UKRAINIAN STATE COMMITTEE OF COMMUNICATIONS AND INFORMATIZATION

ODESSA NATIONAL ACADEMY OF TELECOMMUNICATIONS

after A. S. POPOV

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PHYSICS

Module № 4. „ Physics of optical communication"

PHYSICS OF OPTICAL COMMUNICATION

PART 2: TERM PAPER

for bachelor training of educational area 0924 –"Telecommunications"

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The following methodical guide is about section “Physics of optical communication” of physics course for telecommunications technician. Five stages allow students to learn basics of optical communications buildings and calculations techniques applied to determine main characteristics of four determinative elements of construction of fiber optical communication line. It contains sufficient theoretical information combined with examples of implementation of calculated work part.

Recommended for students of TE-group, educational area 0924 – “Telecommunications”.

CONFIRMED
at the Department session
Protocol № 4
from 10.11.2009

MODULE STRUCTURE

Module № 4 "Physics of optical communication"– 72 hours total.
Lectures – 16 hrs, pract. trainings – 0 hrs, labs – 16 hrs, self-studies – 33 hrs.

LIST OF PRACTICAL TRAINING

Number of lessons	Denomination of lessons	Hours
Module № 4		
1	Parameters of light-emitting diodes and lasers. External quantum efficiency.	2 self
2	Calculation of parameters of light-emitting diodes and lasers.	2 lab
3	Modulators and its characteristics.	2 self
4	Calculation of characteristics of modulators.	2 lab
5	Light guides. Losses in optical fibers. Frequency dispersion.	2 self
6	Calculation of parameters of optical fiber.	2 lab
7	Photoelectric cells. Photodiodes.	2 self
8	Calculation of parameters of photo diodes.	2 lab

METHODICAL INSTRUCTIONS
ON IMPLEMENTATION OF TERM PAPER

- For implementation of term paper students must study sections **“Optics”** and **“Physics of optical communication”** of course of physics for telecommunications technician.
- Term paper is consists of five mutually connected assignments on stages: **4.1**; **4.2**; **4.3**; **4.4**; **4.5**. Student must implement on one assignment from each stage. Concrete numbers of assignment on each stage and initial data in thirty variants is indicating at **Table 1**. Number of the variant is determining by the index of surname of student at a group journal.
- ***Report*** is implementing on white unruled sheets of format of A4. Writings should be made on one side of the sheet. Sheets are sewn together at the folder.
- On the cover there is need to mark title of the work, ***number of the variant***, surname and initials of student, code of group.
- Calculation part it is necessary to dispose in order of numeration of the stages.
- Calculation part of any stage must contain eleven points (see examples):

1. ***Title of the stage;***
2. ***Theoretical information*** (answers on control questions of the theme);
3. ***Complete statement*** of a stage assignment.
4. ***Short writing*** of statement.
5. Transformation of a value of given quantities to the ***system of units CI.***
6. ***Scheme*** or explanatory plan.
7. ***List of laws*** and ***formulas*** which explain the physical phenomena of theme of the stage. All ***denotations*** at the formulas need an ***explanations***.
8. ***Literal solution***. From the listed at point **7** formulas it is necessary to make system of equations and to obtain expression of each desired quantity through given quantities at the literal (symbolic) representation.
9. ***Checkout of measurement unit*** of each desired quantity on correspondence to the expected measurement unit. For this purpose each symbol in the formula of a literal solution to substitute with its measurement unit and realize the necessary transformations.
10. Only after correspondence of measurement units to the expected it is possible to find the ***numerical solution***. Calculation should be transacted with three significant digits.
11. ***Results*** of execution of calculated part of a stage.

At the end of work it is necessary to enumerate the list of the used literature. Besides this guide is recommended to use literature from bibliography given at the end of this guide.

Every time, if does not indicated, consider that $T = 300\ K$.

ARBITRARY NOTATIONS

t – time;

x – coordinate;

S – sectional area;

$c = 3 \cdot 10^{8}$ m/c – light speed;

$e = 1{,}602 \cdot 10^{-19}$ C – modulus of charge of the electron, charge of the hole;

m_0 – $9{,}11 \cdot 10^{-31}$ Kg – rest mass of free electron;

$h = 1{,}38 \cdot 10^{-34}$ $J \cdot s$ – Planck constant;

k – $1{,}38 \cdot 10^{-23}$ $J/K = 8{,}62 \cdot 10^{-5}$ eV/K – Boltzmann constant;

$\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m – electric constant;

ε – relative permittivity;

T – temperature;

kT – thermal energy;

$h\nu$ – photons' energy;

ν – photons' frequency;

E – electron (or hole) energy;

n – electron concentration; p – hole concentration;

τ_n – electron lifetime; τ_p – hole lifetime;

D_n – coefficient of electron diffusion; D_p – coefficient of hole diffusion;

E_g – energy gap between valence and conductivity band;

U – potential difference;

$\mathbf{E}$ – intensity of electric field;

η_{ext} – external quantum efficiency of LED;

η – quantum efficiency of photoeffect;

j – current density;

j_S – density of saturation current;

ρ – specific resistance; ρ_D – darkness specific resistance;

γ – specific conductivity;

$\Delta\gamma$ – specific photoconductivity; γ_D – specific conductivity of darkness;

Δn – concentration of nonequilibrium photo electrons;

Δp – concentration of nonequilibrium photo holes;

g – generation rate of the charge carriers;

α – coefficient of light absorption;

R – coefficient of luminous reflectance;

ϕ – quantum intensity of radiation (photon flux density);

L_{OPT} – effective length of light absorption.

MAIN CONCEPTS AND FORMULAE

At given term paper student must build fiber optical communication line (FOCL). For this it is necessary to calculate and select quantities of basic parameters of four determinative elements of construction of FOCL: light-emitting diode (LED), modulator, optical fiber and photodetector. Characteristic of each element of FOCL must obey of three kinds of conditions:

1. Emission ***wavelength*** of LED must correspond to the low-loss transmission window of optical fiber (see Fig. 3) and photo detector must effective absorb such radiation. The operating voltage of modulator it is necessary to calculate according to a wavelength of emitted light.
2. LED ***current*** should be enough for emitting of such radiation that it has sufficed for generation of the given current of a photo detector taking into account losses in modulator and optical fiber.
3. Frequency of the modulating signal must doesn't be greater than the cutoff frequency of each of four determinant elements.

THEME 4.1
LIGHT-EMITTING DIODES (LED)

In the time of learning of the optical properties of semiconductor devices the most convenient form of representation of p-n junction is it energy band diagram, which is shown in **figure 1**.

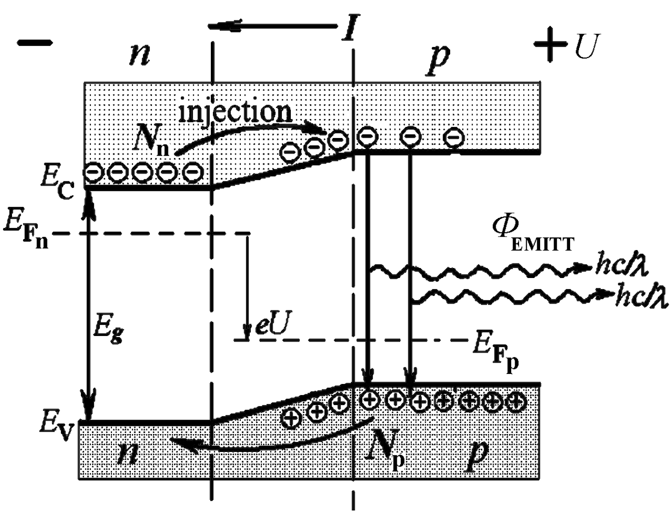


Figure 1 – Band diagram of LED

Designation of energy levels and quantities are next:
E_C – conductivity band bottom,
E_V – valence band top;
E_g – energy gap (width of forbidden band) is a difference of energy E_C–E_V ;
n_n – electron concentration at n-region,
p_p – hole concentration at p-region;
U – magnitude of forward voltage and
eU – correspondent energy,
I – current passed through the LED; Φ_{EMITT} – number of emitted photon which go out from the LED; N_p and N_n – number of holes and electrons which are injected through the p-n junction.

The main physical quantity, which characterize the quality of LED is external quantum efficiency η_{EXT} – ratio between number of emitted photons which go out from the LED Φ_{EMITT} to total number of holes and electrons which pass through the p-n junction ($N_p + N_n$):

$$\eta_{EXT} = \frac{\Phi_{EMITT}}{N_p + N_n}. \qquad (1)$$

If take the quantities Φ_{EMITT}, $N_p + N_n$ is measure at time unit, then current passing through the LED is equal:

$$I_{LED} = e(N_p + N_n). \qquad (2)$$

Then power of light, which goes out from the LED is determine as:

$$P_{EMITT} = \Phi_{EMITT}\, h\nu.$$

Substitute the equations (1) and (2) and obtain the emission power of LED:

$$P_{LED} = \eta_{EXT}(N_p + N_n)\cdot h\nu = \eta_{EXT}\frac{I_{LED}}{e}\cdot h\nu. \qquad (3)$$

At the equation (3) and next h and e are constants (view arbitrary notations).

