Chapter 2
New Terahertz Security Opportunities Based on Nanometric Technology

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Abstract To identify weapons hidden under the apparel of people walking through entrance gates it is important to use THz illumination of sufficient power levels and fast image detection and processing. Various approaches of THz generation by nanometric dimensions are under studies in connection with semiconductor structures as well as electron beam systems. The issues of a THz camera are discussed. Power-level increases require paralleling many sources such as those of two-laser optical mixing in suitable non-linear materials or those of ballistic resonances in heterostructures of nanometric dimensions. In particular heat-sinking optimization is required so that THz-illuminating sources can be distributed along the frame of the entrance door for efficient employment of imaging facilities. THz detection is then using optical mixing so that phase and amplitude data can be derived by a matrix of pixels for ultrafast imaging. These pixels need to have antennas with low side lobes to avoid ghost images, produced by transverse resonances of the pixel matrix. The THz frequencies employed are initially aimed at narrow-band facilities of 830 GHz to identify metal and dielectric objects. This means that the required antennas for sending and detection can be based on dipole schemes. The ultimate wide-band possibility to identify the chemical compositions of explosive materials needs the wide-band antennas, such as half-spherical Si lenses.

Keywords THz • Optical mixing • Ballistic electron resonance • Field-emission • Security

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2.1 Introduction

Electromagnetic signals at Terahertz frequencies have the advantage that their photon energies are in the low meV range and therefore not capable to break up organic molecules of living cells. Therefore they have been considered for many applications such as airport surveillance. Such scanners can detect metals such as those of weapons hidden under clothing from a distance of several meters, without exposing the persons to harmful radiation. There are many other applications, such as identifying the validity of documents by identifying THz metallic thin-film structures covered by only optically in transparent paints. THz spectroscopy is used to characterize many materials, including packaging, explosives and drugs. A recent application has been to characterize single-wall nanotube thin film electrodes. In another approach, using a separate pump beam to excite charge carriers in a material shortly before the THz analysis is carried out; information about ultrafast carrier dynamics may be obtained. A recent example of such time-resolved THz measurement deals with poly (3-hexylthiophene) and methanofullerene blended films.

THz radiation can pass through clothing and packaging, but they are strongly absorbed by metals and many other inorganic substances. THz sources use a number of basic techniques, namely either harmonic extraction from the mm-waves or using various methods from the optical signals. The possibility of deep-infrared lasers by quantum-cascading reaches the low THz frequencies of interest only by cooling to liquid nitrogen or below.

Here then several approaches are described as developed by the research team of the author and his international research partners, together with an assessment of the capability for wide-spread applications. Of course a decision is made here to not base the approach on such techniques as quantum cascade lasers, where low-temperature usage appears to be required for the generation of lower THz frequencies as required for the security issues under consideration.

2.2 Ballistic Electron Wave Swing (BEWAS)

A new type of THz source is presented, which can provide relatively large signal powers up to 2 THz. It is based on an electron resonance structure formed by a semiconductor heterojunction structure. The electrons in n-layer need to be accelerated by V_e – applied alternating voltage. They reach the barrier of the widegap semiconductor and are reflected without any loss of kinetic energy. They then travel ballistically towards the opposite barrier, where they are reflected again. When V_e changes the polarity, this process continues. The resulting electron resonance produces THz signals. The new concept is based on room-temperature reflection of ballistic electrons in a short (length L typically 150 nm) high-mobility n-type semiconductor terminated at both ends by wide band gap materials. The length L is sufficiently short for ballistic electron resonance to occur at room temperature. The reflection occurs at the edge of the heterojunctions without any loss of kinetic

