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Laser Diode Radiation Phase Non-Uniformity Influence Account for Improvement Phototachymeter Accuracy Characteristics

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Introduction

There is a problem of accuracy measurement deterioration at phase phototachymeters on laser diodes (LD) creation because the sources of radiation are non-uniform. For the LD used in phase phototachymeters, modulation phase variations in a near zone are characteristic. Non-uniformity of a radiation field along *a p-n junction* is determined by presence of local areas in the semiconductor with various nonequilibrium charge carrier (NCC) lifetimes, determining amplitude-frequency and transitive characteristics of the laser, and also a radiation delay concerning a radiating current pulse. Distinction in carriers' lifetimes is caused by concentration alloying impurity non-uniformity, defects of structure and an injection current on junction section. The disorder of a modulation phase at frequency of 1 GHz can reach 40°, in diodes with wide ohmic contact [1], and result in a significant error at distances measurement. Errors caused by the regular phase shifts brought by the light detector, real beginning points position and the end measured points line in a phototachymeter aperture and a reflector, time and phase delays in electric circuits, passage of modulated light to optical environments with the refraction index which is distinct from an average atmosphere refraction index, usually do not exceed 1°.

It is obvious, that the design of precision phase phototachymeters of a modulation phase variation represents a significant problem.

Phase method of distance measurement

In a basis of phase phototachymeter work lays the phase method of distribution time measurement of injection laser radiation modulated by an analog signal, providing a small error that is necessary at their application in a geodesy and in a precision range finding.

The phase distances measurement method is illustrated with the simplified scheme of a phase phototachymeter submitted on Fig. 1. We shall assume, that the LD radiates harmonious fluctuation of circular frequency ω with initial phase φ_0

$$U_1 = U_{m1}\sin(\omega t + \varphi_0)\,, \qquad (1)$$

where U_{m1} - amplitude of a voltage, ω - a modulation frequency, φ_0 - an initial modulation phase.

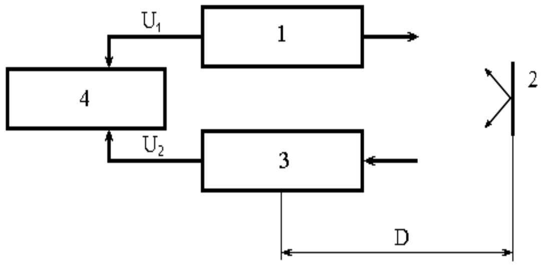

Fig. 1. The simplified scheme of a phase phototachymeter: 1 - the laser diode; 2 - reflector; 3 - photodetector; 4 - phasometer

Coming along distance D up to a reflector and back, the signal gets to a photodetector and at its output harmonious fluctuation with amplitude U_{m2} and a phase detained for time τ_{2D} is formed:

$$U_2 = U_{m2}\sin[\omega(t + \tau_{2D}) + \varphi_0]. \qquad (2)$$

Thus the formula (2) does not take into account phase shifts in circuits of the transmitter and the receiver. A voltage U_1 and U_2 phase difference is measured by phase meter.

$$\varphi_{2D} = \omega\tau_{2D} = 2\pi f\tau_{2D}\,. \qquad (3)$$

Knowing radiation speed a distribution along the measured distance D, required distance is received as

$$D = \frac{v\tau_{2D}}{2} = \frac{v\varphi_{2D}}{4\pi f}\,. \qquad (4)$$

The elementary phase phototachymeter allows to determine unequivocally distances only up to half of wavelength λ corresponding to a modulation frequency f, when $\varphi < 2\pi$.

Modern laser diodes allow to measure essentially distances in day time conditions up to several kilometers, and at night up to several tens of kilometers within the limits of direct visibility that is limited to radiation capacity generated by them and reception features. Accepted measured range is 15 km, it is defined unequivocally, if LD radiation is modulated by frequencies about 10 kHz. However using existing phase difference measurement methods of an accepted and sent signal it is impossible to achieve high distance measurement accuracy at a laser diode radiation modulation frequency about tens kilohertz. It is possible to raise distance measurement accuracy, having essentially increased a LD radiation modulation frequency. Generally phase shift φ_{2D} is represented as

$$\varphi_{2D} = 2\pi N + \varphi . \quad (5)$$

Having substituted (5) in (4), we shall receive the basic equation (2) for phase range finding:

$$D = \frac{v}{2f}(N + \frac{\varphi}{2\pi}) . \quad (6)$$

Elimination of distances definition ambiguity in phase phototachymeters

There are two unknown values in expression (6): distance D, and an integer of the phase cycles N stacked along a line $2D$.

