TERAHERTZ – YESTERDAY, TODAY, AND TOMORROW

TERAHERTZ – AYER, HOY, Y MAÑANA

Carlos A. Duque[1], Anton Tiutiunnyk[1,2], Álvaro L. Morales[1], Volodymyr Akimov[1,2], Ricardo L. Restrepo[3], Oksana Fomina[2], Víctor Tulupenko[1,2]

[1] Grupo de Materia Condensada, Instituto de Física, Universidad de Antioquia UdeA, Calle 70 No. 52-21, Medellín, Colombia
[2] Donbass State Engineering Academy, Kramatorsk, Ukraine
[3] Escuela de Ingeniería de Antioquia-EIA, Medellín, Colombia

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Abstract

The term terahertz (*THz*) became one of the most popular words in science nowadays. Why? And what is it? Why more and more scientific books, articles, and conferences are being devoted to this topic all over the world? Why *THz* centers are being established at many universities and laboratories? Why do *THz* programs appear in different countries? The article brings you short answers to these questions. It explains what *THz* radiation is and what a so-called *THz* gap is. We touch the peculiarities of the *THz* radiation and mention its important applications. Then we consider the state of the art in *THz* science. As it is impossible to cover all the scientific and technical aspects of the *THz* science in the short review, therefore we only touch the semiconductor nanostructure-based devices and technologies in two most important fields; namely, we will look at *THz* sources and detectors, paying particular attention to their differences from conventional optical devices. And we hope that readers of this article will become more familiar with *THz* science and they will also try to find their own ways of implementing *THz* radiation into their scientific activities.

Keywords: Terahertz radiation, semiconductor nanostructures, terahertz devices.

Resumen

El término terahertz (*THz*) se convirtió en una de las palabras más populares de la ciencia hoy en día. ¿Por qué? ¿Y qué es esto? ¿Por qué cada vez más libros, artículos y conferencias científicas se están dedicando a este tema en

Víctor Tulupenko viktor.tulupenko@yandex.ru

todo el mundo? ¿Por qué centros *THz* se están estableciendo en muchas universidades y laboratorios? ¿Por qué han aparecido programas académicos sobre *THz* en diferentes países? El artículo presenta respuestas breves a estas preguntas. En él se explica lo que es la radiación *THz* y que es la llamada brecha *THz*. Presentamos las peculiaridades de la radiación *THz* y mencionamos sus aplicaciones más importantes. Más adelante, describimos el estado del arte en la ciencia *THz*. En un artículo corto es imposible cubrir todos los aspectos científicos y técnicos de la ciencia *THz*, por lo tanto, restringiremos la discusión a los dispositivos y las tecnologías basadas en nanoestructuras semiconductoras en dos campos muy importantes a saber, las fuentes y detectores de *THz*; prestando especial atención a sus diferencias con respecto a los dispositivos ópticos convencionales. Esperamos que los lectores adquieran una familiaridad suficiente con la ciencia de *THz* y que traten de encontrar sus caminos propios para implementar la radiación *THz* en sus actividades científicas.

Palabras Clave: Radiación terahertz, nanoestructuras semiconductoras, dispositivos de terahertz.

1. Introduction

THz science got a tremendous development for the last two decades. It includes three main kinds of applications directions: generators (sources), detectors, and accessories (antennas, tuners etc.). Due to the large amount of achievements in this field, this review will limit to some topics that appear to be the most relevant to the readers. The following considerations have been taken into account: Provide the maximum benefits to THz technology operators, such as easy to use THz equipment and room temperature operation, and the scientific interest of the authors in sources and detectors of THz radiation

The article is organized as follows. In part 2 we consider the definitions of the *THz* radiation and a *THz* gap. Part 3 is devoted to the peculiarities of *THz* range and part 4 concerns with the *THz* applications.

