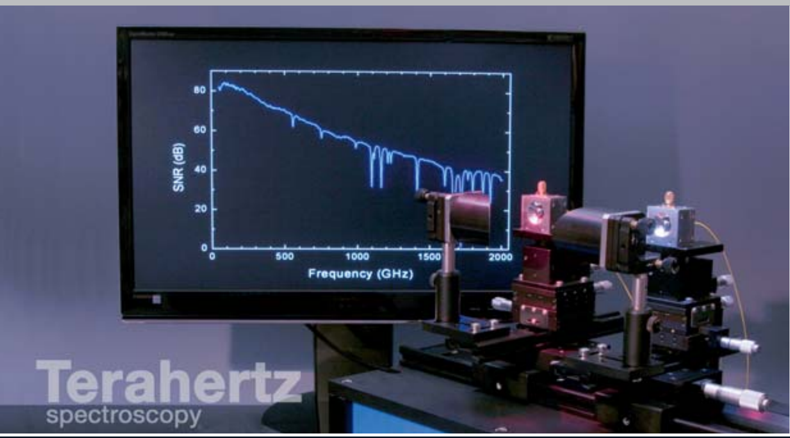
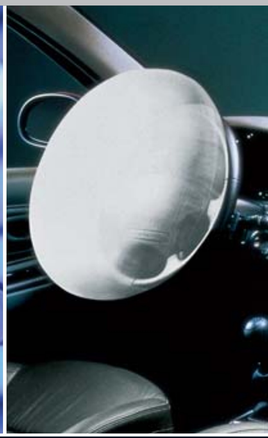
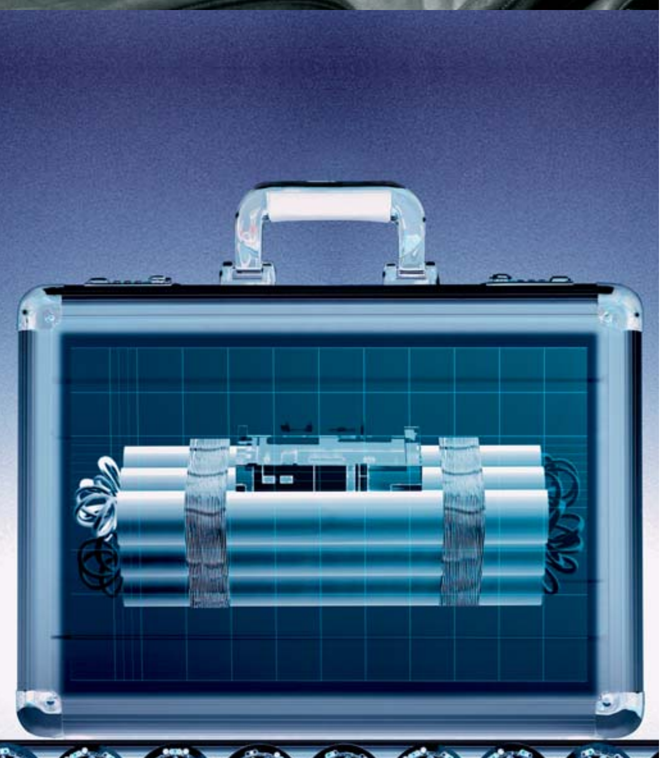
Lasers for Terahertz

Pulsed Femtosecond and cw Tunable Diode Lasers





A Passion for Precision.



Terahertz
The Final Frontier of the Electromagnetic Spectrum

Between radio waves and infrared

The terahertz range refers to electromagnetic waves with frequencies between 100 GHz and 10 THz, or wavelengths between 3 mm and 30 µm. Light between radio waves and infrared has some unique properties. Compared to visible or near-infrared wavelengths, terahertz radiation undergoes less Rayleigh scattering in amorphous materials. Compared to microwaves, on the other hand, there is less diffractive scattering. Consequently, synthetics and textiles, but also paper and cardboard are transparent to terahertz waves. Many biomolecules, proteins, explosives or narcotics also feature characteristic absorption lines – so-called spectral "fingerprints" – at frequencies between 0.1 and 2 THz. Unlike X-rays, terahertz waves do not have any ionizing effects and are generally considered biologically innocuous.

Until recently, the generation of intensive, directional terahertz radiation was difficult, and the terahertz range has long been considered the final frontier of the electromagnetic spectrum.

Closing the terahertz gap

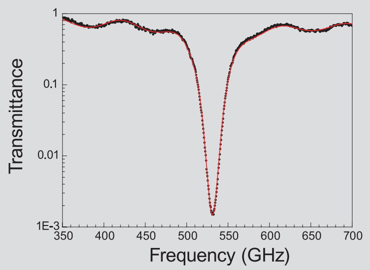
Now, frequencies between 0.5 and 5 THz have become the domain of laser-based techniques. Recent optoelectronic approaches make use of femtosecond lasers or tunable diode lasers emitting in the near-infrared. Photomixers, photoconductive switches or nonlinear crystals then convert the laser output into terahertz waves, either broadband or spectrally resolved.

State-of-the-art laser technology has thus helped to finally bridge the terahertz gap, and has opened up a wealth of new applications – in basic and applied science, homeland security, high-speed communication and industrial process control.

TOPTICA has been cooperating with researchers in the terahertz arena from the beginning. As a result, TOPTICA is now the only company worldwide that serves scientists and engineers in the two most important optoelectronic approaches – pulsed and continuous wave (cw) terahertz generation.

Spectroscopy

Applications of terahertz spectroscopy are manifold. Numerous gases and organic solids, including chemical agents and explosives, show distinct spectral fingerprints in the terahertz range. A spectrum can be obtained in transmission or reflection mode, using either pulsed or cw terahertz radiation. Advantages of a time-domain setup are a wide bandwidth and short acquisition times, whilst a frequency-domain system has the benefit of frequency selectivity and resolution. Key requirements in spectroscopy are a high signal-to-noise ratio of the terahertz power, and an excellent repeatability of the signal, when sample and reference scans are to be compared.

