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621.373.8(075.8)

86 7

382

(3 20.03.2013 .)

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. . , . . - . : « » , 2015. – 342 .

ISBN 978-966-598-586-0

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(
: Light amplification by stimulated emission of
radiation,
), (:
Microwave amplification by stimulated emission of radiation,
: ()
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621.373.8(075.8)

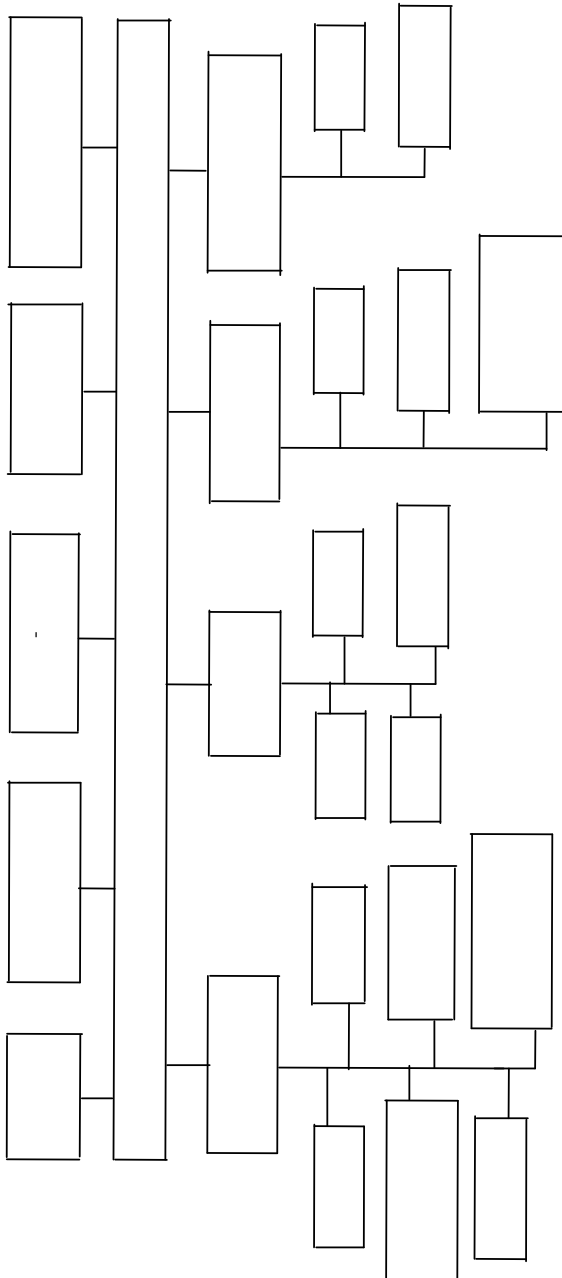
86 7

ISBN 978-966-598-586-0

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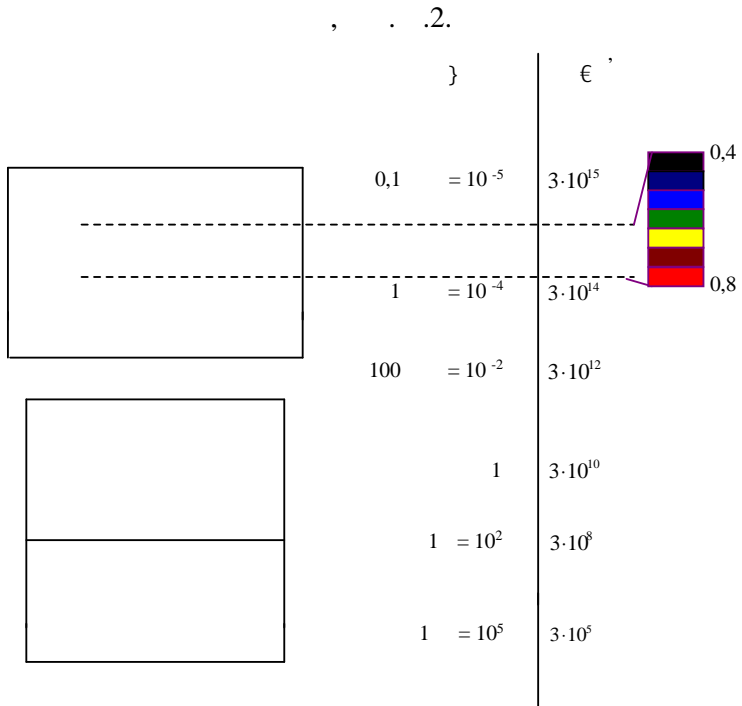
ПРЕДИСЛОВИЕ

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10^{-8} .
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 : Light amplification by stimulated emission of radiation,
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 10^{12} .
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10^{-7} .

$$z(t) = A \sin(\omega t + \varphi),$$

, ω φ t .

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λ = ν T (- , ν -

), ν = $\frac{1}{T}$ -

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0,7

$$(\lambda = 0,35 \text{ m}), \dots$$

()

()

$$v = \frac{1}{T} \varphi$$

$$A_p^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\varphi_1 - \varphi_2)$$

$$\varphi_1 - \varphi_2 = 0$$

$$\varphi_1 - \varphi_2 = \pi$$

$\varphi_1 \quad \varphi_2,$

« »

(, z),

t,

$$E(t) = E_0 \sin 2\pi \left(vt - \frac{z}{\lambda} + \varphi \right),$$

$\lambda -$, $v\lambda -$,

$\pi.$

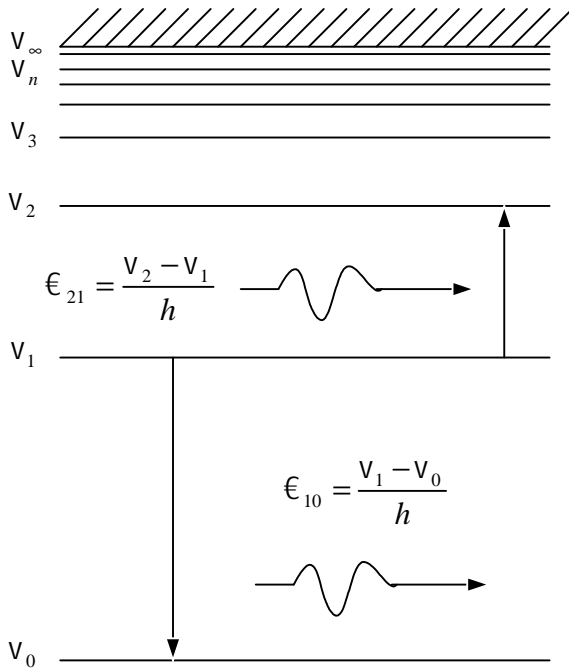
, $\frac{R}{r}$, $R -$
 , $\frac{1}{R^2}$.
 (. 1.1).
 10^8

1.

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1.1.

, , , , -
 , , , , -
 , , , , -
 $\varepsilon_0, \varepsilon_1, \dots, \varepsilon_n, \dots,$.
 « »
 ε_0 (. 1.1),
 $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n$.
 () .
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. 1.1.

1913 . (

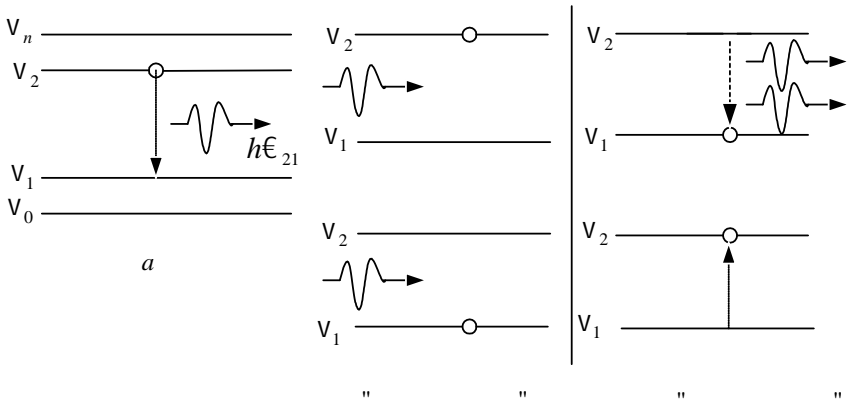
$$\nu_{mn} = \frac{\epsilon_m - \epsilon_n}{h},$$

$h = 6,626 \cdot 10^{-34} \text{ Дж} \cdot \text{с}$, $\epsilon_m - \epsilon_n =$

$h\nu_{mn}$ — энергия фотона, ϵ_m — энергия верхнего уровня, ϵ_n — энергия нижнего уровня, $\epsilon_m > \epsilon_n$.
 «...» (1.1).
 ϵ_{mn} — энергия фотона, $\epsilon_m - \epsilon_n = h\nu_{mn}$.
 $\lambda = 0,63 \text{ мкм}$,
 $\epsilon_n - \epsilon_m = h\nu_{nm} = 3,1 \cdot 10^{-12} \text{ Дж} = 1,9 \text{ эВ}$ (1.1).
 $1,6 \cdot 10^{-12} \text{ Дж}$.
 $\lambda = \frac{c}{\nu}$ ($c = 3 \cdot 10^{10} \text{ см} \cdot \text{с}^{-1}$).

1.2.

$\epsilon_2,$
 $\epsilon_1.$ $h\nu_{21}$
 $h\nu_{21}$ (. 1.2,).
 ()
 $\Delta t,$
 $A_{21},$
 $\epsilon_2 \rightarrow \epsilon_1 (\epsilon_2 > \epsilon_1).$ N_2
 $\epsilon_2,$ 1
 $N_2 A_{21}$
 $N_2 A_{21} h\nu_{21}.$



. 1.2.

10^{-8} .

10^8 .
 $\Delta t \approx 10^{-8}$.

$\Delta \epsilon$ (.) .
 $v_{21} = \frac{\epsilon_2 - \epsilon_1}{h}$.

« . 1.2, » .

E^2

$n.$

$v_{21},$

ϵ_1

$\epsilon_2,$

$1(. 1.2,).$

$1;$

$(. 1.2,$

$(. 1.2,).$

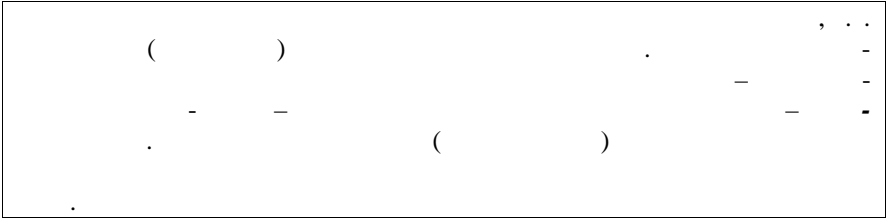
$(. 1.2,).$

1.3.

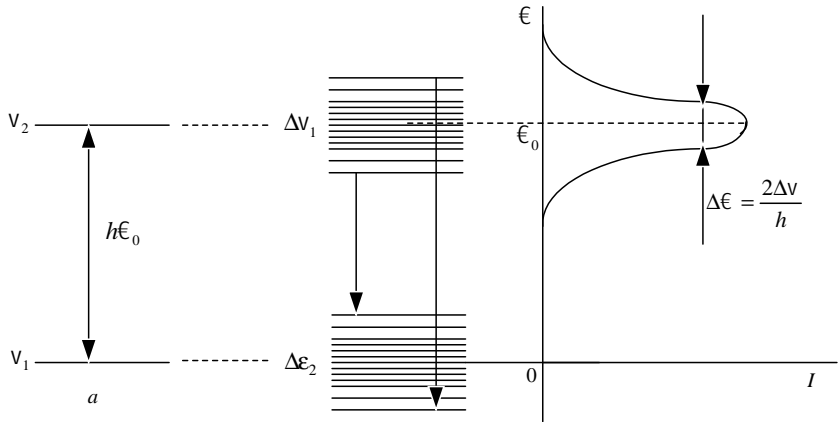
() .

$$h\nu = \varepsilon_2 - \varepsilon_1$$

, ...



$$\nu_0 = \frac{\varepsilon_2 - \varepsilon_1}{h} \quad (. 1.3,).$$



. 1.3.

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 $v + \Delta v$, . . -
 1.5. -

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$$\Delta\varepsilon \propto \frac{h}{\Delta t},$$
 Δt -
 ε -
 $\Delta\varepsilon$. « »
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: ε -
 Δt , v Δt . -
 ε $h\nu = \varepsilon_2 - \varepsilon_1$, -
 Δv .
 :

$$\Delta v = \frac{1}{\Delta t},$$
 Δv -
 Δt -
 , $\frac{1}{1}$, ,
 Δv ,
 $\frac{\Delta v}{v}$. - -
 $v = 10^{-14}$ ()
 100 10^{-16} (1
 100 ,
).

ϵ_1 ϵ_2 , Δv . 1.3, ,) (, -
 (. 1.3,). -
 « » (-
 $h\nu_0 = \epsilon_1 - \epsilon_2$, -
 ν_0 .

1.4.

$N_2 > N_1$, $\epsilon_2 \cdot N_2$ -
 $\epsilon_2 \cdot N_1$ ϵ_1 , ϵ_2 , ...

$$\nu = \frac{\epsilon_2 - \epsilon_1}{h}$$
 $\epsilon_1 \rightarrow \epsilon_2$, ϵ_2
 « »
 « » ,
 , ...

z,

« »

ϵ_2 . 1.4. , N_2

L $E = E_0 e^{\frac{\alpha z}{2}}$

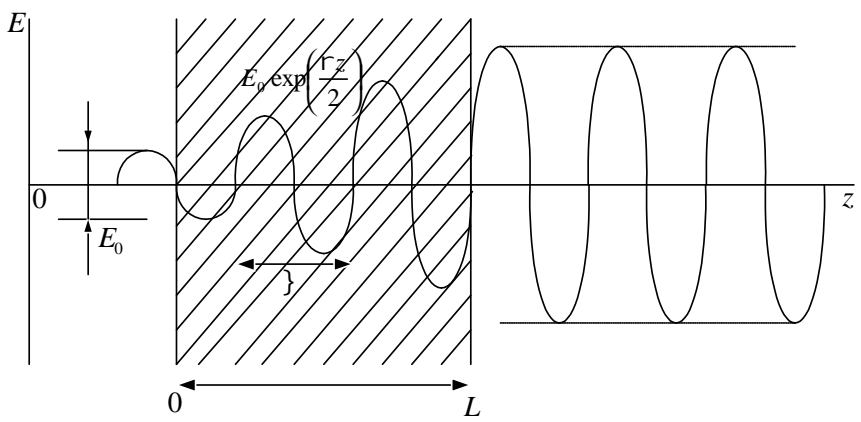
α

$z = \frac{1}{\alpha}$

α -1.

, , ...

$N_2 < N_1$.



. 1.4. « »

« »

« ».

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N_2

N_1 .

() . α

$N_2 - N_1$

ϵ_2 , $W -$

ϵ_1 , N_1 , ϵ_2 , N_2 , WN_1 , WN_2 , $\ll \gg$.

$\ll \gg$ ($\ll \gg$).

$\ll \gg$

$h\nu = \epsilon_2 - \epsilon_1$, $\ll \gg$

$h\nu$,

$h\nu W \Delta N$, $\Delta N = N_2 - N_1 - \Delta N$

$\alpha \propto h\nu W \Delta N$.

$\Delta \epsilon$:

$$W \rightarrow \frac{1}{h^2} d^2 \frac{E^2}{\Delta v}$$

E^2

, $d -$

, v , d , Δv .

ΔN , W , :

$$\alpha \rightarrow \frac{1}{hc} \frac{v}{\Delta v} d^2 \Delta N.$$

ϵ_2 , « » $\epsilon_2 - \epsilon_1 = h\nu$, ϵ_1
 ϵ_2 , N_2 , N_1 , ϵ_1 .

$h\nu = \epsilon_m - \epsilon_n$,

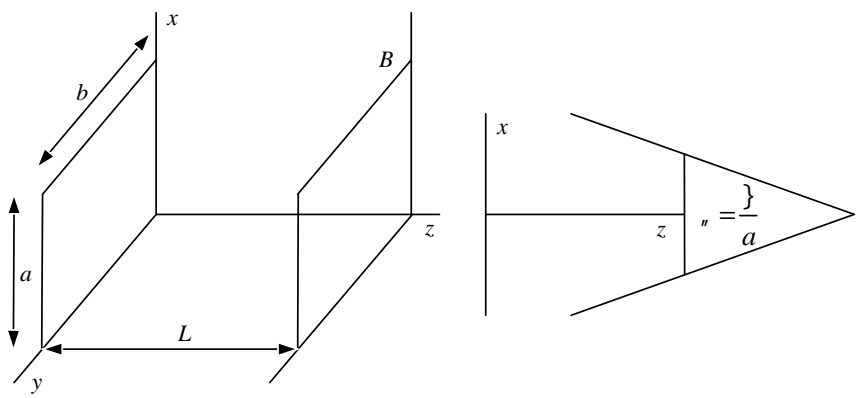
$I = I_0 e^{(\alpha - \beta)z}$.

$L = \frac{\lg 100}{10^{-2} \lg e} = 5$.

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. 1.5.

z

[1]:

$$E_z(t, z) = E_{0z}(t) \sin \frac{2f}{L} z = E_{0z}(t) \sin \frac{fq}{L} z.$$

$$E_z - , E_{0z} -$$

$$, q = \frac{2L}{\lambda} -$$

$$z. , L = 10 ,$$

$$\lambda = 5 \cdot 10^{-5} ,$$

$$q = 4 \cdot 10^5.$$

$$(z = 0, z = L)$$

z,

$$\theta = \frac{\lambda}{a} (. 1.5,). ,$$

$$(\theta \approx 10^{-4} \dots 10^{-5})$$

(

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« »

(

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$$\Delta N = N' - N,$$

, ...

$$\Delta N$$

(, (. .)

