

Short GaAs/AlAs superlattices as THz radiation sources

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Abstract— Semi-conductor devices based on diodes with Schottky barrier are widely used in room temperature applications in the THz frequency range. However, application of Schottky barrier diodes in these frequencies is limited by several factors: long time of carrier passage through the barrier and relatively large specific capacity. Shorter times of the response and the smaller value of specific capacity can be achieved by creation of the diodes on the basis of semi-conductor superlattices. For these diodes we have also minimized values of series resistance R_s and parasitic capacity C_{par} of a substrate carrying the diode. An area of the active region of the diode was less $2 \times 10^{-8} \text{ cm}^2$. Measurement results of the output power level, efficiency and output harmonics content at room temperature are shown for the devices based on the new planar superlattice diodes for input frequency ranges 10-20 GHz, 78-118 GHz and 180-240 GHz. In this report the superlattice device applications as THz radiation sources are discussed.

I. INTRODUCTION

The terahertz domain of the electromagnetic spectrum with frequencies between 0.5 and 5 THz is of great interest to astronomers and spectroscopists. Today, several efficient technical approaches are well established for high resolution spectroscopy in the THz region. Backward wave oscillators (BWO) are tunable and powerful monochromatic radiation sources, which have been phase locked for frequencies up to 1.26 THz [1]. With sideband techniques even higher frequencies are attainable [2, 3], which are not easy to handle and laborious in most cases. Alternatively, tunable far IR laser systems [4, 5] achieve excellent spectra. However, the paucity of laser lines prevents the complete coverage of larger spectral ranges. Beside the development of these high resolution sources, also Fourier transform spectrometers are

used to cover the complete THz spectral range, albeit with low resolution and limited sensitivity. Furthermore, the absolute accuracy of far-IR. The most compact THz radiation sources are THz-frequency lasers and Fourier transform spectrometers strongly depend on the accuracy and the availability of calibration lines. Multipliers, based on harmonics generation due to the non-linearity of the current-voltage or capacitance voltage characteristic of a fast electronic device. One well known frequency multiplier is the Schottky barrier diode, which is successfully used in spectroscopy and astronomy by many groups. See references [6, 7]. In most cases the input frequency is supplied by a powerful cw Gunn-Oscillator or a solid state FET amplifier. Most often these devices are operated as frequency doublers and triplers. Higher order harmonics are available too, however, only with considerably lower power. As a consequence Schottky diodes require relatively high input frequencies with considerable input powers in the range of Milliwatts to reach the THz-range. Therefore it is necessary to cascade several multipliers. Good examples for such devices are multiplier chains especially designed for the 1.5 THz regime [8] and 1.9 THz regime [9]. However, their employment for different applications is limited since they are optimized for a certain restricted frequency window.

Application of diodes with barrier Schottky in this frequency range demands increase in limiting frequency of work of the diode, f_p (the frequency determining the top border of a working range of the diode). Limiting frequency is determined directly by features of the physical processes proceeding in semi-conductor structure: in particular, for diodes with barrier Schottky flight electron inertia active area. So, time of flight for the best diodes about 1 ps [7]. On

the other hand, limiting frequency is substantially caused by influence parasitic capacities of the diode, C , and its consecutive resistance, R_s , consisting of resistance of thickness of the semiconductor, contact connections and conclusions of the diode. The specific capacity of the diode with barrier Schottky with the area of active region in units square now makes micron not less than 10^{-7} F/cm², and reduction R_s by doping increase is limited to value of concentration $5 \cdot 10^{17}$ sm³ [10, 7].

Shorter times of the response and smaller sizes of values of specific capacity can be achieved by creation of planar diodes on the basis of semi-conductor superlattices [11, 12]. Superlattices have also the volt-current characteristic with negative differential conductivity [13] which is kept down to frequencies above 1 THz [14]. Set of these properties makes superlattices by rather attractive object of researches, as the generators made on their basis and frequency multipliers and as detectors and mixers can form a basis of new solid-state sources and receivers of THz electromagnetic waves. A semiconductor superlattice [13] can show a negative differential resistance giving rise to the build-up of domains. Recently it has been shown that domains in semiconductor superlattices can be used for frequency multiplication. During a cycle of a microwave field, domains are created and destroyed. The corresponding current gives rise to higher harmonics of the microwave field. The frequency multiplication has been demonstrated for fundamental frequencies near 20 GHz [15] and near 70 GHz [16]. Here, we report on a frequency multiplier based on SLED, which operates as radiation sources up to 2.7 THz. We produced comparison SLED and Schottky diode by observation of the submm waves beats arising in SLED and Schottky structures, illuminated by two microwave signals. Studying the emission spectrum from SLED was driven by an electric field of 20 GHz, near 100GHz with a Fabry-Perot interferometer, 120-140GHz and 190-220 GHz with a Fourier Transform Spectrometer (FTS), by driving HEB at 1THz with a SL-tripler and by investigating with Superlattice Multiplier, pumped by BWO(110,210-260GHz), an absorption line of deuterated water vapor and methanol gas.

II. SUPERLATTICE ELECTRON DEVICE

The key element of the frequency multipliers, harmonic generator was a superlattice electron device(SLED). The made SLED (Fig.1) had two ohmic contacts of the different area located on the top border of a superlattice in parallel to its layers in the structure. High-frequency currents flew through a gold pad, the active element, an n⁺ GaAs layer and the large-area mesa to the second contact pad or in the reverse direction. The superlattice (Fig.2) with length 112 nm had 18 periods, each period (length 6.22 nm) with 18 monolayers GaAs and 4 monolayers AlAs and was homogeneously doped with silicon (2×10^{18} cm⁻³).

