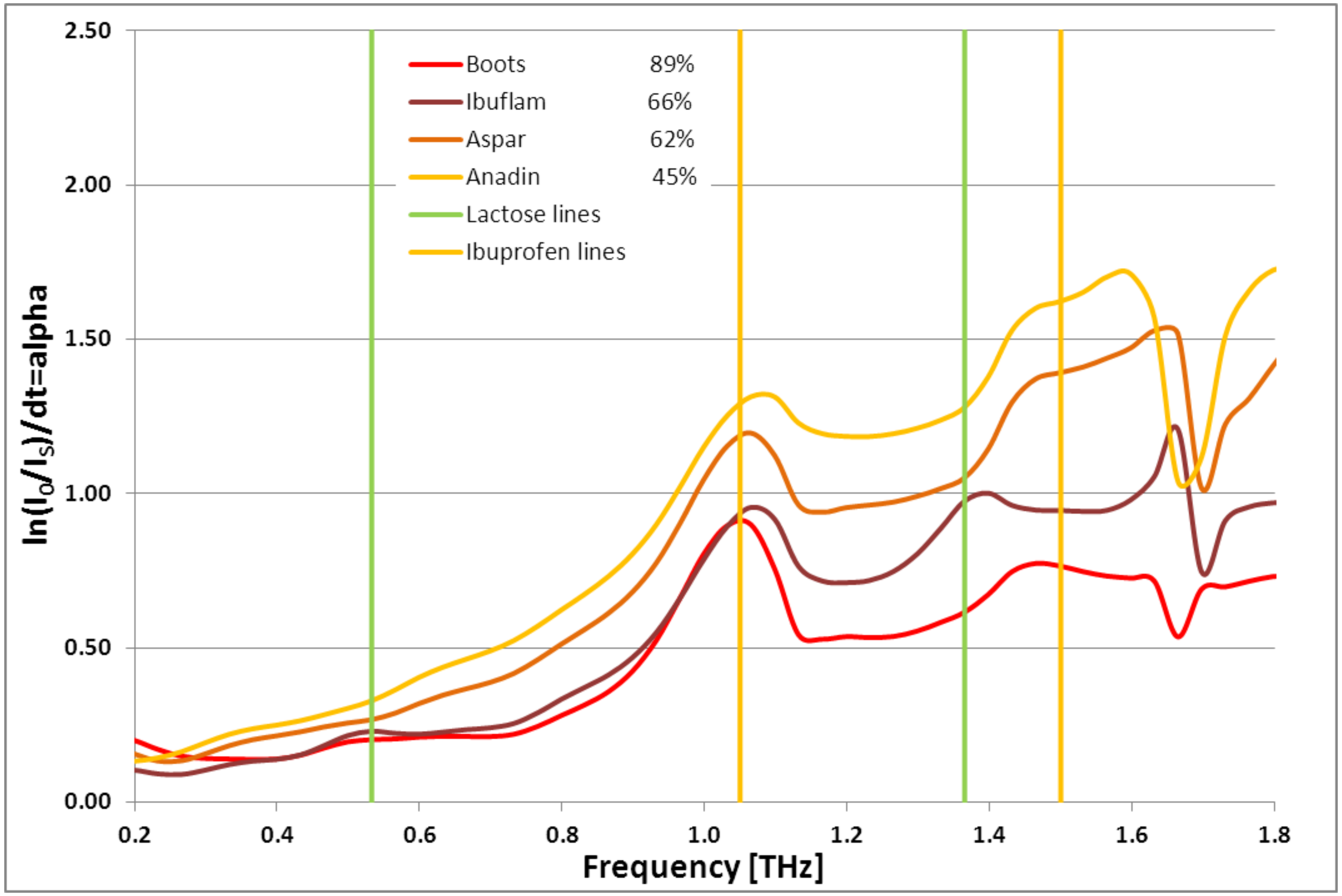


Hyperias
Hyper-spectral imaging

Hyperias

Pharmaceutical Application

Higher Concentration of Ibuprofen



Pharmaceutical Application

Measuring Drug Concentration

- Fillers in tablets add absorption lines and change overall absorption
- Absorption in Ibuprofen w/o Lactose rises with decreasing Ibu concentration (absorption in starch)
- In Ibuprofen-Lysin the Ibuprofen-absorption at 1.05THz is quenched

