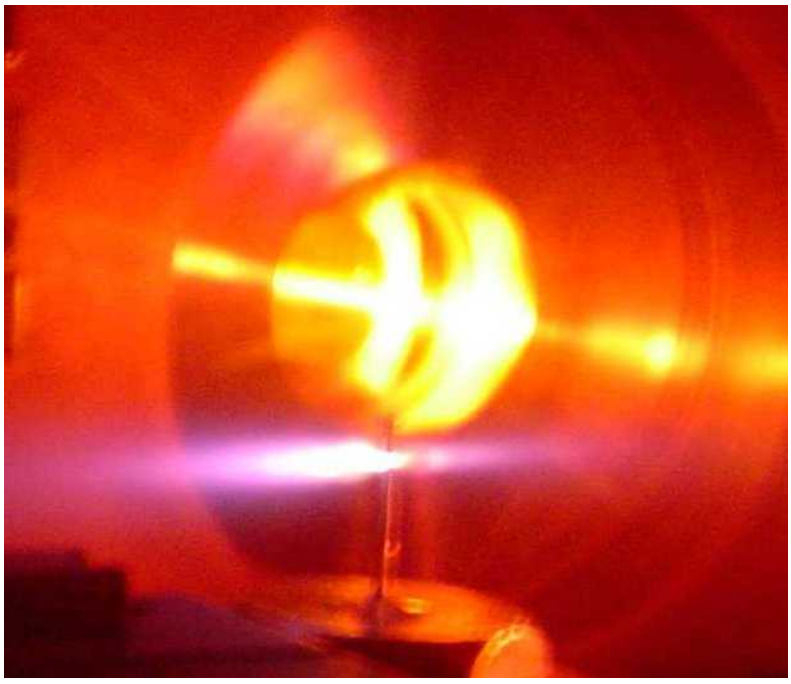
Applications

Ultrafast optics pushes the frontiers of[1]

- telecommunications
- industrial, medical, and bio-technologies
- frequency and time metrology
- ultrafast (pico-, femto-, attosecond) metrology
- high-field science
- coherent light sources



The purple light originates from helium atoms excited by intense, few-cycle laser light. The laser pulses propagate along the axis of the purple lobes (horizontally) through the helium gas. The strongly-driven helium atoms radiate x-rays coherently, which – as a consequence of phase-coherent emission – form a highly-collimated, laser-like X-ray beam. The experiment performed at the Vienna University of Technology in 2004 has resulted in the generation of coherent X-ray light at a photon energy of 1 keV (wavelength ~ 1 nm) for the

[1] Many illustrations have been borrowed from the *Ultrafast Optics* lecture course of Prof. Rick Trebino at the Georgia Institute of Technology, Atlanta.

first time[2] (photo courtesy of J. Seres, Vienna University of Technology, for more details see the attached report of the Photonics Spectra magazine).

Optical telecommunications

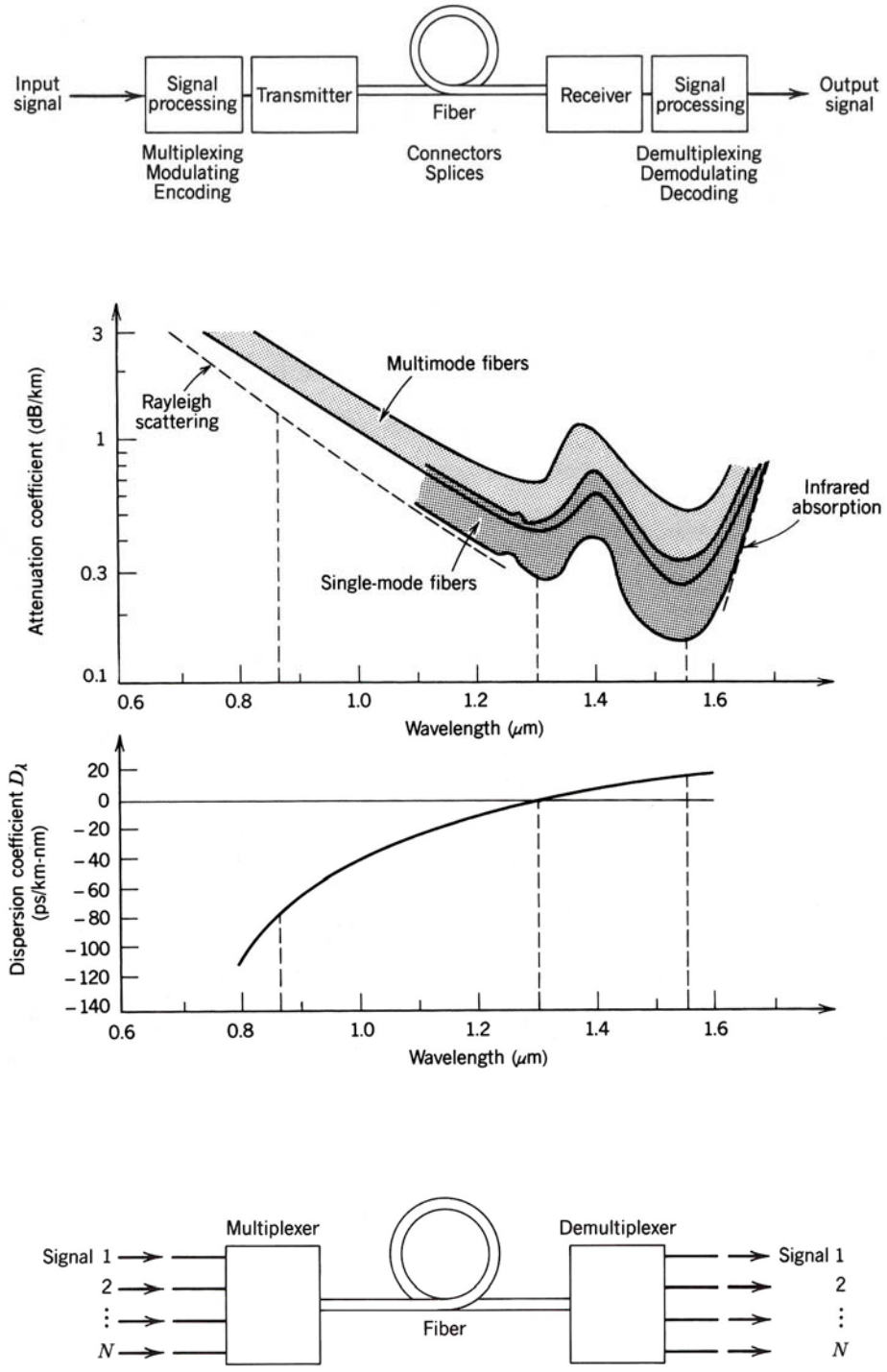


Fig. VIII-53

[2] J. Seres, E. Seres, A. Verhoef, G. Tempea, C. Streli, P. Wobrauschek, V. Yakovlev, A. Scrinzi, C. Spielmann, F. Krausz, "Source of coherent kiloelectronvolt x-rays," *Nature* 433, 596 (2005).

The 1450-1600 nm low-loss spectral window has a bandwidth of ~ 20 THz ⇒

⇒ offers data transmission with an ultimate rate of 5-10 Terabit/s through a single optical fibre ultimately over thousands of kilometres by means of

- Wavelength-division multiplexing (WDM) or time-division multiplexing (TDM)
- Femtosecond infrared seed sources
- Broadband infrared amplifiers
- Dispersion management, soliton(-like) propagation

Instrumentation for high-speed measurements: electro-optical sampling

The concept of electro-optic sampling: a pico- or sub-picosecond laser pulse triggers an electric transient at the input of some fast electronic circuit. The response of the circuit is measured by the output voltage inducing a change in the refractive index of an electro-optic medium (e.g. $LiTaO_3$), which is probed by another replica of the sub-picosecond pulse (Fig. VIII-54). Such an electro-optical sampling system constitutes a *sub-picosecond-resolution / Terahertz-bandwidth oscilloscope*.

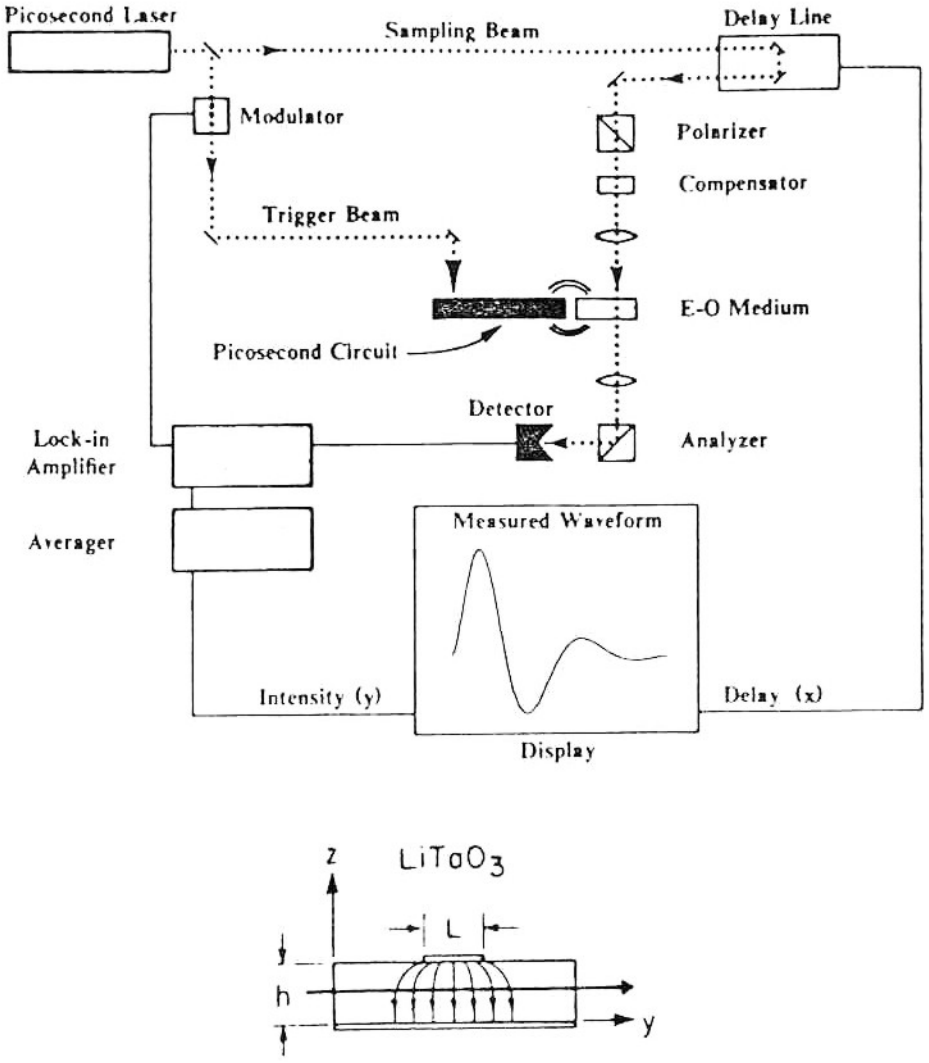


Fig. VIII-54

Electro-optic sampling can also be implemented in a non-invasive manner by measuring either

- a change in the refractive index induced inside the wafer (Fig. VIII-55)

or

- the electric fields above the integrated circuit by a small electro-optic crystal tip (Fig. VIII-56)

