Resonant signal transmission in optical structures with periodical profile of permittivity

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Abstract. We consider a general physical approach to enhance the efficiency of terahertz bolometric detectors. The approach is based on the concept of resonant tunneling of an electromagnetic wave which is similar to quantum particle tunneling in quantum mechanics. Placing resonator under nontransparent conductive layer (plasma, metal or superconductor) helps to increase under certain conditions the field intensity both beyond the nontransparent layer and within it, thus enhancing the detection efficiency. If the frequency of the incident radiation matches with one of the eigenfrequencies of a resonator the effect of resonant tunneling through the conducting layer can be observed. Replacing single resonator with a resonator sequence separated with conductive layers result in formation of an absorption band instead of one resonant frequency. The calculations have shown that absorption of up to 60\% of the energy of the THz pulses can be easily achieved in the considered structures even at the detection of broadband radiation.

1. Introduction

The detection efficiency of terahertz electromagnetic waves using traditional photomultiplier tubes and semiconductors with a small band gap is significantly reduced [1]. Nowadays various microbolometers [2-6] using the interaction between electromagnetic radiation and electron ensembles are applied. In this project we consider a general physical approach to enhance the efficiency of terahertz bolometric detectors. The approach is based on the concept of resonant tunneling of an electromagnetic wave which is similar to quantum particle tunneling in quantum mechanics.

It is known from the optical-mechanical analogy that the potential energy in quantum mechanics is similar to the relative permittivity in the electromagnetic theory. Thus, a dielectric medium with the permittivity $\varepsilon > 0$ corresponds to the potential well while the medium with $\varepsilon < 0$ can be considered as a potential barrier.

The optical-mechanical analogy has many practical applications. For example, this approach has been successfully applied to the radiocommunication blackout problem. It is known that aircrafts and rockets moving at supersonic speed in the atmosphere are covered with plasma sheath. Hence, we cannot use for telemetry and control microwaves with frequencies less than the so-called plasma frequency $\omega_p$. Since almost all telecommunication systems use the frequencies that are less than the plasma frequency,
we have a problem. In this [7] article it is proposed to cover the antenna receiving the signals with a dielectric layer. Such a structure can be considered as an electromagnetic resonator, and from quantum-mechanical point of view it is similar to the potential well separated from the area of infinite motion by a potential barrier. Then using the analogy between optics and quantum theory we can state that if the frequency of incident radiation $\omega$ coincides with one of the eigenfrequencies of resonator (dielectric layer) the wave-field will penetrate through the plasma sheath and fill the resonator even in the case when $\omega < \omega_p$. In the nonresonant case, the wave field is dominantly rejected from the plasma layer and filling is negligible.

Now we have to mention that the effective filling of the resonator by wave-field at a certain frequency is accompanied by effective absorption in the conducting layer. So, similar approach can be applied in order to increase the efficiency of bolometric photodetectors. A bolometer is a thermal radiation detector. The operation principle of the bolometric detector is that the temperature-sensitive element contained in the bolometer is heated by the absorbed flux of electromagnetic energy and thus its electrical resistance changes. Obviously, efficient penetration of the electromagnetic field into the conductive region may have a marked beneficial effect on the photodetector efficiency. In this [8] work it is proposed to place a dielectric layer under the external absorbing layer. In this case, the field will penetrate much better both into dielectric and absorbing layers, which leads to increase in sensitivity of photodetection. For such a system we obtain resonant transition of narrow frequency range or even single frequency. The idea of the present work is to increase the operation range of the frequencies that we are able to detect using a bolometer.

2. The numerical simulation of resonant tunneling effects within the periodic structure based on doped and undoped GaAs layers

2.1. Parameters of the investigated structure
The spectral range where electromagnetic radiation is efficiently absorbed can be expanded by replacing the conducting layer and the dielectric layer under it with a periodic structure consisting of a sequence of dielectric and conducting layers. A sequence of doped (conducting) and undoped (non-conducting) GaAs layers with a thickness of 1 μm and 9 μm respectively deposited onto a metal substrate has been chosen as an investigated structure (Figure 1). Incident electromagnetic radiation with the frequency $\omega$ is on the right.

![Figure 1](image.png)

The real part of $1-\varepsilon(z)$ (equivalent to potential in quantum theory) for a sequence of N=5 doped and undoped GaAs layers. Thickness of undoped GaAs (equivalent to potential well) $a=9$ μm, thickness of doped GaAs (equivalent to potential barrier) $b=1$ μm.