In part 5 we review the status of THz technologies before the nineties of Twenty Century, before its further explosive development in connection with achievements in Nanotechnology. Part 6 deals with the modern *THz* equipment working at room temperature, and part 7 is devoted to some future trends in *THz* science and technology.

2. What is THz radiation and what is THz gap?

We cannot imagine our life without technical devices using electromagnetic waves. We hear radio, watch TV programs, use navigators, communicate with other people through mobile phones, and heat up our food in a microwave – here and in many other devices we use the electromagnetic waves in our common life, which makes our life easier and more comfortable. And we must understand that different devices use different wavelengths. It means that the way we use electromagnetic waves depends on their wavelength λ (or frequency ν as they are connected through the speed of light in medium $c = \lambda\nu$). Now let us define the term terahertz (shortly *THz*), to which all this article is devoted to. Namely the prefix tera means 10^{12} and the frequency $\nu = 1THz = 10^{12}$Hz and consequently, the period $T = 1/\nu = 10^{-12}$s = 1ps. The corresponding wavelength (in vacuum) is $\lambda = 3\times10^{-4}$m = 0.3mm = 300µm and wave number $k = 1/\lambda = 33.3\text{cm}^{-1}$. In accordance with corpuscular-wave dualism of light, the electromagnetic wave of frequency ν can be treated as a flux of light particles (photons) with their (photon) energy $\varepsilon = h\nu$. Here $h = 6.626 \times10^{-34}$Js is the so-called Plank's constant. Then the energy of 1*THz* photon is 4.1×10^{-3}eV = 4.1meV and equivalent temperature (defined from $\varepsilon = k_BT$, with k_B being the Boltzmann's constant: $k_B = 1.38\times10^{-23}$J/K) T = 48K. Now let us delimit the *THz* range. It is noteworthy that while defining the THz range there is no consensus among authors on the strict definition of it. Some of them suppose that *THz* range is between 0.1 and 10*THz* (with corresponding λ = 3mm…30µm), others locate it between 0.1 and 50*THz* (λ = 6µm). In our opinion, we believe that the most appropriate range lies between 0.4mm (0.75*THz*) and 40µm (7.5*THz*), it completely covers the band of a so-called *THz* gap.

In the literature THz gap is understood as the range of frequencies (wavelengths) where either there were not any generator operating at these frequencies until now or if such sources existed, they were extremely complicated and expensive devices (often not intended for common commercial applications and used in scientific laboratories by experienced staff). Different physical mechanisms operate at the two edges of the mentioned spectral band. The strong sensitivity to the wavelength within this range determines the type of active devices to be developed. It is worth noticed that the long-wavelength edge is often called the sub-millimeter range, and physical properties seem to be more wave-like than particle-like. Namely within this range, classical electronic generators of electromagnetic radiation work more efficiently. Some examples of operating devices include: backward wave [1], gyrotron [2], klystron [3] oscillators and solid-state ones like resonant tunneling, Gann and IMPATT (IMPact ionization Avalanche Transit-Time) [4] diodes and multipliers on the base of Schottky diodes. These devices cannot operate at shorter wavelengths, because of the fundamental limitations imposed on their sizes by wavelength of radiation.

In the short-wavelength edge the electromagnetic radiation may be treated as a flux of photons, therefore, particle-like approaches are more convenient. For such a reason, the use of lasing is very common. We will focus on semiconductor-based injection lasers using PbSnTe or PbSnSe salts as active elements. Laser schemes operating in the THz range face several challenges, mostly due to the low energy of the quanta of light and the difficulties in achieving enough inversion in the population of carriers, while considering the small difference among energy levels.

In summary, from above mentioned challenges it is required a further development and testing of new generation technologies operating at the THz range and also combining the best of the physical properties from the two edges of the spectral band. However, limit the analysis to developmental aspects is not enough because the processing of THz signal is as important as the process of development of new technologies. At the core of these challenges can be mentioned the small energy of THz quanta and the specific peculiarities of the THz range to be discussed below. The schematic representation of the electromagnetic spectrum around the THz range is included in the Fig.1.