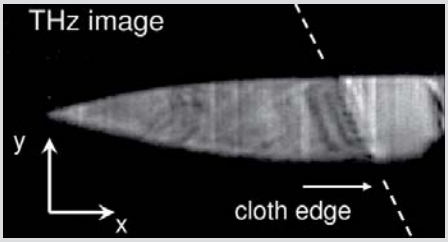


Absorption signature of α-Lactose monohydrate (M. Grüninger, University of Cologne + TOPTICA terahertz kit).

Homeland security

In security-related applications, the two main advantages of terahertz radiation are the penetration of opaque materials on one hand, and a high chemical selectivity on the other hand.

Identifying the individual compounds in a mixture of gases by their fingerprint requires a terahertz spectrometer with a high bandwidth (e.g. 100 .. 1500 GHz), yet a frequency resolution on the MHz level. TOPTICA's laser technology has already been implemented in a terahertz gas spectrometer, which aims at the control of the air quality in public institutions. Here, trace amounts of potential threat chemicals have to be detected against a spectral background of a cluttered environment.

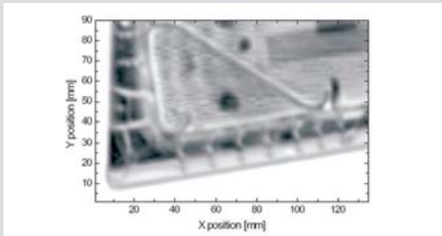


Terahertz image of a ceramic knife (Teraview Ltd. + TOPTICA DFB laser).

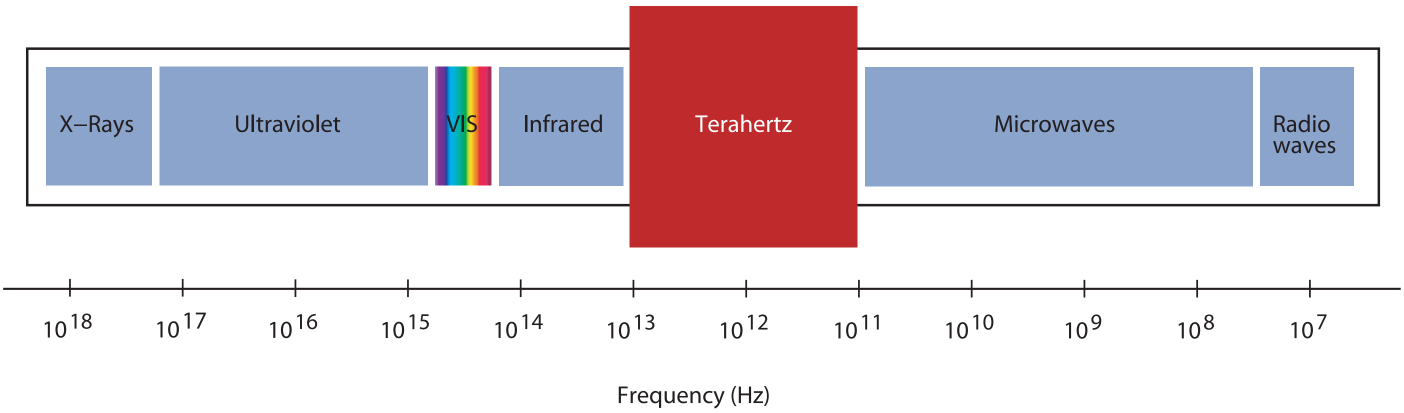
Imaging

Many plastic compounds and synthetics are transparent for terahertz light. This has been used for non-contact analysis and even imaging of hidden objects. For instance, terahertz imaging of the safety covers of airbags provides an alternative to conventional - destructive - testing methods.

Thus far, terahertz images are usually created in a pixel-by-pixel scan, with total acquisition times ranging from tens of minutes to several hours. Ongoing research is focused on multipixel, real-time terahertz cameras. A video-rate imaging source could also help to examine the water content of foodstuffs inside their air-tight packaging, or the structure of pharmaceuticals.



Terahertz image of an airbag cover (M. Koch, University of Braunschweig + TOPTICA DFB laser).



Log-spiral antenna.

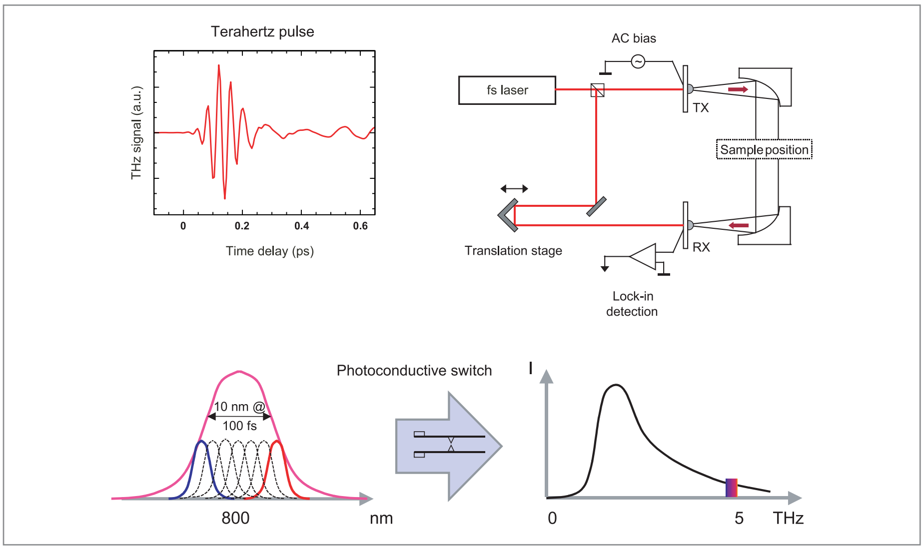
Terahertz Generation
Laser-based Techniques

Optoelectronic terahertz generation

The spectroscopically interesting frequency band of 0.5 – 2 THz is not easily accessible. Electronic sources like Gunn or Schottky diodes with subsequent frequency multipliers provide high output levels (mW range) up to some 100 GHz, yet become inefficient in the submillimeter range. They also require elaborate production skills and can hardly, if at all, be frequency tuned. Direct optical sources, like quantum cascade lasers, commonly require cryogenic temperatures and suffer from poor beam profiles and low spectral purity.
Optoelectronic terahertz generation is an expression for indirect methods, where near-infrared laser light illuminates a metal-semiconductor-metal structure. This generates a photocurrent that, in turn, becomes the source of a terahertz wave. Both pulsed and cw techniques have been realized, and both have their advantages and limitations. Pulsed terahertz radiation offers a higher bandwidth (typically 0.1 .. 5 THz) and permits very fast measurements – a spectrum can be acquired within milliseconds. On the other hand, the frequency resolution is limited to several GHz. Vice versa, a cw system features a somewhat lower bandwidth (typ. 0.1 .. 2 THz) and requires longer measurement times – acquiring a spectrum typically takes several minutes. Yet the frequency can be controlled with extreme precision, down to single MHz.