The permittivity for such a system can be written like this

$$
\varepsilon_\omega = \begin{cases} 
\varepsilon_0 & \text{within the undoped GaAs} \\
\varepsilon_0 - \frac{\omega_p^2}{\omega^2 + \nu^2} + i \frac{\omega_p^2 \nu}{(\omega^2 + \nu^2) \omega} & \text{within the doped GaAs} \\
\varepsilon_{\text{air}} & \text{outside the structure}
\end{cases}
$$

(1)
Here $\varepsilon_0 \approx 10.89$ is a high frequency permittivity of GaAs, $\nu = 3.02 \times 10^{12} c^{-1}$ is the frequency of collisions of electrons, $\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m^*}}$ is plasma frequency of an electronic gas, $m^* = 0.067m$ is an effective electron mass, $n_e = 1.9 \times 10^{19} \text{ cm}^{-3}$ is the electron density, $\varepsilon_{air} = 1$ is the permittivity of the atmospheric air.

2.2. Spatial distribution of electric field strength

The numerical simulation of such a system has been carried out. Figure 2 shows the spatial distribution of the field in the case of 1 dielectric layer. It can be seen that the incoming radiation penetrates well into the structure if its frequency coincidence with the resonant frequencies of dielectric layer, while in the nonresonant case the penetration is insignificant.

![Figure 2](image1.png)

When we increase the number of dielectric and conducting layers, the band structure of field modes (photonic crystal) will be formed as allowed energy bands are formed for a periodic potential in quantum theory. And it is these frequencies that effective absorption will be observed for. Figure 3 shows the spatial distributions of the electric field in the case of 5 and 10 resonators. Each figure shows the first 3 modes from the lower band.

![Figure 3](image2.png)

2.3. Filling factor

Now we introduce the filling factor $F(\omega)$ which represents the degree of resonator filling by the incoming radiation flux as the ratio of the squared absolute value of electric field strength amplitude $E$
of the wave transmitted into the region of undoped GaAs to the squared absolute value of the incident electric field strength amplitude $E_0$:

$$ F(\omega) = \max \left\{ \frac{|E|^2}{|E_0|^2} \right\} $$

(2)

The filling factor in dependence on the transmitted signal frequency is shown on the Figure 3. The filling factor was calculated for the first resonator, the furthest from the region of the infinite motion (indicated by the arrow).

The general formula for calculating the resonant frequencies of a structure with one resonator looks like this:

$$ \omega_n \approx \frac{\pi c}{a \sqrt{\varepsilon}} n, $$

(3)

where $a$ is the width and $\varepsilon$ is permittivity of a resonator.

In the case of a sequence of dielectric and conducting layers we obtain spectral bands of effective filling [9]. And the position of spectral filling bands corresponds to the frequency range where the electromagnetic field is efficiently absorbed in the structure.

2.4. Absorption

It was already mentioned above that the dependence of the fraction of absorbed power on the frequency of incident radiation is important for analysis of the studied structure as a detector of electromagnetic radiation with given spectral properties. This dependence was calculated by the formula

$$ \eta(\omega) = \frac{\omega_p^2 v}{\omega^2 + v^2} \frac{\int E^2(z)dz}{cE_0^2}, $$

(4)

where the integral is calculated only over the set of conducting layers. We note that absorption in the outer conducting layer is observed for an arbitrary radiation frequency. Consequently, to increase the contrast of the function $\eta(\omega)$, it is reasonable to “record” the detected signal from all layers except the outer one. The efficiency of absorption of the signal calculated as a function of its frequency for different numbers of conducting and dielectric layers in the structure is shown on the Figure 5.
The position of spectral absorption bands corresponds to the frequency range where the electromagnetic field efficiently fills the structure, i.e. to shift the resonance to the lower frequencies one should increase the width of dielectric layers (3) and vice versa. The width of absorption bands is determined by the coupling between “the potential” wells. Thus, increasing the width or the doping level of the doped GaAs layers results in reducing the width of absorption bands. An increase in the number of layers results in an increase in the density of modes in the band, which smooths the frequency dependence. The calculations show that absorption of up to 60% of the energy of the THz pulses can be easily achieved in the considered structures even at the detection of broadband radiation.

In order to choose the optimal parameters of the investigated structure, we analyzed the dependence of the electromagnetic energy absorbed in the doped GaAs layers on the carrier concentration in these layers. Figure 6 shows that the decrease in the electron concentration results in the increase in absorption.

To sum up, for the studied GaAs structure varying parameters (width and permittivity) of undoped GaAs leads to frequency tuning of absorption bands, varying parameters (width and doping level) of doped GaAs leads to width tuning of absorption bands and absorbed energy fraction tuning and
increasing the number of layers in GaAs structure leads to zone formation and smoothing frequency dependence in the absorption bands.

3. Conclusions
We have proposed a simple general approach for improving the detection of THz signals by means of the use of resonance periodic structure based on doped (conducting) and undoped (non-conducting) GaAs. We managed to provide the absorption of about 60% of the incident radiation of a given frequency range, the width and position of the effective absorption band of such bolometers is determined by thicknesses of conducting and dielectric layers that can be varied at the stage of fabrication.

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