

DETECTION OF LASER RADIATION PARAMETERS

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On the possibility of using the dynamic Franz – Keldysh effect to detect the parameters of high-power IR laser radiation

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Abstract. **The increase in the absorption of light by a semiconductor (when the light photon energy is somewhat smaller than the semiconductor bandgap or equals it) in the presence of a strong light wave (for which the semiconductor is transparent) has been investigated. The possibility of designing novel light detectors for measuring the energy parameters and spatial and temporal characteristics of high-power IR laser radiation is demonstrated.**

Keywords: *Franz – Keldysh effect, semiconductor, intrinsic absorption edge, laser*.

1. Introduction

The Franz – Keldysh effect is the shift of intrinsic absorption edge of a semiconductor in a strong electric field [1]. This effect manifests itself in both dc and ac electric fields; it is used in modulation spectroscopy of semiconductors [2], as well as in tuning the working frequency of semiconductor lasers and in amplitude modulation of light [3]. These applications imply electric field frequencies many lower than the light frequency. However, it was reported in [4, 5] that the spectral characteristics of single-crystal gallium arsenide near the intrinsic absorption edge significantly change under exposure to high-power terahertz radiation [4] and IR laser radiation [5]. According to the data of [5], the absorption of light with a photon energy somewhat smaller than the semiconductor bandgap or equal to it significantly increases in the presence of high-power IR laser radiation and depends on its intensity. This phenomenon was interpreted as the dynamic Franz–Keldysh effect in [5].

In this paper, we report the results of a detailed study of the change in the semiconductor absorption of light with a photon energy somewhat smaller than the semiconductor bandgap, induced by high-intensity laser radiation for which the semiconductor is transparent.

From the practical point of view, it is of interest to study the induced variations in the edge absorption, because such data can be used to design light detectors for measuring the parameters of radiation of high-power mid- and far-IR lasers.

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2. Estimation of the effect value

In the 'optical' sense the Franz – Keldysh effect means a red shift of the absorption spectrum. Therefore, to estimate the change in the edge absorption of light, one must know the shape of the absorption spectrum near the absorption edge and the spectral shift in the presence of a strong light wave.

Keldysh's paper [1] contains expressions for the probability of photon absorption in a semiconductor near the band edge in the absence and in the presence of homogeneous electric field. A comparison of these expressions shows that, when an electric field of strength E_{el} is applied to a semiconductor, the probability of absorbing a photon with an energy $\hbar\omega$ somewhat smaller than the bandgap E_0 or equal to it and, therefore, the optical absorption coefficient change proportionally to the function

$$F(E_{el}) = \left[\frac{\pi(e\hbar E_{el})^2}{m_{ef}(E_0 - \hbar\omega)^3}\right] \times \exp\left[-4\sqrt{2m_{ef}}\,\frac{(E_0 - \hbar\omega)^{3/2}}{3e\hbar E_{el}}\right]. \quad (1)$$

Here, m_{ef} is the reduced effective carrier mass.

The function $F(E_{el})$ increases monotonically with increasing E_{el} from zero to infinity. However, when speaking about the increase in the edge absorption of a semiconductor placed in an electric field, one would expect the minimum value of this function to exceed unity. The following condition for applicability of expression (1) was given in [1]:

$$\sqrt{m_{ef}}\,\frac{(E_0 - \hbar\omega)^{3/2}}{e\hbar E_{el}} < 1. \quad (2)$$

This means that formula (1) is valid only in a limited range of values of the photon energy deficit $E_0 - \hbar\omega$ and the field strength E_{el}.

Indeed, if the left-hand side of inequality (2) is equal to 0.8 or smaller, the function $F(E_{el})$ necessarily exceeds unity and, therefore, the edge absorption coefficient of the semiconductor increases in the presence of electric field.

