Proceedings

of the

20th IMEKO TC2 Symposium on Photonics in Measurement

May 16-18, 2011
Linz
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IMEKO

AUSTRIAN CENTER OF COMPETENCE IN MECHATRONICS

JOHANNES KEPLER UNIVERSITY LINZ | JKU

Proceedings of the
20th IMEKO TC2 Symposium on Photonics in Measurement (20th ISPM)

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International Measurement Confederation (IMEKO)
Technical Committee 2 – Photonics (TC2)

Institute for Measurement Technology (EMT)
Johannes Kepler University (JKU)

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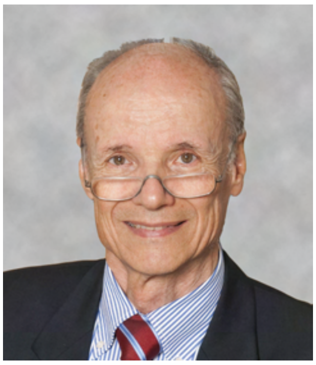
Preface



Following the sharp downturn in the global economy in recent years, the year 2010 was marked by a recovery period and slight growth. Manufacturing companies have now stabilized in many areas and record steadily rising orders. Even in the fields of optical technologies companies achieved a significant growth over the previous year. According to realize sustained growth these companies should have the ability to think permanently about new innovations and their implementation in production. Especially the robust realization of increasingly efficient manufacturing processes lead to the mandatory use of effective and reliable measurement devices. According to their high accuracy combined with extremely short measurement cycles, optical measurement techniques offer enormous potential for competitive companies. The Technical Committee 2 'Photonics' (TC2) of the IMEKO operates since its foundation in the research and development of components and systems for photonic measurements. This year we will have our 20$^{\text{th}}$ 'Symposium on Photonics in Measurement'. After successful events in Hungary, Germany, Poland, Czech Republic, Bulgaria, USA and China we will now have our first TC2-Symposium in Austria. At this point I would like to thank my colleague Prof. Zagar from the Johannes Kepler University of Linz who kindly agreed to host the symposium and all members of the National Organizing Committee for organizing. Furthermore, I would like to thank all TC2 members and colleagues who have participated enthusiastically in the contents of our 20$^{\text{th}}$ TC2 event. From my point of view the future innovation of industry is benefiting in particular from a well-developed research environment. Universities and research institutions can support the development of new leading edge technologies in joint activities and are also able to educate much-needed skilled workers for high-tech companies. Therefore the research and innovation policy will continue to play a special role for a common and successful collaboration of science and industry.

Prof. Tilo Pfeifer

– Member of the General Council –

– Chairman of TC2 –

Chairman's Welcome Message

Ladies and Gentlemen, on behalf of the International Measurement Confederation's Technical Committee on Photonics TC2 we would like to welcome you all, who have arrived to take part at the 20$^{\text{th}}$ IMEKO TC2 Symposium on Photonics in Measurement being held in Linz, Austria, from May 16$^{\text{th}}$ to May 18$^{\text{th}}$ 2011. The areas covered by Photonics in Measurement are playing an increasingly important role in our everyday lives and are used in a wide range of activities. With rapidly growing hardware performance and the advent of new devices, new boundaries are continually being established. This years symposium, the 20$^{\text{th}}$ in a successful series aims to bring researchers from various fields together to share their new thoughts, findings and applications. This symposium has attracted both established academics and research students from around the world. The research papers show that exciting work is being undertaken in the numerous topics from interferometry to spectroscopy from image sensing to the fields of Terahertz-Technologies from fibre optics to speckle techniques to name just a few. In addition, interaction between delegates attending the conference has led to new ideas and exciting research directions. The response from the academic community has been great, with almost 50 submissions received. Each paper has been carefully reviewed by at least two reviewers to ensure research quality. Thirtythree papers are published and presented at the conference. The papers are organized into seven themes. The authors have contributed towards new knowledge and understanding, and have provided research results and applications that will be of important value to researchers, students and industry alike. We are grateful to all the contributors who have presented their valuable work to the research community. We are also deeply indebted to the reviewers for their time and professional opinions on the submissions. We understand many reviewers have sacrificed their spare time in order to meet the tight time schedule. We sincerely wish you a very pleasant stay during the conference and a nice trip home with plenty of pleasant memories of this event in Linz. We give our best regards to he participants of the 20$^{\text{th}}$ IMEKO TC2 Symposium. Welcome to Austria! Welcome to Linz!