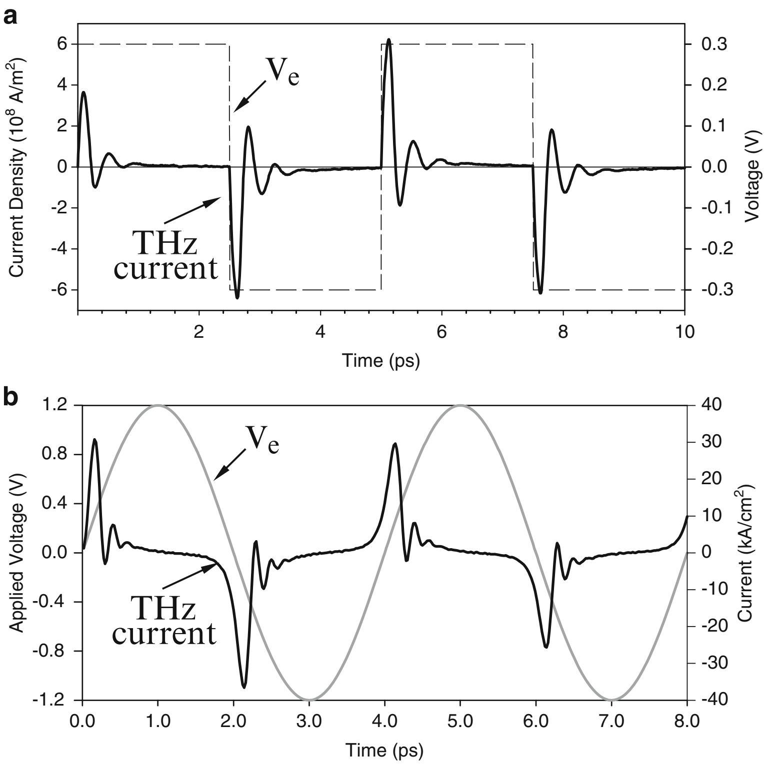


Fig. 2.1 Temporal evolution of current density in response to (**a**) square-wave and (**b**) sinusoidal signal

energy. The electrons are accelerated towards the barrier by an energizing RF voltage V_e, (of typically 100 GHz) sinusoidal or pulse-shaped voltage. The electrons are reflected several times with gradual loss of energy due to occasional scattering. They then need to be accelerated again by the opposite phase of the voltage of V_e. The material to be selected needs to exhibit good ballistic properties and InGaAs is considered here, although there are possibly even better materials.

Monte Carlo simulation, undertaken by Prof. D. Sheng Ong [1] under Humboldt Fellowship with the author in Darmstadt, has shown that this device gives an efficiency of more than 40 % of a suitably designed 1 THz device (Fig. 2.1). This device is not a harmonic generator for V_e (say the 100 GHz input), but generates the THz signal by electron resonance. The device is therefore an electron wave device which can be considered to be equivalent to the electromagnetic wave resonator, i.e. the well-known laser. The energy is provided by the applied V_e. The fabrication of an n++InGaAs–InAlAs–n InGaAs–InAlAs-n++InGaAs structure with ohmic contacts at both ends is performed by the research student Ion Oprea [2] in Darmstadt (Figs. 2.2 and 2.3).

Fig. 2.2 Epitaxial layers of the wafer used

Layer	Thickness(nm)	Doping(cm^{-3})
n^{++}-$In_{0.53}Ga_{0.47}As$ contact	150	$1x10^{19}$
$In_{0.52}Al_{0.48}As$ barrier	15	undoped
$In_{0.53}Ga_{0.47}As$ spacer	3	undoped
n^{+}-$In_{0.53}Ga_{0.47}As$	144	$1.5x10^{16}$
$In_{0.53}Ga_{0.47}As$ spacer	3	undoped
$In_{0.52}Al_{0.48}A$ barrier	15	undoped
n^{++}-$In_{0.53}Ga_{0.47}As$ contact	2000	$1x10^{19}$
InP substrate S.I.		

CST Microwave Studio solver was used to design and calculate the microstrip circuitry. The microstrip circuitry was fabricated on a ceramic thermoset polymer composite substrate and the devices were flip-chip soldered on it. The measurements were performed with the setup consisting of an Anritsu MG3692A signal generator, the microstrip circuitry embedded in a microstrip test fixture and an HP 8565E spectrum analyzer. The results are presented in Fig. 2.3b. These depend of course on the frequency dependence of the terminating network. An optimization should be possible for a selected output frequency by employing electronic resonance terminations. To enhance the effect, several of these resonant structures can be operated in series, provided that the electron charges in several neighboring swings do not interfere with each other to affect the operation negatively. The series connection has also the benefit of enhancing the impedance of this device as required for suitable incorporation in an electronic structure.