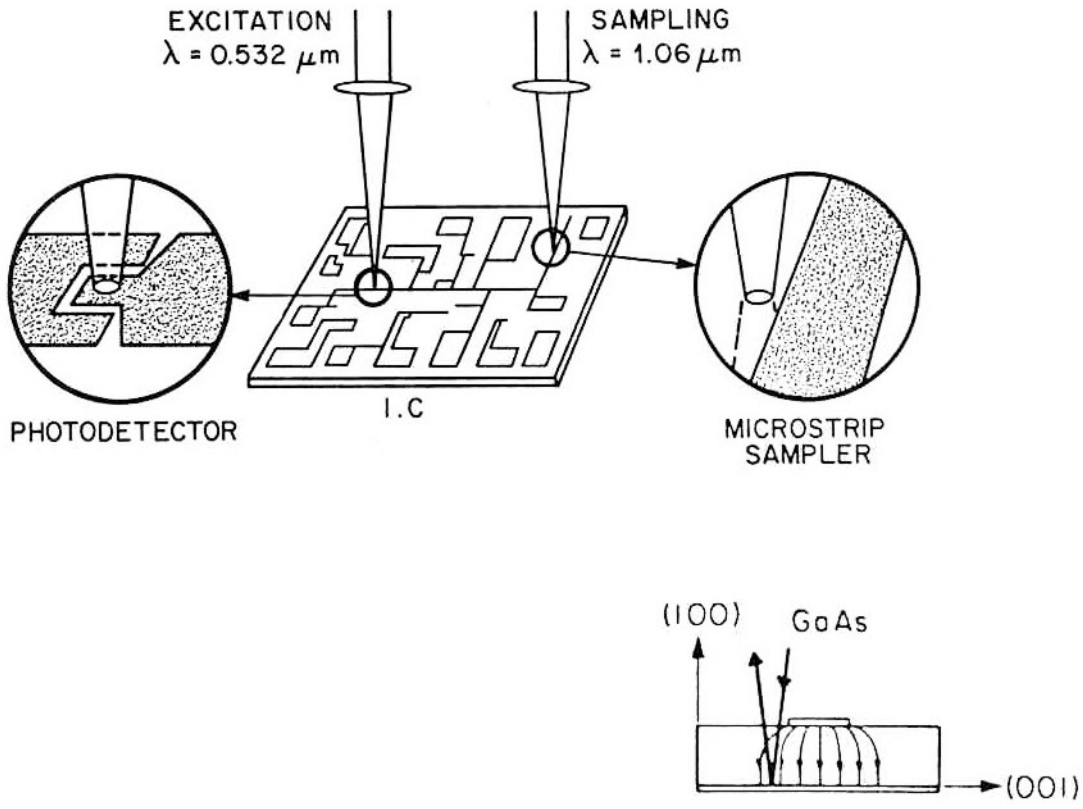


Fig. VIII-55

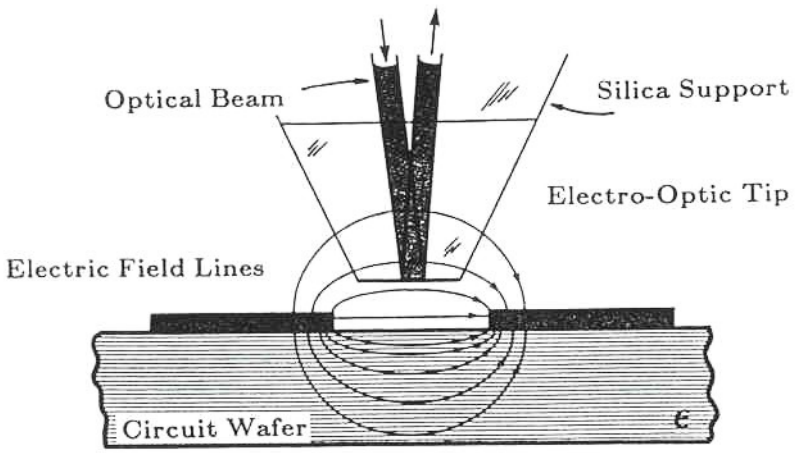
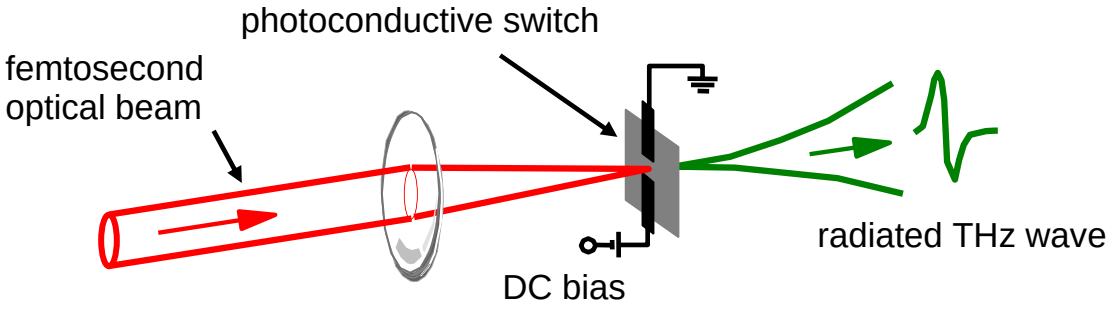


Fig. VIII-56

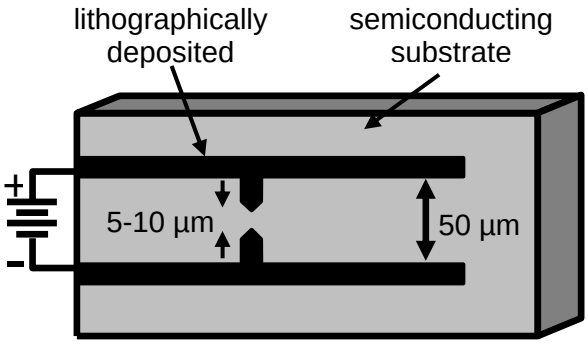
Electro-optic sampling: key technology for pushing the limits of high-speed electronics!

Broadband THz (T-ray) generation and applications[3]

Femtosecond light constitutes the most powerful tool for generating broadband THz pulses. One of several possibilities: a femtosecond pulse induces conductivity in a biased photoconductive switch. Accelerating charge emit light. Emission is proportional to the time-derivative of the induced current, resulting typically in a single-cycle pulse of some hundred femtosecond duration (Fig. VIII-57).

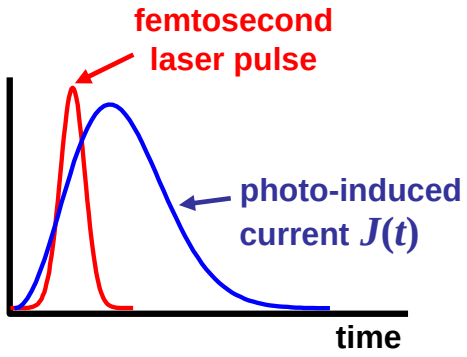


Typical THz photoconductive emitter:



Radiated field:

$$E(t) \propto \frac{\partial J}{\partial t}$$



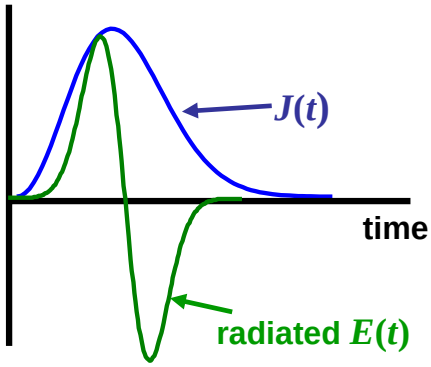


Fig. VIII-57

[3] D. Mittleman (ed.), "Sensing with THz radiation", Springer, Heidelberg, New York, 2002

Detection and measurement of THz waves

uses the same fs optical pulse that generates it. This induces conductivity in a photoconductive switch, which then yields more current when the THz pulse is present, resulting in a cross-correlation between the THz waveform and the laser intensity. As the laser pulse is shorter, the cross-correlation yields directly the THz field variation (Fig. VIII-58).

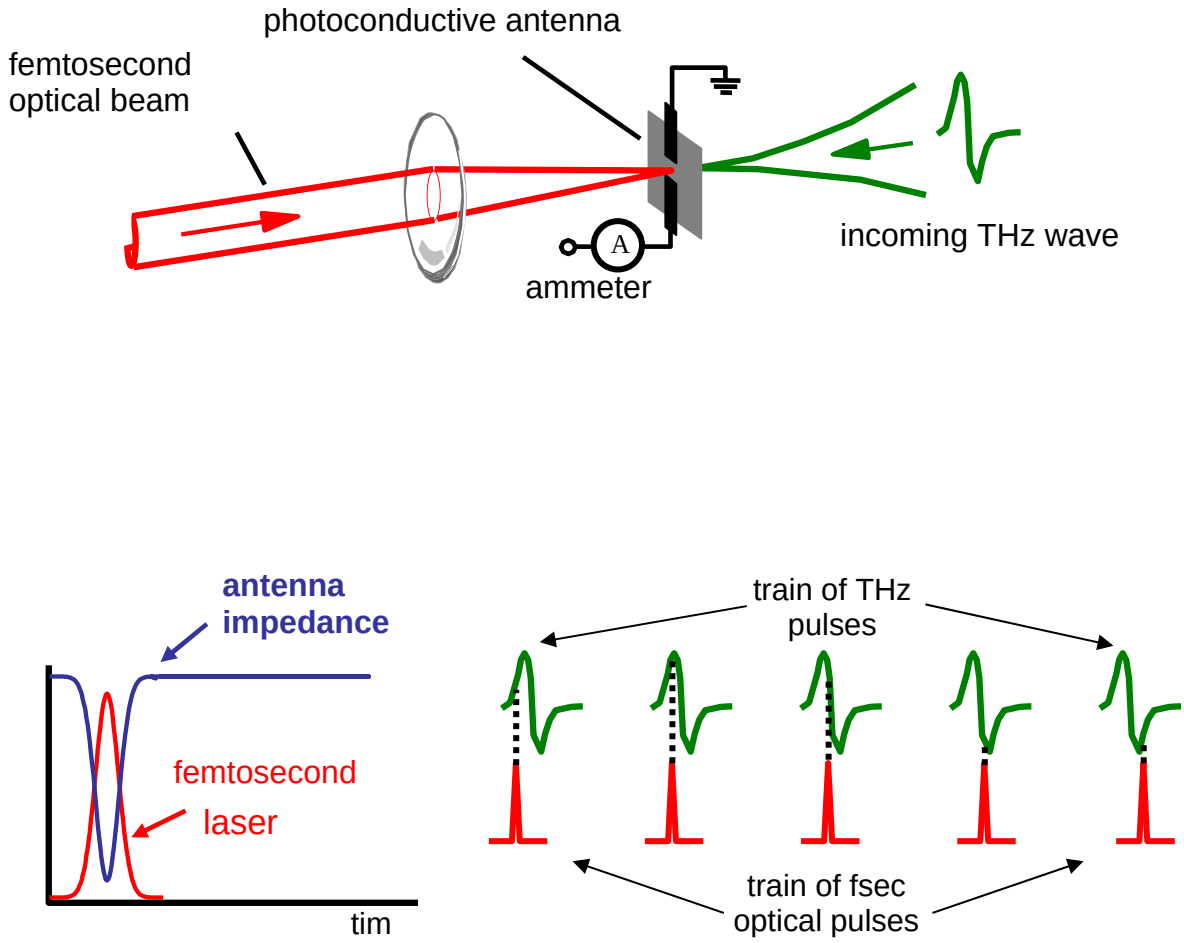


Fig. VIII-58

A typical THz waveform as detected by a photoconductive sampler is shown in Fig. VIII-59. Knowing $E(t)$, the spectrum can be calculated simple by Fourier transformation. This method is called *time-domain spectral analysis* and constitutes the most important technique for spectral analysis in the THz domain.

