



# **International Conference on THz and Mid Infrared Radiation and Applications to Cancer Detection Using Laser Imaging**

**Workgroup Meetings  
of COST ACTIONS MP1204 and BM1205**

**October 10 - 11, 2013**

**Sheffield Hallam University  
United Kingdom**

## Conference Programme

Thursday, October 10			Friday, October 11		
time	Presentation title/ author	Chair	time	Presentation title/ author	Chair
9:45 – 10:00	Opening				
10:00 – 10:40	<b>Manijeh Razeghi - Women in Thz, Invited Keynote Talk</b> Pushing the frontiers of monolithic integration: a compact THz revolution	Mauro Pereira and Dragan Indjin	10:00 – 10:40	<b>Angela Dyson - Women in Thz, Invited Talk</b> Mechanisms for THz Generation in GaN	Manijeh Razeghi
10:40 – 11:10	<b>Maurizio Dabbicco - Invited Talk</b> Optical Feedback Interferometry in Semiconductor Lasers		10:40 – 11:20	<b>Renata Butkutė - Women in Thz, Invited Talk</b> Bismides for Laser Diode Active Layers	
11:10 – 11:40 coffee break			11:20 – 11:40 coffee break		
11:40 – 12:05	<b>Johanes Koeth - Invited Talk</b> Tunable single mode quantum cascade lasers with shallow-etched distributed Bragg reflector	Kamil Kosiel	11:40 – 12:20	<b>Martin Koch - Invited Talk</b> Devices to guide and manipulate THz waves	Angela Dyson
12:05 – 12:30	<b>Santiago Royo - Invited Talk</b> Skin and laser imaging research activities at CD6		12:20 – 13:00	<b>Miriam Vitiello - Women in Thz, Invited Talk</b> Nanowire and graphene FETs as powerful detection systems across the THz range	
12:30 – 12:55	<b>Janis Spigulis - Invited Talk</b> Multimodal skin imaging: concept and prototype device		13:00 – 13:20	<b>Tomasz Ochalski</b> Optical emission of a strained direct band-gap Ge quantum well embedded inside InGaAs alloy layers	
12:55 – 13:30	<b>Paul Dean - Invited Talk</b> Coherent imaging and sensing using the self-mixing effect in terahertz quantum cascade lasers		13:20 – 13:40	<b>Anna Szerling - Women in THz</b> Epitaxy and device fabrication for AlGaAs/GaAs THz quantum-cascade lasers	
13:30 – 15:00 lunch			13:40 – 15:00 lunch		
15:00 – 15:25	<b>Lukas Emmenegger - Invited Talk</b> Recent advances in QC laser spectroscopy for ambient air monitoring	Oleg Mitrofanov	15:00 – 15:40	<b>Irmantas Kašalynas - Invited Talk</b> Multispectral terahertz imaging with the compact THz detectors designed for room temperature operation	Miriam Vitiello
15:25 – 15:50	<b>Thierry Bosch - Invited Talk</b> Blood flow measurements by self-mixing laser velocimetry		15:40 – 16:20	<b>Oleg Mitrofanov - Invited Talk</b> High-spatial resolution THz near-field imaging using surface waves	
15:50 – 16:15	<b>Francesco Mezzapesa - Invited Talk</b> QCLs based coherent imaging via optical feedback interferometry		16:20 – 16:40	<b>Mauro Pereira</b> Recent progress in microscopic approaches to transport and optics of semiconductor TERA-MIR materials	
16:15 – 16:35	<b>Adonis Bogris</b> Noise properties of injection locked quantum cascade lasers		16:40 – 16:50	<b>Closing address</b>	
16:35 – 18:00 Coffee and poster session					
18:00 – dinner			18:00 – dinner		

INVITED  
AND  
CONTRIBUTED TALKS

# Pushing the frontiers of monolithic integration: a compact THz revolution

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The THz spectral range (1-10 THz) is extremely interesting for applications such as explosive and drug detection, security screening (T-ray imaging), astronomy, and medical imaging. Many of these applications have the potential to impact (and safeguard) our daily lives, and, as such, have a tremendous appeal to the general public and industry. Many different types of systems are currently being developed, as all new technology is developed, by building benchtop sources from discrete components. Still, however, there is no ideal THz source that can operate at room temperature and is also compact, efficient, tunable, and inexpensive.

As telecommunication technology has done over the past 30 years, monolithic integration is the next logical step in pushing THz technology closer to an ideal source. Wafer scale processing allows for mass production with high yield and low cost. Toward this end, development of both component and integration technologies are critical.

One promising platform which will be discussed, based on InP, is intracavity difference frequency generation using mid-IR quantum cascade lasers (QCLs). This technique combines a dual frequency pump laser with engineered intersubband nonlinearity to generate narrow linewidth THz radiation inside a single waveguide. Besides providing a wealth of beautiful physics to study, this technique allows for compact, room temperature operation over a wide spectral range. Our group, utilizing state-of-the-art QCL technology, is making steady progress in this field. We have already demonstrated broad, monolithic spectral coverage (1-4.6 THz) and high peak power (215  $\mu\text{W}$ ) at room temperature using narrow linewidth integrated sources and Čerenkov phase-matching.

Though the current implementation is a good start, theory predicts significantly higher powers are possible. In addition, improvements in integration are expected to lead to dynamic tuning and continuous operation. With further development, this portable platform will one day be an enabling technology for a variety of THz research topics and applications.

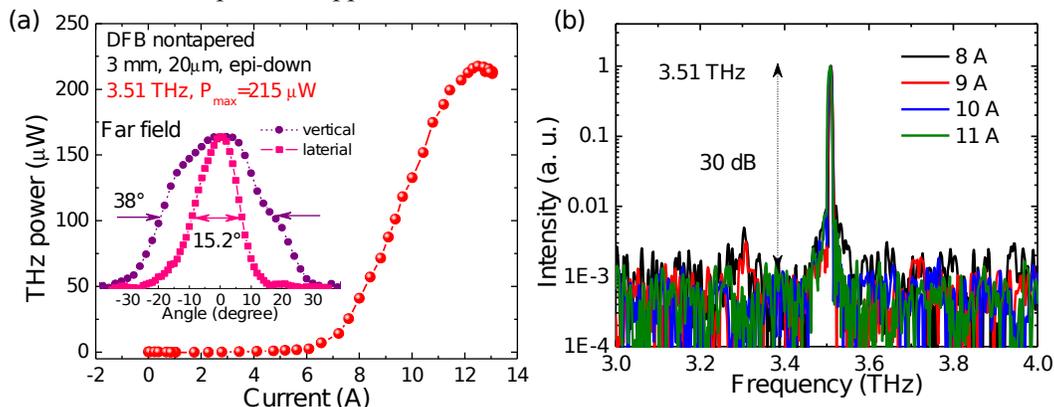


Fig. 1 THz power as a function of current for an epilayer-down mounted device. The inset is the THz far fields at 10 A in vertical and lateral directions. (b) THz spectra at different working currents.

# Optical Feedback Interferometry in Semiconductor Lasers\*

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Optical Feedback Interferometry (OFI), also known as Laser-Self-Mixing (LSM), has been the subject of extended research for more than thirty years. It happens in all kind of lasers when part of the emitted radiation is allowed to re-enter the laser cavity following interaction with some external matter. Semiconductor lasers have exhibited the largest sensitivity to delayed coherent optical feedback and a number of applications have been proposed and demonstrated based on OFI in diode lasers [1]. However, their relatively large spectral width, is a limiting factor in high resolution measurements. On the other hand, gas lasers having an intrinsic narrower linewidth and a prospective higher signal-to-noise ratio, are restricted to the *very weak* feedback regime because of the high reflectivity of their output coupler mirror and poor efficiency. Recently available Quantum-Cascade-Lasers (QCL) promise to merge the opportunity offered by the two types of laser in terms of narrow linewidth and high sensitivity. I will present a comparison between bipolar (diode) and unipolar (QCL) semiconductor laser dynamics with delayed optical feedback [2]. Forecasting results in diode as well as in mid-infrared QCL promise to open new perspectives for applications of OFI in chemical sensing and material science.