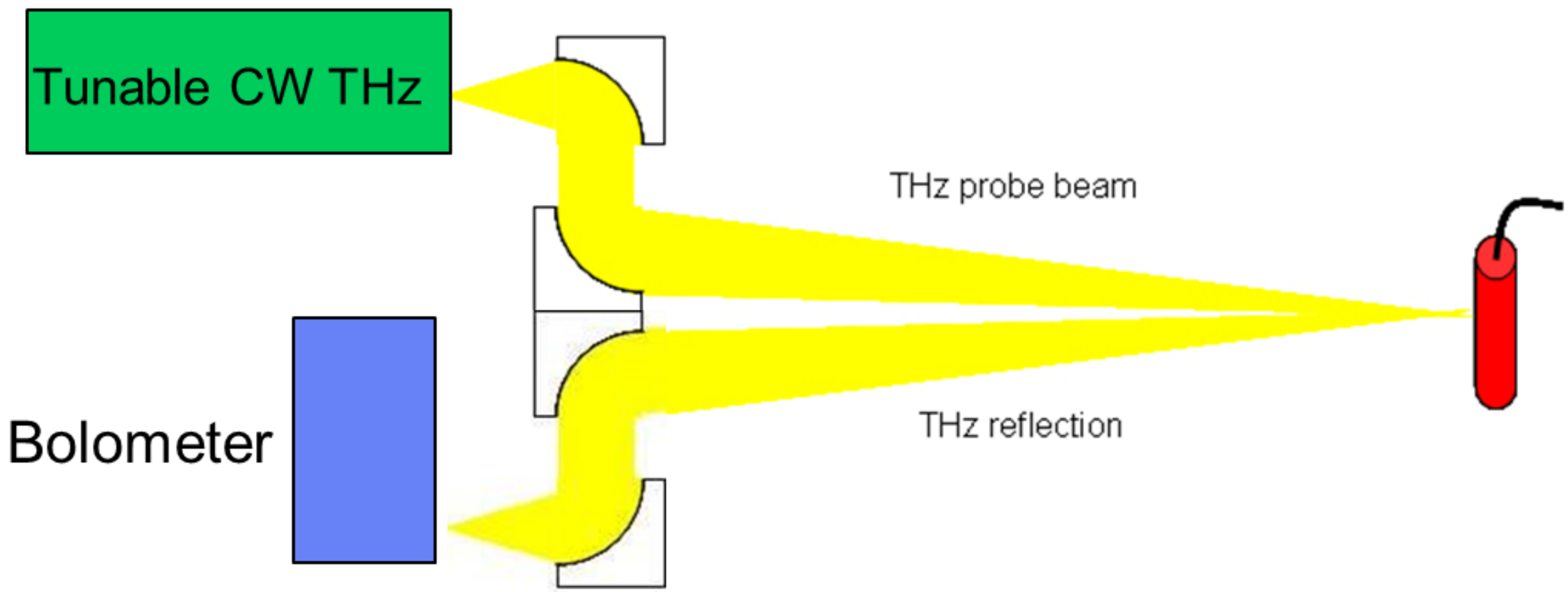
Presentation Outline

- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - **Security / Defense**
- Open Innovation