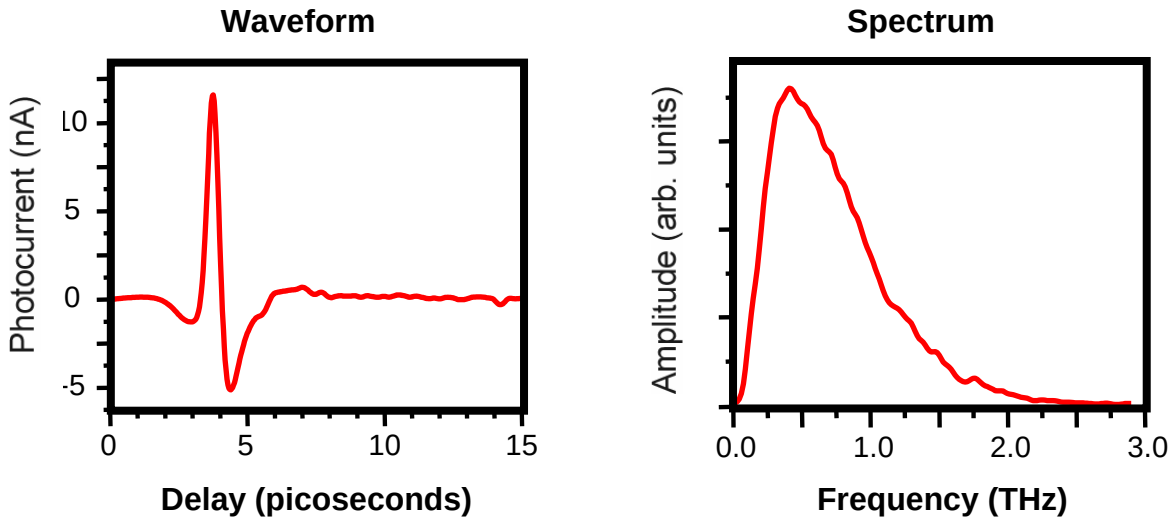


Fig. VIII-59

Electro-optic sensing

allows *time-domain THz spectrometry* in both samples (Fig. VIII-60) as well as free space over extended distances (VIII-61). measuring the spectrum in this way before and after a sample irradiated with a THz beam yields the absorption spectrum of the sample in the THz range (Fig. VIII-60). With radiation generated by few-femtosecond laser pulses the incredible spectral range from 0.1 – 100 THz can be covered!

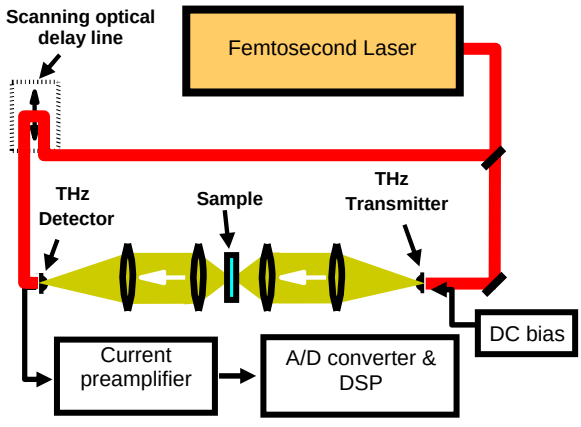


Fig. VIII-60

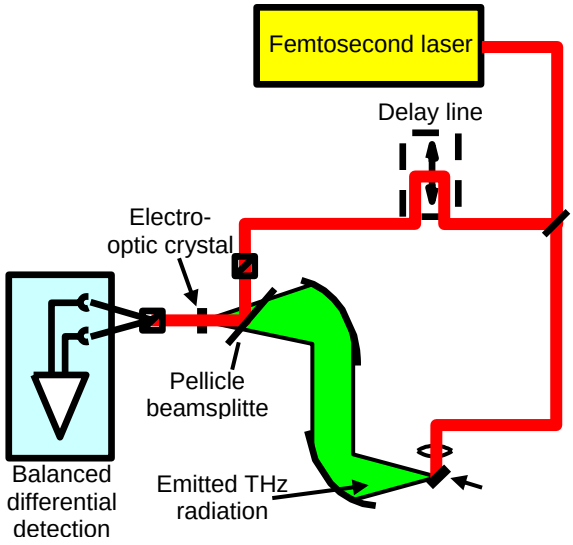


Fig. VIII-61

One of the many applications: studying species in flame ⇒ insight into the microscopic processes during combustion phenomena

THz imaging in microelectronics, biology and medicine

Benefits from the fact that many materials that are opaque to visible light are transparent in the THz range.

THz imaging in microelectronics: THz sees the metal leads through the plastic packaging (Fig. VIII-62). Fault detection in integrated circuits.

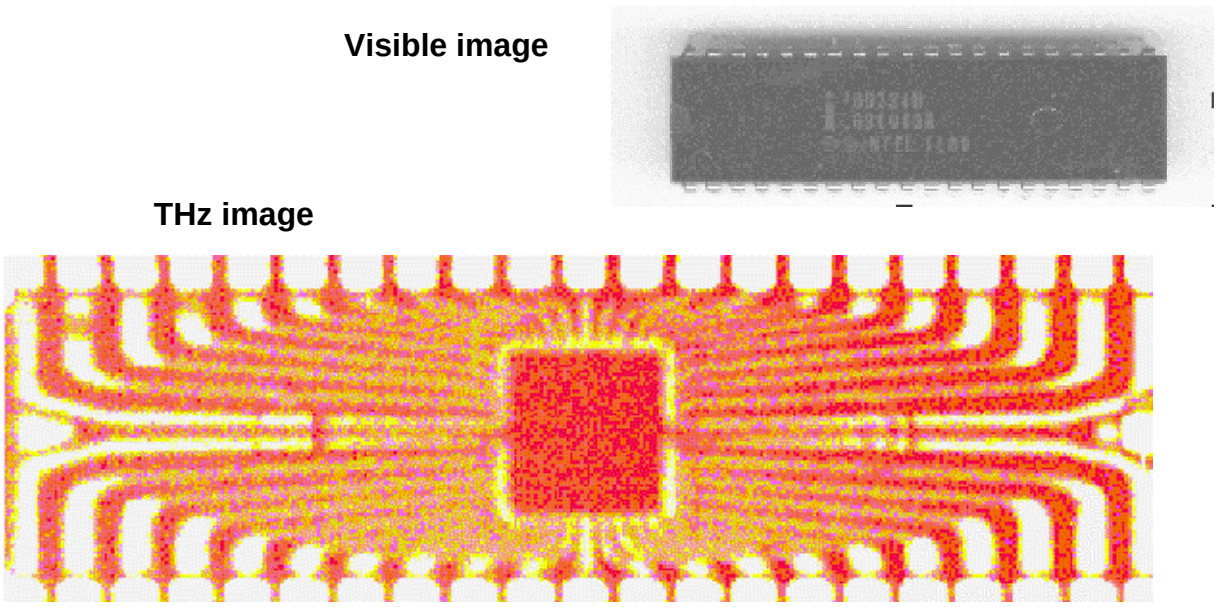


Fig. VIII-62

THz imaging in biology: water detection in plants.

Proof-of-principle experiment: a leaf is allowed to dry somewhat, and then watered. As it rehydrates, THz transmission decreases. Changes smaller then 1% are detectable (Fig. VIII-63).

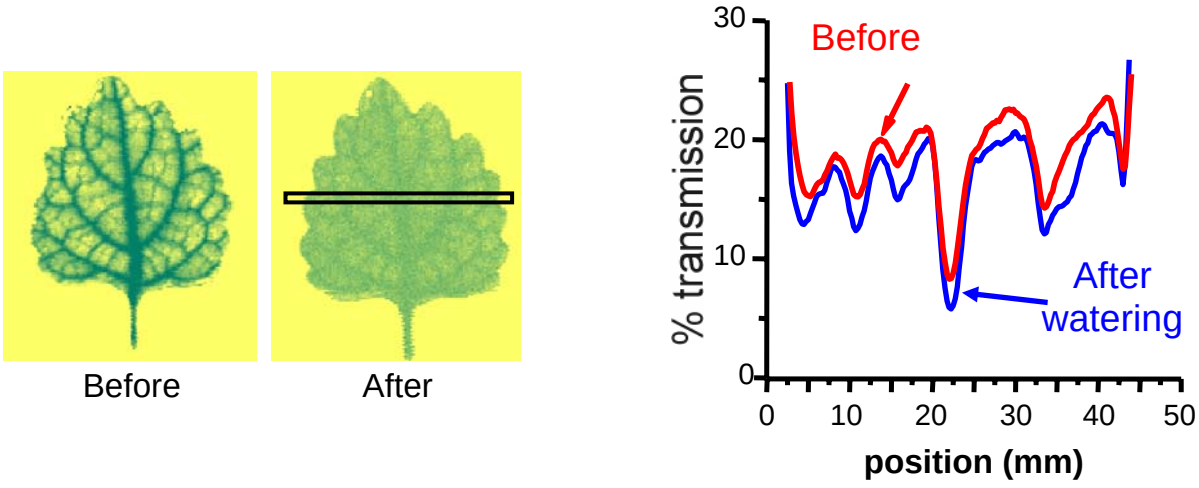
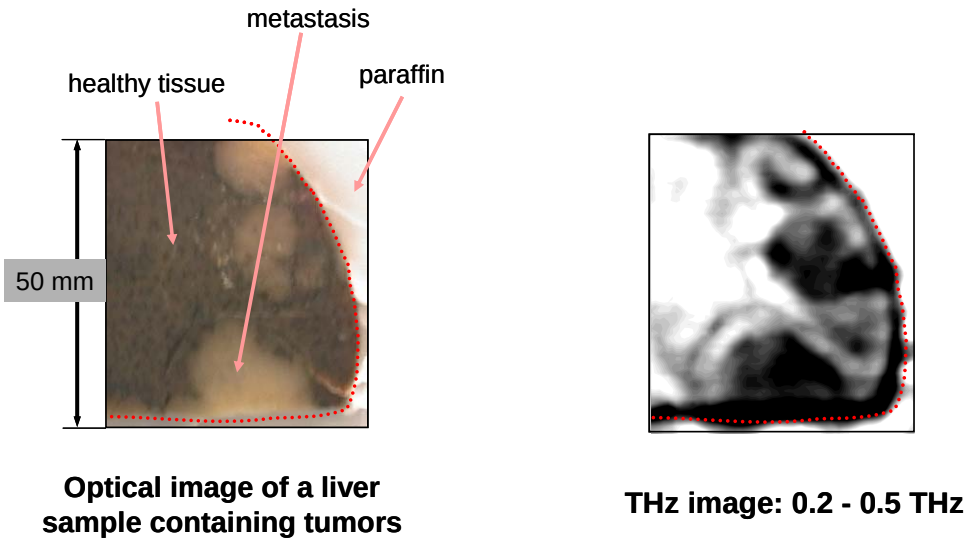


Fig. VIII-63

THz imaging in medicine: tumour detection

Tumours appear to have different THz absorption properties from normal tissue (Fig. VIII-64). They can be detected with a resolution of ~ 0.1 mm without having to rely on ionizing radiation.



