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This book describes the main properties of the terahertz (THz) band electromagnetic oscillations and waves and the distinctive effects of their interaction with matter. The principles of operation, design and parameters of THz sources based on quantum effects as well as charge carrier transport are considered. The reasons for the so-called “terahertz gap” existence is discussed. A detailed description of THz band lasers, photoconductive, semiconductors, superconductors and vacuum devices is given. The book considers, in detail, the problems of advancing “classical” vacuum electron devices into the THz band. It establishes a unified approach to terahertz electron devices based on various physical effects. The book pays considerable attention to the new types of both solid-state and vacuum electron devices that work in the THz band.

CONTENTS

PREFACE

The rapid growth of the information transfer rate in the modern world has led to an increase in the working frequency of radio-electronic systems. Over the past century, the maximum operating frequency of communication systems has grown by almost a million times and has come close to the terahertz band. The same tendency is observed in radar systems. Many other areas of science and technology now use THz band electromagnetic radiation.

The terahertz band occupies an intermediate position in the spectrum of electromagnetic oscillations, between the microwave and optical bands. Electromagnetic oscillations and the waves of the THz band have several characteristics that distinguish them from those of the adjacent bands, and these have a significant impact on methods of generation, amplification and reception, as well as on the choice of the most promising areas of application.

The main advantage of THz range radiation is the ability to provide a high information transfer rate in communication systems and a high resolution in radar and radio imaging systems. THz radiation interacts intensely with plasma, metals, semiconductors, superconductors and dielectrics, which can expand the capabilities of spectroscopy and other technologies. The non-heat influence of THz radiation on living objects is also being studied intensely.

However, despite the apparent advantages of the terahertz band oscillations in a wide number of applications, the development and implementation of THz equipment meet with substantial difficulties due to the low efficiency of both the quantum and classical devices operating in this range of the spectrum.

When quantum devices (in particular, lasers) move from the optical to the THz band, they decrease sharply in their efficiency and output power. The miniature size of both the THz band vacuum and semiconductor electron devices prevents the development of compact, powerful coherent sources of terahertz radiation using traditional technology. Because of these difficulties, the so-called “terahertz gap” arose, in which there is a deficit of coherent sources of radiation that are both efficient and relatively compact.

Currently, many research teams around the world are working to fill this gap. The number of publications on the problems of the generation and detection of terahertz band electromagnetic radiation is growing every year, so it has become difficult for device designers to follow them. Despite the presence of several monographs on terahertz band electron devices [106], [216], [146], [27], [152], [162] as well as reviews, [210], [38], [57], [153] not all the questions related to this problem are being considered in them. In particular, the problems of advancing “classical” vacuum electron devices into the terahertz range are not sufficiently discussed [67].

This book presents an attempt to systematise the available information about the properties of THz band radiation and the effects of its interaction with substance. Sources and detectors of the terahertz range are also considered. The main problems connected with the development of efficient sources and receivers of terahertz radiation are formulated, and the basic methods of generation, amplification, and detection of oscillations are described.

The author hopes that this book will be useful to designers of microwave and terahertz equipment, students and postgraduates studying microwaves, terahertz electronics, and similar subjects.

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The author

MAIN NOTATIONS

The book uses the SI international system of units. Scalar values are denoted by Latin letters in italics *(a, A)* or Greek letters (α, ψ). Mathematical constants are denoted by upright font Latin or Greek letters (e, I, π). Characters, denoted vectors, tensors, and matrices are bold (**a**, **A**). When necessary, matrix notations (including column and row vectors) are enclosed in straight brackets (|**a**|, |**A**|), and tensor symbols are overlined twice ($\overline{\overline{\varepsilon}}, \overline{\overline{\mu}}$). The matrices determinants and norms are enclosed in double straight brackets (||**A**||). Complex amplitudes (phasors) in specified instances are given with points above the symbol ($\dot{\mathbf{E}}, \dot{\mathbf{H}}$). Operators are denoted by Latin handwritten letters ($\mathscr{R}$, $\mathscr{H}$).

