

## Advances in Terahertz Technology with Emphasis on Quantum Cascade Lasers

R. Reeder, E. Velmre

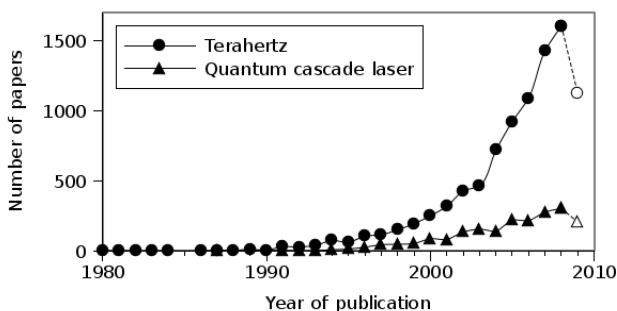
Department of Electronics, Tallinn University of Technology,  
Ehitajate tee 5, 19086 Tallinn, Estonia, phones: +3725278075, +3726202162; e-mails: reeno.reeder@gmail.com, evelmre@ttu.ee

A. Udal

Department of Computer Control, Tallinn University of Technology,  
Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +3726202110; e-mail: audal@va.ttu.ee

### Introduction

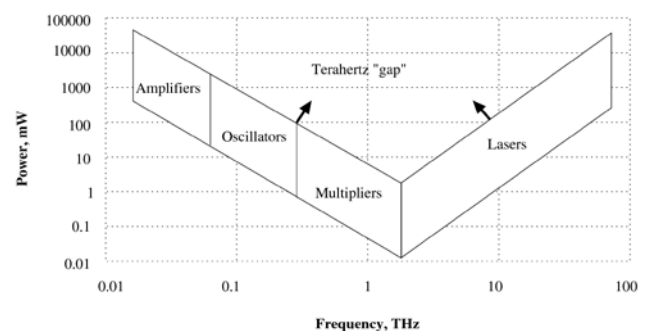
After several rises and falls of enthusiasm in terahertz domain during many decades [1], it seems that at last the T-rays research and technology has found the real boost during last 10 years. At that an important role have had the long time waited solid state source - the Quantum Cascade Laser (QCL) which idea was proposed already in 1971 by R. Kazarinov and R. Suris but the real working devices were realized in mid-infrared region region (3-5  $\mu\text{m}$ ) only in 1994 [2] and in THz-region in 2002 [3]. The increase of relevant research during last 10 years has been impressive, see Fig.1.



**Fig. 1.** Annual number of published papers that contain either keyword “terahertz” or “quantum cascade laser” according to the ISI Web of Science database. Year 2009 is incomplete as not all publication have arrived

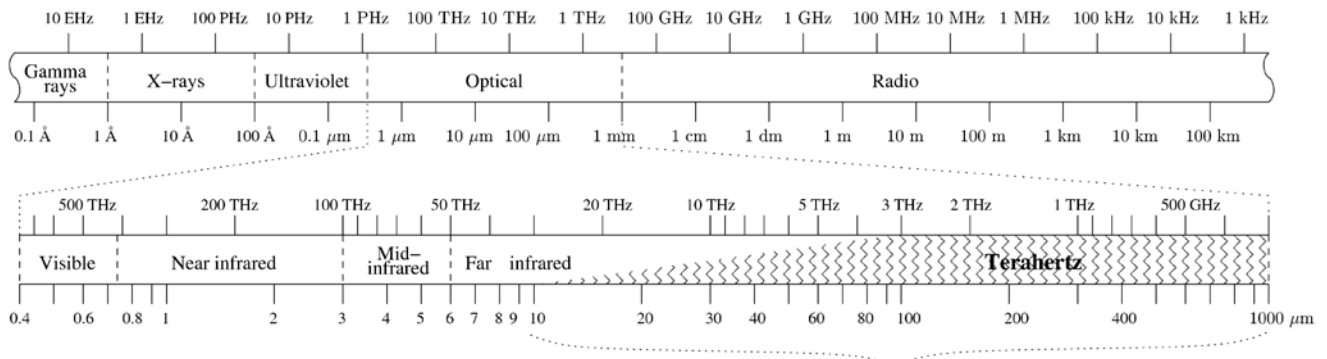
Terahertz frequency area promises many new applications on spectroscopy, terahertz imaging and microscopy, genetic sensing, detection of biological and explosive hazards, astronomical telescopes [4], high-speed wireless communications [5, 6], and even real-time terahertz imaging at video rate [7, 8].

Historically the THz range was often called as “terahertz gap” because of the lack of sources in this part of spectrum. Solid-state electronics capability was limited for a long time at terahertz frequencies, for example, in 1922 the unexplored region was between the wavelengths of 0.2 and 2 mm [9]. The early emitters in this range were either very inefficient or their development was complicated [1], leaving the beginning of the race in this area to the end of 20<sup>th</sup> century. In 2005 the clear gap in power still existed in the field of the solid-state THz sources [1], see Fig.2.