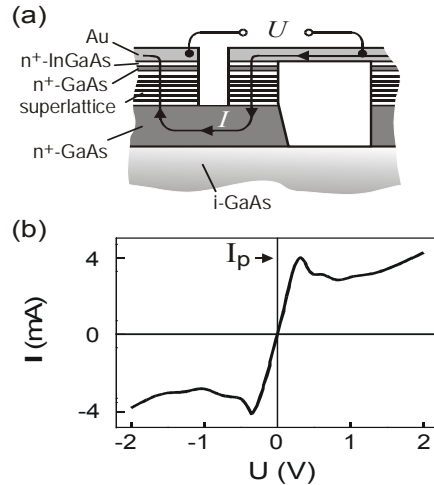


Fig.1 (a) Sketch of the SLED based on the GaAs/AlAs superlattice; (b) SLED current-voltage characteristic at 300 K

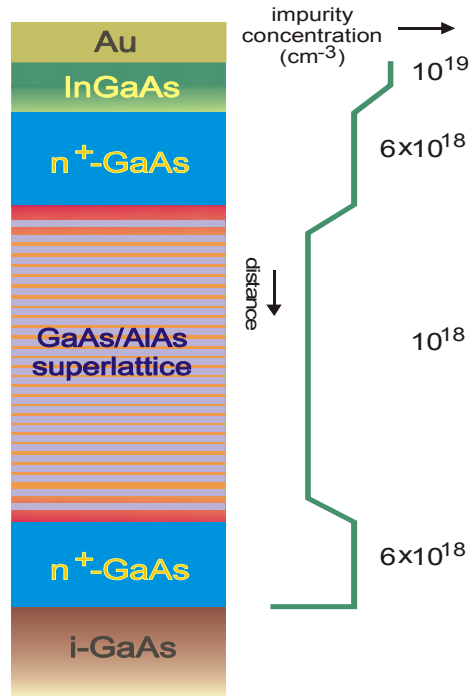


Fig.2 the view of the superlattice structure

The miniband width (25 meV) was sufficient to lead to miniband rather than hopping transport. By molecular beam epitaxy, we had grown, on an intrinsic-GaAs substrate, an n⁺ GaAs layer (thickness 1.5 μm; doping 6×10^{18} cm⁻³), GaAs/AlAs gradual layer (thickness 32 nm), then the superlattice, again a gradual layer and n⁺ GaAs and an n⁺ InGaAs gradual layer (25 nm) and finally an n⁺ InGaAs layer (20 nm, doping 10^{19} cm⁻³) serving as ohmic contact. The gradual layers delivered smooth transitions with respect to layer thicknesses and doping, respectively.

Current-voltage characteristic of the SLED subject to a static voltage is presented in Fig. 1b. The current increases almost linearly for a voltage smaller than the critical voltage (U_c), reaches its maximum value (I_p) at the critical voltage

and then decreases. Kinks in the current-voltage characteristic can be attributed to the formation of the electric field domain within the superlattice region. For definition of resistance of ohmic contact the made SLED were used, namely, the voltage enclosed to the SLED, was expressed through a current proceeding through it and resistance of the SLED. Calculation and measurement of resistance of various sites SLED structures have allowed to find resistance of ohmic contact of the small area. Results of calculation of resistance of contact R_k for structures of the various area are submitted on fig. 3 (the top part). In the considered file of SLEDs (100 pieces) with the area of active region from 2 up to $6 \mu^2$ prevail. Resistance of contact to growth of the area decreases as $1/S$, therefore it is expedient to proceed to resulted resistance $R_k \times S$ of contact. On fig. 3 (the bottom part) is submitted dependence of the resulted resistance of contact on its area. Averaging on a file of SLED gives average value of the resulted resistance about $2 \times 10^{-7} \text{ om/sm}^2$. The received value of the resulted resistance is in the good consent with values of resistance of the ohmic contacts generated by a method molecular-beam epitaxi on basis $\text{Ga}_{1-x}\text{In}_x\text{As}$ ($5 \times 10^{-7} \text{ om/sm}^2$) [12], and also InAs ($2 \times 10^{-7} \text{ om/sm}^2$) [7]. On fig. 3 (insert) results of comparison of resistance of ohmic contact R_k with resistance of superlattice R_2 and resistance n +-layer R_n are resulted. For the areas of active region of the diode smaller $2 \mu^2$ resistance R_n is less than resistance of ohmic contact because of strong dependence of the last on the area. Full consecutive resistance of the diode ($R_k + R_n$) appears much less resistance of a superlattice. With growth of the area of active region contact resistance quickly decreases, resistance R_n varies slowly and becomes comparable with resistance of a superlattice R_2 at $S=10 \mu^2$.

Thus, use of threefold connection InGaAs at formation of ohmic contact in SLEDs on basis GaAs/AlAs of a superlattice has allowed to reduce considerably consecutive resistance of the SLED in comparison with its value for SLEDs with ohmic contact on the basis of alloy Au-Ge . For reduction of parasitic capacity of substrate C_{par} of the SLED, the substrate thickness in the place of the air bridge has been finished up to 2-4 microns. See Fig.1. The mechanical stability of the SLEDs appeared sufficient for carrying out of electric measurements on a direct current and mounting in various circuits of devices of THz range of frequencies. Thus limiting frequency of such SLEDs with the area of active area $4 \mu^2$ on the basis of a superlattices from 18 periods has made approximately 4-6 THz

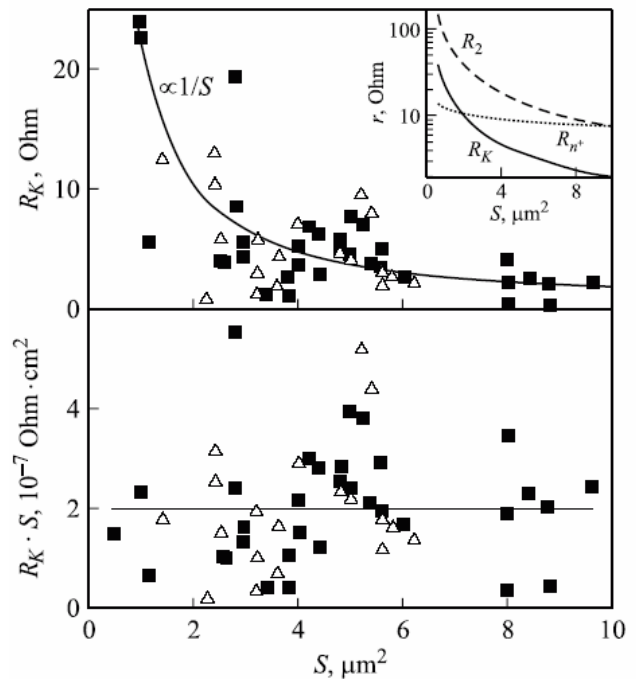


Fig.3 The top part: dependence of resistance of ohmic contact from its areas for SLEDs with length of a superlattice of 18 periods, received as a result of processing experimental data and by averaging on all file of SLEDs (a continuous line). The bottom part: dependence of the resulted resistance of ohmic contact on its area received as a result of processing experimental data and by averaging on all file of diodes (the same designations). An insert: dependence of contact resistance (a continuous line), resistance of a superlattice (a shaped line) and n +-layer of the SLED (dashed line) from the area of active region.