The maximum working frequency of work of LED (frequency of modulating signal at internal method of modulation of emission) is determined by lifetime of electrons which are injected to p-base τ_n:

$$f_{max} = \frac{1}{2\pi\cdot\tau_n}. \qquad (4)$$

At given work for production the LED are introduce 3 compositions of triple semiconducting compound $Ga_xIn_{1-x}As$ (composition 1), InP_yAs_{1-y} (composition 2), $Al_zGa_{1-z}As$ (composition 3).

Energy gap E_g of such semiconductors is depend from parameters of composition:

$Eg\ [eV] = (0{,}36+1{,}08x)$ – for **composition 1** ($Ga_xIn_{1-x}As$),

$Eg\ [eV] = (0{,}36+0{,}97y)$ – for **composition 2** (InP_yAs_{1-y}), (5)

$Eg\ [eV] = (0{,}77+1{,}37z)$ – for **composition 3** ($Al_zGa_{1-z}Sb$).

Student must determine the chemical formula of composition of semiconductor given at **Table 1**, according to variant. Parameter of composition x, y, z must determine the semiconductor, which will radiate light with wavelength:

$$\lambda = \frac{hc}{E_g}. \qquad (6)$$

This emission wavelength must exactly agree with the wavelength of one of the quartz optical fiber low-loss transmission window (see **Fig. 3**), number of which is given at **Table 1**. The quartz optical fiber has four transmission windows at near infrared spectrum: 0,85, 1,15, 1,33 and 1,55 μm. The maximum of emission power must correspond to such wavelength.

Electrons which participate in radiation have a variation in values of energy which depends on semiconductor temperature $\Delta E_{EL} \sim kT$. Emission band at energy units

$(E_g – \Delta(h\nu)/2\,; E_g+\Delta(h\nu)/2)$

is determine the interval of photon energy, quantum intensity of which is greater than the half maximum of quantum intensity; $\Delta(h\nu)\sim kT$ – is a half-width of emission band at energy units.

Wavelength is depend from photon energy hv:

$$\lambda = \frac{hc}{h\nu}. \tag{7}$$

Take into account then the photon emission energy $h\nu$ is large greater than the difference of energy $d(h\nu)$ at emission band $\Delta(h\nu)$, it is possible to differentiate the formula (7):

$$\frac{d\lambda}{d(h\nu)} = hc\cdot\frac{1}{(h\nu)^2} = hc\cdot\frac{\lambda^2}{(hc)^2} = \frac{\lambda^2}{hc}. \tag{8}$$

If replace sign of differential d to sign of increment Δ, we obtain the expression for half-width of emission band at wavelength units as a ***full width*** of ***half maximum (FWHM)*** of spectrum of quantum intensity:

$$\Delta\lambda = \frac{\lambda^2\cdot\Delta(h\nu)}{hc}. \tag{9}$$

Then emission band at wavelength units is determine as interval

$(\lambda – \Delta\lambda/2 \div \lambda+\Delta\lambda/2)$.

The emission band at frequency units it is possible to get if calculate the frequency of emission from expression (7) and half-width of emission band at frequency units from (9):

$$\Delta v = \frac{c\cdot\Delta\lambda}{\lambda^2}. \tag{10}$$

Then emission band at frequency units is determine as interval

$(\nu – \Delta\nu/2 \div \nu+\Delta\nu/2)$.

THEME 4.2
MODULATORS

Structure of electro-optical modulator is shown on the **Fig 2.** The elecrooptical effect is based on fact, that some solid materials have difference of the refractive indexes for light waves which are polarised in perpendicular plane and parallel plane relative to the applied electric field. This difference depend on value of applied voltage.

On **Fig. 2** the input light wave propagate along the axis z and it must be polarized under an angle of 45 degrees relative to the applied electric field $\mathbf{E_{0x}}$, then light waves which are polarized in perpendicular plane $E_y(\omega)$ and parallel plane $E_x(\omega)$ have an equal amplitudes.

When the external electric field $\mathbf{E_{0x}}$ is applied along axis x the difference of the refractive indexes of light waves which are polarized in perpendicular plane $E_y(\omega)$ and parallel plane $E_x(\omega)$ is appeared:

$$\Delta n = \frac{n^3 r \cdot \mathbf{E}_{0\mathbf{x}}}{2}, \tag{11}$$

where $\mathbf{E}_{0x}$ – electric intensity of applied external field directed along axis x; n – refractive index at absence of external field; r – electro-optical coefficient of Pockels.

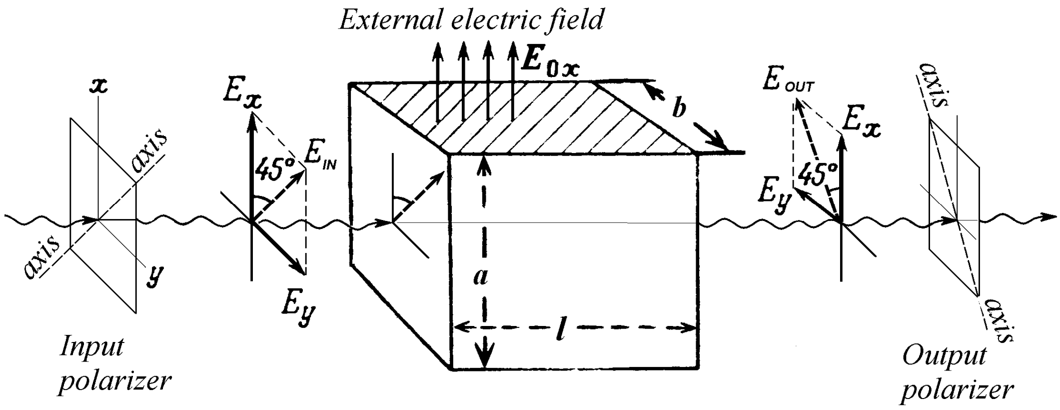


Figure 2 – Electro-optical modulator on the base of Pockels cell.

At the result, after transiting along the crystal length l in output light wave component $E_x(\omega)$ and $E_y(\omega)$ obtain the optical path difference:

$$\Delta_{\text{OPT}} = \Delta n \cdot L = \frac{n^3 r \cdot \mathbf{E}_{0\mathbf{x}} \cdot l}{2}. \tag{12}$$

Correspondent phase difference between the components $E_x(\omega)$ and $E_y(\omega)$ is

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta_{\text{OPT}} = \frac{\pi \cdot n^3 r \cdot \mathbf{E}_{0x} \cdot l}{\lambda}. \tag{13}$$

If $\Delta_{\text{OPT}} = \lambda/2$, then wave which is polarized in perpendicular plane $E_y(\omega)$ obtain the space lag relative to the wave which is polarized in parallel plane $E_x(\omega)$ on $\lambda/2$ and its maximum replace the minimum. At the result, the polarization of output light wave turned on 90° relative to plane of polarization of input light wave.

Thus if crystal with dimensions $a{\times}b$ is placed between crossed polarizers, then output light signal is zero at missing the voltage but output light signal achieves the maximum when applied external "half-wave voltage":

$$U_{(\lambda/2)} = \mathbf{E}_{0\mathbf{x}} b = \frac{\lambda b}{n^3 r \cdot l} \tag{14}$$

Value $n^3 r$ is a quality factor of electro-optical material.

For coincidence of shape of the output pulse with shape of control voltage pulse it is necessary that the transmission time of light wave through the crystal was less the control voltage pulse length. If pulse time is not great, we can accept the condition when optical wave transmission time through modulator 20 times less then pulse period of control voltage:

$$\frac{l}{c/n} = \frac{T}{20}. \quad (15)$$

Then maximum possible modulating signal frequency is limited by the cell length according to equation:

$$f_{\max} = \frac{c}{20n \cdot l}. \quad (16)$$

For work of Pockels cell a polarized light is needed. When the Pockels cell is using in optical links in common with the sources of noncoherent emission (which are LED's), at polarization on an input polarizer the half of light power is lost: δ_{POL} =0,5. Then the total coefficient of efficiency of modulator is:

$$\Delta_{MOD} = \delta_{POL} \cdot \delta_{MAT}, \quad (17)$$

where δ_{MAT} – transmittance of a material of a Pockels cell.

THEME 4.3
OPTICAL FIBERS

For building optical communication line in this work it is offered to use the single-mode optical fiber to avoid additional limitings on length of the light-guide, related to an intermodal dispersion.

Narrow light pulse with spectral half-width $\Delta\lambda=\lambda_2-\lambda_1$ after the passage on a single-mode light-guide will have some broadening. This take place in result of frequency dispersion, when the light with maximum wavelength λ_2 propagate faster than the light with minimum wavelength λ_1 (at case of normal dispersion).

The pulses were not overlapping. Therefore the pulse repetition frequency cannot be higher than the frequency limit $f_{\max}$ at which the long-wave edge λ_2 of the one pulse do not overtake on the guide end the short-wave edge λ_1 of the previous pulse. Inversely proportional to it smallest pulse repetition period $T_{\min}$ is equal to difference of propagation time of short-wave edge t_1 and long-wave edge t_2 of spectrum of light pulses:

$$T_{\min} = t_1 - t_2.$$

Let's taking into account, that velocity of light propagation in medium depends on wavelength:

$$\upsilon = \frac{c}{n(\lambda)},$$

then obtain

$$T_{\min} = \frac{n(\lambda_1) \cdot L}{c} - \frac{n(\lambda_2) \cdot L}{c} = \frac{[n(\lambda_1) - n(\lambda_2)] \cdot L}{c}.$$

where λ_1 and λ_2 – are determine edges of spectral half-width $\Delta\lambda$ of transmitted light; $n(\lambda_1)$ and $n(\lambda_2)$ – correspondent refractive indexes for short-wave λ_1 and long-wave λ_2 edges of spectral half-width, L – length of the light-guide, c – speed of light in vacuum.