B – magnetic flux density, V·s/m^2;
B – reactive electrical conductance, S;
$c = 2.9979 \cdot 10^8$ m/s – speed of light in vacuum;
D – electric flux density, A·s/m^2;
e = 2.71828 – basis of natural logarithms;
$e = 1.602 \cdot 10^{-19}$ C – absolute value of the electron charge;
$\mathbf{e}_\mathrm{i}$ – a unit vector of axis *i* of orthogonal curvilinear coordinate system;
$\mathbf{e}_\mathrm{n}$, **n** – ort of the external normal to the surface;
E – electric field intensity, V/m;
f – frequency, Hz;
G – active electrical conductance, S;
$h = 6.626176 \cdot 10^{-34}$ – Plank constant, J·s
$\hbar = h / (2\pi)$ – reduced Plank constant.
H – magnetic field intensity, A/m;
$\mathrm{i} = \sqrt{-1}$ – imaginary unit;
I – electric current, A;

J – electric current density, A/m^2;
$\mathbf{J}_s$ – electric current surface density, A/m;
k, **k**- wave number, wave vector, 1/m;
k_0, $\mathbf{k}_0$ - wave number, wave vector in the free space, 1/m;
$k_B = 1.380 \cdot 10^{-23}$ – Boltzmann constant, J/K;
M - magnetisation, A/m;
n - refractive index of the medium;
n_p, n_g – phase and group velocities slowing factor;
P – power, W;
p - power density vector (energy flux), W/m^2;
P - electric polarization (electric moment), A·s/m^2;
Q – resonator's quality factor;
q – electric charge, C;
R – active electrical resistance, Ohm;
U, *V* – Voltage (electric potentials difference), V;
W – energy, J;
w – energy density, J/m^3;
$\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}}, \mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$ – axes of the Cartesian system of coordinates;
X – reactance, Ohm;
Y – complex admittance, S;
Y_0 – characteristic admittance of the medium, S;
Y_c – characteristic admittance of the transmission line, S;
Y_g – wave admittance of the transmission line, S;
Z – impedance, Ohm;
Z_0 – characteristic impedance of the medium, Ohm;
Z_c – characteristic impedance of a transmission line, Ohm;
Z_g – wave impedance of a transmission line, Ohm;
α – attenuation constant, 1/m;
β – phase constant, 1/m;
γ – transverse propagation constant, 1/m;
δ – skin depth, m;
ε – absolute permittivity, А·с/(В·м);
$\varepsilon_0 = 10^7/(4\pi c^2) \approx 8.854 \times 10^{-12}$ – dielectric constant, А·с/(В·м);
$\eta_0 = 120\pi \approx 377$ Ohm – characteristic impedance of vacuum;

κ - electrical susceptibility;
λ – wavelength in the free space, m;
λ_c – critical wavelength of a transmission line, m;
λ_g – wavelength in a transmission line, m;
μ – permeability, V·s/(A·m);
$\mu_0 = 4\pi \times 10^{-7} \approx 1.257 \times 10^{-6}$ – magnetic constant, V·s/(A·m);
$\mathbf{\Pi}$ – Poynting vector, W/m^2;
ρ – density of the electric charge, C/m^2;
ρ – resistivity, Ohm/m;
σ – conductivity, S/m;
τ - relaxation constant, s;
φ - phase;
Φ - magnetic flux, V·s;
χ – magnetic susceptibility;
$\omega = 2\pi f$ - angular frequency, s^{-1}.

INTRODUCTION

According to ITU[1] recommendations, the terahertz frequency band (THz band, T-rays) occupies a part of the electromagnetic oscillation spectrum from $3 \cdot 10^{11}$ to $3 \cdot 10^{12}$ Hz (wavelengths in free space of 1 mm…100 μm). However, often, the THz band is expanded to 0.1 – 10 THz ($1 \cdot 10^{11}$ – $1 \cdot 10^{13}$ Hz), which corresponds to wavelengths in free space from 3 mm to 30 μm.

Fig. I-1 shows the position of the THz band in the electromagnetic oscillation spectrum. As one can see, it is located between the microwave and optical bands. The generation and detection of THz radiation are performed by devices based on free charge carrier transfer, as well as by devices based on the quantum transitions of bound charged particles from one energy state to another.

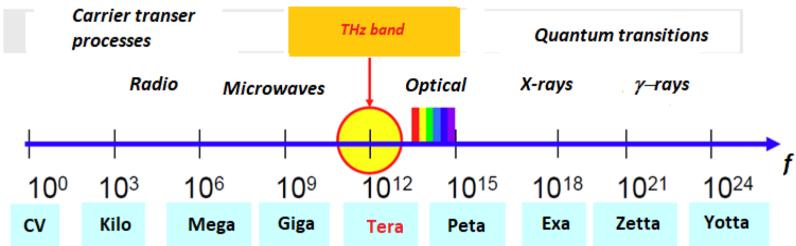

Fig. I-1. Electromagnetic oscillation spectrum

The first work devoted to the study of terahertz electromagnetic radiation properties appeared more than a century ago [148]. Since then, interest in this part of the electromagnetic oscillation spectrum has been continuously increasing. A. Glagoleva-Arkadyeva made a significant contribution to the field [59], developing a device known as the mass emitter. The device consisted of a vessel filled with metal sawdust suspended in oil. The

[1] International Telecommunication Union

rotating wheel was partially immersed in this vessel from the top. This wheel captured a thin layer of the oil and sawdust mixture. A voltage, applied to the wheel in its upper part, caused an electrical breakthrough between the grains of sawdust and the generation of electromagnetic waves whose length was comparable with the size of the sawdust particles. The author managed to produce electromagnetic waves with a wavelength of 50 mm – 80 μm, thereby filling the gap between microwaves and infrared radiation.