Optical image of a liver sample containing tumors

THz image: 0.2 - 0.5 THz

Fig. VIII-64

THz imaging in dentistry: caries detection (Fig. VIII-65)

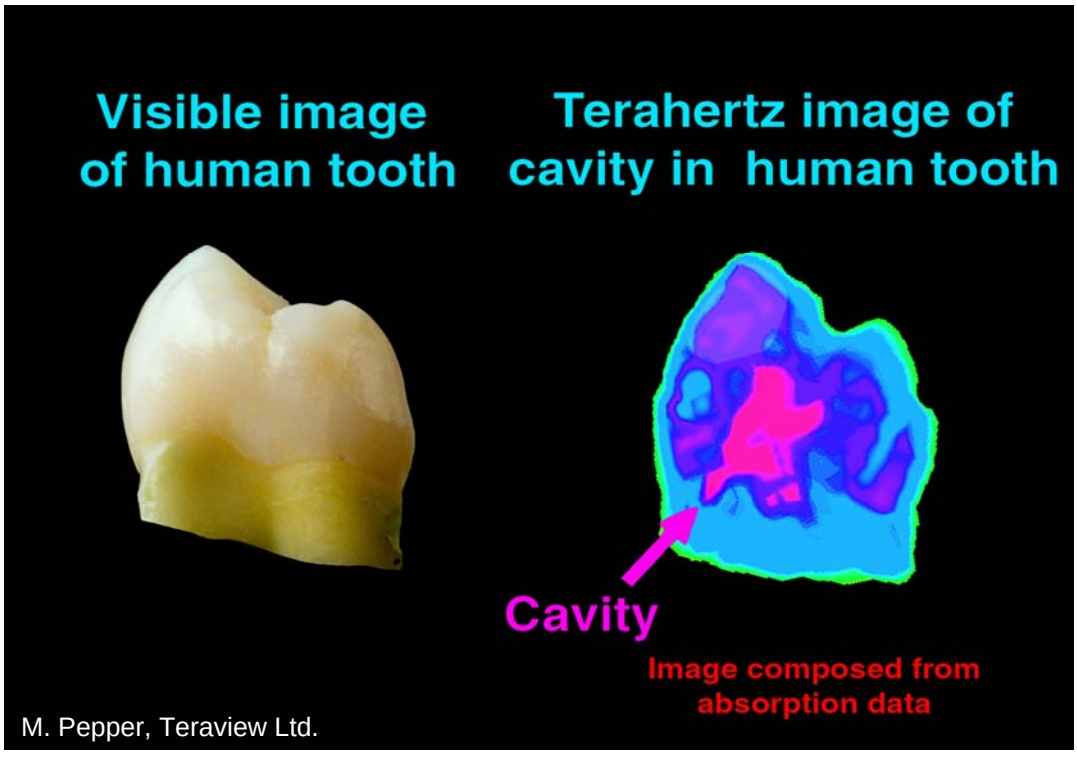


Fig. VIII-65

Biological/medical imaging with ultrashort laser pulses

Problems of traditional microscopy

- Many objects are clear and require generally toxic stain to be seen.
- Objects must usually be sectioned (sliced) to be observed.
- Some objects are inaccessible to microscopes, such as the inside of a blood vessel or the retina of the eye.
- Most objects are “turbid,” that is, they scatter a lot. This is the big challenge in medical imaging inside the human body.
- Optical microscopy has limited spatial resolution (l/2), and a lot of stuff is smaller.

Ultrashort-pulse imaging techniques address these problems.

Two-photon/multiphoton microscopy

The intensity of fluorescence light emerging in the illuminated sample is proportional to the square (two-photon microscopy) or the cube (three-photon microscopy) of the incident focused light intensity. Hence both the transverse and the axial size of the emitting volume is smaller than the illuminated one, resulting in substantially improved lateral as well as depth resolution (Fig. VIII-66).[4]

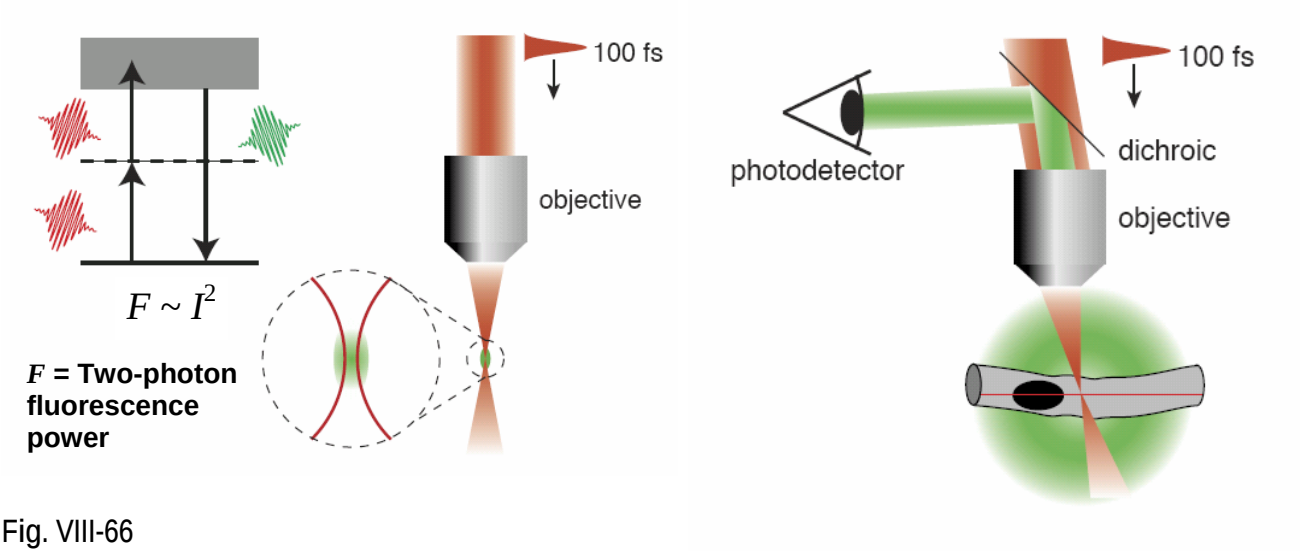
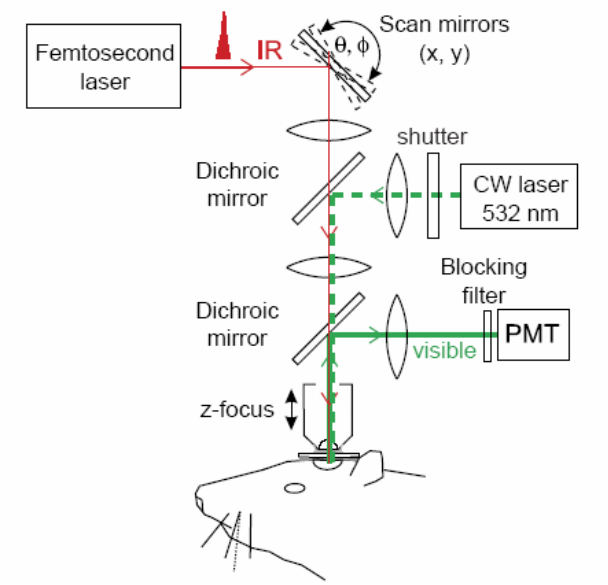


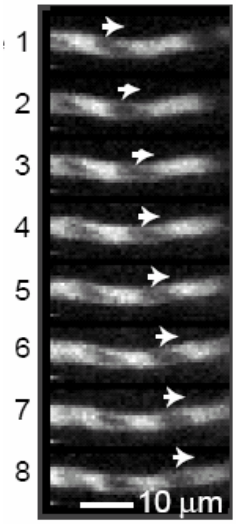
Fig. VIII-66

Two-photon imaging of a rat brain (Fig. VIII-67).[4]

[4] Images due to Chris Schaffer, Uinv. California, San Diego



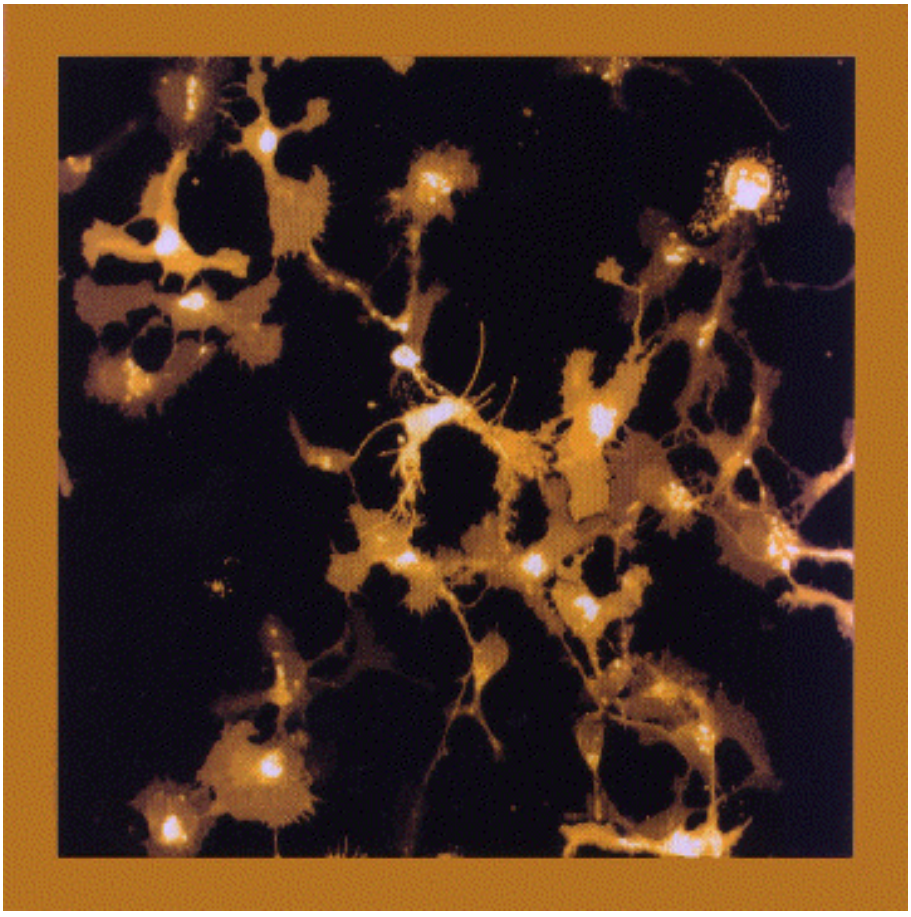
Blood vessels



Fast imaging allows red-blood-cell motion to be discerned.

Fig. VIII-67

Two-photon imaging of brain tissue



Living rat hippocampal neurons were stained with DiO, and imaged using pulsed illumination at 900 nm. These were imaged one day after staining and plating onto a poly-lysine-coated plastic Petri dish. The image shown in Fig. VIII-68 is a projection through 50 sections of 0.3 um each. No dye bleaching was observed during scanning. The imaging had no adverse effect on the health of the cells, compared to unscanned regions in the same dish after another day in culture.[5]

Fig. VIII-68

[5] Steve Potter, Georgia Institute of Technology, Atlanta

Third-harmonic microscopy

In the tight focus of a femtosecond laser beam high intensities give rise to non-linear optical effects. As a result, third harmonic (TH) light is produced on one side of the focus...