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$$\frac{N_m}{N_n} = \exp\left[-\frac{\epsilon_m - \epsilon_n}{kT}\right],$$

$N_m, N_n, \epsilon_m, \epsilon_n$

$$\Delta N = 0.$$

$(N > N)$,

β .

R ,

$$R = \frac{I}{L}.$$

0,99.

$$I - I = I(1 - R).$$

), (

$$I = I \left(1 - \frac{1-R}{L} \right)^z$$

,

$$I(z) = I_0 e^{-\beta_1 z},$$

$$\beta_1 = \frac{1-R}{L} -$$

, t, :

$$I(t) = I_0 e^{(\alpha - \beta_1)ct}.$$

$$\alpha > \beta_1,$$

I

$$\alpha$$

$$\alpha = \beta_1.$$

$$\alpha > \beta_1 + \beta$$

β :

$$\alpha > \beta_1 + \beta = \frac{1-R}{L} + \beta.$$

, β . :

$$\alpha >= \frac{1-R}{L} + \beta + \beta = \frac{1-R}{L} + \beta .$$

$$\Delta N ,$$

$\alpha,$

$$\Delta N > \frac{\frac{1-R}{L} + \beta}{\frac{1}{hc} \frac{v}{\Delta v} d^2} .$$

$$\Delta N$$

$\beta.$

$$\Delta N$$

d

$$v, \Delta v .$$

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$$v_p ,$$

$$\Delta N$$

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($\theta \approx 1$).

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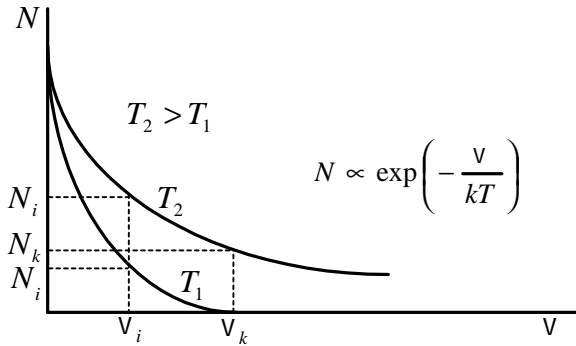
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(1.6):

$$N_n = C \exp\left(-\frac{\varepsilon_n}{kT}\right).$$



1.6.

$T_1 \quad T_2 > T_1$

()

$$R = \frac{pV}{T}$$

$$N_a = (6,02486 \pm 0,00016) \cdot 10^{23},$$

$$k = \frac{R}{N_a} = (1,38054 \pm 0,00018) \cdot 10^{-16} \text{ ———} =$$

$$= (8,6167 \pm 0,0004) \cdot 10^{-5} \text{ ———}.$$

1.6

(1.4)

$$\frac{N_m}{N_n} = \exp\left(-\frac{\epsilon_m - \epsilon_n}{kT}\right)$$

$T \rightarrow \infty$

$0 \rightarrow \infty$

)

1.7, :

$$N_n = C \exp\left(-\frac{V_n}{kT_1}\right).$$

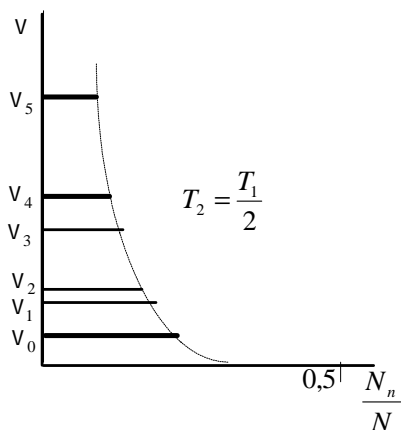
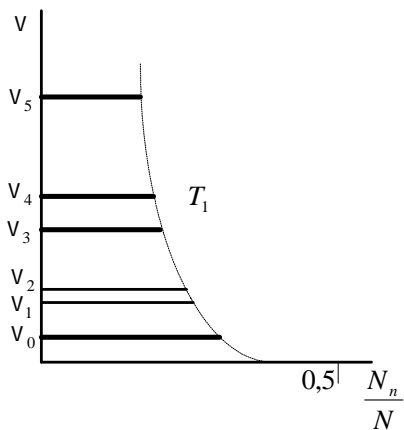
T_2 ,

(. . 1.7,),

T_2

(. . 1.7,).

T_1 .



. 1.7.

$\rho_1(\cdot)$ $\rho_2(\cdot)$

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1.5.1.

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ϵ_2

$$v = \frac{\epsilon_2 - \epsilon_1}{h}$$

« » ϵ_1 .

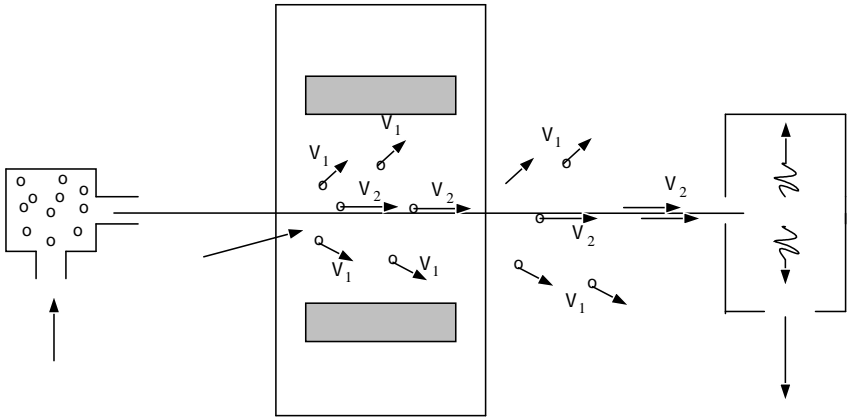
, . 1.8.

$\Delta\epsilon$ ().

$\Delta\epsilon$

ϵ ,

« »



. 1.8.

ϵ_1

ϵ_2 (ϵ ,

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. 1.9.

$\epsilon_2 - \epsilon_1$

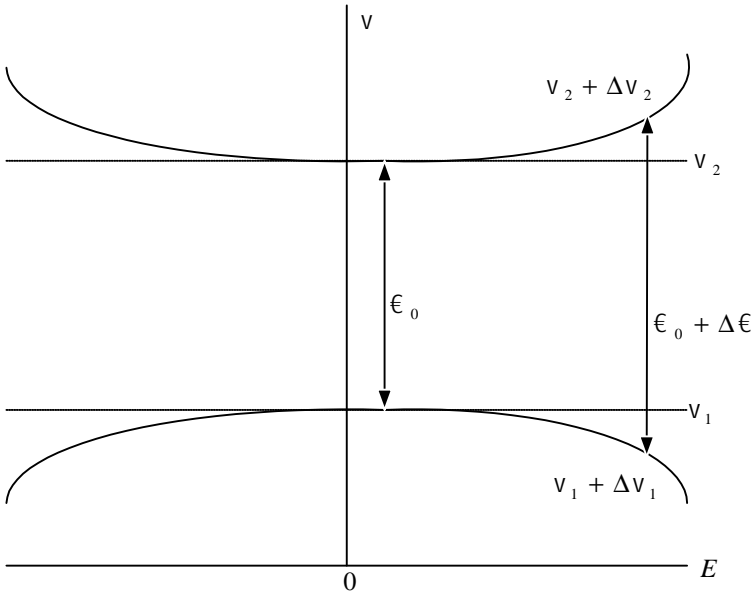
$$v_0 = \frac{\epsilon_2 - \epsilon_1}{h}$$

$$\Delta\varepsilon_1 = -\frac{\alpha^2 E^2}{\varepsilon_2 - \varepsilon_1}, \quad \Delta\varepsilon_2 = \frac{\alpha^2 E^2}{\varepsilon_2 - \varepsilon_1},$$

$\alpha \ll \dots$

$$\Delta v = \frac{\Delta\varepsilon_2 - \Delta\varepsilon_1}{h} = \frac{2\alpha^2 E^2}{h(\varepsilon_2 - \varepsilon_1)} = \frac{2\alpha^2 E^2}{h^2 v_0}.$$

$$\alpha E \ll (\varepsilon_2 - \varepsilon_1), \dots$$



. 1.9.

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E.

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1.5.2.

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ϵ_1 ϵ_2 ,

$\frac{\epsilon_2 - \epsilon_1}{h}$, v.

W- 1

1 « » « »

WN_1 WN_2 .

N_1 N_2 ,

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N_1 .

, N_2

N_1 . ($N_1 - N_2$)

, ... ,

$\epsilon_1, \epsilon_2, \epsilon_3$ (. 1.10,).

$$v_{31} = \frac{\epsilon_3 - \epsilon_1}{h}.$$

$\epsilon_1 \rightarrow \epsilon_3$, N_3 , N_1 , $\epsilon_1 \rightarrow \epsilon_3$

$\epsilon_2 \rightarrow \epsilon_3$

$\epsilon_1 \rightarrow \epsilon_2$, N_2

N_1 (. 1.10,). $\epsilon_1 \rightarrow \epsilon_2$

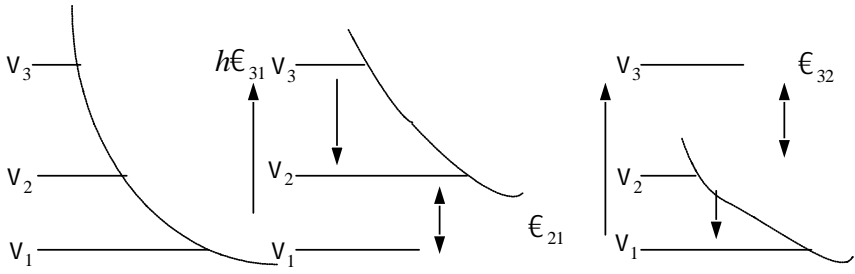
$$v_{21} = \frac{\epsilon_2 - \epsilon_1}{h}$$

$\epsilon_2 \rightarrow \epsilon_1$.

$\epsilon_2 \rightarrow \epsilon_3$.

ϵ_2 , $\epsilon_1 \rightarrow \epsilon_3$, N_3 , N_2 (. 1.10,).

v_{32} .



. 1.10.

1.5.3.

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1.5.4.

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2.1.

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$$\lambda \sim \dots (\lambda \sim \dots)$$

$$20 \dots (\dots)$$

$$\sim 10^6 \dots$$

$$(\dots)$$

$$\sqrt{2} \dots (\dots 2.1).$$

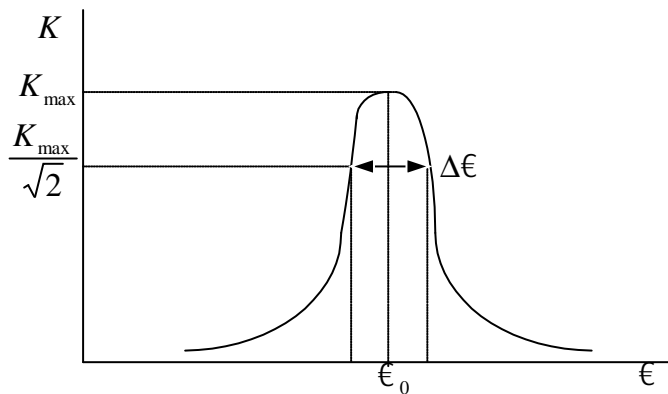
$$K_{\max}$$

$$(\dots)$$

$$\dots (\dots)$$

$$\dots (\dots)$$

8-10



. 2.1.

»

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$$d = 22 \quad (2.2).$$

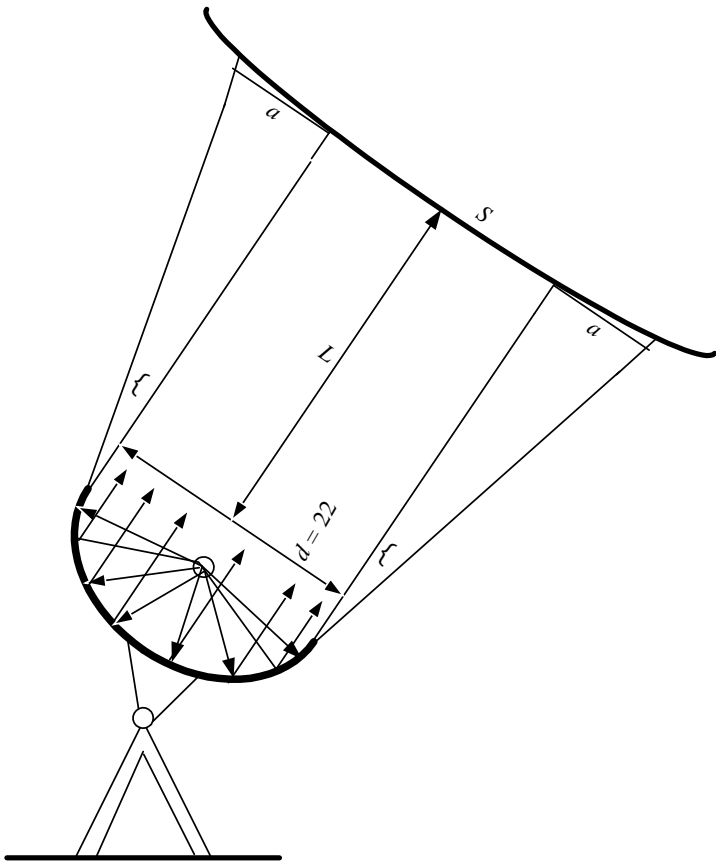
$$\lambda = 1$$

22

φ

$$\frac{\lambda}{d}$$

φ



. 2.2.

, $\lambda = 1$ $\varphi = \frac{1}{22} \text{ rad} = 2,6^\circ$.

« » (,
 S) $D = d + 2a = d + 2L \tan \varphi$, $L -$
 $D = 30\ 000$, $L = 300\ 000$, « »
 , . . .

10 $\lambda = 1$
 $\varphi = 10^{-5} \text{ rad}$, 3 ,

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 40 – 50-

$$(\lambda \sim 1)$$

λ .

2.2.

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(. 1.2).

€_{mn}

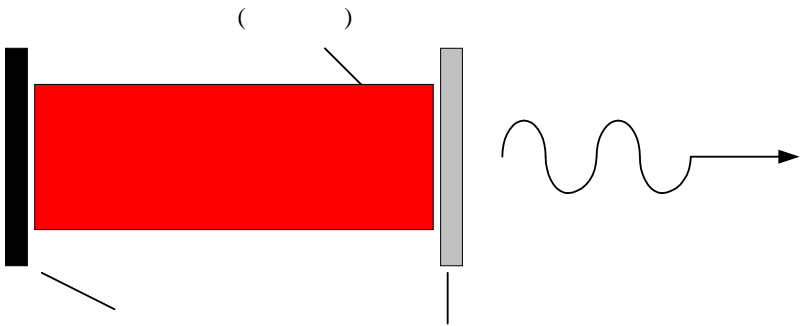
V_m V_n , -
 ϵ_{mn} -

(1.3)



(1.5).

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 (. 1.4).
 (. 2.3).



. 2.3.

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 (. 1.2).
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2.

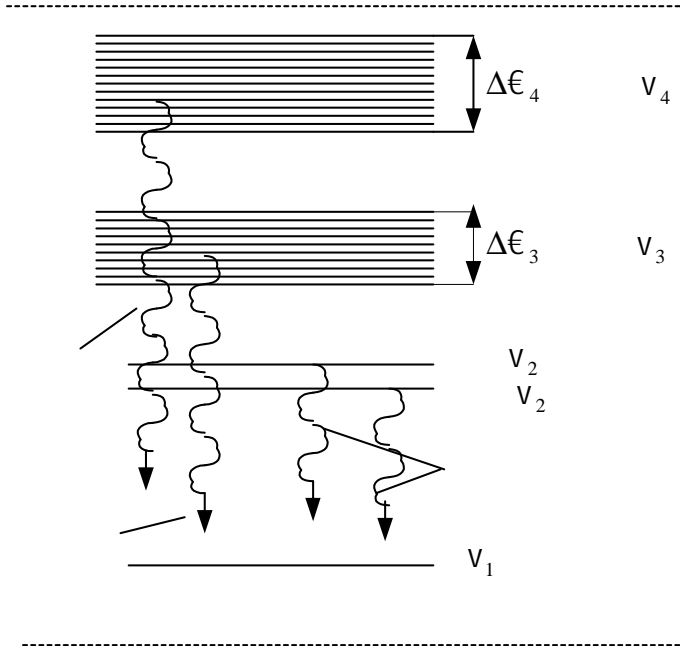
3.

2.3.

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(0,05 %).

. 2.4.

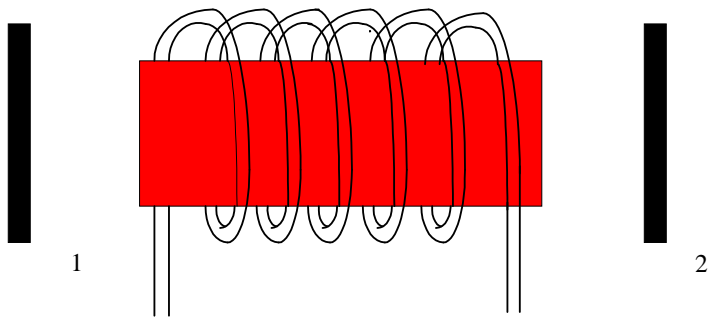
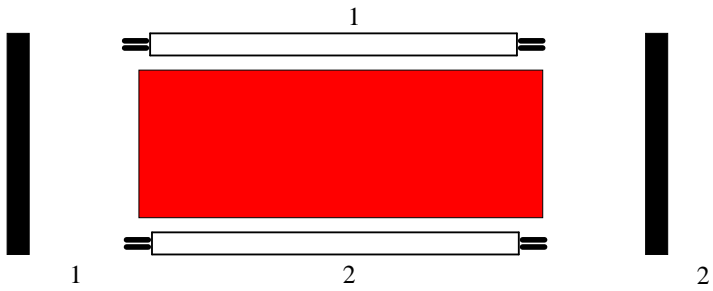


. 2.4.