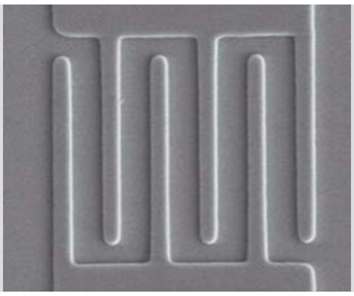
Selected terahertz generation methods				
	Frequency	**Power**	**Pros**	**Cons**
Direct methods **Quantum cascade lasers**	1.5 .. 10 THz	10 .. 100 mW	High power	Cryogenic temperatures, low tunability
Gas lasers	1 - 100 THz	10 .. 100 mW	High power at selected frequencies	No tunability, intricate technology
Schottky-, Gunn-diodes	< 100 GHz (< 1.5 THz with frequency multipliers)	Watt (nW)	Very high power at low frequencies	Limited tunability, elaborate production required
Indirect methods **Photomixers (cw)**	0 .. 2 THz	50 nW .. 10 µW	High resolution, frequency selectivity	Low power
Photoconductive switches (pulsed)	0.1 .. 5 THz	10 .. 100 µW	Broad spectrum, temporal information	Lower resolution than cw

Time domain terahertz



Pulsed terahertz radiation is generated with femtosecond lasers. The ultrashort laser pulses are focused on a semiconductor material, generating a fast current transient. This leads to the emission of electromagnetic wave packets with a broad spectrum in the terahertz range.

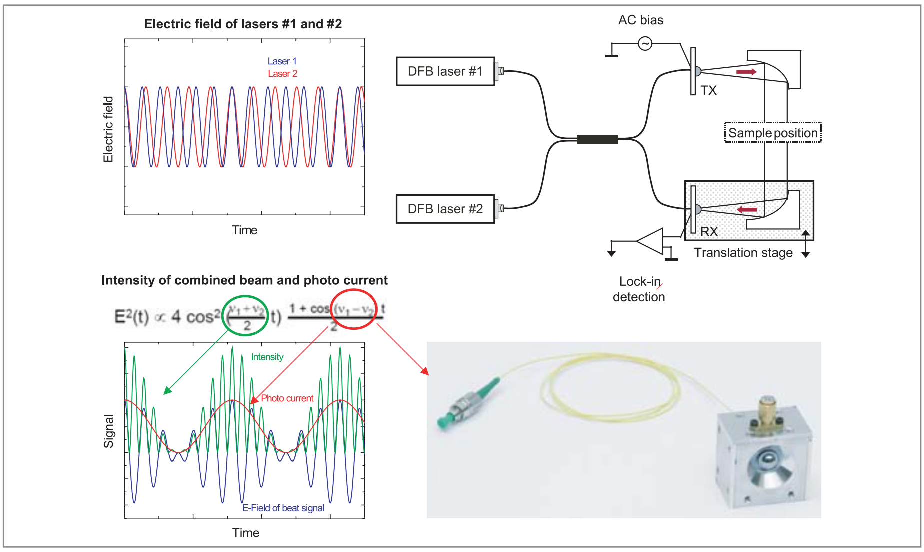
The most established emitter technologies are photoconductive switches, based either on GaAs or InP semiconductors. Other common terahertz generation mechanisms employ optical rectification at surfaces or in nonlinear crystals, such as GaP, ZnTe or DAST. Excitation wavelengths for the different approaches range from 750 nm to 1.6 µm.



Finger photomixer (SEM image by Th. Göbel, University of Darmstadt).

All of these wavelengths are now conveniently accessible with TOPTICA's ultrafast fiber lasers cabinet. The FemtoFiber® series provides superior specifications in a compact, turn-key system, without the complexity and price tag of Ti:Sapphire lasers.

Frequency domain terahertz



Continuous-wave (cw) terahertz radiation is obtained by optical heterodyning: the terahertz emitter ("photomixer") is irradiated with two near-infrared lasers of adjacent wavelengths. An antenna structure emits an electromagnetic wave at the terahertz difference frequency. Benefits of cw terahertz techniques are a wide bandwidth and a high spectral purity.

Most photomixers employ GaAs and require laser wavelengths below 870 nm. More recently, InP-based emitters have been demonstrated, operating in the telecom wavelength band of 1.5 µm.

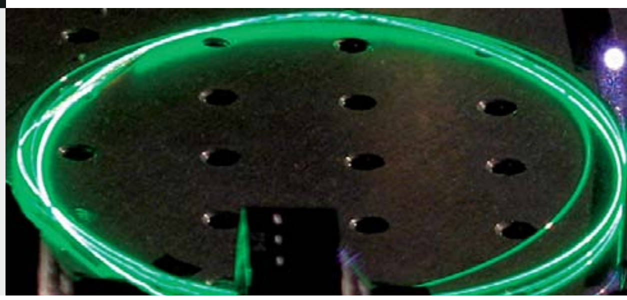
TOPTICA's tunable DFB lasers have been used in some of the leading laboratories for terahertz photomixing. Our patented technique of laser frequency control achieves an unmatched frequency resolution on the 1 MHz level. Latest-generation photomixers now form the basis of TOPTICA's proprietary cw terahertz spectroscopy kit.