The electromagnetic wave intensity I in a transparent medium with a refractive index n is related to the electric field strength by the well-known expression

$$E_{el} = \sqrt{\frac{2I}{n e \varepsilon_0}}. \quad (3)$$

In this case, expression (1), with allowance for (3), takes the form

$$F(I) = \left[\frac{2\pi I(e\hbar)^2}{m_{\rm ef} nc\varepsilon_0 (E_0 - \hbar\omega)^3}\right] \times \exp\left[-4nc\varepsilon_0\sqrt{2m_{\rm ef}}\,\frac{(E_0-\hbar\omega)^{3/2}}{6e\hbar I}\right]. \quad (4)$$

Formula (4) describes the increase in the edge absorption of light by a semiconductor placed in the field of a strong light wave with an intensity I and, therefore, determines the red shift of the edge absorption spectrum.

The spectral dependence of the edge absorption coefficient k_ω of a semiconductor, which yields good agreement with the experimental results, was reported in [6]:

$$k_\omega = \frac{A}{\Gamma\sqrt{2\pi}}\int_0^{E_1}\sqrt{E^2 - E_0^2}\,\exp\left[-\frac{(\hbar\omega - E)^2}{2\Gamma^2}\right]{\rm d}E, \quad (5)$$

where Γ is the parameter of absorption line broadening and $A = {\rm const}$ [2].

The shift of the intrinsic absorption edge of a semiconductor in the field of a strong light wave with $\hbar\omega_{\rm L} \ll E_0$ ($\omega_{\rm L}$ is the wave frequency) is taken into account as follows: $F(E_{\rm el})$ (1) is introduced as a factor into formula (5). This additional factor is important at the absorption edge and can be interpreted as the red shift of the entire curve (5).

Finally, the expression determining the effect of a strong light field on the absorption of light with a photon energy $\hbar\omega \leqslant E_0$ near the intrinsic absorption edge of the semiconductor has the form

$$k(I,\omega) = k_\omega F(I). \quad (6)$$

According to (1), the increase in light absorption should be more pronounced in the semiconductors with a small reduced free-carrier mass. Hence, it is reasonable to estimate the value of the effect, for example, for arsenide gallium and then use this material in the experiment. The calculated dependence of the increase in the absorption of 1.38-eV light by arsenide gallium ($E_0 = 1.4$ eV at $T = 300$ K) with an increase in I is shown in Fig. 1.

Obviously, in the presence of light with $\hbar\omega_{\rm L} \ll E_0$ and intensity $\sim 10^8$ W cm^{-2} one would expect a several times increase in the edge absorption coefficient of arsenide gallium. This means that when weak short-wavelength light with a photon energy $\hbar\omega \leqslant E_0$ and intense long-wavelength light with a photon energy $\hbar\omega_{\rm L} \ll E_0$ pass simultaneously through a semiconductor plate, one can observe a significant change in the intensity of the transmitted short-wavelength light.

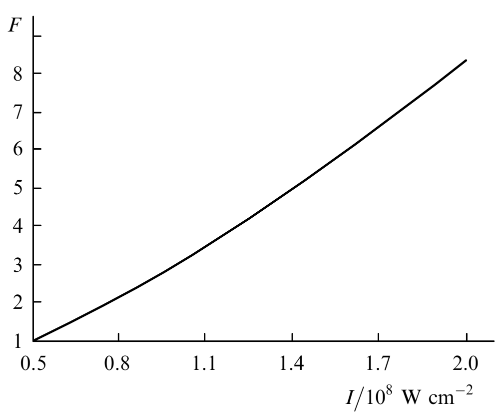

Figure 1. Function $F(I)$ for GaAs at $\hbar\omega = 1.38$ eV

3. Experiment

The experiment consisted in the observation of the absorption of weak short-wavelength ($\hbar\omega \leqslant E_0$) light in a GaAs sample in the presence of high-power long-wavelength ($\hbar\omega_{\rm L} \ll E_0$) laser radiation and without it.

