Monitoring Terahertz Technology

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Summary

This report covers further aspects of possible military use of terahertz radiation in the communication area. An analysis of what can be expected in terms of implementation of terahertz technology in various aspects of communication has been elaborated with a projection of applications in communication in the next 2 to 10 years. Feasible scenarios are discussed with present limitations and the future potential of terahertz technology in the communication area. In view of the present most promising developments an all-solid-state approach with nonlinear optical techniques and telecom lasers will lead to a quick breakthrough in the next two years. The need to identify the frequency window for application in communication, requires the development of a tunable source.

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0. Introduction

The terahertz region of the electromagnetic spectrum is relatively unexploited mainly because its range of frequencies is too high for conventional electronics (10^{11} Hz) and too small for semiconductor lasers and detectors (10^{12} Hz). In the last few years the terahertz frequency range has attracted interest and new research and development is now anticipating its great potential. The various applications of terahertz technology go from medical diagnostics and security applications to industrial control processes and communication. Terahertz imaging techniques have experienced an important advance in medical diagnostics and security applications. In the communication area both civil and military, terahertz technology has also received a lot of attention with the promise to become a mass-market five years from now.

We present an overview of the most important scenarios for the application of terahertz technology in the communication area and the technology and market for the existing and future terahertz systems.

1. Wireless communication

THz communications technology has been relatively unexplored, and as the demand for high-data-rate wireless communication continues to grow, researchers are turning to higher frequencies and are exploring the THz region. [1]. One of the most effective approaches to achieve much higher data rates of >10 Gbit/s is to increase the carrier frequencies to the terahertz regime 0.1 THz and higher. For example: using MMW (millimeter wave) and photonic technologies research groups at NTT in Japan [2] developed an optical sub-terahertz source that generates optical sub carrier signals whose intensity is modulated at a frequency of 0.125 THz. The set-up of this sub-terahertz source is shown in figure 1. An optical intensity modulator modulates the optical sub carrier signals using the data signals. Subsequently the modulated signal is amplified by an optical amplifier and fed into the sub-terahertz emitter. In the emitter a photodiode converts the optical signals into sub-terahertz signals, which are amplified and radiated toward the receiver via an antenna. Finally these sub-terahertz signals are amplified and demodulated by an envelope detection scheme.

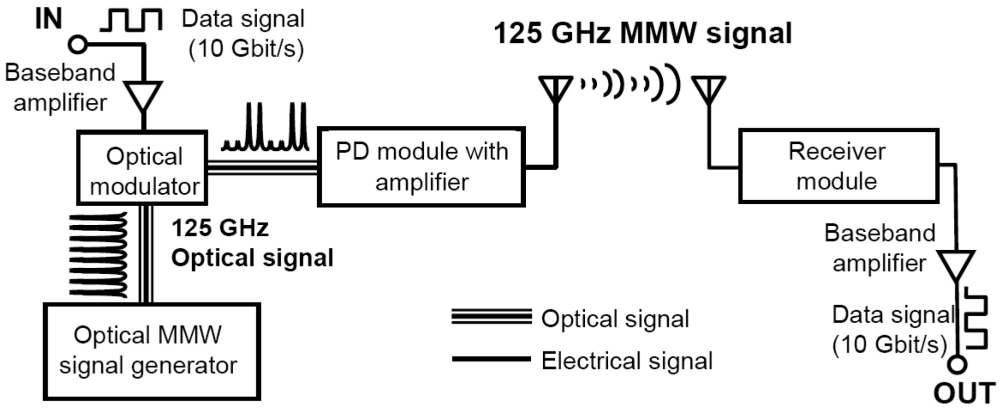

Figure 1. Block diagram of a 0.12 THz band wireless link system.

A similar approach as the one shown in figure 1 was used to develop a sub-terahertz source based on optical heterodyning [3]. In this approach optical signals are converted to sub-terahertz signals using a uni-traveling carrier photodiode (UTC-PD) which are pin photodiodes based on InP/InGaAs and operating at 1.55 μm [4]. The emission is typically tunable up to 1.5 THz and typical applications include sub-THz wireless communication.

The maximum output power from the amplifier integrated UTC-PD in this demonstration exceeded 10 dBm at 0.12 THz band. This photonics-based transmitter is shown in figure 2 and has been demonstrated for a long distance (>1 km) link using a high-gain antenna. It marks a precedent for future systems that will operate at terahertz frequencies.

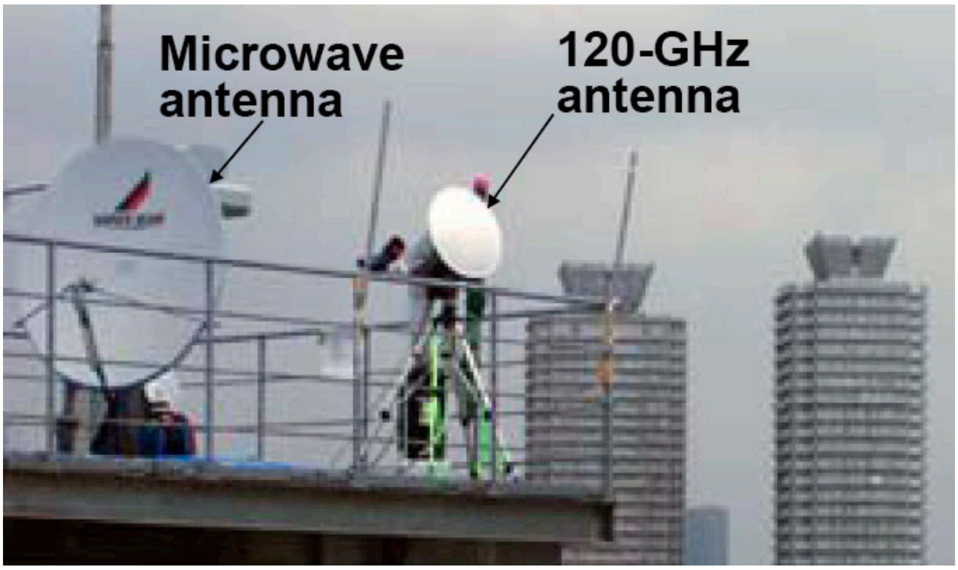

Figure 2. Photonics-based transmitter for field tests.

Additional efforts to move into the terahertz region (0.1 – 10 THz) of the spectrum have been reported. Examples are photomixers which are typically semiconductors with an antenna structure deposited on them [4]. With the advances of epitaxial growth of photoconductive materials, these photomixers have developed quite quickly in the last 30 years. Typical output powers for photomixers are in the 1-2μW range for photoconducting antenna structures based on low temperature grown (LTG) GaAs. The operating wavelength is approximately 800 nm. Photomixers operating at 800 nm are currently available however the development of these photomixers for pump laser operation at 1.5 microns has been quite challenging. Researchers at the Fraunhofer Heinrich-Hertz Institute (HHI) in Germany [5] have successfully developed InGaAs photomixers for use with the latest development of fiber lasers operating at 1.5 microns.