Standoff Spectroscopy

Threat Detection

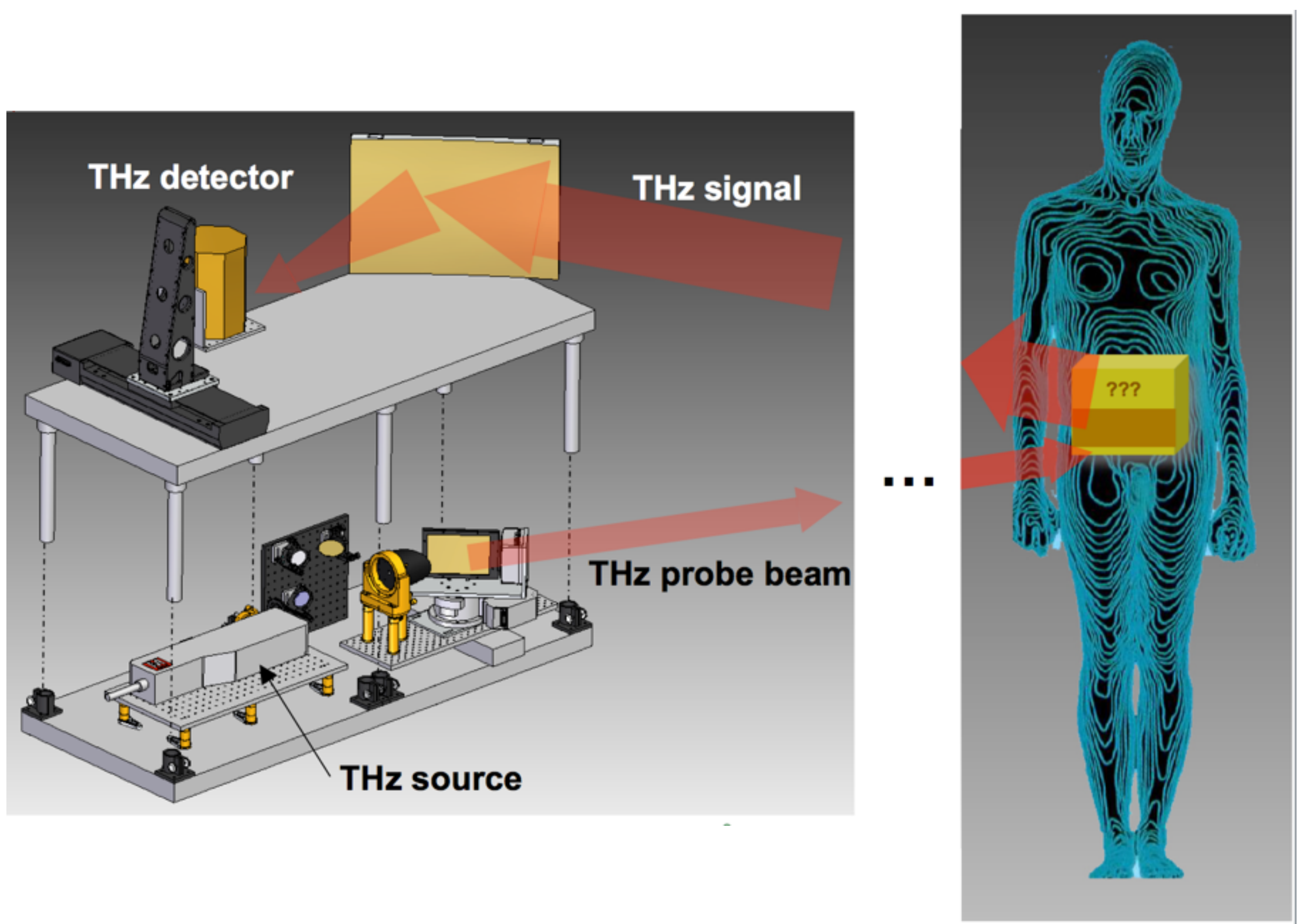
Detecting Energetic Materials at Range



Standoff Spectroscopy

Threat Detection

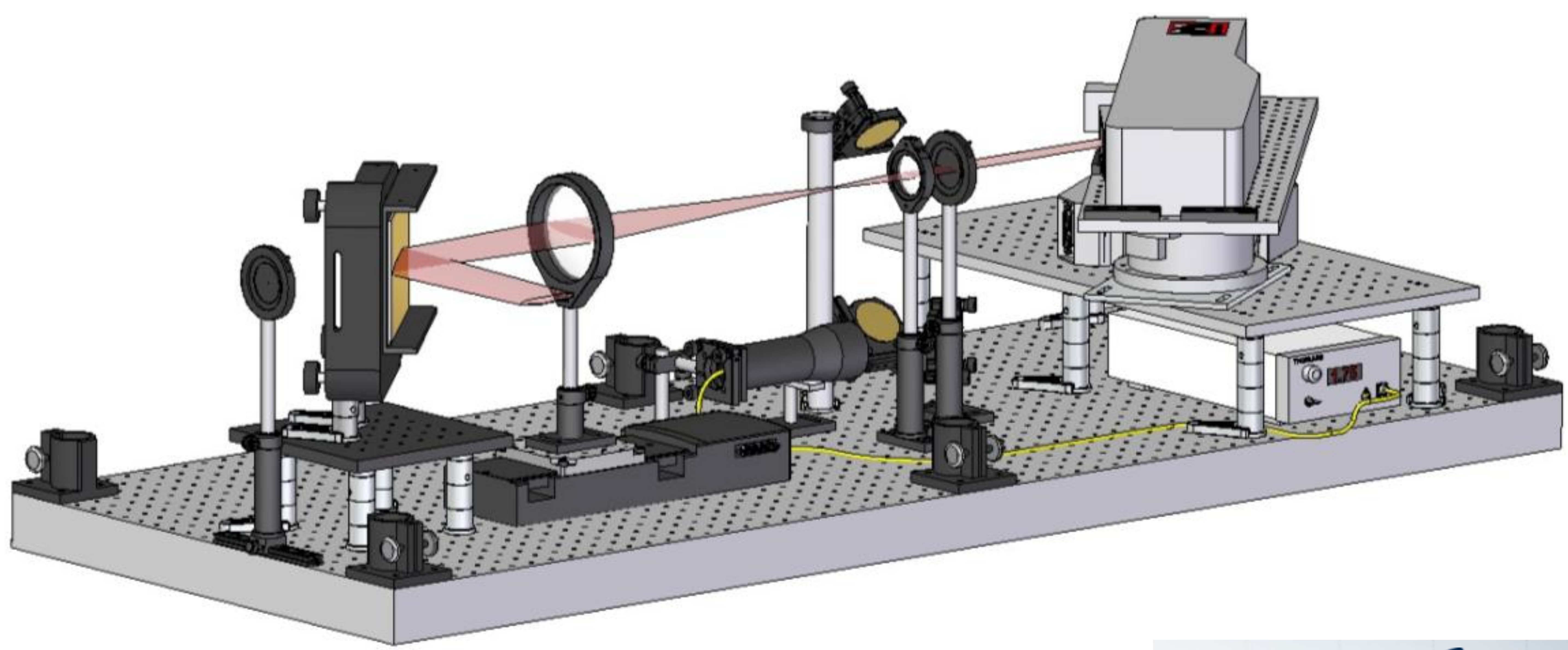
Development of hyper spectral standoff detection system