... and the other...

but they interfere destructively due to the Gouy phase shift in the focused Gaussian beam (Fig. VIII-69).[6]

Breaking the symmetry of the focus prevents totally destructive interference and some of the third harmonic light is emitted ⇒ third-harmonic imaging is sensitive to interfaces.

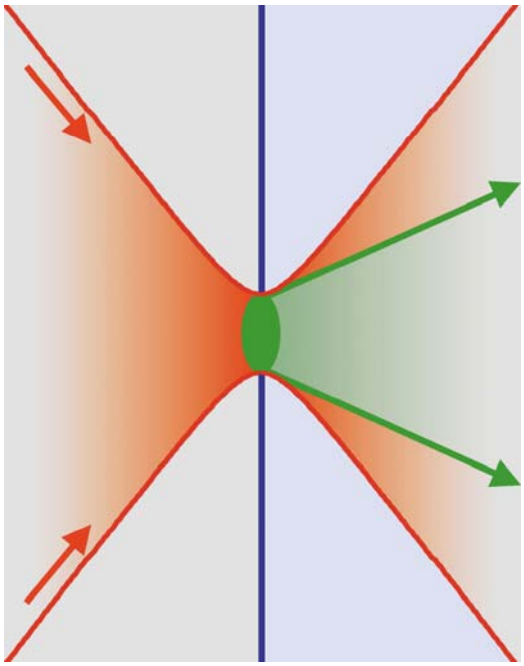
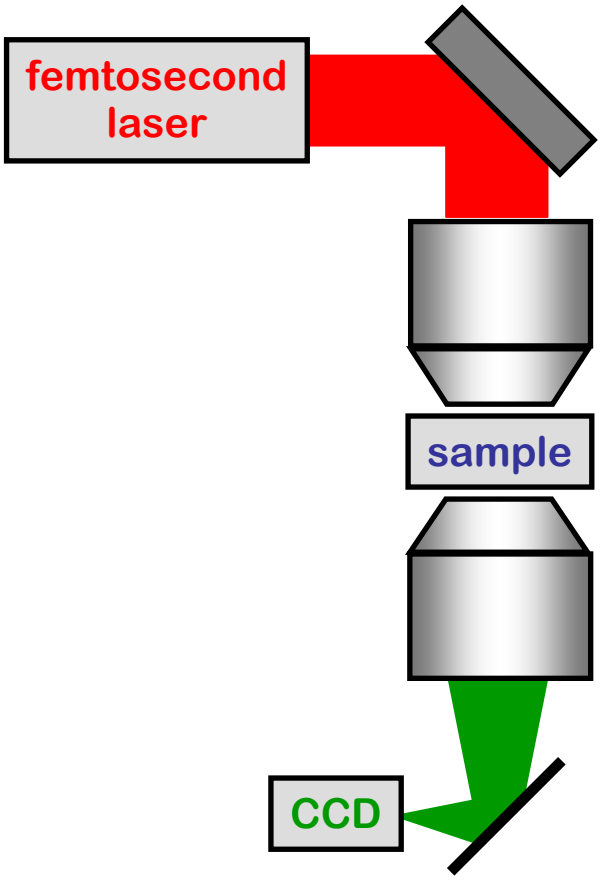


Fig. VIII-69



The third harmonic of the incident light is produced when an interface breaks the symmetry of the focus, providing inherent optical sectioning.

Normal optical microscope objectives are used to focus the input light and collect the TH signal light.

The sample can be scanned in x and y (and maybe z) directions. Or a large beam with a microscope collection lens can be used for single-shot operation (Fig. VIII-70).[6]

Background-free, requires no additional staining.

Provides inherent optical sectioning.

Non-fading in nature (stains fade with time).

Uses IR, rather than visible or UV, so is less damaging to the specimen.

Is less bothered by phase distortions in the medium than conventional microscopy.

Fig. VIII-70

[6] J. Squier, Colorado School of Mines, US

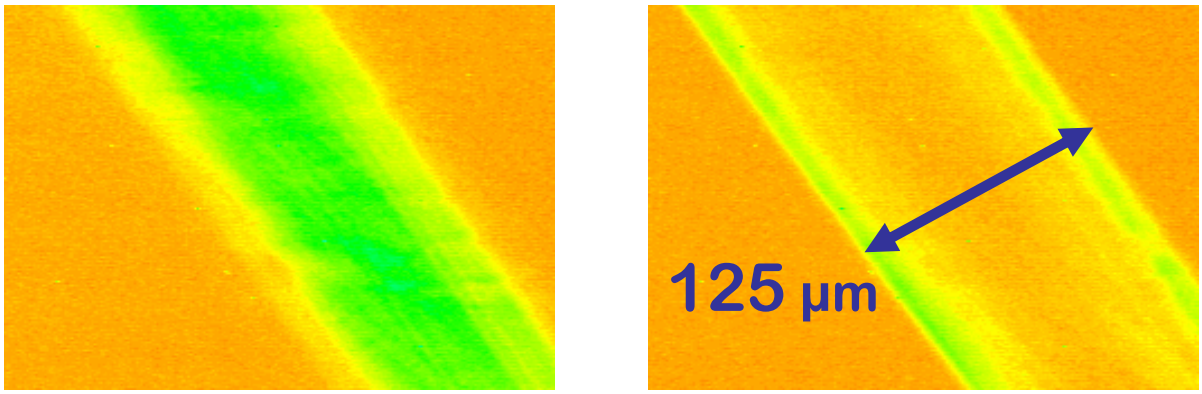


Fig. VIII-71 Third-harmonic imaging of low-contrast interfaces: an optical fibre immersed into an index-matching fluid. The third harmonic signal is generated at the interface of jacket and cladding; no image processing or background subtraction was used here. (~100 fs pulses at 1.2 µm, 1 kHz repetition rate.)[7]

Optical coherence tomography, OCT[8]

Optical distance ranging with broadband (short-coherence-length) light[9] draws on a simple concept: time-resolve back-scattered light to obtain depth resolution and scan transversely to obtain lateral resolution (Fig. VIII-72).[10]

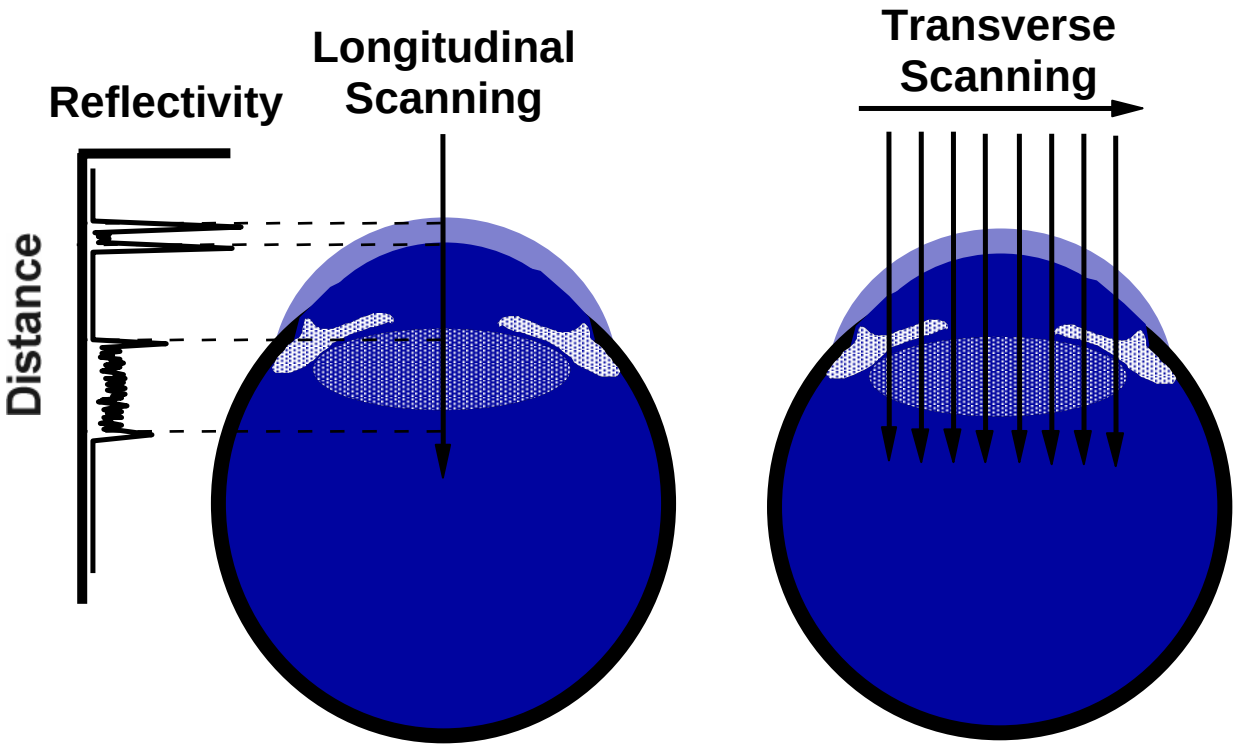


Fig. VIII-72

[7] J. Squier, Colorado School of Mines, US
[8] Illustrations and figures of this section kindly provided by J. Fujimoto (MIT) and W. Drexler (Univ. Vienna).
[9] Huang, *et al.*, *Science* 254 (1991).

Time-resolution of the back-scattered signal can be obtained by measuring the correlation of the back-scattered light with a reference replica of the same broadband light in a scanning Michelson interferometer. When the interferometer paths are equal, the intensity fringes are the strongest. The accuracy (depth resolution) is determined by the coherence length (Fig. VIII-73). The broader the spectral width of the light source, the shorter the coherence length, the higher the resolution. The broadest-band light can currently be produced by femtosecond lasers.