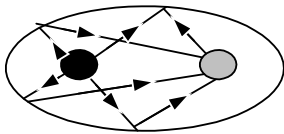


V_1, V_{2a}, V_{2b} -
 V_3, V_4 ,
 $V_2 \rightarrow V_1$ 7000
 $\overset{0}{A}$ - . V_3
 V_1 , $V_4 \rightarrow V_1$
 , (r)
 r - -
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 V_3, V_4 , (10^{-8})
 V_2 , V_2 -
 V_3, V_4 -
 V_1 , -
 V_{2a}, V_{2b} , V_2 « » 10^{-3} ,
 V_2 ,
 V_1
 V_3, V_4 , V_2
 V_2 ,
 V_1, \dots -
 V_{2a}, V_{2b} , V_1 .

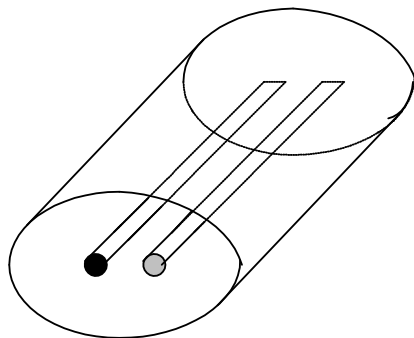
$\epsilon_1 \quad \epsilon_3 \quad \epsilon_4$
 $\epsilon_1 \quad \epsilon_2$
1.1 1.2).
« Cr^{+++} ».
« » –
 $\epsilon_3 \quad \epsilon_4 \quad \epsilon_2$
.2.5.
(.2.5,)
(.2.5,).
(.2.6),



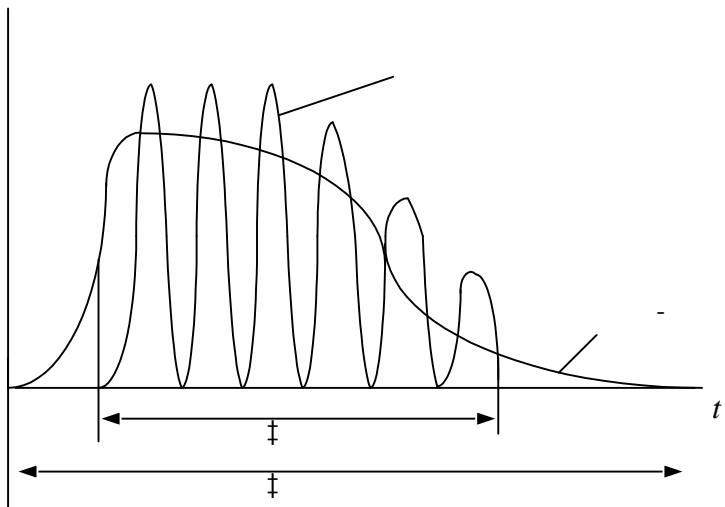
.2.5.



.2.6.



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 ϵ_2
 ϵ_3 ϵ_1
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 10^{-6} c (.2.7).
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 ϵ_2 , ϵ_1 , $\sim 10^{-8} \text{ c}$
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.2.7.

ϵ_2

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 ϵ_2 ,
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.2.8.

(.2.8,)

ϵ_1

ϵ_3

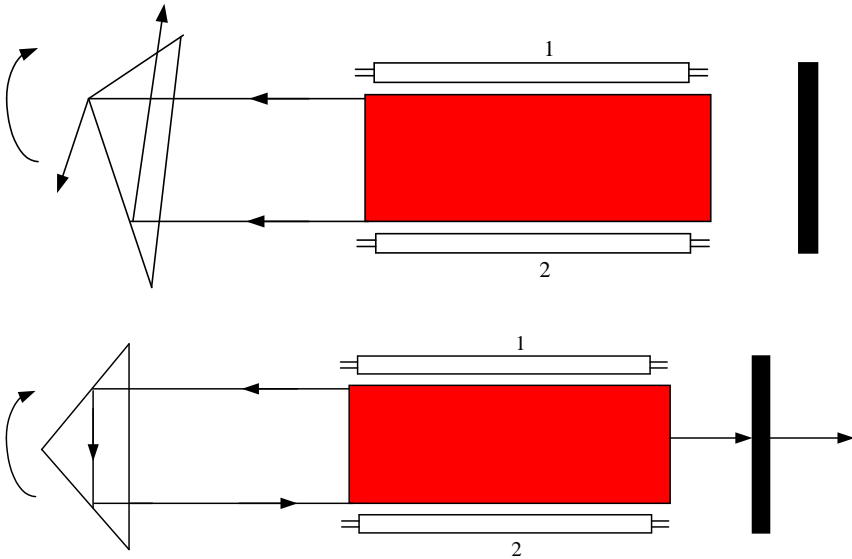
ϵ_4

ϵ_2

.2.8, .

ϵ_1

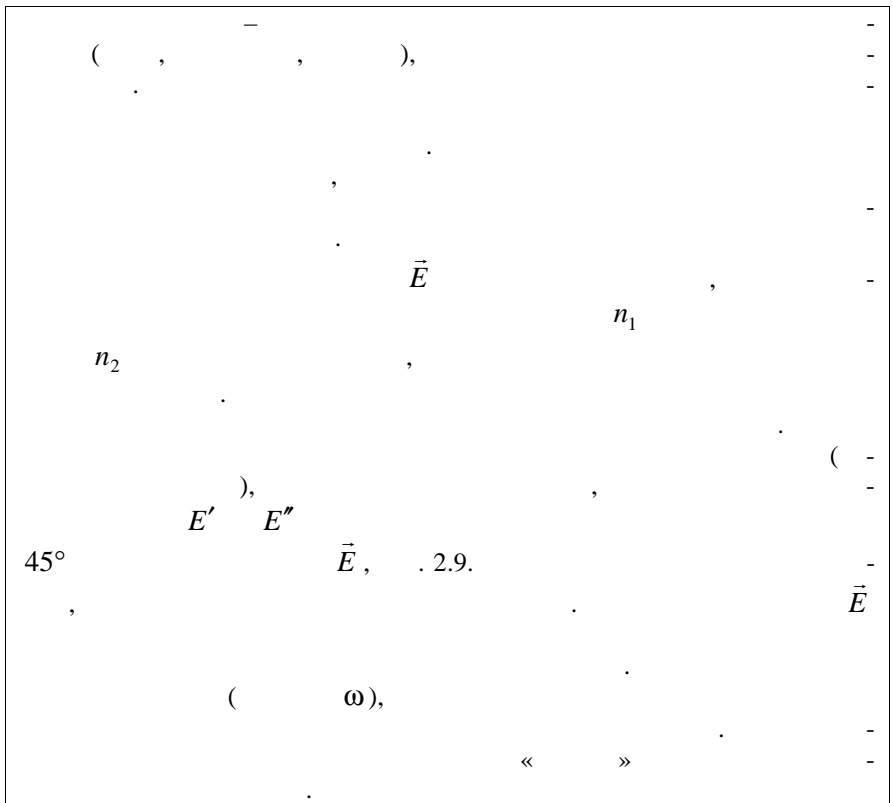
ϵ_2

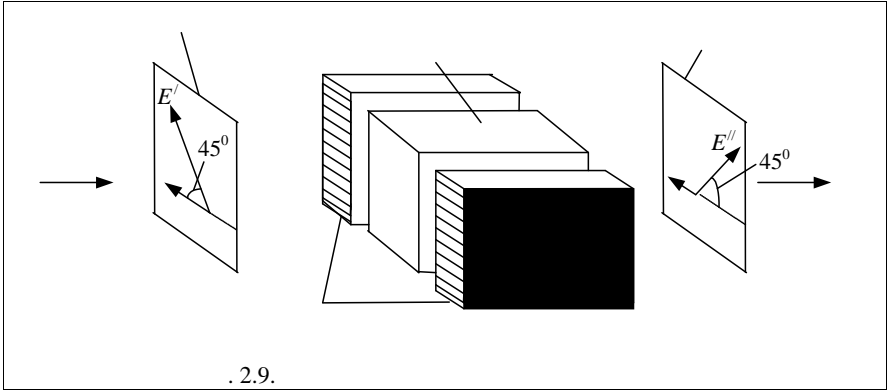


.2.8.

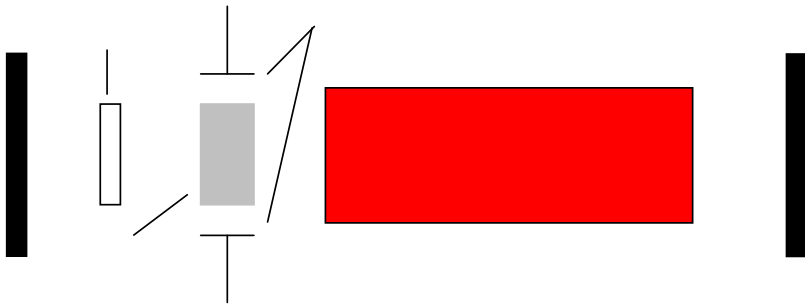
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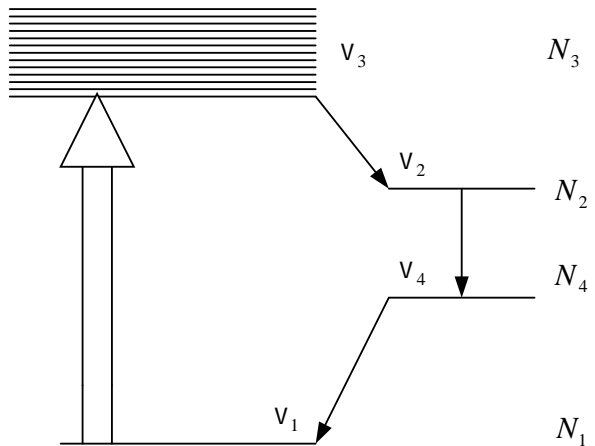




, . . . -
 , . 2.10.



90° , -
 ,
 (10^{-8}) , -
 $(\sim 10^{-8})$. -
 , -
 , -
 (Nd) , -
 (CaF_2) , (Dy) -
 (Sm) . -
 , -
 - .
 $\lambda \sim 0,7$, λ , -
 $\lambda = 1,06$, $\lambda \sim 2,5$ -
 Dy . -
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 .
 ϵ_3 , ϵ_2 , . 2.11. -
 , -
 ϵ_4 , ϵ_1 , ϵ_2 . -
 ϵ_1 , -
 N_4 , ϵ_1 -
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 ϵ_4 , -
 ϵ_2 , -
 $\Delta N = N_2 - N_4$ -
 ΔN , -
 $(15-20)$, -
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. 2.11.

Dy
F₂

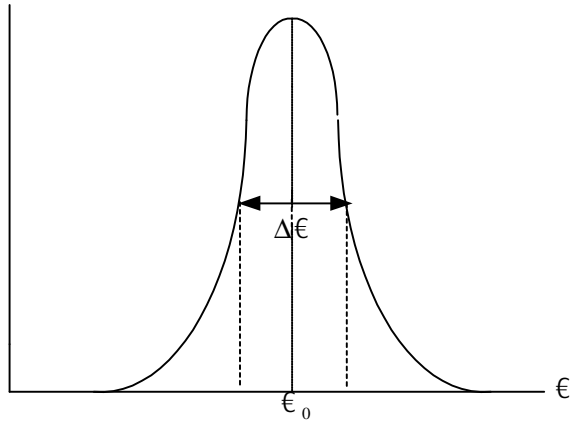
2.3.1.

λ (ν)

$$\nu = \frac{\epsilon_m - \epsilon_n}{h}$$

$h\nu_0$,

ν_0 ,
 $\Delta\nu$.
 (1.3).
 ϵ_0 .
 $\Delta\nu$, $\Delta\nu = 10^{11}$
 $\epsilon_0 = 4 \cdot 10^{14}$,
 $\frac{\Delta\nu}{\nu_0} = 2,5 \cdot 10^{-4}$, ...
 ϵ_0 ,
 ϵ_0 , .2.12.
 ϵ_0 (
 .2.12).
 λ .



. 2.12.

: , ([2]). - (-
) , (100 %) -
 , , -
 . , -
 . , -
 $\frac{2L}{\lambda}$ (L - -
), . 2.13, . 2.13 -
 . (), () -
 , (L) -
 , -

$$\lambda_n = \frac{2L}{n},$$

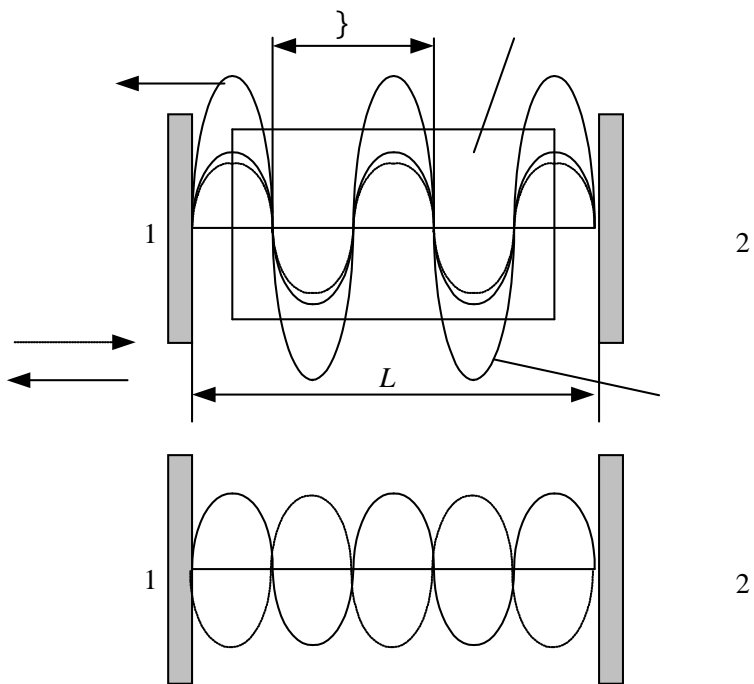
$n -$

(. 1.4) () :

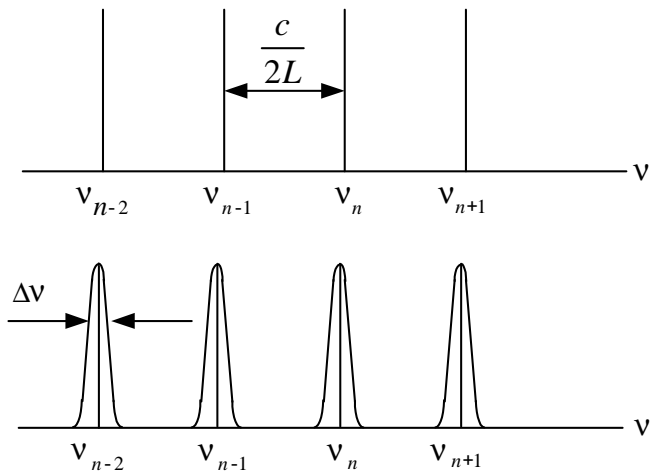
$$\epsilon_n = \frac{c}{2L} n,$$

$$\frac{c}{2L},$$

, .2.14 ().



.2.13.

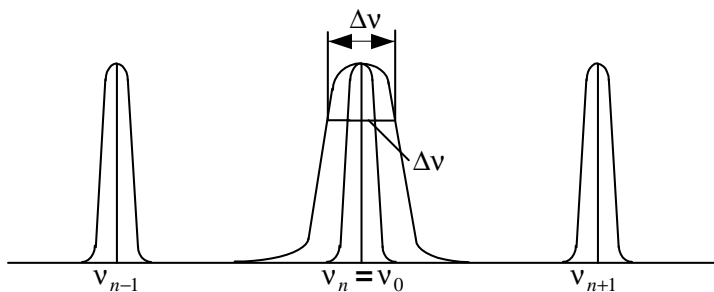


. 2.14.

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 , 100 %.
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 $\Delta\epsilon$
 ϵ_n (. 2.14,).
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 ϵ_0
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100 %, ,
 , 90 %, , -
 0,1 -
 10 , . -
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 €₀ . -
 () Δ€ , €_n -
 v. -
 , . 2.14, . -
 Δ€ . -
 (€_n - €_{n-1}), ... Δ€ < $\frac{c}{2L}$,

€_n, . 2.15.



. 2.15.

$$\Delta v < \frac{c}{2L}$$

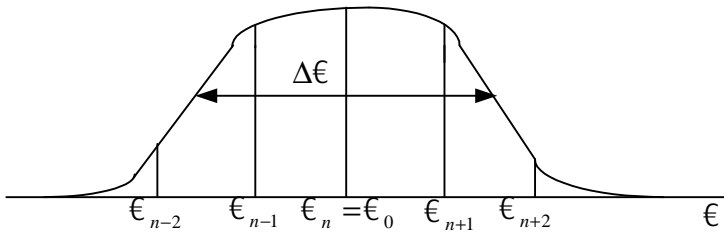
$\Delta \epsilon$, ϵ_n , ϵ_0

$$\left(\Delta v > \frac{c}{2L} \right)$$

ϵ_n ,

(. 2.16),

(,).



. 2.16.

$$\Delta v > \frac{c}{2L}$$

, (,),
 , . 2.16.
 , , ϵ_0
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$\epsilon_0,$

$\epsilon_{n-1} \quad \epsilon_{n+1} (\quad)$

2.3.2.