2.3 Double Step-Recovery Diodes for Diffusive Electron Resonance a Further New Concept for THz Signal Generation

A heterostructure equivalent to the well-known step recovery diode principle, arranged as a double structure gives a new nonlinear device for highly efficient harmonic THz signal generation. Like in the case of step recovery diodes, these devices exhibit promising performance especially for the generation of higher order harmonics. Theoretical and experimental results are presented. The well-known

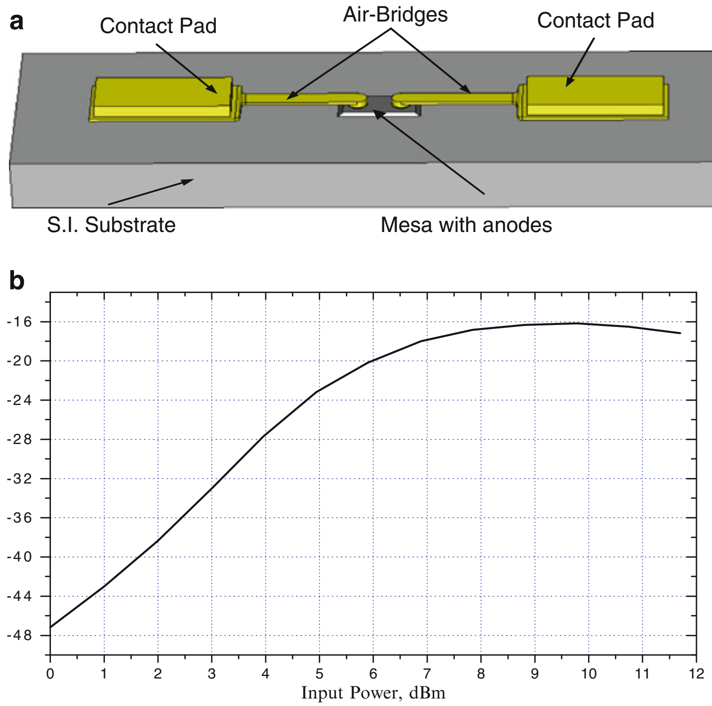
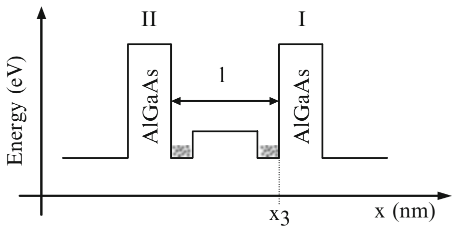


Fig. 2.3 (**a**) Test structure employed and (**b**) preliminary measurements of the output power from a two barrier BEWAS (the vertical scale is the uncalibrated output power, and the correct values were not determined. The output frequency was around 0.06 THz and the input at about 15 GHz, therefore this represents only a feasibility of the effect and not yet a try THz source)

Fig. 2.4 Schematic illustration of the energy band profile for enhanced THz harmonic output by diffusive transport



step recovery effect of pn-junctions can be realized in a highly improved way by transferring the basic principle to heterojunctions. In fact, two barriers opposing each other via a narrow-gap semiconductor such as AlGaAs/GaAs/AlGaAs or InAlAs/InGaAs/InAlAs with a suitable n-doping can be considered as two step-recovery-diode junctions in opposition, which operate without any dc bias requirement. There are several types of structurization. One has a localized bile electron source in front of the barriers, as shown by Fig. 2.4. Here a suitable doping is employed (see Fig. 2.4).

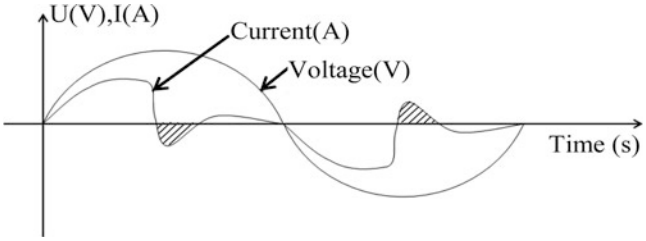


Fig. 2.5 Variation of the output harmonic signal as function of the input RF versus time for equivalent double step recovery diode