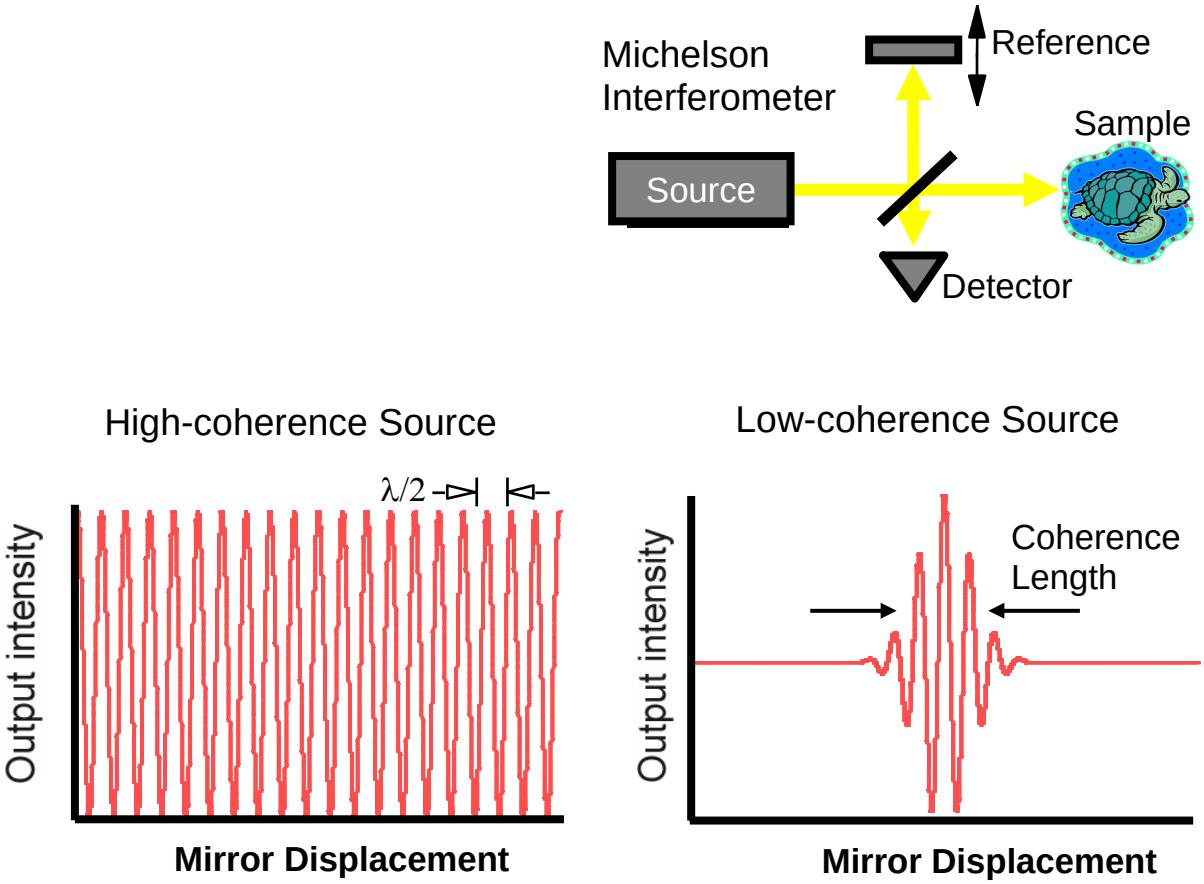


Fig. VIII-73

With state-of-the-art commercial[11] sub-10-fs Ti:sapphire lasers unparalleled depth resolution of ~ 1 micron could be demonstrated at the University of Vienna (Figs. VIII-73, 74).

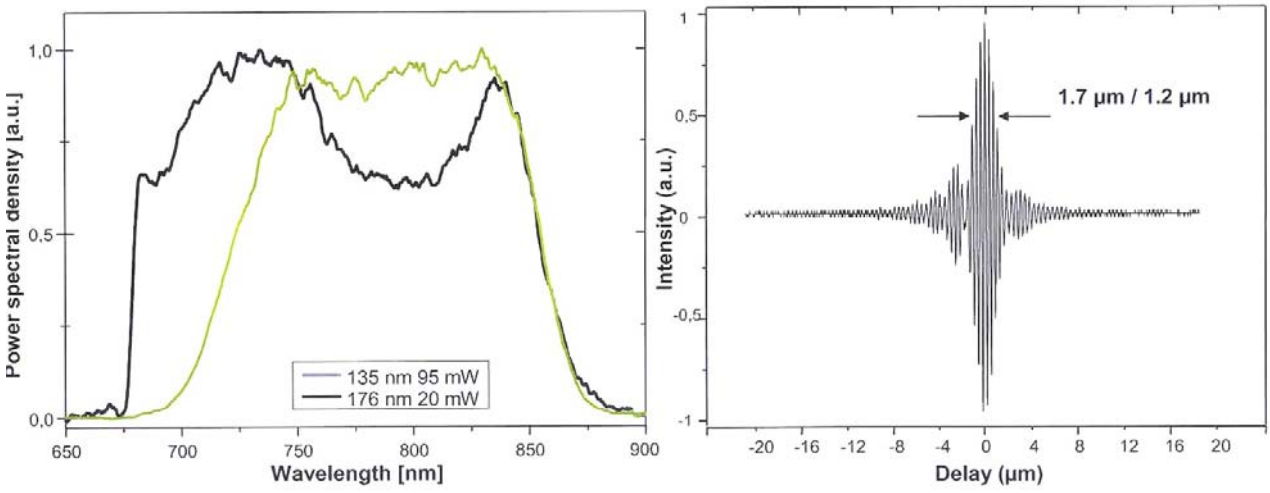


Fig. VIII-74

[11] www.femtolasers.com

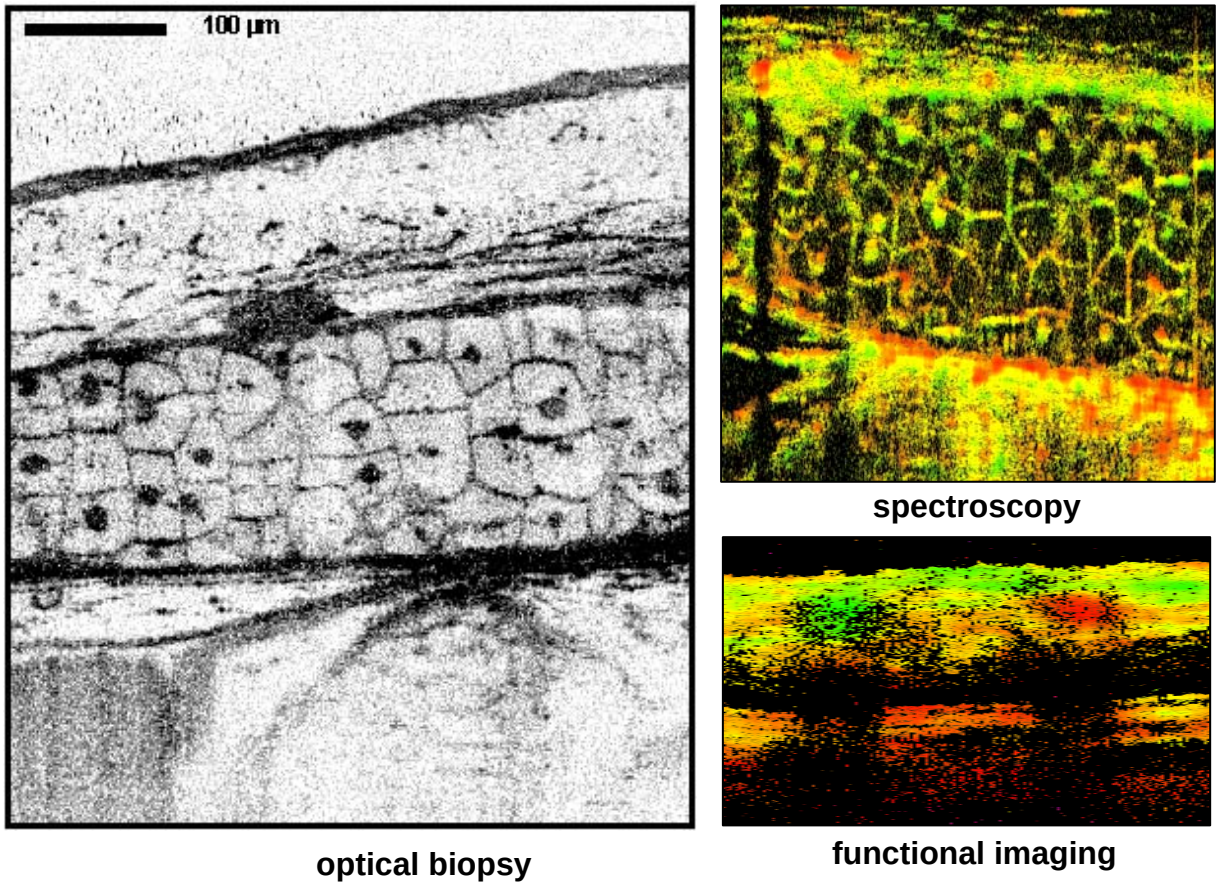


Fig. VIII-75 Ultrahigh-resolution OCT images of the human eye recorded with sub-10-fs illumination[12].

Fig. VIII-76 OCT imaging on patients at the General Hospital of Vienna.[12]

[12] W. Drexler *et al.*, University of Vienna

OCT inside a blood vessel

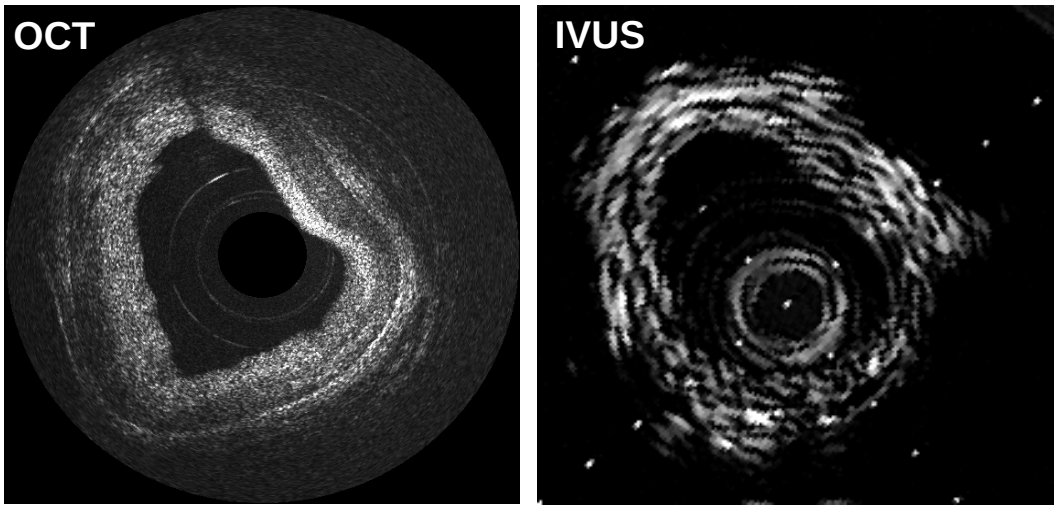


Fig. VIII-77 The OCT images have significantly higher resolution than intravascular ultrasound (IVUS).[13]

Nanoscale biological imaging with visible light: stimulated-emission depletion (STED) microscopy

In spite of the challenges posed by diffraction, in the last decade physical concepts have been worked out that break the diffraction barrier and open up far-field fluorescence microscopy with nanometre scale resolution. The most powerful one has been STED microscopy, which defeats the diffraction barrier through saturated quenching of the fluorophore. STED utilises synchronized picosecond excitation and depletion pulses[14].

Excite with an ultrashort pulse. Probe with a doughnut STED beam.

Intense STED beams deplete fluorescence except where their intensity is zero.

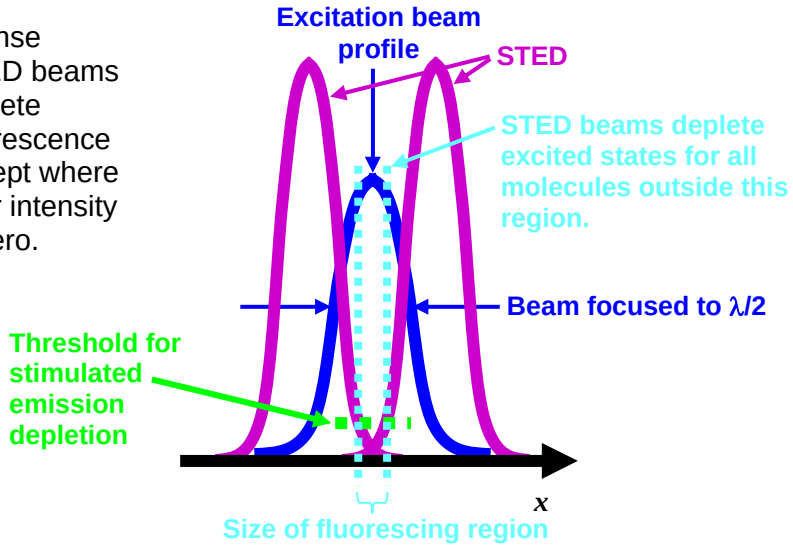


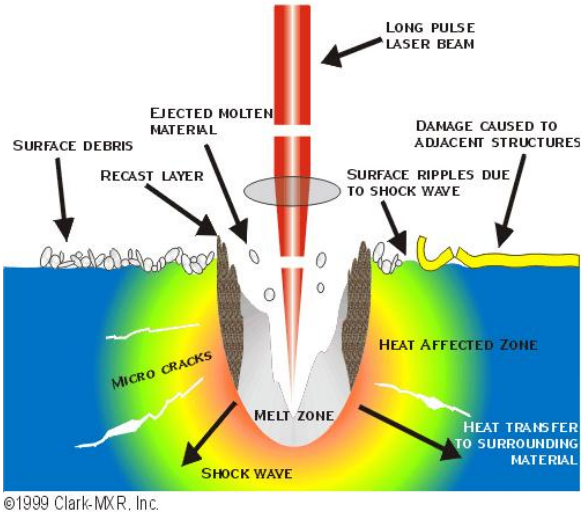
Fig. VIII-78

[13] Brezinski, *et al.*, *Am. J. Cardiology* 77 (1996)

[14] S. Hell, Max-Planck-Institut f. Biophysikalische Chemie, Göttingen

Ultraprecise machining, structuring and cutting with femtosecond laser pulses

Femtosecond laser pulses can machine all materials and with unparalleled precision.



