Calculation of the vision range for light signals from a navigation complex based on scanning electronically pumped semiconductor laser. Part. I. Power parameters of the light source and threshold characteristics of vision

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Power and time characteristics of a navigation complex based on a scanning electronically pumped semiconductor laser are calculated. In this laser a semiconductor crystal is pumped with an electron beam being scanned across the crystal in the mode of TV-frame scan. The axial intensity of radiation at the output of a laser beacon was taken to be 131.2 W/sr at each of the three wavelengths: λ = 0.52, 0.57, and 0.63 μm. We have determined time and spatial characteristics of the orientation zone and the size of the "uncertainty zone". It is shown that the size of the uncertainty zone obtained cannot essentially spoil the quality of navigation information. The criteria for solving the vision problem are considered and spectral threshold and comfortable characteristics of vision are calculated depending on the conditions of observations.

Introduction

Efficiency of the optoelectronics systems operation in the ground layer of the atmosphere is determined by the source parameters, threshold characteristics of the receiver, and atmospheric transmission, which in the visible spectral region is mainly determined by the atmospheric aerosol. Therefore, calculation of the visibility range for a visual laser navigation complex with a scanning electronically pumped semiconductor laser (SEPSL) under conditions of the coastal marine atmosphere can be divided into three blocks, namely, calculation of the energy and time characteristics of a semiconductor laser, calculation of the threshold characteristics of vision, and calculation of the laser radiation attenuation in the ground layer of the coastal marine atmosphere.

At present, laser navigation aids (NA) with the optical-mechanical control over laser beam scanning[1–5] have gained wide application in providing the safety in coastwise navigation within narrow waters of the coastal areas. The visibility and accuracy characteristics of such NA have been studied quite well.[1,6–8]

However, in a number of cases, laser NA with the optical-mechanical control units do not satisfy practical needs in the speed of operation, resolution, and accuracy. One of the possible ways to solve this problem is using a semiconductor scanning electronically pumped laser in the visual laser NA.[9–11] The control over energy and spatial properties of radiation in SEPSL is performed by means of the electron-beam tube which scans the electron beam and can obtain a set of spatially-separated radiations with different wavelengths.

However, no thorough estimation of the range efficiency of such a complex has been made until so far.

1. Calculation of SEPSL energy characteristics in orientation zones

1.1. Optical arrangement of a SEPSL

The scanning electronically pumped semiconductor laser consists of an electron-beam tube with a beam scanning system and a semiconductor target (ST).[10,11] Principle of SEPSL operation was based on the conversion of electron beam energy in a semiconductor crystal, being the active laser medium, into optical radiation. The laser produces radiation at λ = 0.52, 0.57, and 0.63 μm wavelengths with the output power about 1 W at each of these wavelengths. The wavelengths are determined by the type of crystal, set of stoichiometric composition of its semiconductor material, and correspond to the basic chromatic characteristics of NA.[4,5]

The optical-forming system (OFS) consists of two spherical lenses. It forms the directional pattern of the laser radiation making the mean divergence of the beams equal to 0.34 min of arc, and transfers the image of the emitter to the orientation zone. The orientation zone is formed synchronously with the electron beam scanning across the semiconductor crystal. The OFS provides high quality of the picture of both the lasing target and the beam directional pattern in the orientation zone.

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Consider the SEPSL optical arrangement (Fig. 1).

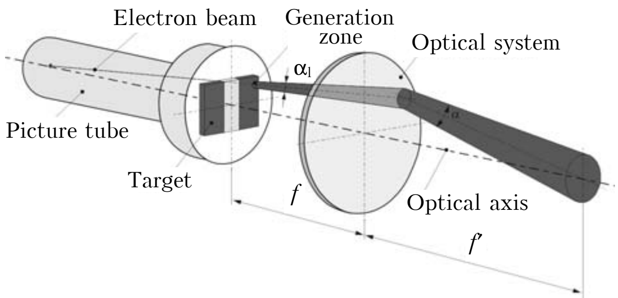

Fig. 1. Simplified optical layout of the navigation complex based on SEPSL.

An electron beam is formed in the cathode-ray tube. It is scanned across a semiconductor crystal (target) in the frame scan mode. Time of a single line scan is about t_{line} $1.75 \cdot 10^{-5}$ s. The vertical sweep frequency ν equals to 75 Hz. The zone of emission generation coincides with the zone scanned with the electron beam. The electron beam characteristics and the OFS optical parameters allow one to adjust the aperture and shape of the emitting area, as well the distribution of the output radiation density, and, accordingly, temporal and spatial characteristics of the orientation zone. Depending on the scanning parameters, the navigation complex (below called laser beacon) can deliver light signal in a flashlight mode of different time modulation.