With this technology terahertz frequencies in the range 0.1 to 1.5 THz can be reached with reasonable amplitudes. As shown in figure 3, the response decreases towards higher terahertz frequencies.

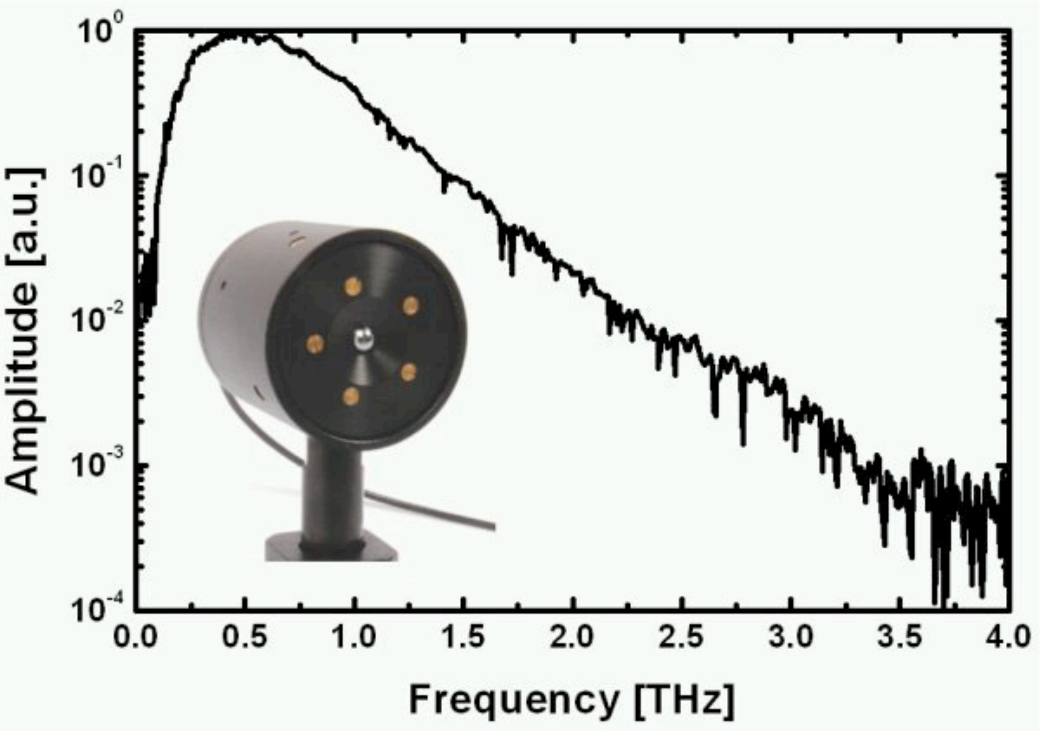

Figure 3. Broad terahertz spectrum of 1.5 micron photomixers [5]

Although in a limited frequency range, terahertz detection is also feasible with these photomixers. Laboratory tests are ongoing and the estimated time for a fully developed terahertz spectrometer with frequency range up to 2 THz is estimated in 2 years. Figure 4 shows a schematic of the proposed terahertz spectrometer developed at the Fraunhofer Heinrich-Hertz Institute.

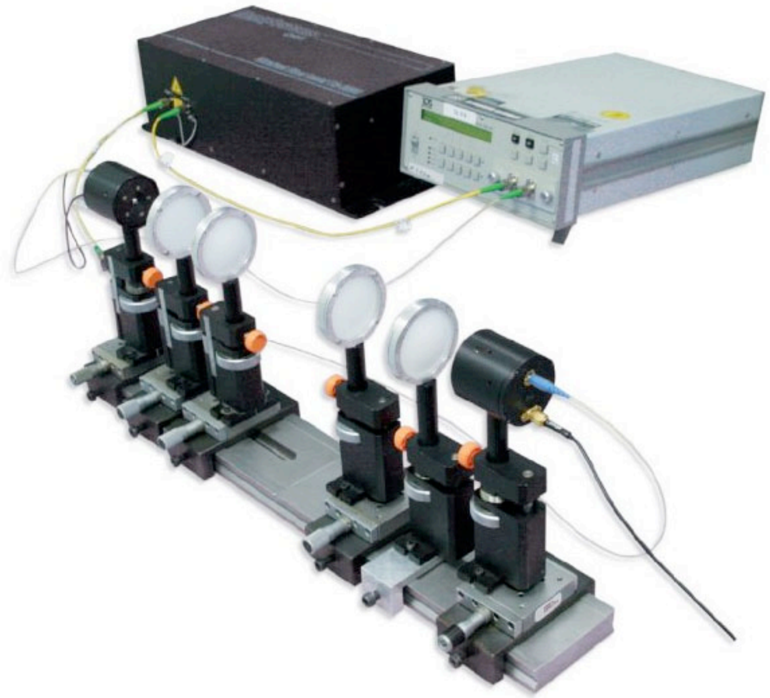

Figure 4. Terahertz setup with fiber-coupled photomixers [5].

In the communication area, researchers in Germany recently transmitted audio signals by means of a THz communication channel using a newly developed room temperature semiconductor THz modulator [6]. The authors used a standard THz time domain spectroscopy set-up and modified it to transmit signals up to 25 kHz over a 75 MHz train of broadband THz pulses. The two-dimensional electron gas (2DEG) modulator used is based on the well-established technology for producing high electron mobility transistors (HEMT) the electron density can be controlled by the application of an external gate voltage. Figure 5 shows a diagram of the 2DEG modulator structure. The depletion of such an electron gas provides sufficient depth of modulation for transmitted THz radiation.

