Application Notes

Broadband terahertz generation and detection
Widely tunable and narrowband THz sources
Applications of THz waves

The interest in terahertz electromagnetic radiation stems from the unique interactions of these rays with matter, which can be exploited in various applications. Terahertz waves excite molecular vibrations and lattice vibrations in materials, which make THz radiation very interesting for spectroscopy and material identification.
Terahertz radiation is non-ionizing, very sensitive to water and hydration state, and transparent to non-polar substances such as nonconductive polymers, paper, packing material, etc. Therefore material irregularities, defects, enclosures, not seen with other techniques, can be visualized with terahertz radiation. THz radiation has therefore a high potential for the non-destructive materials testing.

There are several techniques to produce terahertz radiation. We have developed **novel organic THz generators,** with optimized properties that make them ideal materials for the efficient generation and detection of terahertz radiation. Based on these materials we developed compact systems for THz time-domain spectroscopy:
1) ***TeraSys***® – **ULTRA**, with ultra wide THz bandwidth for spectroscopy and imaging up to 20 THz, and real time acquisition of 4 spectra per second
2) ***TeraSys12***® featuring wide THz bandwidth for spectroscopy and imaging up to 12 THz; improved detection that allows real time acquisition of 4 spectra per second (www.rainbowphotonics.com)
3) ***TeraSys***® ***– AiO,*** offering THz bandwidth up to 20 THz
4)***TeraSys***® up to 12 THz
5) TeraIMAGE® for transmission and imaging up to 14 THz or 20 THz with a detection speed of 3 spectra per minute. We have also developed a unique tunable single-frequency THz source, ***TeraTune***®, with a very wide tunability range 1–20 THz and a narrow linewidth < 100 GHz.

Terahertz radiation

The terahertz range of the electromagnetic spectrum is situated between high frequency electronics (microwaves) and long wavelength photonics (infrared light).
Terahertz radiation is easily accessible by means of blackbody radiation, but it is a challenge to separate the signals from the natural background. Several techniques have been used to generate electromagnetic waves below and above this so-called "THz frequency gap". Figure **1** shows the rough power levels of some of them. Electronic techniques can be used to generate waves with frequencies (mainly by electronic frequency multiplication of lower frequency sources) up to about 0.5 THz. From 0.3 to 3 THz Auston switches are very popular sources. Nonlinear optical techniques (optical rectification and difference-frequency generation) can be used to cover the

frequency range between 0.3 to 50 THz and quantum-cascade lasers between roughly 20 THz and 100 THz.

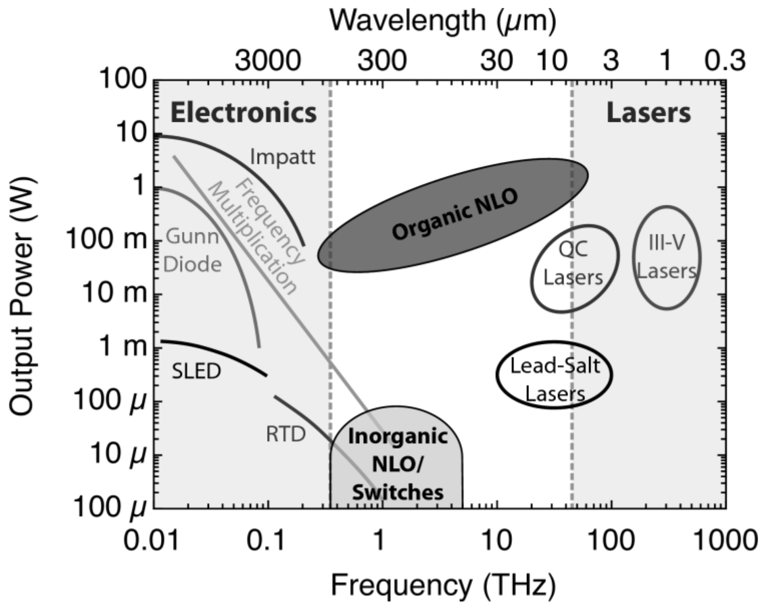

Figure 1: Approximate output power (either CW or peak power) as a function of frequency (wavelength) of electromagnetic radiation in the THz range and around when using different generation techniques. Adapted and updated from M. Tonouchi, Nat. Photonics 1, 97 (2007).

Broadband THz sources

Most broadband THz sources are based on the excitation of different materials with ultrashort laser pulses in the femtosecond range. Photoconduction and optical rectification are two of the most common approaches for generating broadband THz pulses. Optical methods are used for the generation of broadband terahertz sources, and due to the increasing progress in laser technology these methods have been the most developed in the last 20 years.

In the **photoconductive** approach a femtosecond laser generates an ultrafast photocurrent in a photoconductive switch or semiconductor using electric-field carrier acceleration. The achievable bandwidth is limited to a few THz due intrinsic limits of the carrier lifetime in semiconductors.