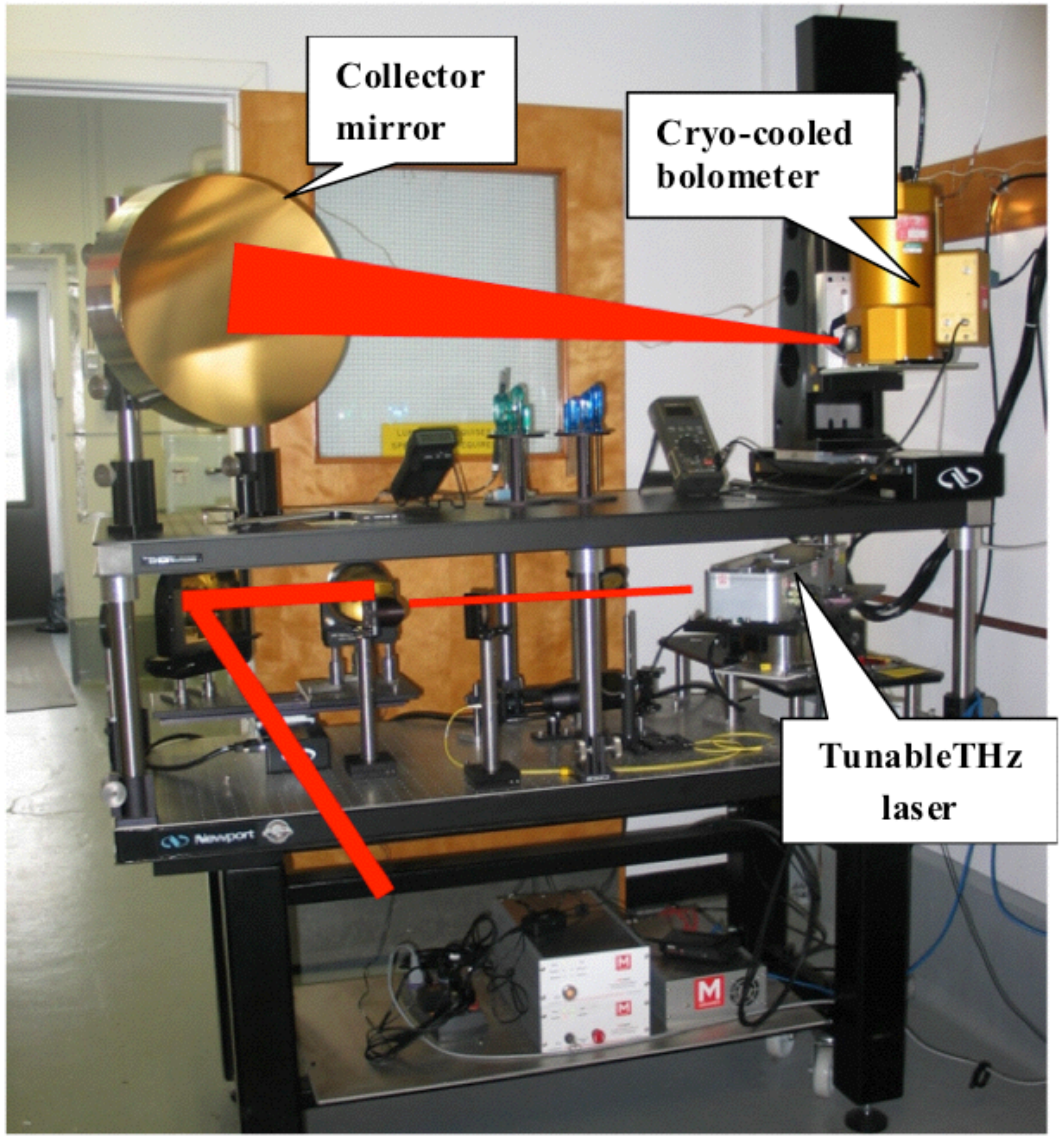
DEFENCE R&D DÉFENSE

Standoff Spectroscopy System Configuration

- Telescope to control the focussing of the THz beam
- A folding mirror for beam starring
- Visible laser boresighted with THz beam via a removable mirror to ease the pointing