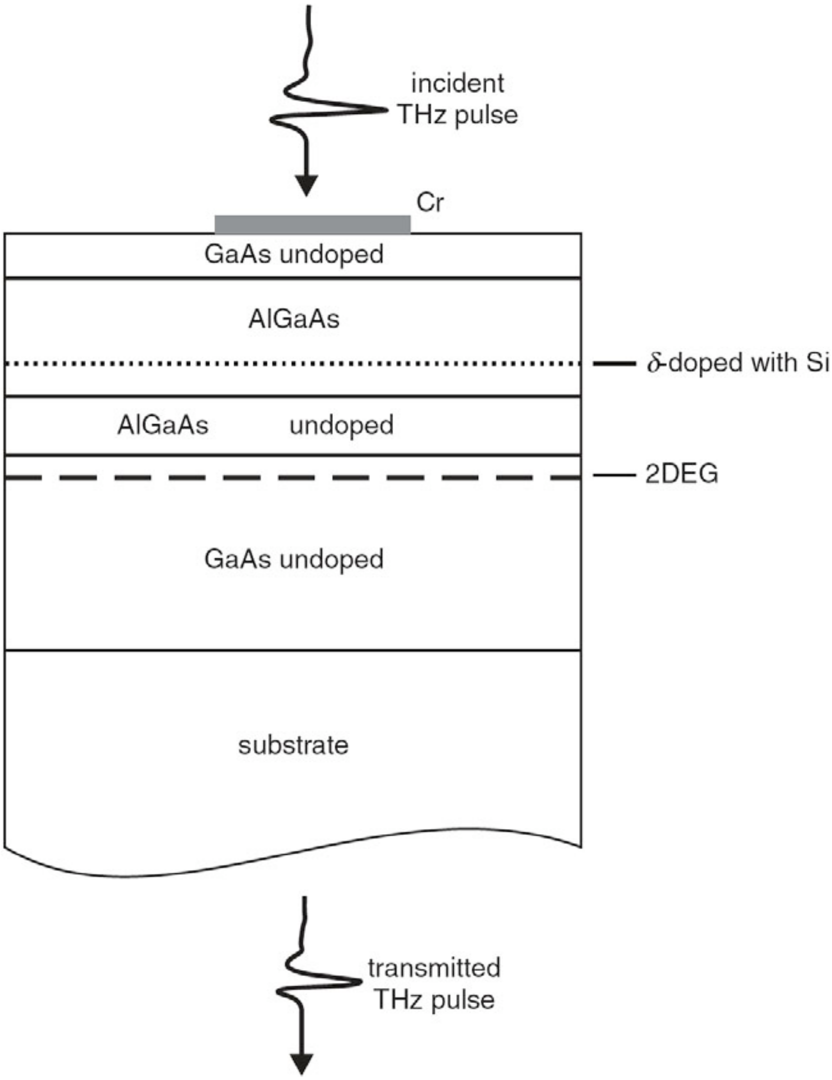

Figure 5. Schematics of a two-dimensional electron gas (2DEG) modulator device

The modulator is placed at the intermediate focus of the standard THz time-domain spectroscopy set-up. The experimental set-up is shown in figure 6.
The pulsed THz radiation is generated using a photoconductive antenna which is excited by 20 fs pulses from a Ti:sapphire laser with a repetition rate of 75 MHz. The THz pulses with frequencies between 0.1 and 3 THz are then collimated, focused and finally directed onto a silicon-on-sapphire (SOS) antenna.

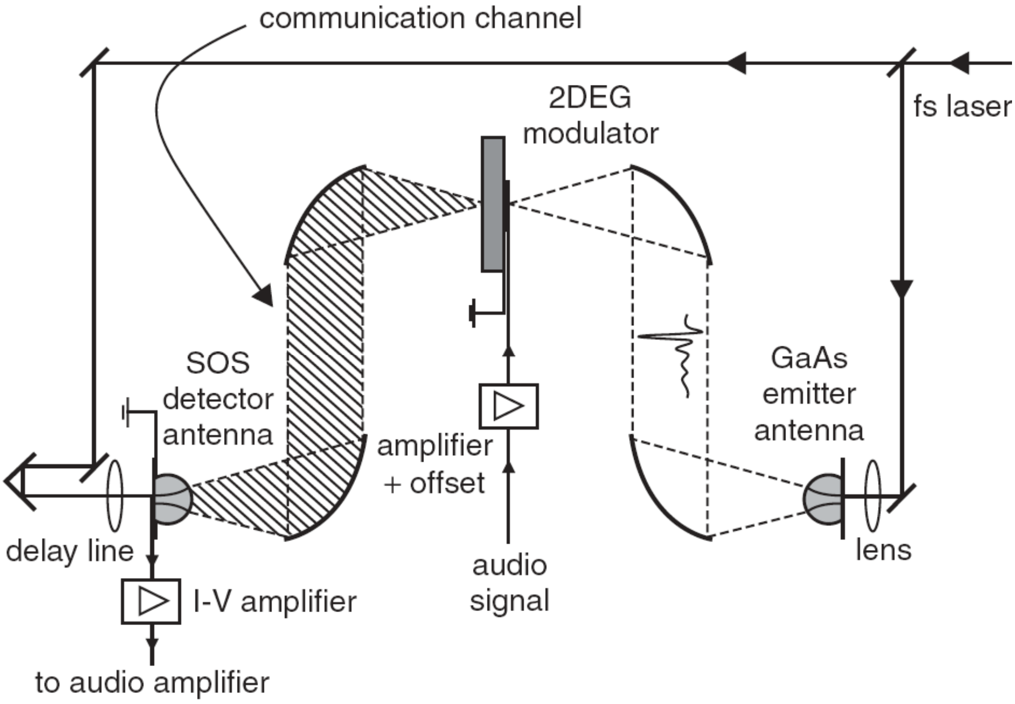

Figure 6. Modified THz-time-domain spectroscopy set-up. Silicon on Sapphire (SOS)

This first demonstration of audio signal transmission was followed by a video signal transmission at a carrier frequency of 0.3 THz based on Schottky diode mixers and metal waveguide technology [7].

Although it will be difficult to upgrade the system to higher frequencies, the system shows the feasibility of communication links at sub-terahertz frequencies. This could be extended to the (sub) terahertz frequency range by using more adequate emitters and detectors (see section 3).

2. Quantum Cascade Lasers

The improvement in nanotechnology has led to the development of semiconductor-based narrowband THz sources known as **quantum cascade lasers** (QCL). The first QCL was developed in 1994 [8] with a lasing frequency of 70 THz. QCL are semiconductor lasers in which only electrons are involved and the transition occurs within the sub bands formed from the conductions band of a specially engineered heretostructure. Conventional laser diodes are bipolar interband devices while QCL are known as unipolar (only electrons) intraband (or inter-sub band) emitters, they emit at a fixed frequency depending on structuring and material.

Efforts are going on towards operation at room temperature and lower terahertz frequency where detectors are most likely to be available. Most of these lasers have to be operated at low temperatures due to rapid thermal degradation. However efforts are on the way to increase the (presently) short lifetime for room temperature operation at higher powers. In 2008 the first room-temperature terahertz quantum cascade laser source based on intracavity difference-frequency generation was demonstrated [9]. This new source emits 300 nW power at commercially available thermoelectric cooler temperatures around room temperature. The terahertz operation frequency is around 5 THz. By optimizing the semiconductor nanostructure the power could be further increased up to a few milliwatts in the near future. In a recent publication [10] cryogenic operation at 3 THz in pulsed operation has been demonstrated at a power level of 0.5 mW and a temperature of 123 K.