Superlattice Structures are made in Ioffe Physico-Technical Institute, St. Petersburg. SLED are designed and made in Radiophysics Department, Nizhny Novgorod State University.

III. Measurements

The block for test measurements are shown on the Fig.4. The block consists of a single mode waveguide, diagonal horn and SMA connector. For different frequency ranges the waveguide sizes are changed. For multipliers the single mode waveguide for pump was added. We produced measurements for direct comparison SLED and Schottky diode. For this we used the method [17]

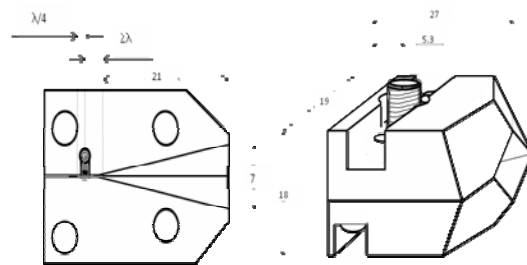


Fig.4 Block for test measurements (output frequency more 550GHz)

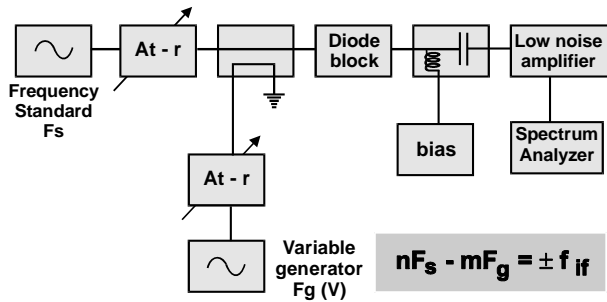


Fig.5 Experimental setup for observation of the submm waves beats

Experimental setup are shown on the fig.5. The tested structures, mounted in the diode block, are irradiated by two signals F_s and F_g . Low frequency signal of beats f_0 between the harmonics nF_s and mF_g , arising in the tested structure, can be determined with equation $nF_s - mF_g = \pm f_0$, where n and m are whole numbers. The signal f_0 is fixed by spectrum analyzer with input band 0.1-1.5GHz. Varying F_g it's possible to determine the maximum number of SBMM harmonics m and n , arising in the tested structures.

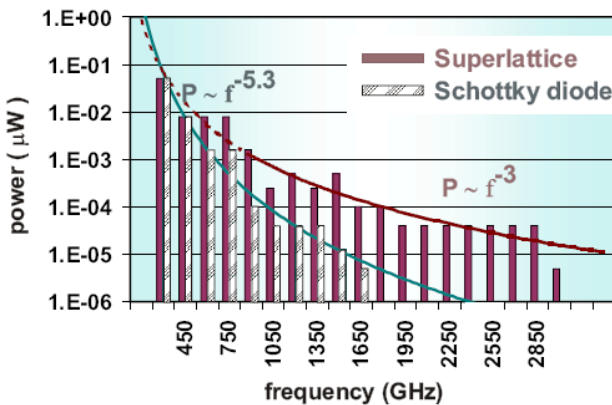


Fig.6 Result of comparison of the SLED and Schottky diode

The result of comparison of the SLED and Schottky diode are shown in fig. 3 for F_g 100-115GHz and F_s 125-150GHz. It shows us, that SLED is more effective for generating high number harmonics than Schottky diodes.

Measurements have been carried out in Radiophysics Department, Nizhny Novgorod State University.

IV. DEPENDENCE OF THE RADIATION POWER EMITTED BY A SLED SUBJECT TO A HIGH FREQUENCY ELECTRIC FIELD AT DIFFERENT TEMPERATURE

Output spectrum of the harmonic generator was measured using Fourier Transform Spectrometer (FTS). 20 GHz monochromatic signal was applied from the HP 83752B frequency synthesizer to the harmonic generator in all measurements.

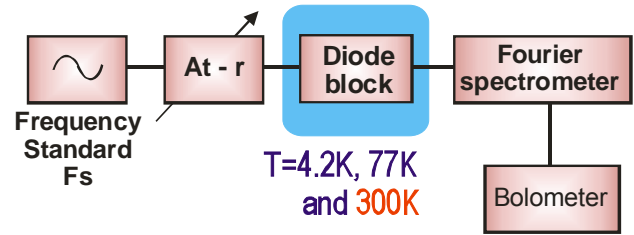


Fig.7 Experimental setup for harmonics generation of SBMM waves

Harmonic generator was mounted into an Infrared Lab dewar, so that measurements at different temperatures can be performed. Results of the tests at 300 K, 77K, and 4.2 K are presented in Fig. 2. Absolute amplitude of the response was not calibrated. The magnitude of the harmonics become one order as large with the temperature decreasing from 300 K to 4.2 K.