$W,$

W

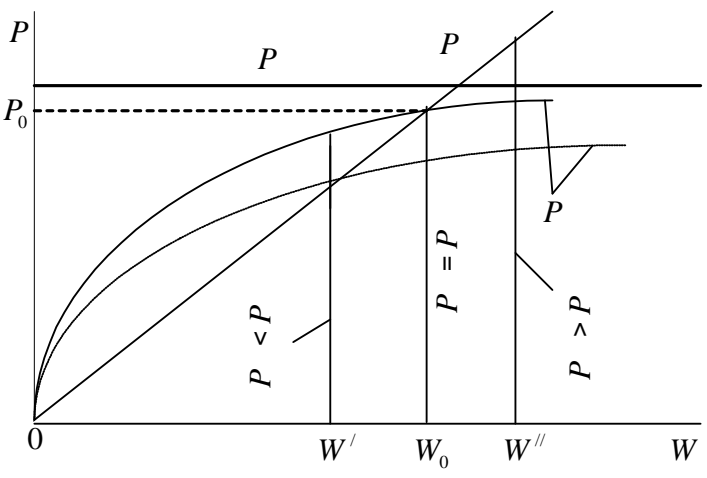
P

W

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 P , -
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P , P . -
 , P P (. 2.17). -



. 2.17. P P
 W ,

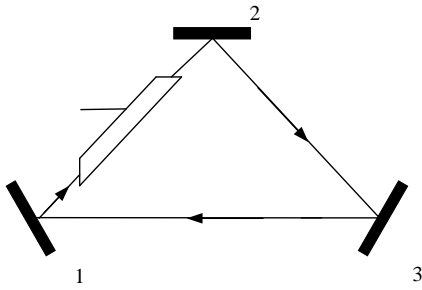
. 2.17: $P > P_0$. ,
 W , $P(W)$

$P(W)$.

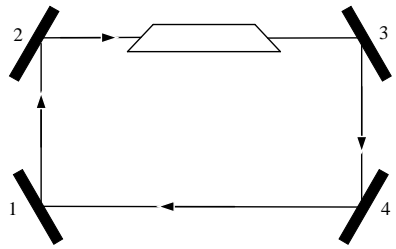
2.3.3.

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. 2.18.

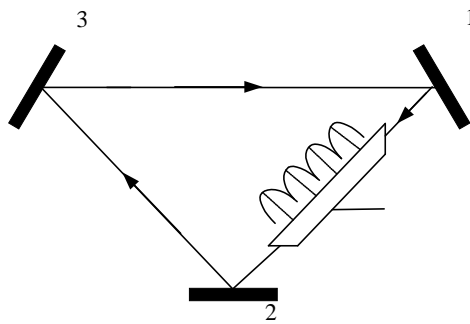


. 2.18.



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. 2.19.



. 2.19.

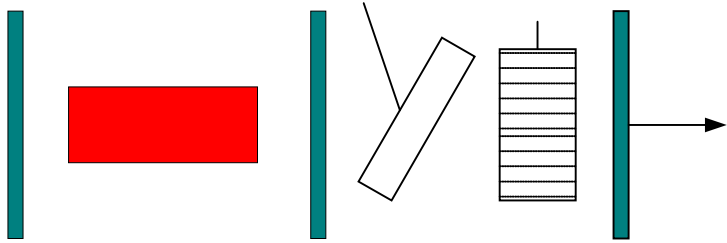
2.4.

1-2

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(. 4)

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.2.20.

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3.1.

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$(10^4 \dots 10^9) \Omega$

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(,) . , , (,), (,) .

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(~10),

(~10²²),
(~10⁻²¹).

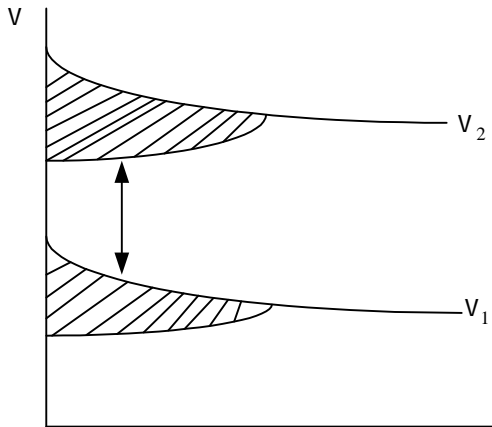
$$1 \cdot 1 = 1,60219 \cdot 10^{-19}$$

$$F = Ee$$

$$\vec{E} = \frac{\vec{F}}{q}$$

$$a = \frac{F}{m} = \frac{Ee}{m_e}$$

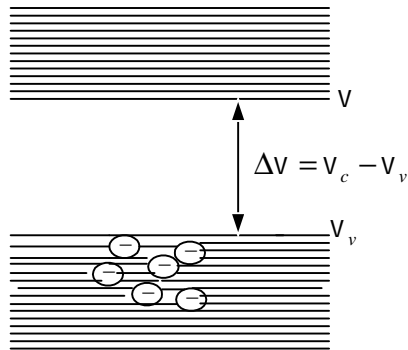
$$= 0$$



. 3.1.

$\Delta\varepsilon$.

$\Delta \epsilon$ (.3.2).



. 3.2.

$$\Delta \epsilon \quad -$$

$$(1 \dots 2) \cdot 10^{-3} \quad (1 \dots 3) \quad -$$

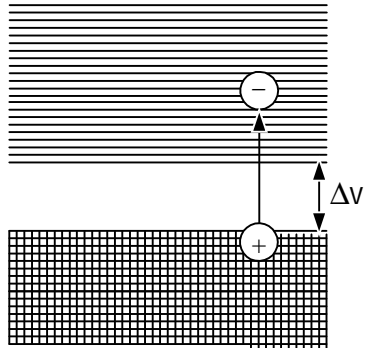
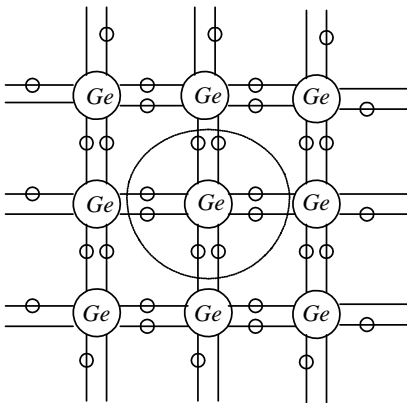
$$\Delta \epsilon \sim (3 \dots 10) \quad .$$

$$\Delta \epsilon \quad -$$

. 3.3, .

(> 0)

(. 3.3,),



. 3.3.

();

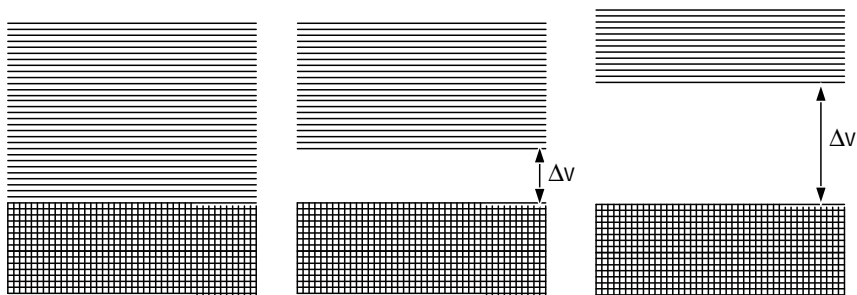
()

$\Delta\varepsilon$.
- 3 ,

$\Delta\varepsilon > 6$.

$\Delta\varepsilon = 0,1$

. 3.4.

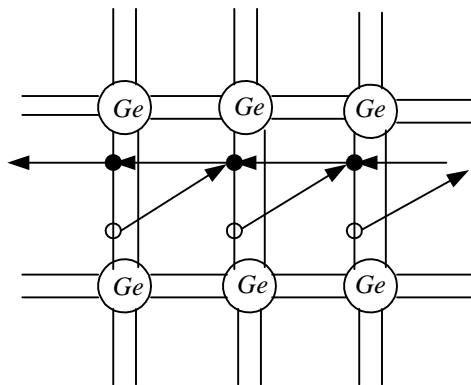


. 3.4.

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« ».

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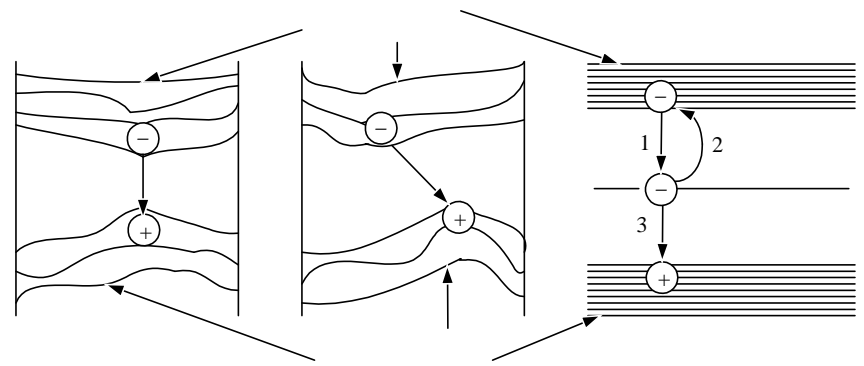
. 3.5.

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 $\Delta\varepsilon$,
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 kT ,
 $\sim 0,025$.

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 (« »),
 (. 3.6, ,).

$\Delta\varepsilon$.



. 3.6. :
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 () ()-
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 , $\Delta\varepsilon$.

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$$J_n = qn\mu_n E, \quad J_p = qp\mu_p E,$$

$q -$ () ; $n, p -$
 $;$ $\mu_n, \mu_p -$

$$\mu = \frac{v}{E}, \quad v -$$

$$J = J_n + J_p = qE[n\mu_n + p\mu_p],$$

3.2.

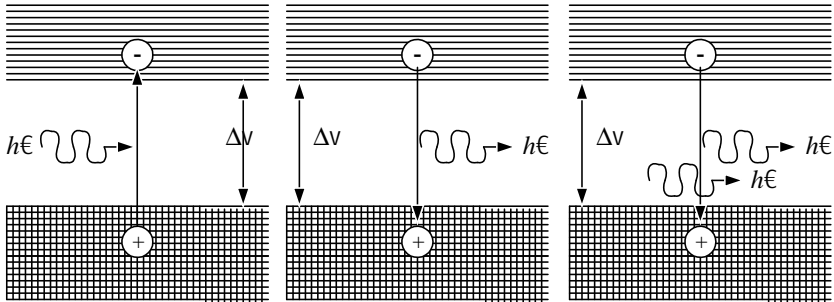
, « » « », -
 , , -
 , , $\Delta\varepsilon$, . . -
 $h\nu > \Delta\varepsilon$. $h\nu < \Delta\varepsilon$ -

. 3.7.

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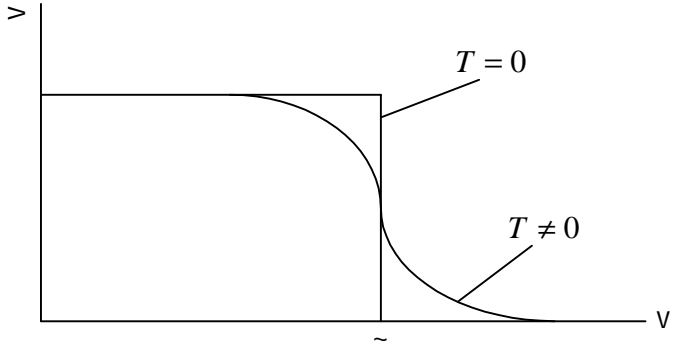
	(, ().
),	(
= 0	-

($\epsilon > \mu -$, $\epsilon < \mu$),
 , . 3.8.



. 3.7. :
 () - ; () -
 , ; () -
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 , $\epsilon > \mu$.
 $\epsilon < \mu$, 1 (, . 3.8).
 :

$$f(\epsilon) = \frac{1}{\exp\left(\frac{\epsilon - \mu}{kT}\right) + 1}$$



. 3.8.

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 « » ϵ_c , — «
 » ϵ_v .
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 $p-n$.
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3.3.

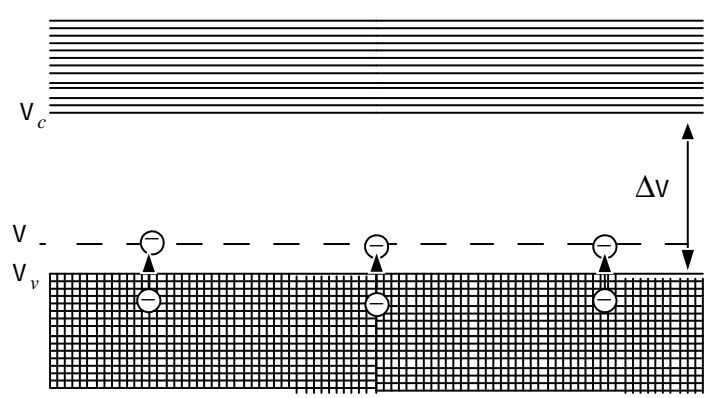
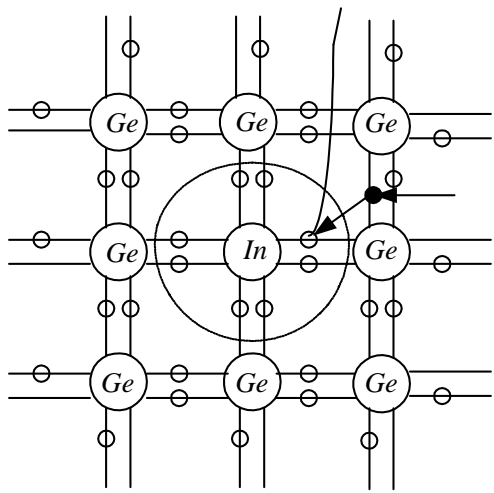
3.3.1.

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 (4 + 3 ⊕ 1).
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 .3.9, .
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 ()
), . . $p > n$.
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 ,
 ($J_p > J_n$). .3.9,
 .
 , .3.9, .
 (0,01 – 0,07),
 ,
 Δε.
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.3.9. () - : () - ;

, , , , , , . , , , , , . 3.10, . , , , , . 3.10, . (« ») , . , . (,) (. 3.10,)

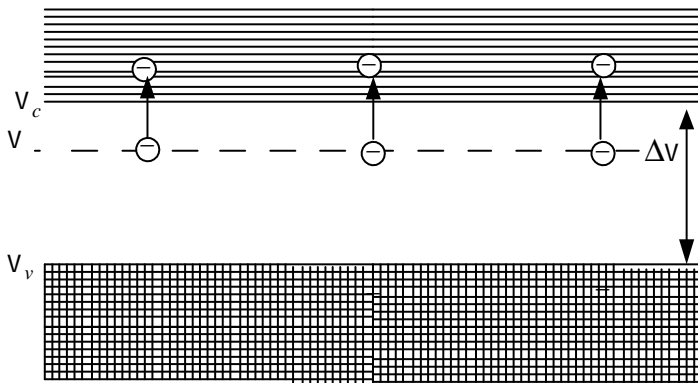
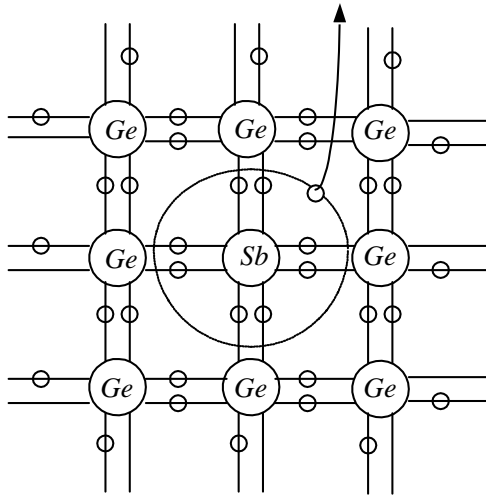
(0,01 – 0,07) ,

(

)

$\Delta\varepsilon$.

$n -$



. 3.10.

() - : () -

;

— , . . . n - ,

$n_i \approx 2,5 \cdot 10^{13} \text{ }^{-3},$ $4,4 \cdot 10^{22} \text{ }^{-3}.$ 10^9

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, , n -

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$$n_n p_n = p_p n_n = n_i p_i = A^2 \exp\left(-\frac{\Delta \varepsilon}{kT}\right),$$

k — , n_i, p_i —

3.3.2.

()



$$p - n \quad (\text{ . 3.11, })$$

N N .

$(p_p \approx N_a, n_n \approx N)$.

$N \gg N$

$(p_p \gg n_n)$.

1000 ,

$p - n$

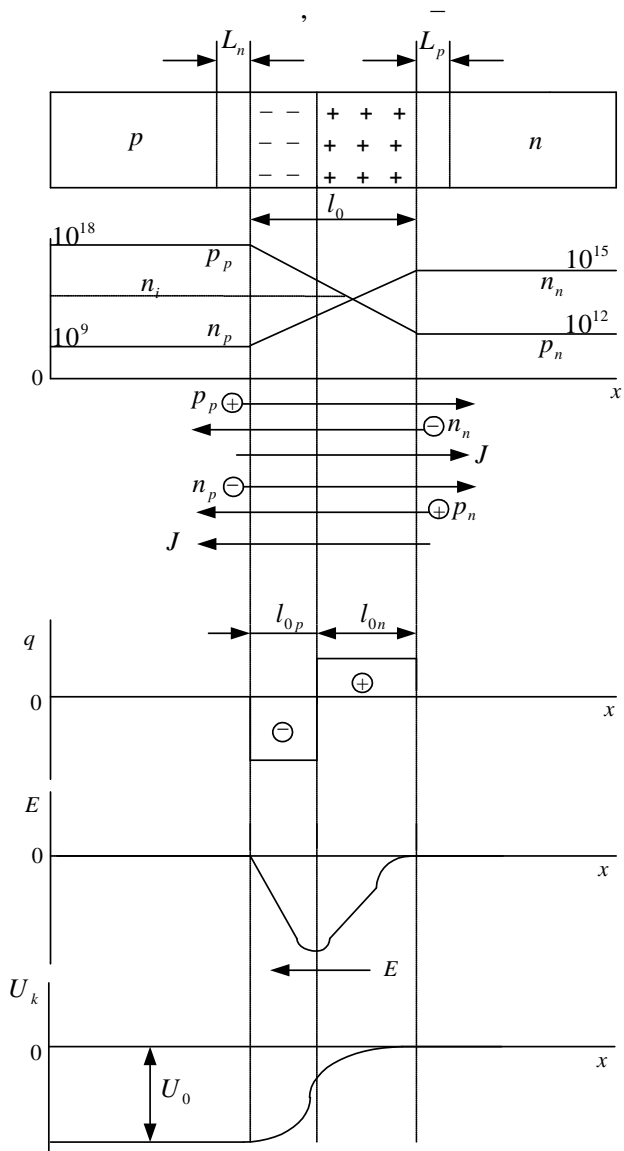
3.11,

$$n_i = 2,5 \cdot 10^{13} \quad ^{-3} .$$

$$n_p = 10^9 \quad ^{-3}, p_n = 10^{12} \quad ^{-3},$$

$$n_n p_n = p_p n_p = 10^{27} \quad ^{-3} .$$

$p - n$



. 3.11.