As we can see the development of the quantum cascade lasers has been quite dramatic in the last couple of years, and the implementation of these sources plus the development of adequate detectors will lead to commercial systems for various applications in a time frame of minimum 5 years. Although the fixed frequency of these devices is not appropriate for application in communication where broadband frequencies are required, the development of these devices goes in equal pace as developments of other terahertz devices as the photomixers or the all-optical systems.

3. All-Solid-Optical Sources

Nonlinear optical techniques to generate terahertz radiation are taking an important place among the various approaches to generate and detect terahertz radiation. These techniques were not seriously considered for applications until recently with the availability of mature telecom lasers. The laser development of telecom lasers as well as the development of novel materials allow the realization of small compact systems that can be used for both generation and detection of terahertz radiation in various applications in particular communication.

3.1 Broadband Terahertz Generation

Optical rectification techniques were described in the report Q1. In optical rectification, a high-intensity ultrashort femtosecond laser pulse passes through a transparent crystal material that emits a terahertz pulse without the need of any applied voltage. It is a nonlinear-optical process, where a nonlinear material is quickly electrically polarized at high optical intensities. This changing electrical polarization emits terahertz radiation. It is called rectification because the rapid oscillations of the electric field of the laser pulse are “rectified” and only the envelope of the oscillations remains. Since the medium is non absorbing, the polarization instantaneously follows the pulse envelope implying that there is practically no limit on the speed at which the polarization can be switched on and off.

The energy of the terahertz radiation comes from the exciting laser pulse so in this case the conversion efficiency depends mainly on the nonlinear coefficient of the material. A typical experimental set-up for generation and detection of THz waves using optical rectification is shown in figure 7.The laser source was an amplified Ti:sapphire laser with a central wavelength of 776 nm and a repetition rate of 1 kHz. Typical pulses had an energy of 0.8 mJ and 160 fs duration [11]. The nonlinear crystal DAST was used both as generator of the THz waves and as detector.

The bandwidth of pulses generated by optical rectification is limited by the laser pulse duration, terahertz absorption in the nonlinear crystal, the thickness of the crystal, and a mismatch between the propagation speed of the laser pulse and the terahertz pulse inside the crystal.

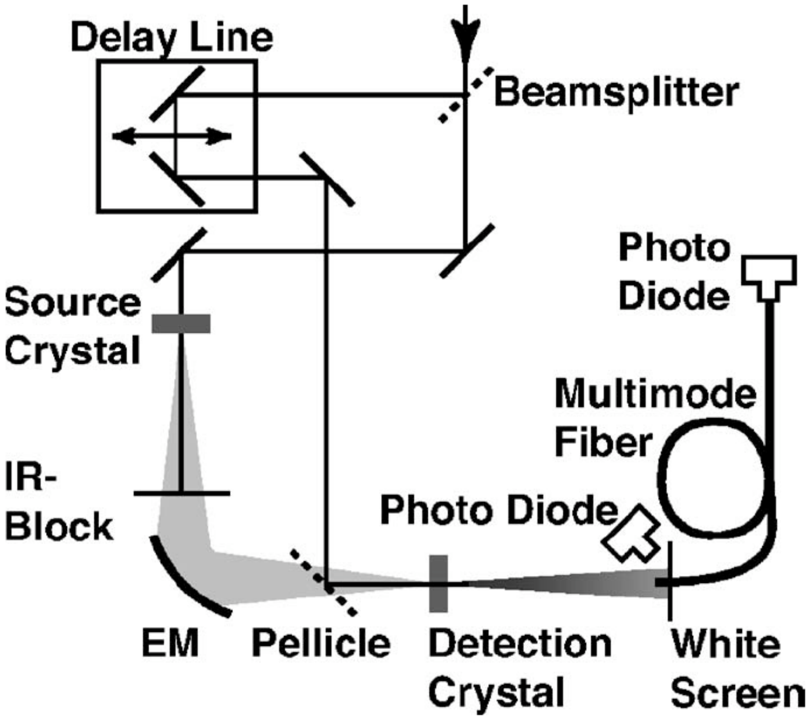

Figure 7. Experimental set-up for the generation of THz pulses by optical rectification and their detection. DAST crystals are used as source and detection; EM: ellipsoidal mirror; IR block is a piece of paper that blocks the pump beam and its second harmonic but that is transparent to THz radiation [11].

Typically, a thicker crystal will generate higher intensities, but lower THz frequencies. Bandwidths as large as 30 THz have been obtained using this mechanism [12], and theoretically it is possible to boost the generated frequencies to 40 THz or higher. One big advantage of this approach is the possibility of very compact engineering and high terahertz powers with the progressing development of compact pulsed telecom lasers and new materials optimized for terahertz applications like DAST. Researchers at the ETH-Zurich [13] have explored and demonstrated the potential of this technology. In cooperation with Rainbow Photonics and with a government funded project the first THz spectrometer for security and pharmaceutical applications produced by Rainbow Photonics AG will enter the market in June 2009. The experimental set-up based on optical rectification, combining the nonlinear organic crystal DAST and a femtosecond telecom laser is shown in figure 8.

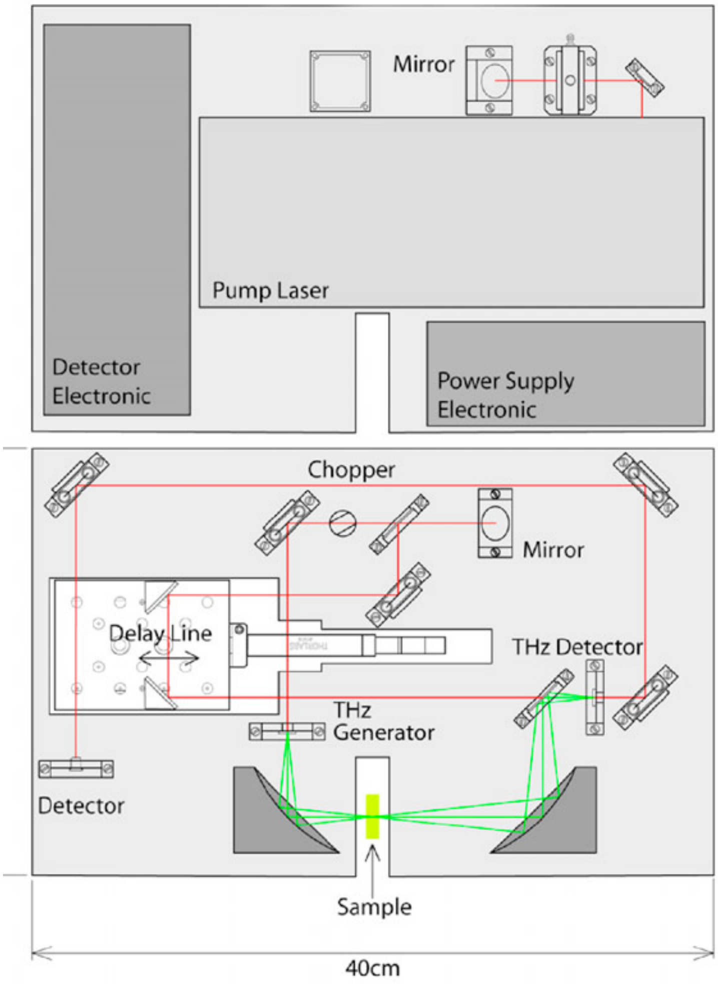

Figure 8. Block diagram of the THz spectrometer from Rainbow Photonics AG.

