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INFLUENCE OF POLARIZATION AND MISALIGNMENT ON THE SIGNAL OF A TRAP DETECTOR

Introduction

Modern development of many branches of a science and engineering puts increased requirements to accuracy of measurement of power of laser radiation in a wide range of frequencies and power. There is a significant need for precise measurement of absolute value of power from a source of radiation in the optical region with a low or ultralow level of power (from several a milliwatt up to units of nanowatt and less).

Essential progress in creation of power measuring instruments in the optical range on the basis of photodiodes was carried out recently due to development of silicon photodiodes with practically 100 % internal quantum efficiency in an optical range, i.e. each photon of the detected radiation absorbed by the photodiode generates a electron-hole pair. The internal structure and a mode of operation of such photodiode make probability of a recombination of carriers in a material of the diode small enough and, therefore, the registered photocurrent is directly proportional to power of the detected radiation.

Further great advance in a development of high-precision instruments measuring the power of optical radiation was achieved at realization of the scheme of a photodetector, which for the first time was offered in [1]. The feature of this scheme is inclusion in structure of the photodetector of several photodiodes so that radiation, having got in the photodetector and, interacting with photodiodes, has undergone several reflections from them and practically was completely absorbed up by the detector. Similarly, the measuring devices have received the name trap detectors. One of variants of the optical circuit of such device is given in fig. 1. At realization of such or similar scheme, the photodetector assembled on the basis of photodiodes with 100 % internal quantum efficiency, have nearly 100 % external quantum efficiency. Almost all radiation incidents on the photodetector take part in formation of a useful signal. Further, the idea of creation of such measuring device was realized in a number of the scientific metrological centers [2]. The result of these works was creation of several variants of similar precision instruments measuring power of the optical radiation and having various characteristics.

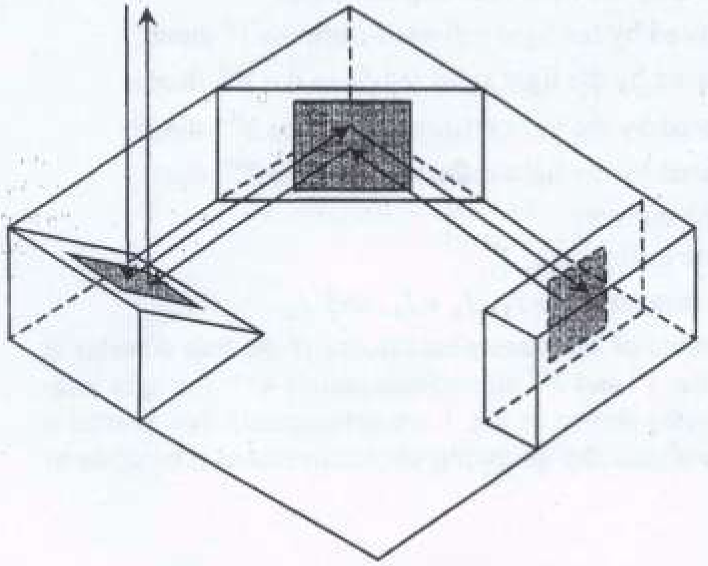


Fig. 1. The variant of the photodiodes arrangement in trap detector

At outcome a reflection trap detector with three photodiodes was developed. The optical scheme is given in fig.1. The photodiode trap detector consists on three Hamamatsu photodiodes S1337 the output currents of which can be measured separately or in total. For the last purpose the photodiodes can be connected parallel. Special adjusting prisms realized a very stable set-up. The trap detector is intended for absolute measurements of laser power with an error of less than one percent at power levels as low as 10 pW. However tolerances due to manufacturing of the prisms and fastening of the photodiodes have to be considered.