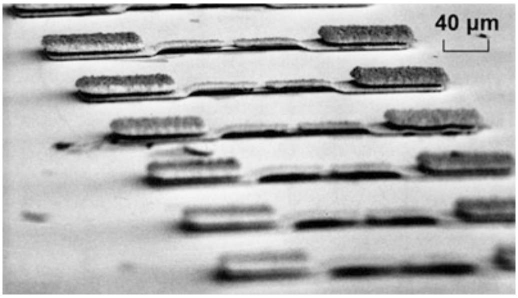


Fig. 2.6 SEM picture of two fabricated devices connected in planar approach

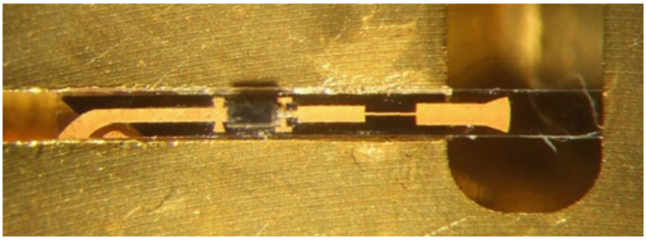


Fig. 2.7 Microscope picture of the fabricated circuitry with the device mounted on a gap of the microstrip line

When the fundamental wave voltage is applied, the electrons from the higher potential trough travel towards the lower potential barrier by diffusive transport. When the electrons reach the opposite barrier, they are stationary there so that the current is abruptly terminated. When the opposite phase of the fundamental takes place, these electrons are travelling to the opposite barrier until they are stationary there (see Fig. 2.5). This step-recovery type of behavior produces sharp interruptions of current, ideally-depending on the design –half through the phase. Such current interruptions have a considerable harmonic constant, which can be taken out by filtering. Experimental realizations [3] are shown by Figs. 2.6 and 2.7.

The cut-off frequency of the new types of devices was estimated to exceed 1 THz. Therefore, and for ease of manufacturing and measurement, frequency multiplication from W-Band frequencies (75–110 GHz) to approximately 300 GHz was chosen as a first step to validate the theoretically found results. The fabrication approach included a planar tripler circuit on a quartz substrate and the growth and dicing of two of the structures shown in Fig. 2.4, connected in series configuration. The device was flip-chip mounted on a 50 μm thick substrate with the microstrip circuitry developed and optimized by simulation for sufficient impedance match and low transmission losses. Figure 2.7 shows a microscopic view of the planar circuitry. Using WR-03 and WR-10 waveguides as input and output in split-block technology provided a fully waveguide based tripler setup with the possibility of TRL-calibration and error correction. A geometrical model of the device was used within full 3D field simulation software to include parasitic effects of the device structure. When feeding the input waveguide of the resulting split-block with a frequency of 102 GHz the output signal around 306 GHz was clearly detectable proving that the theoretical approaches hold. The measured efficiency, however, did not reach the simulated values up to now. Higher input power and improved circuit design with tunable elements are expected to raise the efficiency for tripling operation to higher values.

2.4 Optical Pulsed Techniques and Continuous Wave Methods

To generate THz radiation using suitable materials such as some of the compound semiconductor materials as targets, the optical excitation can be provided [4] by typically a 12-fs mode-locked Ti:sapphire laser of center frequency 790 nm and repetition rate 75 MHz. The emitted THz radiation is then detected either using a pneumatic Golay cell (incoherent detection) or in a conventional time-domain spectroscopy arrangement using electro-optic (coherent) detection.

An extension of the ballistic device is the use of simultaneous dc biasing and the generation of mobile electrons in a short quantum well of smaller gap values by a pulsed optical signal. The optical pulses can be longer than half of the THz period due to space charge limited effect of electron bunch transfer. Therefore, this approach can be extended also to the involvement of low-cost femtosecond laser pulsers together with a dc bias voltage. Instead of solid-state ballistics, corresponding laser-pulse initiated field emission of electron bunches in a THz vacuum resonator can be employed, too [5]. Another approach was also recently published, where resonant tunneling structures were employed to sharpen the electron energies of the ballistic electrons [6], see Fig. 2.8.

By using two laser emissions with frequency differences in the THz range, continuous wave sources can be obtained for very convenient application conditions. A considerable effort is under way in Darmstadt, as can be seen by a large range of recent publications (see [7–11]).