Optical Rectification is an alternative mechanism for pulsed THz generation. A femtosecond laser is used as well, and the energy of the terahertz radiation comes directly from the exciting laser pulse. In this case the conversion efficiency depends, beside the parameters of the pump laser, mainly on the electro-optic coefficient and the proximity of the phase-matching conditions of the material.
In optical rectification, a high-intensity ultrashort laser pulse passes through a transparent crystal material that emits a terahertz pulse without any applied voltages. Figure **2** shows a schematic of optical rectification with a pulsed femtosecond laser with organic crystal generators DAST or DSTMS. In this nonlinear-optical process, a nonlinear material is quickly electrically polarized at high optical intensities. This changing electrical polarization emits terahertz radiation. It is called rectification because the rapid oscillations of the electric field of the laser pulse are “rectified” and only the envelope of the oscillations remains. Since the medium absorption is low, the polarization instantaneously follows the pulse envelope implying that there is practically no limit on the speed at which the polarization can be switched on and off, i.e. there is no intrinsic limit on the bandwidth as for the photoconductive antennas.

The bandwidth of the THz pulse generated by the optical rectification process is limited by the length of the pump laser and the velocity matching conditions in the generator and detector material. THz bandwidth achievable for pump laser sources with various pulse lengths is illustrated in Figure **3**. The materials for THz generation by optical rectification are discussed in the following section.

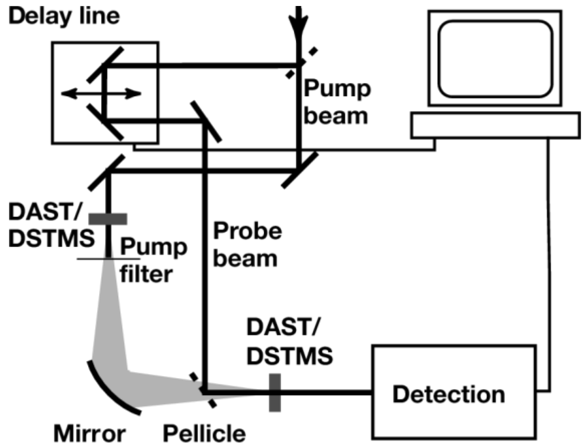

Figure 2: Scheme of the setup for generation and detection of THz pulses in organic THz generators DAST or DSTMS. The generation is based on optical rectification of femtosecond pulses, while the detection is based on electro-optically induced changes of the refractive index in a THz detector, induced by the THz electric field and probed by an optical probe beam.
For inorganic semiconductors most often the electro-optic sampling is used,[1] while we use THz induced lensing in case of organic crystals.[2]

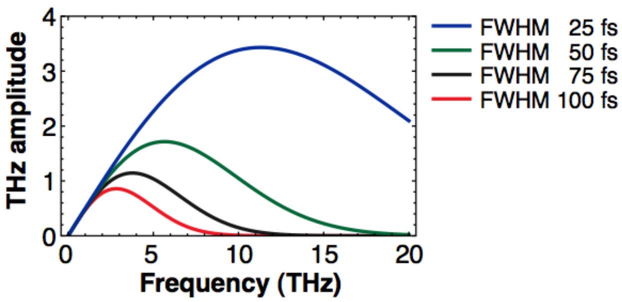

Figure 3: Terahertz frequency range for femtosecond laser sources with various pulse lengths (FWHM from 25 fs to 100 fs) in case of perfectly phase-matched THz generation materials.

Materials for THz generation

Due to the larger nonlinear optical susceptibilities and velocity matching between THz and optical pump waves of organic materials compared to the inorganic ones, much larger power levels, limited by the damage thresholds of the materials, can be obtained by using organic materials as THz generators.
Table 1 shows most relevant material parameters for THz wave generation for best organic crystals compared to inorganic crystals as well as for an electro-optic polymer LAPC. As it can be seen in this table, the organic crystals OH1, DSTMS and OH1 show the largest figure of merit FM_{THz}. Phase matching is possible when the THz refractive index n_{THz} is close to the group index n_g at the mean optical pump wavelength.[3] This kind of phase matching is usually referred to as group velocity matching and is commonly used for broadband THz-wave generation by optical rectification of fs pump lasers. [3]

