THz communications and relations to frequency domain THz spectroscopy

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***Abstract*—This paper presents an overview of THz-technologies, and especially their use for communications. Different approaches on the physics of THz radiation are discussed, from the Radio Frequency (RF) perspective, as well as from the Far Infrared (FIR) optic signals' perspective and Nano electronics' and molecular electronics' perspective. Experiments with THz Continuous Wave (CW) frequency domain spectroscopy are presented. The goal of the experiment was to determine a frequency band with constant received power, high Signal to Noise Ratio (SNR) and no water absorption lines near such potential frequency band. From spectroscopy experimental result suitable frequency bands with bandwidth of 20 GHz to 50 GHz were found, what promises the possibility of achieving high communication data rates in next few years of several hundred Gb/s over distances about 1 km using THz waves. So, the relations between transmission media spectroscopy measurements and channel amplitude frequency characteristic was shown. From the instrumentation description it is also evident that, the experimental platform used is suitable for research and, as well for the education purpose, in communications', sensors', and materials' courses and related curses.**

Keywords— THz communications, THz technology, state of the art, spectroscopy.

I. INTRODUCTION

THz Electromagnetic (EM) waves are EM waves between microwaves and infra-red (IR) optical waves, i.e. in the frequency range from 300 GHz to 10 THz. The corresponding wavelengths λ in free space ($\lambda = f / c_0$, where c_0 is the speed of EM waves in free space) are in the range from 1 mm down to 30 µm. The THz phenomenon has been known for a long time, appearing under different names, such as millimetre, submillimetre and extreme far infrared. The early use of submillimetre electromagnetic waves was in the domain of Earth Atmosphere Molecular Spectroscopy and Astronomy and Space Applications.

In the last 20 years a great attention and progress has been achieved in the research and practical applications of THz-technologies, due to some of the specific characteristics of THz EM- waves.

However, there were, and still remain, some problems in the domain of research and practical commercial cost effective implementations, which should be considered further. There are still some understanding of THz' daunting physical phenomena and modelling of THz-waves' propagation in different transmission media, like earth atmosphere, which should be improved further. For long range communications and radar applications over 10 metres, the big problem is the atmospheric attenuation of THz-waves, because the atmosphere absorbs (water molecules in it), refracts, and scatters THz-waves. Another potential application is in the field of Detection of Hazardous Materials and Gases. The problem is accurate detection on distances over 10 m. Additionally, some materials, such as sugar and plastic explosives are difficult to distinguish. To build compact THz sources with efficient energy conversion efficiency is still a very big problem. In the domain of Medical Applications, the limitations are dielectric heating and low deep body penetration of few a millimetres.

The main goal of our paper was to confirm the connection between transmission media spectroscopy measurements and its' magnitude frequency characteristics. Therefore, the goal of our experiment was, as known from communication theory, to find for the communication potential frequency bands with constant received signal (power), high SNR and no water absorption regions or lines near the potential frequency band. From experimental result some conclusions a given about possible use of this THz-bands for high data rate communication.

The paper is organised as follows. In Section II, an overview of THz technologies is reviewed, especially THz-communications. In Section III, some problems of understanding THz-phenomena will be given and appropriate THz-waves' propagations, especially in atmosphere. Section IV describes our experimental set up with THz-spectroscopy using a CWFM (Continuous Wave Frequency Modulated)-spectrometer. Section V presents experimental results, followed by conclusions and used references.

II. STATE OF THE ART OF THZ TECNOLOGY

A. Sources, amplifiers, THz signal receivers

In the past, the big problem was to build power efficient THz-sources, and great progress was made in recent years.