Prof. Bernhard Zagar

– Chair IMEKO TC2 Symposium 2011 –

Prof. Małgorzata Kujawińska

– Co-Chair IMEKO TC2 Symposium 2011 –

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Programme & Venue

For more information on sessions and presentations refer to the table of contents or the programme folder in the welcome package. The appendices contain a complete list of authors and keywords.

Monday • May 16, 2011

08:00 – 15:30	Registration Desk
10:30 – 10:50	Welcome Ceremony
10:50 – 12:00	Keynote Lecture: Terahertz – a Novel Frequency Domain for Industrial Metrology Elmar E. Wagner
12:00 – 13:15	Lunch
13:15 – 15:15	Session 1: Interferometry
16:00 – 19:00	Guided Tour: VOEST 'World of Steel' ('Stahlwelten') (Bus departure 15:30 at AEC)

Tuesday • May 17, 2011

08:30 – 09:50	Session 2: Optoelectronics, Deflectometry & Illumination Techniques
09:50 – 10:10	Coffee break
10:10 – 11:30	Session 3: Image Sensing & Image Processing
11:30 – 12:45	Lunch
12:45 – 14:25	Session 4: Spectroscopy & Scattering Techniques
14:25 – 14:40	Coffee break
14:40 – 15:40	Session 5: Laser Speckle Techniques
15:40 – 17:00	Guided Tour: Ars Electronica Center (AEC)
18:30 –	Conference Dinner (Restaurant CUBUS, 3rd floor, AEC)

Wednesday • May 18, 2011

08:30 – 09:50	Session 6: Applications, Optical Testing & Nano-Structures
09:50 – 10:05	Coffee break
10:05 – 12:05	Session 7: Terahertz Techniques & Light/Laser Sources
12:05 – 13:30	Lunch | TC2 Meeting 13:00 – 13:30 (in parallel)
13:30 – 16:00	Bus Transfer – Guided Tour: JKU Campus & Science Park
16:00 –	Closing

The symposium will be held at the Ars Electronica Center (SkyLoft, 3rd floor, AEC):

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Contents

TERAHERTZ – A NOVEL FREQUENCY DOMAIN FOR INDUSTRIAL METROLOGY

Elmar E. Wagner
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The Terahertz part of the electromagnetic spectrum around 10^{12} Hz covers the gap between microwaves and infrared radiation. Due to the lack of efficient sources and detectors this frequency range was not easily accessible so far. It offers new options for monitoring, sensing, and testing. Many materials used in everyday life exhibit high transparency whilst others show fingerprint absorption permitting specific detection. The radiation is safe to living nature since the photon energy is several meV only, far below the threshold energies required to break chemical bindings or to cause mutations of genes.

The commercial availability of femtosecond lasers as pump sources has led to the significant advancement of the THz technologies in particular in conjunction with the usage of the time domain spectroscopy (TDS). This coherent detection scheme allows the detection of small THz signals superimposed to high thermal background radiation. Using semiconductors with extremely low carrier lifetime, the optical (fs) pulse acts as both the exciting pulse at the THz generation side and the sampling pulse for the detector.

Though most of the developments conducted so far have been with TDS, numerous other technologies are under development with narrow and broad band THz sources using conventional attenuation techniques in transmission or in reflection. Quantum cascade lasers (QCLs) for instance, which are based on inter-subband transitions in multi-quantum well structures are promising candidates for powerful narrow band THz sources. In most cases such QCLs are operated under cooled conditions for better stability and higher output power. THz radiation is able to excite low frequency vibrations of molecules. Thus THz analysis is sensitive to small bonding forces and high masses, resp. As most polar materials show fingerprint structures, the technology can be used as a new tool operating in a different frequency regime. It thereby addresses other characteristics of matter, being specific and cross-sensitive in a different way than radiation of other frequency ranges, in particular X-rays. The spectroscopic information combined with imaging techniques reveals the high potential of THz technologies in many areas of applications.