This THz spectrometer is compact, transportable, covers a terahertz range from 0.3 to 5 THz, and features the use of DAST a highly nonlinear material produced with proprietary and patented technology by Rainbow Photonics AG. The same material is used as generator and detector and is commercially available at Rainbow Photonics AG [14]. The terahertz spectrometer is shown in figure 9.

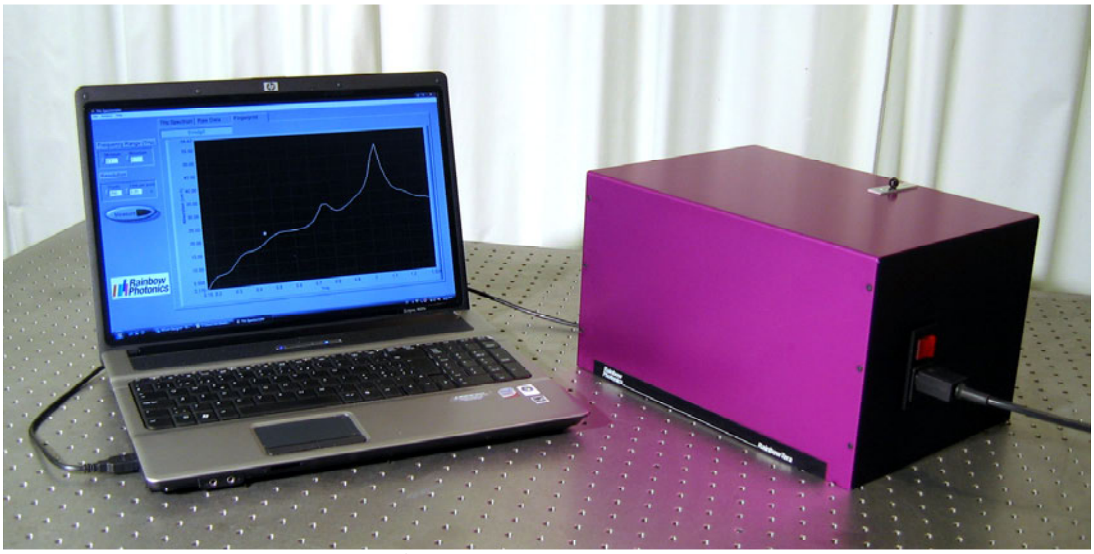

Figure 9. Terahertz spectrometer for security and pharmaceutical applications.

3.2 Tunable Narrowband Terahertz Generation

For applications in communication tunable narrow band sources are needed, and one of the most promising methods to generate tunable terahertz radiation from optical pump sources using nonlinear crystals is “difference-frequency generation” (DFG). In this approach two laser beams (or two signals generated in an optical parametric oscillator OPO) are combined in the nonlinear material to generate tunable terahertz radiation. A schematics of a typical experimental set-up using DFG is shown in figure 10.

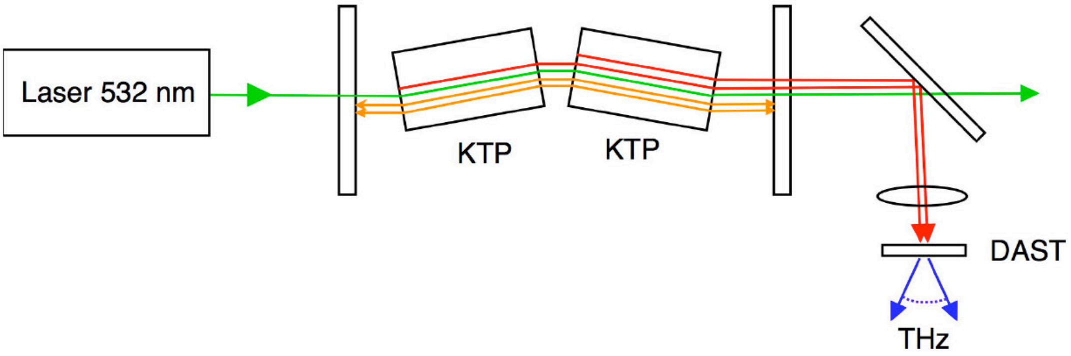

Figure 10. Experimental set-up to generate THz waves via difference frequency generation.

In this approach, two laser beams (typically in the near infrared wavelength range). To generate these two beams a frequency-doubled Q-switched Nd:YAG laser is pumping the two KTP crystals within the optical parameter oscillator (OPO) resonator. Consequently they are mixed in the nonlinear optical crystal, yielding a long-wavelength (THz) radiation. The spectral properties of the generated THz radiation depend on tunability and spectral bandwidth of the two mixing laser beams. There are only few reports on the generation of broadly tuneable THz radiation using DFG techniques [15]. The best performance has been demonstrated using optical parametric oscillators (OPO's) providing two wavelength-tuneable laser beams for the DFG in a DAST crystal, which possesses a very high effective electro-optic coefficient.

In a recent publication [16] a DFG system based on DAST was demonstrated over a tunable range of 0.1 to 11 THz, results are shown in figure 11. The extrapolation to higher frequencies is only limited by the lack of appropriate detectors.