The spectroscopy range of frequencies between 0.5 THz and 5 THz is interesting. This is impossible to implement directly with semiconductor lasers. One direct method is to use a QCL (Quantum Cascade Laser), but it requires a very low operating temperature (40 K). The technology with Voltage Controlled Oscillators (VCO) in combination with frequency doublers or multipliers is inefficient, complex and, therefore, expensive. There are two optoelectronic approaches which are very promising and have low cost. At first, a near IR laser is focused on an appropriate semiconductor structure, and the second uses femtosecond pulses that produces waves in the THz-domain. The first optoelectronic technique for generating THz-sources was used in our experiments. Similar progress was made in designing THz-waves amplifiers and receivers/detectors. For example, an FET (Field Effect Transistor)-based a THz detector with different bow tie antennas for frequencies from

0.85 to 1 THz was presented in [1]. High Mobility Electron Transistors (HEMT) or Heterojunction Bipolar Transistor (HBT) were improved significantly for operation at THz frequencies. Recently III-V HEMT or HBT, were implemented for devices operating at 300 GHz [2]. Significant progress has also been made in silicon Complementary Metal Oxide Semiconductor (CMOS) and SiGe (HBTs). CMOS-high frequency systems still have a lack in Bandwidth.

For high power THz-sources vacuum devices THz-gyrotrons were developed, but were impractical due to their relatively huge dimensions [3].

B. Communications

The progress in THz technologies has also enabled rapid progress in communication applications. The status of technology, standardization and regulation was reported in [4].

The authors in [5] discussed and gave a vision and suggestion how to build the future architecture for connection of the optical network with a THz link with bandwidth of more than 50 GHz for future communications beyond 5G and enable the optical network Quality of Experience (QoE). The goal is, therefore, to exceed the current data rate of 100 Gb/s and achieve a data rate of terabits per second with almost zero latency. The need for novel THz information theory frameworks was pointed out, which will consider channel characteristics and features of interference in the THz-band. They pointed out three application scenarios, THz wireless backhaul, THz wireless access for cyber-physical systems, and THz wireless local access. The concept of a wireless optical radio system was proposed based on photonic radio, motivated by recent experiments with 256-QAM or even 1024-QAM achieving 64 Gbd (1.32 Tb/s) over distances of 400 km. In comparison with Radio over Fibre (RoF), at photonic radio concept, the RF-carrier is not modulated and uses a baseband infrastructure. For THz transceivers front end, High Mobility Electron Transistors (HEMT) or Heterojunction Bipolar Transistor (HBT) can be used; III-V HEMT or HBT for devices operating at 300 GHz was reported only recently. Significant progress was made also in silicon Complementary Metal Oxide Semiconductor (CMOS) and SiGe (HBTs). CMOS-high frequency systems still have lack in bandwidth.

The potential use of THz communications in heterogeneous mobile networks and vehicular communication is presented in [6]. The latest achievements in THz and light wave communications are published in [7].

THz-channel model is very important for the designing of THz communications. The main difference of mm waves in comparison to sub-millimetre THz-waves is that THz waves are absorbed progressively by water vapour molecules with increasing frequency. At longer distances and frequencies below 300 GHz, links total loss are dominantly determined by Free Space Path loss (FSPL), while, at THz-frequencies, path losses are influenced significantly by water vapour molecular absorption. At short communication ranges (a few meters to 10 m), the effect of atmosphere and bad weather is minimal. Therefore the regional atmosphere and weather should be taken into account [5]. A physics-based prediction of atmospheric transfer characteristics at THz-frequencies was reported in [8]. The interdisciplinary and systematic approach to modelling and overview of simulation software for predicting atmospheric attenuation between 0.1 and 100 THz are given in [9].

C. Other applications

The THz waves between mm EM waves and IR light have some interesting features, which enable many useful applications. THz waves are non-ionising, but penetrate clothing, paper, cardboard, plastics, and similar materials. They are absorbed by water molecules (water vapour), and still more by liquid water and many organic substances, depending on the chemical composition of the material.

Some biomolecules, proteins, explosive materials or narcotics have characteristic absorption lines, called spectral “fingerprints”, at frequencies between 0.1 and 5 THz.

For radars, the THz-waves enable high range resolution due to the high bandwidth; range resolution is reciprocal to bandwidth. Radar using a THz frequency of 812 GHz is presented in [10].