Hands-off fiber lasers

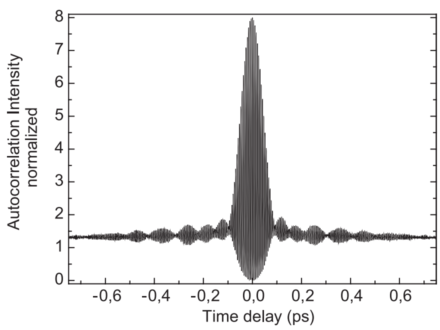
The **FemtoFiber pro** series offers hands-off fiber laser sources, with fundamental 1560 nm and second harmonic 780 nm wavelengths available from one unit. For both wavelength ranges, optimum specifications for terahertz generation are provided: highest power levels of more than 350 mW (1560 nm) or 140 mW (780 nm) and very narrow pulses of less than 100 fs.

The **FemtoFiber pro** lasers come in a compact design, based on reliable telecom components to assure long lifetimes. The **FemtoFiber pro** lasers are thus a cost-effective, reliable alternative to bulky and expensive Ti:Sapphire lasers in the time-domain terahertz research field.

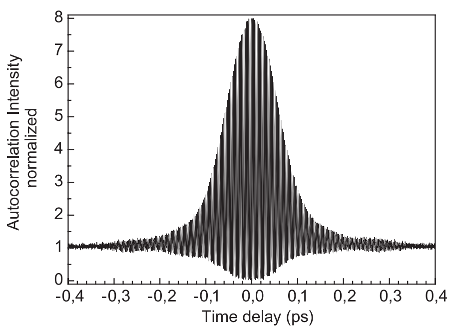
fs Laser Packages
Hands-off Sources for Time Domain Terahertz



Laser data

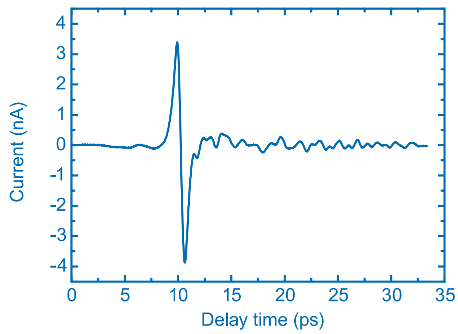


Typical auto-correlation diagram of the pulses at 1560 nm.

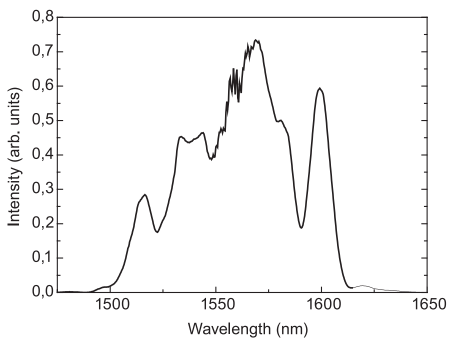


Typical auto-correlation diagram of the frequency-doubled pulses at 780 nm.

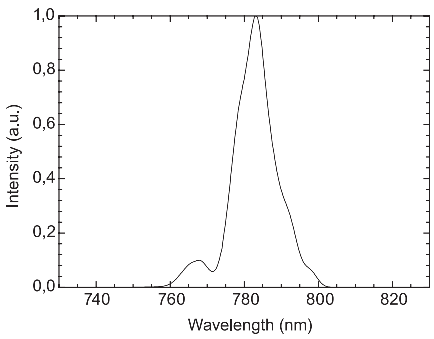
Terahertz data



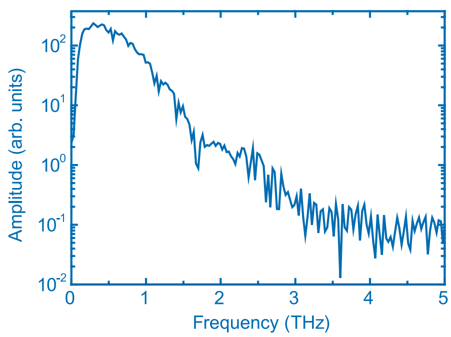
Typical terahertz transient.



Typical spectrum of the fundamental wavelength around 1560 nm.



Typical spectrum of the second-harmonic wavelength around 780 nm.



Corresponding terahertz spectrum (Fourier transform of transient).

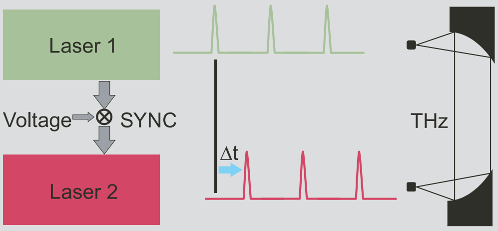
Electronically controlled sampling (ECOPS)

In time-domain spectroscopy, a terahertz pulse is usually sampled with a time-delayed copy of the excitation pulse. An absorption signature manifests itself in a decrease of the amplitude and a delay of the waveform of the pulse. A comparison of spectra acquired with and without the sample in place enables a determination of the complex refractive index of the material under test.