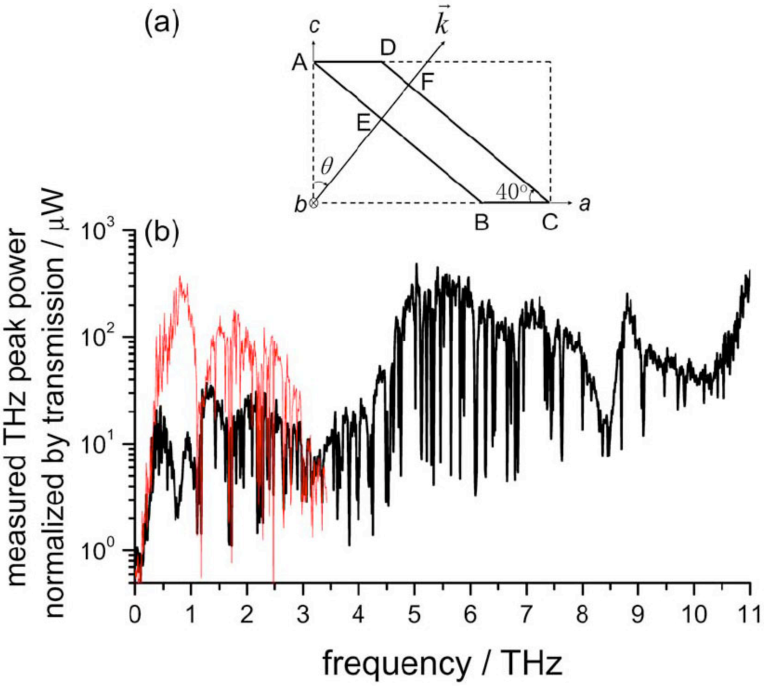

Figure 11. (a) DAST crystal cut for optimized generation of terahertz radiation. (b)Terahertz peak power generated in a DAST crystal by difference frequency generation using two polarization directions [16].

These systems based in difference frequency generation allow the selection of the appropriate THz bands to avoid water absorption. They also offer high power limited only by laser pump power, and therefore delivering larger transmission range. Systems based in this approach will have an impact in the communication area due to their tunability, performance and compactness.

4. Terahertz for Military Applications

4.1 Communication bands

Communications at THz frequencies are very attractive due to the availability of the broad frequency band available above 0.3 THz and due to the communications bandwidth which can be used. Frequencies above 0.3 THz are currently unallocated by the US Federal Communications Commission [17] (also included in the appendix). A window from 0.275 to 0.3 THz is reserved for communications. In Europe the allocation ends at 0.275 THz. Hence, there is free communication bandwidth above 0. 275 THz. Systems that work at these high frequencies already fall into the terahertz range. In the next sections we present an analysis of the possible scenarios with an impact in communication applications in the military area.

4.2 Communication point-to-point via terahertz link.

Communications at THz frequencies through the atmosphere are limited by the strong absorption caused by water vapor as well as the relatively low power from currently available sources and the low detection efficiency. For example for a 1 mW source and a detection sensitivity of 1 pW, the working dynamic range of 60 dB would allow communication at a range of up to 500 m in an atmospheric transmission window with an attenuation of <100 dB/km /see report Q1). On the other hand this attenuation will allow communications at a certain distance, leaving the information unavailable at other distances and larger. THz may provide multiple data channels with gigabit per second or more for short distance indoor wireless communications.

This point-to-point communication can be applied for communication between two elements in the battlefield or for communication within two subjects in a room; an illustration of this situation is shown in figure 12. The selection of the frequency channel will allow selectivity in the safe range of communication. This scenario can also be realized outdoors, although the communication range still has to be evaluated. Depending on the desired range of operation one or other terahertz frequency can be used, therefore it is important to have an adequate tunable terahertz source.

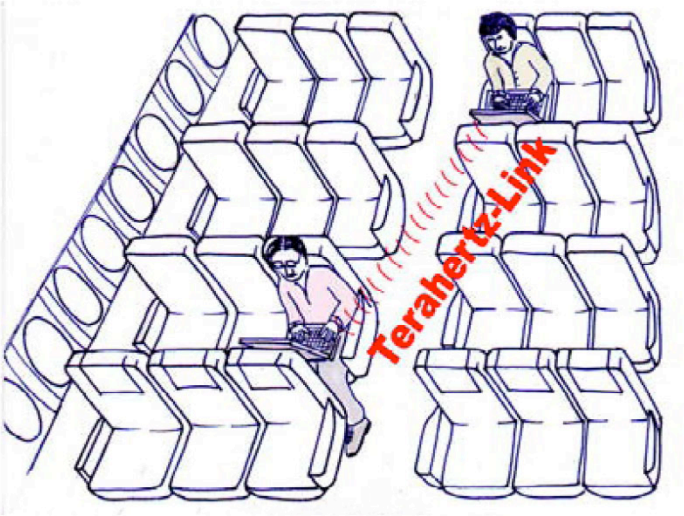

Figure 12. Communication point-to-point via an indoor terahertz link.

Atmospheric transmission windows may allow application of THz for short-range tactical communication. In some cases, the limited transmission distance may be an advantage, if we consider the clutter and congestion of voice channels in combat zones. THz signals are not far ranging as free-space damping heavily attenuates them. Furthermore, THz links will have to be directed. Because of these two properties THz waves could provide secure links which would be ideal for a communication on the battlefield for example between tanks or individual soldiers.

Point to point indoor communication, within a room or within a building can be affected if the terahertz link is shattered; this situation is illustrated in figure 13. In this situation the presence of back-ups can solve the problem. This back up can be understood as special reflectors on the walls or ceiling that may re-direct and amplify the terahertz radiation establishing the terahertz link again.

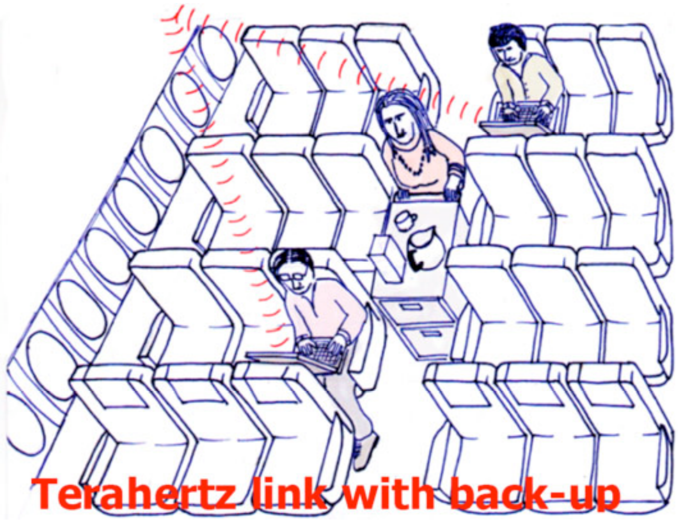

Figure 13. Terahertz link with back-up

4.3 Inter-satellite communication via terahertz link.

Despite the strong atmospheric absorption and low source efficiency presently existing, there are possible communications applications for this frequency range. For satellite-to-satellite communication, atmospheric absorption is not a problem unless the path grazes the Earth's atmosphere. Figure 14, shows the atmospheric attenuation in the THz range between 0.1 and 2 THz [18].