The semiconductor sample (single-crystal gallium arsenide of the AGP-2 grade, transparent in the mid-IR spectral range) was shaped as a 1-mm-thick disk, 22 mm in diameter. The source of high-power long-wavelength laser radiation was a TEA CO_2 laser with a characteristic shape of the laser pulse (it had a pronounced leading spike with a FWHM of 30 ns and a full width of 700 ns at the base level). The pulse energy was varied by changing the pump energy within 0.1 – 0.4 J. The typical oscillogram of the laser pulse, recorded by an FSG-22A photoresistor (the signal from which arrived at an S8-12 oscilloscope), is shown in Fig. 2a.

The short-wavelength radiation source was a pulsed GaAs laser LPI-14 with a pulse energy of $\sim 10^{-5}$ J and an FWHM of 80 ns. The shape of the laser pulse is shown in Fig. 2b. The energy of the short-wavelength light photon is approximately equal to the semiconductor bandgap. The semiconductor laser wavelength was tuned by changing its temperature with subsequent thermal stabilisation.

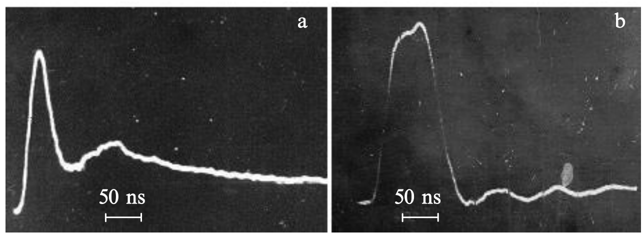

Figure 2. Pulses of (a) a TEA CO_2 laser and (b) a semiconductor LPI-14 laser.

Thus, the GaAs plate was simultaneously irradiated by two pulsed lasers: a TEA CO_2 laser and a semiconductor laser with light photon energies of 0.117 and 1.38 eV, respectively. The CO_2 laser radiation with an energy of 0.38 J in a pulse was focused on the sample into a spot 3 mm in diameter, whereas the LPI-14 radiation was focused into a 1-mm spot. Both laser beams were spatially aligned on the sample. The leading spike in the CO_2 laser pulse contains generally about 25 % of the total pulse energy. This means that within the spike duration the sample was exposed to laser light with an intensity of ~ 100 MW cm^{-2}. The semiconductor laser pulse transmitted through the plate was recorded by an LFD-2 photodiode, the signal from which arrived at an S8-12 storage oscilloscope.

Figure 3 shows the oscillograms of the semiconductor laser pulses transmitted through the plate that correspond to different time shifts of the leading edges of the LPI-14 and CO_2 laser pulses. It can be seen that the pulse shape significantly differs from the initial. In the left photograph the leading spike position corresponds approximately to the middle of the semiconductor laser pulse, and there is a dip at the centre, whose width and shape correspond to those of the leading spike in the CO_2 laser pulse. In the right photograph the spike in the CO_2 laser pulse coincides with the leading edge of the semiconductor laser pulse. Evidently, the distortion of the pulse shape is due to the change in the GaAs bandgap, which is, in turn, induced by the CO_2 laser radiation; this change manifests itself in the shift of the intrinsic absorption edge of the semiconductor and, correspondingly, in the enhanced absorption of the semiconductor laser light.

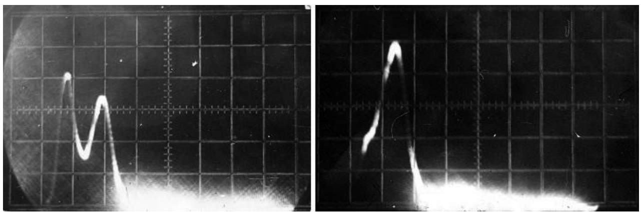

Figure 3. Semiconductor laser pulse after transmission through a GaAs plate.