If for the given wavelength range we know dispersion rate $dn/d\lambda$ and the pulse spectral half-width $\Delta\lambda$, we can obtain the difference of refractive indexes for short-wave and long-wave edges of the spectral half-width of transmitted light:

$$n(\lambda_1) - n(\lambda_2) = \frac{dn}{d\lambda} \cdot \Delta\lambda .$$

Then finally:

$$T_{\min} = \frac{dn/dl \cdot \Delta\lambda \cdot L}{c}, \tag{18}$$

The specific attenuation describe a losses in the light-guide:

$$\beta_0 = \frac{10}{L} \cdot \log(P_{\mathrm{IN}}^{\mathrm{FIB}} \;/\; P_{\mathrm{OUT}}^{\mathrm{FIB}}) \tag{19}$$

where $P_{\mathrm{IN}}^{\mathrm{FIB}}$ – power of input light, $P_{\mathrm{OUT}}^{\mathrm{FIB}}$ – power of output light at the end of fiber by length L [km].

Then total attenuation along the fiber by some length L:

$$\beta = \log(P_{\mathrm{IN}}^{\mathrm{FIB}} / P_{\mathrm{OUT}}^{\mathrm{FIB}}) = \beta_0 \cdot L \tag{20}$$

The power of output light it is possible to determine as:

$$P_{\mathrm{OUT}}^{\mathrm{FIB}} = P_{\mathrm{IN}}^{\mathrm{FIB}} \cdot 10^{-\frac{\beta_0 \cdot L}{10}} = P_{\mathrm{IN}}^{\mathrm{FIB}} \cdot e^{-0.23\beta_0 \cdot L} \tag{21}$$

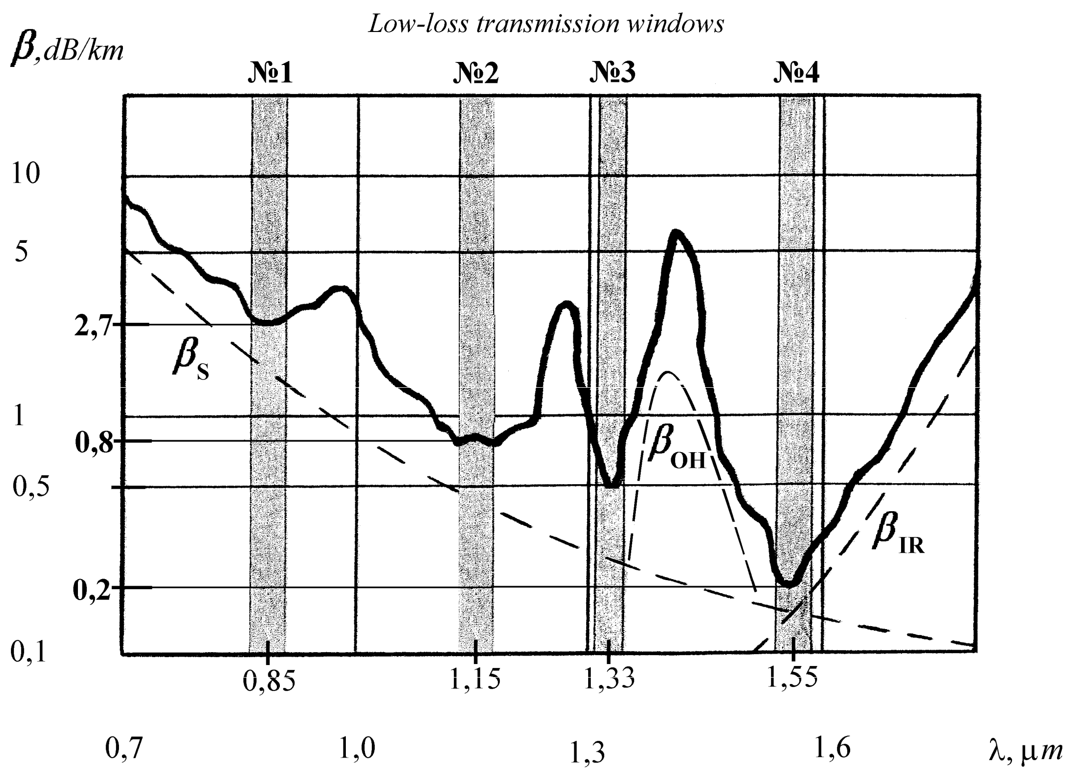


Figure 3 – Specific attenuation β of a silica fiber as a function of wavelength and the main contributions to it: electronic IR absorption (β_{IR}), OH-absorption (β_{OH}) and Rayleigh scattering (β_S).

In optic links often use the quartz fiber. Spectral attenuation of a quartz is shown on **Fig. 3**. As follows from chart, the four absorption minimums are exists: 2.7, 0.8, 0.5 and 0.2 *dB/km* – low-loss transmission window. Subject to complex of conditions is choose the defined transmission window with certain value of wavelength and specific attenuation. The wavelength of maximum of emission power of LED, which determine from relation (6), must exactly correspond to such transmission window.

THEME 4.4
PHOTODIODES

Electrons of a semiconductor can absorb a light only if energy of photons greater than energy gap of given semiconductor. Such light is photoactive for given semiconductor because absorbed photons generate free electrons and holes. But if energy of photons greater than two energy gap, the light is absorbed near the surface, where generated free carriers at once recombine through surface states. Such light is not photoactive.

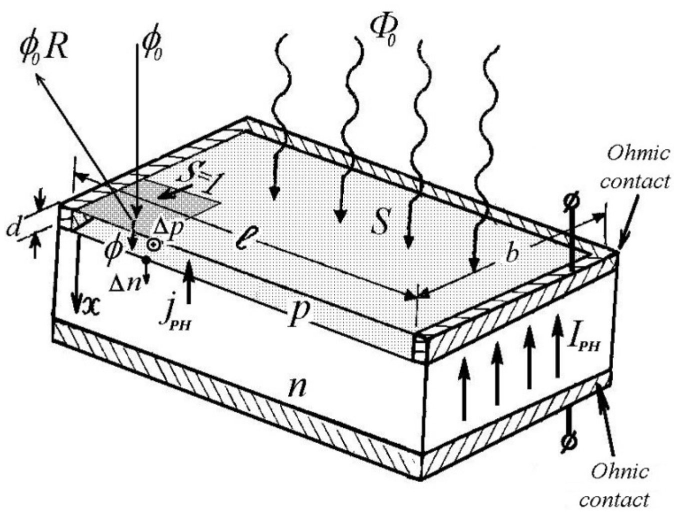


Figure 4 – Internal photoelectric effect

Thus, for given semiconductor with energy gap E_g , light is photoactive when its spectral maximum correspond to photon energy $h\nu$, which belongs to an interval:

$$h\nu \in [E_g\ ; 2\ E_g]. \tag{22}$$

And other way, given light with maximum of spectrum corresponding to photon energy $h\nu$ is photoactive for all semiconductors with energy gap Eg , which belongs to an interval:

$$E_g \in [h\nu\ /\ 2\ ;\ h\nu]. \tag{23}$$

The luminous flux which exposes a photodetector is characterised by a quantum light intensity ϕ_0 - quantity of photons which is falling on 1 m^2 of area of exposed surface for one second. Then the input light power of photodetector with exposed surface area S:

$$P_{\text{IN}}^{\text{PHOTO}} = \phi_0 \cdot S \cdot h\nu\,. \tag{24}$$

If light is photoactive, then it is absorbed, and its quantum efficiency is decreased according to the Bouguer law:

$$\phi(x) = \phi_0(1 - R) \cdot \exp(-\alpha x)\,, \tag{25}$$

where R – coefficient of optical reflection, α – coefficient light absorption, x – depth of light penetration.

Optical generation rate of charge carriers in a thin semiconductor layer is directly proportional to reduction rate of quantum light intensity:

$$g(x) = -\eta \frac{d\phi}{dx} = \eta \cdot \alpha \cdot \phi_0 (1-R) \cdot \exp(-\alpha x), \qquad (26)$$

where η – quantum efficiency of internal photoelectric effect.

Let the photodiode with p-n junction, which have thin p-region with thickness *d* (base) and area of exposed window S is illuminate by the light with quantum intensity ϕ_0. For the photodiode it is characteristic, that the incident light is completely absorbed at the near-surface layer *d*, then the optical generation rate at p-region not depend on absorption coefficient:

$$g = \frac{\eta \cdot \phi_0 (1-R)}{d}. \qquad (27)$$

Density of nonequilibrium photoelectrons and photoholes which are generated by light at photodiode base *d*:

$$\Delta n = \tau_n g = \tau_n \cdot \eta \cdot \phi_0 (1-R)/d; \qquad (28)$$

$$\Delta p = \tau_p g = \tau_p \cdot \eta \cdot \phi_0 (1-R)/d, \qquad (29)$$

where τ_n, τ_p – electrons and holes lifetime.