The advantage of using THz technology in this application is the larger bandwidth and consequently higher transmission rate as compared to microwave communications. The all-electronic conversion from the THz carrier to microwave links will be straightforward and at the same time, the size of the antenna will be reduced, which favors smaller satellite systems.

One problem usually found in optical communications is attenuation caused by scattering and absorption by clouds, rain, dust, etc. In the Rayleigh scattering regime, the scattering cross section increases with shorter wavelengths as the 4th power of the inverse wavelength. THz and millimeter waves experience much less scattering loss than optical wavelengths.

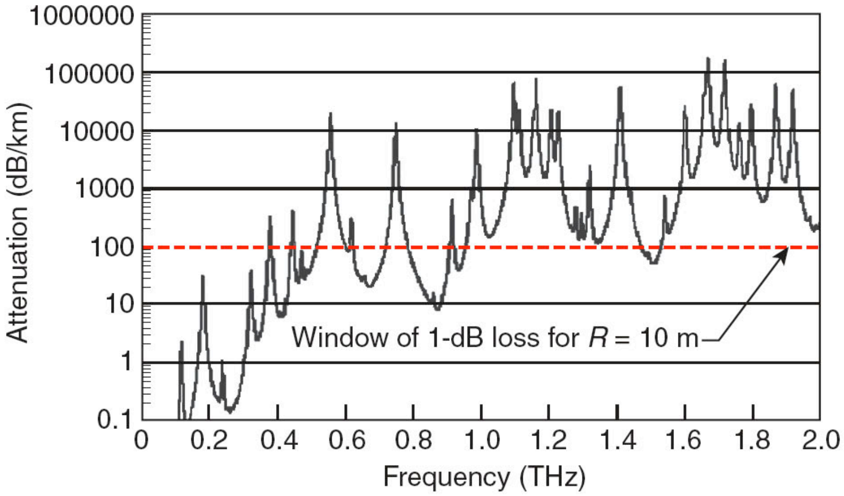

Figure 9. Atmospheric attenuation in the THz frequency range [18].

Millimeter band communications can be used as a backup to an optical terahertz link in case of rain or heavy clouds. Similarly THz can be used for short distances if heavy particles like smoke or dust are present in the air.

5. From Prototype to Real Field Demonstrator

During this monitoring we have revised different concepts and techniques for generation, detection, transmission, modulation and propagation of terahertz waves. An analysis has been made on its possible use for military applications, transmission channels, used frequencies, transmission distances and dependences on atmospheric parameters. The development of this technology has grown rapidly in the last 5 years and much of the progress has been made in optically based techniques for which applications in security and high resolution imaging and spectroscopy has been proved.

For applications in communication with an impact in military applications, we distinguish between short, middle, and long range communications. Due to the attenuation of terahertz waves in the atmosphere it is important to identify the terahertz “window” or “channel” up to 20 THz and higher where a terahertz link or a point-to-point communication should be established. Three main technologies for terahertz applications have developed quickly towards the next generation of screening devices for identification of hazardous and toxic materials concealed by clothing and packaging. The systems have a multidisciplinary technological approach and their high development is opening applications in advanced communication systems and high-resolution radars. These main technologies involve: radio-electronic systems, quantum cascade based systems and nonlinear-optically-based systems. THz communication systems require the development of emitters, detectors, modulators and frequency filters. Some of the recent advances focus in the realization of adequate sources leaving the detection to bolometric techniques. Recent developments in quantum cascade lasers bring their performance close to room temperature, but still at single frequencies. Photomixers and nonlinear materials have developed in such a way that they can be used as generators, combined with the latest development of telecom lasers, enabling an all-solid-state technology that allows compactness and robustness. They can also be used as detectors using nonlinear optical techniques.

The organic material DAST has several advantages over photomixers:

1. Larger nonlinearities, requiring less powerful pump lasers for large THz intensities
2. Cheaper technology in comparison with epitaxial techniques
3. Can be used as generator and detector
4. Larger terahertz frequency range (0.3–20 THz)
5. Potential to develop a tunable source using difference frequency generation techniques [16].

Spectrometers for applications outside the laboratory based on this novel organic material will be available in June 2009, two years before the announced spectrometers based in photomixers. With all the technological know-how, it is possible to anticipate tunable systems for application in communication and based on the nonlinear material DAST in about two years time.

In table 1 we summarize the state of the art of the present technologies with a perspective to communication application. The need to identify the terahertz window of operation makes it necessary the availability of a tunable terahertz source. We also indicate the required innovation and the time to realization.

Devices	**Frequency**	**Bandwidth**	**Output Power**	**Tunability**	**Detection**	**Availability**	**System for application in communication (short range)**
QCL-Quantum Cascade Lasers	1.38 THz (110K)	narrow	mW	–	other	Commercial	- Not appropriate yet - Low temperature operation
UTC-PD	0.1 and 1 THz	broadband	µW	–	other	Laboratory	Only below 1 THz
Photomixers	0 to 1.5 THz	broadband	mW	no	can be used as detector	Commercial	Not appropriate, first spectrometer for other applications will be available in 2 years.
Nonlinear Optics OR (DAST)	**0.3 – 20 THz**	**< 100 GHz**	**µW**	**no**	**can be used as detector**	**Commercial: generator and detectors since 2002**	**Complete spectrometer for other applications in June 2009**
Nonlinear Optics DFG (DAST)	**0.3 – 50 THz**	**<100 GHz**	**mW**	**yes**	**can be used as detector**	**Proof of concept**	**1 year time for a laboratory prototype for use in communication. Two years from now for a field demonstrator**

Table 1. Present technology for terahertz sources, possibility to use as detector and future in the short-range THz communication area.

6. Conclusion

The major advances in terahertz technology have been achieved over the last five years: terahertz quantum cascade lasers are reaching lower frequencies and high temperature of operation, the development of best materials for generation and detection of terahertz has reached maturity and are commercially available, and improvements in antenna design provide an interesting perspective in approaching terahertz frequencies.

Among the terahertz applications that had led to the development of next generation of screening devices are in security for identification of hazardous and toxic materials concealed by clothing and packaging, spectroscopy, and medical applications. The systems operate at terahertz frequencies and have a multidisciplinary technological approach. The developed technology will enable applications in advanced communication systems and high-resolution radars that require highly integrated miniaturized terahertz transmitter-receiver and where the infrastructure needed to move the terahertz technology from the laboratory to the field is not yet available.

