3. Publishable summary

3.1 Project context and objectives

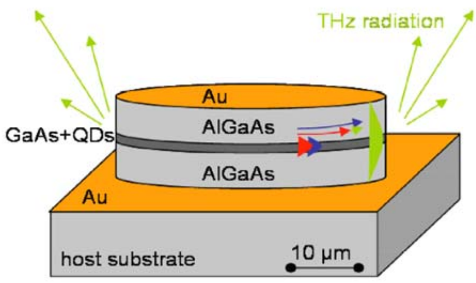
Today's most popular structures for generating and detecting broadband THz pulses, photoconductive dipole antennas excited by femtosecond lasers, suffer from large size and high cost problems. As far as the generation and detection of CW THz radiation is concerned, conversely, no significant progress in terms of emitted power has been demonstrated in photoconductive generation during the last few years, with maximum outputs limited to the 100 nW range below 1 THz, and quickly decreasing to the nW range at 2 THz. At higher powers, THz quantum cascade lasers (QCLs) emit more than 50 mW (peak) in the pulsed regime, but are poorly tuneable and only operate at cryogenic temperatures.

Various routes to the nonlinear generation of THz frequencies have been explored to date in different materials, based on difference-frequency generation (DFG), optical rectification or parametric generation. However, all these THz nonlinear sources are passive and require external pulsed pump laser sources, making the overall systems neither compact nor practical outside research laboratories. An interesting perspective is provided by highly confining photonic structures, allowing the integration of laser pump sources and DFG media, and resulting in a compact and rugged device of a few μm^2 in size. A THz source based on DFG in a dual-λ mid-IR QCL has been recently proposed. [1] However, due to mode competition and heavy pumping, it is severely limited by free-carrier absorption (FCA) at THz frequencies, and it can only emit pulses of a few hundreds of nW at 300 K.

Here we focus on DFG in a whispering-gallery-mode (WGM) microcylinder resonator (MR). In the horizontal plane, guidance is granted by the bent semiconductor/air interface. Increasing the MR radius, more modes can be accommodated in the structure, which will have a smaller free spectral range.

3.2. Work and main results since the beginning of the project

The final TREASURE device is based on a MR etched in a GaAs/AlGaAs double heterostructure that vertically confines the near IR WGMs, like in a standard dielectric waveguide. The cylindrical structure is capped on both sides by a metallic mirror to ensure a double-plasmon, vertical confinement of the THz WGM. In this nested-waveguide scheme, the AlGaAs spacers provide a useful degree of freedom to optimize the spatial overlap of the three interacting modes. The metallic mirrors are also used as contacts for electrical injection into the doped AlGaAs layers. In order to selectively inject the current at the edges of the cylinder where the near-IR WGMs are located, a highly resistive region will be defined by ion implantation in its central part. InAs QD arrays located within the near-IR waveguide are used as active medium. The QD gain is inhomogeneously broadened, a key factor for the simultaneous lasing of two near-IR WGMs without mode competition. The homogeneous broadening of QDs will allow



The TREASURE device

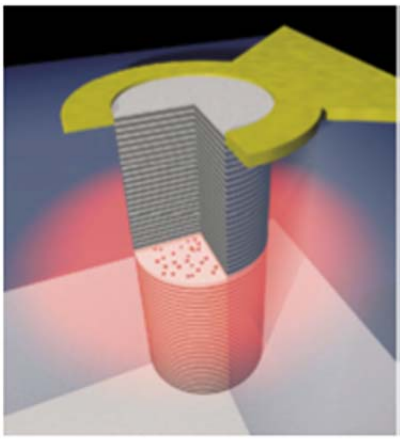
emission at frequencies down to 1.5 THz. Conversely, an upper limit of 6.5 THz is set by GaAs rest-strahlen band.