Although visible and *THz* ranges look to be located next to each other, in reality their wavelengths (frequencies) differs two orders of magnitude at least.

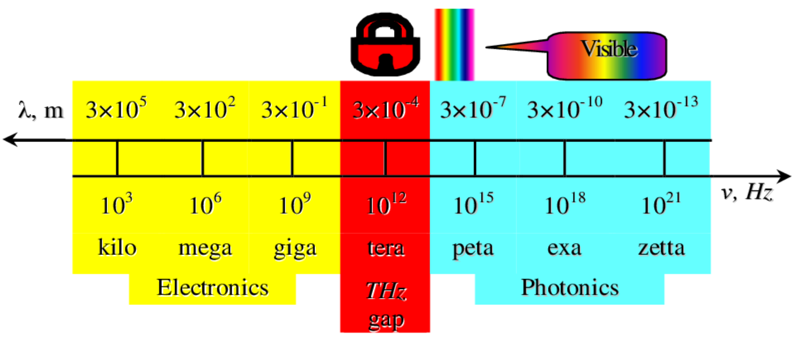

FIGURE 1. The *schematic representation of an electromagnetic spectrum and the position in it of a THz range. Note that the upper scale (directed to the left) corresponds to wavelength λ, measured in meters, while the lower scale (directed to the right) is for frequency, measured in Hertz (Hz).*

3. Peculiarities of THz radiation

Peculiarities of *THz* band are mostly conditioned by several factors. The first one is the small energy of the *THz* photons. Recall both the average kinetic energy of free electrons in condensed matter as well as the average oscillation energy of atoms around their equilibrium positions at room temperature are around 27 meV, and at (very important in physics) liquid nitrogen temperature are about 7 meV, while the energy of 1 THz photon is

4.1 meV. It means that it is extremely difficult to create any artificial and stable distribution of charge carriers (inversion population of carriers) at these two energies suitable for practical used temperatures since the Brownian motion of particles destroys any ordered distribution. Additionally, low energy of THz radiation creates great difficulties in the processing of information because of a large thermal noise. Indeed, any object with a temperature above 0 K also emits radiation in the *THz* range – on the long wavelength tail of spectral distribution of emitted energy. Fig. 2 shows the distribution of the spectral density of energy for the black body (Planck's formula) for temperatures 77K, 200K (approximately the lower on the Earth and room temperature. Here a similar curve for the Sun surface (T = 6000K) is also shown. It is seen in Fig.2, that in spite of tremendous difference in spectral densities of emitted power in the visible and infrared ranges, in the *THz* band they differ not so much. As a result a big thermal noise superimposes on useful *THz* signal. Second feature is that *THz* radiation is very well absorbed by the Earth atmosphere as it is shown, for example, in Fig.14 of the work [6]. It is seen in that picture that the main absorbent for the *THz* spectrum is water vapor. It means that THz radiation cannot propagate in the Earth atmosphere on a big distance - it is possible either in vacuum or in an ultraboundary waveguide filled with an inert gas. Besides, rotation and vibration spectra of many other molecules lie in the THz range. Third remarkable feature of the *THz* radiation is that it can penetrate through many materials like plastic, ceramic ones and dress clothing. Fourth peculiarity followed from the first tree already mentioned, but due to its great importance we put it separately. Here we mean that due to the small energy of *THz* photons they are harmless for the human tissue, and taking into account their absorption by water as well as their big penetrating ability they can be used in medicine for the different purposes.