## References

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# Skin and laser imaging research activities at CD6\*

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We will overview recent progress in the main lines of research being developed at UPC-CD6 and related to the content of COST Actions MP1205 and MP1204. UPC-CD6 is a research centre devoted to the development of research projects in the field of Photonics Engineering, linked to the University. By use of an innovative management orientation and the entrepreneurial spirit of its members, research activities are linked to market requirements. Research is developed in optical metrology, visual optics optomechanical design and hyperspectral imaging. Most of the basic research projects target direct market requirements which, in most cases, brings on the generation of patents and spin-off companies (10 companies by 2013, invoicing 7M€ and employing 70 persons).

One of the most productive research lines in the late years involve skin imaging based on structured light fringe projection. Different project related to skin measurement have been developed for applications as diverse as aesthetic surgery or evaluation of cosmetic treatments, both for dermatologists, industrial partners and doctors. Results of different instruments built with this purpose will be shown, showing in-vivo measurements of wrinkles, roughness and volumes on real patients [1].

Another research line to be outlined in the talk is related to the development of a prototype of high-definition time-of-flight (TOF) camera system with adjustable spatial resolution enabling to get to 2Mpx TOF images, a hundred times larger than conventional systems, reliable under outdoor imaging conditions [2].

However, regarding laser imaging, most of the activity is concentrated in self-mixing lasers. Our late results involve contributions on active feedback [3] and speckle control of lasers [4], and in nanometric accuracy self-mixing interferometry [5]. Some applications at different scales will be presented [6], including biomedical ones .

## References

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# Multimodal skin imaging: concept and prototype device\*

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Based on our previous research [1-7], a concept of multimodal skin imaging comprising RGB colour imaging at polarized white LED illumination with spectral imaging at four selected wavelength bands, photoplethysmography imaging (PPGI) of skin blood perfusion [8] and imaging of skin autofluorescence photo-bleaching rates [9] was developed. The concept has been implemented in a prototype device for non-contact multimodal skin imaging [10]; its improved version is under development.

Photoplethysmography video-imaging technique for remote control of regional anaesthesia (RA) efficiency before and during surgeries [11] deserves a special attention. This technology has been successfully tested at Riga Traumatology and Orthopaedic Hospital during wrist surgeries. Physiological response to RA is a notable increase of peripheral microcirculation that can be detected by the PPGI device as increased amplitude of skin blood pulsations; it serves as the START signal for surgery.

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# Coherent imaging and sensing using the self-mixing effect in terahertz quantum cascade lasers

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We present recent advancements in the development of coherent terahertz (THz) imaging and sensing systems that exploit the self-mixing (SM) effect in quantum cascade lasers (QCLs). SM occurs when radiation from a laser is partially reflected from an external object and injected back into the laser cavity. The reflected radiation interferes ('mixes') with the inter-cavity field, producing variations in the emitted power and terminal voltage [1]. Thus, by combining the local oscillator, mixer, and the detector all in a single laser, this technique allows the development of simple, self-aligned systems that can sense both the phase and amplitude of the THz field reflected from samples. We demonstrate the coherent nature of this sensing technique in two distinct imaging modalities: Depth-resolved reflection imaging, whereby the phase-shift induced upon reflection is interpreted in terms of surface morphology of the sample; and a novel swept-frequency approach that enables extraction of target complex refractive indices with a high degree of accuracy.

For depth-resolved imaging the QCL was operated in continuous-wave, just above the lasing threshold, where the laser is most sensitive to the feedback of radiation. At each pixel the sample was scanned longitudinally and the SM interferometric waveform recorded over several periods. Each of these waveforms was then fitted to a three-mirror model [2] that describes the laser system under feedback. The phase parameter in this model can be equated to the distance travelled by the THz radiation in the external cavity, and hence to the depth of the surface of the sample.

In our second sensing approach, we employ a novel swept-frequency coherent imaging scheme that can be performed without mechanical modulation or longitudinal scanning of the sample. By fitting the acquired SM signals to the three-mirror model, both amplitude-like and phase-like images of the sample can be obtained. Different materials impose different phase-shifts on the incident THz wave according to their complex refractive index, dominated by its imaginary part. We can thus relate the operating parameters of the laser under feedback to the complex refractive index of the target.

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# Recent advances in QC laser spectroscopy for ambient air monitoring

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Infrared (IR) spectroscopy is a powerful tool for gas sensing. Especially attractive is the mid-IR spectral region where the molecules of interest have their fundamental absorption bands with cross sections that are three to five orders of magnitude larger than in the near infrared (NIR). With the availability of quantum cascade lasers (QCLs), light sources have become available that allow the development of gas sensors that are exceedingly sensitive and highly selective. This will be illustrated by two recent examples of analyzers based on quantum cascade laser absorption spectroscopy (QCLAS) for ambient air monitoring.

Nitrogen dioxide (NO<sub>2</sub>) is one of the most prominent air pollutants and highly relevant in photochemical processes. Chemiluminescence, the standard method for NO<sub>2</sub> analysis, involves the reduction of NO<sub>2</sub> to NO before its detection and is thus influenced by other nitrogen containing species. We show a QC laser based trace gas analyzer that is well suited for remote locations with very low NO<sub>2</sub> mixing ratios. It is based on two room temperature cw quantum cascade lasers (6.3 μm and 5.3 μm, Alpes Lasers, Switzerland) and a thermoelectrically cooled IR-photodiode (Vigo, Poland). Using a newly developed astigmatic Herriott sample cell with 200 m optical path length, we obtain a precision in field measurements of 3 ppt and 10 ppt for NO<sub>2</sub> and NO, respectively [1]. In the laboratory, the best precision was even lower reaching 1 ppt for NO<sub>2</sub>. The system was validated in a three month field campaign under predominantly free tropospheric air conditions.

Isotope ratios of trace gases contain highly valuable information about their sources, sinks and transport processes from the local to the global scale. While isotope ratio mass spectrometry (IRMS) has been the method of choice, laser spectroscopy is rapidly gaining importance, because it can deliver real-time data with unprecedented temporal resolution at moderate cost and instrument size. We developed a QCLAS that has been continuously running for over five years, measuring the stable CO<sub>2</sub> isotopes in the free troposphere at the High Altitude Research Station Jungfraujoch (3580 m a.s.l.), Switzerland [2]. The instrument is based on the differential absorption technique in the 4.3 μm spectral range. It delivers both δ<sup>13</sup>C and δ<sup>18</sup>O of CO<sub>2</sub> at atmospheric abundance with a precision of 0.02 ‰ at 10 minutes integration time [3]. The high temporal resolution of the δ<sup>13</sup>C time series allows the detection of pollution events and their source signature. We present the development of the instrumental set-up, the improvements of the most critical parts and the resulting performance. Then, we discuss recent advances to obtain high-precision measurements with much smaller sensors and lower power consumption [4].

## References

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# **Blood flow measurements by self-mixing laser velocimetry**

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The need for in-vivo blood flow measurement with non-intrusive methods is well recognized. Self-Mixing Interferometry (SMI) that allows designing of compact Doppler sensors [1] has recently shown ability to measure flows in micro-scale channels [2]. In this work, we present SMI flow sensor that accurately measures local velocity in fluids and enables reconstruction of a velocity profile inside a micro-channel. SMI is a self-aligned interferometric technique that uses the laser as both the transmitter and the receiver thus offering high sensitivity, fast response, and a simple and compact optical design. The system described here is based on a commercial semiconductor laser and has been designed to achieve a micrometer range spatial resolution. The sensor performance was validated by reconstructing the velocity profile inside a circular cross-section flow channel with 320  $\mu\text{m}$  internal diameter, with a relative error smaller than 1.8 %. The local flow velocity is directly measured, thus avoiding the need for model based profile calculation and uncertainties inherent to this approach. The system was validated, for a blood phantom (fat milk diluted in water), by successfully extracting the flow profiles in both Newtonian and Non-Newtonian liquids. The present work, in addition with previous realizations demonstrating the capability of parallel sensing with laser arrays [3], is an important milestone towards in-vivo subcutaneous blood flow scanning systems that should be a major progress in early diagnosis for skin cancers.

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# QCLs based coherent imaging via optical feedback interferometry

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We retrieve the phase signature in coherent imaging based on a quantum cascade laser (QCL) subjected to optical feedback. QCLs are intrinsically stable regardless of the optical feedback, mainly because of their small linewidth enhancement factor (typically less than one) as well as the absence of relaxation oscillations (class-A laser)<sup>[1]</sup>. Also, QCLs are known to be very sensitive to small fractions of emitted radiation back-reflected into the laser cavity, hence well suited for a variety of relevant applications including, but not limited to, sensing, spectroscopy and metrology. In this work, we study the effect of optical feedback levels on the phase sensitivity in a coherent imaging system based on a both THz and MIR quantum cascade laser, showing the existence of a threshold for phase detection and its potential applicability.