Since the beginning of the project, we have shown that GaAs/AlAs MRs containing quantum dots (QDs) can sustain simultaneous lasing of WGMs in the near IR [2-3], with Q factors >10^4 in pillars with diameters ≈3µm, enabling simultaneous lasing of several WGMs without mode competition, even for pumping levels well above threshold. THz generation through DFG between these WGMs is predicted for MRs with diameters > 20µm, based on a combination of two phase-matching schemes. [4]

Moreover, we have numerically shown that DFG process in the TREASURE device involves two high-Q, TE-polarised near-IR WGMs and a low-Q, TM-polarised THz WGM that leaks out all around the MR edge. Due to controlled diffraction from a plasmonic grating fabricated in the ground plane of the MR, the THz field will radiate almost vertically, although the THz WGM in the MR is TM. Preliminary effective-index and coupled-mode calculations, combined with fully vectorial FDTD, predict several phase-matched DFG wavelengths in the above THz range, for two QD wavelengths around 0.93 µm, for MR heights spanning approximately from 4 to 6 µm, and radii around 40 µm. So far, THz output of a fraction of µW is expected, for near-IR laser powers in the 10 mW range (i.e. with negligible two-photon absorption), but design/fabrication optimization is under way.

The first MR samples have been fabricated at the end of the 1st year, and will be experimentally studied in the following months. A fruitful interplay has already started, between fabrication steps, characterisation results and design refinement.

Finally, and well in advance with respect to the official schedule, we have obtained important design results in terms of THz power extraction and far-field optimisation.



Schematics of the electrically driven WGM QD microlaser demonstrated during year 1.

THE TREASURE PROJECT (May 2010 – April 2013)

During the first year of the project, we have:

1. demonstrated lasing in QD WGRs, in the CW regime at 100 K, under optical pumping, as well as electrical pumping at 10 K;
2. progressed in the modeling of the laser heterostructure (composition profile and doping), the linear and nonlinear behavior of near-IR and THz WGMs, as well as the radiating features of the THz emitter;
3. fabricated and tested the experimental setup for the linear and nonlinear optical characterization of passive and active WGRs.

CONCLUSION AND PERSPECTIVES

Most relevant result of TREASURE's first year:

- Demonstration of lasing in QD WGM MRs under electrical pumping.

Main issues in the next semester:

- Confirm via fully vectorial FDTD the effective-index predictions of THz DFG between 2 and 6 THz, in the microwatt range.
- Characterize the first WGM MR samples.
- Achieve the lasing of optically pumped MRs at 300K.
- Achieve low-threshold lasing in electrically-pumped MRs.

3.3. Expected final results and their potential impact and use

The device concept developed within TREASURE will open new perspectives for various THz technological applications, mainly due to the compact and rugged form of the device, to its low-power consumption, and to its room-temperature operation. The expected level of performances is unprecedented both in and outside Europe. Moreover the device is scalable, in the sense that the elementary emission units of the device can be multiplied and integrated, thus forming THz emitter arrays. This opens the possibility of adjusting the total emitted power and creating a flexible platform to address poorly solved problems, such as THz bio-chemical sensing and THz imagery.

To recapitulate, the TREASURE project will deliver a device, electrically pumped at room temperature, which generates a high intensity and spectrally pure THz radiation. The TREASURE technology will form a platform that will allow further development of both the technology itself and the applications based on this technology, beyond the duration of the project.

Further development of the TREASURE technology may allow phase-locking of several THz emitters, enabling coherent addition of the outputs of an array of N emitters with an even higher output power ($I_{out} \propto N^2$) as well as the possibility of steerable beams from phased arrays. A room-temperature, electrically pumped light source with such properties will have profound impact on the technological development of our society, as detailed below.

Market reports predict that in 10 years, the worldwide market for THz technology will increase from its current annual volume of approximately 10-30 million dollars to approximately 500 million dollars. This increase will be driven by emerging applications of THz technology, including security and screening applications, biomedical applications, non-destructive evaluation and testing applications, and THz wireless communication technology. The successful TREASURE project will have a significant and positive impact on all these applications, and will lead to a further increase of the volume of the market for THz technology.

