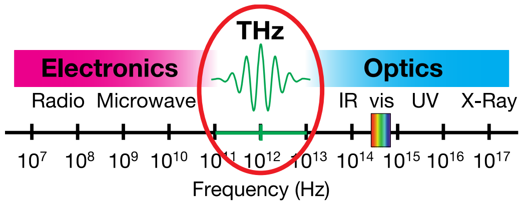
Public Summary

The **Terahertz spectral range** of the electromagnetic radiation located between the electronic and the optical range (0.1 - 100 THz) was not readily reachable until recently. In the last decade there has been a boom in the development of broadband and tunable sources of THz radiation. The interaction of THz waves with matter has opened a whole new regime for the investigation of



molecular interactions, while the transparency of most non-ionic materials (paper, plastics, clothes etc.) make it ideal for the non-destructive inspection of materials, for which other wavelengths are absorbed, as well as for security applications.

THz imaging is a relatively new field of investigation, which is in continuous evolution. The realistic domains of application of THz radiation can be very wide. For instance, THz imaging can be used for non-destructive materials testing, such as quality control in the polymer industry, plastic welding inspection, quality control of food products, security inspection, etc.

Broadband THz pulses for spectroscopic applications may be generated by several methods using femtosecond laser pulses combined with photoconductive switches and semiconductor surfaces, as well as by optical rectification in nonlinear optical crystals. The total THz power generated with these techniques is distributed over the spectral content of the pulses, therefore the power density at any particular frequency is inherently low. To obtain reasonable conversion efficiency for a certain THz frequency, a narrower band pulsed output with high beam peak power is preferred.

THz sources with high brilliance, high peak power (more than 10 W), compact, all solid-state, and room temperature operation required for applications other than single shot spectroscopy are not available. For example, such a source could be an excellent tool for imaging applications and non-destructive materials testing. **Single-frequency THz sources** should be designed for THz frequencies where water vapor absorption is negligible, and the material under investigation is most sensitive.

One straightforward way to obtain a narrow-frequency THz wave is to use **difference-frequency generation (DFG)**, which can be achieved by mixing two distinct narrowband laser beams in a nonlinear optical material. This approach however, has a few disadvantages: the losses that occur when combining two beams in a dual-wavelength output beam, the synchronization of the pulsed lasers, the size of the system and of course, the price and availability of two different laser systems with the appropriate wavelengths, which would lower the efficiency of such THz sources. We proposed a new concept to overcome these disadvantages.

In the project COSIT we proposed to developed a new kind of **integrated high-power single-frequency terahertz source**, where one single laser emits at two distinct phase-matchable wavelengths with the exact wavelength separation required for the generation of the desired THz frequency inside the same cavity, with a collinear and synchronized output. This new concept single-frequency terahertz source offers the following advantages:

- Pulsed single-frequency terahertz (THz) source in the range of interest for important applications
- High brilliance, i.e. high spectral brightness with narrow bandwidth < 100 GHz
- Good spatial beam profile with $M^2 < 1.4$
- Only one pump laser required
- No synchronization needed
- Compact all-solid-state
- High energy efficient
- Room temperature operation
- Low cost
- Possibility for full integration
- Great potential for industrial platform

This new kind of **integrated high power single frequency terahertz source** operates at room temperature, and will include a **dual-wavelength solid-state infrared laser** developed specifically for this application with two different intra-cavity laser materials that will emit at close but distinct infrared wavelengths.

The combination of the two emitted wavelengths in organic materials **OH1** (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene) malononitrile) and **DSTMS** (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate) produced monochromatic THz radiation at a frequency determined by the difference of the infrared wavelengths. We developed two different **terahertz sources**, one operating at **4.27 THz** and the other one at **9.3 THz**. These frequencies are sufficiently far away from the water absorption lines and therefore large propagation distances of the THz waves can be realized in devices e.g. for remote materials testing. For these two THz sources two different dual-frequency lasers TWIN-1 and TWIN-2 were built. The first is based on Nd:YAG and Nd:YLF as laser hosts, with emission wavelengths at 1.338 μm and 1.313 μm. TWIN-2 uses Nd:YAG and Yb:YAG as laser hosts, with emission wavelengths at 1.03 μm and 1.06 μm. Both TWIN-1 and TWIN-2 operate within a common and compact laser cavity.