Theoretical consideration of trap detector errors

Let us assume that the light travels to the first photodiode along the z-axis of a base coordinate system. The normal of the first photodiode is given by the vector $n = \begin{pmatrix} n_x \\ n_y \\ n_x \end{pmatrix}$. For example $n = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}$ if an appropriate coordinate system is chosen and the angle of incidence on the 1st diode equals 45°. In this case the unit vector within the plane of incidence which is orthogonal to the z-axis is given by

$$e'_y = \frac{n-(n\,e_z)\cdot e_z}{|n-(n\,e_z)\cdot e_z|}$$

where e_z is the unit vector along the z-axis. The prime of vector e'_y indicates that e'_y not necessarily equals e_y, of the base coordinate system.

The unit vector perpendicular to the plane of incidence is given by

$$e'_x = \frac{e_z \times n}{|e_z \times n|}$$

If radiation with the electrical field vector E reaches the first photodiode it can be separated into a component oscillation within the plane of incidence

$$E_p = E\cdot e'_y$$

and a component oscillating perpendicularly to the plane of incidence

$$E_s = E\cdot e'_x$$

Both components are partially reflected where the reflection coefficients are different for both components. The coefficients are given by Fresnel's equations. The non-reflected part of the radiation is absorbed by the photodiode (the transmission of the photodiode equals zero) and produces the photocurrent I_1.

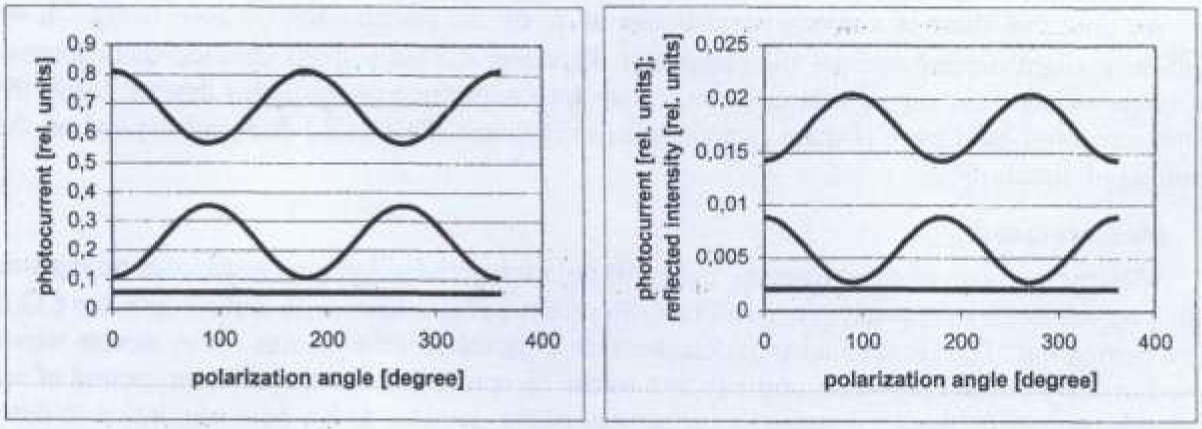
For the second photodiode the new z-axis is given by the direction of the light reflected by the first diode. Together with the normal vector of the 2nd diode we obtain the plane of incidence and the s- and the p-component of the light reaching the 2nd diode. Again we calculate the reflected and the absorbed part of both components where the absorbed light produces the photocurrent. This procedure is repeated totally five times. Thus we obtain five photocurrents (see fig 1):

- I_1 is the photocurrent of the 1st diode produced by the light reaching the trap;
- I_2 is the photocurrent of the 2nd diode produced by the light reflected from the 1st diode;
- I_3 is the photocurrent of the 3rd diode produced by the light reflected from the 2nd diode;
- I_4 is the photocurrent of the 2nd diode produced by the light reflected from the 3rd diode;
- I_5 is the photocurrent of the 1st diode produced by the light reflected from the 2nd diode.

There is experimental access to the following currents:

- I_1 and I_2 can be measured when the 3rd diode is blocked;
- If the path to the 3rd diode is opened, we can measure $I_1 + I_5$, $I_2 + I_4$, and I_3.