In their first experiments Hertz, Popov and Marconi used spark-gap transmitters, which generate damped oscillations with a centre frequency of about 100 MHz, i.e., lying in the short-wave band. However, such oscillations cannot be used to transmit speech or music. Therefore, arc and machine generators were developed in the early 1900s, operating in the continuous mode, but in the lower frequency range – tens and hundreds of kilohertz. Using a kind of machine generator – the Alexanderson alternator – Fessenden (USA) performed the first radio transmission of music in 1906. The transmitter's operating frequency was 100 kHz. Electromagnetic waves of this frequency propagate along the Earth's surface with relatively little attenuation. Large antennas are needed for the transmission and receipt of these signals.

With the advent of vacuum tubes, the frequency choice expanded, but in the 1920s, speech and music were transmitted mainly on long and medium waves. In the late 1920s and early 1930s, amateur radio operators noticed that they could receive the signals of low-power short-wave transmitters at a distance of thousands of kilometres. They discovered that radio waves were being reflected from the ionised layers of the Earth's atmosphere. Thus, the beginning of a continuous increase in the radio channel carrier frequency was initiated. The emergence of television in the 1930s gave additional motivation to this trend since high-quality TV could only be realised using the ultra-high-frequency band.

Radar has given a decisive impetus to the increase in the working frequency of radio systems. The accuracy of the target coordinate's determination directly depends on the operating frequency of the radar, so the development of high-power sources of microwave radiation has become the main objective for developers of radar stations. J. Randall and H. Boot at the University of Birmingham, England, successfully solved this problem, creating a multi-cavity magnetron in 1940. Their first magnetrons operated at a frequency of 3 GHz, with pulse power of up to 10 kW.

After World War II, microwave vacuum electronics continued to evolve rapidly. The theory of the high-frequency electromagnetic field interaction with charged particle beams was developed, new types of devices were invented, and their production technology was improved.

In the mid-1950s, the first microwave semiconductor devices – tunnel diodes – appeared. In the 1960s, the IMPATT diode (IMPact ionisation Avalanche Transit-Time diode) and a Gunn diode (a transferred electron device, TED) were invented. These diodes produce tens of milliwatts of power at frequencies of up to 10 GHz. At the same time, microwave transistors appeared – both bipolar and field-effect types. Now, the maximum operating frequency of these devices exceeds 100 GHz. However, developers face severe difficulties in advancing both microwave vacuum and semiconductor devices into the terahertz band.

Elementary charged particles (CPs) are the source of electromagnetic radiation in an electronic device. These particles can be within the composition of atoms or ions (bound charged particles) or can move relatively freely to macroscopic distances (free particles).

The bound charged particles in quantum systems (atom, molecule, crystal) occupy specific energy levels. The emission of a quantum of electromagnetic radiation (a photon) occurs during the particle's transition from a higher energy level to a level with lower energy. The emitted photon carries away an energy equivalent to the difference between the energies of the two levels. During the reverse transition, a particle absorbs a photon. The operation of the numerous light sources, in particular, lasers, is based on the photon emissions by bound charged particles. A. Einstein showed that the probabilities of junction "from top to bottom" and "from bottom to top" are the same. Therefore, for the operation of quantum sources, it is necessary to maintain a state in which the number of particles at the upper energy level exceeds the number of particles at the bottom level (population inversion). In lasers, such an inversion is maintained by pumping energy.

Free charged particles radiate electromagnetic energy (photons) if they move with deceleration (*bremsstrahlung*). Radiation also occurs when a particle moves near a surface separating two media (*transition radiation*) and when it moves at a velocity higher than the speed of light in a given medium (*Vavilov-Cherenkov radiation*). Oscillation radiation and some other radiation mechanisms also exist. All of these effects are used in microwave electronic devices.

During the 1930s–1950s, a large number of microwave vacuum electron devices were invented, which made it possible to generate and amplify oscillations with a frequency of up to 30 GHz. However, the further advancement of these devices towards higher frequency bands turned out to be difficult because the device size is strictly connected to the radiation wavelength. With an increase in the frequency of n times, the main dimensions of the device must decrease n times, and its area – and the ability to dissipate heat – n^2 times. The law $Pf^2 = C_e$ expresses this relationship, where P is the output power, f is the frequency, and C_e is the constant, the value of which is determined by the type of device.