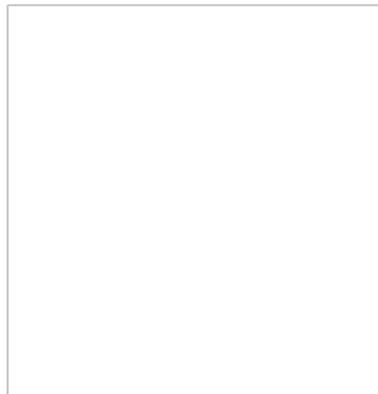


Fig.1: Effect of optical feedback levels on the phase sensitivity in QCL-based imaging. The intensity of SM signal is in mV. (a) Reflectivity image at high level of optical feedback. (b) Phase information (SM fringes) are retrieved only by reducing the feedback level.

Figure 1 shows a representative reflection image as acquired by raster-scanning the specimen with a linear-motor stage. In the self-mixing scheme, a single QCL acting as a source and detector of mid-IR or THz radiation, is used to obtain the reflection image of a sample as well as the phase profile without ambiguity. Here, the sample is purposely tilted ( $\text{yaw} = 0.125^\circ$ ) to acquire the phase profile. Fringes associated with the spatial phase information are not visible in Fig. 1(a), and can be retrieved only by reducing the optical feedback, as shown in Fig. 1(b). Finally, the study of the phase sensitivity against optical feedback and the physical limitation of the phase signal detection is also demonstrated in the THz domain.

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# Noise properties of injection locked quantum cascade lasers

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Quantum-cascade lasers (QCLs) are IR sources based on intersubband transitions that can operate in a wide range of wavelengths (from 3.5 to 150  $\mu\text{m}$ ) [1]. Since their invention in 1994 there has been tremendous progress towards the implementation of powerful tunable or single mode lasers which are capable of either continuous wave or pulsed operation at room temperature (RT) [1]. Although QCL technology is nowadays accepted as the dominant one for the support of emission at the mid-infrared and THz range, its physical properties are not utterly mapped till today. This paper attempts to highlight the noise properties of quantum cascade lasers when operating under optical injection from another QCL source for the first time. The experimental work presented here is supported by a numerical model [2] which takes into account the intrinsic properties of the mid-infrared QCLs. The results showed that injection locking is capable of reforming the noise statistics of the slave source especially when the latter is operating near the threshold. A reduction of the relative intensity noise (RIN) in the order of 8 dB was observed which is significant for noise sensitive applications such as sensing and absorption spectroscopy. Moreover, with proper variation of the optical injection using optical attenuation between master and slave lasers, it was possible to observe the locking bandwidth. It is interesting to note that the profile of power evolution depends on critical intrinsic characteristics of the source such as the linewidth enhancement factor, therefore injection locking could be also utilized in order to indirectly measure laser parameters with the assistance of the numerical model.

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## Acknowledgements

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# Mechanisms for THz Generation in GaN

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The large band gap and consequent high breakdown field make GaN an ideal material for the exploitation of the high-field transport properties of electrons. The band-structure of GaN makes it a suitable candidate for the transferred electron (TE) effect to give rise to a negative-differential-resistance (NDR). Another mechanism for generating NDR arises from the zone-centre conduction band itself where an inflection point results in a negative effective mass (NM) at high electron energies. To what extent these two mechanisms can be discriminated depends crucially on the position of the lowest upper valley. The range of values given in the literature vary by a factor of 2, with a recent experimental determination using time-resolved optical methods giving 1.1 eV [1]. This uncertainty does not pose a problem for devices based on the Gunn effect since the important parameters are the strength of the Fröhlich interaction and the relevant phonon energies, and these are well-established. A cut-off frequency can be estimated by assuming rapid thermalization and using the density-of-states ratio for the  $\Gamma$  and U valleys. The predicted cut-off frequency in GaN is 430 GHz. We estimate the cut-off frequency in the NM case to be 1.1THz.[2] The interplay of these two mechanisms has been studied via an ensemble Monte-Carlo code covering a wide parameter space.[3]

In high electric fields hot electrons interact strongly with polar optical phonons, with the result that the phonon population is driven far from thermodynamic equilibrium and can be described as being hot. How strong this effect is depends on the lifetime of these hot phonons. We predict the existence of a hot-phonon negative differential resistance (NDR) in GaN[4]. We show that this is a consequence of a wave-vector dependence of lifetime caused by the effect of coupled plasmon-phonons. Anti-screened long-wavelength modes have shorter lifetimes, screened shorter-wavelength modes have longer lifetimes, the boundary between them being determined by the temperature-dependent Landau damping. The higher density of screened modes means that the average lifetime is of order of the lifetime of the bare phonon. Its increase with electron temperature (field) is responsible for the NDR. The NDR is more pronounced at higher electron densities when there is strong coupling between the plasmons and phonons.

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# Bismides for Laser Diode Active Layers

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Bismide-based active layer of the laser diodes could significantly improve their performance characteristics. Even dilute density of Bi atoms in the alloy leads to a large reduction of its energy band gap. *E.g.*, GaAsBi with 10% of Bi has a band gap corresponding to technologically important 1.55  $\mu\text{m}$  spectral range. On the other hand, substitution of just 4% of arsenic by bismuth in GaInAs lattice matched to InP substrates shifts that wavelength as far as to 6  $\mu\text{m}$ . Moreover, the addition of bismuth increases the spin-orbit splitting of the valence band, which leads to the suppression of non-radiative Auger recombination. In this work, the structures with quantum wells from ternary GaAsBi and quaternary GaInAsBi compounds have been grown by molecular beam epitaxy (MBE) on GaAs(100) and Fe-doped InP(100) substrates, respectively. The low substrate temperature (lower than 330°C) and the arsenic to gallium flux ratio close to the stoichiometric are the most important parameters, responsible for Bi incorporation. At first, technological conditions were optimized by growing 30-50 nm-thick GaAsBi or GaInAsBi layers. From high-resolution X-ray diffraction (HRXRD) measurements the bismuth content of about 6% and 5% for ternary and quaternary compound, respectively, was evaluated. Be-doped GaAs and AlInAs were used as barrier materials for GaAsBi and GaInAsBi QW structures. In both cases 50 nm-thick top and 100 nm-thick bottom barriers were grown at high temperatures usually used in GaAs and InP-based technologies. Bismide wells were grown in the temperature range of 240°C–300°C. The thickness of wells varied from 5 to 20 nm. The atomically flat (r.m.s. of the order of 0.13-0.29 nm) and Bi-droplet free surface QW structure was evidenced by atomic force microscopy. The TEM cross-sectional images revealed sharp interfaces between the well and barrier layers in GaAs:Be/GaAsBi as well AlInAs/GaInAsBi structures. Room-temperature photoluminescence (PL) measurements showed the intensity enhancement using Be-doped GaAs barriers for GaAsBi QW. The maximum emission wavelength reached for this type quantum structure was 1.2  $\mu\text{m}$ . On the other hand the 2.4  $\mu\text{m}$  wavelength was achieved in AlInAs/GaInAsBi quantum structures.

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# Devices to guide and manipulate THz waves

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We will present a several quasi-optical devices which were developed, produced and or tested at the Philipps-University Marburg during the last three years. First, low cost THz lenses and transmission blaze gratings, which are easily produced by compression molding will be discussed [1,2]. Secondly, we present a waveplate made of a stack of ordinary white copy paper. The design frequency can be adjusted by varying the paper stripe thickness [3]. Thirdly, we have developed a fully flexible one-dimensional photonic crystals for terahertz frequencies based on alternating layers of a highly refracting polymeric compound and a pure polymer [4]. As fourth device, we present a switchable THz notch filter which uses the THz birefringence of the liquid crystal BL037 [5]. The notch filter can be switched between a transparent and an opaque state and allows for a filter depth of 35 dB at 350 GHz. Finally, we will present two devices which allow for a manipulation of THz beams. The first device is a THz lens with a variable focus [6] containing a terahertz-transparent liquid. By injecting and draining the liquid into the lens one can vary the lens curvature, which in turn leads to a shorter or longer focal length. The second device is a freely programmable THz diffraction grating based on an electrostatically actuated, computer controlled array of metallic cantilevers [7]. This device has been developed at the University of Tokyo and was tested at Marburg University.