1 G. Gallot and D. Grischkowsky, "Electro-optic detection of terahertz radiation," J. Opt. Soc. Am. B 16, 1204 (1999)
2 A. Schneider, I. Biaggio, P. Günter, "Terahertz-induced lensing and its use for the detection of terahertz pulses in a birefringent crystal," Appl. Phys. Lett. 84, 2229 (2004)
3 Schneider, A.; Neis, M.; Stillhart, M.; Ruiz, B.; Khan, R. U. A. & Gunter, P., "Generation of terahertz pulses through optical rectification in organic DAST crystals: theory and experiment," *J. Opt. Soc. Am. B*, **2006**, *23*, 1822-1835

	n_o	n_g	n_{THz}	r (pm/V)	FM_{THz} $(pm/V)^2$
DAST	2.13	2.26	2.29	47	5600
DSTMS	2.08	2.19	2.20	49	6100
OH1	2.16	2.33	2.28	52	7400
LAPC	1.6	1.8	1.7	52	1700
GaAs	3.37	3.61	3.63	1.6	66
ZnTe	2.83	2.18	3.16	4	160
InP	3.2	3.16	3.54	1.45	40
GaP	3.12		3.34	1	17
ZnS	2.3		2.88	1.5	7
CdTe	2.82		3.24	6.8	470
$LiNbO_3$	2.2	2.18	4.96	28	1100

$$FM_{THz} = \frac{n_o^6 r^2}{16 n_{THz}}$$

Table 1: Relevant parameters of organic and inorganic nonlinear optical materials that have been investigated for optical-to-THz frequency conversion. Refractive index n_o and the group index n_g at the pump optical wavelength; refractive index n_{THz} in the THz range; electro-optic coefficient *r*; figure of merit FM_{THz} for THz generation by optical rectification.

Organic crystals:
DAST, DSTMS, OH1

LAPC: guest-host polymer
[X.M. Zheng et al, J. Nanoelectron. Optoelectron. **2**, 58 (2007)]

Inorganic crystals: GaAs, ZnTe, InP, GaP, ZnS, CdTe, $LiNbO_3$

Best inorganic electro-optic materials, such as $LiNbO_3$ are far from optimal phase-matching conditions and can only be used in special configurations. Therefore, although having lower electro-optic coefficients and figures of merit, most commonly semiconducting electro-optic materials, such as ZnTe are used because they can operate close to phase matching. Organic materials combine both high figures of merit and possibility for velocity matching, therefore we chose these materials for our instruments. Organic crystals DAST, DSTMS and OH1 show best phase matching for fs laser sources in the telecom wavelength range 1200–1600 nm, which makes them very attractive for compact table-top THz instruments. They can also operate close to velocity matching in a broad range of THz frequencies, making possible broadband THz generation with low-power fs laser sources. Figure **4** shows an example of a broadband THz field generated in organic crystal DSTMS using ***TeraSys***® – **ULTRA** in comparison with the filed generated by a semiconducting antenna using a compact fs fiber laser source.

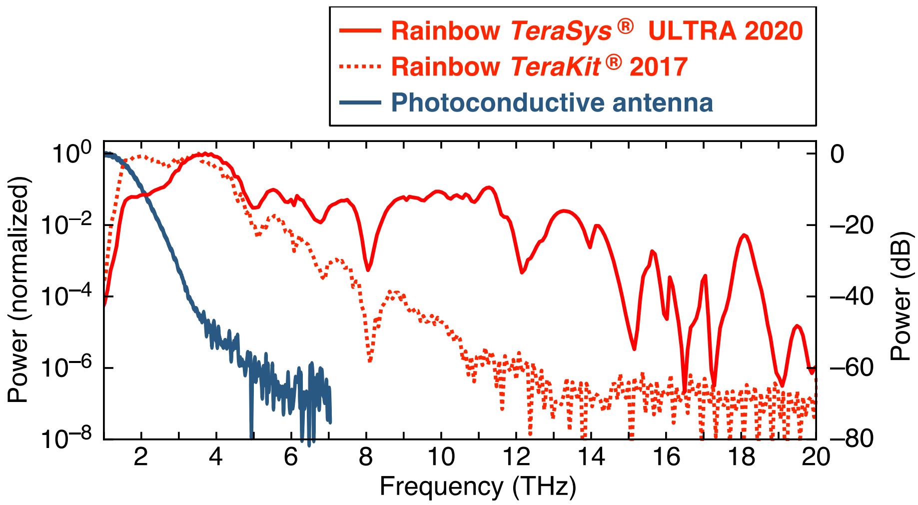

Figure 4: THz field amplitude as a function of frequency for a THz pulse generated in an organic crystal DSTMS (in ***TeraSys***® – **ULTRA**) using femtosecond pump lasers and THz time-domain spectroscopy, and typical range reached with PC antennas.

Organic THz generators and detectors

Terahertz generators and detectors are produced and optically prepared at the facilities of Rainbow Photonics in Switzerland. Rainbow Photonics AG is the worldwide only commercial producer of organic single crystalline THz generators.