A rather unique feature in the THz frequency range is the property of most dielectric and insulating materials of being highly transparent or showing only weak and structureless attenuation. This allows chemical analysis of samples through dielectric covers like packaging material. Water on the other side exhibits strong absorption and metals are opaque due to the excitations of plasmons.

The specific features of the interaction of THz radiation with matter can be exploited in many applications of industrial metrology. Concealed defects like delamination or corrosion, creeping of moisture, the homogeneity of colours or adhesives, are examples for industrial quality assurance issues that can be addressed by THz technologies. High power pulsed or cw sources still under development are strongly needed to permit fast scanning or 2-dimensional imaging in industry. In pulsed mode operation the travel time of the radiation can additionally be exploited for distance metering by means of THz radar thereby providing access to 3D imaging .

CURRICULUM VITAE

Elmar Wagner has studied physics at the Technical University of Munich. After investigating electrooptical properties of III-V compounds at the Max-Planck Institute in Stuttgart he started working on diode lasers at Hewlett-Packard in Palo Alto and became Director R+D of AEG-Telefunken's Optoelectronic Division in Heilbronn in 1980. From 1986 he was Director of the Fraunhofer-Institute of Physical Measurement Techniques in Freiburg, a position he has preferentially been involved in the application of optoelectronics and he has resigned from at the end of 2010. Elmar Wagner is professor at the Technical University of Kaiserslautern.

HIGH-POWER MONOCHROMATIC TERAHERTZ RADIATION: METROLOGICAL ASPECTS

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Abstract – The Novosibirsk free electron laser is nowadays the most intense source of terahertz radiation. It generates monochromatic coherent radiation as a continuous stream of 100-ps pulses with a repetition rate of 5.6 MHz. Radiation wavelength can be, at present, gradually tuned within the spectral ranges of 120-240 μm and 40-70 μm. Average power of the radiation at the user stations reaches several hundred watts. Unique features of NovoFEL radiation, from one hand, require development of techniques for radiation imaging and characterization and, from other hand, enable the development of new metrological methods and techniques. In this paper we deal with both these aspects. Unique results obtained at one of the user stations of the Novosibirsk free electron laser during past years are reviewed.

Keywords – Terahertz region, free electron laser, imaging, spectroscopy, metrology.

I. INTRODUCTION

The exponentially-growing number of publications devoted to the development of terahertz sources and applications of terahertz radiation reflects the expectation of a breakthrough to new technologies involving this frequency band. The invention of broadband terahertz generators, which are based on femtosecond lasers, triggered research in terahertz imaging and tomography, spectroscopy, non-linear optics, biology and medicine, materials science, security, and other applications.

In applications which require a tunable monochromatic coherent radiation, the backward wave oscillators (in the millimeter and high submillimeter regions), injection-seeding parametric generators, and difference-frequency generators are commonly used. However, the average power of all above mentioned generators is very low. These techniques and methods are described in a comprehensive review [1].

More intense terahertz radiation can be emitted using sources based on the radiation of relativistic electrons in magnetic structures like synchrotrons and free electron lasers [2]. Novosibirsk free electron laser (NovoFEL) had been commissioned in 2004 [3, 4]. It is now a user facility. In this paper we give a comprehensive review of recent experimental achievements in terahertz optics and photonics at one of the user station with emphasis on the metrological aspects.

II. SENSING AND METROLOGY OF HIGH POWER TERAHERTZ RADIATION

A. Real-time imaging devices

The absence of commercially available devices designed for imaging of high-power terahertz radiation have required the development of novel methods and techniques or adapting the existing ones. Three devices were routinely used for the imaging at the “Spectroscopy and radioscopy” user station. Two of them operate as “secondary” recorders sensing not the THz radiation directly, but its thermal print on a screen (see Fig. 1, a)

Temperature-sensitive phosphor plate (TSPP). A Macken Instruments, Inc. kit, containing eight temperature-sensitive phosphor plates [5] and a mercury lamp, was initially designed for near- and mid-infrared radiation imaging. We used this system for terahertz radiation imaging [6, 7]. The plate area, equal to 75x75 mm, enables recording images of a large size. A drawback of the system is a low sensitivity to terahertz radiation in comparison with the infrared radiation, because of a high transparency of the phosphor layers in the THz range. An image obtained using the TSPP, plate #7, with a Princeton Instruments PIMax2 intensified camera as a final image recorder is shown in Fig. 2, a. A “FEL”-shaped metal slot mask illuminated by the free electron laser Gaussian beam

(Fig. 1, b) was used as an object in this and following experiments.