III. PHYSICS AND UNDERSTANDING OF THE THZ PHENOMENA

For further progress in the research and development of THz technology it is important to understand the really daunting THz physical phenomena better. THz frequencies lie between microwaves and infrared optic waves. So THz-waves exploit features of EM-waves, as well of optical waves, photons, i.e. as waves and particles. Therefore, we can use the equations of EM-waves’ propagation and of photonic (optics) equations. Here, it is necessary to mention that, already the legendary scientists Nikola Tesla was also talking about three different appearances of electricity: In the form of electromagnetic wave, plasma and light.

It is interesting, that plasma waves appear in Field Effect Transistor (FET) and in High Electron Mobility Transistor (HFET), and can be used for implementation THz generators, mixers, multipliers and detectors [11], [12], [13]. Instead of a concentrated, lumped model, a distributed transmission line approach should be applied, to get more correct results.

The cut-off frequency of an FET transistor is proportional to the inverse of electron transit time:

$$f_t = 1/(2\pi T) \tag{1}$$

In FET, plasma waves with linear dispersion may appear:

$$\omega = k \cdot s \tag{2}$$

where ω is radial frequency, k is the wave vector. Here, s is the plasma wave velocity:

$$s = \left(\frac{eU}{m}\right)^{1/2} \tag{3}$$

where e is an electron charge, U is the gate to channel voltage swing, and m the electron effective mass.

The velocity of plasma waves is approximately 10^8 cm/s, which is much larger than the drift velocity of two dimensional (2D) electrons.

The two dimensional system in FET is usually called 2D electronic gas. Then, the free path of inter-electronic collision is smaller than the sample length and free path collision with phonon A similar situation appears in AlGaAs/GaAS HEMT with surface electronic concentration n_s approximately equal to 10^{12} cm^{-2}. Then 2D-electrons behave as a fluid and the equation of motion of 2D electronic fluid can be described with an equation similar to the Euler hydrodynamic equation:

$$\frac{\partial v}{\partial t} + v\cdot\frac{\partial v}{\partial x} + \frac{e}{m}\cdot\frac{\partial U}{\partial x} + \frac{v}{\tau} = 0 \qquad (4)$$

where $\partial U/\partial x$ is a longitudinal electrical field in the channel, and $v(x,t)$ the local electron speed, τ is the momentum relaxation time.

Using gradual channel approximation for surface electron concentration $n_s = CU/e$, where C is the gate-to-channel capacitance per unit area, one can write:

$$\frac{\partial U}{\partial t} + \frac{\partial (Uv)}{\partial x} = 0 \qquad (5)$$

The last equation is an analogy to the hydrodynamic equation for shallow water, with gate to channel voltage U as water level, e/m is analogy to free-fall acceleration. FET is used as a resonator for the plasma waves with the fundamental frequency

$$\omega_0 = \frac{\pi\cdot s}{2\cdot L} \qquad (6)$$

where L is the FET channel length.

Also, Nano electronic and molecular (biomolecular) electronics will be emerging in the near future. In this case, quantum Nano-features will determine the behaviour of components and systems, and, therefore quantum and relativistic physical theories should be taken in account [14].

IV. EXPERIMENTAL SETUP

For determining the potential frequency bands for communications in the THz band, we performed a simple experiment. It was done using the Continuous Wave Frequency Domain (CWFD) THz spectroscopy platform TeraScan 1550 from Toptica Photonics [15]. Fig.1 presents the principal scheme of the used experimental setup. Systems combine mature DFB (Distributed Feedback) diode lasers with state-of-the-art GaAs or InGaAs photo-mixers. There are two systems. The TeraScan 780 system offers an outstanding bandwidth, and the TeraScan 1550 provides new achievements in terms of power and dynamic range. Both systems use proprietary “DLC smart” control electronics. We used the TeraScan 1550 platform in our experiment. TerraBeam is a subsystem with dual-colour DFB-lasers, with digital driver electronics and precise frequency control. Two Photo Conductive Antennas (PCA’s) are used, one for transmitting and one for receiving THz waves.

The experiment was performed in a frequency range from 50 GHz to 1200 GHz with a frequency step of 1 GHz, 15 samples’ overlap and 3 ms integration time. The output of the receiving antenna is photocurrent, with shapes equal to the received THz waves. The THz wave frequency is equal to the difference of the two lasers frequencies, inherent in the beat signal obtained by multiplying two optical waves, colours, 1546 and 1550 nm, respectively [15],[16],[17],[18].