Figure 5: THz generators/detectors optically prepared and mounted for applications. Standard aperture sizes range from 2 to 5 mm; larger sizes are available upon request.
The generators exhibit a high damage threshold of over 150 GW/cm2 at 150 fs pulse length and 1500 nm.
High THz electric fields of over MV/cm have been generated by our generators.[4,5]

Figure **6** shows best application ranges of our THz generators: pump lasers in the wavelength range 1200–1600 nm are most suitable. Shorter the pulse, larger will be the generated THz bandwidth when using optical rectification, as shown in Figure **3**.
The list of publications using our organic crystals DAST, DSTMS and OH1 can be found here: http://www.rainbowphotonics.com/pdf/Publications_THz_generators.pdf

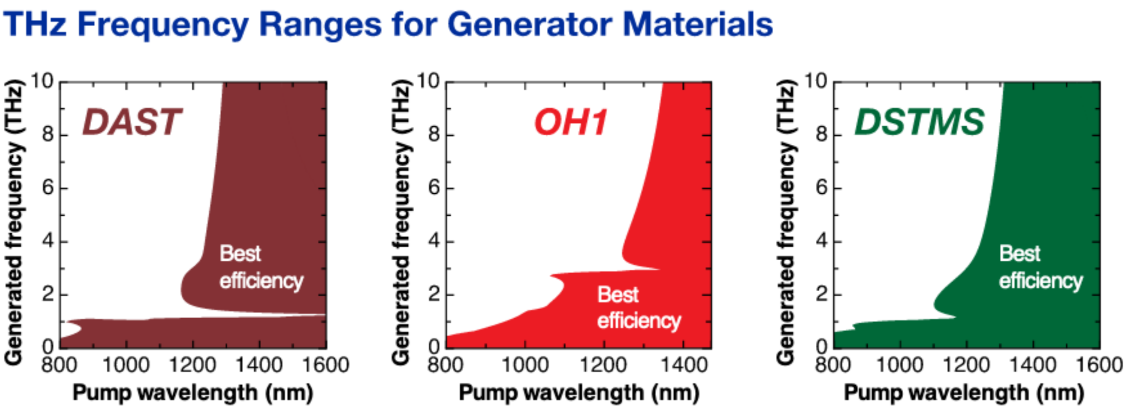

Figure 6: Best application ranges of organic single-crystalline THz generators DAST, OH1 and DSTMS. The shaded ranges present areas of coherence length exceeding 0.5 mm. Pulsed lasers with wavelengths between 1200 and 1600 nm are best suited as pump lasers for our THz generators.

Detection: In THz time domain spectroscopy, one can use common techniques for the detection of THz signals generated in organic crystals. To achieve best detection efficiency in a broad THz range, same organic materials can be also used for electro-optic detection using a different principle as for standard electro-optic sampling,[1] which is limited to optically isotropic materials. For organic crystals (or other birefringent materials) THz-induced lensing can be used with a similar sensitivity as the electro-optic sampling.[2]

4 Hauri, C. P.; Ruchert, C.; Vicario, C. & Ardana, F., "Strong-field single-cycle THz pulses generated in an organic crystal," Appl. Phys. Lett. 99, 161116 (2011)
5 Ruchert, C.; Vicario, C.; Hauri, C. P., "Scaling submillimeter single-cycle transients toward megavolts per centimeter field strength via optical rectification in the organic crystal OH1," Opt. Letters 37, 899 (2012)

Terahertz time-domain spectroscopy and imaging with *TeraSys*® – ULTRA and *TeraIMAGE*®

The ***TeraSys***® – **ULTRA** provides the Ultra-Wide THz bandwidth on the market for Spectroscopy and Imaging and the ultimate solution for real time, THz imaging and spectroscopy. It is a compact terahertz instrument addressing: sensing, detection, analysis and processing methods at terahertz (THz) frequencies in real time. It is based on organic crystals to allow access to terahertz frequencies up to 20 THz not available with conventional antennas. It features real-time acquisition with 4 spectra per second. The ***TeraSys12***® provides as well real time acquisition with a THz bandwidth of up to 12 THz.

Figure 7: ***TeraSys***® **– ULTRA** optical board (52 cm x 65 cm2).

Figure 8: *TeraIMAGE*® optical board (scanning range 50 x 50 mm2).

The THz detection in ***TeraSys***®**– ULTRA** is optimized using special optical and electronic components (the details are confidential) so that a high SNR (signal to noise ratio) can be achieved already using relatively low-power femtosecond fiber lasers. An example of the time-domain THz signal and its spectrum is shown in Figure 9. It features an acquisition time of 4 spectra per second