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# **Nanowire and graphene FETs as powerful detection systems across the THz range**

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Terahertz technology has become of large interest over the last few years for its potential in non-invasive imaging, spectroscopic and biological applications. In this context, the development of a breakthrough solid-state technology for fast and high-temperature detection of THz emission, especially in the operating frequency range of Quantum Cascade Lasers ( $\tau^{-1} > 1$  THz) is highly desired.

Commercially available THz detectors are indeed based on thermal sensing elements being either very slow (10-400 Hz) (Golay cells, pyroelectric elements), or requiring deep cryogenic cooling (hot-electron bolometers), while those exploiting fast non-linear electronics (Schottky diodes) are mostly limited to the range  $< 1$  THz.

The talk will offer an overview on our recent development of high detectivity, room-temperature THz detectors coupled with ultra-stable, high power THz quantum cascade lasers. Antenna-coupled field effect transistors have been developed as plasma-wave THz detectors in both InAs nanowire and graphene channel material. Room temperature operation has been achieved up to frequencies of 3 THz, with noise equivalent power levels  $< 10^{-10}$  W/Hz<sup>1/2</sup>, and high-speed response. Large area fast imaging applications of the detectors provided a reasonably good spatial resolution, making the proposed technology already exportable for practical applications across the far-infrared.

# Optical emission of a strained direct band-gap Ge quantum well embedded inside InGaAs alloy layers\*

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We studied the optical properties of a strain-induced direct band-gap Ge quantum well embedded in InGaAs. We showed that the band offsets depend on the electro-negativity of the layer in contact with Ge, leading to different types of optical transitions in the heterostructure. When group-V atoms compose the interfaces, only electrons are confined in Ge, whereas both carriers are confined when the interface consists of group-III atoms. The different carrier confinement results in different emission dynamics behaviour. This study provides a solution to obtain efficient light emission from Ge [1].

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# Epitaxy and device fabrication for AlGaAs/GaAs THz quantum-cascade lasers

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The paper presents main problems of technology of AlGaAs/GaAs epitaxial structures as well as technology of device fabrication for terahertz-range quantum-cascade lasers (THz QCLs). The studied laser heterostructure is of a three-quantum-well design [1], which operation is based on radiative intersubband transitions taking place in a double-well region and on resonant-phonon depopulation of the laser's lower state.

Epitaxy of the presented structures creates specific problems, in part because of a very long-lasting (typically over 10-hour long) deposition process and hence a risk from loss of stability of an epitaxial system. The other difficulties come when compositions and thicknesses of individual layers are to be determined within the grown multilayered structure that usually contains relatively low-aluminum-containing nanometer-sized barriers (typically  $\approx$  15%-Al-containing ones). A significant problem is to be solved with adjustment of an appropriate low doping level of the laser's active region.

The crucial problems of the device fabrication technology concern electrical and optical properties of junctions formed by semiconductor structure and metallic layers working as waveguide claddings of the laser, as well as an appropriate method of integration of the laser structure and a receptor substrate, in terms of electrical parameters and mechanical stability of this connection.

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The authors acknowledge support from MPNS COST ACTION MP1204 and BMBS COST ACTION BM1205.

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# High-spatial resolution THz near-field imaging using surface waves

Miguel Navarro-Cia,<sup>1,2</sup> Michele Natrella,<sup>1</sup> Raimund Mueckstein,<sup>1</sup>  
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Imaging and spectroscopic analysis at terahertz (THz) frequencies can provide a number of capabilities for biomedical applications, including testing of skin tissue for cancerous cells. A major challenge for such applications is achieving sufficient sensitivity for detection of variations in tissue properties at THz frequencies. Although THz absorption due to water present in the tissue provides a differentiating factor, this effect must be detected in a small area of the tissue, often of a sub-wavelength size, creating a difficult challenge for THz imaging systems.

In this presentation we will discuss capabilities of THz near-field imaging using THz surface waves. Surface waves, or surface plasmon waves, can be used to enhance the electromagnetic wave interaction with small objects and therefore to enhance the sensitivity of THz techniques [1]. We will discuss imaging of small sub-wavelength size dielectric objects, using THz surface waves and THz near-field probes. We will also discuss the use of surface waves for confining THz waves to extremely small volumes ( $< \lambda^3/10^4$ ), surpassing the diffraction limit experienced by the free space propagating beams [2]. Such a system enables THz spectroscopic analysis for in a small volume only several microns in size. We show that utilizing THz surface waves and near-field probe technology can provide a step toward applying THz spectroscopy for high-resolution biomedical applications.

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# Multispectral terahertz imaging with the compact THz detectors designed for room temperature operation \*

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Terahertz (THz) waves (wavelength 1.0-0.1 mm) have variety of applications due to nonionizing radiation character and feature to penetrate many packaging materials like paper, plastic, wood and others. In addition, many substances have fingerprint-like absorption spectral signatures in the THz region. Therefore, multispectral THz imaging path a way for nondestructive packages screening as well as content determination. The main tool for THz spectroscopy and imaging is assumed to be a coherent THz time-domain spectroscopy (TDS) systems [1]. Even if the TDS system is outstanding scientific instrument, it remains rather bulky and complicated; however, for many practical applications one needs reduced complexity, size and cost solutions. A compact THz imaging system can be assembled of discrete components like THz lasers and single- or multi-pixel detectors [2,3]. And at discrete fingerprint frequencies, the spectroscopic THz imaging was recently demonstrated using the InGaAs bow-tie (BT) diodes [4] and the antenna coupled field effect transistor (TeraFET) detectors [5]. The sensitivity of fast and robust BT diodes displays weak dependence on frequency up to 1 THz [6]; meanwhile the TeraFETs fabricated by silicon CMOS technology are able actually to provide considerably larger sensitivity and efficient THz detection up to 4.3 THz frequency [5].

In this work, we demonstrate a multispectral THz imaging system based on compact room-temperature THz detectors. Test samples were prepared of different chemicals; the spectral signatures of the samples were measured by Fourier transform spectrometer in vacuum environment. The content of plastic container was screened and the homogeneity of the samples inside a container was estimated by the multispectral THz imaging means.

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# POSTERS

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# Advanced SAR and computational mutagenesis used in evaluation of cancer-inductor potential of the hMad2 native and mutants<sup>\*</sup>

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Mitotic division of normal cells involves the process of chromosome segregation. The accuracy of this process is assured by the intrinsic mechanics of mitosis and by the error-checking spindle assembly checkpoint (SAC). SAC is a protein complex that stops chromosome division whenever division errors are identified [1]. As components of SAC, the mitotic arrest-deficient proteins Mad1 and Mad2 are critical to prevent cancer or other genetic diseases that occur due to „wrong” cell divisions [2].

Mad2 features important for the conformational transition from inactive opened state to active closed conformation and the topological links (10 amino acids at C-terminal MAD2) with its two best-characterized protein ligands, Mad1 and Cdc20, were previously studied [3] in order to clarify their role in „correct” cell divisions, but till now, the process is not clearly understood.

Here we address the following important aims by using structure-activity relationship (SAR) models and computational mutagenesis:

- (i) Comparison of molecular descriptors (steric, electronic, structural) of native Mad2 and of 74 Mad2 mutants (already-known and rational-design mutants) in order to predict their possible tumor-inducing characters;
- (ii) Evaluation at the molecular descriptors levels of structural changes in C-terminal Mad2 domain, induced by simple and double mutations in Mad2 sequence in order to elucidate a possible contribution of these molecular descriptors to Mad2 function into SAC.

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# Self-mixing effect in a multi-transverse-mode VCSEL and polarization dynamics of the first order transverse modes<sup>1</sup>

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We present an experimental study of a sensor that can be used to simultaneously measure target translations along the optical axis and target rotations in the orthogonal plane. We used a multi-transverse mode Vertical- Cavity surface-emitting laser subject to optical feedback. When the operating conditions preserved the moderate feedback regime, the power along the two polarization modes was modulated according to both target linear displacement and rotation. The simultaneous measurement of both polarization intensity modulations allowed for the independent estimation of the two degrees of freedom of motion.