$p-n$

(.3.11,) : - -

$n-$, $n-$ - - . -

. 3.11 L_n, L_p - -

,

.

, $n-$, - ,

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(l_{0p}, l_{0n}) (p_p, n_n)

10^{18} 10^{12}

10^{15} 10^9 10^{-3} (.3.11,). -

-

$n-$ -

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$n-$, -

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() $p-n-$ () , -

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$n-$. 3.11, . $p-$

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l_0

(\dots)

$(N \approx N)$

$l_{0p} = l_{0n}$

$N \gg N$

$l_{0p} \ll l_{0n}$

(\dots)

$J = J = 0$

(\dots)

J ,
 n - ,
 p - . J -
 $p - n$ -
 L_n -
 L_p - n (. 3.11,).

$p-n$ U ,

$$E = \frac{\partial U}{\partial x} .$$

$$U_0$$

:

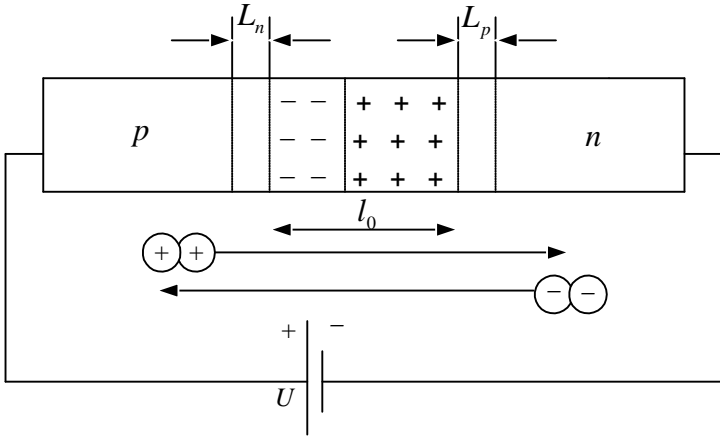
$$U_0 = \varphi_T \ln \frac{p_p}{p_n} = \varphi_T \ln \frac{n_n}{n_p} ,$$

$$\varphi_T = \frac{kT}{q}$$

$(t^\circ = -273 + 300, = 300 = 27^\circ)$ $0,5$;
 U_0 $0,7 - 0,8$.
 $\Delta \epsilon$.

p , $p - n$, n , U , $p - n$, $p - n$. 3.12.

$U = U - U$. $p - n$.



. 3.12. $p - n$

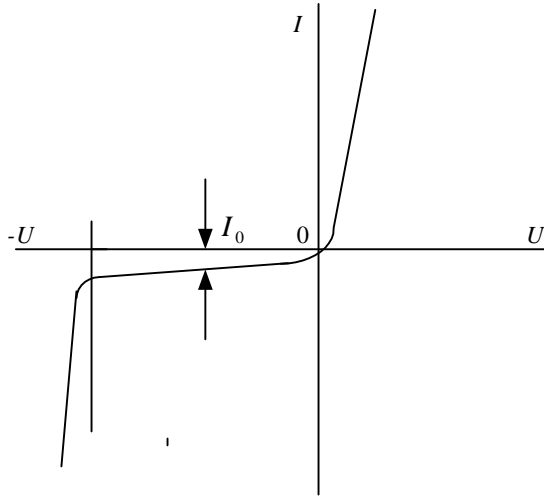
$|U| > |U|$,

$p - n$

$|U| = |U|$ $p - n$

n

3.13.



3.13.

$$I = I_0 \left(\exp \left[\frac{eV}{kT} \right] - 1 \right),$$

(, $U < 0$)
 n -
 U .

I_0 .

, , . 3.13.

- n -

$$(\quad)$$

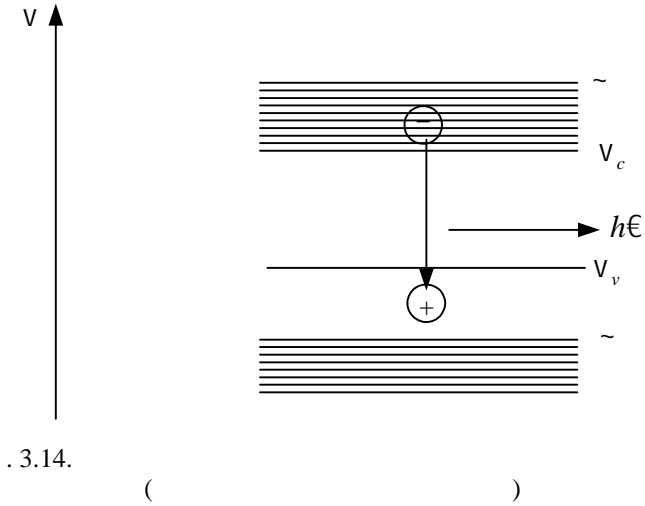
, , (3.13).

3.3.3. p - n - (\quad)

, , = 0

μ , μ ,

(3.14).
 $< \mu$ (\quad)
 $> \mu$



, $> \mu$.

, - :

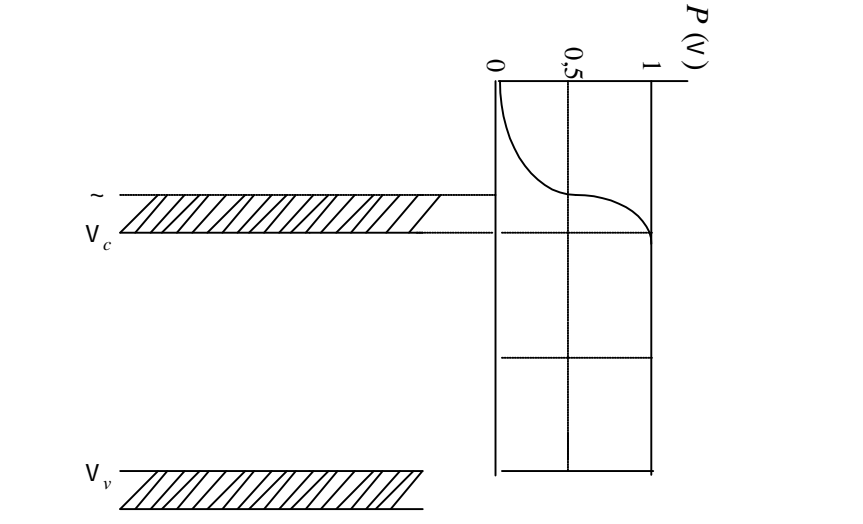
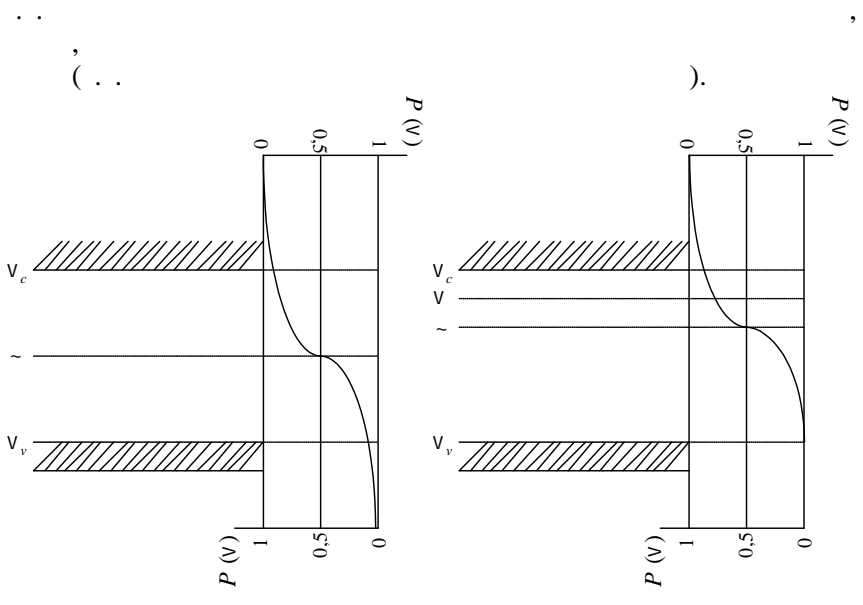
$$P(\epsilon) = \frac{1}{1 + \exp\left(\frac{\epsilon - \mu}{kT}\right)}$$

kT (-).

$$P(\epsilon) = \frac{1}{1 + \exp\left(\frac{\mu - \epsilon}{kT}\right)}$$

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 (.3.15,).
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 (.3.15,),
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 n- = 0
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 μ
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 .3.14), . . .
 μ - μ > Δε .
 .
 μ - μ > Δε ,



3.15. $:() -$; $() -$
 $n -$; $() -$ $n -$

μ (.
 . 3.14), . . .
 $\mu - \mu > \Delta \epsilon$.

$\mu - \mu > \Delta \epsilon$
 . . .
 (. . .).

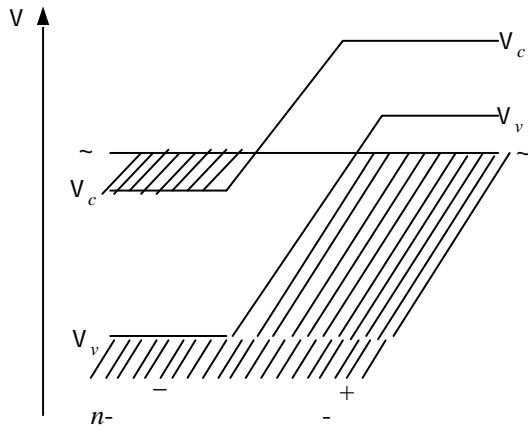
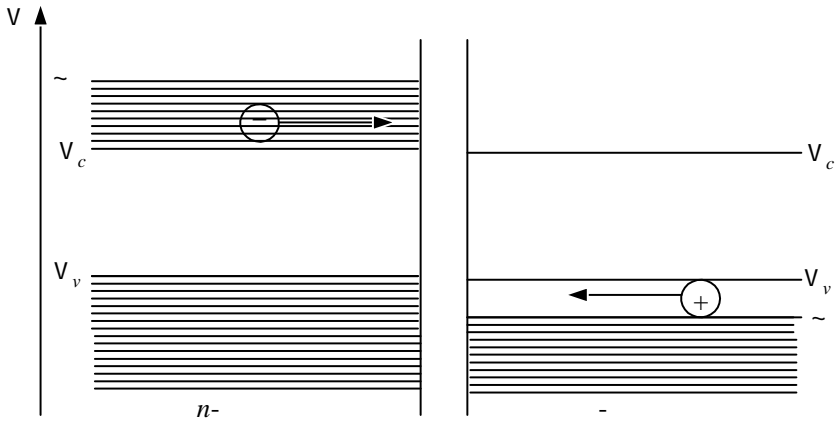
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$n-$
 $p-n-$ (. 3.16,),
 :
 $\mu - \mu > \Delta \epsilon$.

$n-$
 $p-n-$, , .

$$\mu - \mu > \Delta \epsilon .$$

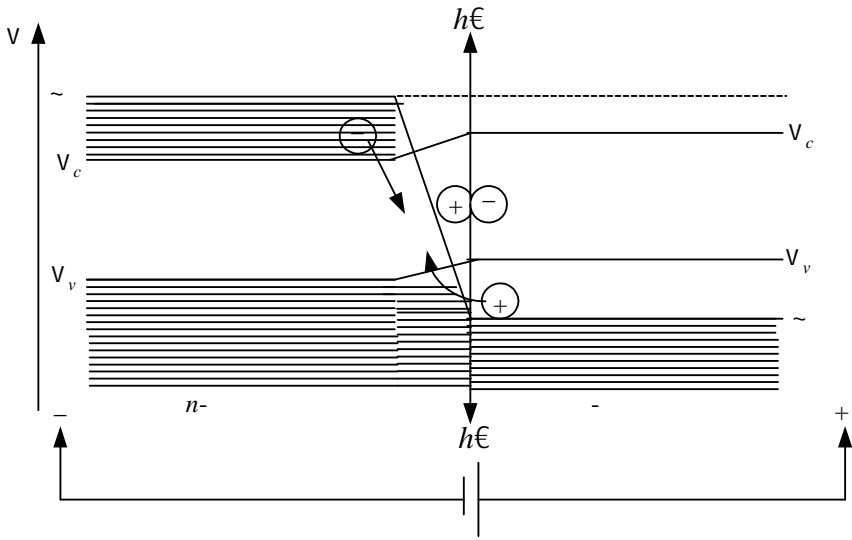
$p-n$ (. 3.16,),



. 3.16.

$p-n$: () -
; () -

$p-n$, . . . , $n-$ -
 $\Delta\epsilon$, U ,
 . 3.17.



. 3.17. $p-n$ U

$p-n$, -
 :
 (. -).
 , .
 , $\mu - \mu > \Delta\epsilon$.
 , $p-n$ -
 . $p-n$ -
 , . . . -

$p-n$

(. . . 3.1).

3.1

		λ , Å	
ZnS	80	3300	
ZnSe	80	4530	
CdS	4 – 300	4850 – 7960	
CdSe	80	6100	
CdSe	80	6950	
CdTe	4 – 80	7900 – 7960	
GaPAs	80 – 300	8300 – 8360	-
GaAs	4 – 300	8200 – 9000	
GaSb	20	15300	-
InAs	20	30080	-
InSb	20	49590	-
Te	20	38440	-
PbS	4	42700	-
PbTe	4	64100	-
PbSe	4	85500	-

$p-n$

(, ,)

$p-n$

\bar{E} N_1 N_2

$$\frac{N_1}{N_2} = \exp\left(\frac{h\nu_2}{kT}\right),$$
$$N_1 - N_2 > 0.$$

$N_2 > N_1,$

$$T_{1,2} < 0.$$

$N_2 - N_1.$

$\Delta\varepsilon$

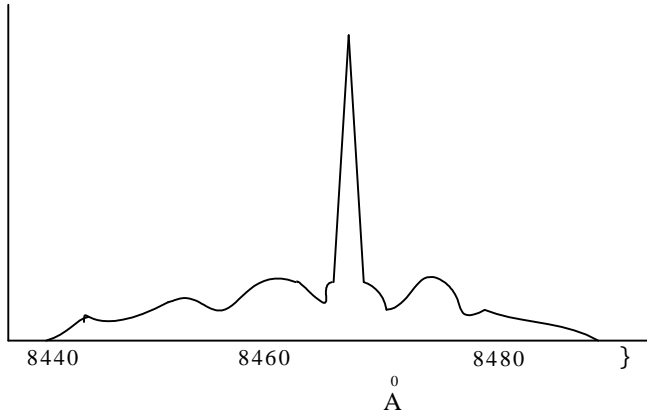
»:

p-n-

p-n-

p-n-

(. 3.18).



. 3.18.

GaAs

p-n-

p-n-

1 ' 2

p-n-

3.4.

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 (0,5) ,
 ,
 Δε .
 , , . ,
 Δε .
 , (Δε)
 Δp .
 , ε_c « »
 ε_v ,
 ,
 - , 3Δε .
 .
 (~2Δε)
 , (~Δε)
 ,
 ,
 μ - μ > Δε .
 ,

, GaAs $1 - \frac{A}{2}$ 50 .

$p-n$ (~ 20 %).

() l ,

:

$$l = 0,11\rho^{-1} \left(\sqrt{1 + 22,4\varepsilon_0^2} - 1 \right),$$

ε_0 - , ρ - $\frac{1}{3}$.

, GaAs ~ 20
 $\sim 0,1$, . . . 100 , $p-n$.

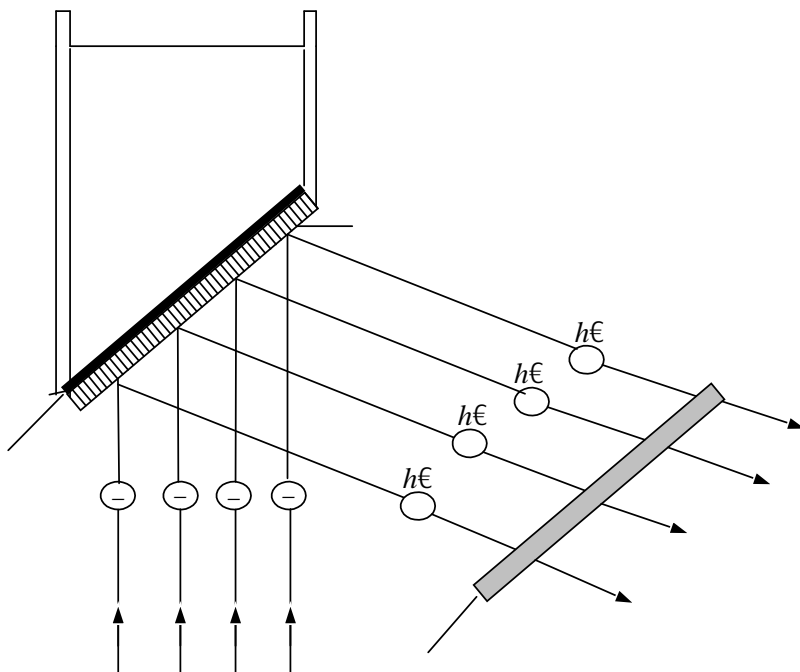
($p-n$)
 (~ 60 %)

(. . . 3.1).