Clear aperture d of the OFS is 168 mm, and its focal length $f = 302$ mm. The target is set in the focal plane of the OFS perpendicularly and symmetrically with respect to its optical axis and is made of three crystals arranged as shown in Fig. 2. The width of side crystals is $D_s = 16.285$ mm, while that of the central crystal is $D_c = 5.43$ mm. The height of the crystals $H = 28$ mm.

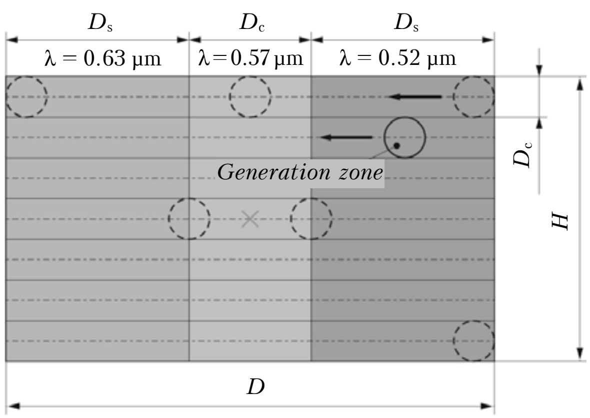

Fig. 2. Schematic view of the target used in calculating the flicker coefficient.

Radiation source in SEPSL is the region of ST crystal hit by the focused electron beam (see Fig. 2). This region is the *generation zone*, which has circular shape with the diameter $d_l = 30$ μm. The optical radiation emitted from the generation zone propagates as a divergent beam confined within a solid angle Ω set by the plane angle α_l, equal to 25°. The OFS transforms the beam and makes its divergence angle α equal to 0.34 min. of arc.

As a result, three color orientation sectors are formed at the beacon output: green, yellow, and red. The sectors have the following angular dimensions:

– the central sector (yellow) has the angular size $\alpha_c = \alpha_y = 1°$, along the horizontal direction;

– the side sectors (green and red) have the angular sizes $\alpha_s = \alpha_r = \alpha_g = 3°$, along the horizontal direction;

– the angular size of sectors, along the vertical direction, is common for all crystals and equals $\beta = 5°$.

1.2. Calculation of the "uncertainty zone" dimensions

Color sectors undergo mixing at the output of the beacon optical system (Figs. 3*a*–*c*), that yields the appearance of the uncertainty zone.

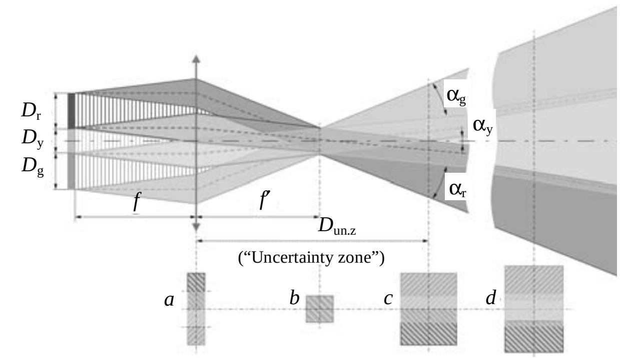

Fig. 3. Principle of color zone formation.

The color sectors become separated after this region except for two narrow transient zones between the adjacent sectors (Fig. 3*d*). The width of these transient zones depends on the size of the generation zone at the border between the target crystals and on characteristics of the optical system that determines the sizes of the light beam cross section. Use of a two-lens system is admissible from the point of view of the pattern quality at a preset accuracy of orientation zone at its boundaries equal to 1′ at the level of 3σ. Increase of the pattern quality owing to the complete correction for aberrations over the entire light field can be achieved by use of a multicomponent lens system. However, it leads to a complication and cost rise of the construction at only insignificant improvement of the quality of the navigational data recorded visually. Therefore, the choice of doublet lens seems to be quite optimal.

Let us estimate dimensions of the "uncertainty zone" $D_{un.z}$ using the principles of geometric optics and the optical arrangement presented in Fig. 4.