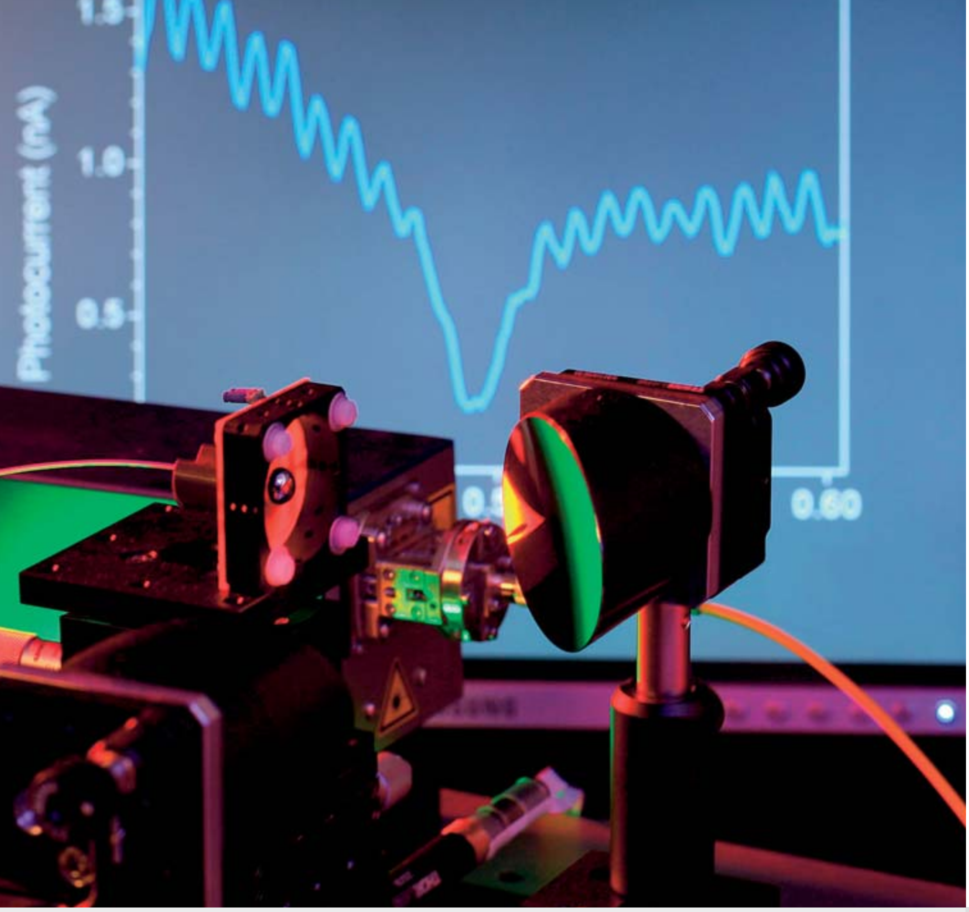
TOPTICA offers a unique kit for time-domain terahertz spectroscopy: Electronically controlled optical sampling (ECOPS) removes the need for a scanning mechanical delay line. The technique makes use of two FemtoFiber lasers, phase-locked to one another. One system thus generates the terahertz pulse, the other one is used for optical sampling – faster than other methods, and without loss of timing accuracy.

ECOPS - Mode of operation

ECOPS - Implementation for terahertz



Recommended laser system	
Terahertz applications at 1560 nm	
Laser system	**FemtoFiber pro**
Wavelength	1560 nm ± 30 nm
Pulse duration	< 100 fs
Repetition frequency	80 MHz
Average power	> 350 mW
Terahertz applications at 780 nm or 1560 nm (simply switchable by user)	
Laser system	**FemtoFiber pro SHG**
Wavelength	1560 nm ± 30 nm / 780 nm ± 5 nm
Pulse duration	< 100 fs
Repetition frequency	80 MHz
Average power	> 350 mW @ 1560 nm / > 140 mW @ 780 nm
Key features	
Terahertz generation via optical rectification or photoconductive switches	
Hands-off, turnkey systems	
Saturable absorber mirror (SAM) technology for most reliable performance	
Polarization maintaining (PM) fiber assembly	
Optional: ECOPS technique replacing mechanical delay line	



cw Laser Packages
Ideal Sources for Frequency Domain Terahertz

Modular product packages

TOPTICA offers four different product packages – Standard Package, High Power Extension, Precision Frequency Control Extension and cw Terahertz Spectroscopy Kit – to help customers select the most suitable components for their cw terahertz experiment. The packages are fully modular and can be combined and upgraded depending on the requirements of the experiment.

The laser heart of these packages is TOPTICA's DL DFB system. Distributed feedback diodes comprise a frequency selective grating within the active section of the semiconductor. The grating restricts the laser emission to a single longitudinal mode. Thermal tuning of the grating pitch yields very wide continuous frequency scans – by selecting two diodes with appropriate wavelength offset, one can tune the terahertz difference frequency continuously, from 0 to 2 THz.

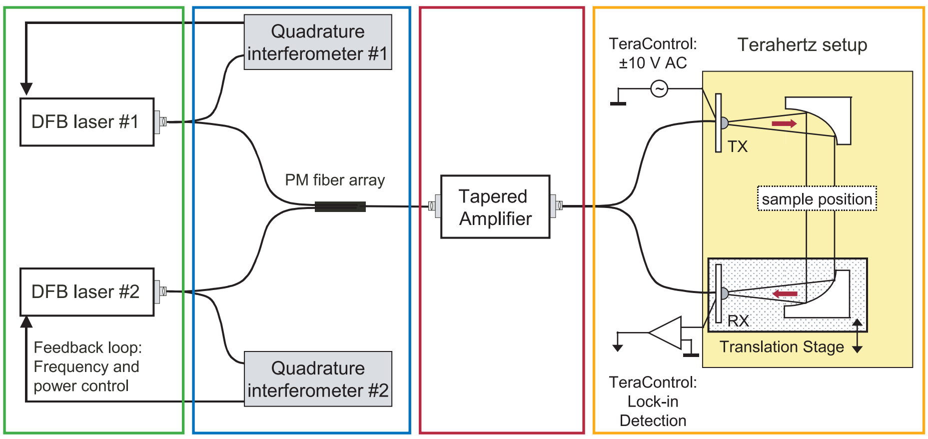
The Precision Frequency Control Extension uses a patented technique of laser frequency control to achieve an unmatched frequency resolution on the 1 MHz level. Standard Package, High Power Extension and Precision Frequency Control Extension are available at both 850 nm and 1550 nm.

These packages are complemented by a proprietary terahertz spectroscopy kit, which incorporates the latest technological advances in GaAs-based photomixer technology. The spectroscopy kit provides all of the required components to get a cw terahertz measurement started!