The thickness of absorption area *d* is make quite thin, that, the generated in p-region minority photoelectrons practically at once without losses comes to the p-n junction and transits further away to the n-region, forming a drift photocurrent j_{PH} which will flow in a direction matching to a reverse current. Generated in p-region majority holes can not overcome the potential barrier and remains at p-region. Then photocurrent density flowing across area *S* of p-n junction (**Fig. 4**), at neglecting of losses from photocarrier recombination, we may define as:

$$j_{PH} = \frac{I_{PH}}{S} = \frac{e\Delta N}{\tau_n S} = \frac{e\Delta n \cdot d \cdot S}{\tau_n \cdot S} = e \cdot \eta \cdot \phi_0 (1-R). \qquad (30)$$

At the result, the n-region will be charged negatively, but p-region – positively. The photo-EMF U_{PH} is generated. Positive potential of U_{PH} on p-region correspond to a forward bias of p-n junction, which decreases a potential barrier, therefore a forward diffusion current j_{DIFF} of electrons from n-region and holes from p-region will start to flow. The value of j_{DIFF} determined by volt-ampere characteristic

$$j = j_S \left(\exp\frac{e \cdot U}{kT} - 1 \right), \qquad (31)$$

with positive value of $U=U_{PH}$. In (31) j_S – is a saturation current density, and *T* – absolute temperature of p-n junction. Thus, the forward current j_{DIFF} compensates a photocurrent j_{PH}.

If the circuit of illuminated photodiode will be open (idle mode), the forward current magnification is prolonged until both currents will be equal, then a total current through p-n junction will be equal to null:

$$j_{TOT} = |j_{DIFF}| - j_{PH} = 0 \qquad (32)$$

The maximal possible potential difference created at this case by photodiode, is called idling voltage. If we substitute (30) and (31) into (32) we obtain relation between quantum light intensity ϕ_0 and idling voltage U_{ID}:

$$j_S\left(\exp\frac{e\cdot U_{ID}}{kT}-1\right)-e\cdot\eta\cdot\phi_0(1-R)=0\ . \qquad (33)$$

At photodiode mode to p-n junction a reverse bias is applied and current through p-n junction is consist of sum of reverse current j_{REV} (determined by (31) with negative value of $U= -|U_{REV}|$) and photocurrent j_{PH} (30):

$$j_{TOT}=|j_{REV}|+j_{PH} \qquad (34)$$

Dark current (in a light absence) must be smaller as possible. At the reverse bias dark current j_{REV} is practically equal to saturation current j_S then:

$$j_{TOT}=j_S+j_{PH} \qquad (35)$$

At photodiode design showed on fig. 4 the area of p-n junction practically equal to exposed window, then current through diode:

$$I_{PH}=j\cdot S=[e\cdot\eta\cdot\phi_0\cdot(1-R)+j_S]\cdot S. \qquad (36)$$

Maximal cutoff frequency of photodiode work f_{max} (maximum pulse repetition frequency at which photocurrent is has time to fall down from its maximum value to zero) is determined by time of exit of charge carrier from base τ_{OUT}:

$$f_{max}=\frac{1}{2\pi\cdot\tau_{OUT}} \qquad (37)$$

and time of exit of charge carrier is smaller, when the base d is thin:

$$\tau_{OUT}=\frac{d^2}{2D_n}=\frac{d^2 e}{2kT\mu_n} \qquad (38)$$

Here is take into account then charge carrier diffusion coefficient $D_n=\frac{2kT\mu_n}{e}$, where μ_n is charge carrier mobility.

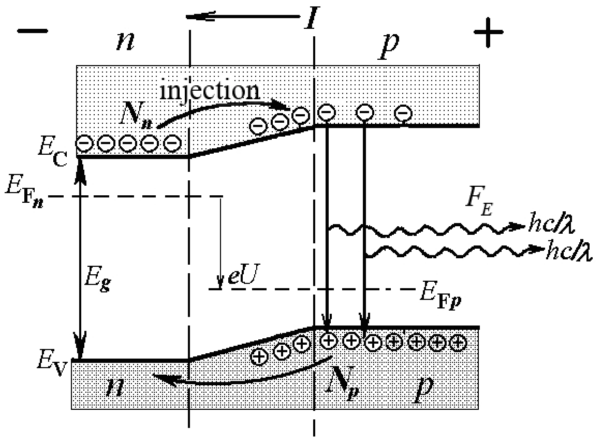
EXAMPLES OF IMPLEMENTATION OF CALCULATED WORK PART

Stage 4.1 Calculation of light-emitting diode (LED)

LED is fabricated from triple semiconducting compound: $Al_{\mathbf{v}}Ga_{\mathbf{1-v}}As$, which has energy gap determined by the aluminum atomic fraction **v** at correspondence with expression: $Eg[eV]=(1{,}43+1{,}37\mathbf{v})$.

LED is used for work at fiber-optical communication line with quartz optical fiber at transmition window №1. External quantum efficiency of LED is 0,6. Electron lifetime at LED n-region is equal $3\cdot10^{-9}$s.

Let`s define aluminum atomic fraction **v** at triple semiconducting compound and write down its formula. Define half-width of emission band at wavelength units (if at energy units it equal to 1,5 $kT$ ) and emission maximum at electron volt. Let`s calculate emission power at LED output at current 10 *mA* and modulated signal maximum frequency.

Input data: Composition: $Al_vGa_{1-v}As$; Transmission window №1; η_B=0,6; τ_n=$3\cdot10^{-9}$s; $\Delta h\nu$=1,5·kT; T=300°C; I_{LED} = 10 mA =	10·10^{-3}A	
Find: **v**, formula of compound – ? $\Delta\lambda$; $h\nu_0$; P_{LED}; f_{MAX} – ?		

Calculations:

For the high efficiency of fiber optical communication line, LED should have a maximum of emission intensity at wavelength, which corresponds to minimum of specific attenuation of optical fiber.

According to chart of spectral distribution of attenuation of the quartz fiber (**Fig. 3**) we define wavelength, which corresponds to light absorption at transmission window №1 (according to a statement):

$$\lambda=0{,}85\ \mu m = 8{,}5\cdot10^{-7} m.$$

At this wavelength LED emission intensity must be maximal.

Using formula (7) of given manual, let's define photon energy which corresponds to this wavelength:

$$h\nu = \frac{hc}{\lambda}, \qquad (1.1)$$

where h – Planck constant, c – light speed, λ – wavelength of maximum LED emission.

On the other hand, LED has a maximum of emission intensity at wavelength, which corresponds of a photon energy equal to energy gap E_g of semiconductor, which is used for fabrication of LED:

$$h\nu = E_g\ [J]. \qquad (1.2)$$

According to input data, the triple semiconductor with composition

$$Al_v Ga_{1-v} As$$

is used for fabrication LED. Let's define aluminum fraction **v** from ratio, which is characteristic for composition 4 (according to a statement):

$$E_g\,[eV] = (1{,}43+1{,}37\mathbf{v}). \qquad (1.3)$$

Take into account that $E_g[eV]=E_g[J]\ /\ 1{,}6\cdot10^{-19}$, we obtain:

$$v = \frac{E_g - 1{,}43}{1{,}37} = \frac{(h\nu)/1{,}6\cdot10^{-19} - 1{,}43}{1{,}37} = \frac{(hc/\lambda)/1{,}6\cdot10^{-19} - 1{,}43}{1{,}37}.$$

Emission band half-width of LED $\Delta\lambda$ we define by formula (9) of given manual:

$$\Delta\lambda = \frac{\Delta\nu \cdot \lambda^2}{c} = \frac{\Delta h\nu \cdot \lambda^2}{h \cdot c} = \frac{1{,}5 \cdot kT \cdot \lambda^2}{hc}.$$

Power of light emitted by LED is defined by formula (3) of given manual:

$$P_{\text{LED}} = I_{\text{LED}} \cdot \eta_{\text{EXT}} \frac{h\nu}{e} = I_{\text{LED}} \cdot \eta_{EXT} \frac{hc}{\lambda \cdot e}.$$

Modulating signal maximum frequency at direct modulated method is defined by formula (4) of given manual:

$$f_{\max} = \frac{1}{2\pi \cdot \tau_n},$$

where τ_n– lifetime of electrons injected to p-base.

Let`s check units of measurements of values:

$$[\text{h}\nu] = \frac{J \cdot s \cdot m / s}{m} = j;$$

$$[\text{v}] = \frac{(J \cdot s \cdot m / s / \text{m}) / C - [1]}{[1]} = \frac{eV - [1]}{[1]} = [1];$$

$$[\Delta\lambda] = \frac{J/\deg ree \cdot \deg ree \cdot m^2}{J \cdot s \cdot m/c} = m;$$

$$[P_{\text{LED}}] = A \frac{J \cdot s \cdot m/s}{m \cdot C} = \frac{J}{s} = W;$$

$$[f_{\max}] = 1 / s = Hz.$$

Let`s put numerical values into obtained formulae and carry out calculations:

$$h\nu = \frac{6{,}63 \cdot 10^{-34} \cdot 3 \cdot 10^8}{8{,}5 \cdot 10^{-7}} = 2{,}34 \cdot 10^{-19}\ J = 1{,}46\, eV;$$

$$\text{v} = \left(\frac{6{,}63 \cdot 10^{-34} \cdot 3 \cdot 10^8}{8{,}5 \cdot 10^{-7}} - 1{,}43 \right) / 1{,}37 = \frac{1{,}46 - 1{,}43}{1{,}37} = 0{,}0237;$$

$$\Delta\lambda = \frac{1{,}5 \cdot 1{,}38 \cdot 10^{-23} \cdot 300 \cdot (8{,}5 \cdot 10^{-7})^2}{6{,}63 \cdot 10^{-34} \cdot 3 \cdot 10^8} = 2{,}26 \cdot 10^{-8}\ \text{м} = 22{,}6\,\text{nm};$$