It became possible to overcome this law, or rather, to substantially increase the constant on its right side, due to the transfer from closed to open electromagnetic systems. Open resonators, whose dimensions are much larger than the wavelength, are used in free-electron lasers (FELs), gyroresonance devices, and orotrons. These devices can deliver significant power at very high frequencies, including the terahertz range, and FELs can operate up to the X-ray range. However, the mass, dimensions and cost of these devices (or, more precisely, installations) exclude their extensive use. The exception is orotrons. However, these require high magnetic fields for their work.

The development of THz semiconductor devices is also hampered due to their microscopic active regions, the size of which is determined by the carrier's transit time in them. This time should be less than the oscillation period, which determines the active region's small length (base or gate length). Hence, the maximum allowable value of the voltage on the active region decreases, and so does the output power of the device. At present, the output power of terahertz semiconductor devices is several orders lower than the output power of vacuum devices operating at the same frequency.

The development of microwave electronics, aimed at further increasing the operating frequency, output power and other parameters of microwave devices, led to the appearance of terahertz electronics. Therefore, the methods and solutions used in microwave electronics underlie the design of higher-frequency devices. A detailed presentation of vacuum microwave electronics is contained in the books listed in references [186] and [187], and that of vacuum and semiconductor microwave electronics in the works listed in reference [68]. The book [84] considers the interaction between electron devices and surrounding circuits, which has to be optimised.

The invention of lasers in the 1960s made it possible to create quite powerful sources of coherent radiation in the optical range (frequencies of $10^{14}\ldots10^{15}$ Hz). However, there are serious difficulties to be faced in reducing the operational frequency of lasers. As the frequency decreases, the photon energy

$$E = hf \tag{I.1}$$

decreases accordingly; therefore, the same number of photons emitted per unit of time corresponds to a lower radiation power. Besides, in the terahertz range, the difference ΔE between working energy levels becomes comparable with the energy of thermal oscillations $k_B T$; therefore, at room temperature, it is challenging to create the significant population inversion ΔN necessary for the lasers. Indeed, at $W_2 - W_1 = \Delta W = hf \ll k_b T$, where W_1 and W_2 are energies of lower and upper energy levels,

$$\Delta N = A\mathrm{e}^{-\frac{W_1}{k_B T}} - A\mathrm{e}^{-\frac{W_2}{k_B T}} \approx A\left(1 - \frac{W_1}{k_B T} - 1 + \frac{W_2}{k_B T}\right) = A\frac{hf}{k_B T}. \tag{I.2}$$

It follows from (I.1) and (I.2) that for quantum radiation sources, in the first approximation, the law $Pf^{-2} = C_q$ takes place.

The values of C_e and C_q in modern devices are such that the curves $P = C_e f^{-2}$ and $P = C_q f^2$ intersect near the frequency $f_{gap} \approx 1$ THz, forming the so-called terahertz gap – the frequency range in which the output power of classical and quantum sources of radiation is minimal. Filling this gap is one of the most pressing problems of modern electronics, given the advantages that the use of the oscillations and waves of the terahertz band provides in various fields of science and technology.

CHAPTER 1

INTERACTION OF TERAHERTZ RADIATION WITH MATTER

1.1. Propagation of THz waves

The famous Maxwell's equations describe the macroscopic electromagnetic field, including the THz band field. The differential form of these equations states:

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}; \tag{1.1.1}$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0; \tag{1.1.2}$$

$$\nabla \cdot \mathbf{D} = \rho; \tag{1.1.3}$$

$$\nabla \cdot \mathbf{B} = 0. \tag{1.1.4}$$

Here **J** and ρ are densities of electric current and electric charge, created by free charged particles. These densities are the sources of the electromagnetic field.

Constitutive equations couple flux densities and field intensities:

$$\mathbf{D} = \varepsilon \mathbf{E}; \tag{1.1.5}$$

$$\mathbf{B} = \mu \mathbf{H}, \tag{1.1.6}$$

where $\varepsilon = \varepsilon_0\varepsilon_r$ and $\mu = \mu_0\mu_r$ are the absolute permittivity and permeability, $\varepsilon_0 = 10^7/(4\pi c^2) \approx 8.854\cdot 10^{-12}$ A·s/(V·m), $\mu_0 = 4\pi\cdot 10^{-7} \approx 1.256\cdot 10^{-6}$ V·s/(A·m) are dielectric and magnetic constants, and $c = 2.998\cdot 10^8$ m/s is the speed of light in free space.