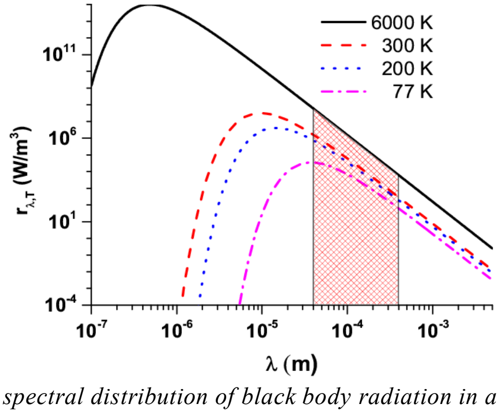

FIGURE 2. *THE spectral distribution of black body radiation in a log-log scale at different temperatures. Highlighted area corresponds to the THz gap as defined in the text. Note, that 200 K is for the lowest temperature on the Earth, 300 K is for approximately room temperature and 6000 K is the temperature of the Sun surface.*

4. THz applications - why is it so hot?

The lack of active, commercially attractive, convenient, and operational THz range devices nowadays opens many opportunities for new developments. Many of these potential applications have been tested in laboratory settings and a subgroup of them will be reviewed in what follows.

4.1. THz in medicine

How to determine the precise boundaries of cancerous tumors inside a living organism in real time, historically, marked the first application of THz radiation in medicine (see Reference [7]).

In fact healthy and cancerous cells respond differently to *THz* radiation. For example, authors of the Reference [8] discuss the reflected impulse responses of healthy and cancerous cells and they conclude that there are differences in the refractive indices and absorption coefficients for both types of cells. For teravision applications an important parameter is the spatial resolution. From physical considerations it is limited by the wavelength of the *THz* radiation, and is of the order of one hundred micrometers. But using special design of the output aperture the authors in [9] got the value of 7 micrometers. Since the *THz* radiation is mostly absorbed by water, and the water comprises about 80 % of the weight of human body, the penetration depth of *THz* radiation into the human body is not so large and therefore it can (could) only be used for terahertz imaging of skin and not so deep underneath skin layer [10]. The progress in the teravision of internal organs is expected to be achieved by using flexible probes and nanoscale *THz* active devices [11]. Cancer treatment is another potential application of the *THz* radiation in medicine. Even though, modern medicine is only at the beginning of this path, it is already established, that absorption coefficients and refractive indices [8,12], electrical conductivity and permittivity [13], are dependent on the *THz* frequency of applied radiation and are different for healthy and cancer cells. These correlations allow us to hope finding reliable ways for cancer treatment by using *THz* radiation. Indeed, it is possible to imagine medical practioners irradiating cancerogenic tumors with *THz* radiation which kills only the cancer cells and it is absolutely harmless for the healthy ones, in contrast with the usual high energy radiation – either *X*-rays, or γ-rays having big penetrative ability and destroying on their way both cancer and healthy cells. Undoubtedly, all of humanity is waiting for such developments by physicists and physicians. In addition, there are other applications of THz in medicine (for example, in the study of dental caries), and we are confident that this number will increase to a great extent with the availability of cheap and easy to use for conventional medical personnel THz equipment.

4.2. Security applications

After the tragic events of September 11, 2001 in the United States, many countries have adopted their own programs for the development of THz-based screening. One of the main reasons for that is the ability of *THz* radiation to penetrate through plastic, ceramics, clothes and, consequently, to see hidden things. It is possible to find in the INTERNET pictures (similar, for instance, to that shown in Fig. 11 of Reference [14]), sketching the know-how of using *THz*-based screening to see the hidden objects under clothes (or under plastic, or under another materials) and different kinds of weapons. We also have to mention here that *THz* radiation is very sensitive to different kinds of explosive, including liquid ones, as well as to the various drugs, which are extremely difficult to be distinguished with either other machinery methods or trained animal. It is obvious that such teravision equipment is extremely important at the airports (and some of them already have such systems) and in some other places crowded with people. It is again worth emphasizing that such systems are harmless to the human body. Another example of using teravision in security applications is shown in the Figure 3 [15]. The ability to see through walls in the *THz* range is shown in Fig. 3 using Legos. It is extremely important in the fight against the terrorists who seized the hostages. There are other interesting examples in various branches of homeland security.