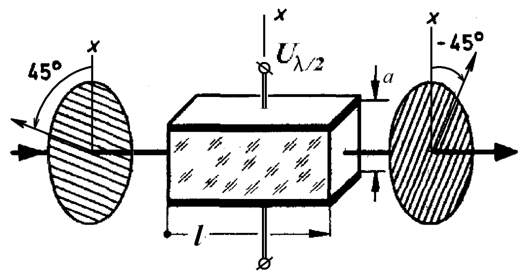
$$P_{\text{LED}} = 10 \cdot 10^{-3} \cdot 0{,}6 \frac{6{,}63 \cdot 10^{-34} \cdot 3 \cdot 10^8}{8{,}5 \cdot 10^{-7} \cdot 1{,}6 \cdot 10^{-19}} = 8{,}78 \cdot 10^{-3}\ Wt = 8{,}78\, mWt;$$

$$f_{\max} = \frac{1}{2 \cdot 3{,}14 \cdot 3 \cdot 10^{-9}} = 5{,}3 \cdot 10^7\, \text{Гц} = 53\text{MHz}.$$

Results: v = 0,0237; $Al_{0,0237}Ga_{0,9763}As$;
λ= 0,85 μ*m*; $\Delta\lambda$ = 22,6 *nm*; $h\nu$ = 1,46 *eV*;
P_{LED} = 8,78 *mW*; $f_{\max}$ = 53*MHz.*

Stage 4.2 Calculation of modulator

Emitted by chosen LED on **Stage 4.1** the light is modulate by half-wave voltage applied to Pockels cell. Material quality factor of which is equal 0,2 nm/V and Pockels electrooptic coefficient is 10^{-11} m/V. Transmittance of cell material is 0,84. Let`s calculate Pockels cell half-voltage with traversal dimensions 0,5×0,5 mm and with length 15 mm. We define maximal frequency of modulating signal. We will calculate the modulator output light power.

Input data:		
$n^3r = 0{,}2\ nm/V$;	$0{,}2\cdot10^{-9}\ m/V$;	
$l = 15\ mm$;	$15\cdot10^{-3}\ m$;	
$r = 10^{-11}\ m/V$;		
$a = b = 0{,}5\ mm$;	$0{,}5\cdot10^{-3}\ m$	
$\delta_{MAT} = 0{,}84$.		
$U_{\lambda/2}$ – ? $f_{\max}$ – ? P_{OUT}^{MOD} – ?		

Calculations:

Half-wave control voltage of Pockels cell modulator

$$U_{(\lambda/2)} = \frac{\lambda a}{n^3 r \cdot l}, \qquad (2.1)$$

where a – cell traversal dimension, n^3r – quality factor, l – cell's length. Wavelength of modulated light is equal to wavelength of maximum of LED emission which we obtain at **Stage 4.1**:

$$\lambda = 0{,}85\ \mu m.$$

Maximum possible modulating signal frequency is limited by cell's length at correspondence with ratio:

$$f_{\max} = \frac{c}{20 n \cdot l}, \qquad (2.2)$$

Reflective index can be defined by quality factor $F{=}n^3r$ of cell material:

$$n = \sqrt[3]{\frac{F}{r}}, \qquad (2.3)$$

r – Pockels electrooptic coefficient.

Then

$$f_{\max} = \frac{c}{20 \cdot l} \cdot \sqrt[3]{\frac{r}{F}}$$

Pockels cell modulator efficiency is shown what part of a light wave pass through it and it is defined by product:

$$\delta_{MOD} = \delta_{POL} \cdot \delta_{MAT},$$

where δ_{MAT} – transmittance of a material of a Pockels cell, $\delta_{POL} = 0{,}5$ – losses of polarization.

All power emitted by LED, which at correspondence with **Stage 4.1** is equal to $P_{EM} = 8{,}78\ mW$, is supply to modulator

$$P_{OUT}^{MOD} = P_{INP}^{MOD} \cdot \delta_{MOD}.$$

Check units of measurement of obtained values:

$$U_{(\lambda/2)} = \frac{m \cdot m \cdot V}{m \cdot m} = V;$$

$$f_{\max} = \frac{m}{s \cdot \sqrt[3]{m \cdot V \cdot m \Big/ V \cdot m}} = \frac{1}{s};$$

Put numerical values and carry out calculations:

$$U_{\lambda/2} = \frac{8{,}5 \cdot 10^{-7} \cdot 5 \cdot 10^{-4}}{2 \cdot 10^{-10} \cdot 0{,}015} = 142\,V;$$

$$f_{\max} = \frac{3 \cdot 10^{8}}{20 \cdot \sqrt[3]{\frac{2 \cdot 10^{-10}}{10^{-11}} \cdot 0{,}015}} = 3{,}68 \cdot 10^{8}\ \mathrm{s}^{-1} = 368\,MHz;$$

δ_{MOD}=0,5·0,84=0,42;

P_{OUT}^{MOD}=8,78·10^{-3} ·0,42=3,69·10^{-3} *W* =3,69 *mW*.

Results: $U_{\lambda/2}$ = 142 V; $f_{\max}$ = 368 *MHz*; δ_{MOD} = 0,42; P_{OUT}^{MOD} = 3,69 *mW*.

Stage 4.3 Calculation of optical fiber

Light which emitted by LED at correspondence with **Stage 4.1**, after modulation by desired signal with parameters which was calculated on **Stage 4.2**, is transmit at quartz light-guide with dispersion 18 mm^{-1} at transmission window №1 **(Fig. 3)**.

Let`s calculate maximum length of optical fiber if pulse passing frequency must be no less then modulating signal frequency from **Stage 4.2**. Define total attenuation along the optical fiber at obtained length and at how many times light power decrease. Calculate power of output light at the end of optical fiber.

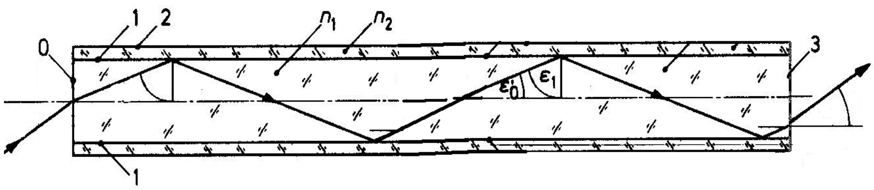
Input data:

$$\frac{dn}{d\lambda} = 18mm^{-1} = 18 \cdot 10^{-3} m^{-1}$$

Spectral window №1;

L ; β – ?;

$P_{OUT}^{FIB}/P_{IN}^{FIB}$; P_{OUT}^{FIB} – ?



Calculations:

Spectral half-width of a light sygnal correspond to emission band half-width of a LED, obtained on **Stage 4.1**:

$$\Delta\lambda = 22.6\ nm = 22.6 \cdot 10^{-9}\ m.$$

Maximal pulse repetition frequency at light-guide is limited by the optical fiber length correspondence to ratio, which we obtain from equation (18):

$$f_{\max} = \frac{1}{T_{\min}} = \frac{c}{(dn/d\lambda)\cdot\Delta\lambda\cdot L}, \quad (3.1)$$

where c – light speed, $dn/d\lambda$ – dispersion of material of light-guide, $\Delta\lambda$ – spectral half-width, L – optical fiber length.

Hence

$$L = \frac{c}{(dn/d\lambda)\cdot\Delta\lambda\cdot f_{\max}},$$

where maximal pulse repetition frequency at light-guide $f_{\max}$ must be no more than maximum modulating signal frequency at modulator from **Stage 4.2**.

We chose the maximal pulse repetition frequency at light-guide maximal pulse repetition frequency at light-guide equal to maximum modulating signal frequency at modulator from **Stage 4.2**:

$$f_{\max} = 368\ MHz = 3.68\cdot 10^{8}\ Hz.$$

Power of output light at the end of optical fiber according to (21):

$$P_{\text{OUT}}^{\text{FIB}} = P_{\text{IN}}^{\text{FIB}} \cdot e^{-0.23\beta_0\cdot L}, \quad (3.2)$$

where value of specific attenuation β_0 we find from **Fig. 3** for transmission window №1 of quartz optical fiber:

$$\beta_0 = 2{,}7,$$

and intput light power at the origin of optical fiber is equal to output light power at the end of modulator from **Stage 4.2**:

$$P_{\text{IN}}^{\text{FIB}} = P_{\text{OUT}}^{\text{MOD}} = 3{,}69\ mW = 3{,}69\cdot 10^{-3}\ W.$$

Total attenuation along the optical fiber by length L is:

$$\beta = \beta_0\cdot L. \quad (3.3)$$

Total decreasing of light power along the optical fiber:

$$\frac{P_{\text{IN}}^{\text{FIB}}}{P_{\text{OUT}}^{\text{FIB}}} = e^{0.23\beta_0\cdot L}.$$