It is easy to notice that $\sqrt{\varepsilon_0\mu_0} = 1/c$. The relative permittivity and permeability ε_r, μ_r can be scalars or second-rank tensors for anisotropic media. Here we do not consider bianisotropic media. These values may also depend on the intensities of the electric and magnetic fields at neighbouring points of the medium (spatial dispersion) and at previous moments (time dispersion). In this book, dispersive media are not considered. We also do not consider nonlinear media, the permittivity and (or) permeability of which depend upon field intensities.

Having calculated the curl of the equation (1.1.2), substituting in the resulting expression equation (1.1.1) and taking into account (1.1.5), we get

$$\nabla\times(\nabla\times\mathbf{E}) + \varepsilon\mu\frac{\partial^2\mathbf{E}}{\partial t^2} = -\mu\frac{\partial\mathbf{J}}{\partial t}, \tag{1.1.7}$$

Applying the well-known identity of vector analysis to (1.1.7), we obtain the wave equation for the electric field intensity:

$$\nabla^2\mathbf{E} - \varepsilon\mu\frac{\partial^2\mathbf{E}}{\partial t^2} = \mu\frac{\partial\mathbf{J}}{\partial t} + \frac{1}{\varepsilon}\nabla\rho. \tag{1.1.8}$$

Similarly, we get the wave equation for the magnetic field intensity:

$$\nabla^2\mathbf{H} - \varepsilon\mu\frac{\partial^2\mathbf{H}}{\partial t^2} = -\nabla\times\mathbf{J}. \tag{1.1.9}$$

Equations (1.1.8) and (1.1.9) are valid for the electromagnetic field in a linear homogeneous isotropic medium, the parameters of which do not depend on time.

Suppose that all the components of the electromagnetic field depend on time according to the harmonic law:

$$a(\mathbf{r},t) = \mathrm{Re}\left[\dot{A}(\mathbf{r})\exp(\mathrm{i}\,\omega\,t)\right],$$

where $a(\mathbf{r},t)$ is the instantaneous value of any field component, $\dot{A}(\mathbf{r}) = A_m(\mathbf{r})\,\mathrm{e}^{-\mathrm{i}\varphi_0(\mathbf{r})}$ is the complex amplitude of the value (phasor), A_m is the amplitude, and φ_0 is the initial phase of the field component. Substituting this expression in (1.1.8) and (1.1.9), we obtain the Helmholtz equations for complex amplitudes:

$$\nabla^2\dot{\mathbf{E}} + k^2\dot{\mathbf{E}} = \mathrm{i}\,\omega\,\mu\,\dot{\mathbf{J}} + \varepsilon^{-1}\nabla\,\dot{\rho}; \qquad (1.1.10)$$

$$\nabla^2\dot{\mathbf{H}} + k^2\dot{\mathbf{H}} = -\nabla\times\dot{\mathbf{J}}. \qquad (1.1.11)$$

Current density in the Maxwell equations is the sum of the conduction current density $\mathbf{J}_c$ and the external current density J_i. By Ohm's law $\mathbf{J}_c = \sigma\mathbf{E}$, where σ is the medium's electrical conductivity. Substituting this expression in (1.1.10), we find

$$\nabla^2\dot{\mathbf{E}} - \mathrm{i}\,k\eta_0\sigma\dot{\mathbf{E}} + k^2\dot{\mathbf{E}} = \mathrm{i}\,\omega\mu\dot{\mathbf{J}}_i + \varepsilon^{-1}\nabla\dot{\rho}, \qquad (1.1.12)$$

where $\eta_0 = \sqrt{\mu_0/\varepsilon_0} = 120\pi \approx 377$ Ohm is the characteristic impedance of the free space (vacuum) and $k = \omega\sqrt{\varepsilon\mu}$ is the wavenumber. Introducing the fictitious densities of the magnetic current $\mathbf{J}_m$ and charge ρ_m, we obtain a similar equation for the magnetic field intensity:

$$\nabla^2\dot{\mathbf{H}} + \mathrm{i}\,k\eta_0^{-1}\sigma_m\dot{\mathbf{H}} + k^2\dot{\mathbf{H}} = -\mathrm{i}\,\omega\varepsilon\dot{\mathbf{J}}_m - \mu^{-1}\nabla\rho_m. \qquad (1.1.13)$$

where $\sigma_m = \mathbf{J}_m\mathbf{H}^{-1}$ is the magnetic conductivity.