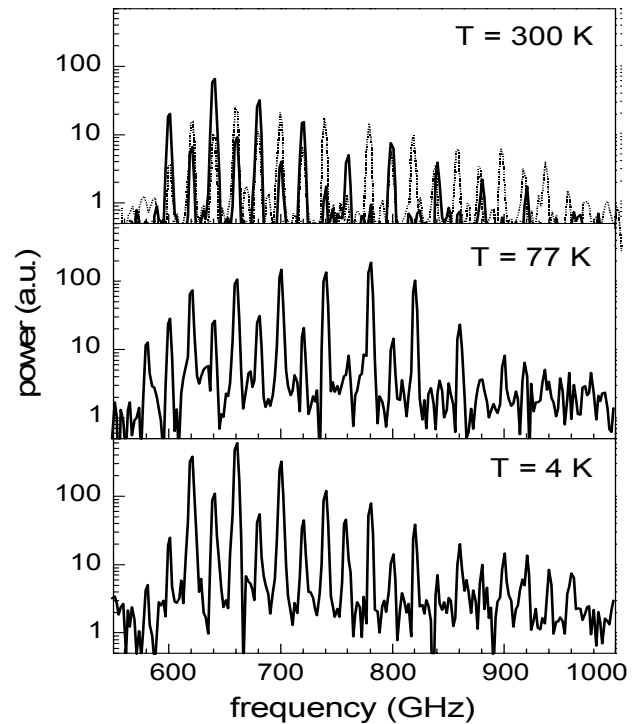


Fig. 8 FTS spectrum of the harmonic generator at 300 K (upper part), 77K (middle part), and 4.2 K (lower part) for input signal power of 5 dBm (dotted) and 13.2 dBm (solid)

Results of the tests at 300 K, 77K, and 4.2 K are presented in Fig. 8. Absolute amplitude of the response was not calibrated. The magnitude of the harmonics become one order as large with the temperature decreasing from 300 K to 4.2 K.

Measurements have been carried out in Institute for Space Research (SRON).

V. SUPERLATTICE FREQUENCY MULTIPLIER FOR THE SUBMILLIMETER WAVELENGTH RANGE

The SLED was built in a two-waveguide arrangement (Fig. 9 c) suitable for the microwave pumping and the extraction of higher-harmonic radiation. We analyzed radiation with a Fabry-Perot interferometer [18] (Fig. 9d) and registered radiation with a liquid helium cooled silicon bolometer.

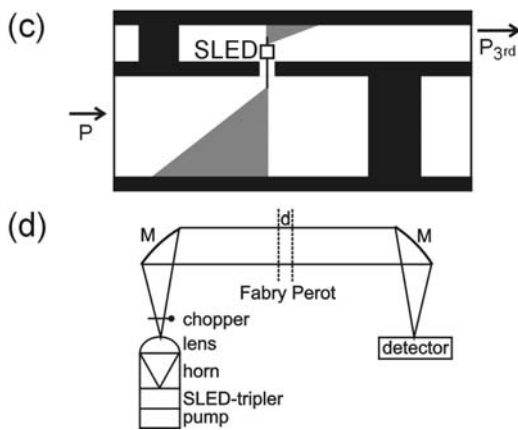


Fig. 9 c, frequency tripler. d, arrangement.

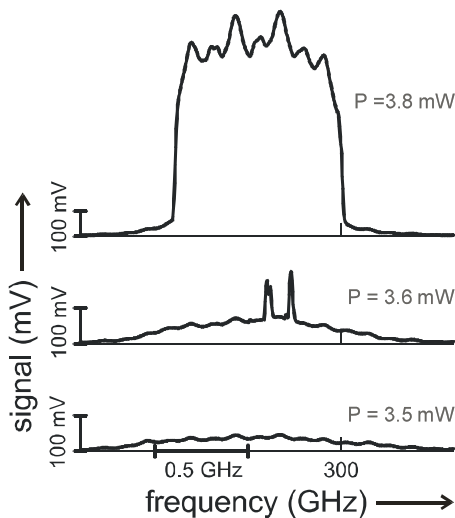


Fig. 10: Output signal of the frequency multiplier for the third harmonic (around 300 GHz).

The emission was especially strong at a frequency near 300 GHz (Fig.10). The emission characteristic has been obtained by pumping the tripler with radiation of a frequency synthesizer (3 mW power). By pumping with a stronger source (BWO) we obtained strong emission in a larger frequency band. The Fabry Perot interferogram (Fig.11) showed that the 3rd harmonic was the strongest. However, also higher harmonics have been observed in the Fabry Perot interferogram curve. Various investigations of the frequency tripling have been published elsewhere [19, 20].

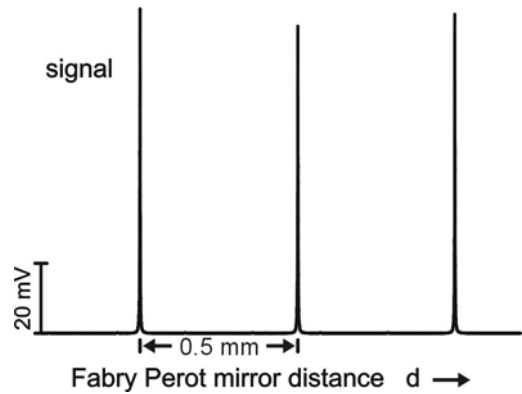


Fig.11 Fabry Perot interferogram.

Also we report a semiconductor superlattice frequency quintupler for tunable generation of submillimeter wave radiation in a wide frequency range. Pump radiation (frequency 100 -140 GHz few mW) was converted to 5th harmonic radiation (500 to 700 GHz; power few μ W).

The superlattice quintupler Fig.12 has an input waveguide with a low frequency cutoff at 75 GHz and an output waveguide (and a horn) with a cutoff frequency of 450 GHz. A superlattice diode is coupled by a finline antenna to the input waveguide and a wire antenna to the output waveguide.

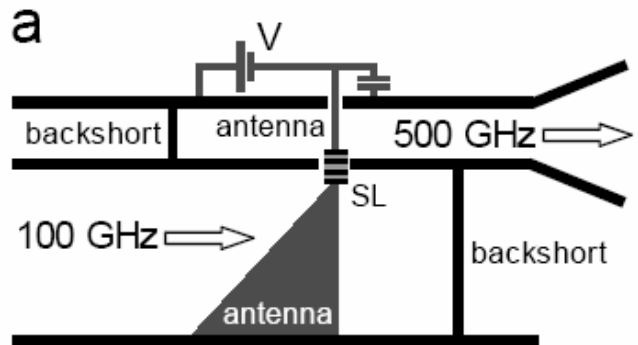


Fig.12 Fabry Perot interferogram.