All of the packages employ single-mode fiber technology, which enables a particularly flexible, convenient and safe operation of the terahertz system.

cw Terahertz packages

Product	Wavelength	Laser power (fiber output)	Scan range per diode	Frequency accuracy	THz scan range
Standard Package	853 + 855 nm	2 x 50 mW	± 1.3 nm	2 GHz abs. 10 MHz rel.	0 - 1800 GHz
	1550 nm		± 2.2 nm		0 - 1200 GHz
High Precision	853 + 855 nm	2 x 40 mW	± 1.3 nm	100 MHz abs. 1 MHz rel.	0 - 1800 GHz
	1550 nm		± 2.2 nm		0 - 1200 GHz
High Power	853 + 855 nm	2 x 100 mW	± 1.3 nm	Cf. packages above	0 - 1800 GHz
	1550 nm	2 x 500 mW	± 2.2 nm		0 - 1200 GHz
Spectroscopy Kit	853 + 855 nm	Terahertz power~ 0.5 µW power @ 300 GHz SNR: 80 dB @ 100 GHz, 50 dB @ 1 THz			50 - 1800 GHz



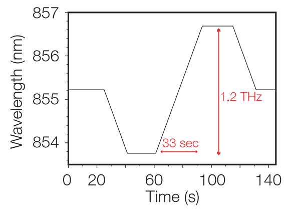
Standard Package

The **Standard Package** offers the essential laser equipment needed for difference frequency generation in the terahertz range. It comprises two DL DFB lasers, fiber-optic beam combination, and laser driver electronics. The diodes are carefully selected with respect to their tuning range and wavelength offset.

The **Standard Package** is available both at 850 nm and 1550 nm.

Precision Frequency Control Extension

Ultimate spectral resolution is achieved with the **High Precision Extension**. The frequency of each laser is adjusted with an accuracy of typ. 1.5 MHz (beat linewidth @ 80 ms), using a patented interferometer design. This stability translates directly into the linewidth and resolution of the terahertz signal – achieving the highest resolution of any tunable cw terahertz system on the market.



High Power Extension

The **High Power Extension** employs TOPTICA's established semiconductor amplifier technology (BoosTA™). The two-color output of the **Standard Package** is amplified and coupled into a 50:50% fiber-optic splitter, providing the required laser beams for terahertz generation and detection.

A 1550 nm version of the **High Power Extension** is also available, employing an Erbium-doped fiber as gain medium.

Standard Package.

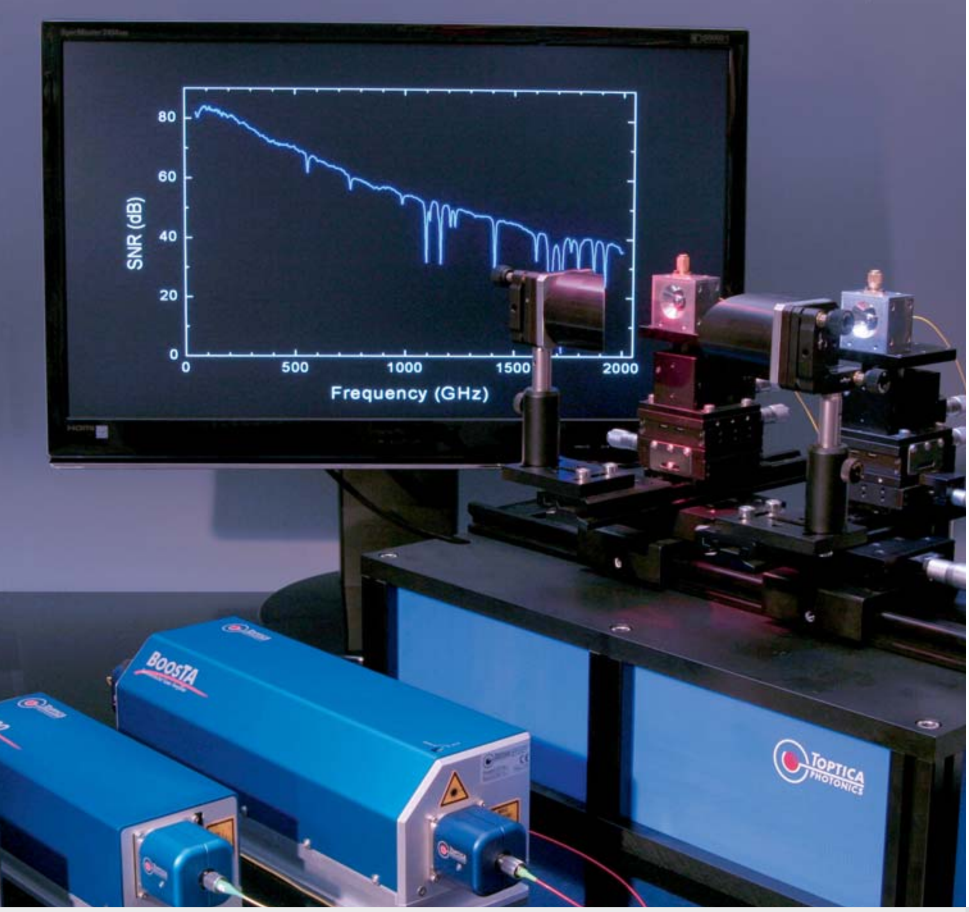
Precision Frequency Control Extension.

High Power Extension.

Standard Package
Key features
Laser power: 50 mW per 2-color fiber output
Difference frequency tuning range: 0 .. 1.8 THz typ.
Difference frequency tuning speed: Up to 0.1 THz/s
Difference frequency accuracy (absolute): < 2 GHz
Difference frequency resolution (relative): 10 MHz
Includes:
2 x DL 100 L DFB diode lasers, with optical isolators (60 dB) and fiber couplers
SM/PM fiber combiner (2 inputs, 2 outputs)
Complete control electronics (19“ rack with monitor, temperature and current controllers, analog interface)

Precision Frequency Control Extension
Key features
Requires Standard Package
Can be used with High Power Extension (optional)
Difference frequency accuracy (absolute): 100 MHz typ.
Difference frequency resolution (relative): 1 MHz
Includes:
SM/PM fiber combiner (2 inputs, 2 tap outputs, 2 dual-color outputs)
2 x iScan interferometers for power and frequency control of the seed lasers
Control electronics with USB 2.0 interface

High Power Extension
Key features
Requires Standard Package
Laser power: > 150 mW per two-color fiber output
Frequency tuning and resolution: See Standard Package or Precision Frequency Control Extension
Includes:
BoosTA 850 nm, 750 mW
FiberDock @ input and output
60 dB output isolator
SM/PM fiber splitter (50:50 %)



cw THz Spectroscopy Kits

Leading-edge Photomixer Technology

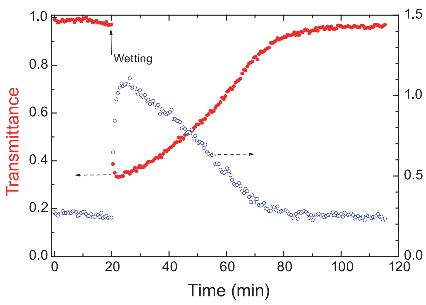
Highest SNR, broadest bandwidth

TOPTICA's new cw Terahertz Spectroscopy Kit has been designed for institutes and companies who want to develop their own, proprietary analytical setup. The open, multi-purpose design enables a convenient and flexible adaptation into any terahertz assembly. The Spectroscopy Kit comprises a pair of state-of-the-art photomixers for terahertz generation and detection, a low-noise transimpedance amplifier, and a digital lock-in amplifier.