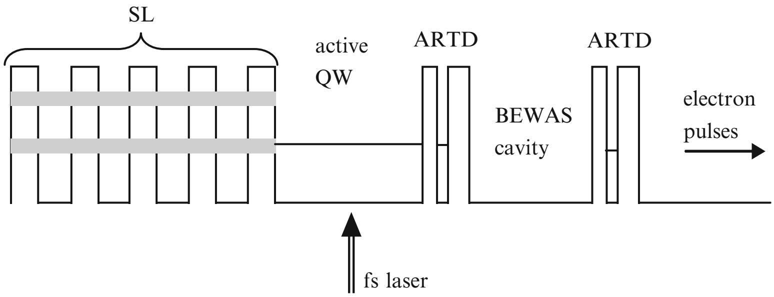
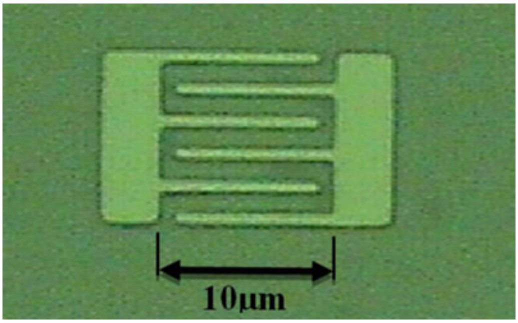


Fig. 2.8 Schematic representation of the conduction band of the THz source

The dominant cw optoelectronic technology here is *photomixing employing materials with short mobility lifetimes and charge-carrier lifetimes* (corresponding to ultrafast trapping and ultrafast recombination, respectively). The most successful and until recently the only available material is LTG-GaAs (LTG: Low-Temperature-Grown) with a carrier trapping time constant of about 0.3 ps and a recombination time constant of several ps. Antenna-coupled photomixers on the basis of LTG-GaAs have proven to be versatile emitters and detectors of THz radiation providing for high signal-to-noise ratios in optoelectronic systems. And this is despite the fact that the emitters even of these workhorses of cw THz optoelectronics have output powers of not more than 1–2 μW. While LTG-GaAs for a long time has been the only useful choice for cwphotomixing, more recently new ultrafast GaAs-based materials and growth/preparation techniques have emerged such as GaAs with ErAs island and ion-implanted GaAs. In synchrony with the development of a wider material basis and inspired by an improved understanding of the material-science aspects concerning ultrafast materials, attempts to develop ultrafast materials also for wavelength ranges other than 0.8 μm, and namely for the 1.55-μm telecom window, finally begin to look promising. Materials with short lifetimes, high mobility of the photo-generated charge carriers and the required high dark-resistivity emerge (among others, LTG-GaAsSb at TU Darmstadt) thus gradually establishing a potential for THz optoelectronics based on 1.55 μm lasers.

There is a long-established consensus in the community that it is highly desirable to establish 1.55 μm THz optoelectronics and move away from the 0.8-μm wavelength regime. The first reason is the superior properties of the relevant semiconductor materials as compared with GaAs, notably the higher electron mobility, which promises a larger sensitivity of THz detectors and, together with the better thermal conductivity, let us expect the generation of more output power of the THz emitters. The second reason is the possibility to link THz optoelectronics with the 1.55 μm telecommunications technologies. This by itself brings with it a number of advantages, the first and foremost being that of the much more advanced performance status of high-power semiconductor lasers and (fiber) amplifiers with operation at a single lateral and longitudinal mode. Costs of these lasers are also significantly lower and the lifetimes longer. In addition, with the fact in mind that

Fig. 2.9 First step product photomixer (Ni Material 93 nm above **N$^+$i GaAs**)



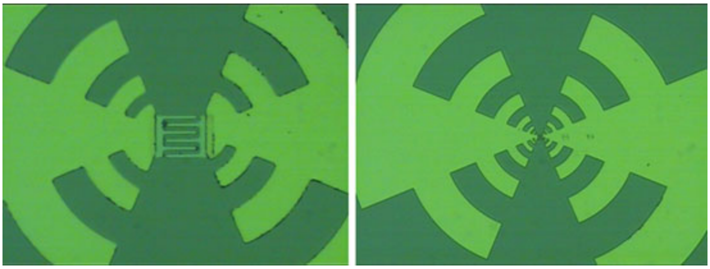


Fig. 2.10 Second step complete antenna with photomixer (Cr 20 nm + Au 105 nm above N+i GaAs)