As a specific example of the impact of the TREASURE device, consider its use as replacement of the current state-of-the-art for generation of frequencies above 1 THz, namely photo-mixing of two laser lines with a frequency difference corresponding to the generated THz frequency. Despite the fact that photo-mixer transceivers have been developed for more than one decade, the power levels available from such devices remain rather low, especially at high frequencies. For instance, in the 2-3 THz band maximum output powers are of only a few nW. Such low power levels are among the main factors limiting the bandwidth of photoconductive transceivers. Note that merely increasing the power of the laser diode pumps is not a solution to this problem since beyond $\sim 50\text{mW}$ pump, photo-mixers suffer from permanent thermal damage.

Thus the TREASURE device offers the exciting and commercially attractive possibility of replacing a system consisting of two laser sources, optical feeds, power supplies, and photo-mixing circuit, with a single integrated, electrically pumped component, capable of generating orders of magnitude higher THz intensity at the interesting frequency band above 2.5 THz.

An important example of the applications that will be enabled by the TREASURE technology is the detection of trace gases. From an environmental point of view, an important application of gas phase spectroscopy at THz frequencies is given by the study of chemical processes in the upper atmosphere, which are important in ozone formation and destruction. Indeed, many atmospheric molecules have strong absorption bands in the far IR e.g. water, oxygen, carbon monoxide, the hydroxyl radical, and nitrogen to name a few.

For instance the hydroxyl radical (OH) in the stratosphere is an important player in known ozone depletion cycles, and is also a critical element for the formation of photochemical smog. OH is also critical in many combustion based industrial processes. For instance the temperature profile of a flame can be obtained from the concentration of OH. For all these reasons the quantification of this gas phase radical is a key objective for various fields of applied and fundamental research and in particular for environmental monitoring. Other than in the UV, which suffers from interference from nearby SO_2 and $C_{10}H_8$ transitions, the strongest absorption lines of OH are located around 2.5 THz (2.510 THz and 2.514 THz) and are suitable for its detection at low concentrations. Frequencies around 2.5 THz are particularly well suited for atmospheric monitoring. In fact this frequency band is located in a relatively transparent window of the atmosphere, with the closest significant water transition found approximately 50 GHz away from OH absorption lines. Unlike the infrared and UV domains, THz radiation offers the advantage of being insensitive to scattering caused by the presence of aerosols or particulate matter, allowing studies of industrial emissions and flames to be undertaken. THz spectroscopy is thus an excellent solution for the measurement of OH at low concentrations and under various conditions including flames and industrial emissions such as smoke.

In this context, the TREASURE coherent generation and detection technology will have major impact on the feasibility of future gas detection systems based on far-infrared spectroscopy.

The TREASURE technology is scalable to arrays. This directly opens up the possibility of using this technology for future focal-plane imaging. Although certain mid-IR focal-plane imaging systems are capable of detecting THz radiation at sufficiently high intensity, no focal-plane imaging systems are currently optimised for high sensitivity in the THz range. Thus, the TREASURE technology, being inherently frequency-selective, offers completely new imaging capabilities including chemical specificity, hyper-spectral imaging, and high suppression of thermal background radiation in the 2.5-6 THz region.

Finally, and independently of the impact on THz technology detailed above, we would like to stress the additional scientific impact of TREASURE project: on WGM physics (Q factors well beyond 10^5 are promised by optimised etching and passivation), QD lasers (high power WGM lasing at room temperature), and accurate refractive index models in the THz range.

3.4. Address of Project site

www.treasure-project.eu

References

[1] C. Pflügl et al., Appl. Phys. Lett. 93, 161110 (2008).

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[4] A. Andronico et al., Opt. Lett. 21, 2416 (2008).