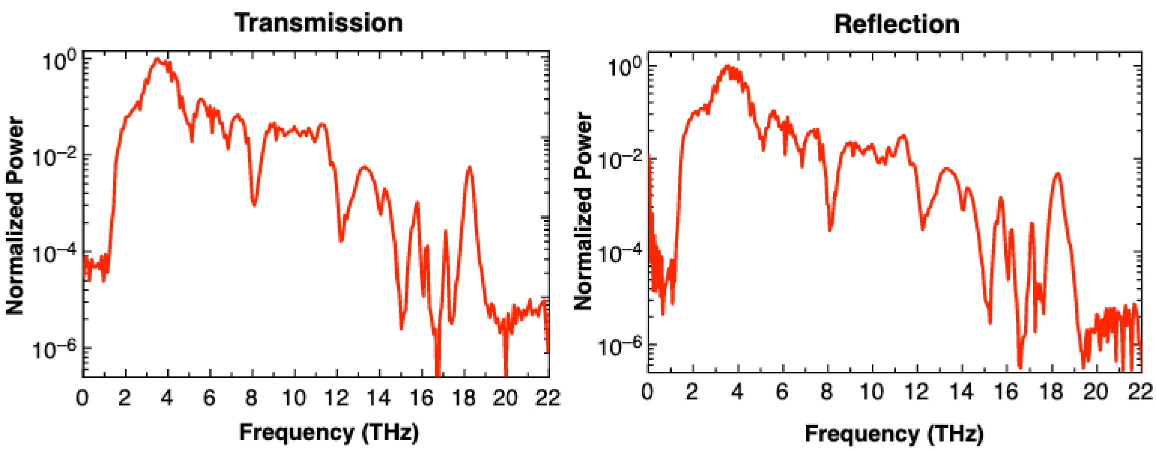

Figure 9: THz time-domain signal amplitude and amplitude spectrum in ***TeraSys***® **– ULTRA** using 0.45 mm thick DSTMS crystals for THz generation and detection, and a pump laser with 20 fs pulse length, average power of 120 mW and 3.5 nJ energy/pulse.

The THz time-domain spectrometer with imaging option, ***TeraIMAGE®***, includes, beside the spectroscopic part, which is the same as in ***TeraSys®***, the imaging part with all necessary mechanics control and data acquisition software for scanning objects up to 50 x 50 mm^2 (larger available upon request). Examples obtained with ***TeraIMAGE®*** are shown in Figure 10 and 11.

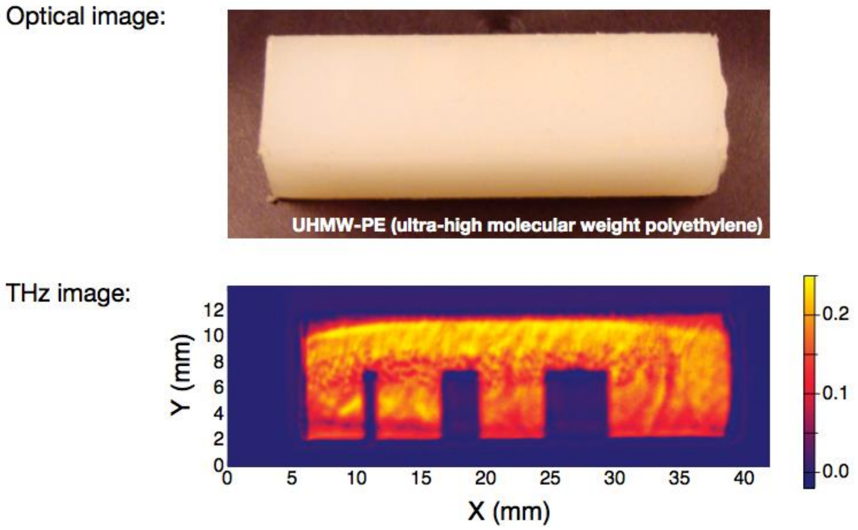

Figure 10: Optical image (made by a usual photocamera) and terahertz image (made by ***TeraIMAGE®***) of a piece of plastics with optically invisible defects.

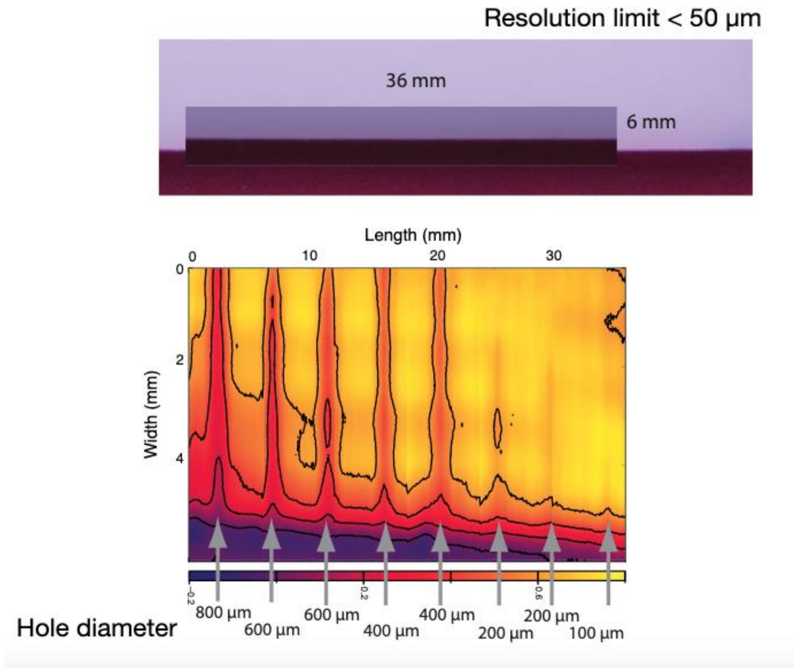

Figure 11: THz image of hidden holes in UHMWPE (Ultra high molecular weight polyethylene) detected with the ***TeraIMAGE®.***