Long laser pulses heat the surrounding volume during the interaction

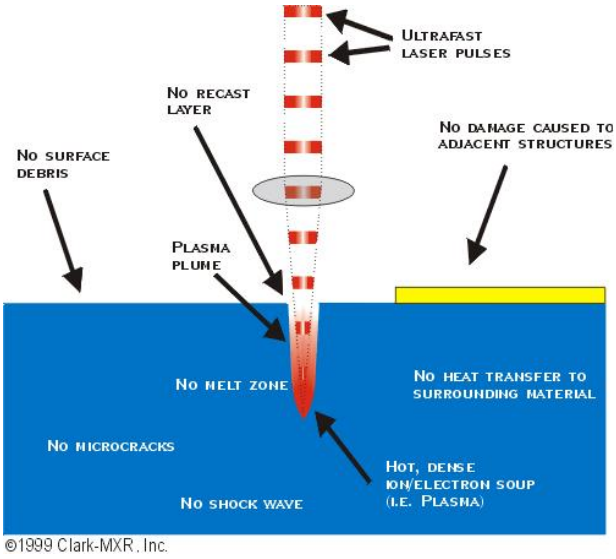
⇓

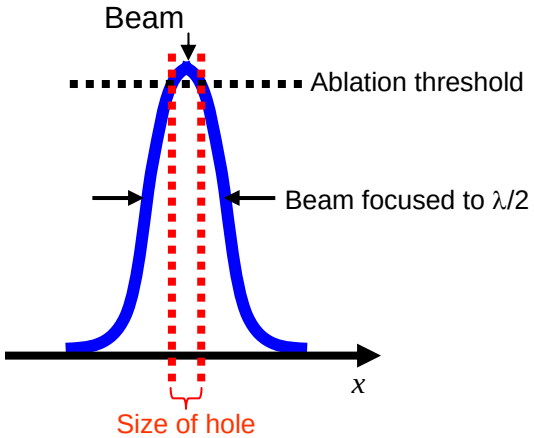
much larger volume affected than irradiated

During ultrashort exposure there is no time for heat diffusion

⇓

precise, well-controlled machining





Ultrashort pulses remove or modify material through highly nonlinear processes in dielectrics

⇓

sharp threshold for irreversible modification

⇓

machined volume can be a small fraction of the focal volume

⇓

Nanoscale machining

- Interaction of intense ultrashort laser pulses with materials open a new energy deposition regime independent of thermal conduction and hydrodynamics.

- High energy densities can be created in a thin surface layer. This results in rapid ionization and material removal with most of the deposited energy being carried by the ejected material.

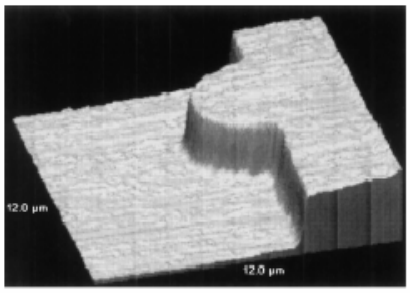
- High energy densities can be created in the interior to create 3D structures.

- Intense laser-material interaction in dielectrics is not dependent on finding stochastic defects to supply initial electron for dielectric breakdown. Ablation threshold is therefore more deterministic.

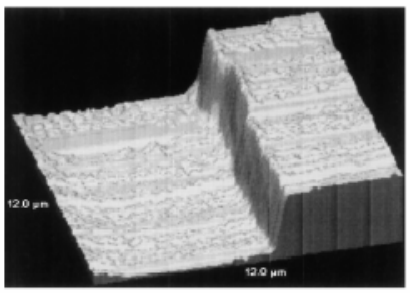
⇓

Femtosecond lasers enable precise processing of any material with minimal collateral damage and unparalleled reproducibility and precision.

Mask repair



(a)



(b)

Fig. 4. AFM topographical images of (a) a programmed defect and (b) the repaired site. The height of the chromium layer upon the quartz substrate is approximately 100 nm.

S. Nolte, B. N. Chichkov, and H. Welling, *et al., Laserzentrum Hannover,* Germany, *Opt. Lett*. 24, 1999

IBM to license 100-femtosecond mask repair tool
By R. Colin Johnson
EE Times October 9, 2002

YORKTOWN HEIGHTS, N.Y. — IBM Corp.'s T.J. Watson Research Center has announced that it is releasing its proprietary sub-100-nanometer lithographic mask repair technology for general license. IBM uses the femtosecond-laser-based technology to repair masks damaged by metal splatter, gallium staining and pitting. The all-optical method also avoids problems created by ion beam methods, currently the main competing technology at sub-100-nm feature sizes, the company said.

Periodic nanostructures

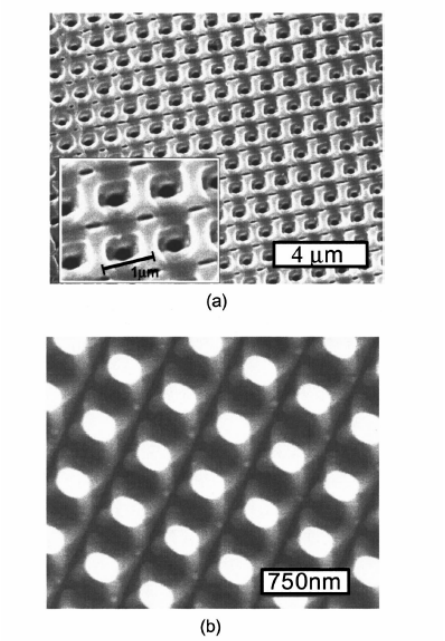
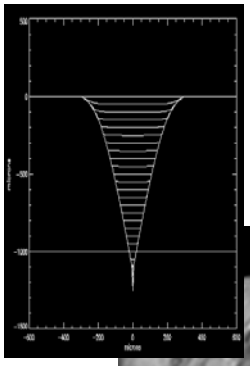


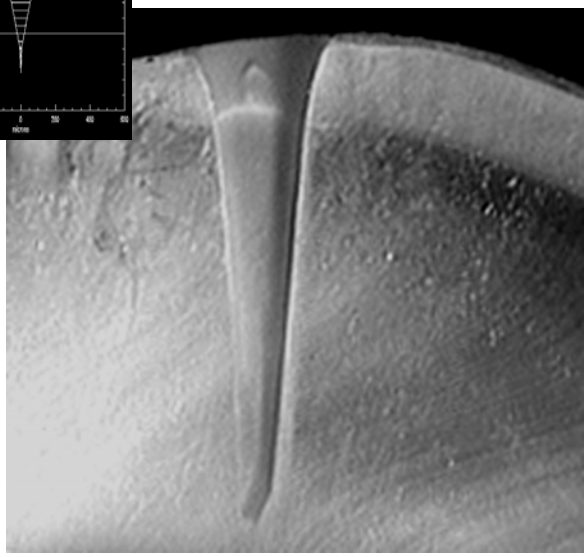
FIG. 3. Influence of the colliding angles on the morphology of double gratings. Pulse energy was 100 μJ for each grating. (a) SEM image of a double grating encoded with the colliding angle of 45° for both exposure. The inset is a magnified view. Two-dimensional array of holes (~200 nm diameter) is formed. (b) SEM image of a double grating encoded with the crossing angle of 90° for both exposures. Two-dimensional array of islands is seen, regarded as a simple superposition of the crossed gratings.

Periodic nanostructure array in crossed holographic gratings on silica glass by two interfered infrared-femtosecond laser pulses
K. Kawamura, N. Sarukura, M. Hirano, *et al.*, *Tokyo Institute of Technology, Tokyo,* Japan
Appl. Phys. Lett. 79, 2001

Pain-free dental treatment with femtosecond laser pulses



Numerical simulation of hole drilled in human dentin by train of 350 fs pulses.



Cross section of a conical hole drilled in tooth by a femtosecond laser system.

With no thermal shock, there is no collateral damage to adjacent tissue.

With no heat diffusion, there is no pain!

Technology mature and available but at present to expensive!

M.D. Feit *et al*, *LLNL, Livermore, USA*

Precision surgery

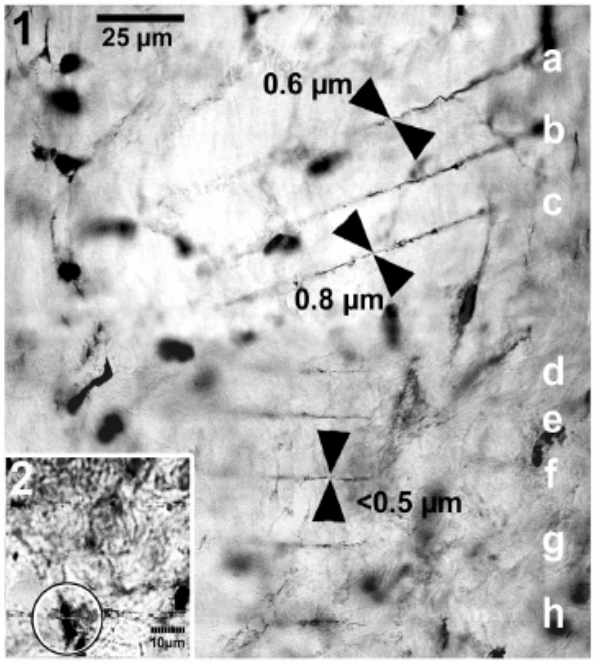
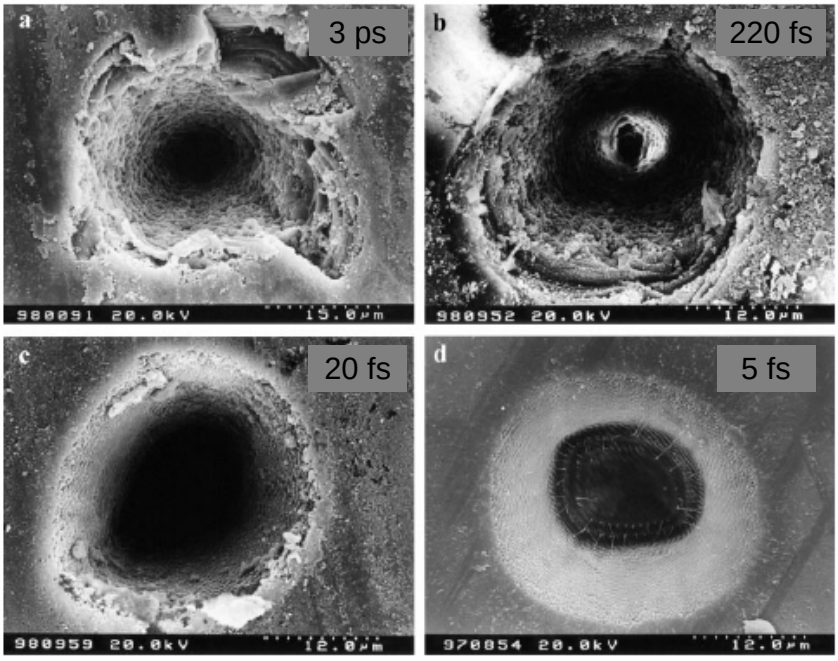


Fig. 2. Histological examination of a HE-stained cryosection after laser exposure by 488 nm laser scanning microscopy reveal precise <1 µm line cuts. No visible signs of collateral damage were found. The lower left image demonstrates an intratissue cut through a single nuclei at 90 µm tissue depth.