The length of "uncertainty zone" along the optical axis can be written by the following expression

$$D_{un.z} = \frac{2f}{D_c}\left(R + \frac{D_c}{2}\right), \tag{1.1}$$

where D_c is the horizontal size of the central zone of the semiconductor target, mm, R is the radius of the beam cross section in the lens's plane, mm, determined by the formula

$$R = f \tan(\alpha_l/2). \qquad (1.2)$$

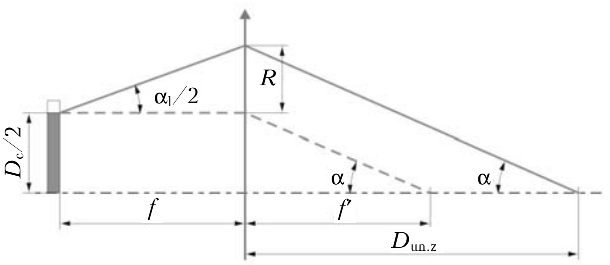

Fig. 4. Geometrical scheme of ray tracing in the scanning beam for calculating the "uncertainty zone" size.

If $\alpha_l = 25°$ and $f = 302$ mm, then $R \approx 67$ mm. Therefore, according to formula (1.1), $D_{un.z} \approx 7.755$ m. Having in mind that vessels do not approach visual NA closer than several hundred meters, this size of uncertainty zone does not effect the navigation data quality.

1.3. Calculation of the power characteristics of the beacon radiation

In determining power characteristics of radiation in the orientation zones, the following assumptions have been made: optical system has no aberrations therefore one can neglect the losses in it. In this case, radiation flux P_{e0} generated by the target is equal to the radiation flux at the output of the beacon optical system. However, the beam changes its spatial characteristics after transformation in the optical system that involves change in the radiation spectral density. Besides, it should be taken into account that in the process of scanning, the periodical visual impact of the light beam on an eye occurs during a short time, which is shorter than the vision inertia.

The periodic effect estimation is expressed through the flicker coefficient K_{fl}, which is determined by the duration of optical radiation pulse t_{pul} recorded at the moment of generation zone activity and by scanning frequency ν:

$$K_{fl} = \nu t_{pul}. \qquad (1.3)$$

Pulse duration t_{pul} depends on the generation zone diameter d_l, vertical and horizontal size, H and D, of the target (see Fig. 2), time of the electron beam travel along a line t_l being related with them by the following expression

$$t_{pul} = \frac{d_l}{D} t_l. \qquad (1.4)$$

Having in mind the above mentioned size of the target, $t_{pul} = 1.374 \cdot 10^{-8}$ s.

According to formula (1.3), the flicker coefficient of the optical signal is $K_{fl} = 1.03 \cdot 10^{-6}$ taking into account that human vision does not resolve separate pulses within a single frame and perceives it as a whole.

Intensity of radiation I_e at the beacon output along the viewing direction is determined, with the account for the flicker coefficient, by the following expression:

$$I_e = \frac{P_e}{\Omega} K_{fl}, \qquad (1.5)$$

where P_e is the *instant* power (flux) of the radiation beam, W; $\Omega = \pi \sin^2(\alpha/2)$ is the solid angle, determined by the angle α. The solid angle $\Omega = 7.85 \cdot 10^{-9}$ sr corresponds to the angle $\alpha = 5.73 \cdot 10^{-3}$ deg.

According to formula (1.5), the axial intensity of radiation at the laser beacon output reaches 131.2 W/sr at each of the wavelengths.

2. Criteria of solving the vision problem

2.1. System of visual functions

Eyesight of a person is characterized by three main functions,[12–15] namely, by the threshold brightness L, threshold contrast k, and by the limiting angular resolution δ. These quantities are interconnected, and there is no sense in considering each of them separately. The function connecting these characteristics, can be conditionally written as follows

$$f(L, k, \delta) = 0. \qquad (2.1)$$

Geometrically, the function (2.1) can be presented as a surface in axes L, k, and δ. If the point is below the surface, the object is invisible, but if it is above it the object becomes visible. If the object of observation is flashing, the observation time should also be taken into account in determining the threshold conditions, which already make up a four-dimensional surface. Besides, the detection reliability is introduced, being set by the assurance factor. Then, the threshold conditions become the five-dimensional surface. In a particular problem, the threshold conditions can be expressed by the function analogous to formula (2.1) with one or another number of interrelated variables.