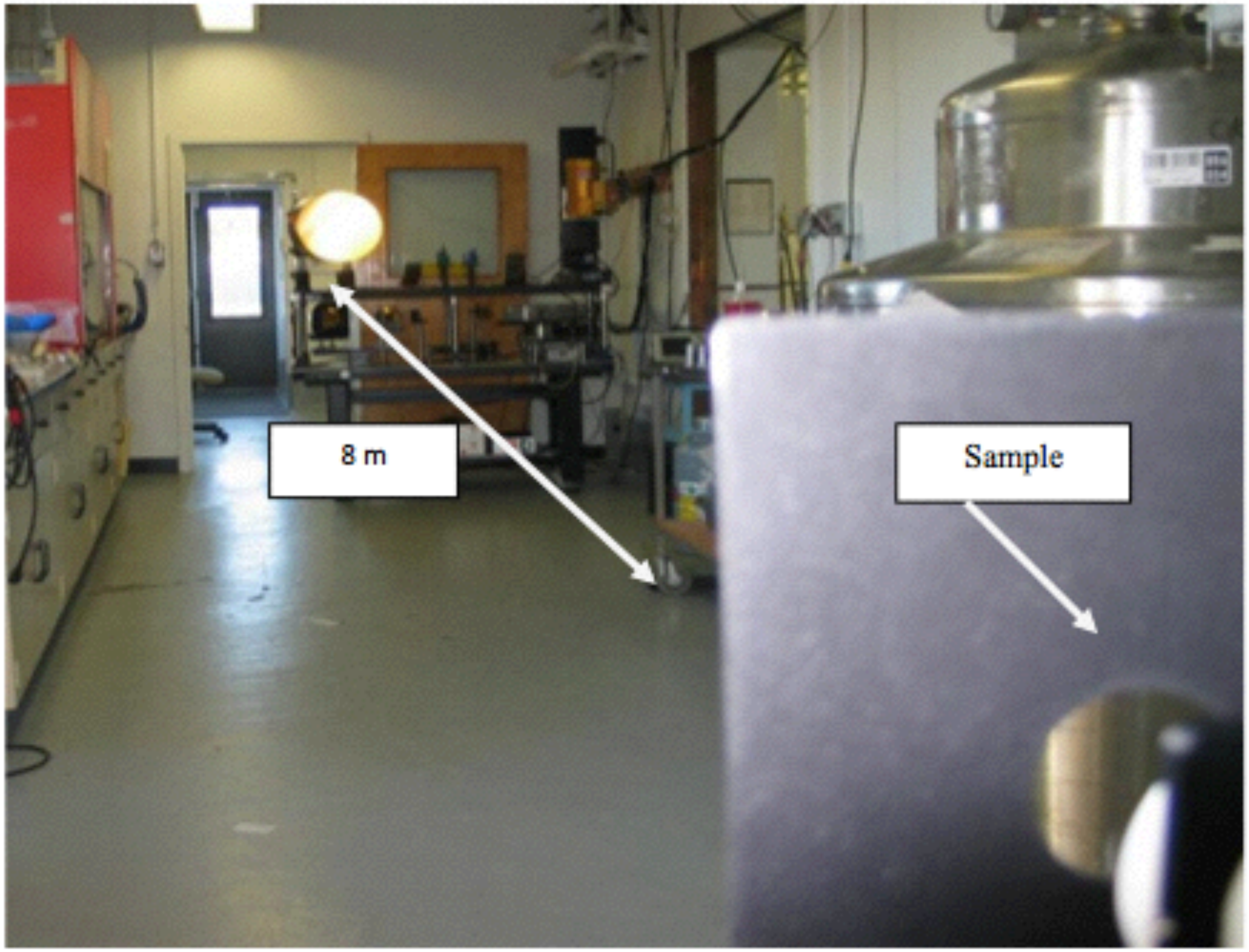
Standoff Spectroscopy Experiments



Target

DEFENCE DÉFENSE

Standoff Spectroscopy Experiments

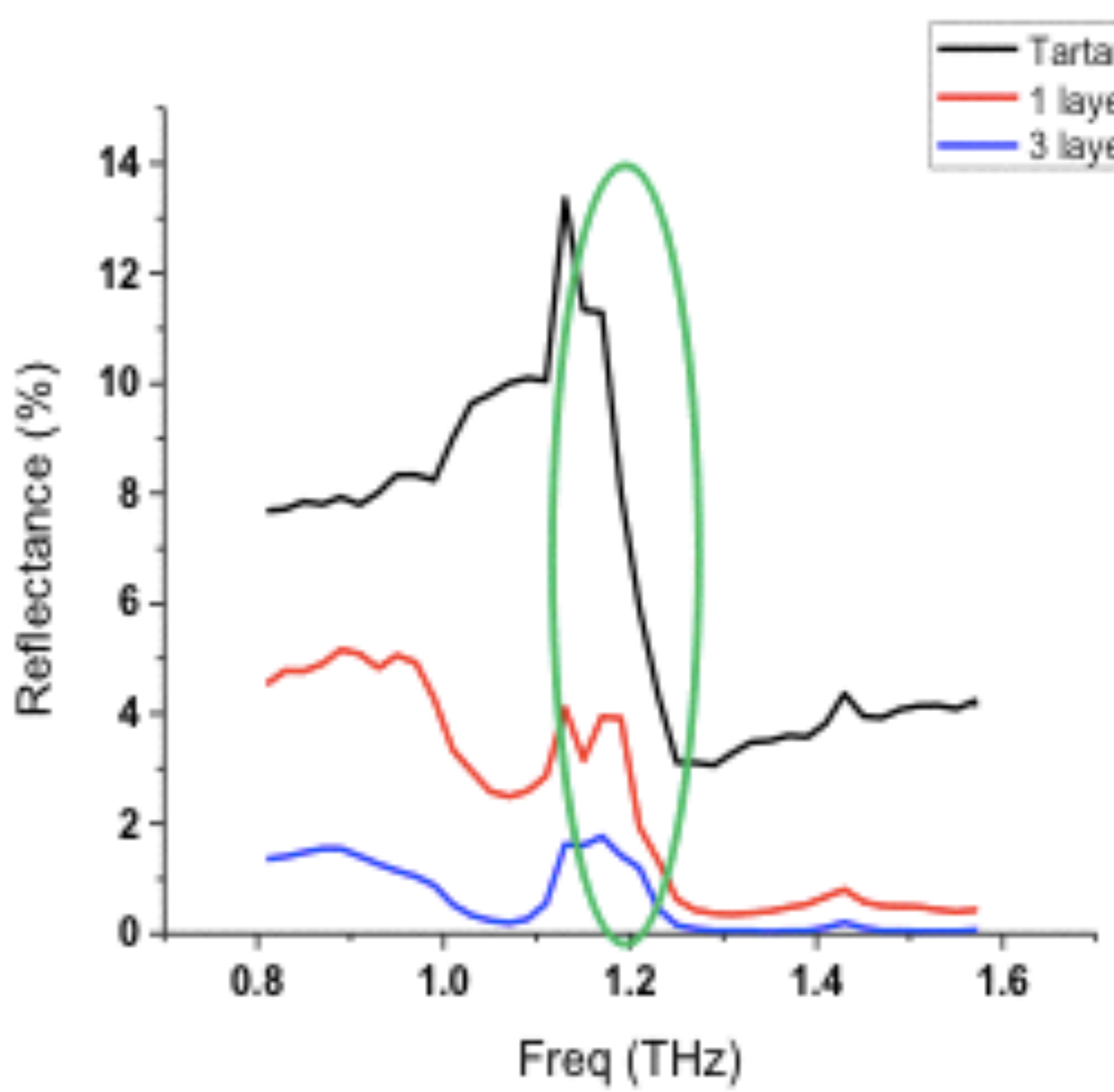


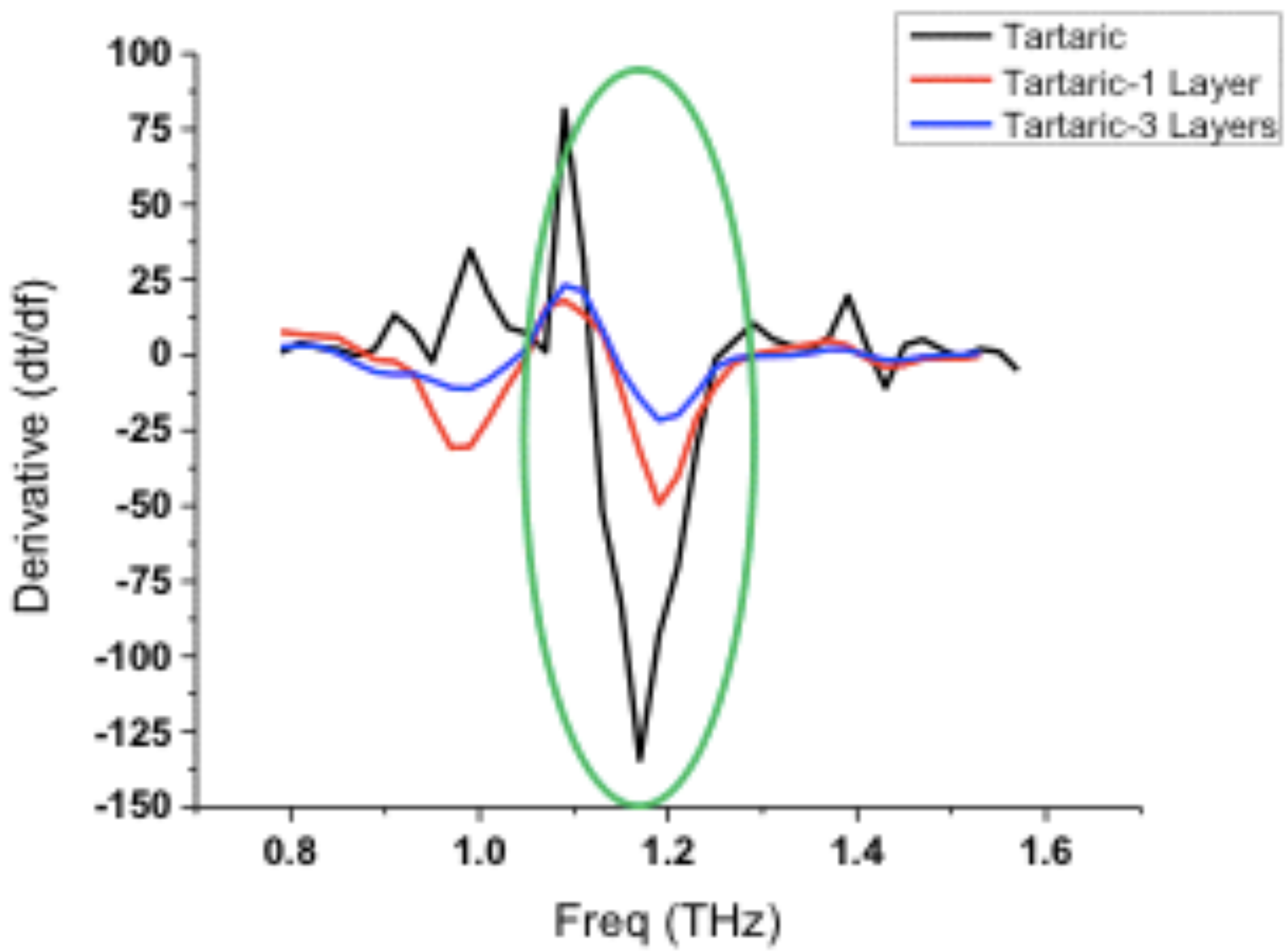
DEFENCE DÉFENSE

Standoff Spectroscopy

Experiments

Detection of tartaric acid



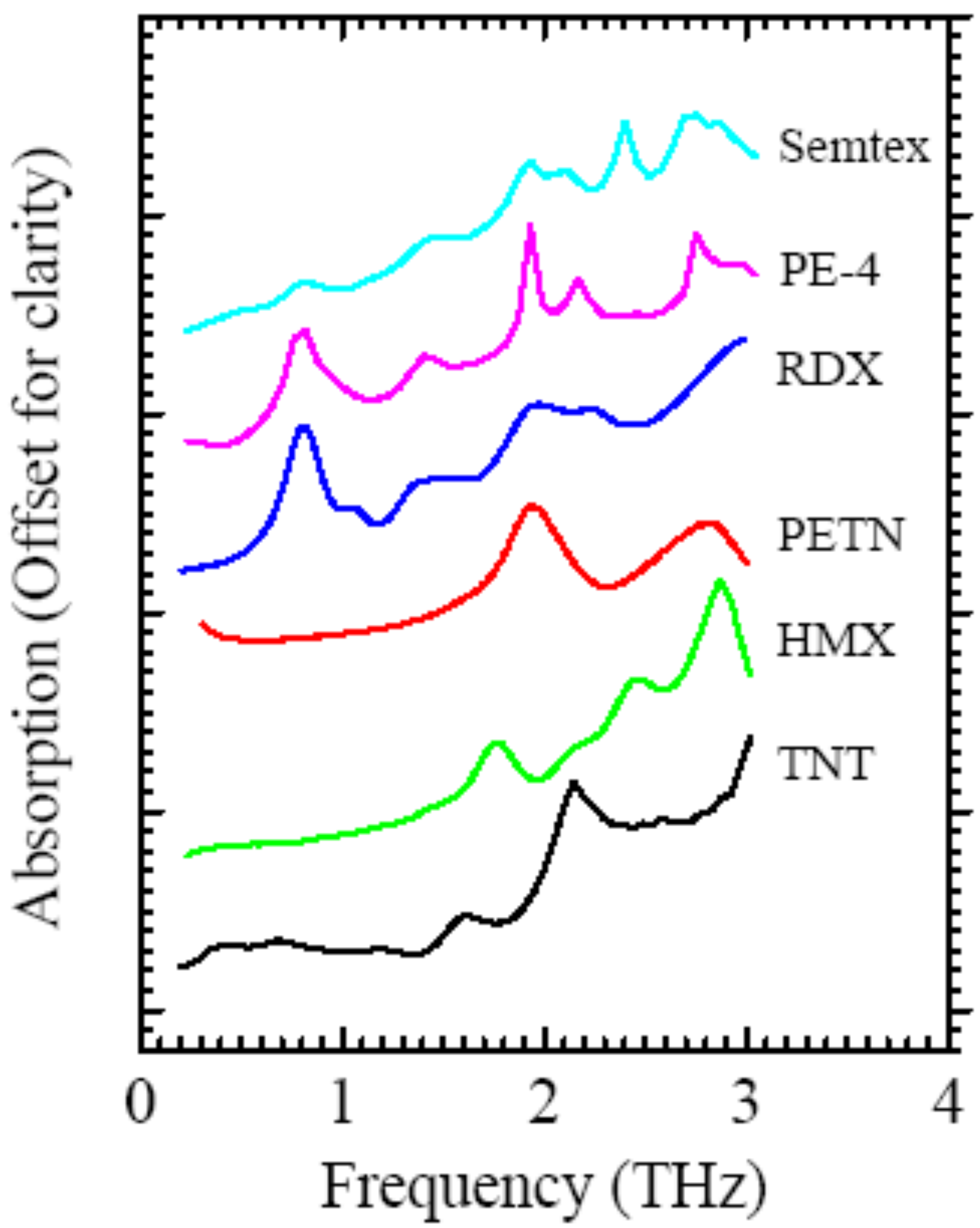


DEFENCE DÉFENSE

Standoff Spectroscopy

Threat Detection

Spectral Signature of a Number of Explosives