**Fig. 2.** Existing gap and development goals in the solid-state terahertz sources field

The conventional central terahertz range lays between the frequencies 1÷10 THz [7] (corresponding wavelengths are from 300  $\mu\text{m}$  to 30  $\mu\text{m}$ ), but the good consensus is missing about the exact wider boundaries, especially from far-infrared (FIR) side. The wider THz range varies in the literature from 300 GHz to 30 THz [4, 10-13], overlapping partly the FIR region, see Fig. 3 on next page. Quite sure is boundary with microwaves (wavelength 1 mm).



**Fig. 3.** Electromagnetic spectrum with focus on terahertz region. There is a small consensus about the location of border between FIR and T-rays area

### Advances in Terahertz Sources

The variety of terahertz sources is quite large by today. Narrow-band THz radiation can be produced by free-electron lasers and fast diodes. Broadband terahertz radiation can be produced by thermal sources, laser-driven sources, and by short electron bunches in accelerators [14]. Depending on the type of application, either narrow or broadband sources can be used. Most of the possible applications expect the emitter to have high power and small dimensions, and to be cheap and portable. Today, there are several techniques that provide high power, but the equipment for that is often not very compact, being rather built in to a laboratory, than portable.

The first source best satisfying the need for high power is Free Electron Laser (FEL). It is a monochromatic tunable oscillator having good power but unfortunately it is unportable. There are reports that say about 400 watts of average and 600 kW of pulse power in the range of 1.3 – 7.5 THz using FEL [15] that are remarkably good result. Another report tells about a 1-watt average result in the range of 0.5 – 1.5 THz [16].

Another way to produce high power broadband THz radiation is using subpicosecond electron bunches in an accelerator. Using this technology 20 watts of power have been measured in the terahertz region [14].

An also good technology yielding relatively good power in THz band is gyrotron, which use vacuum tubes that emit terahertz beams by bunching electrons with cyclotron motion in a strong magnetic field [17]. In the experiments by Idehara *et al* the frequency of the gyrotron is tunable between 120 GHz and 1080 GHz having magnetic field of 20 T at the highest frequency, giving output power from several tens of watts to several hundreds of watts [18,19]. The equipment of these experiments is very large, occupying even several floors, but making the device compact is under progress.

The next way to generate the radiation is using *p*-Germanium laser which is based on population inversion between light and heavy holes. Up to 100 mW of power in the range of 170 – 200  $\mu\text{m}$  (1.7 – 1.5 THz) have been reported [20]. A bad side of this source is the requirement for low temperatures near 15 K [21].

Quite an old method to produce terahertz emission is using CO<sub>2</sub> gas laser, either based on molecular pumping [22] or mixing of different frequencies [23]. Molecular pumping have a relatively broad spectrum, ranging from 0.580 to 4.25 THz, giving 20 – 30 mW output power [22].

Another method is to use tunnel injection transit time diodes, which are so called TUNNETT diodes [24]. Reports are showing up to 140  $\mu\text{W}$  power in 0.355 THz frequency [25].

Backward-wave oscillators that use biplanar interdigital slow wave circuits are reported to give 23.8 mW near 0.650 THz [26].

Up to 1.1 mW power in the range of 3.2 – 4.8  $\mu\text{m}$  have been obtained [27] using the difference frequency generation. This is a principal method to get higher frequency  $\omega_3$  by summing two lower frequencies  $\omega_1$  and  $\omega_2$  [28].

Optical rectification which is based on mixing two frequencies, was first showed in 1962 [29]. This method is based on the inverse process of the electro-optic effect.

Terahertz radiation from nano-acoustic motion of standing waves in an impedance-mismatched layer sandwiched by GaN-based piezoelectric heterostructures have been investigated recently [30]. This may lead us to a new way to produce terahertz radiation.

By combining monolithic microwave integrated circuit amplifier frequency tripler chips, output power > 1 mW have been demonstrated at around 0.9 THz [31].

Simulations have been done by the authors of the present work too using spontaneous radiation from laterally pumped quasiparabolic GaAs/AlGaAs quantum wells [32]. The results show at 7 THz ca 100–200 W/m<sup>2</sup> output power couple times over blackbody radiation up to temperature 400K.

### Advances in Development of Quantum Cascade Lasers

A small hop can be seen near 1994 when the MIR Quantum Cascade Laser was demonstrated by Faist *et al* [2]. Shift to the THz domain in 2002 [3] initiated also the terahertz era in semiconductor emitters. After that a bigger hop in general was near 2004 caused by commercial sources coming to the market. This boosted up the publishing of results on application related experiments.

Currently, Quantum Cascade Lasers are the only semiconductor devices operating from the mid-infrared region to the THz range of frequencies [33].