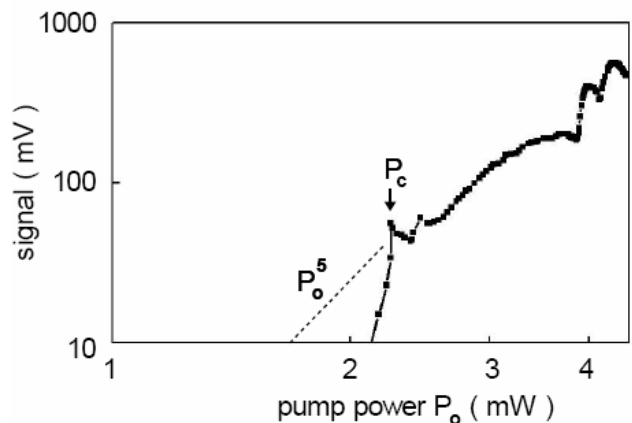


Fig.13 The 5th harmonic power

The quintupler was pumped with radiation of Gunn oscillators. We determined the spectrum of the output radiation either by use of a Fabry-Perot interferometer with a Golay cell as detector. A power meter allowed to measure the power of the radiation.

The 5th harmonic power Fig.13 showed a strong increase above a critical pump power P_c and then increased further with increasing pump power. Below P_c , the signal is increasing much steeper than the dependence (P_0^5) expected for a conventional frequency quintupling. We attribute P_c to the onset of domain formation; i.e. at P_c , the amplitude of the pump field reached the critical field (V_c). Accordingly, at larger pump power, the pump field was able to create to annihilate during each half cycle a domain giving rise to the frequency multiplication. The power level at strongest pumping was few μ W. It was almost the same over the whole frequency range 500 - 700 GHz we studied. The power corresponded to a power conversion of about 0.1 percent.

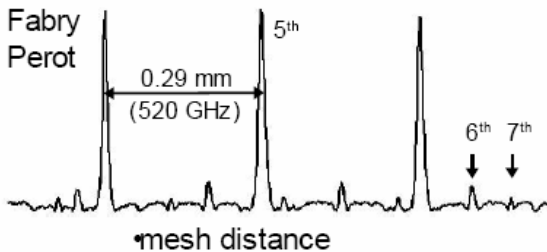


Fig.14 Fabry Perot interferogram.

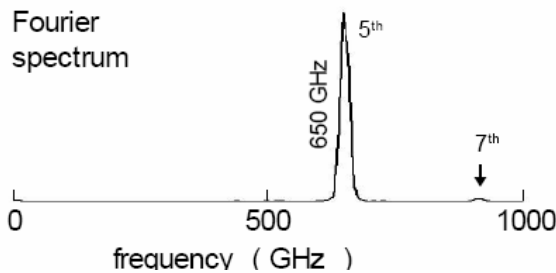


Fig.15 Fourier spectrum

The Fabry-Perot interferogramme and the spectrum measured with the Fourier transform spectrometer Fig.14 and Fig.15 indicate, that the emission was mainly at the 5th harmonic. The Fabry-Perot interferogramme delivered, additionally, signal peaks for the 6th and 7th harmonics. The 6th harmonic occurred because of not pure asymmetry of the superlattice. The 6th harmonic did not appear in the spectrum that was obtained for a higher input frequency. The reason is most likely a different matching to the output waveguide.

Measurements have been carried out in Institut für Angewandte Physik, Universität Regensburg.

VI. EXPERIMENTAL STUDY OF THE HARMONIC GENERATORS, BASED ON SUPERLATTICES, IN WIDE FREQUENCY RANGE 120-220 GHz.

The non-biased superlattice diodes was driven by an electric field with of 120-140GHz and 190-220 GHz. For measurements the same experimental setup shown on the fig.7 was used. The frequency synthesizers (20 GHz) with frequency multiplier chains and MIMIC [18] power amplifiers was used for pump. We observed intensive enough 3th (apr.50-100 μ W), 5th (apr.10-20 μ W),7th (apr.1-2 μ W),9th(apr. less 0.1 μ W).

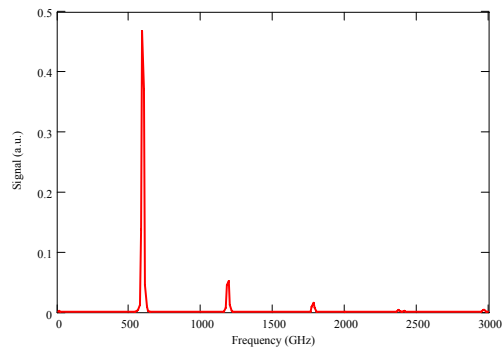


Fig.17 The output signal with input frequency 197.4GHz. It's observed intensive 3th (apr.50-100 μ W) harmonic. Before bolometer was used 12dB attenuation.

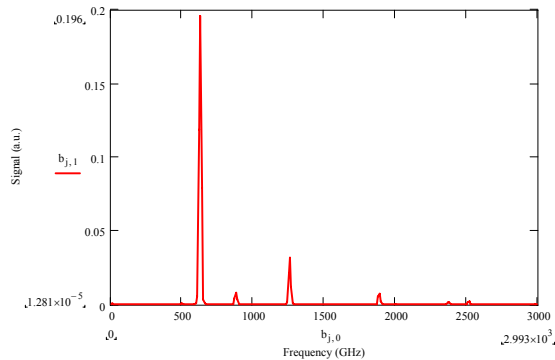


Fig.18 The output signal with input frequency 124 GHz. It's observed the intensive 5th (apr.10-20 μ W) and 7th(apr.1-2 μ W) harmonics. Before bolometer was used 12dB attenuation.