Thermal recorder (TR). A near-infrared 128x128 focal plane array was used for visualization of thermal prints of the terahertz beam on screens exposed to the radiation [8]. Being a rather sensitive device, it suffers from a low spatial resolution and was usually used for optical systems alignment. An image of the mask recorded with the TR is shown in Fig. 2, b

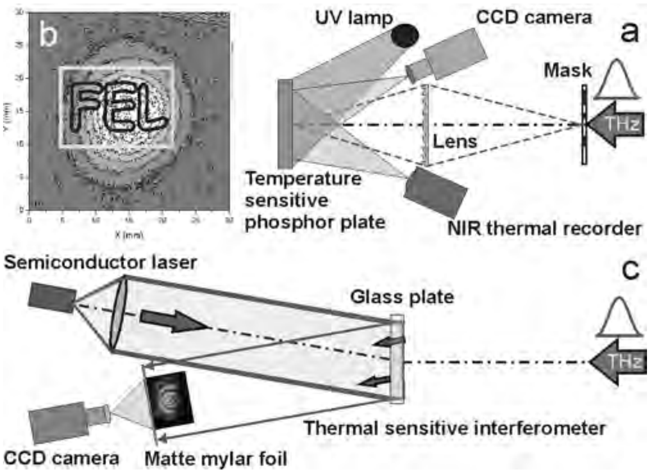

Fig. 1: THREE DEVICES FOR IMAGING IN TERAHERTZ - (a) A thermal recorder and a system based on temperature quenching of luminescence; (b) drawing of one of the masks and the terahertz beam cross-section; (c) the thermal sensitive interferometer.

Fig. 2: IMAGES OF THE MASK FEL WITH - (a) The temperature sensitive phosphor plate, (b) the thermal recorder and (c) the microbolometer focal plane array.

Microbolometer focal plane array (MBFPA). An uncooled vanadium oxide 320x240 MBFPA was applied to direct recording "terahertz video" with frequency up to 90 frames per seconds [9]. It was found [10, 11] that the sensitivity of the MBFPA is the highest among all other imagers, but much less in the terahertz range than in the mid-infrared range for which the FPA was originally designed. To discover a reason, we have measured the absorption of the array materials and found they absolutely do not absorb terahertz radiation. The mechanism of sensitivity became obvious after discovering that the sensitivity harmonically depends on the angle of the radiation polarization [12], which means the antenna effect is probably the main mechanism for heating of the microbolometers in the terahertz range.

B. *Thermal sensitive Fizeau interferometer (TSFI) as an absolute power meter*

One more system for terahertz beam imaging, a visible-light Fizeau interferometer (Fig. 1, c), which plane-parallel glass plate was exposed to terahertz radiation, served as an absolute power meter [13]. The glass plate was illuminated by a plane wavefront of coherent monochromatic radiation from a red semiconductor laser. The waves reflected from two surfaces of the plate interfered on a matte screen and were recorded with a CCD camera. The terahertz radiation, being absorbed in a thin layer of the glass plate, heated it up and changed the optical path length in the heated areas. For the glass BK7 one interference fringe corresponds to absorbed energy of 5.1 J/cm^2. An image of the FEL beam is presented in Fig. 3. It has to be emphasize the device can be used for measurement of a power density distribution of any radiation which the glass plate is opaque to. We applied the technique, for example, for imaging of ultraviolet KrF-laser radiation.