The main problems with QCL-s are their low working temperature and small power. The main emphasis is on developing these properties – to increase working temperature, where they are still effective, and to increase the power in general.

During last couple years, the THz QCL-s have been quickly approaching the higher temperatures and longer

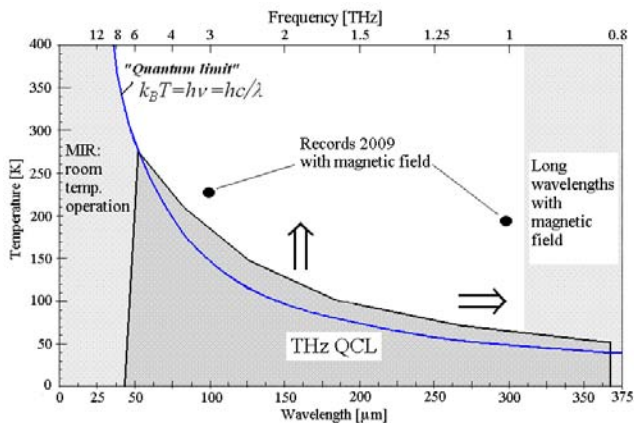
wavelengths by applying different sophisticated design ideas and the strong external magnetic field. By 2008 the maximum operating temperature without external magnetic field was increased to 178K in pulsed mode and 117K in continuous wave (CW) mode at the lowest frequency of 1.2 THz [34].

In 2009 demonstrated Wade *et al* (5 leading research centers of USA) that with resonant phonon desing and with strong magnetic field (over 16 T) may be achieved QCL work in 1 THz regime at temperatures up to 215 K, and 3 THz regime at up to 225 K [35]. In the resonant-phonon design scheme, the population inversion is ensured by selectively injecting electrons through resonant tunnelling into the upper state of the laser transition [35].

The room temperature lasers exist in MIR range [36], e.g. InGaAs-AlAsSb QCL 3–4  $\mu\text{m}$ , several mW at 270 K [36]. Using metal grating distributed feedback, continuous wave room temperature operation at wavelengths 4.5–7.5  $\mu\text{m}$  and output power 20 mW is achieved [37].

The general trends of THz QCL development are illustrated in Fig.4 below. At longer wavelengths the design problems become especially complicated if the temperature energy exceeds the energy of quantum:

$$k_B T \geq h\nu = h c \lambda \quad (1)$$



**Fig. 4.** The achieved results and general trends of development of THz quantum cascade lasers

The output frequency of QCL-s can be tuned either by bias voltage [38] or by external cavity properties [39]. Recent achievements include also Quantum Cascade Lasers with Ultra-Strong Coupling Injection with peak power of 8W (2W) at 80K (300K) [40].

## Conclusion

Since the year 2002 the development of THz Quantum Cascade Lasers has become an extremely dynamic research field. The present paper discusses the recent advances in this area.

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**R. Reeder, E. Velmre, A. Udal. Advances in Terahertz technology with Emphasis on Quantum Cascade Lasers // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 8(104). – P. 47–50.**

Starting from the year 2002 when the development of quantum cascade lasers shifted from mid-infrared to the terahertz domain, the remarkable rise in the terahertz research has followed. The paper discusses the recent achievements in development of the terahertz radiation sources with emphasis on quantum cascade lasers. Moving towards the higher working temperatures, longer wavelengths and higher output power is discussed. Ill. 4, bibl. 40 (in English; abstracts in English, Russian and Lithuanian).

**P. Рээдэр, Э. Вэлмрэ, А. Удал. Успехи квантово-каскадных лазеров в области терагерцовой технологии // Электроника и электротехника. – Каунас: Технология, 2010. – № 8(104). – С. 47–50.**

Начиная с 2002 года, когда рабочие частоты квантово-каскадных лазеров сместились со средне-инфракрасного в терагерцовый диапазон, наблюдается заметное ускорение темпа исследований в области терагерцовой технологии. Обсуждаются последние достижения в разработке источников терагерцового излучения, в частности квантово-каскадных лазеров. Отмечается постепенное движение в направлении более длинных волн, а также более высоких рабочих температур и выходных мощностей. Ил. 4, библи. 40 (на английском языке; рефераты на английском, русском и литовском яз.).

**R. Reeder, E. Velmre, A. Udal. Kvantinių-pakopinių lazerių naudojimas terahercinėms technologijoms tobulinti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 8(104). – P. 47–50.**

Pastaruoju metu jau plačiai taikoma terahercinė technologija. Straipsnyje aprašomi šios technologijos kvantiniai-pakopiniai lazeriai. Pažymėta, kad ryškėja tendencija grįžti į ilgesniųjų bangų diapazoną, didinant darbo temperatūrą bei išėjimo galią. Il. 4, bibl. 40 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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