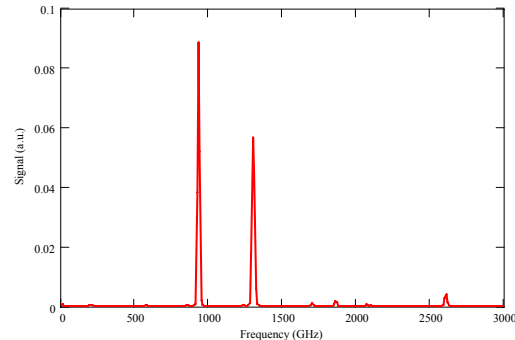


Fig.19 The output signal with input frequency 187.2 GHz. Observed the intensive 5th and 7th (1-2 μ W) harmonics. Even the 9th harmonic was visible (100-200nW).

Measurements have been carried out in Institute for Space Research (SRON).

VII. DRIVING HEB MIXER WITH A SUPERLATTICE MULTIPLYER

The possibility of using the superlattice (SL) multiplier as a local oscillator at a frequency of 1THz for a hot-electron bolometer (HEB) mixers has been demonstrated in the experiment, which was carried out in the DLR Institute of Planetary Research, Berlin. The setup is shown in Fig. 20; it consists of a phase-locked backward-wave oscillator at 300 GHz and the SL Tripler with a diagonal horn. Fig.21 and Fig.22 show relative output power and the intensity radiation pattern of the SL Tripler, respectively. The optimally pumped voltage-current characteristic of the HEB mixer is shown in Fig.23 along with the unpumped curve. The output power of the SL-Tripler slightly less than 1 μ W was estimated with the calibrated Golay cell detector.

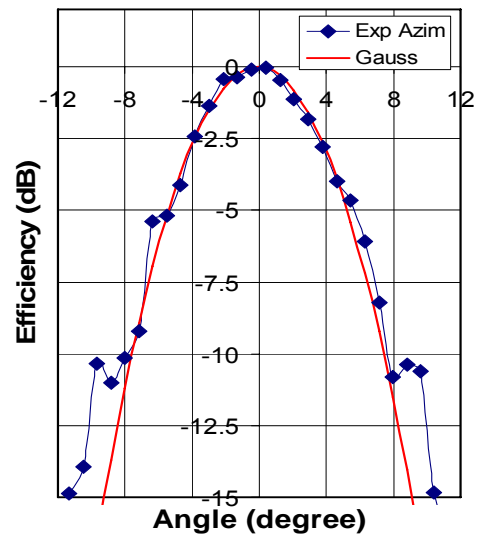


Fig.22 Intensity radiation pattern in the far field of the SL-Tripler horn.



Fig.20 Experimental setup. 300 GHz BWO with an output power \approx 20 mW (multimode) and the SL-Tripler providing output power \leq 1 μ W at frequencies up to 1 THz.

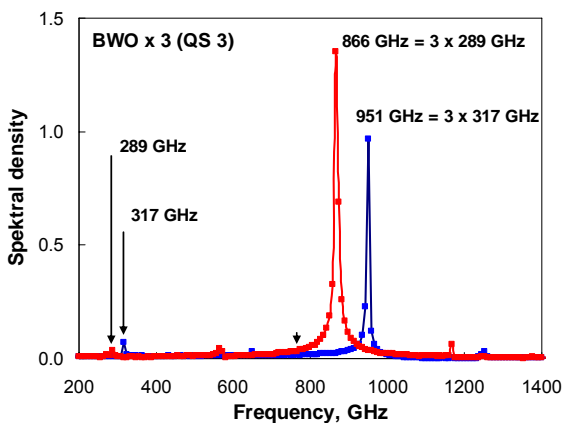


Fig.21 Relative output power of the SL-Tripler in the frequency band 866-951GHz.

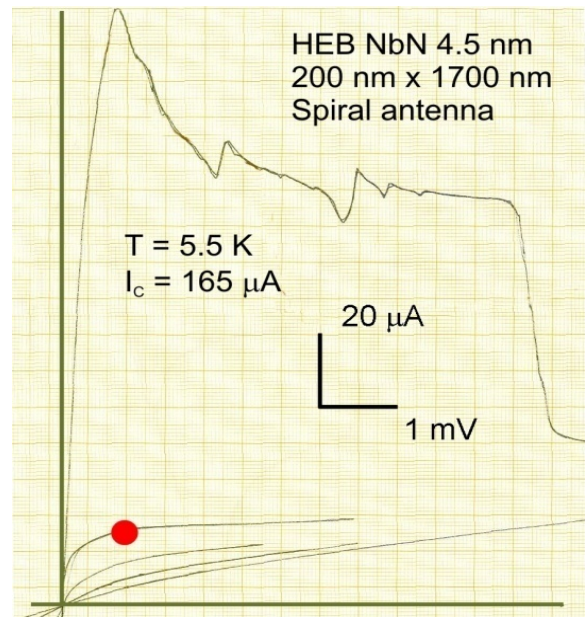


Fig.23 Voltage-Current characteristics of the HEB optimally pumped with the SL-Tripler. Red point marks the optimal operation regime.

VIII. SL MULTIPLIERS FOR BROADBAND MOLECULAR SPECTROSCOPY COVERING 300GHZ TO 2700GHZ WITHOUT GAPS

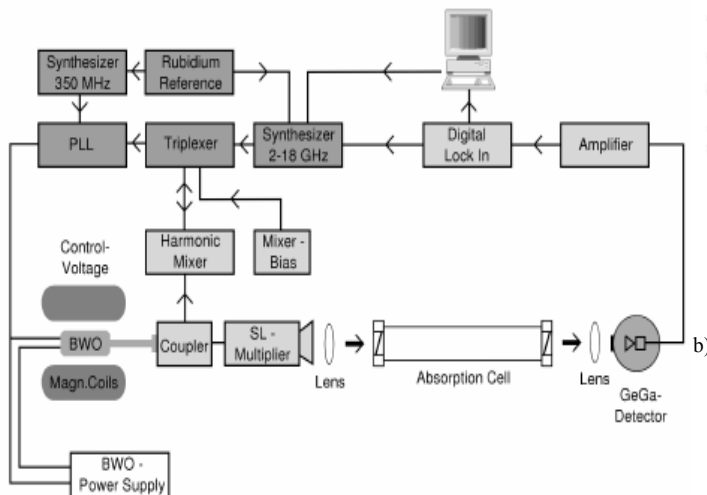


Fig.24 A sample Setup of the THz-Spectrometer with Superlattice Multiplier. I.Physikalisches Institut, Universität zu Köln, Germany.