FIGURE 3. *The police need to see a hostage, terrorist and his gun through the wall or door. THz transceiver is just the right device for this. [15].*

4.3 THz in communications

We all use mobile phones in our daily life and we also witnessed the increase in the ability to transmit more and more information. In fact, modern societies have gone from talk-only mobile phone, to real-time face-to-face smart communication devices. Probably many people have heard that improving the quality of communication is related with the introduction of 1G ... 4G standards for mobile phone communications. Currently all the information transmitted through wireless channels, including GPS navigation, is done in the gigahertz (*GHz*) frequency domain. However, modern societies are looking for much faster exchange of information than it happens nowadays between mobile phones and transceiver stations. For example, in January 2015, "the Federal Communications Commission (FCC) of the United States voted "to change … the minimum download speed from 4 Mbps to 25 Mbps, and the minimum upload speed from 1 Mbps to 3 Mbps" [16]. Based on current trends, it is expected that in a few years from nowFCC will again suggest a shift towards higher values of the speed in the transfer of information, which would involve increased values of frequencies. In this connection it worth noting that practically all the *GHz* frequency range up to 300*GHz* (0.3 *THz*, which is the frontier of *THz* band) is already "specified and designated by the U.S. FCC, while the *THz* range is still free from such regulation" [16]. Thus, in order to transfer a much higher volume of information, technolgists and developers must master the *THz* domain. While dealing with such challenges, some concerns arise. As it was stated above the *THz* radiation is strongly absorbed by the atmosphere, therefore, it only could be used for inside-room communication within approximately 10 m. It is hard to foresee its use when people are moving outside (away) from buildings.

A possible solution to the above-described limitation might be that, THz-based infrastructure could be used only for information transmission along telecommunication backbones. This way, it will be kept isolated from the direct contact with the atmosphere. The "last-mile" end-user services might be implemented once again appealing to the GHz-based technology. Besides that, the use of THz-based technologies requires synchronization between clock's frequencies in integrated circuits and peripherals operating within the THz range. Some promising solutions already appeared in 2014 when the DARPA announced the creation of the 1 THz transistor by using InP.

Taking into account the above-mentioned facts, it seems that THz-based applications would be found among outer-space technologies rather anything else. The communication between spacecraft's is an example where THz-based technologies might be applied.

4.4. Atmosphere monitoring

The fact that the majority of molecules have their vibration and rotation spectra (their "fingerprints") in the *THz* range allows one to use it for atmosphere monitoring and gas analysis. That is particularly important due to problems with heating of the Earth atmosphere. Again, do not be amiss to recall that the *THz* radiation is harmless to maintenance personnel.

4.5. Material inspection, control of quality etc.

Ability of *THz* to penetrate through the plastic can be used for checking its uniformity in the process of its preparation or, if appropriate, in detecting contamination and cavities in it. The same is also possible for asbestos, concretes and many other materials. In the electronic industry the possibility of automatic non-destructive quality control of the deposited films is extremely important. Particular importance is in control of uniformity of tablets in the pharmaceutical industry. Obviously, there is no sense in enumerating the possible fields of application of the *THz* radiation as it can be used in practically every branch of human activity. And the number of such application is constantly increased.

5. THz yesterday

Here we recall the situation that prevailed in the *THz* science up to the end of the 1980's. By the beginning of the laser era the main laboratory sources of *THz* radiation were the water cooled mercury lamp and globar – electrically heated in vacuum rod of carborundum (SiC). In a sense, globar is a model of a black (more exactly – gray) body. Bolometers (devices based on the change of electrical resistance with the temperature) and Goley cells (devices based on a change in size with temperature) were used. They were (and are now) considerably slow, with the rise time not less than 10^{-3}s units. Then in the middle of the 1970′s the gas lasers for this range (it was then called as a far infrared range of the spectrum) were created. Their main disadvantages were the optical power (usually by using CO_2 laser) pumping, water cooling, practical impossibility of tuning, and necessity in using the experienced staff to control the lasers. At the same time the fast, with rise time of the order of 10^{-8}s, cooled detectors, based on the ionization of shallow impurities in semiconductors by a *THz* radiation were developed. Then at the beginning of the 1980's the first semiconductor laser working at low (primary at helium) temperatures in crossed electric and magnetic fields on the base of p-Ge was developed [18]. In spite of its many drawbacks, following from numerated conditions for its work, it is up to now the most powerful semiconductor laser, which can produce in the pulse regime up to 10 W.