The goal of the experiment was to determine a frequency band with constant received power, high SNR and no water absorption near the potential frequency band.

Table I presents some important TeraScan 1550 features, to imagine better the system capacity and possibility of its use in different applications.

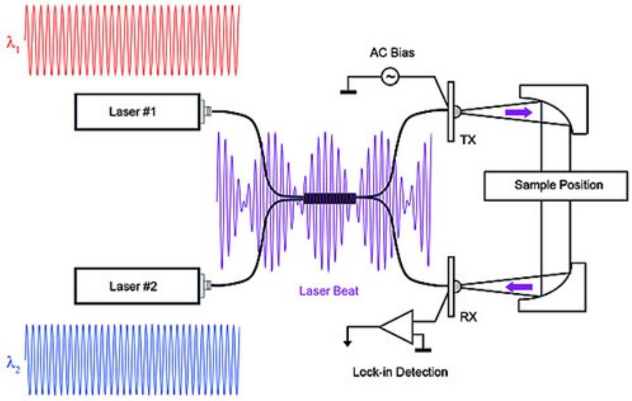

Fig. 1. Principal scheme of the experimental setup with CW Frequency Domain Spectrometer [15]

TABLE I. SOME IMPORTANT TERASCAN 1550 FEATURES [15]

Components and Systems Features	
Lasers:	TeraBeam 1550
Emitter:	#EK-000724, InGaAs photodiode
Terahertz receiver:	#EK-000725, InGaAs photomixer
Antenna type:	Bow-tie
Emitter and receiver bandwidth:	Approx. 3 THz
Difference Frequency Tuning:	1.2 THz (up to 2.7 THz with Tuning Range Extension)
Tuning Speed:	Up to 100 GHz / sec
Frequency accuracy:	< 2 GHz
Minimum frequency step size:	< 10 MHz
Terahertz power (type):	100 µW @ 100 GHz, 10 µW @ 500 GHz
Terahertz dynamic range:	90 dB @ 100 GHz
(300 ms integration time):	70 dB @ 500 GHz
Laser size and weight:	Two DFB pro BFY laser heads, each with dimensions 60 x 120 x 165 mm (H x W x D), 1 kg
Control unit:	DLC smart
Controller size (H x W x D) + weight:	19" and 1 RU (H x W x D: 45 x 480 x 290 mm), 4 kg
Computer interface:	Ethernet
Software Control:	Software with GUI (Graphical User Interface) + Remote command interface
Key advantages:	High bandwidth with one set of lasers High terahertz power, compact laser unit

Dynamic range measurements of the TeraScan 1550 system are presented in Fig. 2, [15]. The TeraScan 1550 system components are shown in Fig. 3.

Some possible applications with TeraScan 1550 are plastic inspection, material research, gas sensing, security and many others, so many new possible applications should be discovered.

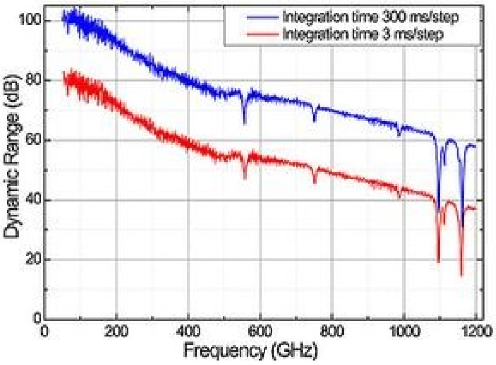

Fig. 2. Dynamics range of a TeraScan 1550 system [15]

Fig.3. Photos of TeraScan 1550 components: Lasers, PCAs, electronic optomechanics [15]

Extension modules can be added, as shown in Fig. 4, not used in our experiment. The photo of the experimental setup for THz-CW Frequency Domain Spectroscopy in our laboratory is shown in Fig. 5.