In the present spectrometer setups we used two different SL multipliers designed for input frequencies centered at 100 GHz (SL I) and 250 GHz (SL II). In all experiments presented here only unbiased Superlattice multipliers were used in order to maximize the power fed into the odd numbered harmonics.

The SL multipliers have been used in combination with two continuously tunable BWO oscillator as input radiation sources, delivering output powers of 10-60 milliwatts throughout the entire frequency range from 78 to 118 GHz for SL I and from 130 to 260 GHz for SL II. The BWOs are stabilized in frequency via a phase locked loop (PLL) w.r.t. a rubidium reference with a frequency accuracy $\delta f/f = 10^{-11}$. For detection of SL output power below 2.33 THz a magnetically tuned InSb Hot Electron Bolometer (NEP = $3.5 \text{ pW} = \text{pHz}$) has been deployed, while a Ga doped Ge photoconductor with significantly higher sensitivity (NEP = $0.6 \text{ pW} = \text{pHz}$) has been used for higher frequencies. A sketch of the spectrometer setup is shown in Fig.19. The main fraction of the fundamental output radiation generated by the BWO is coupled into the SL multiplier and only a small fraction is used for the PLL circuitry. Two high density polyethylene lenses focus the harmonics generated in the SL through a 3.5 m long absorption cell into the detector. The detector signal is frequency selectively amplified, and 4 demodulated by a lock-in amplifier. In all cases the $2f$ frequency modulation technique is used for recording spectra.

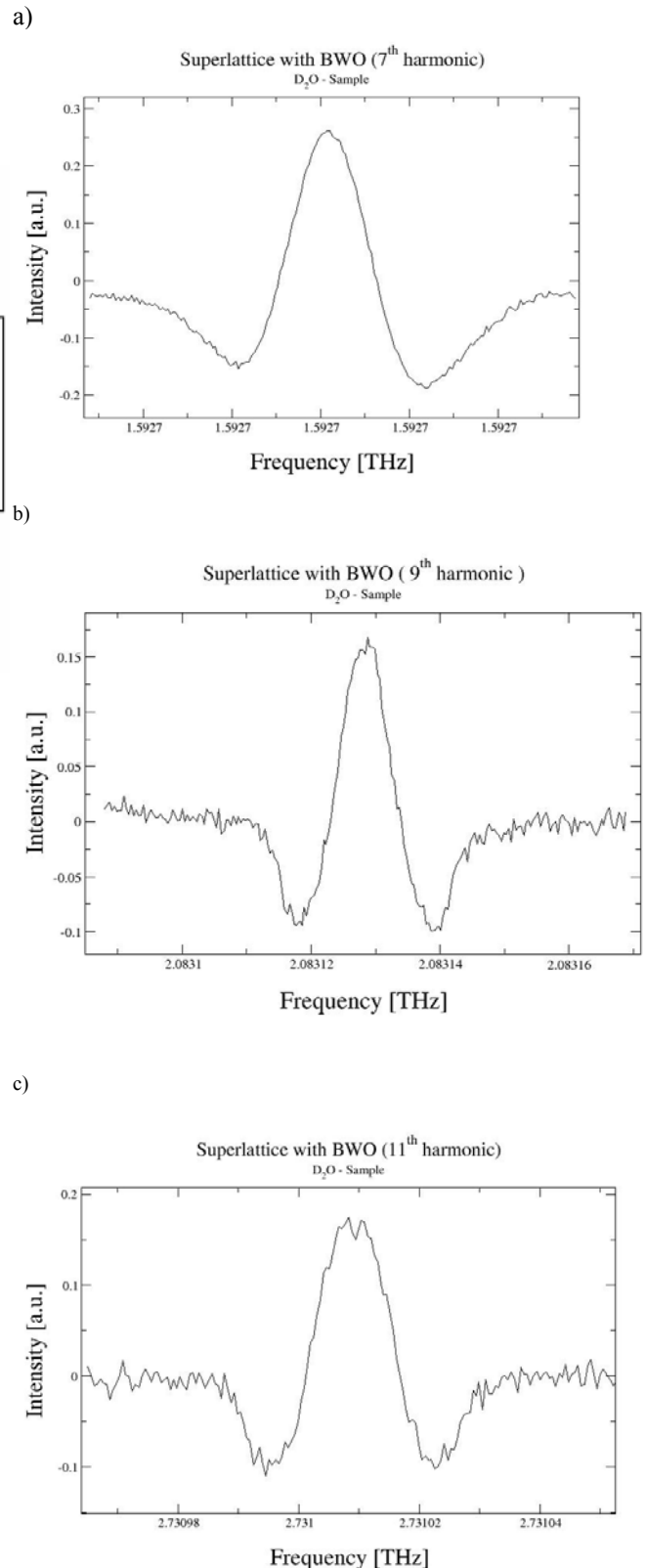


Fig. 25 a,b,c Spectrum of deuterated water vapor, obtained by the 7-11th harmonic of the superlattice frequency multiple SL II

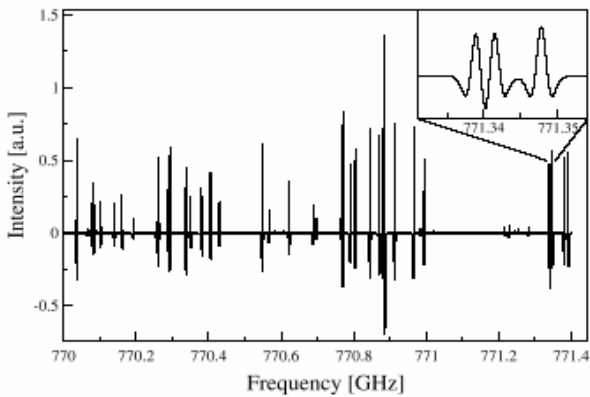


Fig.26 Broadband scan of methanol using the 7th harmonic generated by SL I the upper right corner a blow-up is shown, which demonstrates the high spectral resolution of the measurement and the low noise

The measurements show us that the SL operated sources are indeed producing higher order odd harmonics in sufficient supply for laboratory spectroscopy, very high line accuracies can be achieved, broad band scans are feasible and overall very high frequencies up to 2.7 THz can be used for spectroscopy.