Let`s check unit of measurement:

$$[L] = \frac{m/s}{(1/m)\cdot m\cdot(1/s)} = m.$$

Put numerical values and carry out calculations:

$$L = \frac{3\cdot 10^{8}}{(18\cdot 10^{-3})\cdot 22{,}6\cdot 10^{-9}\cdot 3{,}68\cdot 10^{8}} = 2{,}006\cdot 10^{3}\ m = 2{,}01\,km;$$

$$\beta = 2{,}7\cdot 2{,}006 = 5{,}41\ dB;$$

$$\frac{P_{\text{IN}}^{\text{FIB}}}{P_{\text{OUT}}^{\text{FIB}}} = e^{0.23\cdot 2{,}7\cdot 2{,}006} = 3{,}47;$$

$$P_{\text{OUT}}^{\text{FIB}} = 3{,}69\cdot 10^{-3}\cdot e^{-0.23\cdot 2{,}7\cdot 2{,}006} = 3{,}69\cdot 10^{-3}/3{,}47 = 1{,}06\cdot 10^{-3}\ W = 1{,}06\,\text{m}W.$$

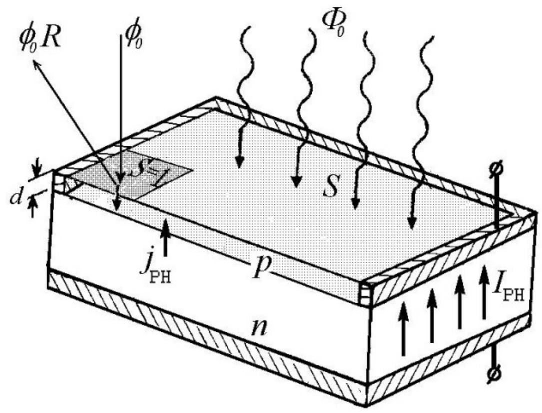
Results: $L = 2{,}01\ km$; $\beta = 5{,}41\ dB$;
$P_{\text{in}}^{\text{wave}} / P_{\text{IN}}^{\text{FIB}} = 3{,}47$; $P_{\text{OUT}}^{\text{FIB}} = 1{,}06\ mW$.

Stage 4.4 Calculation of photodiode

Light is emitted by the LED, which has been calculated on **Stage 4.1**, after modulation by the desired signal with parameters obtained on **Stage 4.2**, transmits by the quartz optical fiber at correspondence with **Stage 4.3**, and then illuminate thin p-region of photodiode with area 8 mm^2 and thickness 1 μm. Saturation current density of p-n junction is 10 A/m^2 and carrier mobility 0,01 $m^2/(V{\cdot}s)$. Optical reflection coefficient from base surface is 0,18; quantum efficiency of internal photoelectric effect is 0,92.

Let`s calculate maximum energy gap of semiconductor useful for creation of photodetectors for absorption of given light signal. Calculate maximal possible voltage of given photodetector at idle mode at illumination power which we obtain at stage 4.3. Define output photocurrent at photodiode mode at such illumination power. Compute, in how many times obtained photocurrent is more than dark current. Define maximum work frequency of photodiode. Process losses are not considering.

Input data:	
S=8 mm^2;	$8{\cdot}10^{-6}$ m^2;
d=1 μm;	10^{-6} m;
$j_S=10^{-2}$ A/m^2;	
μ_n =0,01 $m^2/(V{\cdot}s)$;	
R=0,18;	
η=0,92.	
$E_{g\ max}^{PHOTO}$ – ? U_{ID} – ? j_{PH} – ? f_{max} – ?	



Calculations:

Energy band width of photodetector must be not greater then photon energy at emission band maximum of LED, so:

$$E_{g\ \max}^{PH} = h\nu = hc/\lambda; \qquad (4.1)$$

in electronvolts:

$$E_{g\ \max}^{PH} = \frac{hc}{\lambda}/1{,}6\cdot 10^{-19},$$

where λ – light wavelength, which corresponds to maximum emission of LED, ν - its frequency.

At correspondence with **Stage 4.1** wavelength of incoming to photodetector radiation is equal:

$$\lambda=0{,}85\ \mu m=8{,}5{\cdot}10^{-7} m,$$

Input light power of photodetector, in compliance with **Stage 4.3**, is equal to output light power of optical fiber:

$$P_{IN}^{PH}=P_{OUT}^{FIB}= 1{,}06\ mW= 1{,}06{\cdot}10^{-3}\ W.$$

Input light power is related with input quantum intensity ϕ_0 by ratio:

$$P_{IN}^{PH}=P_0=\phi_0\cdot S{\cdot}h\nu=\phi_0\cdot S{\cdot}hc/\lambda, \qquad (4.2)$$

where S – area of exposed window.

Then generated at p-region the photocurrent density through p-n junction is:

$$j_{PH}=e\cdot\eta\cdot\phi\cdot(1-R), \tag{4.3}$$

where η – quantum efficiency of internal photoeffect; R – light reflection coefficient from photodiode base surface.

At idle mode photocurrent j_{PH} is equal to diffusion current j_{DIFF} (31), whith positive value of $U=U_{PH}$:

$$e\cdot\eta\cdot\phi_0(1-R)=j_S\left(\exp\frac{e\cdot U_{ID}}{kT}-1\right) \tag{4.4}$$

where j_S – saturation current density; T – absolute temperature of p-n junction.

From which idling voltage is:

$$U_{ID}=\frac{kT}{e}\ln\left(1+\frac{e\eta\varphi_0(1-R)}{j_S}\right)=\frac{kT}{e}\ln\left(1+\frac{e\eta\lambda P_0(1-R)}{Shc\cdot j_S}\right)$$

At photodiode mode the photocurrent can be written from input light power P_0:

$$I_{PH}=j_{PH}\cdot S=e\cdot\eta\frac{\lambda P_0}{hc}(1-R). \tag{4.5}$$

We can calculate in how many times will be increased a photodiode current under such illumination power:

$$\frac{I_{PH}}{I_{DARK}}=\frac{j_{PH}}{j_S}=e\cdot\eta\frac{\lambda P_{IN}^{PH}}{hc}\frac{(1-R)}{S\cdot j_S}$$

Maximum work frequency of photodiode f_{max} is defined by ratio (37) and (38):

$$f_{max}=\frac{kT\mu_n}{\pi\cdot d^2e}$$

where μ_n – carrier mobility; d – base thickness of photodiode.

Let\`s check units of measurements:

$$[E_{g\ max}^{PH}]=\frac{J\cdot s\cdot m/s}{m}/1{,}6\cdot10^{-19}=J/1{,}6\cdot10^{-19}=eV;$$

$$[U_{ID}]=\frac{J/dgree\cdot dgree}{C}=V;$$

$$[I_{PH}]=C\cdot\frac{m\cdot W}{J\cdot s\cdot m/s}=A;$$

$$f_{max}=\frac{J/dgree\cdot dgree\cdot m^2}{m^2\cdot C\cdot V\cdot s}=\frac{1}{s}=Hz.$$

Put numerical values and carry out calculations:

$$E_{g\ max}^{PH}=\frac{6{,}63\cdot10^{-34}\cdot3\cdot10^8}{8{,}5\cdot10^{-7}}/1{,}6\cdot10^{-19}=1{,}46\,eV;$$

$$U_{ID}=\frac{1{,}38\cdot10^{-23}\cdot300}{1{,}6\cdot10^{-19}}\ln\left(1+\frac{1{,}6\cdot10^{-19}\cdot0{,}92\cdot8{,}5\cdot10^{-7}\cdot1{,}06\cdot10^{-3}\cdot(1-0{,}18)}{8\cdot10^{-6}\cdot6{,}63\cdot10^{-34}\cdot3\cdot10^8\cdot10^{-2}}\right)=0{,}228V;$$

$$I_{PH} = 1{,}6 \cdot 10^{-19} \cdot 0{,}92 \cdot \frac{8{,}5 \cdot 10^{-7} \cdot 1{,}06 \cdot 10^{-3} \cdot (1-0{,}18)}{6{,}63 \cdot 10^{-34} \cdot 3 \cdot 10^{8}} = 5{,}47 \cdot 10^{-4}\,\text{A} = 0{,}547\,\text{mA};$$

$$f_{\max} = \frac{1{,}38 \cdot 10^{-23} \cdot 300 \cdot 0{,}01}{3{,}14 \cdot 10^{-12} \cdot 1{,}6 \cdot 10^{-19}} = 8{,}24 \cdot 10^{7}\ \text{Hz} = 82{,}4\,\text{MHz}.$$

Results: $E_g^{PH}{}_{\max}$ = 1,46 *eV*; U_{ID} = 0,228 *V*; I_{PH} = 0,547 *mA*; $f_{\max}$ = 82,4 *MHz*.

Stage 4.5 Matching of fiber-optical communicational line elements

1) Let's check correspondence of LED emission wavelength to modulator half-wave voltage, optical line spectral window and photodetector energy gap with.

2) Let's check sufficiency of a LED current I_{LED} = 10 *mA* for generation of light power, which enough to create photocurrent I_{PH} = 0,547 *mA* (modulator losses and optical fiber attenuation take into account).

Without taking into account of process losses, we obtain power's transformation equations in process of signal passage through optical communication line:

$$P_{OUT}^{LED} = I_{LED} \cdot \eta_{EXT} \frac{hc}{\lambda_0 \cdot e};$$

$P_{IN}^{MOD} = P_{OUT}^{LED}$; $\quad P_{OUT}^{MOD} = P_{IN}^{MOD} \cdot \delta_{MOD}$;

$P_{IN}^{FIBER} = P_{OUT}^{MOD}$; $\quad P_{OUT}^{FIBER} = P_{IN}^{FIBER} \cdot e^{-0{,}23 \cdot \beta}$;

$P_{IN}^{PHOTO} = P_{OUT}^{FIBER}$; $\quad I_{PH} = e \cdot \eta \dfrac{\lambda \cdot P_{IN}^{PHOTO}}{hc}(1-R)$.