the significance of the 1.55-μm wavelength regime arose from fiber, one would like to draw on the vast available fiber technologies there in order to enable the building of robust, hands-off and eye-safe THz systems where the optical power is delivered through fibers and where the THz unit of the system can be spatially separated by many meters from the optical unit containing the light source. An advantage not to be forgotten is the sustained advance of the telecommunications components technology which would also feed and support technological advances in THz optoelectronics in the future. The N$^+$i GaAs was developed (TU Darmstadt Laboratory) into complete photoconductive devices by using the Lithography, Photoresists and Developers and by using the specific Lithography Mask (log-periodic antenna) for photomixers and antennas suitable for THz wavelengths (see the figures below) (Fig. 2.9).

Photomixing can be very generally defined as the optical heterodyne down conversion of two laser beams with detuned frequencies (here in the THz range). The "photoconductive mixer" or photomixer consists therefore of a current source, able to deliver a current modulated at high frequencies, connected to a planar distributed circuit such as a planar antenna or a coplanar waveguide. The active element, i.e. the photomixer is essentially a photoconductor (Fig. 2.10).

The photoconductance of the switch is modulated by the optical beating of the two CW laser sources (each assumed to be single mode), producing a THz current

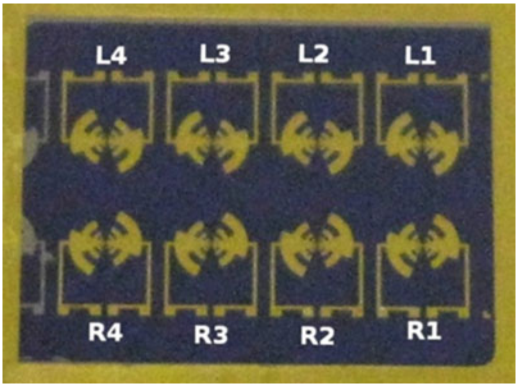


Fig. 2.11 Complete sample with 8-antenna with photomixer

which when feed into a planar antenna generates electromagnetic radiation in the THz frequency range. The advantages and novelty introduced by the usage of **N^+i GaAs** as the photoconductive material resides in the extremely short carrier trapping time (suitable for modulation of the photocurrent at very high frequencies) and also the high dark resistivity and the relatively high mobility (Fig. 2.11).

2.5 Field Emitters of Electrons in Vacuum to Generate THz Signals

New types of Terahertz generators are proposed which is based on field emission of electrons into vacuum. Here are vacuum travelling-wave structures used to generate such signals, as well as revisited triode type tubes such as the dynatron. A particular suggestion is a heterostructure field emitter of electrons involving laser pulses [12].

Electron beam based sources promise great efficiency. A novel miniaturized tunable, portable THz source use the Dynatron oscillator concept [12]. Electron beam based sources promise there the great efficiency required. Presently 200 GHz radiation sources are employed in airport body scanners which are several dm^3 in size. Industry requires a miniaturized source to enhance speed and resolution of the scanning process. A portable THz source for this frequency range uses the Dynatron oscillator concept. This is composed of a triode tube with a grid voltage higher than the anode voltage. This configuration accelerates secondary electrons from the anode to the grid, which makes the dynatron to act as a negative resistance. A serial or parallel oscillator circuit is connected between the anode and a working point potential source with a value lower than the extraction grid. The primary electron beam charges the oscillator capacitance to self-excited oscillations, see Fig. 2.1.

In the presented system a miniaturized triode with field electron emitter is employed, having a cathode to grid capacitance of $24 \cdot 10^{-18}$ F and a total beam