Narrowband widely tunable THz source: *TeraTune*®

Many materials exhibit specific absorption features (fingerprints) not only in the THz range up to about 3 THz, mostly investigated because this range that can be reached by photoconductive antennas, but also higher above, see Table **2**. Also, the attenuation in air due to water-vapor absorption, which limits the range of application possibilities below about 10 THz becomes much smaller (up to four orders of magnitude at 18 THz!) above 10 THz (see Figure 11), which makes it interesting to extent the THz range up to 20 THz.
Table 2: THz fingerprints of explosives and related compounds [from Liu et al., Proc. IEEE].[6]

Explosive & Related Compound	Measured Absorption Peak Position (THz)
TNT	1.66, 2.20, 3.69, 4.71, 5.52, 8.28, 9.12, 9.78, 10.65, 11.01,13.86, 15.15, 16.95, 17.37, 19.17, 19.89
RDX	0.82, 1.05, 1.50, 1.96, 2.20, 3.08, 6.73, 10.35, 11.34, 12.33, 13.86, 14.52, 17.74, 18.12, 20.13
HMX	1.78, 2.51, 2.82, 5.31, 6.06, 11.28, 12.00, 12.54, 12.96, 13.74, 14.55, 18.15, 18.60, 19.38
PETN	2.0, 2.84
Tetryl	5.97, 10.11, 11.28, 14.67, 16.14, 18.36
2-amino-4, 6-DNT	0.96, 1.43, 1.87, 3.96, 5.07, 6.27, 8.49, 9.87, 10.77, 12.15, 13.44, 16.68
4-amino-2, 6-DNT	0.52, 1.24, 2.64, 3.96, 5.04, 5.82, 7.53, 9.30, 10.20, 11.13, 13.86, 14.97, 17.70
4-Nitrotoluene	1.20, 1.37, 1.86, 6.75, 8.85, 10.83, 14.04, 15.66, 18.51
1,3,5-TNB	4.17, 4.62, 10.05, 11.19, 13.80, 15.75, 19.05
1,3-DNB	0.94, 1.19, 2.37, 10.56, 12.18, 15.33, 17.13
1,4-DNB	3.24, 3.96, 5.55, 10.38, 12.45, 13.29, 15.21, 15.54
2,4-DNT	0.45, 0.66, 1.08, 2.52, 4.98, 8.88, 10.56, 11.58, 12.81, 14.34, 15.69, 19.05, 20.04
2,6-DNT	1.10, 1.35, 1.56, 2.50, 5.61, 6.75, 9.78, 11.43, 13.32, 13.89, 15.39, 17.25
3,5-dinitro aniline	0.96, 1.20, 3.18, 4.62, 5.04, 5.91, 7.44, 10.62, 10.98, 14.46, 16.41, 18.18
2-nitro diphenyl anine	2.19, 2.58, 2.88, 3.45, 5.13, 6.18, 7.56, 10.08, 12.33, 13.05, 15.00, 15.60, 16.29, 17.34, 18.51, 19.32

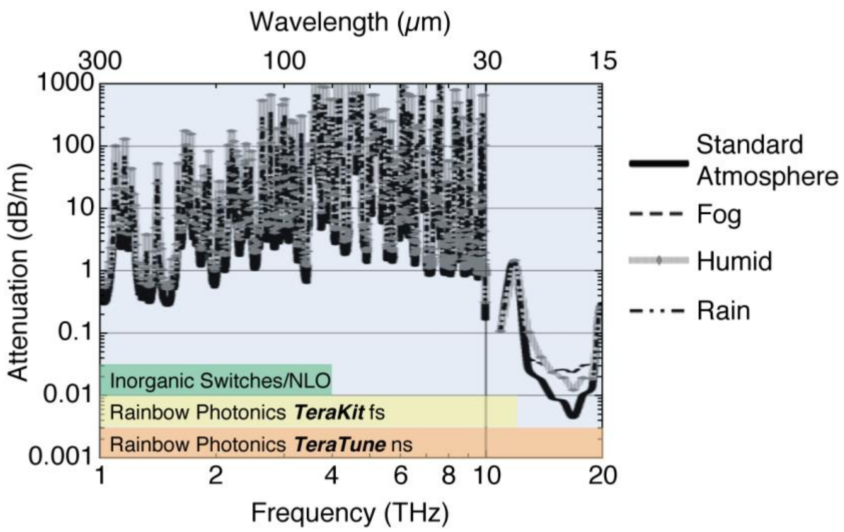

Figure 11: Attenuation of THz radiation in air [from Appleby et al, IEEE 2007][7]. Above 10 THz, the attenuation in air dramatically decreases compared to the attenuation below 10 THz. This opens up a wide range of new application possibilities, such as remote imaging and sensing.