Measurements have been carried out in I.Physikalisches Institut, Universität zu Köln.

IX. THE MEASUREMENTS MIXING SIGNALS OF SUPERLATTICE FREQUENCY MULTIPLIER AND GAS LASER IN THz FREQUENCY BAND USING HEB MIXER.

HEB mixers now is the most sensitive receiver in THz frequency band. We used this device for investigation harmonic content of superlattice multipliers, pumped in frequency range 100-120GHz, near 1800GHz and 2500GHz. We observe the 17th Fig.27 and 19th Fig.28 harmonics by using the line of gas laser 1891.2743, and 23th Fig.29 and 25th Fig.30 by using the line of gas laser 2522.7816.

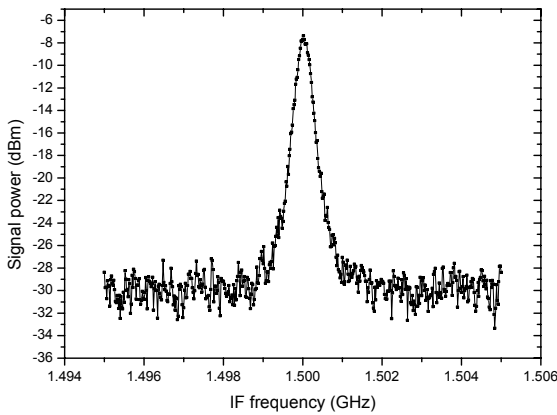


Fig.27 Mixing signal of superlattice frequency multiplier ($F_s = 111.1631941 \times 17 = 1889.7743$ GHz) and the gas laser at 1891.2743 GHz using HEB mixer

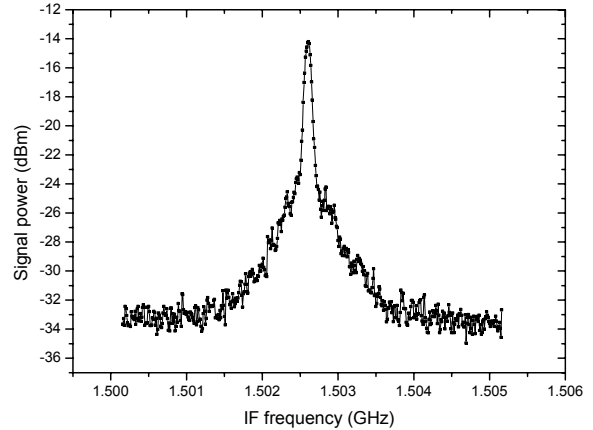


Fig.28 Mixing signal of superlattice frequency multiplier ($F_s = 99.46179921 \times 19 = 1889.7742$ GHz) and the gas laser at 1891.2743 GHz using HEB mixer

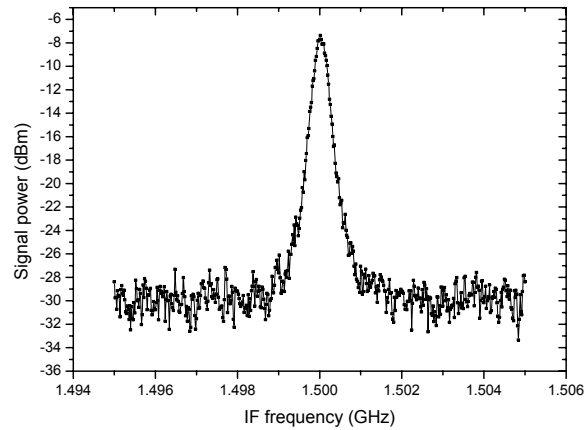


Fig.29 Mixing signal of superlattice frequency multiplier ($F_s = 109.629391 \times 23 = 2521.1475993$ GHz) and the gas laser at 2522.7816 GHz using HEB mixer

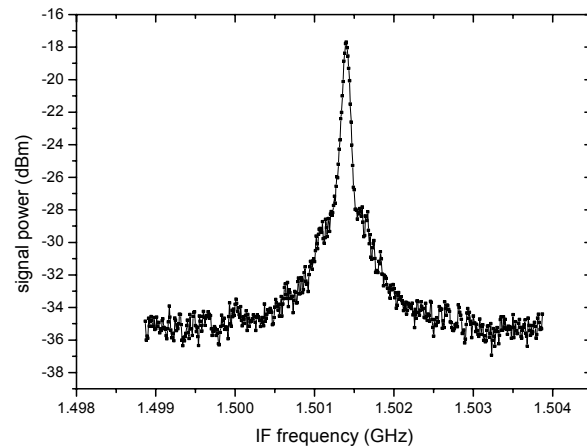


Fig.30 Mixing signal of superlattice frequency multiplier ($F_s = 100.85164 \times 25 = 2521.2816$ GHz) and the gas laser at 2522.7816 GHz using HEB mixer

Measurements have been carried out in Institute for Space Research (SRON).

CONCLUSION

The optimisation of SLED for SBMM application is produced. It's found that multipliers based on SLED have Higher Harmonic Content compared to Schottky devices. The Capability for High Resolution Spectrometer up to 3THz is demonstrated. Room temperature SLED multipliers operation as well as 77K and 4K is shown. On the base of measurements in various radio systems SBMM lengths electromagnetic waves it is possible to draw a conclusion, that devices on short GaAs/AlAs superlattice now are real Thz radiation sources. In future this devices will be invstigated for locking quantum cascade laser up to 4 THz with 20-50 GHz LO and for broadband LO for SIS and HEB THz mixers.

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