The general solution of the equation (1.1.12) is

$$\dot{\mathbf{E}} = \dot{\mathbf{E}}_0^i\,\mathrm{e}^{-\mathrm{i}\mathbf{kr}} + \dot{\mathbf{E}}_0^r\,\mathrm{e}^{\mathrm{i}\mathbf{kr}}, \qquad (1.1.14)$$

where $\dot{\mathbf{E}}_0^i, \dot{\mathbf{E}}_0^r$ are the incident and reflected wave phasors at the beginning of the coordinate system, $\mathbf{k} = (k' - \mathrm{i}\,k'')\mathbf{e}_\zeta$ is the wave vector. $k' = k_0\sqrt{\varepsilon_r' \mu_r'}$ is the phase constant, $k'' = k'\sqrt{\mathrm{tg}\,\delta_\varepsilon + \mathrm{tg}\,\delta_m}$ is the attenuation constant, $\delta_\varepsilon = \tan^{-1}(\varepsilon''/\varepsilon')$, $\delta_\mu = \tan^{-1}(\mu''/\mu')$ are angles of dielectric and magnetic losses, $\mathbf{e}_\zeta$ is a unit vector of the wave propagation direction, and $\mathbf{r}$ is a radius-vector of the observation point.

As can be seen from (1.1.14), the wave attenuates during propagation. The skin depth is the distance at which the wave's field intensity decreases by a factor of e. The formula determines it as

$$\delta = \frac{1}{k''} = \frac{95.43}{f\sqrt{\varepsilon_r' \mu_r'}\left(\tan\delta_\varepsilon + \tan\delta_\mu\right)}, \tag{1.1.15}$$

where we obtain δ in millimetres, substituting the frequency f in gigahertz.

The complex permittivity of the metal is $\varepsilon = \varepsilon_0 - \mathrm{i}\,\sigma/\omega$ and in the THz and lower frequency bands $\sigma/\omega \gg \varepsilon_0$. In this case, the formula (1.1.15) takes the form

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}. \tag{1.1.16}$$

1.2. Wave refraction and reflection

Let a plane electromagnetic wave fall from the medium 1 onto a plane surface separating two media with refractive factors $n_i = \sqrt{\varepsilon_{ri}\mu_{ri}}$ and characteristic impedances $Z_{0i} = \sqrt{\mu_i/\varepsilon_i}$, $i = 1, 2$. The wave vector of the incident wave forms an angle φ with the normal to the interface. As in optics, we can introduce rays, the directions of which coincide with the directions of the wave vectors. Three of Snell's laws determine the processes of reflection and refraction of electromagnetic waves:

1. The rays of the incident and reflected waves lie in the same plane

(the incidence plane), normal to the interface between the media.

2. The angle between the incident ray and the normal to the interface (incident angle) is equal to the angle of reflection (angle between the reflected ray and the normal to the interface).
3. The expression relates the refraction angle θ and the incidence angle

$$\sin\theta = (n_1 / n_2)\sin\varphi. \quad (1.1.17)$$

The amplitudes of the reflected and refracted waves are calculated using the Fresnel formulas for parallel (vector **E** lies in the incidence plane) and normal (vector **E** is normal to the incidence plane) polarisations:

$$\Gamma_{\parallel} = \frac{Z_{02}\cos\theta - Z_{01}\cos\varphi}{Z_{02}\cos\theta + Z_{01}\cos\varphi}; \quad (1.1.18)$$

$$T_{\parallel} = \frac{2Z_{02}\cos\varphi}{Z_{02}\cos\theta + Z_{01}\cos\varphi}; \quad (1.1.19)$$

$$\Gamma_{\perp} = \frac{Z_{02}\cos\varphi - Z_{01}\cos\theta}{Z_{02}\cos\varphi + Z_{01}\cos\theta}; \quad (1.1.20)$$

$$T_{\perp} = \frac{2Z_{02}\cos\varphi}{Z_{02}\cos\varphi + Z_{01}\cos\theta}. \quad (1.1.21)$$

These formulas can be written in another form:

$$\Gamma_{\parallel} = \frac{\varepsilon_{r2}k_{1z} - \varepsilon_{r1}k_{2z}}{\varepsilon_{r2}k_{1z} + \varepsilon_{r1}k_{2z}}; \quad T_{\parallel} = \frac{2\varepsilon_{r2}k_{1z}}{\varepsilon_{r2}k_{1z} + \varepsilon_{r1}k_{2z}}; \quad (1.1.22)$$

$$\Gamma_{\perp} = \frac{\mu_{r2}k_{1z} - \mu_{r1}k_{2z}}{\mu_{r2}k_{1z} + \mu_{r1}k_{2z}}; \quad T_{\perp} = \frac{2\mu_{r2}k_{1z}}{\mu_{r2}k_{1z} + \mu_{r1}k_{2z}}. \quad (1.1.23)$$

In the last two expressions, $k_{iz} = \boldsymbol{k}_i \cdot \boldsymbol{e}_z$, , $i = 1,2$ is the projection of the wave vector onto the interface surface.