In a first step we calculated the output currents of the three photodiodes if the trap detector is perfectly aligned (i.e. the angle of incidence on the 1st and 2nd photodiode equals 45°; the light incidences the 3rd diode perpendicularly; the light paths shown in fig. 1 are orthogonal). We assume a refractive index of Silicon of 3.5. In this case we obtain the following photocurrents as a function of the polarization angle of the incoming light:



a *b*

Fig. 2

a – I_1 *(top line),* I_2*, and* I_3 *(bottom line); b* – I_4 *(top),* I_5*, and intensity reflected out of the trap (bottom line)*

The calculation of the difference of the sum of all photocurrents to 100% is constant 0.2% independent of the incoming polarization. This shows that the photodiode trap detects nearly each photon, and on the other hand does not suffer from influence of the incoming polarization.

Now slight misalignments of the first photodiode were considered. Misalignments change both the ray path and the reflection coefficients, which had to be considered in our calculations. We considered four cases of misalignment:

- In case 1 the first photodiode was turned by +2° from the ideal 45° position $n = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}$, where the turning axis was the y-axis perpendicular to the plane of incidence. Therefore the plane of incidence was not affected by the turning;
- In case 2 the first diode was turned by minus 2° around the y-axis;
- In case 3 we turned the first diode by 2° around the z-axis which results in a change of the plane of incidence;
- In case 4 we turned the first diode by 2° around the x-axis which also leads to a change of the angle of incidence on the first diode.

In each case we calculated all currents I_1 to I_5 and the difference of the total current $I_1 + I_2 + I_3 + I_4 + I_5$ to 100% as a function of the polarization angle of the incoming light. The current I_1 as a function of polarization was rather similar to the current I_1 calculated for the ideal case. The main differences were that the amplitude of I_1 in the misaligned case was slightly changed (due to the changes of the reflection factors, because the angle of influence was changed), and that there was a phase shift compared to the current in the ideal case. The phase shift was given by the angle between the plane of incidence in the ideal case (i.e. the xz-plane) and the plane of incidence in the misaligned case. The results are summarized in the following table. In each case the difference of the sum of all photocurrents did not depend on the incoming polarization within a level of 0.01%.

Table

	Ideal case (see fig. 2)	*Case 1*	*Case 2*	*Case 3*	*Case 4*
Angle of incidence on 1st diode	45°	47°	43°	45.035°	45.035°
Lowest current of 1st diode	0.567	0.554	0.579	0.567	0.567
Highest current of 1st diode	0.813	0.825	0.801	0.813	0.813
Phase shift of I_1 compared to ideal case	0°	0°	0°	2°	2°
Difference of sum of all currents to 100%	0.204%	0.189%	0.217%	0.203%	0.203%

We note that there is a strong dependence of I_1 on the polarization (as seen in fig. 2), and in addition a slight dependence on the alignment. However the sum of all photocurrents approaches 100% very well. This shows that a photodetector trap with three photodiodes detects nearly 99.8% of the incoming light even if there is a slight misalignment. This value does not depend on the incoming polarization.

Measurements

With the purpose of experimental testing of polarizing characteristics researches on registration with a trap detector of linearly polarized radiation from a HeNe-laser with wavelength $\lambda = 632{,}8$ nm were carried out. The researched trap detector was established on a precise rotary device which allowed to carry out during measurements turn of the reception head of the detector around of an optical axis on 360^0 without violation to adjustment of the detector as a whole in relation to detected radiation. Thus, except of registration of a total photocurrent of three photodiodes of the detector, there was an opportunity to measure of the contribution to a useful signal from each photodiode separately at each act of its interaction with detected radiation. Received results of these experiments are given in fig. 3. From diagrams it is visible, that measured polarized radiation is unequally absorbed by 1-st and 2-nd photodiodes of the detector at its various orientations concerning a plane of polarization. It proves the chosen geometrical configuration of photodiodes of the detector. The value of a photocurrent from 3-rd photodiode of the detector practically does not depend on orientation of the detector, as it is located perpendicularly to measuring radiation. The carried out researches have shown, that at measurement by the given detector of power of laser radiation at a level of several hundreds microwatt, change of a useful signal on polarization of radiation makes size ~ 0,1 %. This dependence, probably, is caused by discrepancy of installation of photodiodes on the prism, discrepancy of installation of the detector, as a whole is relative detected radiation, disorder in characteristics of used photodiodes etc.