6. State of the art for today

As we are sure that future belongs to the small, electrically driven, cheap and easy in use semiconductor devices (both sources and detectors), and the most promising candidates for them are semiconductor-nanostructure based structures, we briefly touch them here.

6.1. Schottky planar diode

First one will be the Schottky planar diode (SD). The SD use in the *THz* range is based on the varactor-type of the metal-semiconductor junction capacitance and nonlinearities of the I-V curves. SD usually works as frequency multiplier and in this case it has to be used together with the main (master) generator (either some vacuum electronic device, or solid state one), which works at considerably lower frequency [19]. We believe that the most promising way is to use the Gunn generator, as in this case all the structure can be manufactured as monolithic one. The highest cut off frequency of the SD is determined by its capacitance and series resistor – the less these values the bigger the cut off frequency. It is interesting that both reverse and forward bias can be used. In the former case changing the bias involves changing the SD capacity and in the latter case only the series resistor of the device is changed [19]. Due to the decrease in output power with an increase of harmonic number a few stages of multiplication can also be used. The most efficient SDs for now are those made on the base of InP compound rather than AlGaAs one [19]. The advantages of Schottky diodes are fast response time (low capacitance and resistance), easy and cheap to manufacture, and, perhaps, most importantly - the opportunity to work at room temperature.

6.2. Resonant tunneling diodes

There are different types of resonant tunneling diodes (RTD). Here we only have in mind the intraband two-barrier structures [20]. The I-V curves of such structures are like the same for Gunn diodes with the negative resistance in some range of applied bias. Relatively fresh review of RTD can be found in [21]. And quite recently it was announced that generation of radiation had been achieved at frequency of *1.42 THz* [22]. The main benefits of RTDs are similar to those for SDs. Besides, RTDs are compatible with well-developed technologies for manufacturing high efficiency metal oxide field effect transistors (MOSFETs). It means that they can effectively be used in various digital applications.

6.3. THz transistors

Now we briefly touch very intriguing story about ballistic field effect transistor in *THz*, the idea of which was firstly proposed more than twenty years ago [23]. The authors showed that in the ballistic regime when transit time of electron in the channel between source and drain become shorter than momentum relaxation time of electrons, the electron density oscillations (plasma waves) driven by both external circuit elements and gate bias could arise in the *THz* range. Eleven years later that theoretical prediction was experimentally confirmed [24]. Since then there were published some other experimental works, which explained the obtained results in the frame of the two dimensional electronic fluid in the channel [23], including the one with the title "Room-temperature terahertz emission from nanometer field-effect transistors" [25]. And although the authors are based on the theory of [23], they, however, note that some of the features of the obtained results cannot be explained by the theory of electron liquid [23]. Perhaps such works inspired other team [26] of theoreticians to look on the other side of the problem. They made Monte-Carlo simulation of the processes in the channel and came to conclusion that responsible for generation of *THz* radiation in the experimental conditions [25] is be Gunn-like oscillations of the current in the channel. Nevertheless, after that, once more experimental work appeared [27] at which again the mechanism of flowing water [23] was confirmed. We think that, no matter what mechanism is responsible for the generation of radiation, the mere presence of this radiation is very important. In fact, similar radiation generators should be very cheap, because they are based on the already well-developed production technology of such structures.