Taking that into account, expression (6) can be rewritten as

$$D = \frac{\lambda}{2}(N + \frac{\varphi}{2\pi}) . \quad (7)$$

Frequency f on which phase shift is measured is named scale frequency. In a phase range finding applications optical range radiation of an injection laser is usually modulated by scale frequencies from 10 up to 500MHz, and sometimes in a gigahertz range. For allocation of a signal of scale frequency a detecting operation is applied.

Apparently from expression (7), distance D is not determined precisely, as N is not known. It is possible to remove the specified uncertainty in the various ways. For example, it is possible to pick up such LD radiation modulation frequency f_1, at which φ_{2D}=0. Then

$$D = \frac{v}{2f_1} N , \quad (8)$$

where N - an integer of the wave-lengths $\lambda = v/f$ stacked on distances $2D$.

Smoothly increasing frequency, we find the nearest value f_2 at which f_{2D}=0 and as a result the second equation is received, allowing to solve the above-mentioned unambiguity in definition of D:

$$D = \frac{v}{2f_2}(N + 1) . \quad (9)$$

Solving system of the equations (8), (9) is relative D, we have

$$D = \frac{v}{2(f_2 - f_1)} . \quad (10)$$

The reasons of occurrence of a space-time structure of radiation

For semiconductor sources at an amplitude modulation and pulse excitation typically some radiation delay concerning a managing voltage on a *p-n* junction occurs. This delay is related to accumulation of a charge in active area and achieved by system of an inverse threshold population condition. Simultaneously with the specified processes there is the recombination of NCC interfering increase of their concentration. At the description of a NCC relaxation characteristic times are used: τ_u - NCC lifetime for spontaneous radiating; $\tau_б$ - NCC lifetime for spontaneous non-radiative junctions; τ_c - full general spontaneous NCC lifetime, determined as

$$\frac{1}{\tau_c} = \frac{1}{\tau_u} + \frac{1}{\tau_б} , \quad (11)$$

where τ_{cm} – NCC lifetime for stimulated radiating junctions; τ_n – a full NCC lifetime which is found from a ratio [2]:

$$\frac{1}{\tau_n} = \frac{1}{\tau_u} + \frac{1}{\tau_б} + \frac{1}{\tau_{cm}} . \quad (12)$$

Distribution of phase φ on a LD radiating surface a at superhigh-frequency modulation is NCC lifetime function τ and in the elementary case is given by expression:

$$\varphi = arctg(-2\pi f \tau_n) . \quad (13)$$

Thus at presence of areas with various values of lifetimes phase delay change at junction from the first area to the second

$$\Delta\varphi = arctg(-2\pi f \tau''_n) - arctg(-2\pi f \tau'_n) . \quad (14)$$

Model of a phototachymeter

The measuring system (Fig. 2) will consist of the LD *1*, an objective *2* (F = 10 sm) and "screen" *3*. "Screen" in this case is a conditional name as it designates a plane in which there is a studied distribution of a radiation modulation phase. It is at distance of 1 km from a lens. The angular multielement reflector can not be included in system, considering that the objective is at the distance of two measured distances in a "screen" plane. The corner of divergence of LD radiation with wide ohmic contact and area of a radiating recombination with a length of 100 microns was accepted equal 10°.

As the radiator settles down in a focal plane by virtue of its sizes finiteness (not dot source) at a distance the image on the screen formed by the parallel missing beam in the size about 1 meter does not move.

Space-time structure of radiation

During formation of a signal, in area of the size 2Δ a coordinate Y in the screen plane of all sites of LD radiating surface which central beams get in area (Y-Δ; Y+Δ) of influence.

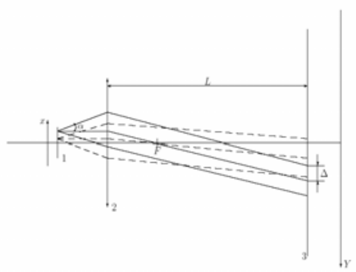

Fig. 2. The scheme of a course of a beam in a modeled phototachymeter

The central beam is necessary for a beam radiated by the diode from some point perpendicularly to the diode plane. Then the following integral is true:

$$I(Y,t)=\frac{K}{2\Delta}\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)g(Kz,t-\tau_L)dz\,, \qquad (15)$$

where 2Δ - length of a site at which distribution of radiation intensity and a modulation phase is analyzed, $I_0\ (Kz)$ - distribution of intensity on the diode, $1/K$ - enlargement factor in optical system ($x = KY$) $K=F/(L-F)$, $g(Kz,\ t)$ – function of radiation modulation.