- Terahertz transmission spectra.
- Energetic compounds and explosives.
- All show characteristic features at terahertz frequencies.
- Most features above 0.5 THz.

Kemp *et. al.*, Proc SPIE **5070**, 44 (2003)

Standoff Spectroscopy

Experiments

Superior Standoff Capabilities

- Increased pulse energy (compared to ultrafast antenna approach) by a factor of ~100
- Spectral brightness is x100 larger in the 1 GHz OPO compared to ~1 THz in ultrashort antenna devices

~10^4 improvement in detection!

Presentation Outline

- Introduction to M Squared Lasers
- Pulsed Terahertz Parametric Oscillator
  - Theory and System Design
  - Towards Continuous-wave Operation
- THz Active Hyperspectral Imager
- Applications
  - Pharmaceutical
  - Security / Defense
- **Open Innovation**

Collaboration

Open Innovation

Partnering with world-leading research organisations to translate novel science & technology into market-leading products

- Open, flexible approach to collaborations
- From blue sky research to products development
- Entrepreneurial team to accelerate commercialisation

Acknowledgements

Our Partners

UNIVERSITÄT SIEGEN

University of St Andrews

MACQUARIE UNIVERSITY

DEFENCE R&D DÉFENSE

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Fraunhofer UK


explore
TOOLS TO DISCOVER