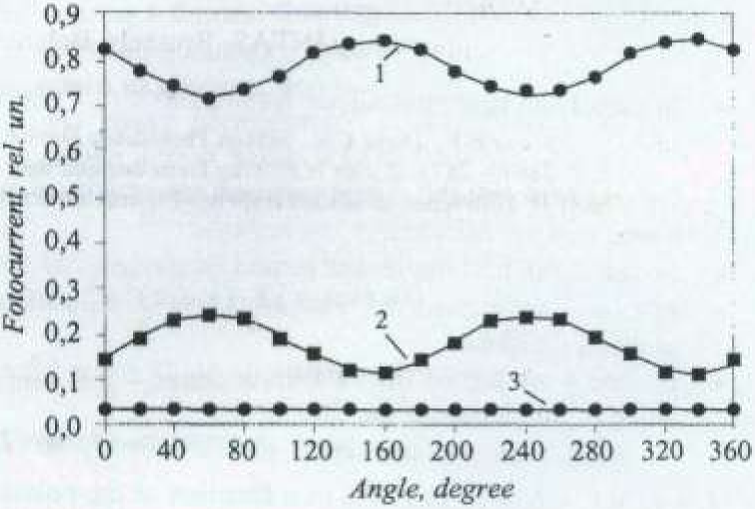


Fig. 3. Fotocurrents versus to the polarization of incident beam: 1 – for first photodiode of the trap detector; 2 – for second photodiode; 3 – for third photodiode

Discussion

The measurements reproduce the calculated results qualitatively well. However there is a discrepancy between the absolute values. There are several possible reasons for this, the most important are:

- In the calculations the refractive index of the active surface of photodiodes that formed the trap detector, was assumed to equal the refractive index of silicon. This is not absolutely correct, as the photodides of a used type have layered structure, where the foto-sensitive layer of silicon was coated by a layer SiO_2 by width from 25 to 30 nm which changes the reflection coefficients.
- The refractive index of silicon depends on the doping of the semiconductor, which is not known.

However our results show that a trap based on three photodiodes delivers accurate measurements of light. We note that our calculations were carried out with linear polarized light. This is no restriction because the measured values are intensities, which do not depend on a phase shift between the polarization components.

As a result of the work it is possible to draw a conclusion, that the designed trap detector allows to carry out measurements of absolute power of laser radiation in optical region with a margin error ~ 0,1 % in a range up to 10^{-3} W and about 5 % at a level of the measuring power 10^{-10} W. The output signal of the developed photodetector within the limits of the received error of measurements does not depend on polarization of the incident radiation in the specified power range.

The fabricated trap detector is intended for measuring the power of well collimated or laser radiation in optical range. The given construction of the detector after insignificant modification allows to measure power of focussed radiation, that is necessary at measuring illumination intensity etc. At that the field of view of such modified detector is equaled 14°. At making up of precise model of operation trap detector by its operation with divergent beams it is necessary to take into account dependence the refractive index for s- and p-polarizations from an angle of indicence.

It is necessary to note, that the calculations according to detector characteristics, adduced in the present paper, are carried without taking into account the dispersion of the refractive index.. But the obtained results remain valid, since the refractive index only slightly depends on wavelength in the visible range 400 nm < λ < 800 nm [3].

The further development of the given class of detectors will allow to create precise instruments measuring power of radiation, both coherent and not coherent, with various spectral characteristics and also to use them for measurement and other radio- and photometry variables. It is necessary to note that the separate problem, which yet has been not solved finally, is development of similar trap detectors for UV and NIR ranges.

Acknowledgement

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