In case of LD radiation modulation by an analog signal

$$g(x,t)=1+p\sin(\omega t+\varphi(x))\,, \qquad (16)$$

where f - a modulation frequency, p - radiation modulation depth factor, $\varphi(Kz)$ - a modulation phase in a near zone.

The finding of a radiation space-time structure in a distant zone (in a plane of "screen") is possible at any law of radiation modulation by a numerical integration (15). However in this case it is necessary to solve numerically the equation which is a part of the integral (15).

In a case of LD radiation modulation by an analog signal substituting (16) in (15) equation is received:

$$I(Y,t)=\frac{K}{2\Delta}\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)(1+p\sin(\omega(t-\tau_l)+\varphi(Kz)))dz\,. \qquad (17)$$

After transformation (17) we have:

$$\begin{aligned} I(Y,t)=\frac{K}{2\Delta}(\sin(\omega(t-\tau_l))\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)(1+p\cos(\varphi(Kz))dz+ \\ +\cos(\omega(t-\tau_l))\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)+p\sin(\varphi(Kz))dz+\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)dz). \end{aligned} \qquad (18)$$

As integrals $\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\cos(\varphi(Kz)dz$, $\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\sin(\varphi(Kz)dz$ and $\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)dz$ don't depend on time (16) it is possible to transform to the form:

$$I(Y,t)=\frac{K}{4\Delta}(A(Y)\sin(\omega(t-\tau_l)+\Theta(Y))+I_{0Y}(Y))\,, \qquad (19)$$

where

$$A(Y)=\sqrt{\left(\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\cos(\varphi(Kz)dz\right)^2+\left(\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\sin(\varphi(Kz)dz\right)^2}\,,$$

$$\theta(Y)=\mathbf{arctg}\left(\frac{\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\sin(\varphi(Kz)dz}{\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)\cos(\varphi(Kz)dz}\right),$$

$$I_{0Y}=\frac{K}{2\Delta}\int_{Y-\Delta}^{Y+\Delta} I_0(Kz)dz\,.$$

From expression (19) it can be seen, that the form of a resulting signal is determined by three values A, Θ and I_{0Y}. With the help of these values it is possible to make the full analysis of signal distortions.

The analysis of radiation modulation phase variations in a distant zone

For modeling of distribution of a LD radiation modulation phase intensity on all the diode area was accepted to be a constant, and distribution of an initial phase in a near zone was set as follows: with step of 10^{-5} m in the random image of phase value changed from 0° up to 20° and was interpolated on all the diode area with the help of a cubic spline. As a result of the system modeling described above the following distribution of a modulation radiation phase submitted on Fig. 3 is received.

Phase disorder on an object has decreased in comparison with phase disorder in a near zone for some sites approximately on 11° and varies in limits ~ 27°.

Appreciable reduction of LD radiation phase nonuniformity influence by distances measurement accuracy by phase phototachymeters needs use of transmitting objects with the big focal length or big diameter receptions. However such objects have big sizes and weight and consequently are inconvenient in application.

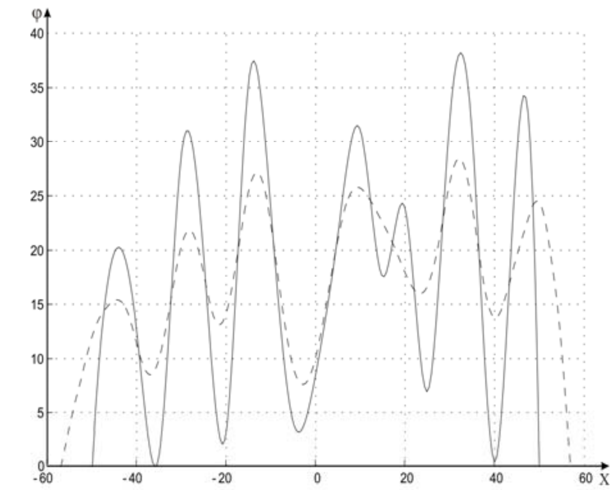

Fig. 3. Dependence of a modulation phase in a LD near zone (a continuous line) and a resulting modulation radiation phase of on an object (a shaped line), counted in a LD near zone