Intratissue surgery with 80 MHz nanojoule femtosecond laser pulses in the near infrared
Karsten König, Oliver Krauss and Iris Riemann, *Universität Jena,* Germany
Optics Express 10, 2002

Nanomachining with sub-10-fs laser pulses

Laser pulses in the 10-fs domain provide a quality of micromachining of fused silica and borosilicate glass that is unobtainable with longer pulses in the range of several100 femtoseconds up to picoseconds. The shortening of the pulses reduces the statistical behaviour of the material removal and the ablation process thus attains a more deterministic and reproducible character. The improved reproducibility of ablation is accompanied by significantly smoother morphology. This offers the potential for lateral and vertical machining precision of the order of 100 nm and 10 nm, respectively.



M. Lenzner, J. Krüger, W. Kautek, F. Krausz, BAM, Berlin, Germany; TU Wien, Vienna, Austria, Appl. Phys. A 68, 1999

Ultrafast metrology and control: tracking and steering microscopic motion

Tracking microscopic dynamics with the *pump-probe technique*: excite the sample with one pulse; probe it with another a variable delay later; and measure the change in the transmitted probe pulse energy or in the properties of other ejected particles, e.g. electrons, emerging from the interaction (Fig. VIII-79).

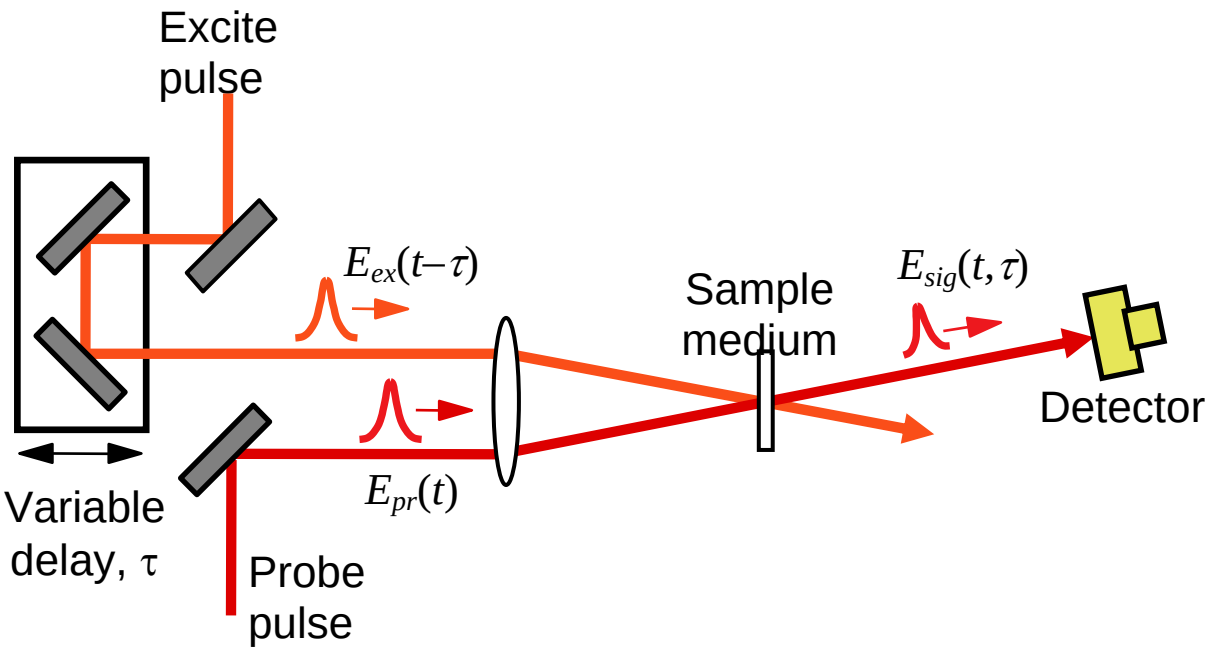
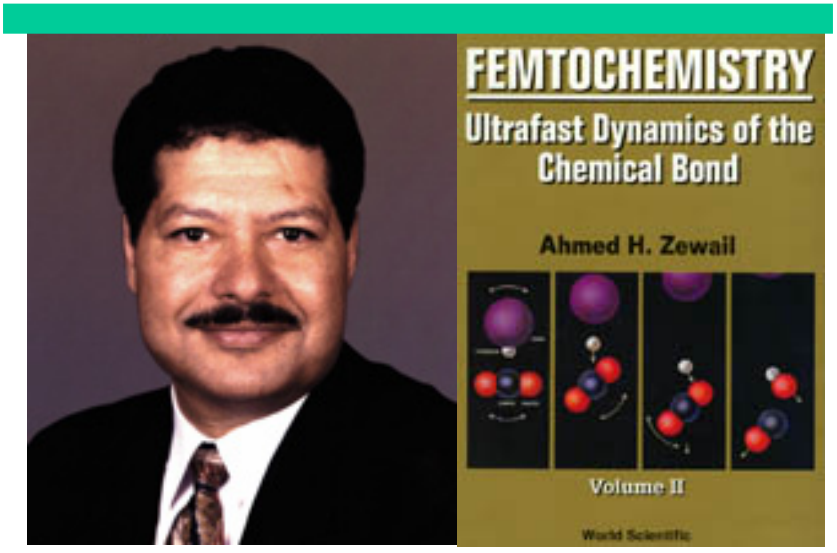


Fig. VIII-79

The 1999 Nobel Prize in Chemistry went to Ahmed Zewail of Cal Tech for ultrafast spectroscopy of atomic motion in molecules. With femtosecond laser pulses, Prof. Zewail has been able to watch how chemical bonds break and form, i.e. chemical reactions happen in real time



Chemical reaction control with femtosecond pulses

Atomic motion can not only traced, but – to increasing extent – also controlled by *shaped femtosecond pulses.* Femtosecond pulses can be shaped in the frequency domain, by controlling the phase and amplitude of the frequency components of the pulse (Fig. VIII-80).

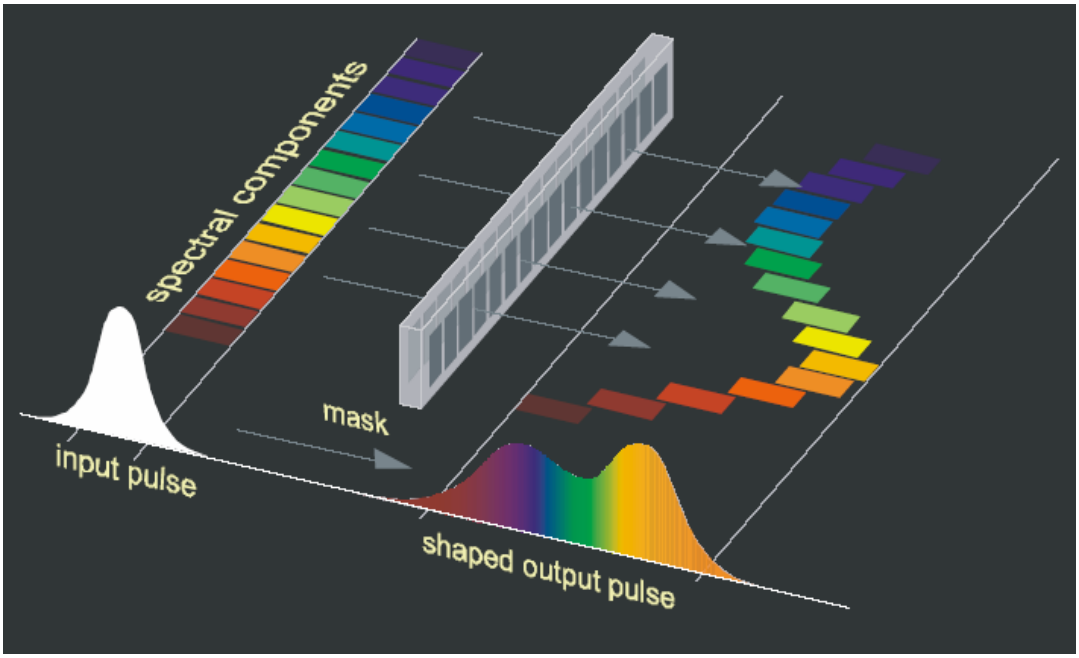


Fig. VIII-80

One might excite a chemical bond with the right wavelength, but the energy redistributes all around the molecule rapidly and may result in breaking the molecule apart in an undesirable manner. Exciting the molecule with a carefully shaped femtosecond pulse allows controlling the molecule's vibrations and producing the desired products (Fig. VIII-81). Femtosecond chemical reaction control was pioneered by Prof. G. Gerber, Universität Würzburg, Germany.

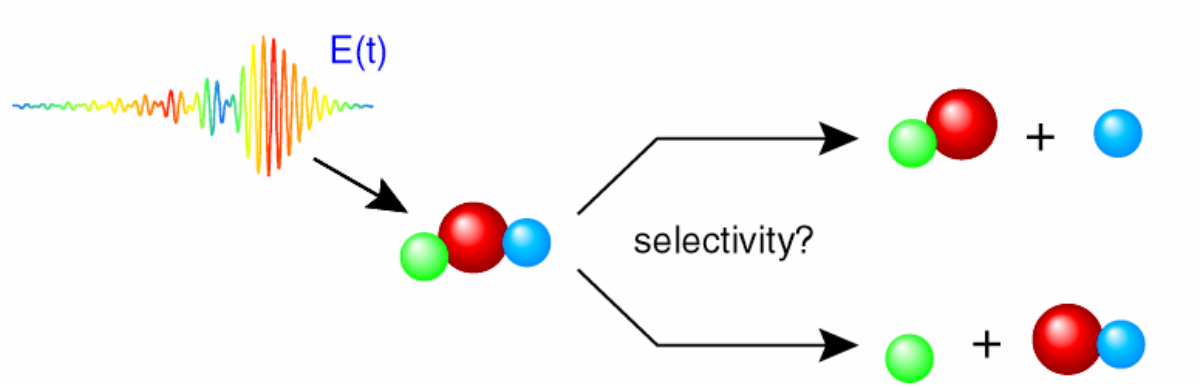


Fig. VIII-82

Can the motion of electrons be traced and controlled in a similar manner?

Yes, by the tools and techniques of experimental attosecond physics!