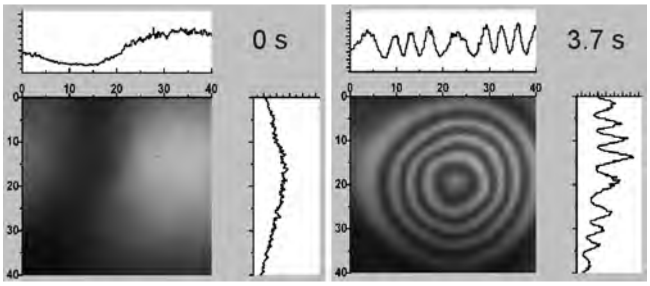

Fig. 3: FEL BEAM IMAGE – Interferograms recorded with TSFI before exposition and at 3.7 s after opening the shutter (frames from a video, 17 fps).

Practically achieved characteristics (time and space resolutions, estimated sensitivity, and maximum frame rate) for the imaging systems using the above described devices are summarized in the Table 1. Crucial role played quality of the lens used in the systems. Bulk TPX plastic lenses distorted images and often melted in the FEL beam. F = 80 mm, 0.8 mm thick polypropylene Fresnel lenses of 80 mm in diameter [14] provided the best quality of terahertz images and were tolerant to high-power radiation.

	TR	TSFI	MBFPA	TSPP	
				Plate #7	Plate #8
Δx (mm)	2	0.3	0.3	1	2
Δt (s)	DS*	0.02	0.02	0.4	1.3
Sensiti-vity	High	Medium	Very high	Very low	Low
f (fps)	25	10 - 50	10 - 50	4 - 25	4 - 25

* depends on screen thermal characteristics

Tab. 1: EXPERIMENTALLY ACHIEVED IMAGING DEVICE CHARACTERISTICS – λ = 130 μm.

It must be mentioned, the thermal sensitive Fizeau interferometer, which was designed rather for radiation power measuring, could be also employed as an imager at the starting stage of the exposure to radiation. The images of the mask letters were clearly visible with a spatial resolution of about 1 mm.

III. METROLOGY USING HIGH-POWER TERAHERTZ RADIATION

Above-mentioned imaging devices were applied to the development of a number of quasi-optic systems.

Speckle-metrology. Speckle patterns in the space domain were first observed in the terahertz spectral range using NovoFEL radiation [15] that enabled development of first speckle-photography and speckle-interferometry quasi-optic systems in the terahertz range. Real-time speckle photography of moving objects illuminated by terahertz laser beam, including the concealed ones, that is important in both industrial and security control systems, has been demonstrated using an optical system with MBFPA.

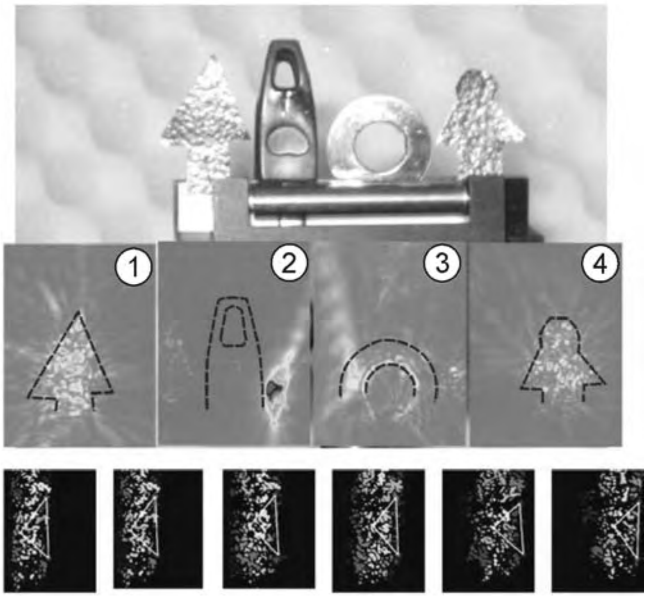

Fig. 4: THE OBJECTS AND THEIR IMAGES EXTRACTED FROM A TERAHERTZ VIDEO RECORDED BY MBFPA AT 27 FPS – The lower row: automatic measurement of an object velocity via speckle movement detection.

In this case the rough objects appear to be visible clearly (see the objects 1 and 4 in Fig. 4). The metal objects became visible if the reflex from any surface is caught by the optical system solid angle. In opposite case, they can be detected thanks to occasional flairs at the sharp edges of the objects (object 3). The plastic objects are seen very bad (object 2), but they can be detected if to illuminate not the objects directly, but a large scatterer placed at the back of the scene.