Phase phototachymeter with the carried modulations frequency

Let's find the approached measured distance value D on two essentially distinguished frequencies, for example $f_1 = f$ and $f_2 = 2f$, and we shall get rid of ambiguity in definition D for each of frequencies. For each measurement we shall write two equations (6), connecting measured distance with a modulation phase variation. Having added the LD phase variation in it

$$D = \frac{v}{2f}(N + \frac{\varphi + \varphi_0}{2\pi}). \tag{20}$$

And the equation (13) connecting a radiation modulation phase variation with a NCC lifetime

$$\varphi_0 = \text{arctg}(-2\pi f \tau_n), \tag{21}$$

where D - the measured distance, φ_0 - the delay of a modulation phase, is defined by intensity a source of radiation, v - a velocity of light; f - frequency at which measurement is made; φ – a phase received at measurement; τ_n – - a NCC lifetime in the LD field from which radiation is accepted; N - quantity of the full waves stacked in the measured distance. Thus, for definition of required distance we have system of the equations:

$$\begin{cases} D = \frac{v}{2f_1}(N_1 + \frac{\varphi_1 + \varphi_{10}}{2\pi}), \\ D = \frac{v}{2f_2}(N_2 + \frac{\varphi_2 + \varphi_{20}}{2\pi}), \\ \varphi_{10} = \text{arctg}(-2\pi f_1 \tau_n), \\ \varphi_{20} = \text{arctg}(-2\pi f_2 \tau_n), \end{cases} \tag{22}$$

where f_1 and f_2 - frequencies at which measurements are made; φ_1 and φ_2 - the phases received at measurement; φ_{10} and φ_{20} - radiation modulation phase delays in a source; N_1 and N_2 - amount of full waves stacked in the measured distance on corresponding frequencies.

It is not easy to be convinced, that the system (22) has the unique solution for $D > 0$ and φ_{10}, φ_{20} belonging to an interval (-π/2; 0]. This solution also will be exact value of distance. We shall note also, that the solution of system (22) cannot be submitted in the closed form, i.e. variables D, φ_{10}, φ_{20} are unknown, it is impossible to set obvious functions of parameters f_1 and f_2, φ_1, φ_2. Therefore it is necessary to apply numerical methods for its solution.

The important advantage of such approach is that it is not sensitive to the sizes of a reception object.

Conclusions

Aprioristic research of LD radiation space-time structure in a distant zone, with the help of the developed theoretical base is lead. It is established, that for a radiation modulation phase on the receiver significant variations are characteristic though they essentially smooth out in comparison with initial, and they grow with the reduction of the sizes of a reception object. Taking that into account, for increase of convenience of use of phototachymeters in field conditions a reflector and optics of a photodetector should be made of the small size, there is actual a question of reduction of an error of measurement. The method is offered, allowing to increase accuracy of distance measurement using a LD with high radiation modulation phase non-uniformity.

Refrences

1. **E. D Karikh., I. S Manak**. Semiconductor lasers. Minsk, BSU, 1999. – 199 p.
2. **Laser range finding** / Vasilev V.P. and others. - Moscow, Nauka, 1995. – 257 p.

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U. S. Bialiauski, I. S. Manak. Laser Diode Radiation Phase Non-Uniformity Influence Account For Improvement Phototachymeter Accuracy Characteristics // Electronics and Electrical Engineering, 2006. – No. 3(67). – P. 5–8.

The mathematical model of the phase range finder is elaborated, allowing to investigate a space-time structure of radiation in a distant zone at phase variations of modulation in a near zone of the laser diode. The method is offered to decrease error of distances measurement by the phase phototachymeter, connected with a phase variation of modulation of the laser diode. Ill. 3, bibl. 2 (in English; summaries in English, Russian and Lithuanian).

В. С. Белявский, И. С. Манак. Учет влияния фазовой неоднородности излучения лазерного диода для улучшения точностных характеристик светодальномера// Электроника и электротехника.– Каунас: Технология, 2006.– № 3(67).– С. 5–8.

Построена математическая модель фазового дальномера, позволяющая найти распределение фазы модуляции излучения лазерного диода в дальней зоне, и исследовано его влияние на точность измерения дальности. Предложен метод минимизации погрешности измерения дальности фазовым дальномером на лазерном диоде с неоднородной пространственно временной структурой излучения. Ил. 3, библ. 2 (на английском языке; рефераты на английском, русском и литовском яз.).

U. S. Bialiauski, I. S. Manak. Lazerinio diodo spinduliuotės netolygumo įtakos fototachimetro tikslumo charakteristikoms nustatymas // Elektronika ir elektrotechnika. ─ Kaunas: Technologija, 2006. – Nr. 3(67). ─ P. 5–8.

Sudarytas fazinio atstumo matuoklio matematinis modelis, leidžiantis tirti erdvinę-laikinę spinduliuotės struktūrą artimojoje lazerinio diodo moduliacijos fazės kitimo zonoje. Pasiūlytas metodas leidžia sumažinti atstumo matavimo paklaidas panaudojant fazinį fototachimetrą, sujungtą su lazerinio diodo moduliacijos fazės keitikliu. Il. 3, bibl. 2 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).