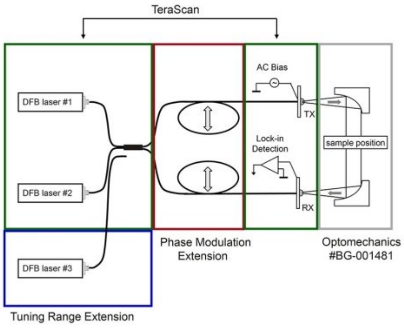

Fig. 4. Possibility of adding extension modules [15]

Fig. 5.. Photo of experimental setup with the TeraScan 1550 platform in our laboratory

V. EXPERIMENTAL RESULTS

The experimental result on the whole frequency range is presented in Fig. 6. We can see the water absorption lines around 550 GHz and 1100 GHz and 1160 GHz clearly, which is compliant with the results in [19] and dynamic range measurements in Fig. 2, even for measurements at short distances of a few centimetres in the air (7 cm in our case). Based on the requirements stated above, the best plausible frequency band of the measured frequency bands seems to be below the 550 GHz water absorption line, and higher than 300 GHz – there are few bands where the received power is constant, SNR is good (signal power is at least 10 times greater than the variance of noise), and we are still below the water absorption line.

From Figure 6 we can determine communication bands' locations and their bandwidths. The potential THz wave communication bands could be viable at 400 GHz and 500 GHz with width of 50 GHz. From Fig. 7, we can also see, that there are another two potential bands at 550 THz and 750 THz with width of 20 GHz. Such bands with very bright bandwidth enable extreme data rates in the range of several hundred Gb/s. ,

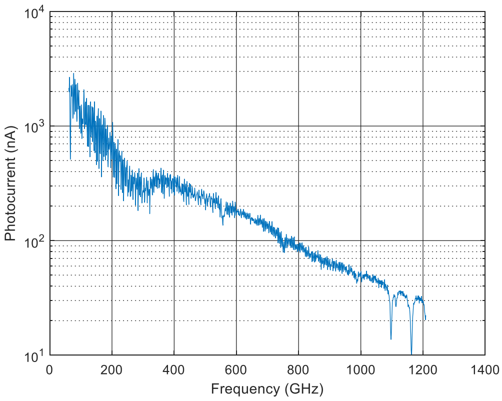

Fig. 6. Transmission over the whole available THz band

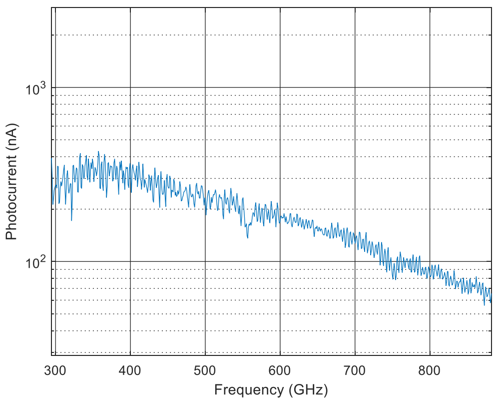

Fig. 7. Results of transmission in the range from 300 Hz to 900 Hz

VI. CONCLUSIONS

In the paper, an overview is presented of the state of the art achievements in THz-technology and THz-communications. Some physical aspects are presented and explained too. The experimental setup for THz-continuous wave frequency domain spectroscopy is presented, and the results of experiment are given. The results are compliant with similar measurements in the references. The obtained results are interpreted in the sine of possible applications in communications. Found frequency bands with bandwidth about 20 GHz to 50 GHz enable extreme data transmission rates, that exceed current data rates of 100 Gb/s, approaching to 0.8 Tb/s over distances about 1 km in next few years, according to implementation of technology with 256 QAM modulation, two antenna polarization and Noise Figure (NF) 10 dBm, without considering potential of MIMO-systems, as was reported in [5].

The results are obtained with instrument for materials' (transmission media) spectroscopy measurements, showing the possibilities to use it for measuring magnitude frequency magnitude characteristics. It is also evident that the used experimental instrumentation is suitable not also for research, but also for education experimentation in curses for communication, sensors, material science and related one. The instrumentation is quite expensive, however it enables multiple researchers and students to use it for remote experimentation with existed in built Ethernet communication.

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