Light emitted from VCSELs is typically linearly polarized with the vector field oriented along one of two orthogonal crystal axes which are perpendicular to the emission direction. The VCSEL can operate at one polarized component or at the two components simultaneously. In the latter case the device shows a polarization instability (an abrupt switch in the optical power from a polarization state to the orthogonally polarized one) known as polarization switching (PS), which occurs as the injection current is increased above the threshold. Experimental studies have shown polarization instability when the VCSEL is subject to coherent and isotropic weak optical feedback [1]. On the contrary in the regime of strong optical feedback the device usually re-establish a polarization stability [2].

In the moderate feedback regime we studied the polarization dynamics of the first order transverse modes and self-mixing effect in a multi transverse mode VCSEL. The optical signal was revealed when the target was translate along the optical axis and simultaneously a liner polarizer, polarizing the optical feedback, was rotated of  $\pi$  rad. The DC photocurrent varied continuously with the rotation of the polarization of the optical feedback and the recording of the DC photocurrent of both polarizations put in evidence the complementary behavior of the two polarization modes. Furthermore the AC photodiode signal recorded the pure translation signal for both polarization component showing that the sawtooth fringes were preserved at any polarization angle, allowing for the measurement of the linear displacement of the target. The simultaneous recording of the AC and DC photodiode signals would thus allow for the measurement of both the rotation angle and the longitudinal displacement of a polarization selective target.

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<sup>1</sup> Acknowledgments: The author(s) acknowledge support from MPNS COST ACTION MP1204 and BMBS COST ACTION BM1205.

# Zero Bias Schottky Junctions for Terahertz detection

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The terahertz (THz) radiation (0.3-10 THz) is a very promising range for applications like sensing or imaging. Recently THz spectroscopy and imaging of ERCs (explosives and related compound) and drugs have been investigated intensively for possible defense and security applications [1]. The GaAs Schottky barrier diode is one of the most important element for terahertz (THz) detectors or mixer and usually is employed as square-law power detectors in millimeter wave integrated circuits working up to 100 GHz. We introduce quasi-optical Schottky diodes without a dc bias, based on quantum tunneling through a curved sub-micrometric Au/Ti/n-GaAs junction [2], fabricated with different integrated broadband antennas; responsivity measurements over the measured range of 0.15 to 0.7 THz using a quasi-optical setup are presented. Our process is fully planar and highly reproducible, in order to fabricate monolithic matrixes of radiation detectors to acquire real-time terahertz images in a focal plane array configuration.

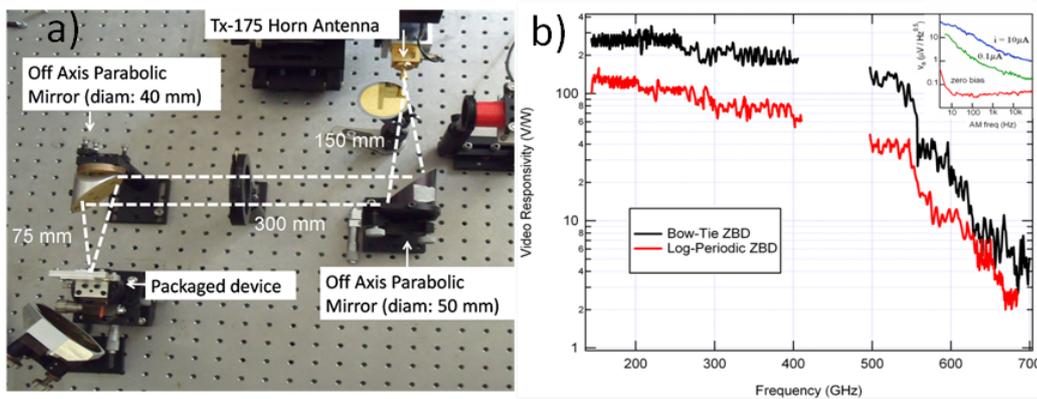


Figure 1: a) Picture of the optical setup. b) Experimental determination of the zero-bias video responsivity  $\beta_0(f)$  of bow-tie ZBD (black line) and log periodic ZBD (red line); inset: noise spectra of a ZBD.

To demonstrate the functionality of our Zero Bias Detectors (ZBDs) as THz rectifiers, we have determined their cut off frequency by irradiating the devices with free-space beams of variable THz frequency. The performances at terahertz frequencies (directivity and noise equivalent power) of the lens-coupled detector were measured by a free-space-coupled 0.15-0.7 THz radiation source (by Virginia Diodes) based on a frequency multiplier chain (see Fig.1a). The optical responsivity at zero bias  $\beta_0(f)$  is plotted in Fig. 1b for two ZBD with area  $0.2 \mu\text{m} \times 1 \mu\text{m}$ , but coupled to the radiation with two different broadband antenna typologies. The bow-tie device shows an higher responsivity, twice than that of the diode with log-periodic antenna, and displays  $f_{ci} \sim 500$  GHz, so the THz bandwidths are very similar in the two devices; the Noise Equivalent Power of the bow-tie device is  $2 \times 10^{-11} \text{ W/Hz}^{0.5}$ , better than  $5 \times 10^{-10} \text{ W/Hz}^{0.5}$  achieved in log-periodic configuration.

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# Electrical properties of nanocrystalline In-doped zinc ferrites \*

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This paper presents results concerning on dielectric behavior and conductivity of the nanosized  $Zn_{1-x}In_xFe_2O_4$  powders ( $x = 0, 0.15, 0.2, \text{ and } 0.3$ ), obtained by coprecipitation method [1]. The dielectric permittivity decreases, and conductivity increases with increasing frequency which can be explained by Koops model [2]. The ac conductivity first increases with the indium content in zinc ferrite, then decreases with further increasing indium concentration, while pure zinc ferrite has the lowest conductivity. This could be explained by the replacement of  $In^{3+}$  ions at tetrahedral and octahedral sites, which is reflected in a number of available of  $Fe^{2+}-Fe^{3+}$  pairs at octahedral sites. The obtained values of activation energy, in temperature range below 500 K, confirm that higher activation energy implies the lower electrical conductivity. Also, the higher values of activation energy suggest that the conduction mechanism involving hopping of polarons. Two different processes have been proposed for the relaxation mechanism, such as the quantum-mechanical tunnelling (QMT) and the classical hopping over the barrier (CBH), or some combination of the two, and it has been variously assumed that electrons (or polarons) are the responsible carriers [3]. The variation of the parameter  $n$  with the temperature of nanostructure  $Zn_{1-x}In_xFe_2O_4$  (obtained from the relation  $\sigma_{ac}(\omega, T) = A(T) \cdot \omega^n(T)$ ) suggest a simple QMT (CBH) conduction for  $x=0$  and 0.3, while QMT model of nonoverlapping small polaron i.e. NSPT [4,5] is the most suitable to explain conduction mechanism for  $x=0.15$  and 0.2.

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# THz metal mesh filters on thick fused silica substrate\*

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Metamaterial-based THz devices, including amplitude/phase and spatial modulators, sensors and filters, play a crucial role for the controlling and manipulating of THz waves [1]. In this paper, we design and fabricate a series of cross-shaped THz bandpass filters ranging from 0.1 to 0.5 THz on commercially available 525  $\mu\text{m}$  thick fused silica substrate. Since at THz frequencies, the thickness of the substrate is comparable to the free-space wavelength, conventional cross-shaped filters suffer from substrate resonances and Fabry–Pérot resonances. To further suppress unwanted frequency components, a complementary cross-shaped structure is added to the original design to form trapped mode excitations [2]. The enclosed crosses and the outer structure have opposite surface current distribution due to their complementary shapes. This results in a high transmission at and near the resonant frequency. Simulation results suggest  $> 80\%$  transmittance with good out-of-band rejection for all designs. The measurements are undertaken using a Rohde and Schwarz ZVA from 75-500 GHz using a collimated beam in quasi optical setup.

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# Interaction of light and valence band excitations in a semi-conductor microcavity at terahertz frequencies

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The coupling of light in a microcavity and intersubband transitions [1] of semiconductor quantum wells leads to interesting effects such as polariton lasing [2] and shows potential for applications in modern optoelectronic devices, especially after the recent experimental demonstration of THz polariton emitters [3]. In this paper, we theoretically investigate the coupling of light and material excitations at terahertz frequencies based on inter-valence bands transition leading to polaritons [4] and antipolaritons [5]. The energy dispersion relation as a function of incident angle is obtained using a simple geometric structure containing GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As multiple quantum wells surrounded by low refractive index AlAs layers to confine the incident light beam. Fig. 1. shows the interacting polaritons and antipolariton at THz frequencies due to absorptions to higher sub-bands and dispersive gain medium.

