Electromagnetic Wave Detection Via Interaction With Non-Uniform Distributed Space Charge In Vacuum

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Abstract. The detection of electromagnetic radiation of subterahertz (up to 0.14 THz) and IR regions obtained from the interaction with non-uniformly distributed space charge in the interelectrode space of a vacuum triode with plane electrodes is experimentally demonstrated. The dependence of the detected signal from the direction of wave polarization and vacuum triode's current characteristics has been investigated. A simple theoretical model, according to which, the detection is due to nonlinearity associated with the non-uniform distribution of electrons along the electrostatic field direction, has been proposed to explain the mechanism of detection. The measured detection characteristics reasonably agree with theoretical results, based on low-level signal approximation and assuming that the current-voltage characteristic of the used devices (triodes) obeys the law of 3/2.

Terahertz (THz) range of electromagnetic radiation (0.1-10 THz) bridges the gap between the microwave and optical regions, and offers significant scientific and technological potential in many fields (sensing, imaging and spectroscopy, diagnostics of various facilities, environmental monitoring, imaging, nondestructive testing, security applications and so forth) [1-3], since the rotational transition frequencies of molecules of gases and liquids, oscillation frequency of complex biological molecules and optical phonons of solids are in this range. Non-ionizing nature and weak scattering of THz radiation in the fine-dispersed media makes it very attractive for use in biology and medicine as well[1,2].

Detection at terahertz frequencies obviously differs from the detection at shorter optical wavelengths and longer radio wavelengths. In comparison to shorter wavelengths, due to the low level of photon energies at terahertz frequencies, ambient background thermal noise is dominant than request cryogenic cooling or long-integration-time radiometric techniques.

Besides, the diameter of THz radiation beam is rather large, which makes a mode converter or matched director (antenna) between the signal and detector element necessary. In terahertz field, RF detection shows better performance than optical detection because the crossover frequency at which an ideal thermal noise limited detector (such as a room-temperature Schottky barrier diode) excels the sensitivity of an ideal quantum detector (like a photodiode), falls between 1 and 10 THz [1]. In comparison to longer wavelength radio techniques, lumped electronic components such as resistors, capacitors, and inductors, as well as amplifiers and low-loss transmission media are not available to terahertz detectors.
Thus, fast and sensitive detectors of optical range, operating on the basis of external or internal photoeffect are not suitable for registration of THz radiation. From the other hand the sensitivity of widespread microwave Schottky diodes decreases rapidly in the THz region and sensitive bolometric receivers are inertial, and therefore they are not applicable for registration of fast processes. Therefore, for successful development of terahertz frequency range it is necessary to implement fast, high sensitive and available detectors operating at room temperature [1-4].

In our recent work we have investigated the detection of terahertz waves by using a vacuum diode, as a consequence of nonlinear interaction of electromagnetic waves with the electron flow [3].

In this work we have investigated the detection of electromagnetic radiation of subterahertz and IR regions obtained from the interaction with non-uniformly distributed space charge in the interelectrode space (space between cathode and grid) of a vacuum triode with plane electrodes.

Block diagram of experimental setup is shown in Fig. 1. As a source of electromagnetic radiation in the subterahertz range standard generator G4-161 (maximum output power ~10mW, tuning range 129-142GHz) was used, and in the optical range - a helium-neon laser LG-125 with output power ~12mW ($\lambda = 3.39\mu$, 1.15µ and 0.63µ). Modulation of radiation was realized by using a mechanical chopper. The modulation frequency was ~1 kHz. As a detector, triode 6S15P was used with the most comfortable design of parallel plate electrodes. To ensure penetration of the electromagnetic wave in the interelectrode space, the lamp was located directly in the path of the electromagnetic wave with polarization vector parallel to the direction of electron flow in the tube, as shown in Fig. 1.

![Figure 1](image-url)

**Figure 1.** Block diagram of experimental setup:
1 - generator (G4-161 or LG-125), 2 - modulator (F = 1kHz), 3 - vacuum triode, 4 - bias voltage source, 5 - anode voltage source, 6 - recording system (a-filter, b-amplifier, c-oscilloscope)

From the regulated DC voltage source $\varepsilon_a$ through a ballast resistor $R_a$ anode voltage $U_a$ was applied and the bias voltage on the grid was applied form the source $\varepsilon_g$ via a resistor $R_g$. The detected signal is removed from the anode and after filtering and amplification was registered with an oscilloscope.