4. Simulation of the experiment

The intensity of light propagating in a medium with a steady-state absorption coefficient changes in correspondence with the Bouguer law. In the case under consideration the absorptive ability of the sample is modulated in time in correspondence with the shape of the TEA CO_2 laser pulse. Therefore, the shape of the semiconductor laser pulse transmitted through the sample is described by the expression

$$I_s^{out}(t) = I_s(t)\exp[-k_0 l F(I)],$$

where $I_s(t)$ is the shape of the short-wavelength pulse at the input of the semiconductor sample; k_0 is the absorption coefficient of semiconductor laser light in the absence of CO_2 laser radiation; and l is the sample thickness.

The shape of the semiconductor laser pulse is fairly exactly approximated by the super-Gaussian function

$$I_s(t) = \exp\left[-0.693\left(\frac{t}{\tau_s}\right)^4\right],$$

where the amplitude of the semiconductor laser pulse is normalized to unity and its FWHM is $2\tau_s = 80$ ns.

The shape of the first spike in the CO_2 laser pulse is described well by the Gaussian function

$$I_p(t) = I_0\exp\left[-0.693\left(\frac{t}{\tau_p}\right)^2\right],$$

where I_0 is the amplitude of the leading spike in the CO_2 laser pulse and $2\tau_p = 30$ ns is the spike FWHM.

Thus, after passing through the GaAs sample, the shape of the semiconductor laser pulse is determined by the expression

$$I_s^{out}(t) = \exp[-k_0 l F(I_p(t))]\exp\left[-0.693\left(\frac{t}{\tau_s}\right)^4\right].$$

The calculated shapes of the semiconductor laser pulse (provided that the tip of the spike in the CO_2 laser pulse corresponds to the middle of the short-wavelength pulse after its transmission through the sample) are shown in Fig. 4. It can be seen that the experimental and calculated data are well-consistent: the modulation depth at the pulse center at an intensity of ~ 100 MW cm^{-2} approximately corresponds to the experimental value.

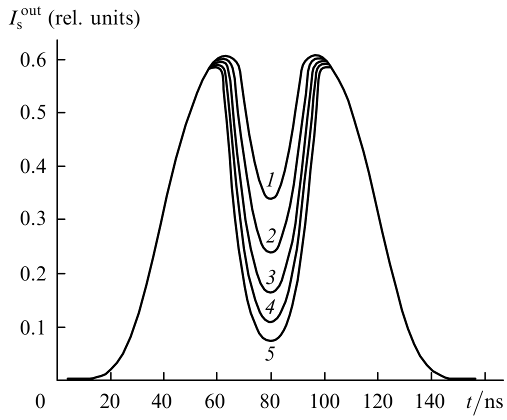

Figure 4. Calculated profiles of a semiconductor laser pulse transmitted through the sample in the presence of CO_2 laser pulses with average leading spike intensities of (*1*) 1.0×10^8, (*2*) 1.2×10^8, (*3*) 1.4×10^8, (*4*) 1.6×10^8, and (*5*) 1.8×10^8 W cm^{-2}.

5. Visualisation of the intensity distribution in the TEA CO_2 laser beam

To demonstrate the possibility of using the effect under study to detect high-power IR laser radiation, we developed an experimental setup, the optical scheme of which is shown in Fig. 5. The TEA CO_2 laser radiation is focused by a lens (*1*). The laser beam passes through a plane-parallel window (*2*), tilted by 45°, to arrive at a semiconductor plate (*3*). The sample is an undoped GaAs plate (transparent at a wavelength 10.6 μm), shaped as a disk 22 mm in diameter and 1 mm thick. After the plate the divergent IR beam passes through the second window (*4*) to arrive at a conical absorber. The windows (*2*) and (*4*) are identical; they are made of BaF_2 and have a dichroic coating (antireflective at a wavelength of 10.6 μm and reflective for short-wavelength light). Simultaneously with exposure to IR light the plate