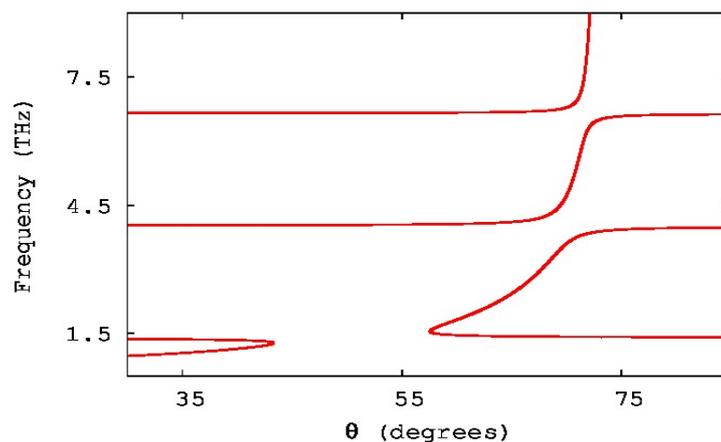


Fig 1. Interacting THz polaritons and antipolariton resulting from coexisting gain and cross absorptions to higher subbands, for a structure containing 10 nm GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As quantum wells in the cavity core. The system is out of equilibrium with  $N=2 \times 10^{11}$  carriers/cm<sup>2</sup> in the second valence subband and all the others empty.

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# Optimized Second Harmonic Generation in GaInAs/AlInAs Quantum Cascade Lasers

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The quantum cascade lasers (QCLs) represent one of the most sophisticated and reliable light sources in the infrared and terahertz region of the electromagnetic spectrum, with a wide range of tunable operating wavelengths, room temperature operation and high output powers. This unique attribute originates from the fact that, unlike in conventional semiconductor lasers, lasing frequency of a QCL depends not only on the constituent materials, but on the structure geometry as well. The broad range of possible fields of application, such as industrial process monitoring, medical diagnostics, biological contaminants, law enforcement and military, led to their fast development and consequently high commercial availability. However, accessing the  $\sim 3\text{-}4\mu\text{m}$  region of the electromagnetic spectrum remains with limited success. This fact has stimulated the need to utilize yet another QCL property – namely the ability to design the resonant intersubband transitions as strongly nonlinear oscillators, consequently enabling the occurrence of large nonlinear optical susceptibilities, which we have done in our work.

Here, we present an innovative procedure for the design and optimization of GaInAs/AlInAs quantum cascade laser structures based on the use of the Genetic algorithm. The purpose of the algorithm is to determine the set of design parameters that would enable the maximization of the second order nonlinear susceptibility, thus facilitating significant optical nonlinearities to take place. Starting from the existing design [1], we obtain the optimized structure and evaluate its energies and wave functions, which enables us to calculate the output characteristics by applying the full self-consistent rate equation modeling of the electron transport in a periodic QCL structure [2].

The results of the calculations predict a noticeable improvement of targeted properties of the optimized design, while at the same time the original design calculations show excellent agreement with experimental results. The described procedure is applicable to various active region designs and can be used for other wavelength ranges.

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# Optimization of GaN THz QCLs

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Room temperature operation has not yet been achieved in THz quantum cascade lasers (QCLs); the current highest temperature record is 199.5 K at 3.22 THz using an  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$  structure [1].  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  presents an opportunity to increase the maximum operating temperature of THz QCLs due to a higher LO phonon energy (92 meV) compared to that of GaAs (36 meV) which is thought will suppress performance degradation mechanisms at higher temperatures [2]. These include thermal back filling and thermally activated LO phonon scattering which occurs as electrons gain enough in-plane kinetic energy to emit an LO phonon and relax to the lower laser level non-radiatively. Monte Carlo, rate-equation [2] and non-equilibrium Greens function (NEGF) [3] models have indeed predicted suppression of these mechanisms. While the semi-classical rate equation models can have good experimental agreement [4], they do not account for coherent transport. Like NEGF, density matrix (DM) modeling accounts for quantum tunneling but is less computationally intensive which allows for use as a QCL design tool. Additionally, the model includes the effect of the enhanced Fröhlich coupling constant in GaN which can reduce gain by energy broadening in resonant LO phonon depopulation structures due to ultra-short lower lasing state lifetimes. Recent work [5] has shown that high temperature operation should be achievable by careful active region design.

The extended density matrix approach outlined in Ref. 6 is capable of simulating a QCL with any number of states and submodules per period. We apply this DM approach and the rate equation model to several GaAs structures which have been characterized experimentally. The model can then be used to optimize a nitride design for a figure of merit (e.g. gain) using parameters such as layer thicknesses, doping and applied bias to find candidate structures with acceptable lower state lifetimes and population inversion automatically.

We would like to gratefully acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC).

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# Vacuum microdiodes as possible sources of THz radiation \*

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Numerical simulations of vacuum diodes of nanometric size, based on the method of molecular dynamics, show current oscillations with a regular amplitude and time interval [1]. These oscillations have the same physical origin as the Coulomb blockade in the single electron transport of quantum dots. The number of electrons in our diode however varies between hundreds and thousands. The time-averaged current corresponds to the Child-Langmuir law. The frequency of the oscillations is in the Terahertz range and it depends on the emitter area and on the electric field across the diode. For a planar micro-diode of given dimension, the modulation frequency can be easily tuned simply by varying the applied potential [2]. Given the small size of our device we expect a very low radiation power. Therefore we need to consider several diodes working in parallel. In this presentation we show that under certain conditions several such diodes working in parallel can synchronize and produce one amplified signal which can be used as a practical THz radiation source. The electron beam structure and the possibilities to control it are also under investigation in our simulations

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# The ability of THz spectroscopy to discriminate between protein solutions with different pH values: implications for cancer detection \*

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Extracellular pH values measured in the tumors are significantly lower than those measured in the adjacent normal tissues of the same patients, while the intracellular pH values of both tumor and normal cells are essentially identical or the tumor cells are slightly more basic than the normal cells [1]. This pH difference between the tumor and normal tissues could be an important feature that contributes to cancer detection using THz spectroscopy.

Here we investigated the ability of THz spectroscopy to discriminate between protein solutions with different pH values. Since biological media are characterized by a high density of proteins, different protein concentrations were also taken into account.

Buffers with pH values of 4, 5, 6, 7 and 8 were used to prepare bovine serum albumin (BSA) solutions with the following concentrations: 40 mg/ml BSA, 100 mg/ml BSA and 250 mg/ml BSA. THz time domain spectroscopy experiments were performed on 10  $\mu$ l solution samples placed in a Teflon holder. In order to understand the influence of pH and protein concentration on THz spectra, we used molecular modeling methods to model BSA structure protonated according to the pH values from the experiments, to model BSA solutions and to simulate their THz spectra.

The experimental results show that THz spectroscopy discriminates between the solutions with different pH values and different protein concentrations. The 40 mg/ml BSA solution presents the highest THz absorption at the pH value of 8 and the lowest at the pH value of 4. The 100 mg/ml BSA solution presents the highest THz absorption at the pH value of 7 and the lowest at the pH value of 6. In the case of the most concentrated (250 mg/ml) BSA solution, the highest THz absorption was measured for the solution with the pH of 6 and the lowest THz absorption was measured for the solution with the pH value of 4.

In conclusion, the sensitivity of THz spectroscopy to pH conditions and protein concentrations should contribute to the identification of differences between tumor and normal tissues relevant for cancer detection using THz radiation.

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# Modelling Optical Nonlinearities in Bulk Semiconductors for Mid- Infrared Applications

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In this paper, optical nonlinearities of bulk semiconductors are described by simple and easily programmable analytical expressions. The quasiequilibrium interband optical polarization [1- 3] that incorporates the relevant many-particle interaction; plasma screening and band gap renormalization is obtained [1, 3, 4]. The result yields an efficient analytical expression for the optical absorption/gain spectra which, in the isotropic limit reduces to the usual Elliott formula for excitons at low densities in contrast with previous results found in the literature

$$\alpha(\omega) = \alpha_0 A(\omega) \frac{\hbar\omega}{E_0} \left\{ \sum_{n=1}^{g^{1/2}} \frac{4\pi}{n} \left( \frac{1}{n^2} - \frac{n^2}{g^2} \right) \delta_r \left( \Delta - \frac{E_n}{E_0} \right) + 2\pi \int_0^\infty dx \frac{\sinh \pi g \sqrt{x}}{\cosh \pi g \sqrt{x} - \cosh \pi \sqrt{x} g^2 - 4g} \delta_r(\Delta - x) \right\} (1)$$

Further application of the Kubo-Martin-Schwinger (KMS) relation [5] yields an expression for the photoluminescence spectra

$$L(\omega) = \left( \frac{\omega n_b}{\pi c} \right)^2 \alpha(\omega) / (e^{\beta(\hbar\omega - \mu)} - 1) (2)$$

The theory is to be applied to the modelling of absorption and luminescence of narrow band gap materials which are relevant for MID- IR applications.