Communication technology is an advanced and dynamically developing branch where high-end technologies and trends appear. Today radio electronics are the brains, eyes and ears of communication, weapon systems and defense technology. Most of these systems operate with highly developed electronics and radar techniques. From the design of such systems is easy to imagine that some antennas will be replaced by terahertz emitting sources. Yet, in spite of the various advantages of terahertz technology, so far, it has not made a breakthrough, as it is expensive and time-consuming to build the required transmitters and receivers operating at this frequency of the spectrum. Some electronic examples of small and portable sources and detectors are becoming now available at frequencies below 300 GHz, and results on fast modulation of terahertz frequencies at 100 KHz have been recently published.

We have revised the three main technologies that will have an impact in the field of communication with terahertz and that could lead to a new type of high-speed, short-range wireless communication network.

The increased demand of bandwidth for fast data transmission applications requires the extension of communication systems to higher frequencies where frequencies above 300 GHz are not allocated. It is to be expected that wireless short-range communication networks will soon push towards the THz frequency range. Systems operating in the GHz range are being developed. THz communication systems require the development of emitters, detectors, modulators and frequency filters.

In the road map for application of THz in communication three main scenarios can be distinguished:

1. Very short range communication: <1m
2. Short range communication: >1m and <30m
3. Middle range communication: >50m

These scenarios for point-to-point communication via a THz link will be the first to be realized in indoor (within a room or within a building) and outdoor communication (middle range).

The three most important aspects that have to be identified in order to implement a terahertz system for indoor communication application are:

1) Decision on stand-off distances: more than 1m, less than 30m, more than 50m.
2) Identification of the frequency window above 1 THz for minimum attenuation of terahertz waves caused by relative humidity in air for the given distance.
3) Decision on the system to be developed.

In view of the need to identify the frequency window for application in communication, the implementation of a terahertz system for application in communication will involve the development of a tunable source. In view of the present developments an all-solid-state approach with nonlinear optical techniques and telecom lasers will led to a quick breakthrough in the next 2 years.

Although lots of research efforts are still needed in the development of sources and detectors for terahertz technology, with the present development it is to be expected that in the next two years the first real demonstration of terahertz applications in communication will be realized. Real world applications can be a reality in five or ten years or before. Japan, Germany, Great Britain and United States have already identified terahertz technology as a key technology for the future allocating millions of Euros for research. With these worldwide efforts the time to technology will be dramatically reduced.

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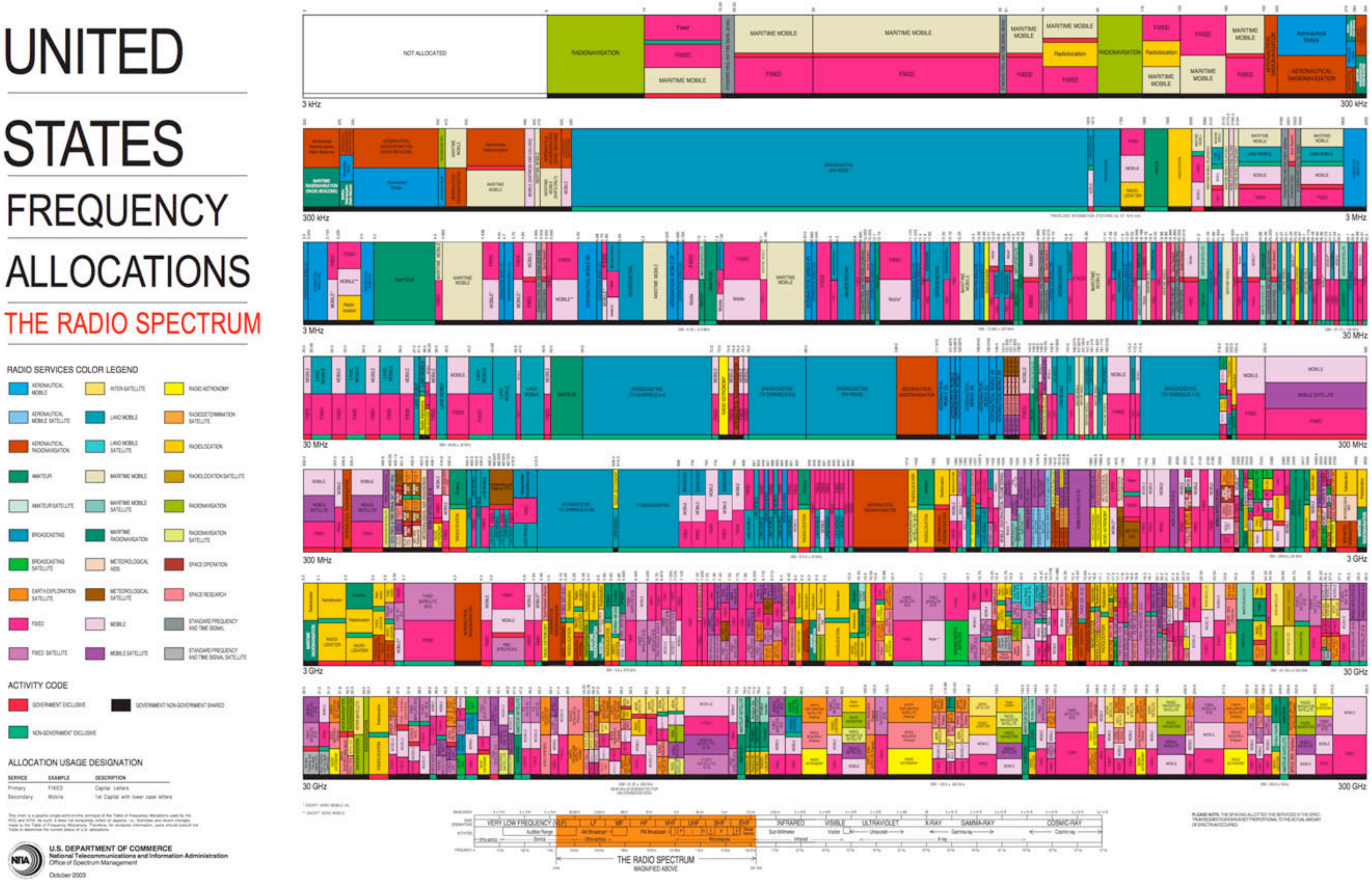
8. Abbreviations

2DEG	Two Dimensional Electron Gas
DFG	Difference Frequency Generation
GaAs	Gallium Arsenide
HHI	Fraunhofer Heinrich-Hertz Institute
HEMT	High Electron Mobility Transistor
InGaAs	Indium Gallium Arsenide
LTG	Low Temperature Grown
MMW	Millimeter waves
mW	milliwatt
nW	nanowatt
OPO	Optical Parametric Oscillator
OR	Optical Rectification
QCL	Quantum Cascade Laser
pW	pico Watt
UTC-PD	Uni-traveling carrier photodiode

Appendix



Appendix 1. Frequency allocation chart