„Classic" holography. In-line and reference beam holography systems were designed using the TSPP. Holograms of the amplitude and phase objects were recorded and reconstructed. An example of an in-line hologram of an amplitude mask is shown in Fig. 5 (left picture). The mask size was 10x10 mm, the Gaussian beam HWHM was equal to 11 mm. Though the Gabor conditions (see, e. g. [16]) were not completely satisfied, quality of the reconstructed image, taking in account that $\lambda = 0.13$ mm, may be considered as very good.

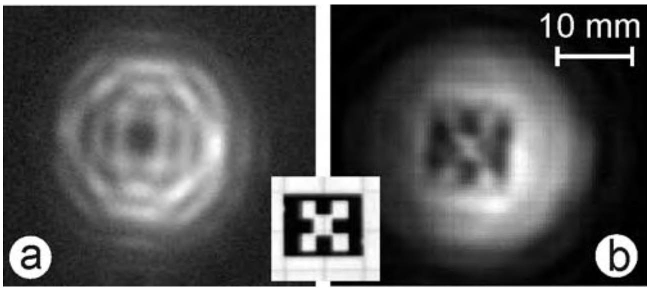

Fig. 5: IN-LINE TERAHERTZ HOLOGRAPHY - (a) A hologram of the shown in the inset mask recorded by TSPP #7 and (b) a numerical reconstruction of this hologram.

Demonstration and application of the Talbot-effect. Talbot effect (the self-imaging of periodical structures illuminated by monochromatic coherent radiation) has been first observed in the terahertz spectral range.

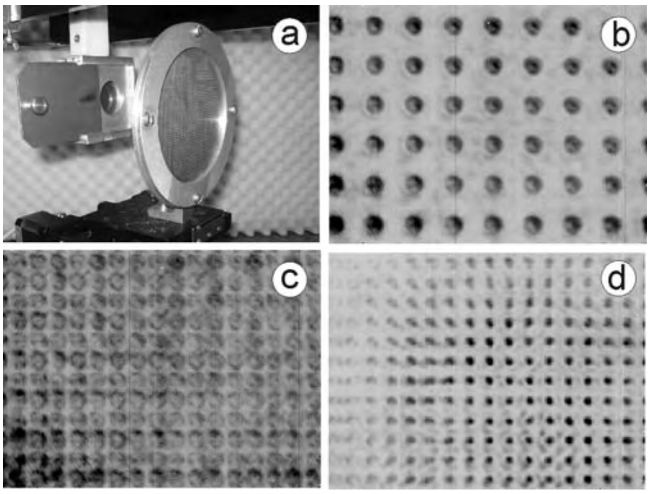

Fig. 6: TALBOT EFFECT IN THE TERAHERTZ REGION - (a) the experimental setup, (b) an image recorded in a main Talbot plane ($Z_T = 2Np^2/\lambda$, where p is a grid period and N is a Talbot plane number), (c) an image in a (N + ¼) fractional Talbot plane, and (d) the distortion of FEL wavefront by a $f = 50$ mm TPX lens; $\lambda = 126$ μm.

In the experiments we used 2D grids of openings with the period from 0.6 to 2 mm and the microbolometer array as a recorder (see the experimental layout in Fig. 6, a). Distances between Talbot self-imaging plates vs. grid period and radiation wavelength are shown in Table 2. Because of limited beam width, the effect disappeared at the distances determined by the Abbe limit. Characteristic Talbot images are presented in Fig. 6, b – d.

The measurement of NovoFEL wavelength with the spectral resolving power up to 300, measurement of distances, real time detection of terahertz wavefronts distortion have been experimentally demonstrated. A unique opportunity for one-shot recording of phase-shifting holograms [17] gives the Talbot “quarter-plane” (Fig. 6, c), because, according to the theory, each of the double-frequency circles has $\pi/2$ phase shift.

p,mm	λ, mm					
	0.656		50		130	
2.0	32 m	12 m	400 mm	160 mm	160 mm	62 mm
1.0	16 m	3 m	200 mm	40 mm	80 mm	15 mm
0.6	9.5 m	1.1 m	120 mm	14.4 mm	45 mm	5.5 mm

Tab. 2: TALBOT EFFECT IN THZ AND VISIBLE REGIONS - Calculated Talbot distances (right columns) and the distances (left columns) where the effect disappears for a Gaussian beam with FWHM = 11 mm; λ = 130 μm.