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# Sub-THz Photonic Crystal Devices

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Photonic Crystal (PC) based devices at mm-Wave and THz frequencies are attractive for future high performance applications in sensing, communications and radar. Within our research we have studied a variety of components that it is possible to create using photonic crystals technology between 75-125GHz, these include: filters [1], waveguides [2], and switches [2].

The PCs are fabricated from a 525  $\mu\text{m}$  high resistivity silicon ( $>10 \text{ k}\Omega\cdot\text{cm}$ ) substrate with a periodic triangular lattice of air holes with a radius of 235  $\mu\text{m}$  and lattice constant of 780  $\mu\text{m}$ . This structure gives rise to a bandgap that extends from 97 – 127 GHz. To create devices defects are introduced into the lattice, a waveguide is a simply a line defect and then filters are made through creation of cavity within the structure by removing several holes. To create a switch the waveguide defect is illuminated by a laser [2], giving rise an extinction ratio of 40 dB demonstrated experimentally. These fundamental devices form the starting point for investigations to realize monolithic integrated photonic crystal architectures.

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**CORELATIONS BETWEEN SKIN CANCER, HEART FAILURE AND SERUM VALUE OF VITAMIN D**

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**INTRODUCTION:** Despite considerable pharmacological, interventional and surgical progresses registered for congestive heart failure (CHF), this severe disease still influences life quality and duration of the patients. Besides, there are a lot of evidences that CHF is strongly associated with neoplasia( due to psychological distress and catecholamines release).

**MATERIALS AND METHODS:** The study enrolled 135 patients, aged between 34 and 87 years, diagnosed with CHF, IV<sup>th</sup> class NYHA (New York Heart Association) and with associated hypovitaminosis D. The following methods were utilized, every 6 months, during 2 years: cardiological and dermatological examinations; body mass index; serum creatinine; serum vitamin D value; transaminases; brain natriuretic peptid (BNP) value; glycemia; complete blood count; echocardiography; thoracic X-ray; electrocardiogram; puls oximetry. The patients were divided in two groups: group A (71 patients) who accepted the administration of vitamin D supplement, according to Endocrine Society guidelines and group B (64 patients) who didn't want to receive vitamin D. All 135 patients received betablockers, diuretics, angiotensin converting enzyme inhibitors/ sartans, statins, antiplatelet/anticoagulants, digoxin(selected cases), oxygen therapy, according to European Society of Cardiology guidelines.

**RESULTS:** The patients from group A registered the following: 1. increasing ejection fraction of the left ventricle with a 13% average(from 25% at the beginning of the study to 38% at 6 months and during 2 years); 2. diminishing BNP value with a 36% average (from 585pg/ml at the first determination to 370pg/ml at the second analysis, after 6 months, maintaining these amelioration during 2 years); 3.increasing arterial oxygen saturation with a 12% average(from 80% to 92%). After 2 years, non-melanoma skin cancer occurred at 3 patients from 71 of group A (4%). Comparing with group A, the patients from group B registered a less amelioration of ejection fraction- 5%(from 26% to 31%); inferior to group A were also the average diminishing of BNP values-15% and the average increasing arterial oxygen saturation-5%. Besides, the 2 years incidence of non-melanoma skin cancer at the group B patients was higher than group A-10 patients from 64 (17% group B-4% group A).

**CONCLUSIONS:** This study proved us, as large trials from specialty literature , that hypovitaminosis D is a worsening factor of contractile dysfunction in CHF patients. The suppliments with vitamin D lead to a significant improvement of these studied patients. Besides, the research proved hypovitaminosis D implication in occurrence of non-melanoma skin cancer, through subtle intervention of this hormone-vitamin D in cell growth and apoptosis regulation, as recent other trials. The originality of the study consists in simultaneous observation of two apparently different diseases:congestive heart failure and skin cancer. Future research involving interdisciplinarity could have a significant clinical impact.

# Quantum cascade laser beam quality measurements using a goniometric system\*

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Mid-infrared quantum cascade lasers are promising sources for the molecular spectroscopy. For this application one of the most important factors is well-formed laser beam. We present accurate system for measuring beam quality. containing goniometric profilometer designed for the large divergent angle laser beams [1]. The advantages and limitations of the goniometric method are discussed in the paper.

The exemplary measurement results obtained by the system are presented. The measured devices were GaAs/AlGaAs quantum cascade lasers grown by solid source MBE [2]. The emitted wavelength was approximately 9.4  $\mu\text{m}$ . Two-dimensional maps and one-dimensional cross-sections of the radiation distribution under various supply conditions are shown. We present also the beam quality parameter  $M^2$  determined for both, fast and slow, axes.

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# Discussion of the development aspects of the quantum cascade laser simulation software\*

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Quantum cascade lasers (QCL) are one of the most promising compact solid state devices for controllable generation of the coherent radiation in the THz and mid infrared (MIR) regions. Since realization of the first MIR QCL in 1994 and the first THz QCL in 2002 and filling of the „terahertz gap” [1] a constant progress has been observed also in the development of the respective QCL simulation software [2]. This has been not a trivial task as it joins many difficult R&D fields as the quantum and semiconductor physics, the optical engineering, numerical methods and the software engineering. We emphasize that in order to achieve the progress in the THz and MIR field in general, besides the computer cluster based and rather time consuming scientific research software, the optimized and reasonably simplified desktop computer based software tools are needed that may find wider usage among the engineers and in students training courses in universities. As it happened with the conventional semiconductor device simulation software in 1980-ies and 1990-ies.

When calculating characteristics of the noncoherent THz emitter source [3], we achieved nearly 2 orders of magnitudes of speeding-up of calculations in comparison with the universal blocks based standard version of the Leeds software system [2] due to the reorganization and optimization of the physical models and the numerical procedures. In the present presentation we analyze the MIR QCL test structures [2] and discuss the rearrangements in the physical models and numerical methods that may yield more optimized (i.e. more accurate and faster) QCL simulation tools.

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# Generation of THz Radiation Using Switchable Metamaterials <sup>\*</sup>

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THz research has undergone major advances in the domain of THz sources and detectors with the emergence of quantum cascade lasers [1], photomixers [2], bolometers and single photon detectors [3]. In this communication we propose a new device that can be classified as a THz source built on metamaterials which is capable of producing electromagnetic waves in the THz range from a pump signal of lower or higher frequency. Both options will be studied and we shall demonstrate that it is possible to use this device to easily obtain THz radiation with large amplitude. The working principle of the device exploits the concept of switchable metamaterials and their non-linearities which allow for a fast reconfiguration of its electromagnetic properties, such as the electric permittivity, magnetic permeability and index of refraction [4], [5]. We focus on the characterization of the various modes of operation of the device. We note, however, that this device cannot work in continuous-wave mode in its current version. We highlighting the advantages and the new possibilities of up/down frequency conversion in the context of the proposed method. The study is confined to the theoretical analysis of the various components that constitute the device, and we provide numerical simulations to corroborate our findings. We describe a possible construction of the device using a near-infrared semiconductor laser as the pump signal.