$p-n$

(. 3.19).

()



. 3.19.

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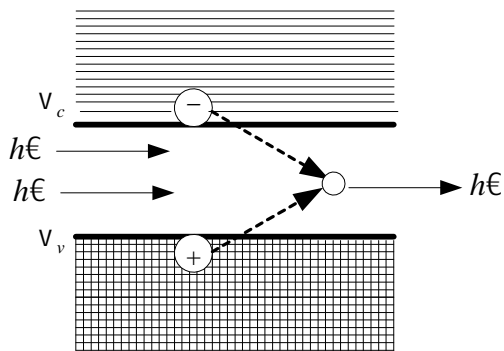
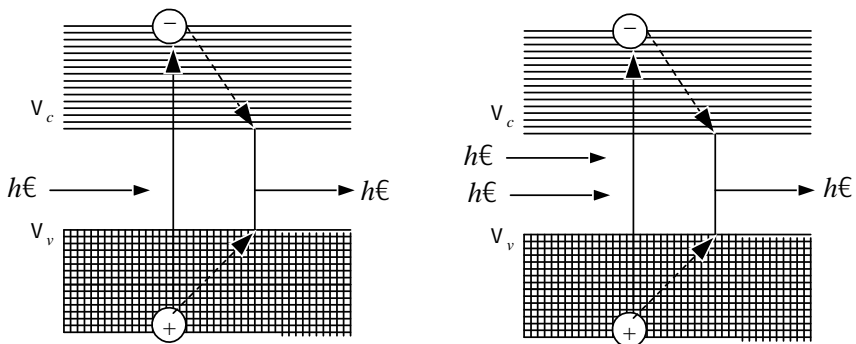
3.5.

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$\Delta\varepsilon$,

(
 $h\nu$

, . 3.20, .



. 3.20.

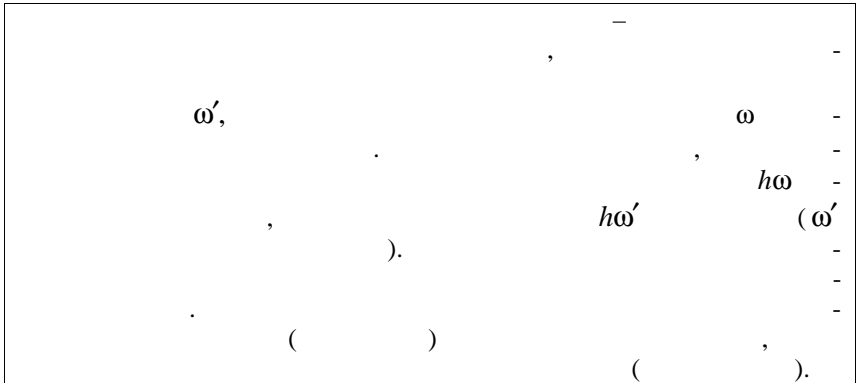
(. 3.20,)

$$h\nu < \Delta\varepsilon,$$

$\Delta\varepsilon$.

ε ε_v , . 3.20, .
GaAs.

GaAs.



. 3.21.

GaAs

(0,5),

(> 200

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(

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10^{-7} .

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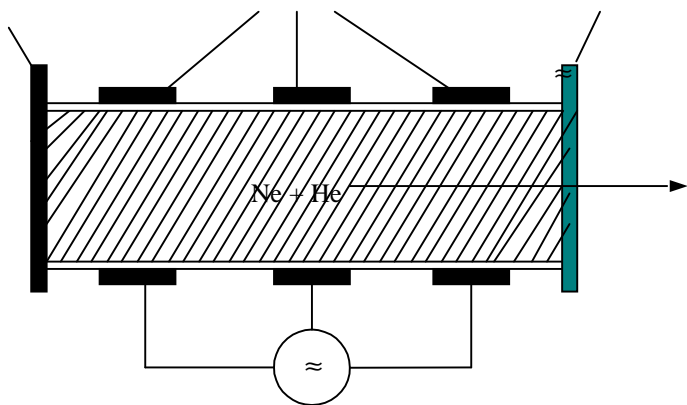
4.

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4.1.

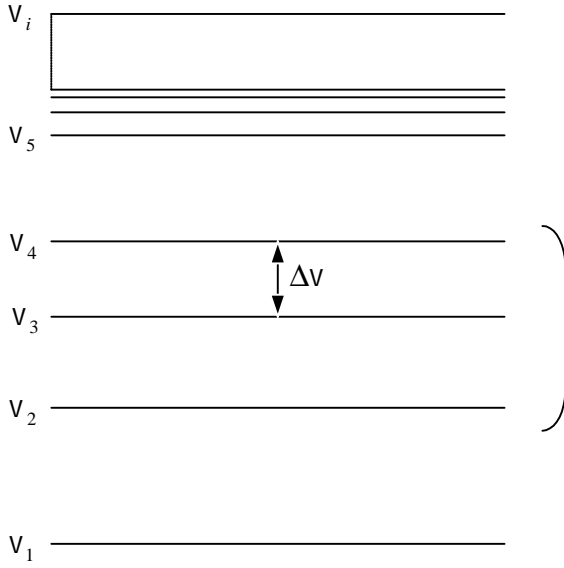
, (Ne) , (He),

(. 4.1).



. 4.1.

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. 4.2.

(,)
 () ϵ_3
 ϵ_2 ,
 ϵ_2 -
 ϵ_2 ,
 ϵ_3 -
 ϵ_2 « » ϵ_3

	-
,	-
.	-

(,) -
 , -
 Ne -
 (.)
).

ϵ_4 ϵ_5 , « » ϵ_2 .
 « » , ,

ϵ_2 , .
 ϵ_3 (.). $\Delta\epsilon$

$\epsilon_i = 5 - 15$, $\Delta\epsilon \sim 0,1 - 1,0$.
 $\Delta\epsilon$ λ 25 1 ,
 .. , -
 , -
) - 120 (. -

$\epsilon_i = 15 - 25$, $\Delta\epsilon \sim 2 - 5$. ,

: $\epsilon_i = 2 - 3$,
 $\lambda = 10 - 100$, ..

(2000 $\overset{0}{\text{A}}$) (0,4) .

(. . 4.1).

4.2.1.

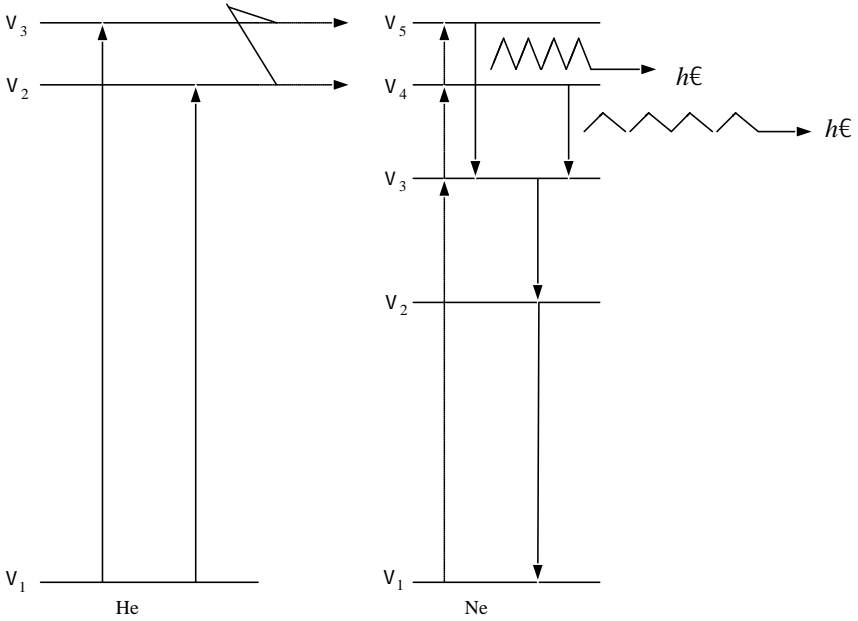
4.3.

4.1

Ne ⁺⁺⁺	0,2358
Ne ⁺⁺	0,3324
N ₂	0,3371
Ar ⁺⁺	0,4880; 0,5145
Kr ⁺⁺⁺	0,5682
Ne	0,6328; 1,1523
Xe	2,061
CO ₂ + N ₂ + He	10,60
H ₂ O	27,90; 118,6

ϵ_2 (. . .).
 Ne
 ϵ_2 ϵ_3
 ϵ_4 ϵ_5 (. 4.3).

ϵ_4 ϵ_5 , ϵ_1 .
 ,
 ϵ_2 ϵ_3 , **Ne** ,
 ϵ_4 ϵ_5 .



. 4.3.

,
Ne , **Ne** . -
 ϵ_4 ϵ_5 ϵ_4
 ϵ_5 **Ne**,
Ne,
 ϵ_4 , ϵ_5 ϵ_3 .

ε_3 -
Ne -
 . -
 . -
 $\varepsilon_4, \varepsilon_5$ $\varepsilon_3,$ -
 , « » , -
 , . -
 ε_2 . -
 2, **Ne** -
 ε_3 2, . . ε_3 -
 , 2. **Ne** -
 $\varepsilon_3,$ -
 . -
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 , $\varepsilon_4, \varepsilon_5$ ε_3 -
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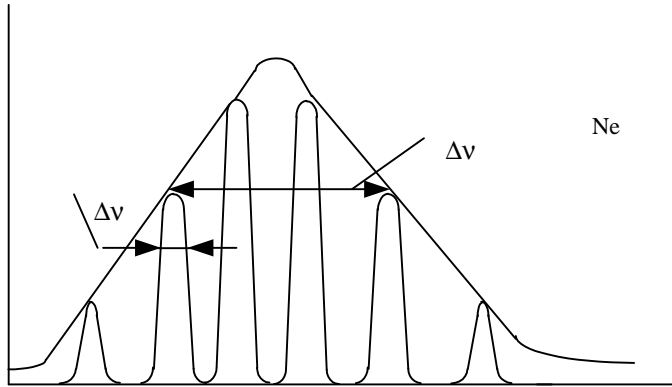
30-40

$$\theta \sim \left(\frac{\lambda}{L}\right)^{1/2}$$

Δv

Ne

(, -), (.
2.3.1), .4.4.



.4.4.

.4.4 , Ne , -
().

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2.3.1).

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(, , -
. .).

(Xe, Kr, Ar, Ne),

4.2.2.

(), (S) (Xe, Kr, Ar, Ne), (Cl).

⁰
A

.4.1).

$\epsilon_3 \quad \epsilon_4$

(.4.5).

ϵ_3

$\epsilon_1,$

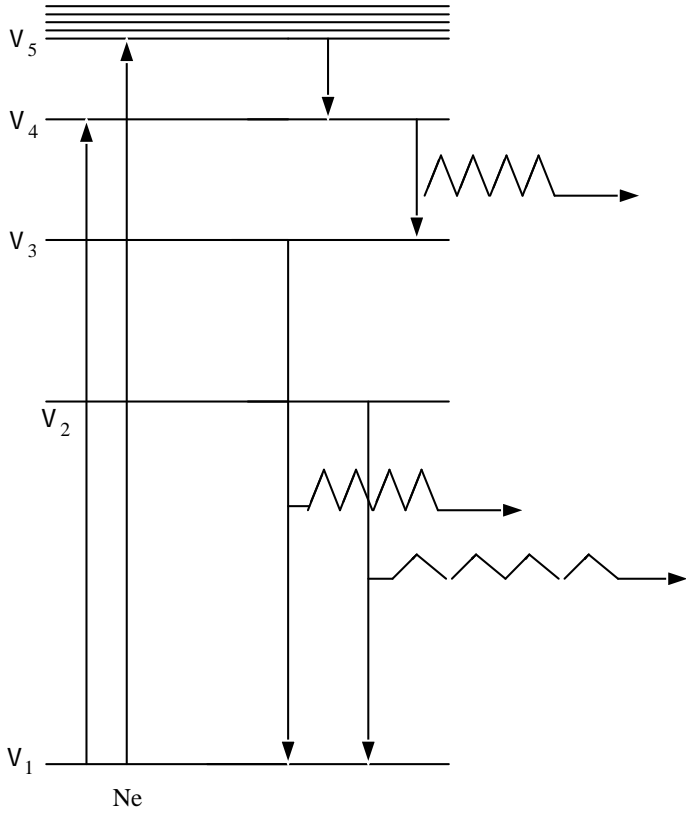
ϵ_4

$\epsilon_4.$

ϵ_5

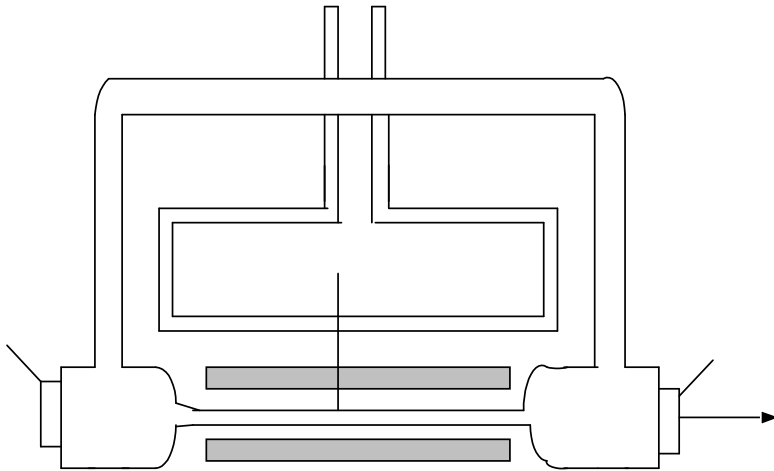
$\frac{A}{2}.$

(~5)



. 4.5.

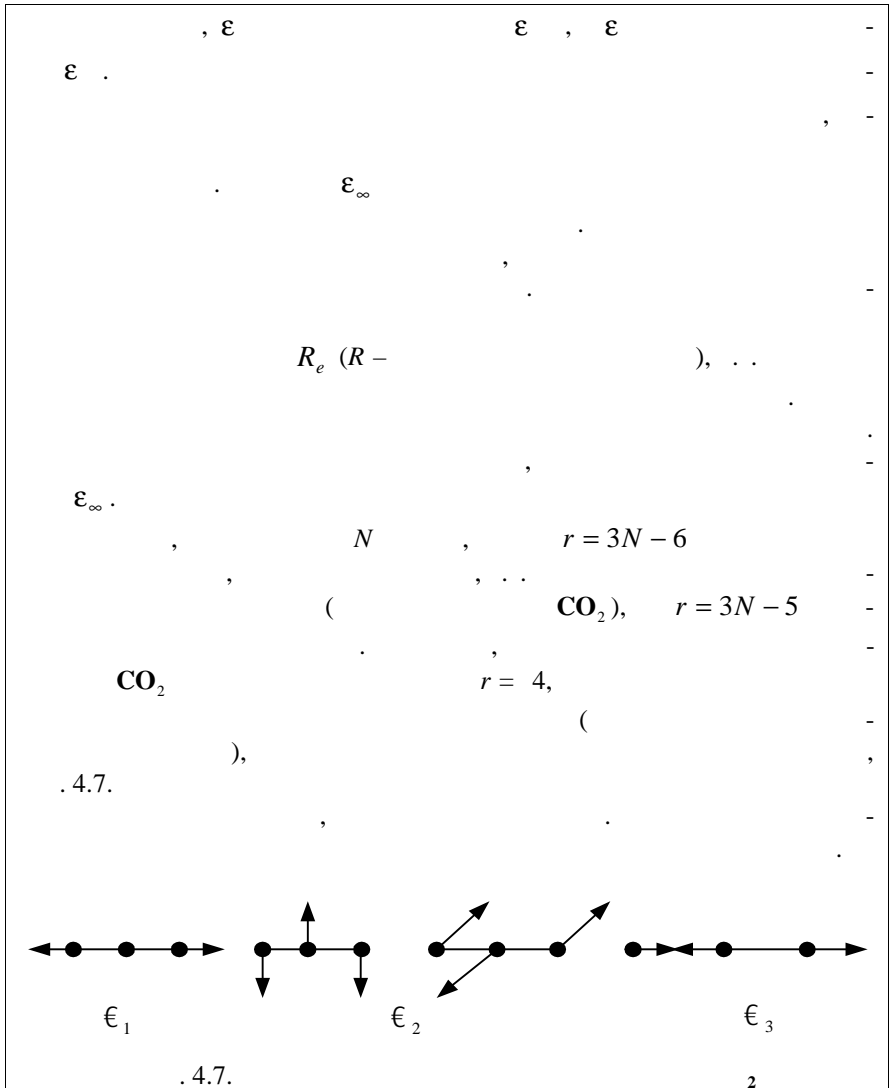
, . 4.6.



.4.6.

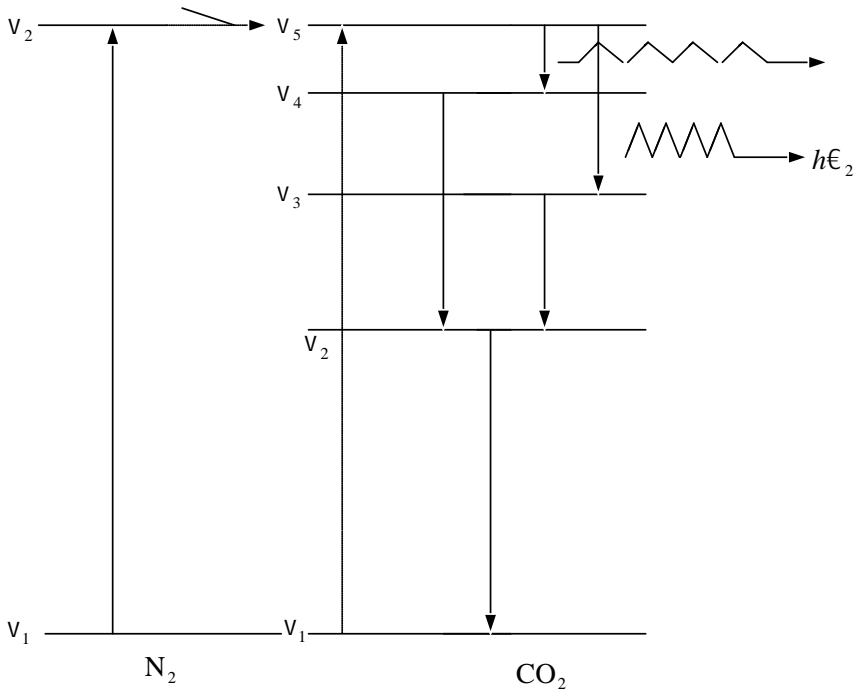
4.2.3.