Visibility of a laser beacon essentially depends on the threshold characteristics of vision, observation conditions, time and power characteristics of the beacon. If a point light source, like a laser beacon, has the angular size less than 10 min of arc, the source image on the retina is so small that it occupies a single light-sensitive retina cell, which has the equivalent angular size of 30 seconds of arc. Therefore, the image is seen as a flashing point. In this case, the image area does not affect the strength of the vision response, which depends only on the light flux, incident on the single element of the retina. The strength of the vision response is proportional to illumination of the pupil of the observer's eye, which is called flash for brevity. Since laser beacon is a point light source, the threshold conditions for it (2.1) are simplified and determined

Table. Relative spectral sensitivity of vision $V(\lambda)$, averaged values of the spectral flash under threshold E_{thr}, and comfortable E_{comf} observation conditions depending on the background brightness B_b

Background	B_b, cd/m^2	$V(\lambda)$			$E_{thr}\cdot 10^{-9}$, W/m^2			$E_{comf}\cdot 10^{-9}$, W/m^2		
		$\lambda = 0.52$	$\lambda = 0.57$	$\lambda = 0.63$	$\lambda = 0.52$	$\lambda = 0.57$	$\lambda = 0.63$	$\lambda = 0.52$	$\lambda = 0.57$	$\lambda = 0.63$
Night	$10^{-5} - 10^{-2}$	0.9350	0.2076	0.0033	0.94	3.40	89.10	6.6	23.8	623.7
Twilight	$10^{-1} - 10$	0.6200	0.9500	0.2700	2.36	2.00	43.38	16.5	14.00	303.6
Day	$10^{2} - 10^{4}$	0.7100	0.9520	0.2650	30.93	16.90	60.70	216.5	118.5	425.5

only by three quantities: brightness or irradiance E on the pupil, flash duration Δt_{br}, and the background brightness B_b, where it is observed.

An important characteristics of vision is the function of the relative spectral sensitivity of vision $V(\lambda)$ of a standard photometric observer. This characteristic was approved by the International Commission on illumination (ICI) and accepted by the national State standard.[16] The function $V(\lambda)$ corresponds to the daytime conditions at the values of the background B_b equal to $(10^2 - 10^4)$ cd/m^2 (Ref. 12). Under night conditions at $B_b = (10^{-2} - 10^{-5})$ cd/m^2 the function $V'(\lambda)$ is used.

The region of twilight vision takes the in-between position at the values of the background brightness B_b equal to $(10^{-1} - 10)$ cd/m^2. It is considered that at the upper boundary of the region the relative spectral sensitivity of twilight vision coincides with the function $V(\lambda)$, while at the lower boundary it becomes the $V'(\lambda)$ function. The experiment conducted in the study discussed in Ref. 17 has shown that the function $V(\lambda)$ recommended by ICI, underestimates the corresponding values in the short-wave part of the visible range. A new function is suggested for $\lambda = 0.38$–0.56 μm, determined by the relation

$$V_{reg}(\lambda) = V_{10}(\lambda) + p\big(V_{10}(\lambda) - V(\lambda)\big), \qquad (2.2a)$$

where $V_{10}(\lambda)$ is the function of relative sensitivity of vision of a photometric observer with the field-of-view angle[12] equal to 10°, p is the weighting coefficient equal to 0.8125.

For the wavelength range from $\lambda = 0.557$ to 0.8 μm

$$V_{reg}(\lambda) = V_{10}(\lambda). \qquad (2.2b)$$

Therefore, for a laser beacon generating radiation at $\lambda = 0.52$, 0.57, and 0.63 μm, the values of the functions $V(\lambda)$ and $V'(\lambda)$ are taken from Ref. 12, and those for twilight vision are determined by use of expressions (2.2a) and (2.2b). The results are presented in the summary table.

2.2. Threshold characteristics of vision

The criterion of detecting the laser beacon radiation is the value of the efficient threshold flash determined by the relation

$$E_{eff}(\lambda) = k'E_{thr}(\lambda), \qquad (2.3)$$

where $E_{thr}(\lambda)$ is the threshold flash at observation of a continuous source, W/m^2; k' is the coefficient that takes into account the flashing nature of the signal light and is determined by the expression

$$k' = \Delta t_{fl} / (\Delta t_{fl} + \theta), \qquad (2.4)$$

θ is the time constant of the vision inertia, s.