6.4. Quantum cascade lasers in THz

The first quantum cascade laser (QCL) with wavelength of generated radiation *4.2 μm* was demonstrated in 1994 [28]. Its remarkable feature is that an electron emits many photons going through inclined in the electric field tunnel- coupled QWs. After that, it took 8 years to increase the wavelength of the QCL to about 68 microns (4.4 *THz*). This laser operated at helium temperature [29]. Subsequent efforts of scientists were directed at increasing the operating temperature, of the emitted wavelength, and achieving continuous operation. As far as we know, the highest operating temperature has been achieved to date is about *200 K* [30]. Authors [31] doubt that ever will be possible to reach operating temperature of *300 K*, but they believe that it will be possible to achieve $T = 240\ K$, at which quite cheap thermoelectric cooling devices already work. But even if it will not be possible to create, so to speak, directly QCL operating at room temperature, there is one more opportunity to use QCLs. Here we have in mind an approach that uses a difference frequency generation (DFG) of two QCLs that are grown (made) on the same substrate, in the same monolithic unit, and can work steadily at room temperature [32]. The undoubted advantage of this source is a broad wavelength tuning of the emission peak. This is because although the initial wavelength tuning of the IR lasers is only performed within narrow limits, but in the *THz* range, this leads to a wide tuning range (0.58 *THz*, which is 15% of the radiation from the center line). Also, the emission line width is of less than 10 *GHz* [32].

6.5. THz detectors

There are a lot of techniques for detecting *THz* radiation and the most sensitive are bolometers, which are cooled to about 100 mK [33]. But following the conception of the article we only shortly touch room temperature *direct* detectors and also divide them into 2 groups. First one combines photo-acoustic, Goley cell type, and pyroelectric detectors. The overall disadvantages of the group of detectors are their slow response times, considerably big thermal noise and they are not sensitive to the wavelength, but to the heat [33]. The second group we attribute is SD and detectors on the base of high mobility field effect transistors. In principle they have the same disadvantages as those attributed to the first group except for their response time is a few order of magnitude shorter than in the first group [34]. And extremely important is the matching of the detection element with antenna and subsequent electronic circuit.

6.6. Some remarks

We did not consider the time domain *THz* generation and detection techniques here although most of the remarkable applications mentioned above were obtained by this technique in scientific laboratories around the world. We suppose that such complicated method is not intended for the ordinary user. We did not mention here such devices like generators on the base of Bloch oscillations in the superlattices [35], which either exist now only as theoretical proposal, or their efficiency, particularly at room temperature is worse in comparison with those considered here. And again, in accordance with conception of the article we omitted here the powerful vacuum devices and free electron lasers as they are not intended for the common use.

7. Future trends

Based on the above-mentioned facts, we foresee the following directions in the development of *THz-based* science as well as for it further advancement and widespread use by the general public. In case of generators, the increase of the emitted power is a must and should reach the *10 mW* level at least. The performance of *THz* detectors has to be also improved. For example, it would be very desirable to achieve NEP (noise equivalent power – one of the main characteristics of detectors) of the order 10^{-11} W/Hz$^{1/2}$ for the SD direct detectors. Different ways, such as using diamond substrates and heat sinks for effective cooling down the devices as well as careful adjustment with input and output circuits can be used for that. Besides, development of technologies for new kinds of materials like GaN, InP and graphene as well as using metamaterials (metamaterial - a structure in which the electric and magnetic properties are determined by periodically distributed in homogeneities and not by the properties of the material itself) can lead to a success [36, 37]. And, of course, too early to write off the silicon technology to improve the performance of already existing devices in the sub-terahertz range. Without any doubt, the improved performance of the *THz* devices at room temperature will infinitely increase their areas of application. And last but not least, to demonstrate the importance of *THz* science and its applications we mention that the global market of *THz* systems in 2014 reached $54.7 millions of dollars and it is forecasted to reach $1.2 billion dollars in 2024 [38].

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intensos sobre las propiedades ópticas de nanoestructuras semiconductoras de InGaAsN/GaAs y GaAlAs/GaAs.

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