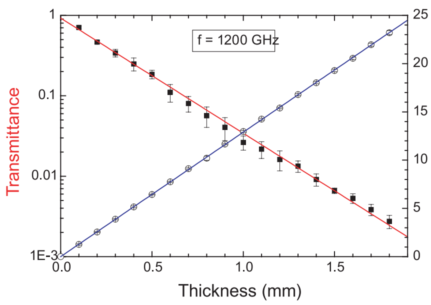
The photomixers are based on GaAs material and suited for laser wavelengths up to 860 nm. They comprise an interdigitated finger structure, integrated within broadband spiral antennae. The design provides a very large bandwidth and an excellent signal-to-noise performance. With TOPTICA's High Power Extension, SNR values of the terahertz power as high as 90 dB at 100 GHz, 60 dB at 1000 GHz, and still 35 dB at 2000 GHz have been obtained.

The photomixers are equipped with a single-mode fiber pigtail, alleviating the need for cumbersome beam alignment.

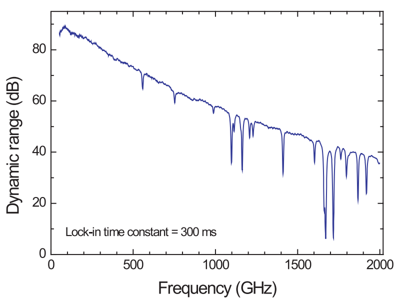
TeraControl: digital lock-in amplifier module.



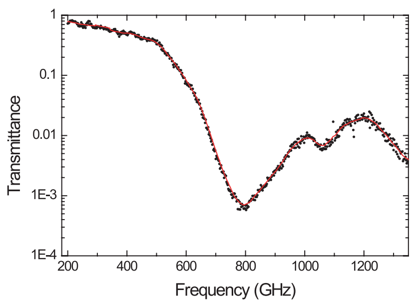
Drying of tissue paper.



Terahertz transmission through individual paper sheets.



System dynamic range. The dips are absorption lines of water vapor.



Terahertz spectrum of the plastic explosive RDX.

Digital lock-in amplifier

Modulation of the transmitter bias voltage, as well as lock-in detection of the receiver photocurrent, is accomplished by TOPTICA's proprietary TeraControl unit TC 110. The TeraControl is part of the laser electronics and unites all of the advantages of a digital lock-in amplifier in a compact module.

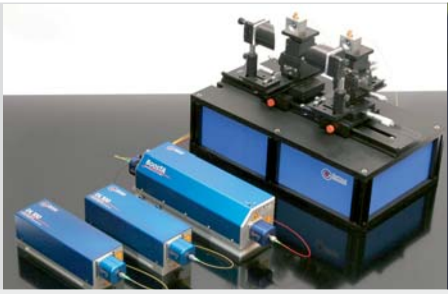
The FPGA-based TeraControl features a digital integrator which is synchronized with the terahertz frequency control. The integrator re-starts as soon as the system is tuned to a new terahertz frequency. This is a substantial advantage compared to conventional analog RC low-pass filters, which require to wait for several time constants. The integration times of the TeraControl are thus about three times larger – at the same overall measurement speed.

An intuitive LabView graphical interface is supplied as part of the delivery.

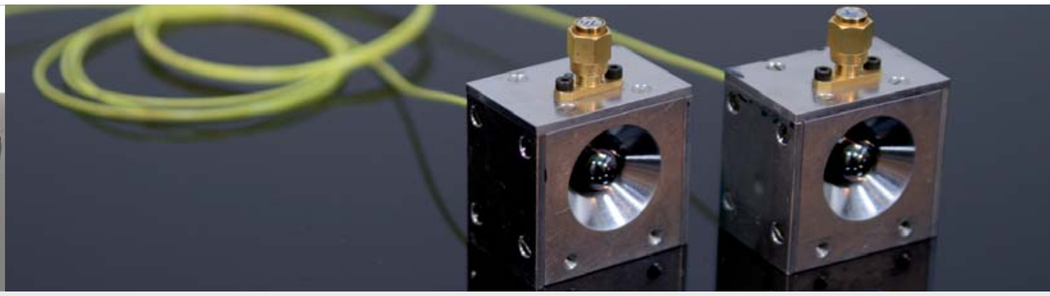
Extended version with terahertz optics

Two versions of the cw terahertz spectroscopy kit are available. The basic version features the two photomixers, the TeraControl unit, a transimpedance amplifier for the detector photocurrent, and the LabView control software.

The extended version further comprises two precision positioning stages for the photomixers, two off-axis parabolic mirrors to collimate and re-focus the terahertz beam, and a motorized delay stage for phase-sensitive terahertz measurements. The entire optomechanics are mounted on a rail system and enable a straightforward adjustment of the terahertz beam path.



Standard Package, High Power Extension + extended cw Terahertz Spectroscopy Kit.



Photomixer modules with single-mode fiber pigtail.