()
 ()
 : $\varepsilon = \varepsilon + \varepsilon + \varepsilon$



CO_2 ,

.4.8.



. 4.8.

CO_2

ϵ_5

ϵ_3, ϵ_4 ϵ_5

ϵ_3, ϵ_4 ϵ_5

CO_2

N_2

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-

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CO_2 N_2 .
 CO_2 N_2 (. 4.8).
 CO_2 $\epsilon_2 - \text{N}_2$,
 CO_2 ϵ_2 ,
 CO_2 ϵ_5 CO_2 ϵ_2 ,
 CO_2 N_2 ,
 CO_2 CO_2 ϵ_5 .
 CO_2 CO_2 ϵ_5 ϵ_5 ,
 CO_2 ,
 CO_2 ,
 CO_2 ϵ_4 ϵ_5 ,
 ϵ_5 (30).

(. 2.3, . 2.8 2.9).
 CO_2 (10⁻³),

(, ,),
 ϵ_1 ,

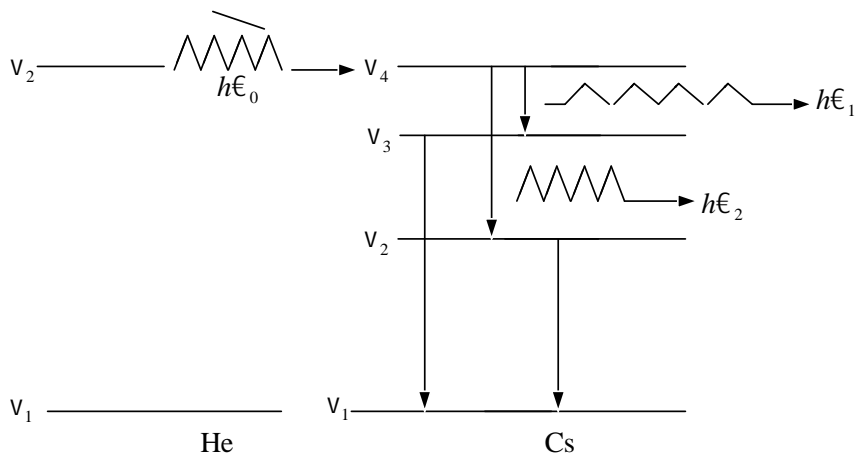
4.3.

(Cs).
 ϵ_4
 ϵ_2 , . 4.9.

($\lambda = 3888 \text{ \AA}$)
 ϵ_4 ϵ_1

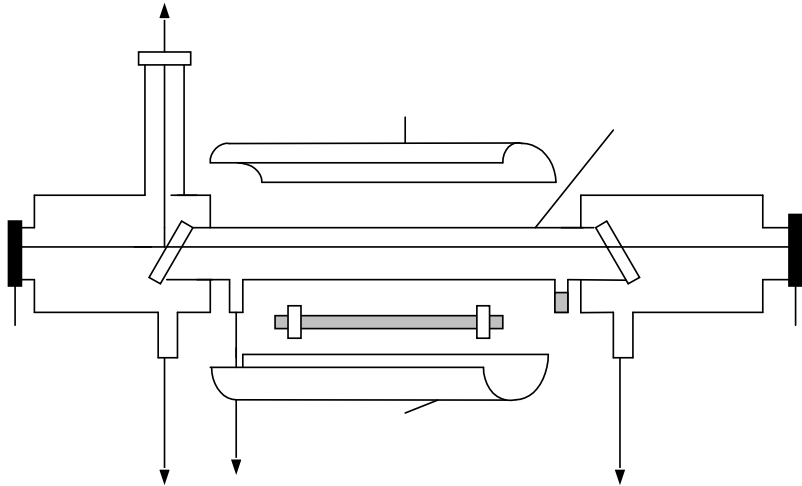
ϵ_4 800

ϵ_4 ϵ_3 ($\lambda = 7,18$).
 « » (. 4.10)
 1,5 ,



. 4.9.

4.4.



. 4.10.

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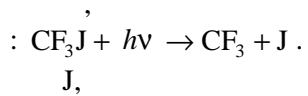
() .

CF_3J .

CF_3J

50

CF_3J



« »

5.

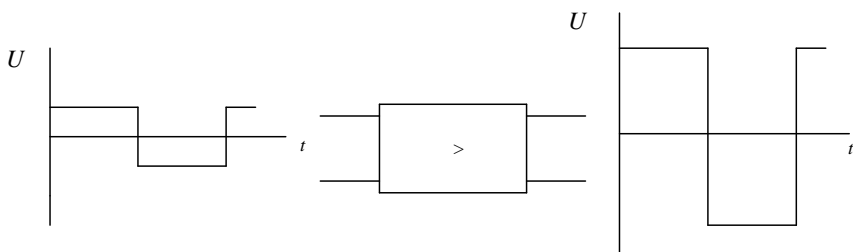
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5.1.

. 5.1.

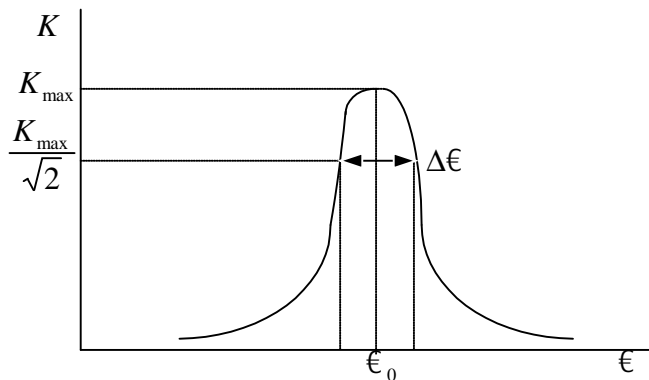
K ,

$$\lambda = \frac{c}{\nu}.$$



. 5.1.

K_{\max}^2 (. 2.1.), . 5.2.



. 5.2.

$\Delta v -$

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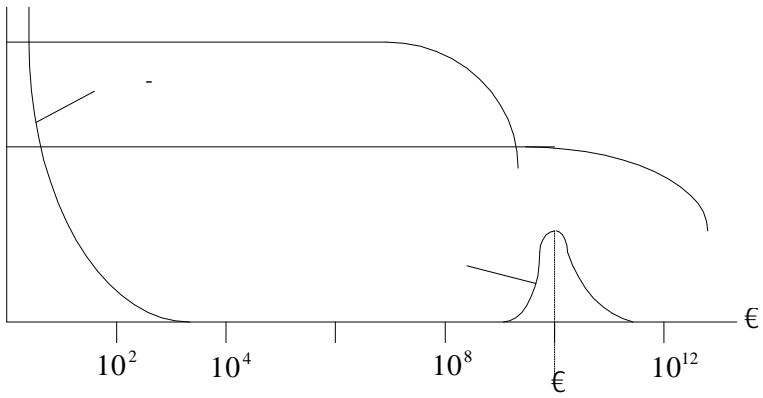
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 10⁷ , .5.3.



. 5.3.

« »

$I \sim \frac{\nu^2}{\exp\left[\frac{h\nu}{kT}\right] - 1}$

(- microwave amplification by stimulated emission of radiation).

(.) -

()

$= 3000 - 1000 \text{ ;}$	-
$= 2 - 4 \text{ .}$	$= 50 - 150$
$- 10 - 50 \text{ ;}$	

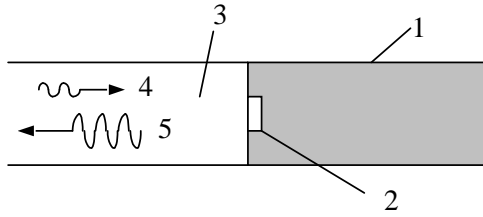
() .

$$h\nu = \varepsilon_2 - \varepsilon_1, \quad \nu -$$

$\varepsilon_1 \quad V_2$,

(.) .

.5.4.



. 5.4.

1 – ; 2 – ; 3 – ;

4 – ; 5 –

(. 1.3),

.

« ».

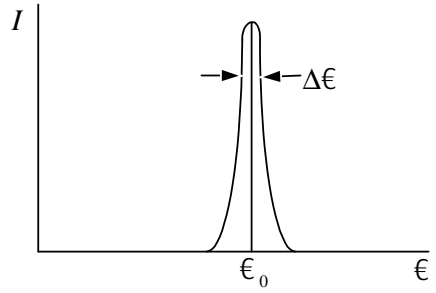
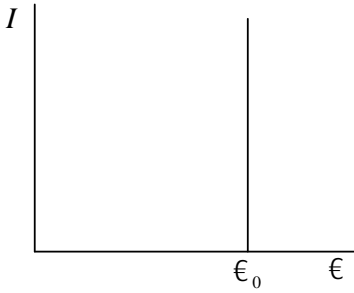
() ().

(. 5.3,).

Δv .

, , Δv .

, . 5.5.



. 5.5.

5.2.

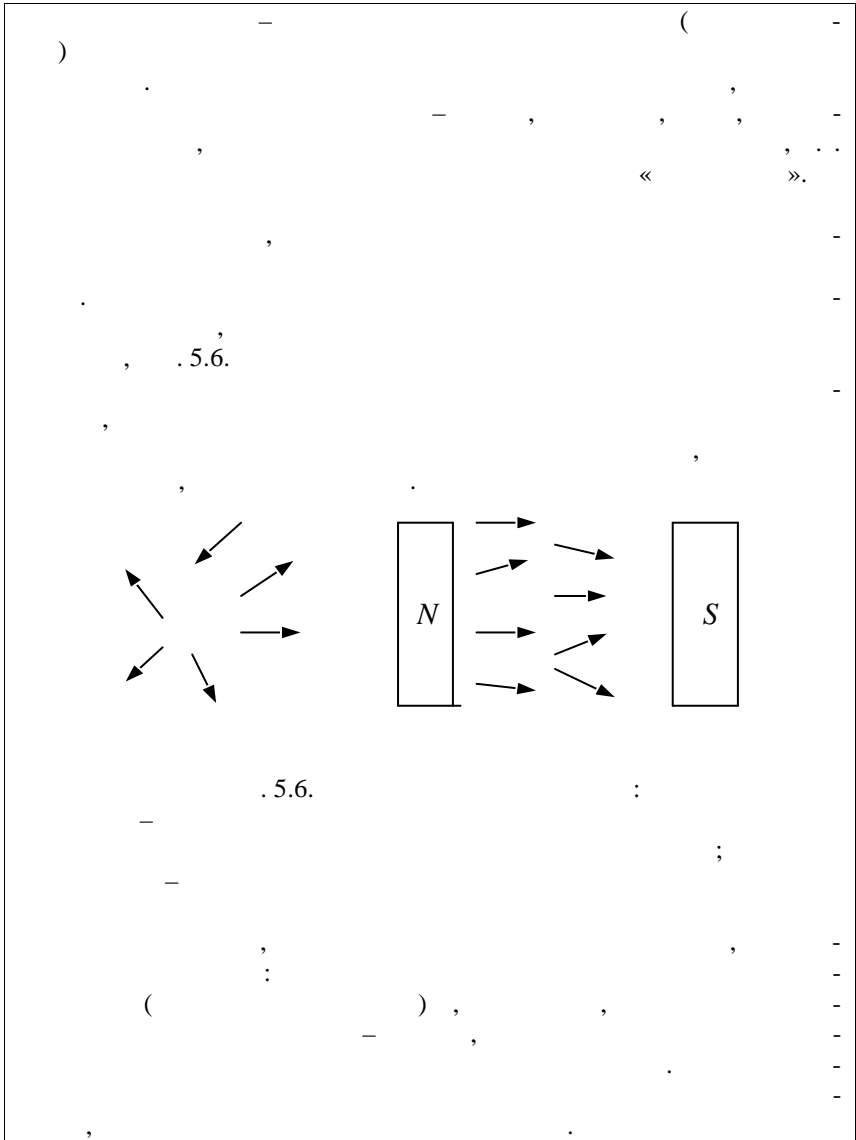
m

$$\frac{eh}{2mc}$$

$$\frac{h}{2}$$

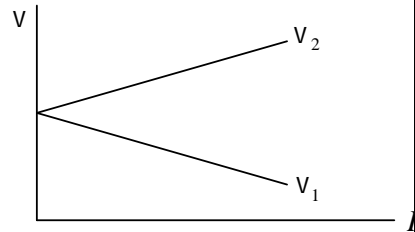
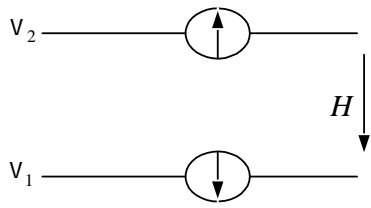
» (, NaCl), (H₂).

(, Fe).



« \vec{H} »
 \vec{H} .
 « \vec{H} », .5.7, .
 ϵ_2
 ϵ_1 , .5.7, .
 (), $\epsilon_2 - \epsilon_1$.

$$v = \frac{\epsilon_2 - \epsilon_1}{h}$$



. 5.7.

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, () .
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 , « » ()
) $\lambda \sim 1$, . . .
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Fe, Co, Ni. **Ti, V, Cr, Mn,**

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$\varepsilon_1, \varepsilon_2$.
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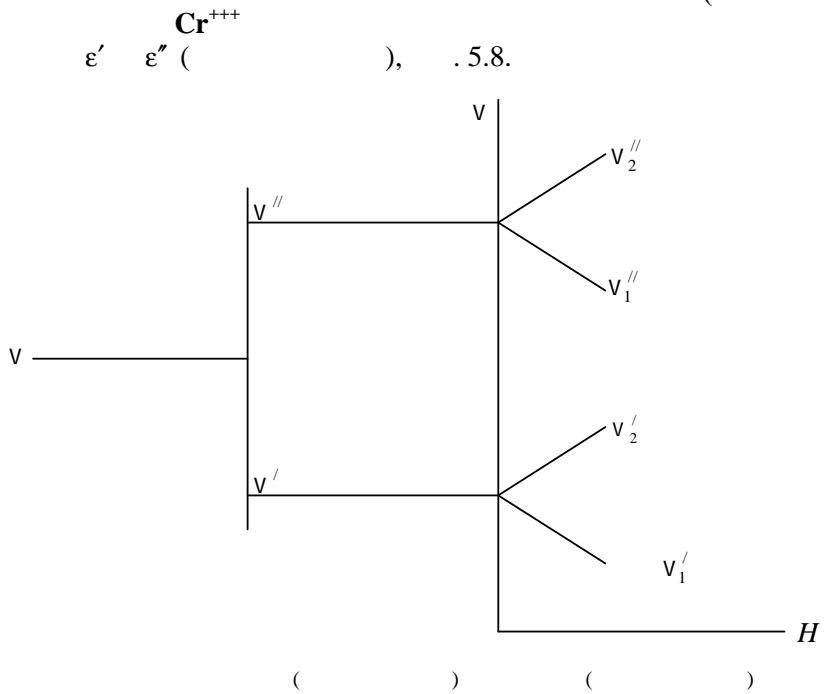
$\varepsilon_1, \varepsilon_2$. . ,
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 V $\varepsilon_2 - \varepsilon_1, \varepsilon_3 - \varepsilon_2$. . ,

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Al_2O_3 ()
 Cr^{+++} ,

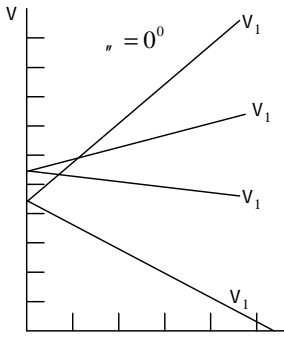


.5.8.

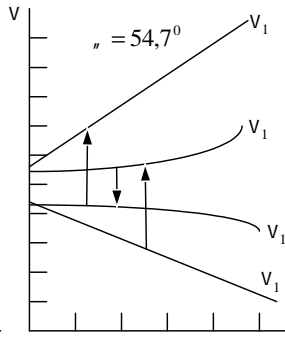
().

.5.9.