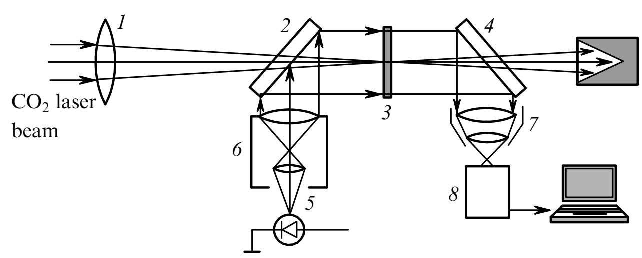

Figure 5. Detection scheme (see text).

(*3*) was irradiated with a probe light beam from a pulsed semiconductor laser (*5*) (LPI-14). An optical system (*6*) served to form a light beam with a uniform intensity distribution in the cross section.

The exposure to IR light leads to a local shift of the intrinsic absorption edge of gallium arsenide. As a result, in the region irradiated with the CO_2 laser beam the absorption coefficient at the short-wavelength wavelength is modulated in correspondence with the IR beam intensity distribution. Under these conditions, the transmission of the short-wavelength beam through the semiconductor plate (*3*) leads to the formation of a negative image of the CO_2 laser intensity distribution. Then this image is transferred by an objective (*7*) to a CCD camera (*8*) (Spiricon LBA-300), which operates in the standby regime. The camera is connected to a computer through an adapter; finally, the image obtained is displayed on the monitor.

Figure 6 shows a photograph of the GaAs plate, which is simultaneously irradiated by probe and CO_2 laser beams. The dark spot is the negative image of intensity distribution in the transverse cross section of the TEA CO_2 laser beam.

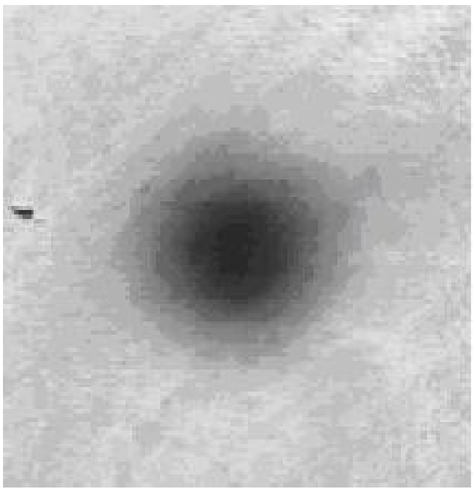

Figure 6. Image of a spot of CO_2 laser radiation.

The result obtained suggest that the observed increase in the absorption of light by the semiconductor near the fundamental absorption edge in the presence of a strong light wave can be a basis for designing run-through analysers of the intensity distribution of high-power IR and submillimetre lasers. The optical elements of lasers (for example, windows) for these spectral ranges are often made of semiconductors (in particular, gallium arsenide). Thus, a semiconductor optical element can be used as a sensitive element of a detector aimed at measuring, for example, the intensity distribution without deterioration of the optical functions of this element. A very interesting feature of these detectors is the almost complete absence of energy loss for high-power long-wavelength beam passing through the sensitive element and, as a result, the absence of its heating.

The effect studied can be used to design not only analysers of intensity distribution but also detectors for visualizing the pulse shape and measuring the energy and power of high-power IR lasers. Note that irradiation of a semiconductor by short-wavelength light leads to the photogeneration of current carriers, which is significantly enhanced in the presence of high-power radiation. Therefore, one can judge about the high-power beam parameters by measuring, for example, the variations in the resistance of the semiconductor plate, which is used as a photoresistor in this case.

6. Conclusions

The comparison and analysis of the experimental data and calculation results showed that the observed change in the light absorption coefficient of gallium arsenide near the intrinsic absorption edge can be interpreted as the dynamic Franz–Keldysh effect.

The possibility of designing radically new detectors for measuring the spatial and temporal characteristics of IR lasers was demonstrated.

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