Table 2.1 Dimensions for IR-sources in the 0.2–10 THz range

Frequency (THz)	Wavelength (μm)	Resonator E0 (μm)	1 electron pulse at 100 V travels (μm) IR window (μm)	S/N at 1 mA DC
0.2	1,500	750	15	173
0.5	600	300	6	77.5
1	300	150	3	54
5	60	30	0.6	24.6
10	30	15	0.3	17

length of 1 μm. EBID field emitters can emit up to 1 mA at an extractor voltage of 20 V. EBID electron emitters can provide at an anode voltage of 100 V a beam power of 0.1 W using the miniaturized focusing optics. Such sources render a very high brightness. As a series oscillator is chosen, this charges the capacitor at the resonance frequency up to Q times the applied fixed anode voltage (Q quality factor of the resonance circuit). The oscillator signals control two miniaturized field emitter electron beam sources, which emit charge pulses in each half wave's time to fly across a resonator, however through opposite apertures with opposite directions, see Fig. 2.2. The amplified signal which controls the left electron beam is reversed by a capacitor (C12) to send the pulse of the second half wavelength from the right side. The signals must be adjusted to be in phase by circuit CAD design. Generating IR-dipole radiation with free flying charges avoids energy loss by resistive energy loss and Joule heating in the emitter wire of an emitter antenna system. Such pulsed free flying beams can couple directly a high percentage of the beam energy into the THz radiation. They suffer no resistive loss like wire transmitters do. If a higher extractor voltage is needed for a more powerful field emission, the oscillator voltage can be amplified with miniaturized triodes with field emission cathodes.

The usable voltage is limited in miniaturized beam sources, due to stability requirements of electrostatic elements. Experimentally 100 V can be used in a safe way in vacuum, especially at metal line distances as small as 1 μm. Electrons reach by acceleration at 100 V a speed of 6 μm/ps. The oscillator voltage cuts the DC beam in charge pulses of half a wavelength in length, which corresponds to half the time span of a period. For example: at 500 GHz the pulse length is 1 psec. To clearly separate the two electric fields each beam must pass an aperture of 6 μm diameter located in the center of the resonator through which the electric and the magnetic field of the Hertz Dipole radiation is delivered into the resonator having a dimension of half a wavelength, which is 300 μm at 500 GHz. The required dimensions for sources in the 0.2–10 THz range are listed in Table 2.1. The radiation emitted from the resonator to both sides is aligned by reflectors and focused by lenses. Our simulation using CST Software (Particle and Microwave Studios) shows that this can be beneficial for the technical realization of the miniaturized THz source (Figs. 2.12 and 2.13).

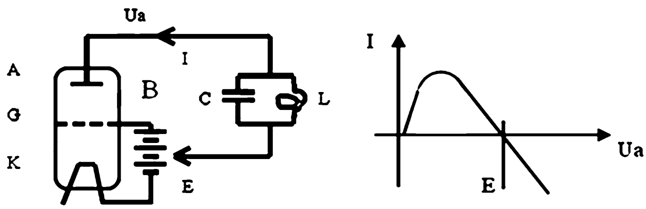


Fig. 2.12 *Left*: Dynatron oscillator circuit with series resonator, *Right*: I–V curve, and work-point E for symmetric oscillation around I = 0 A. A 2 THz oscillator could be obtained with $C = 10^{-16}$ F and $L = 10^{-11}$H

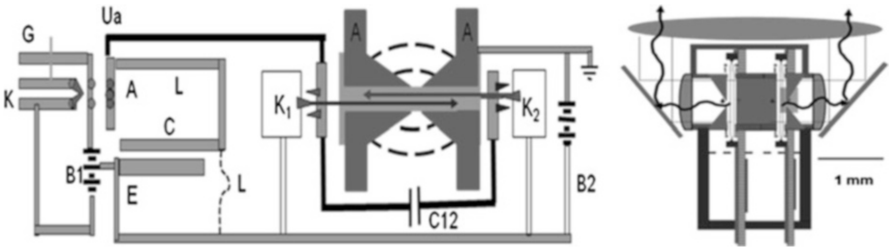


Fig. 2.13 *Left*: Layout of the THz-source. *Right*: 200 GHz source for body-scanner in safety survey applications

2.6 Various Application Areas for Security

2.6.1 Reading Secured Data of Matrix of Metal Squares by THz Wave Reflection

It is common practice to have relevant information stored in optical patterns such as the well-known bar or matrix codes as commonly experienced in supermarkets carrying data like prices as useful for accounting both with the customer as well as with the company administration. There exists an interest to realize this also for THz-wave reading, particularly since this pattern can be covered by a THz transparent, but optically non-transparent paint for security reasons. The information content can then not be recognized in particular by any outside person not having the relevant THz detection equipment. It is even possible to work with flexible substrates and corresponding THz patterns of flexible metal materials as is being developed by a number of laboratories. In fact, instead of metal matrix bars, polymer bars of suitable material for THz interaction might be possible. The pattern might even be optically transparent but THz effective due to its dielectric or conductive properties [13]. Indeed, even money notes are produced by using flexible paints, which often contain THz affecting metals.