[6] H.B. Liu, H. Zhong, N. Karpowicz, Y. Chen, X.C. Zhang, "Terahertz Spectroscopy and Imaging for Defense and Security Applications," Proc. IEEE 95, 1514 (2007).
[7] R. Appleby, H. B. Wallace, "Standoff detection of weapons and contraband in the 100 GHz to 1 THz region",

For some applications a high THz beam power in a narrow band can be preferable than a broadband pulse. The total THz power generated with broadband generation techniques is distributed over the spectral content of the pulses; therefore the power density at any particular frequency is inherently low. To obtain reasonable conversion efficiency for a certain THz frequency, a narrower band pulsed output with high beam peak power is preferred.

TeraTune® is a tunable narrowband THz source with a narrow linewidth of less than 100 GHz and a large tuning range 1–20 THz. Rainbow Photonics introduced this unique THz source to the market in 2012. It is based on difference frequency generation of nanosecond pulses in organic THz generators DSTMS and OH1. The suitable infrared pump pulses are generated in a specially designed dual-wavelength OPO (optical parametric oscillator), which is tunable in the range of 1330–1480 nm and produces two narrowband nanosecond pulses with their frequency difference in the THz range. The wavelengths can be tuned by angular tuning of OPO crystals, which is motorized and controlled by the accompanying software. The generator crystals can be externally switched for achieving the best efficiency at different THz frequencies. High THz peak power of more than 30 W can be reached at 1.25 THz using OH1 generator crystals. The tunability spectrum using 1-mm thick DSTMS crystals is shown in Figure 13.

Figure 12: *TeraTune®*: Tunable (1–20 THz) narrow linewidth (<100 GHz) THz source.

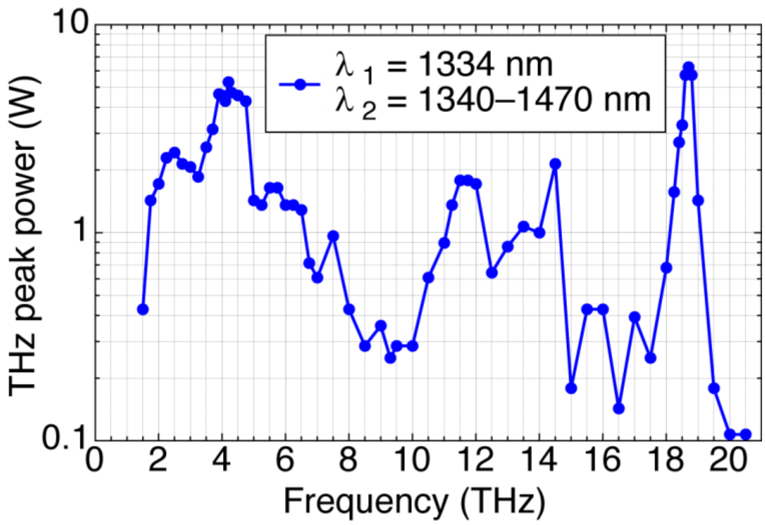

Figure 13: Tuning curve of ***TeraTune®*** using a 1-mm DSTMS THz generator. In some regions the achievable THz peak power is low, which is either due to the THz absorption of the generation material itself or due to non-perfect phase matching. The generation crystal is relatively thick (1 mm), so that high efficiency is achieved where the generation is phase matched.

IEEE Trans. Antennas Propag. 55, 2944 (2007)

Applications of THz waves

Some of the applications of THz waves are related to the unique properties of these waves to excite molecular vibrations and lattice vibrations in the "Reststrahlen" range. In addition the THz waves show low absorption and are transmitted through most non-conductive homogeneous plastics, paper, cartoon, most clothes, etc, and can therefore detect hidden hazardous substances. Therefore besides THz spectroscopy of materials these waves are potentially useful for security applications, but also for the identification of defects in non-conductive materials. For conductive and partially conductive materials, THz spectroscopy can give useful insights into the mechanisms of charge transport in these materials. Here we give some examples of THz spectra and materials testing demonstrated using organic nonlinear optical materials for generation and detection of THz waves.

Figure 14(a) shows the THz spectra of several explosives as measured using THz time-domain spectroscopy.
Figure 14(b) shows a Semtex explosive sample hidden behind two teflon plates as seen by optical waves (left) and THz waves (right; Semtex: green; the yellow area on the upper right corresponds to the red paper sticker shown in the left picture).
Figure 14(c) shows a picture and THz image of a bacillus cereus spores (anthrax) sample hidden in an envelope. Examples of materials testing are shown in Figure 14(d) and (e).
Figure 14(d) shows the optical and THz pictures of a pile of overhead transparencies, where the label "ETH" has been cut out in one of the transparencies (not seen by visible light), and its THz transmission image giving a full contrast image due to the phase shift of the THz wave in the cut-out area (the "defect"). The second picture shows how metallic defects or inclusions (a metal wire with the symbol "NLO") embedded in a plastic can be made visible by THz waves.