From here we obtain:

$$I_{PH} = I_{LED} \cdot \eta_{EXT} \cdot \eta \cdot (1-R) \cdot \delta_{MOD} \cdot e^{-0{,}23 \cdot \beta}.$$

Put numerical values and carry out calculations:

$$I_{PH} = 10 \cdot 10^{-3} \cdot 0{,}6 \cdot 0{,}92 \cdot (1-0{,}18) \cdot 0{,}42 \cdot e^{-0{,}23 \cdot 5{,}41} = 5{,}47 \cdot 10^{-4} = 0{,}547\,mA.$$

3) Maximal frequency of modulating signal of link must be no more than cutoff frequency of any elements of fiber-optical communication line.

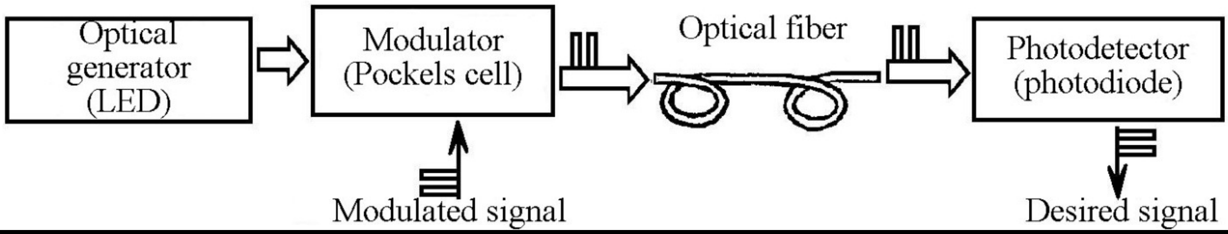
Let's chose the maximal modulating signal frequency as a lowest frequency of any elements of fiber-optical communication line. Is a working frequency of LED, when we used a direct method of a modulation:

$$f_{\max} = f_{\max}^{LED} = 53\ \text{M}Hz.$$

When we will use an external method of a modulation and LED is worked on direct supply voltage, then a lowest working frequency will have a photodiode:

$$f_{max} = f_{max}^{PHOTO} = 82{,}4\ MHz.$$

Values of parameters, which we determined, let's reduce to summary table:



LED	**Modulator**	**Optical fiber**	**Photodiode**
Semiconductor $Al_{0,0237}Ga_{0,9763}As$	Sizes $a \times b \times l = 0{,}5x0{,}5x15mm$	Length L= 2,01 km	Thickness d= 1 μm
Wavelength λ=0,85 μm	Half-wave voltage $U_{\lambda/2}$ =142 V	Spectral window № 1	Energy gap width $E_g^{PHOTO}{}_{max}$=1,46 eV
Emission band Δλ=22,6 nm			Reflection coefficient R=0,18
External quantum efficiency η_{EXT}=0,6	Efficiency δ_{MOD}=0,42	Attenuation β=5,41 *dB*	Photoeffect quantum efficiency η=0,92
Current I_{LED}=10 *mA*			
Output power P_{OUT}^{LED}=8,78 *mW*	Input power P_{IN}^{MOD}=8,78 *mW*		
	Output power P_{OUT}^{MOD}=3,69 *mW*	Input power P_{IN}^{FIBER}=3,69 *mW*	
		Output power P_{OUT}^{FIBER}=1,06 *mW*	Input power P_{IN}^{PHOTO}=1,06 *mW*
			Photocurrent I_{PHOTO} = 0,547 *mA*
Internal modulated signal cutoff frequency f_{max}^{LED} =53 M*Hz*	External modulated signal cutoff frequency f_{max}^{MOD} =368 M*Hz*	Maximal pulse repetition frequency f_{max}^{FIBER} =368 M*Hz*	Work cutoff frequency f_{max}^{PHOTO}=82,4 M*Hz*
Maximal frequency of modulating signal of link at direct method of a modulation f_{max} =53 MHz			

INDIVIDUAL ASSIGNMENTS OF CALCULATED WORK PART

In accordance with your variant to choice on one ***assignment*** *for each* ***stage*** *listed below (The number of stage assignment and all necessary input data are reduced in the* **Table 1***).*

Assignment to stage 4.1 LIGHT EMITTING DIODE (LED)

1) For producing of LED is used triple semiconducting compound one of three composition: $Ga_xIn_{1-x}As$ (composition 1), InP_yAs_{1-y} (composition 2), $Al_zGa_{1-z}Sb$ (composition 3). Energy gap of these compositions defines by equations **(5)**. Number of composition is shown in initial data **Table 1**. LED works at FOCL with quartz optical fiber in transmission window (**Fig. 3**), which number is shown in initial data **Table 1**. External quantum efficiency of LED is equal $(1-0{,}1\sqrt[3]{N})$.

– Define unknown parameter of composition of element in triple compound and write its chemical formula (when the founding parameter of composition less than zero or greater then one, it is necessary to change the composition).

– Calculate wavelength in maximum LED emission. Define half-width of emission band at wavelength units, if half-width of emission band in energy units is equal $2kT/\sqrt{N}$, where N – number of variant. Write down emission band at wavelength units.

– Write down quantum efficiency of LED.

– Define a limited frequency of work of LED (maximum frequency of modulated signal at direct method modulation of light), if electrons lifetime of LED material is $\sqrt[3]{N}\cdot 10^{-9}\,s$.

2) For producing of LED is used triple compound one of three composition: $Ga_xIn_{1-x}As$ (composition 1), InP_yAs_{1-y} (composition 2), $Al_zGa_{1-z}Sb$ (composition 3). Energy gap of these compositions defines by equations **(5)**. Number of composition is shown in initial data **Table 1**. LED works at FOCL with quartz optical fiber in transmission window (**Fig. 3**), which number is shown in initial data **Table 1**. External quantum efficiency of LED is equal $(1-0{,}1\sqrt[3]{N})$.

– Define unknown parameter of composition of element in triple compound and write its chemical formula (when the founding parameter of composition less than zero or greater then one, it is necessary to change the composition).

– Calculate frequency of maximum emission. Define half-width of emission spectrum at frequency units if half-width of emission band at energy units take as $2kT/\sqrt{N}$ where N – number of variant.

– Write down external quantum efficiency of LED.

– Define a limited frequency of work of LED (maximum frequency of modulated signal at direct method modulation of light), if electrons lifetime of LED material is $\sqrt[3]{N}\cdot 10^{-9}\,s$.

3) For producing of LED is used triple compound one of three composition: $Ga_xIn_{1-x}As$ (composition 1), InP_yAs_{1-y} (composition 2), $Al_zGa_{1-z}Sb$ (composition 3). Energy gap of these compositions defines by equations **(5)**. Number of composition is shown in initial data **Table 1**. LED works at FOCL with quartz optical fiber in transmission window (**Fig. 3**), which number is shown in initial data **Table 1**. External quantum efficiency of LED is equal $(1-0{,}1\sqrt[3]{N})$.

– Define unknown parameter of composition of element in triple compound and write its chemical formula (when the founding parameter of composition less than zero or greater then one, it is necessary to change the composition).

– Write down energy of maximum emission. Define half-width of emission spectrum at frequency units if half-width of emission band at energy units take as $2kT/\sqrt{N}$ where N – number of variant.

– Write down external quantum efficiency of LED.

– Define a limited frequency of work of LED (maximum frequency of modulated signal at direct method modulation of light), if electrons lifetime of LED material is $\sqrt[3]{N}\cdot 10^{-9}\,s$.

Assignment to stage 4.2 MODULATOR

1) Light which emitted by calculated on stage 4.1 LED is modulated by half-wave voltage applyed to Pockels cell. Quality factor of material of cell is equal $10^{-9}/\sqrt[3]{N}$ m/V. Transmission coefficient of cell material is equal 0,95.

– Define half-wave voltage for given Pockels cell with traversal dimensions 0,15×0,15 *mm* and length 10 *mm*.

– Calculate reflection indexes difference of two components of transmitted light wave: polarized along external electric field and across to it.

– Define maximal frequency of modulated signal at obtained cell length if Pockels electrooptical coefficient of cell material is equal $\sqrt{N}\cdot 10^{-11}\,m/V$ where N – number of variant.

– Calculate Pockels cell modulator efficiency.

2) Light which emitted by calculated on stage 4.1 LED is modulated by half-wave voltage applyed to Pockels cell. Quality factor of material of cell is equal $10^{-9}/\sqrt[3]{N}$ m/V. Transmission coefficient of cell material is equal 0,9.

– Define cell length, traversal dimensions of which is 0,2×0,2 *mm* and half-wave voltage of which is equal $15\sqrt{N}\,V$, where N – number of variant.

– Define maximal frequency of modulated signal at obtained cell length if Pockels electrooptical coefficient of cell material is equal $\sqrt{N}\cdot 10^{-11}\,m/V$, where N – number of variant.

– Calculate optical path difference of two components of transmitted light wave: polarized along external electric field and across to it.

– Calculate Pockels cell modulator efficiency.

3) Light which emitted by calculated on stage 4.1 LED is modulated by half-wave voltage applyed to Pockels cell. Quality factor of material of cell is equal $10^{-9}/\sqrt[3]{N}$ m/V. Transmission coefficient of cell material is equal 0,85.