From the law (1.1.17) it follows that if $n_1 > n_2$, there is a certain angle of incidence φ_r, at which

$$\sin\theta = (n_1 / n_2)\sin\varphi_r = 1, \tag{1.1.24}$$

wherein the refracted ray propagates along the interface. At larger angles of incidence $\sin\theta$ becomes greater than 1, i.e. the refracted ray disappears, and the wave fully reflects from the interface. Therefore, the angle φ_r is called the angle of total reflection. When $\varphi > \varphi_r$ a surface wave propagates in the second medium along the interface with a phase velocity $v_{pz} = c/(n_1 \sin\varphi)$, this velocity is less than the speed of light in the second medium $u_2 = c/n_2$. In the direction that is normal to the interface, this wave decreases as $\exp(-\alpha k_2 x)$, where

$$\alpha = \sqrt{(n_1 / n_2)^2 \sin^2\varphi - 1}.$$

It also follows from the Fresnel formulas that at the interface of non-magnetic dielectrics the incident wave of parallel polarisation does not experience reflections if

$$\sin\varphi_B = \sqrt{\frac{1 - \varepsilon_2/\varepsilon_1}{\varepsilon_1/\varepsilon_2 - \varepsilon_2/\varepsilon_1}}.$$

The φ_B is called the Brewster angle or the total transmission angle. This effect is not observed for the normal polarisation of the wave.

Full transmission of the wave through the surface of two magnetics is possible for waves of normal polarisation. The Brewster angle in this case is

$$\sin\varphi_B = \sqrt{\frac{1 - \mu_2/\mu_1}{\mu_1/\mu_2 - \mu_2/\mu_1}}.$$

The phenomenon of complete transmission can be used to create radiation polarised in a definite plane.

1.3. Characteristics of THz radiation

The propagation of waves in the terahertz range obeys the same laws as the propagation of waves in the neighbouring ranges. However, the interaction of THz radiation with a substance has several distinctive features. These features are determined, first, by the energy of the THz radiation. At an average frequency of 1 THz, the radiation quantum (photon) energy is equal to 4.1 meV. This energy is insufficient for the ionisation of atoms. Therefore, terahertz radiation (also known as “T-rays”) is safe for living organisms at a sufficiently low intensity. This energy is also insufficient for creating electron-hole pairs in intrinsic semiconductors (the width of the GaAs forbidden zone, for example, is 1.424 eV).

However, the energy of T-rays photons is sufficient to stimulate transitions between closely spaced rotational energy levels of molecules and to excite oscillations of collective modes of deoxyribonucleic acid (DNA), proteins, and plasmons in solids. A quantum of terahertz radiation has energy, which corresponds to the energy of hydrogen bonds and the van der Waals forces of intermolecular interaction. It is also comparable with the magnitude of the superconductors’ energy gap. The atomic and molecular spectra of highly excited Rydberg states locate in the terahertz range. Therefore, molecules of different materials absorb T-rays. The effect can be used to determine the composition of a substance (terahertz spectrometry).

The radiation of a black body at a temperature of 41.6 K has a maximum at the frequency of 1 THz. At room temperature, all bodies also radiate in the terahertz range, but the power of this radiation is negligible. The human body emits thermal electromagnetic radiation with a maximum at the frequency of about 6 THz. The cosmic background radiation has a peak at 282 GHz, so more than half of its total power falls in the terahertz band. Thus, terahertz radiation is always present in our environment.

Substances partially absorb the energy of terahertz band electromagnetic radiation (as well as that of other bands), which leads to their heating. This thermal effect of radiation must be taken into account if the intensity of the radiation is high enough, and the object exposed to the radiation is located at a relatively short distance from the source. However, as a rule, the thermal effect of terahertz radiation can be neglected (except in installations intended for heating – for example, plasma).

T-rays freely penetrate dielectric media, partially reflecting from their surfaces. Following formula (1.1.15), terahertz radiation decays rather quickly in the Earth's atmosphere (at sea level, the skin depth does not exceed a few kilometres). The skin depth of this type of radiation in dielectrics with high losses (including biological objects) is small (from centimetres to fractions of a millimetre), which limits the possibility of obtaining information about the internal structure of these objects.

However, terahertz radiation, compared to optical, propagates quite well through turbid media and fine materials due to the sharp suppression of Rayleigh scattering, the intensity of which is proportional to λ^{-4}. Therefore, T-rays can be used for the translucence of materials and products that are opaque to optical radiation. The short wavelength of THz radiation, as compared to microwaves, allows the use of T-rays to obtain images with a high resolution.