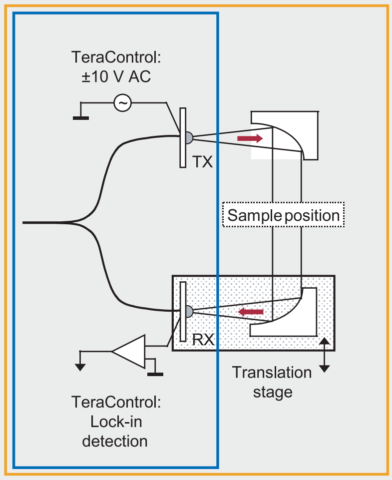
All fiber-based cw terahertz spectroscpy kits		
	Basic	Extended
2 fiber pigtailed photomixers	•	•
TeraControl TC 110 (lock in amplifier)	•	•
Low-noise transimpedance amplifier	•	•
LabView user interface	•	•
2 xyz stages for photomixers	–	•
2 collimating mirrors	–	•
Motorized delay stage	–	•
Optical rails	–	•
Sample positioning stage	–	–
Data processing routines	–	–
855 nm GaAs based antennae	•	•
1550 nm InP based antennae	Est. Q3 / 2010	Est. Q3 / 2010
Key features		
Up to 2000 GHz bandwidth		
Terahertz power ~ 0.5 µW @ 300 GHz typ.		
SNR: 80 dB @ 100 GHz, 50 dB @ 1000 GHz		
Highest resolution: 1 MHz (with High Precision Package)		
Requires cw THz Standard Package		
Recommended with High Power Extension and Precision Frequency Control Extension		

The spectroscopy kit is compatible with the Standard Package. For best SNR results and highest resolution, we recommend our High Power and Precision Frequency Control Extension.

A spectroscopy kit for 1550 nm is currently under development and market introduction is anticipated in 2010.

Spectroscopy Kit

Basic Extended



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Australia & New Zealand
**Lastek Pty. Ltd.
Mr. Alex Stanco
Thebarton Campus
University of Adelaide
10 Reid Street
5031 Thebarton, SA
Australia
Phone: +61 8 8443 8668
Fax: +61 8 8443 8427
sales@lastek.com.au
www.lastek.com.au**

China
**Universal (Hong Kong) Technology Co. Ltd.
Mr. Alex Cai
Room 615-619
Capital Group Plaza
No. 6 Chaoyangmen Beidajie
Beijing 100027, P.R. China
Phone: +86 10 8528 3377
Fax: +86 10 8528 3344
oe@universalhkco.com.cn
www.universalhkco.com.cn**

France
**Opton Laser International
Dr. Costel Subran
Parc Club d'Orsay Université
29, rue Jean Rostand
F-91893 Orsay Cedex, France
Phone: +33 1 6941 0405
Fax: +33 1 6941 3290
ventes@optonlaser.com
www.optonlaser.com**

India
**Simco Global Technology & Systems Ltd.
Dr. R. S. Daryan
Simco House (Head Office)
14 Bhawani Kunj
Behind Sector D-II Vasant Kunj
110017 New Delhi, India
Phone: +91 11 2689 9867
Fax: +91 11 2612 4461
simcorsd@del2.vsnl.net.in
www.simco-groups.com**

Israel
**Lahat Technologies Ltd.
Mr. Kfir Ben-Yehuda
Teradion Industrial Zone
M.P. Misgav, 20179, Israel
Phone: +972 4 999 0151
Fax: +972 4 999 0826
sales@lahat.co.il
www.lahat.co.il**

Japan
**INDECO, INC.
Mr. Kazunobu Takahashi
1-11-14, Kasuga, Bunkyo-ku
Tokyo 112-0003, Japan
Phone: +81 3 3818 4011
Fax: +81 3 3818 4015**

**Sonezaki Sawada Bld. 6F
2-1-13, Sonezakishinchi,
Kita-ku,
Osaka 530-0002, Japan
Phone: +81 6 6341 5799
Fax: +81 6 6341 5798**

**ind@indeco.jp
www.indeco.jp**

Korea
**JINSUNG LASER
Mr. Ha-Won Lee
#535-5, Bongmyung-Dong
Yusung-Gu
Hanjin Officetel Rm# 1016
Daejeon, 305-301, South Korea
Phone: +82 42 823 5300
Fax: +82 42 823 7447
sales@jinsunglaser.com
www.jinsunglaser.com**

Singapore / Malaysia
**Precision Technologies Pte Ltd
Mr. Vincent Chan
211 Henderson Road # 13-02
Henderson Industrial Park
Singapore 159552
Phone: +65 6273 4573
Fax: +65 6273 8898
precision@pretech.com.sg
www.pretech.com.sg**

Taiwan
**SLEO Photonics Co. Ltd.
Mr. Jimmy Chao
6F, No. 2, Lane 74
An-der Streett
Hsin Tien City, Taipei County
Taiwan 231, R.O.C.
Phone: +886 2 2211 5408
Fax: +886 2 2211 5401
sleo.jimmy@msa.hinet.net**

Turkey
**CS Analytical Laboratory Equipments Limited
Mr. Ercan Acikalin
Ergin Sokak No: 27/5
06580 Mebusevier - Tandogan
Ankara, Turkey
Phone: +90 312 223 0302
Fax: +90 312 223 0305
can@csanalitik.com.tr
www.csanalitik.com.tr**

United Kingdom & Ireland
**Mr. Howard Potter
Unit 4H Lansbury Estate
Woking, Surrey, UK, GU21 2EP
Great Britain
Phone: +44 1483 799 030
Fax: +44 1483 799 076
howard.potter@toptica.com
www.toptica.com**

USA & Canada
**TOPTICA Photonics, Inc.
1286 Blossom Drive
Victor/Rochester, NY 14564
U.S.A.
Phone: +1 585 657 6663
Fax: +1 877 277 9897
sales@toptica.com
www.toptica.com**

Every other country not listed:

**TOPTICA Photonics AG
Lochhamer Schlag 19
D-82166 Graefelfing / Munich
Germany
Phone: +49 89 85837-0
Fax: +49 89 85837-200
sales@toptica.com
www.toptica.com**

TOPTICA PHOTONICS

**TOPTICA Photonics AG
Lochhamer Schlag 19
D-82166 Graefelfing/Munich
Germany
Phone: +49 89 85837-0
Fax: +49 89 85837-200
info@toptica.com
www.toptica.com**

**TOPTICA Photonics, Inc.
1286 Blossom Drive
Victor/Rochester, NY 14564
U.S.A.
Phone: +1 585 657 6663
Fax: +1 877 277 9897
sales@toptica.com
www.toptica.com**