– Compute traversal dimensions of Pockels cell if its length is 15 *mm* and half-wave voltage is $14\sqrt{N}$ *V*, where *N* – number of variant.

– Define maximal cell length at maximal possible modulated signal frequency 0,5 *GHz*, if Pockels electrooptical coefficient is $\sqrt{N}\cdot 10^{-11}$ *m/V*, where *N* – number of variant. If we obtain the maximal cell length less than 15 *mm*, then it is necessary to define maximum possible modulated signal frequency at cell length 15 *mm*.

– Calculate phase difference of two components of transmitted light wave: polarized along external electric field and across to it.

– Calculate Pockels cell modulator efficiency.

Assignment to stage 4.3 OPTICAL FIBER

1) Light which emitted by calculated on stage 4.1 LED, after modulation by desired signal, propagate through quartz single-mode light-guide. Number of spectral window **(Fig. 3)** is show in initial data table. Dispersion of material of light-guide is depend from light wavelength λ correspondence to ratio: $10^{-14}/\lambda^3$ m^{-1}. Optical fiber length is $(4{,}5-\sqrt[3]{N})$ *km*, where *N* – number of variant.

– Define a maximum pulse repetition frequency in light-guide.

– Calculate attenuation along the optical fiber of above mentioned length and also at how many times light power is decrease at the result of losses in optical fiber. Other losses are not taking into account.

2) Light which emitted by calculated on stage 4.1 LED, after modulation by desired signal, propagate through quartz single-mode light-guide. Number of spectral window **(Fig. 3)** is show in initial data table. Dispersion of material of light-guide is depend from light wavelength λ correspondence to ratio: $10^{-14}/\lambda^3$ m^{-1}.

– Calculate maximum length of optical fiber at which output light power at the end of optical fiber is decrease in $2\sqrt[3]{N}$ times, where *N* – number of variant.

– Define a maximum pulse repetition frequency in light-guide of obtained length.

– Calculate attenuation along the optical fiber of obtained length. Other losses are not taking into account.

3) Light which emitted by calculated on stage 4.1 LED, after modulation by desired signal, propagate through quartz single-mode light-guide. Number of spectral window **(Fig. 3)** is show in initial data table. Dispersion of material of light-guide is depend from light wavelength λ correspondence to ratio: $10^{-14}/\lambda^3$ m^{-1}.

– Calculate maximum length of optical fiber if maximum pulse repetition frequency must be no less than $2\sqrt[3]{N^2}\cdot 10^8$ *Hz*, where *N* – number of variant.

– Calculate attenuation along the optical fiber of above mentioned length and also at how many times light power is decrease at the result of losses in optical fiber. Other losses are not taking into account.

Assignment to stage 4.4 PHOTODIODE

1) Light emitted by LED that was computed on stage 4.1, after modulation by desired signal with parameters which was obtained at stage 4.2, transmits through quartz optical fiber at correspondence with stage 4.3, and then illuminate thin p-region of photodiode with area $\sqrt[3]{N}\ mm^2$ and thickness $\sqrt[3]{N}\ \mu m^2$ where N – number of variant. Saturation current density of p-n junction is $\sqrt[3]{N}\ A/m$ at carrier mobility at it $0{,}01\cdot\sqrt{N}\ \ m^2/(V{\cdot}s)$. Light reflection coefficient from semiconductor surface is 0,11. Quantum efficiency of internal photoeffect is $(1-0{,}1\sqrt[3]{N})$.

– Calculate maximal energy gap of semiconductor useful for creation of photodetectors for absorption of given light signal.

– Define current which must flow through the LED to generate emission with such intensity which is sufficient to create photocurrent which 300 times more than dark current (taking into account of losses in modulator and optical fiber). For that it is necessary to calculate photocurrent value of photodiode and obtain value of light power which input to photodiode from optical fiber. According to decay along the optical fiber from stage 4.3, calculate corresponding input light power of optical fiber from modulator. By coefficient of efficiency of modulator from stage 4.2 calculate of input light power of modulator. By this power and LED external quantum efficiency value from stage 4.1 calculate necessary current of LED.

– Maximal cutoff frequency of photodiode work. Process losses are not taking into account.

2) Light emitted by LED that was computed on stage 4.1, after modulation by desired signal with parameters which was obtained at stage 4.2, transmits through quartz optical fiber at correspondence with stage 4.3, and then illuminate thin p-region of photodiode with area $\sqrt[3]{N}\ mm^2$ and thickness $\sqrt[3]{N}\ \mu m^2$ where N – number of variant. Saturation current density of p-n junction is $\sqrt[3]{N}\ A/m$ at carrier mobility at it $0{,}01\cdot\sqrt{N}\ \ m^2/(V{\cdot}s)$. Light reflection coefficient from base surface is 0,11. Quantum efficiency of internal photoeffect is $(1-0{,}1\sqrt[3]{N})$.

– Calculate minimal energy gap of semiconductor useful for creation of photodetectors for absorption of given light signal.

– Define current which must flow through the LED to generate emission with such intensity which is sufficient to create photocurrent which 200 times more than dark current (taking into account of losses in modulator and optical fiber). For that it is necessary to calculate photocurrent value of photodiode and obtain value of light power which input to photodiode from optical fiber. According to decay along the optical fiber from stage 4.3, calculate corresponding input light power of optical fiber from modulator. By coefficient of efficiency of modulator from stage 4.2 calculate of input light power of modulator. By this power and LED external quantum efficiency value from stage 4.1 calculate necessary current of LED.

– Define a maximal cutoff frequency of photodiode work. Process losses are not taking into account.

3) Light emitted by LED that was computed on stage 4.1, after modulation by desired signal with parameters which was obtained at stage 4.2, transmits through quartz optical fiber at correspondence with stage 4.3, and then illuminate thin p-region of photodiode with area $\sqrt[3]{N}\ mm^2$ and thickness $\sqrt[3]{N}\ \mu m^2$ where N – number of variant. Saturation current density of p-n junction is $\sqrt[3]{N}\ A/m$ at carrier mobility at it $0{,}01\cdot\sqrt{N}\ m^2/(V\cdot s)$. Light reflection coefficient from base surface is 0,11. Quantum efficiency of internal photoeffect is $(1-0{,}1\sqrt[3]{N})$.

– Show interval of values of energy gap of semiconductors, useful for creation of photodetectors for absorption of given light signal.

– Define current which must flow through the LED to generate emission with such intensity which is sufficient to create photocurrent which 100 times more than dark current (taking into account of losses in modulator and optical fiber). For that it is necessary to calculate photocurrent value of photodiode and obtain value of light power which input to photodiode from optical fiber. According to decay along the optical fiber from stage 4.3, calculate corresponding input light power of optical fiber from modulator. By coefficient of efficiency of modulator from stage 4.2 calculate of input light power of modulator. By this power and LED external quantum efficiency value from stage 4.1 calculate necessary current of LED.

– Define a maximal cutoff frequency of photodiode work. Process losses are not taking into account.

Assignment to stage 4.5 Matching of fiber-optical communication line elements

Draw block diagram of design of fiber-optical communication line.

– Check correspondence of LED emission wavelength to modulator half-wave voltage, optical fiber spectral window and energy gap of photodetector.

– Check sufficiency of a LED current for generation of light power, which enough to create photocurrent with value indicated in assignment 4.4 (modulator losses and optical fiber attenuation take into account). Here is necessary to check calculations of light signal power at all stages of signal transmission without taking into account of process losses (look example 4.5).

– Specify a maximum frequency of modulated signal of link, which must be no more than cutoff work frequency of every determinative elements of fiber-optical communication line.

Reduce a values of parameters, which you determined, in summary table.

Table 1 – Initial data according to variants

Number of variant	Number of composition	Number of transmission window	Number of assignment to stages			
			4.1	**4.2**	**4.3**	**4.4**
1	1	1	**1**	**2**	**3**	**1**
2	2	2	**2**	**3**	**1**	**2**
3	3	3	**3**	**1**	**2**	**3**
4	1	4	**1**	**2**	**3**	**1**
5	2	1	**2**	**3**	**1**	**2**
6	3	2	**3**	**1**	**2**	**3**
7	1	3	**1**	**2**	**3**	**1**
8	2	4	**2**	**3**	**1**	**2**
9	3	1	**3**	**1**	**2**	**3**
10	1	2	**1**	**2**	**3**	**1**
11	2	3	**2**	**3**	**1**	**2**
12	3	4	**3**	**1**	**2**	**3**
13	1	1	**1**	**2**	**3**	**1**
14	2	2	**2**	**3**	**1**	**2**
15	3	3	**3**	**1**	**2**	**3**
16	1	4	**1**	**2**	**3**	**1**
17	2	1	**2**	**3**	**1**	**2**
18	3	2	**3**	**1**	**2**	**3**
19	1	3	**1**	**2**	**3**	**1**
20	2	4	**2**	**3**	**1**	**2**
21	3	1	**3**	**1**	**2**	**3**
22	1	2	**1**	**2**	**3**	**1**
23	2	3	**2**	**3**	**1**	**2**
24	3	4	**3**	**1**	**2**	**3**
25	1	1	**1**	**2**	**3**	**1**
26	2	2	**2**	**3**	**1**	**2**
27	3	3	**3**	**1**	**2**	**3**
28	1	4	**1**	**2**	**3**	**1**
29	2	1	**2**	**3**	**1**	**2**
30	3	2	**3**	**1**	**2**	**3**

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