Many researchers have examined the effects of low-intensity THF radiation on biological objects [143], [154], but a detailed presentation of their investigations is beyond the scope of this book.

1.4. Propagation in the Earth's atmosphere

The properties of electromagnetic wave propagation in the Earth's atmosphere have a decisive influence on the parameters of radar and land wireless telecommunication lines. In this regard, a large number of researchers study these properties. The focus is on the attenuation rate of waves in the atmosphere. The studies are based both on theoretical models [51] and on experimental results [213]. Computational programs that simulate the processes of absorption, such as FASE [49], [165] and others, have been developed. These programs are used in conjunction with a database on the spectra of atmospheric gases. The most commonly used spectroscopic database is HITRAN [62]. As a rule, terahertz spectroscopy in the time domain is used for measurements.

As already noted, terahertz radiation excites rotational levels of molecules. For this, the molecule must have an electric dipole moment. Of the gases that form the Earth's atmosphere, only water and oxygen molecules have a significant dipole moment. Water vapour absorption is the leading cause of the attenuation of the terahertz waves in the atmosphere. Absorption on water dimers, and clusters of a higher order and scattering on raindrops, snowflakes, and dust particles also make a significant contribution to the attenuation of the THz wave.

Fig. 1-1 shows the dependence of the electromagnetic wave attenuation in the Earth's atmosphere at sea level on the frequency in different states of the atmosphere [213]. As can be seen, as the frequency changes from 0.1 to 1 THz, the attenuation increases by almost five orders of magnitude.

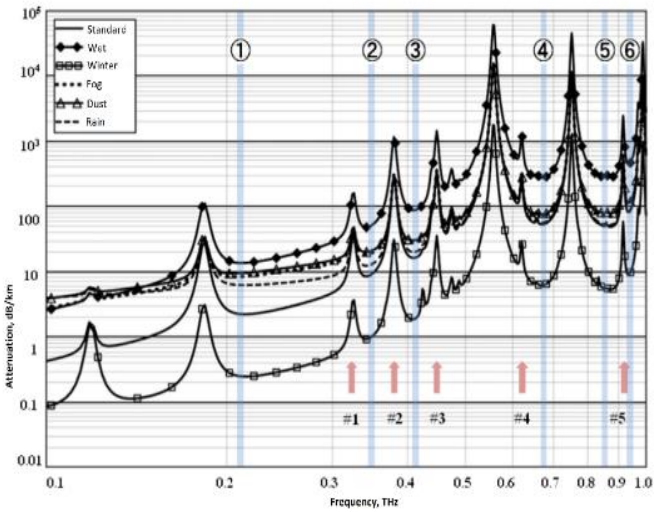

Fig. 1-1. Attenuation of electromagnetic waves in the Earth's atmosphere

The curves shown in the figure correspond to different weather conditions. **Standard** – standard atmosphere with a temperature of 20 °C and relative humidity of 44%, **Wet** – moist air with a temperature of 35 °C and humidity of 90%, **winter** – a temperature of -10 °C and humidity of 30%, **fog, dust, rain** – a temperature of 20 °C and humidity of 44%. All the curves correspond to the pressure at sea level. The numbers with pointers indicate five water absorption lines. As one can see, they are consistent with the experimental data.

The so-called transparency windows have a specific scientific and technical interest. These are frequency bands in which the attenuation is small compared with that in neighbouring areas. The numbers in circles indicate these bands in Fig. 1-1. Table 1-1 gives more detailed data on the position of the transparency windows and attenuation regions in the millimetre wavelength range. The first window locates in the band of 30…51 GHz with a central frequency of 35 GHz, and the second one has a central frequency near 94 GHz.

Table 1-1. Transparency windows and absorption bands

Frequency range, GHz	Transparency windows		Absorption bands	
	Average frequency, GHz	Average wave-length, mm	Average frequency, GHz	Average wavelength, mm
30...51.4	35	8.6	-	-
51.4...66	-	-	60	5
66...105	94	3.2	-	-
105...134	-	-	120	2.5
134...170	140	2.1	-	-
170...190	-	-	180	1.7
190...270	230	1.3	-	-

The density of the Earth's atmosphere rapidly decreases with altitude, and there are no dense clouds and rain at high altitudes. Therefore, THz band waves should be used to communicate with planes, UAVs and satellites. It is also good practice to place radio telescopes in the mountains at a high altitude. Thus, the Mauna Kea radio astronomy laboratory in the Hawaiian Islands locates at an altitude of 4,200 m above sea level with a relative humidity of 2%. Transparency windows with a transmission of 25 to 95% are observed in the frequency range between 0.37 and 1.06 THz [130].