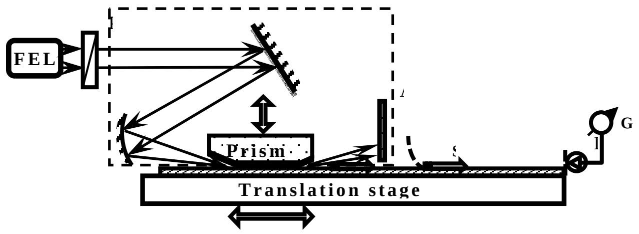

Fig. 7: EXPERIMENTAL CONFIGURATION FOR FORMATION OF SURFACE PLASMONS.

Surface plasmons. Surface plasmon-polaritons (SPP) are a subject of special interest in thin film and material study. The experiments performed up to now using the terahertz time-domain spectroscopy yielded very contradictory results. We re-examined main experimental schemes for SPP coupling and transporting using monochromatic radiation of the free electron laser. The most effective technique for SPP formation appeared to be the configuration (Fig. 7) suggested by Grishkovsky at al.

Because of a high sensitivity of the MBFPA, we were able to perform first study of SPP using the real-time imaging of terahertz wave for different experimental conditions. These results will be published elsewhere.

Imaging attenuated total reflection spectrometer. An attenuated total reflection spectrometer with real-time imaging has been designed and applied to study static and dynamic objects in the terahertz region. A set of the spectrally resolved momentary images at a fixed wavelength is shown in Fig. 8. Gradually tuning free electron laser wavelength, one can record a number of videos at the wavelengths of interest.

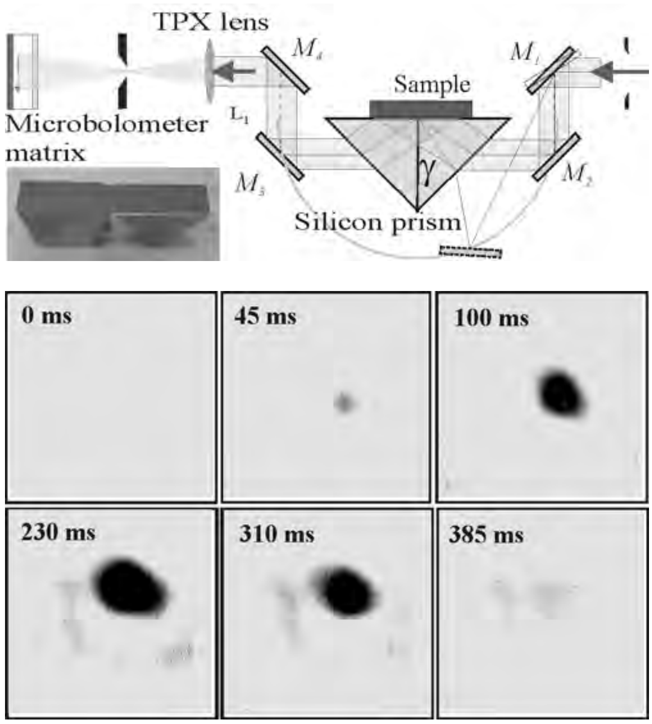

Fig. 8: IMAGING ATTENUATED TOTAL REFLECTION SPECTROMETER – Dynamics of the dilution of the ethanol drop into a water pool (frames from the terahertz video recorded with the MBFPA, f = 26 fps, λ = 130 μm)

IV. CONCLUSIONS

A high-power monochromatic coherent radiation of the Novosibirsk free electron laser was used for the characterization of the imaging techniques developed for employment in the quasi-optical terahertz systems. The imaging devices enabled designing the systems for terahertz speckle-metrology, holography, tomography, spectroscopy, plasmonics and other applications.

V. ACKNOWLEDGEMENTS

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