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# Measurements of subband electronic and lattice temperatures in scattering-assisted terahertz quantum cascade devices<sup>\*</sup>

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The terahertz quantum cascade laser (THz QCL) is one of the most promising sources for the generation of terahertz radiation. However, their operation is still limited to cryogenic temperature. The most used THz QCLs share an active region scheme based on a resonant tunneling injection directly in the upper laser state. These devices appear to be limited to a maximum operating heat sink temperature  $T_H < \hbar\omega/K_B$  ( $K_B$  is the Boltzmann constant). Recently a new active region scheme has been proposed, named scattering-assisted (SA) injection scheme, providing the possibility to overcome the above limit. In this scheme, the energy difference between the injection level and the upper laser level is kept resonant to that of a longitudinal-optical (LO) phonon, so an efficient depopulation via electron-LO-phonon scattering is assured. A critical understanding of the actual lattice temperature ( $T_L$ ) and the individual  $j$ -th subband electronic temperatures ( $T_e^j$ ) is crucial to refine the design of THz QCL active regions with improved thermal performance. In this work we compare the experimental measurements of subband electronic ( $T_e$ ) and lattice temperatures ( $T_L$ ) of THz QCLs with GaAs/Al<sub>0.25</sub>Ga<sub>0.75</sub>As active region scheme based on phonon-SA injection and extraction schemes [1]. Three devices have been investigated, differing for doping region, number of quantum wells composing the active region and the energies of the phonon-assisted transitions as compared with the LO phonon energy  $E_{LO} = 36$  meV. The employed experimental approach is based on a microprobe band-to-band photoluminescence, already successfully utilized for the investigation of THz QCLs based on different active region schemes. The electronic temperature is extracted by the lineshape analysis of the high energy slope of the photoluminescence bands.  $T_L$  is extracted by comparing the photoluminescence peak energy shift induced by heating with a calibration curve obtained by probing the device at zero-current while varying the heat sink temperature.

Below the band alignment for lasing, all the subbands share the same electronic temperatures, which results slightly higher than the lattice one ( $\sim 5$  K) while the heat sink temperature  $T_H$  is fixed to 50 K. A non-equilibrium hot electron distribution has been found above the band alignment for lasing. Differently from resonant phonon scheme where electrons are directly injected into the upper laser level, causing a large extra heating with respect to the lattice [2], in the investigated phonon-SA injection and extraction scheme both laser levels remain much colder and share the same electronic temperature of the extractor level while the injector level is the hottest one. At the largest value of the dissipated electrical power ( $\sim 6$  W) the extra-heating of the injector level respect to lattice is  $\sim 36$  K while the extra-heating of the upper laser level respect to the lattice is  $\sim 26$  K [3]. The observed  $T_e$  increases are much smaller than what previously observed in THz QCLs (for example in resonant phonon THz QCL scheme we observed more than 100 K difference between  $T_e$  and  $T_L$  for 3 W of dissipated power).

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# Room temperature nanodetectors for sensing, security and biomedical applications across the far-infrared.

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The fast and reliable detection of radiation at THz frequencies represents an important issue for a full exploitation of THz technology. Very recently, THz detection in InAs nanowires (Nw) field-effect transistors (FET) has been reported [1-2]. Due to their reduced size, these systems offer a very large cut-off frequency together with the possibility to be arranged in matrix arrays for imaging application across the far-infrared.

The extreme flexibility with which InAs nanowires can be grown allowed us to select a set of high electron mobility nanowires ( $2000 \text{ cm}^2/\text{Vsec}$ ) which have shown good detection performances up to 2.8 THz.

We report on the development of a novel class of nanowire-based THz detectors in which the field effect transistor is integrated in a split-ring narrow-band antenna. When the THz field is applied between the gate and the source terminals of the FET, a constant source-to-drain photovoltage appears as a result of the non-linear transfer characteristic of the transistor. In order to achieve attoFarad-order capacitance we fabricate lateral gate FET with gate widths smaller than 100 nm.

Our devices show a maximum responsivity of 110 V/W without amplification, with impressive noise equivalent power levels  $\leq 10^{-10} \text{ W}/\sqrt{\text{Hz}}$  at room temperature. The frequency noise spectral density shows a flattening to the white noise level at frequency of about 10 kHz.

The detection scheme provided by the split-ring resonant antenna opens a path to novel applications of our technology to metrology, spectroscopy, homeland security, biomedical and pharmaceutical applications. Moreover the possibility to extend this approach to relatively large multi-pixel arrays coupled with THz sources makes it highly appealing for a future generation of THz detectors.

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# Simulated gain bleaching from temperature and intensity in quantum cascade lasers\*

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A theoretical study of the dynamics of two Quantum Cascade Lasers (QCLs) is presented. It is based on a non-equilibrium Green's function (NEGF) treatment of the transport problem, and the model used was recently described by us in [1]. Inserting a time-dependent electromagnetic field allows us to drive the system with a finite intensity. Assuming the same periodicity in the nonlinear response of the system as in the driving field, we then calculate the response function in a truncated Fourier space of the fundamental driving frequency and its higher harmonics. Doing so allows us to first calculate the response of the most prominent part of this Fourier series, such as the fundamental and first harmonics frequencies, but also to expand and include even higher harmonics, should the field strength require it.

Most calculations shown here were done on a four well resonant-phonon QCLs studied by Burghoff *et al.* in [2] where the *gain* of the structure was measured using Time Domain Spectroscopy (TDS). We have previously reported a comparison between their findings and our simulations; suggesting that the measurements do not correspond to linear response [3]. We also presented a method to calculate the intensity inside the laser cavity.

Relating the modeled gain of a QCL to a calculated, measured or assumed value of the waveguide losses provides a way of estimating the ac field intensity. This is done by fixing the gain to the losses and leaving the field strength as a free parameter in order to bleach the gain to the desired level. Using this for the laser studied in [2], we find good agreement to the experiment [3]. The scheme can be used to model QCLs also in the on-state with the stimulated-emission-driven current as we showed in [3]. Although this effect was not so important in the structure of [3], we compare with recent simulations on the structure studied in [4] where it seems to have a larger impact on the system dynamics.

Additionally, temperature effects can also be analyzed in the model, and we show how we can estimate the fractional loss of power with temperature in excellent agreement to the experimental results in [4].

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# The photoluminescence study of heat transport in semiconductor periodic nanostructures\*

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Photonic devices are already in widespread use, but demand for them is growing continuously. High-performance photonic devices like VECSELs or QCLs, which provide new functionalities and applications, contain multi-layered periodic semiconductor structures. High density of interfaces within such structures influences their physical properties, e.g. hinders heat transfer throughout the structure [1-6]. As the temperature increment may lead to degradation of the device, effective heat extraction is very important issue of the device performance.

Thus, the knowledge about heat transport in periodic nanostructures is essential for designers of semiconductor devices [7]. It is noteworthy that this process includes phenomena not occurring in bulk materials. Unfortunately, there is lack of theoretical models which have unambiguous experimental confirmation. Finding a suitable experimental approach is therefore of a great cognitive and applied significance.

The aim of this work was to investigate heat flow in semiconductor periodic structures, such as superlattices. For this purpose, a method of spatially-resolved photoluminescence measurements was applied. We have taken advantage of direct correlation between the value of the energy band gap of the investigated material and its PL spectrum. We have been analyzing optical response of AlGaAs/GaAs periodic nanostructures under various temperature conditions. High spatial resolution of measurements allows for determination temperature distribution within the structure. The results can be used to estimate thermal conductivity of the investigated samples and to confirm the theoretical models describing heat flow in periodic nanostructures.

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# Recent progress in microscopic approaches to transport and optics of semiconductor TERA-MIR materials

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Many substances exhibit rotational and vibrational transitions in the terahertz (THz-0.3 THz up to 10 THz) and mid infrared (MIR-15 THz to 120 THz), jointly called here "TERA-MIR", hence giving access to a spectroscopic analysis of a large variety of molecules which play a key role in security as well as various other areas, e.g air pollution, climate research, industrial process control, agriculture, food industry, workplace safety and medical diagnostics can be monitored by sensing and identifying them via MIR and THz absorption "finger prints".

In this paper I summarize progress in four different topics of modeling materials for this range. I start with effective three dimensional anisotropic materials with new expressions for the nonlinear absorption, gain and luminescence of semiconductor superlattices. described as anisotropic media. The very efficient analytical approximations are easier to program compared to previous material found in the literature [1] and reduce exactly to the excitonic Elliott formula in the limit of isotropic bulk, in contrast with other high density approximations in the literature, that fail to reproduce that limit correctly.

Next the superlattices are fully described in the case of Quantum Cascade Lasers (QCLs) and preliminary results of a cooperation between two teams of COST MP1204, which will lead to the new state of the art QCL simulators are outlined.

The final part of the talk is dedicated to the coupling of light in a microcavity with intersubband excitations considering both intervalence THz transitions [2] and dispersive gain in dilute nitrides.

The theoretical results outlined are intended to stimulate further cooperation between theory and experimental teams in the ACTION and to support Round Robin activities.

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