Here then a matrix of THz-reflecting metal antennas can be employed, where the presence or absence of such structures carries corresponding confidential digital information. It is then required to read this by identifying the far-field reflection pattern by an array of receiving antennas above the structure after it is illuminated by a centrally positioned THz source. An interesting question concerns the use of THz RFID's on flexible substrates, including liquid crystal structures.

2.6.2 THz Camera for Security Issues

Here, in particular, the development of THz power sources out of laser mixing is a primary interest. This concerns non-linearity effects with various types of materials or with semiconductor structures, which initially need to be simulated by using permissible approximations. An important issue is the handling of waste heat in electronic structures introducing new ideas of heat sinking.

The illumination of individual mixers of an array is undertaken by fibres from the output of two lasers operating at the difference frequency of the THz signal to be generated. The mixer array needs to be composed of mixers which are separated from each other by distances as required for good heat sinking. Such schemes are designed by us now on the basis of a heat-conducting thick metal grid. The THz antennas coupling out the electromagnetic waves are designed by us such that a narrow main lobe with only minimal side arms occurs [14, 15].

Work was undertaken towards a photonic Vector Network Analyzer for THz heterodyne phase-coherent measurements [16]. This is based on the combination of a continuous wave (CW) THz photonic transmitter and a CW THz photonic front-end receiver that serve as THz interface extensions for a radiofrequency Vector Network Analyzer (VNA). The proposed PVNA would be able to perform measurements in the THz range, where both magnitude and phase are directly measured, eliminating all the delays associated with typical time-domain schemes, by adding phase control and measurement to existing photonic THz heterodyne receivers. The proposed scheme makes use of commercial, low cost components to achieve a compact and cost-effective system. This approach is the first scheme for vectorial measurements of THz radiation using a photonic approach for both generation and detection, combining in a single scheme the RF, THz and optical frequency regions. This study was presented at the European Microwave Week in Amsterdam.

Imaging techniques are important issues towards the realization of a THz camera. To obtain Continuous Wave (CW) operation the main issue is power handling via suitable heat sinking strategies [17]. Regarding a maximization of THz illumination, a new design structure and a first experimental approach is introduced by using Nitrogen implanted GaAs (N + i GaAs) material as a photoconductive material. Here in particular the continuous interaction, mostly via e-mail, with a doctoral assistant in Darmstadt, Shihab Al-Daffaie, has been continuing. He is pursuing this work technologically and experimentally. The issue of CW operation requires careful heat transfer designs. Here a study is presented regarding multiple source interconnections in a matrix structure. This is aimed at broad illumination schemes.

The image detection is then based on an array of photoconductive antenna heterodyne receivers illuminated with two phase-locked optical wavelengths obtained from an Optical Frequency Comb Generation (OFCG) for CW operation. This architecture allows for an efficient, phase controlled, Local Oscillator (LO) distribution with low losses intrinsic to the use of optical fibers, as well as amplitude and phase recovery due to the coherence of the LO distributed. Tunable operation is achieved using the different lines of the OFCG and broadband design for the photoconductive antenna.

A design involvement concerns the opportunities of nanometric electronics. The assessment of the fabrication techniques are to be studied. The outcome of such work was an invitation by the University of Shizuoka in Hamamatsu, Japan, to present an "Invited Plenary Paper" entitled "Nanoelectronic Technology" on 23rd January, 2012. In connection with these studies a further invited presentation took place at the 22nd International Conference "Radioelektronika 2012" in Brno, Czech Republic, from 17th to 18th April, 2012 with the title: "The New Age: After Microelectronics – now Nanoelectronics".

2.7 Conclusion

It can be concluded that it is most promising with all these miniature nanometric approaches to achieve general security for the many occasions in modern life, where weapons or explosives have to be identified when large numbers of people enter a facility. There are indeed a number of options as described here. The security issue requires of course small dimensions in order to be implemented easily and reliably. Additionally, the overall cost needs to be acceptable for wide-spread usage.

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