The last picture shows the identification of a void in a piece of plastics and Figure 14(e) the impressed credit card number from a credit card hidden in an envelope.

Figure 14(f) shows examples of THz reflection images of polyethylene samples with and without defects. The voids can be made visible in 3D with a resolution of less than 10 µm. This lower than the wavelength (longitudinal) resolution is due to the fact that the phase shift and temporal resolution of the reflected wave can be determined very precisely.

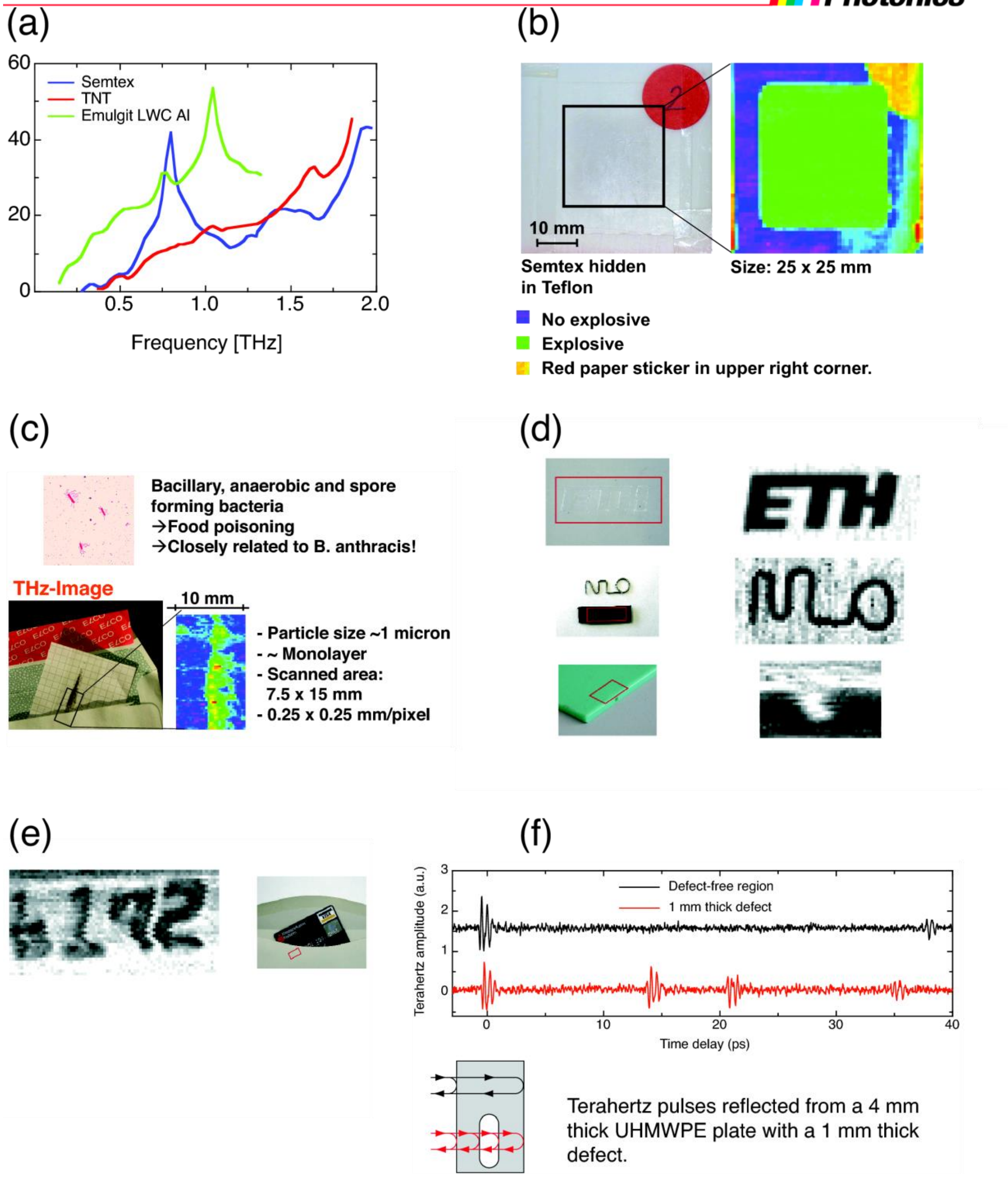

Figure 14: Examples of applications demonstrated by using organic nonlinear optical materials for THz generation and detection.

For more information please contact:

Rainbow Photonics AG, Farbhofstrasse 21, CH-8048 Zurich, Switzerland
Tel: +41 44 419 0505, Fax +41 44 419 0506
info@rainbowphotonics.com