The THz power that can be generated in a compact device is due to the very high nonlinear optical susceptibility, the low THz absorption and the relatively high optical damage threshold and phase matchability of the **OH1** and **DSTMS crystals**. For the 9.3 THz source we designed, produced, and demonstrated a novel **quasi-phase-matched stack of OH1 crystals** to increase the THz power by a factor of five, as compared to a single OH1 crystal.

We also investigated a new alternative idea for the **detection of THz radiation** using DSTMS and OH1 crystals. This technique uses infrared light diffraction from a THz-induced real-time phase grating produced in these high electro-optically active materials.

With all these results, a **fully integrated, compact, all solid-state system** operating at **room temperature** resulted from this research. This high power single terahertz frequency source can be used to investigate non-destructively high molecular weight polyethylene materials for **biomedical applications.** Other future industrial applications were also validated.

The project COSIT addresses the following challenges:

- New **diode pumped dual frequency all-solid state laser** with THz frequency difference.
- Novel **THz generator crystals** optimized for phase-matched THz frequency generation with 1.06 μm and 1.3 μm lasers.
- First use of **quasi phase matching** for single-frequency THz generation in organic materials. Shorter coherence length for pump lasers around 1.06 μm can be overcome by using an alternating arrangement of crystals of appropriate thickness.
- **Single-frequency THz source** by optical difference frequency generation in the novel organic crystals and the dual frequency laser.
- THz induced optical gratings for the novel and efficient **detection of THz waves**.
- **THz imaging** of high molecular weight polyethylene for biomedical applications using single-frequency imaging.

COSIT accomplished work

- During the second year of the project the design, tests, and implementation of the two dual-wavelength lasers continued. Problems and possible solutions as well as contingency plans were carried out to compensate for unforeseen delays.
- Increased work towards optimization of THz generators and structures advanced in the second year of the project. Optimized organic materials DSTMS and OH1 have been produced in sufficient quantities for further characterization and for damage threshold measurements at the selected terahertz frequencies. For the implementation of THz-1 more than 50 THz generators based on DSTMS with various thicknesses and coating were produced. New polishing techniques, particularly for polishing ultra thin organic crystals down to 50 µm, were implemented to achieve the challenging thicknesses required for the fabrication of THz generating structures required for the THz-2 source.
- A first stack of crystals based on the organic material OH1 was designed, assembled and tested with TWIN-2 to generate 9.3 THz.
- The development and implementation of the new diode pumped dual frequency all-solid state laser TWIN-1 and TWIN-2 suffered delays. The implementation and demonstration of the TWIN-1 could not be completed until the preparation of this report. Efforts will continue in the weeks previous to the final review report.
- The single frequency THz-2 source could be demonstrated in month 21 using the new dual laser concept TWIN-2 (emitting at 1.03 µm and 1.06 µm) and the optimized THz generation structures (OH1).
- The design and the determination of the optimum configurations for a new grating-based room temperature technique for detecting coherent THz waves was completed. A compact design based on a Lloyd-type interferometer requiring a single THz beam was also developed. The experimental tests suffered from the delays delay in the realization of the dual wavelength lasers and the THz-1 and THz-2 sources. Nevertheless, much effort was put in testing the principles of the technique and three systems containing alternative sources (non-optimized for this new kind of detection method) were thoroughly investigated. Unfortunately the tests performed using the existing terahertz source ***TeraTune®*** from Rainbow Photonics, and a fully wavelength transposed system based on ps near infrared pulses and an inorganic detection crystal are still inconclusive to date.
- Joint efforts in the consortium led to the demonstration of the THz-2 emitting at 9.3 THz, unfortunately too late to implement the validation in non-destructive testing. Nonetheless the validation in the non-destructive analysis of materials could be successfully realized using other sources with improved THz generators obtained from the project COSIT, demonstrating detection of defects using THz technologies.
- Other potential industrial applications, like thickness measurements and thickness control in plastics, were validated. Measurements down to 26 µm with a precision of 3 µm could be demonstrated.
- In the course of the realization of the COSIT project, it was necessary to develop additional elements such as an IR/THz filter. The SME will announce a new product in 2014 during the Photonics West International Fair. This new product is a special filter that blocks IR radiation and allows a large transmission window from 1 to 10 THz. Such product is not available in the market and will represent a market advantage for the SME.