The dependence of the detected signal from the direction of incident radiation polarization and current characteristics of vacuum triode has been investigated.
To determine the optimal operating point for obtaining maximum detected signal the anode-anode and anode-grid characteristics of the triode were measured (anode-grid characteristics are shown in Fig. 2).

![Fig. 2. Anode-grid VA characteristics.](image)

**Figure 2.** Anode-grid VA characteristics.

In Fig. 3. are shown lamps location in the way of electromagnetic wave propagation and the dependence of the detected signal from the angle $\theta$ between the directions of the electric field $E_\lambda$ and the electrostatic field $E_0$.

![Fig. 3.- a. lamps location in the way of electromagnetic wave propagation: $E_\lambda$ - the electric field of electromagnetic wave, $E_0$ - electrostatic field, $\theta$-angle between the electric fields $E_\lambda$ and $E_{\text{ip}}$, and "+" -is the direction of electromagnetic wave propagation. b. the dependence of the detected signal from the angle $\theta$.](image)
In the case of detection of electromagnetic radiation in the subterahertz range, the dependence of the detected signal from the bias voltage on the grid of vacuum triode is shown in Fig. 4. The analogous dependence has been obtained in IR range.

![Figure 4. The dependence of the detected signal from the bias voltage on the grid of vacuum triode](image)

As expected, when \( \varepsilon_a \approx 60 \text{V} \) (for \( R_a \approx 30 \text{kOm} \), \( U_a \approx 30 \text{V} \)) the maximum detected signal was obtained at a bias voltage of \(-0.3 \text{V}\). The value of maximum detected signal was \( \approx 25 \mu \text{V} \) in the optical range with laser power \( \approx 1 \text{mW} \) and \( \approx 20 \mu \text{V} \) in THz range \((F \approx 0.14 \text{THz})\) with THz power \( \approx 10 \mu \text{W} \).

A simple theoretical model, according to which the detection in vacuum triode is due to the nonlinearity associated with the non-uniform distribution of charge carriers (electrons) along the direction of the electrostatic field, has been proposed to explain the mechanism of detection.

The nonlinear properties of the triode are due to the non-uniform distribution of electrons along the direction of the electrostatic field. We estimate the value of the detected signal, assuming that the current-voltage characteristics obeys the law of 3/2 and does not depend on the frequency of the applied field, when the plane of wave polarization is perpendicular to the electrodes of the triode. If the wave electric field in the space between cathode and grid uniformly, the difference potential grid-cathode, produced by the wave, can be written:

\[
U_{g-} = E_0 d = E_{0-} \cos \omega t = U_{0-} \cos \omega t ,
\]

where \( E_0 \) is electric field of the wave, \( E_{0-} \) its amplitude, \( U_{0-} \) amplitude of produced voltage, \( d \) - is the interelectrode distance, \( \omega \) - the wave frequency. If the lamp applied also anode constant voltage \( U_{a0} \), and grid constant voltage \( U_{g0} \), in the unsaturated regime for the anode current we have

\[
I_a = aU_{eff}^{3/2} = a(U_{g0} + U_{g-} + DU_{a0})^{3/2} ,
\]

where \( a, b, c \) are constants.
where $D$ is the permeability of triode. The value of the coefficient $a$ for the used vacuum tubes is $a = 1mA/V^{3/2}$, and $D \approx 0.025$ (gain constant $\mu \approx 40$).

Estimates based on formula (2) show, that by value of electromagnetic wave intensity $\sim 10\mu W/cm^2$, and with $U_{g0} \approx 0.3V$, the maximum of the rectified current value is $\sim 3nA$. Current recorded in the experiment was $\sim 1nA$. This difference is quite understandable, because in the experiment there was not ensured consistency, and therefore, only a small part of the radiation power penetrated in the interelectrode space.

Because THz waves occupy intermediate region of the spectrum between the IR and subterahertz, the results can be used in future to develop THz detectors based on vacuum devices.

Despite the fact that the sensitivity of the optical range decreased rapidly ($\sim 100$), however, estimates indicate that in solution of the matching problem and an increase of interaction spaces of radiation with an interelectrode space charge, vacuum tubes can be successfully used for detection, and also for frequency conversion of terahertz range radiation.

References

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