The vision inertia time θ depends on the background brightness B_b and is determined by the relation[13]:

$$\theta = 0.13 - 0.08\tanh(\ln B_b + 1). \qquad (2.5)$$

Under night conditions of observations the standard data were used,[4,5] accepted in engineering the visual NA. These data take into account real conditions of observation: limited observation time for detection and recognition of light signals, uncertainty of location and the time of light signal appearance, etc., which are determined by the value of safety or reliability coefficients. According to Refs. 14 and 18, the value of the assurance factor can reach 50.

At daytime and twilight observations on determining E_{thr}, an empirical expression was used[14]:

$$E_{thr} = E'\left(B_b / B'_b\right)^{0.073\ln(B_b/B'_b)}, \qquad (2.6)$$

where $B_b = 5\cdot 10^{-2} - 2.5\cdot 10^4$ cd/m^2; $B'_b = 10^{-2}$ cd/m^2; $E' = 0.45\cdot 10^{-6}$ lux for red light ($\lambda = 0.63$ μm); 10^{-6} lux for yellow light ($\lambda = 0.57$ μm); $0.56\cdot 10^{-6}$ lux for green light ($\lambda = 0.52$ μm).

The characteristics E_{thr}, used in Refs. 4 and 5, and in the expression (2.6), is a photometric quantity. For transition to the power value of E_e (irradiance), the well known photometric expression is used[13] for the case of a monochromatic light with the wavelength λ:

$$E_\lambda = 683 \int_{0.38}^{0.78} E_e V(\lambda)\, d\lambda. \qquad (2.7)$$

Having in mind expression (2.7), we have presented the branch standard values of the flash E_{thr} under night conditions and the averaged flash values calculated by formula (2.6) are presented in the Table, where the irradiance at the eye pupil values are also presented there for conditions of comfortable observations E_{comf}, when the beacon light signal is detected at its location at any point of the viewing field. Moreover, there is no interference at operation with other NA. According to Refs. 14 and 18, E_{comf} exceeds E_{thr} by 6 to 8 times.

References

1. V.E. Zuev, V.I. Peresypkin, V.Ya. Fadeev, and R.S. Konstantinov, *Laser Aids to Navigation* (Nauka, Novosibirsk, 1985), 128 pp.
2. G.A. Kaloshin and A.I. Gordienko, IALA Bull. **3**, 46–51 (2003).
3. G.A. Kaloshin and A.I. Gordienko, IALA Bull. **1**, 30–39 (2004).
4. *Instruction on Aid to Navigation* (ANI-2000) (St.-Petersburg, 2001), 328 pp.
5. *The IALA Navguide*, 4th edition (2002), 220 pp.
6. G.A. Kaloshin and V.V. Nosov, Atmos. Oceanic Opt. **15**, No. 12, 997–1001 (2002).
7. G.A. Kaloshin and Yu.S. Mikheev, Opt. Zh., No. 10, 3–6 (1992).
8. G.A. Kaloshin and A.N. Mal'tsev, Navig. i Gidrogr., No. 13, 100–109 (2001).
9. G.A. Kaloshin, S.A. Shishkin, and S.K. Gauss, in: *Proc. of XII Joint Int. Symp. on Atmospheric and Ocean Optics. Atmospheric Physics* (Tomsk, 2005), p. 91.
10. I. Olikhov and L. Kosovsky, Elektronika, No. 3, 46–49 (1999).
11. D.V. Vasil'ev, Prib. i Sistemy Upravl., Kontrol, Diagnos., No. 12, 19–26 (2004).
12. V.V. Meshkov and A.B. Matveev, *Fundamentals of Light Engeneering.* Part 2. *Physiological Optics and Colorimetry* (Energoatomizdat, Moscow, 1989), 432 pp.
13. A.V. Luizov, *Eye and Light* (Mashinostroenie, Leningrad, 1978), 184 pp.
14. I.A. Zabelina, *Calculation of Stellar Visibility and Far Lights* (Energoatomizdat, Leningrad, 1983), 144 pp.
15. Yu.G. Basov, *Light-signal Devices* (Transport, Moscow, 1993), 309 pp.
16. *Function of Relative Spectral Luminosity of Monochromatic Radiation for Day Vision*. GOST 8.332-78 (Izdat. Standart., Moscow, 1984), 25 pp.
17. M. Viikari, M. Elokholma, and Ya. Ketomaki, Svetotekhnika. No. 4, 7–15 (2005).
18. G.A. Kaloshin and S.A. Shishkin, Navig. i Gidrogr., No. 18, 34–43 (2004).