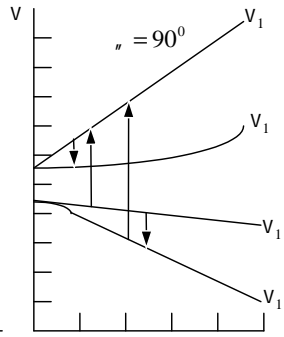
v,



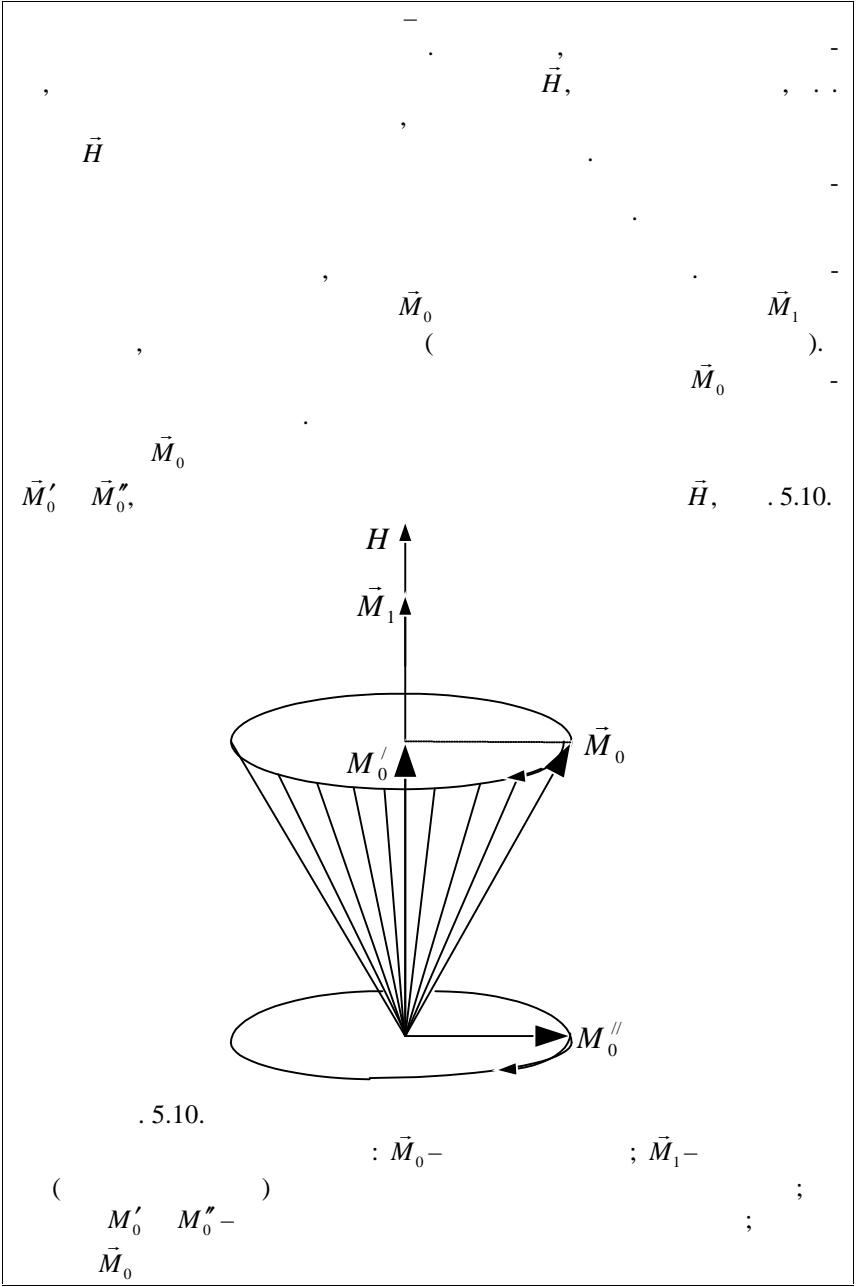
.5.9.



Cr



5.3.



\vec{H} ,

\vec{M}_0 \vec{H} .

M_0''

\vec{H} , $M_0' = \text{const.}$

\vec{M}_0

\vec{H} .

. 5.11.

\vec{M}_0''

\vec{H} .

(\vec{H})

\vec{H} , \vec{H} .

\vec{M}_1 .

\Rightarrow

. 5.11.

M_0'' :

\vec{H} ;

\bar{H}

« » « ».

$$\Delta N = N - N \quad (1.2).$$

« »

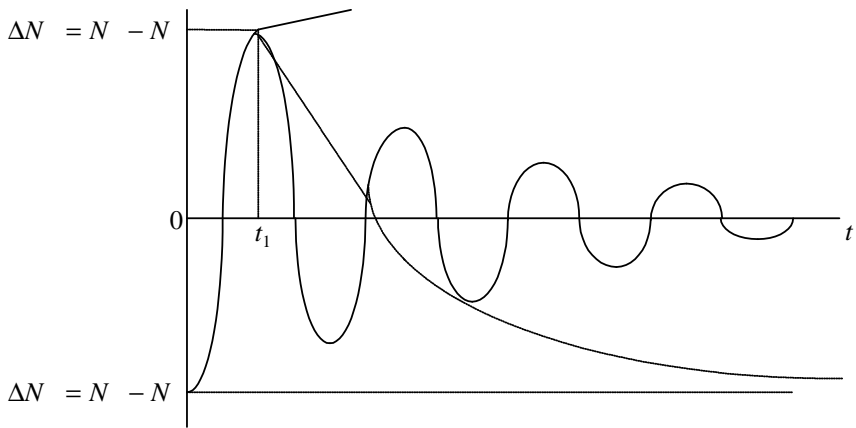
« »

(),

N ,

N

(),



. 5.12.

ΔN

. 5.12

t_1 ,

. 5.13.

. 5.14,

ϵ_1

ϵ_3

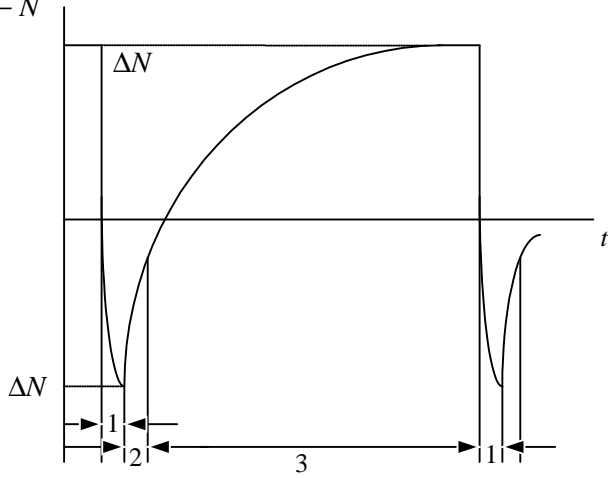
$\epsilon_1 \quad \epsilon_3$

, . . . $N_1 = N_3$.

N_2

($\epsilon_3 \rightarrow \epsilon_2$ $\epsilon_2 \rightarrow \epsilon_1$), . 5.14, .

$\Delta N = N - N$

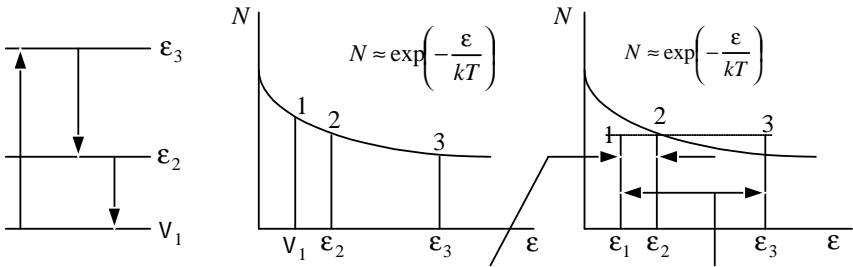


. 5.13.

1 -
3 -

; 2 -

;



. 5.14.

: -

$\epsilon_1 \rightarrow \epsilon_3$;

-

; -

,

$\epsilon_1 \rightarrow \epsilon_2$

ΔN , , ΔN

$\epsilon_1 \rightarrow \epsilon_3$.

ΔN

4,2 - 1,5 , . . .

•

;

•

•

•



. 5.9,

Cr

$$\theta = 54,7^\circ$$

$$\varepsilon_1 \rightarrow \varepsilon_3 \quad \varepsilon_2 \rightarrow \varepsilon_4$$

$$\varepsilon_2 \rightarrow \varepsilon_3, \varepsilon_1 \rightarrow \varepsilon_4, \varepsilon_3 \rightarrow \varepsilon_4 \quad \varepsilon_1 \rightarrow \varepsilon_2$$

$$\varepsilon_2 \rightarrow \varepsilon_3.$$

$$\theta = 54,7^\circ$$

$$3 - 5 \quad > 5$$

$$\theta = 90^\circ \text{ (. 5.9,)}.$$

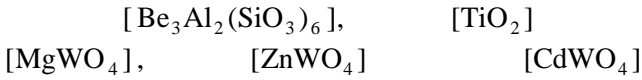
$$\varepsilon_1 \rightarrow \varepsilon_4 \quad \varepsilon_2 \rightarrow \varepsilon_4.$$

$$\varepsilon_4 \rightarrow \varepsilon_3.$$

()

(. 5.9).

< 1



5.4.

5.3.

, ... -

$$E = E_0 \exp(\alpha z),$$

E_0 - , z - -

-1.

Δv . , 100 . , $\frac{10}{= 3}$ () -

3 . -

, - -

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(. 5.6). , ,

[1] , -

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, ... -

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, . 5.15. -

- -

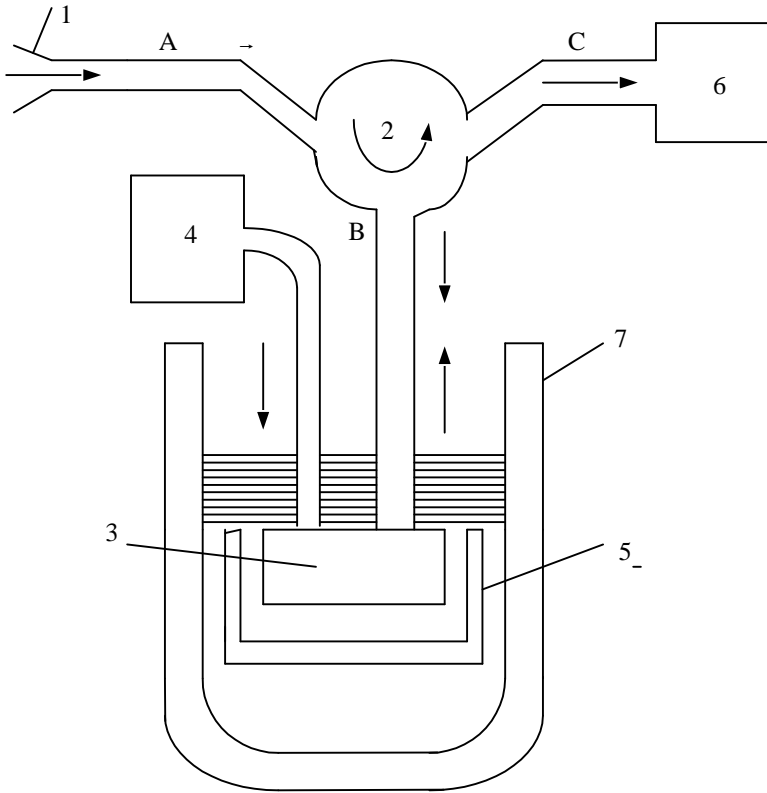
2 () , 1 () . -

, , , -

, , , -

. , , -

, . -



. 5.15.

1 - ; 2 - ; 3 - ;
 4 - ; 5 - ; 6 - ;
 7 - ; A, B, C -

6

5.6).

$$K_0 \Delta v \approx \frac{2\alpha}{\pi} c,$$

$K_0 -$

$v_0 \cdot$

$$\frac{1}{100} \lambda.$$

$K_0 = 10$

Δv

0,2 %

$v_0,$

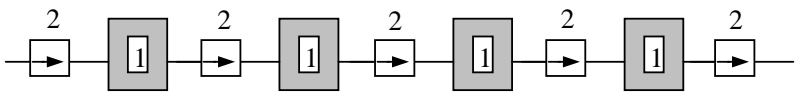
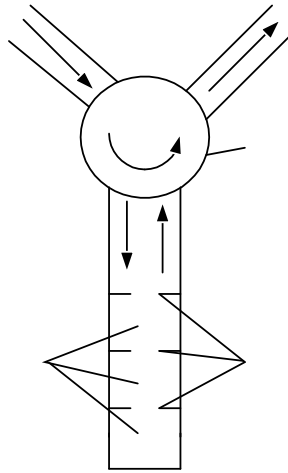
(. 5.16,)

, . 5.16, .

$$K_0 = 100$$

$$\Delta v = 40$$

$$\Delta v = 60$$



. 5.16.

—
—
1 — ; 2 —

:

;

:

Fe₂O₃

(Ni, Co, Mn, Cu),

Fe)

\vec{H}_0

« \vec{H}_0 »

$\vec{H}_0,$ $\vec{M}.$

$\vec{H}_0,$ \vec{M}

$\omega_0,$

$\omega_0 = |\gamma| H_0,$

$\gamma = \frac{e}{mc},$; $m -$; -

$\vec{H}_0,$. .

. 5.17, .

\vec{M}

$\vec{H}_0,$. 5.17, .

$\vec{H}_0,$,

$\vec{H}_0,$. 5.17, .

\vec{H}'

\vec{M}

\vec{H}_0 , \vec{H}' , \vec{H}_0 (

$(\vec{H}'$

$(\mu_+ \mu_-)$

\vec{H}_0 ,

\vec{H}_0

\vec{M}

\vec{M}

α

\vec{H}'

a

. 5.17.

\vec{M}

$\mu_+ \neq \mu_-$

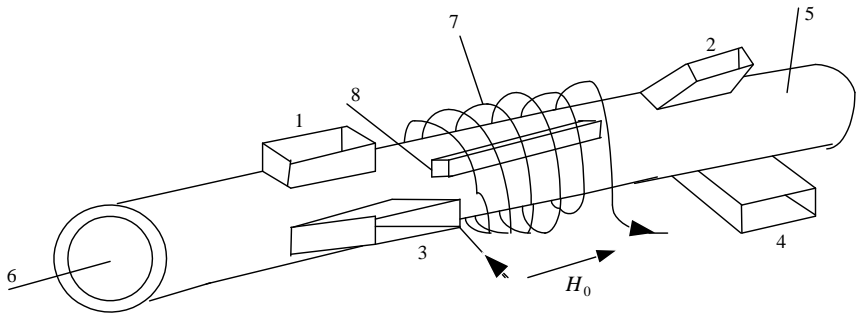
$n = \sqrt{\epsilon_a \mu_a}$

$v = \frac{1}{\sqrt{\epsilon_a \mu_a}}$

μ_a ϵ_a

.....

.....
 . 5.18.
 1 - 4, 45°,
 5, 6,
 7,
 \vec{H}_0 , 8,
 $\theta = 45^\circ$



. 5.18.
 1,
 45°.
 2, 45° 1.
 2,
 5,
 45°, 3,
 45° 2. 3
 1 2, , ...

5.5.

(. 5.1),

« »,

« »,

N_2

α ,

$N_2 - N_1$.

$\frac{N_2}{N_2 - N_1}$.

l ,

$\frac{1}{\alpha}$,

α —

(. 5.4).

$\lambda = 3$, , 0,5 . , -
 1 5 . , -
 , . , , -
 , . , -
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 10 . 100 -
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 , ... -
 . -
 5.3). , , (. , 0,1 . -
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(, 1 1 -
).

(. 5.7). -

70 . -

2 - 10 . -

10 - 20 % -

5.6.

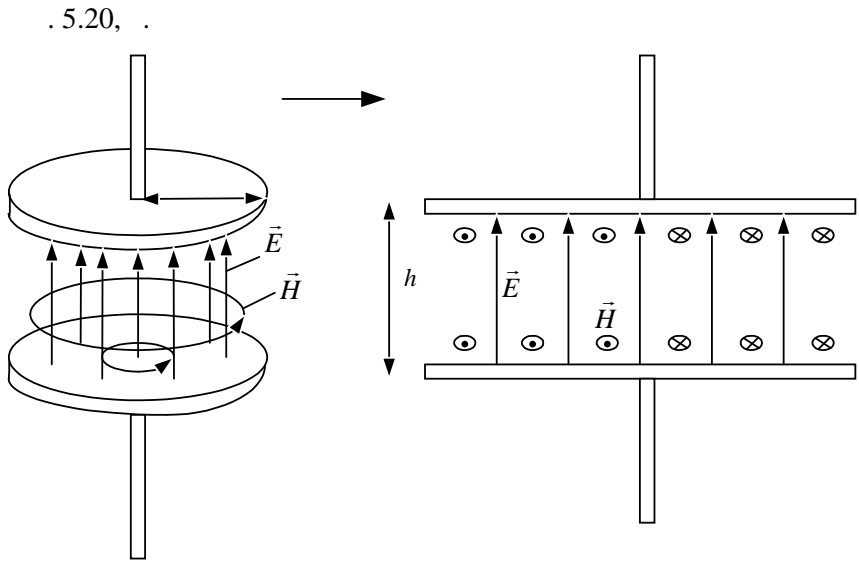
)

(-

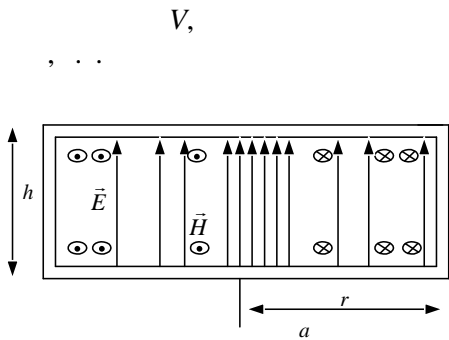
($10^9 - 10^{11}$) -

λ ,

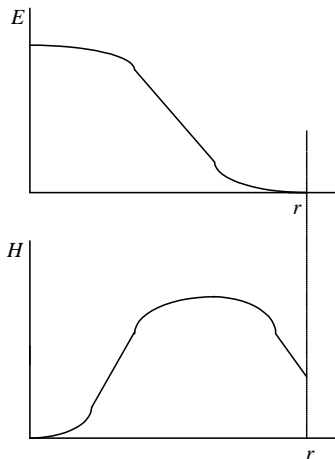
λ ,



(. 5.20,),
 \vec{E}
 90° (. 5.20,).



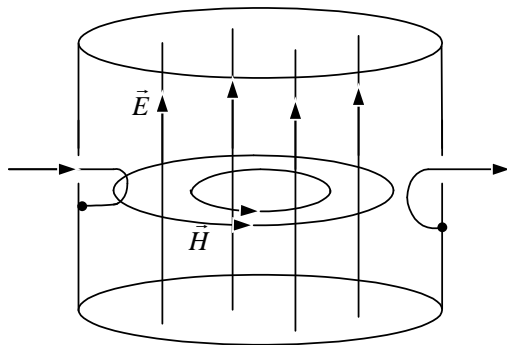
. 5.20.



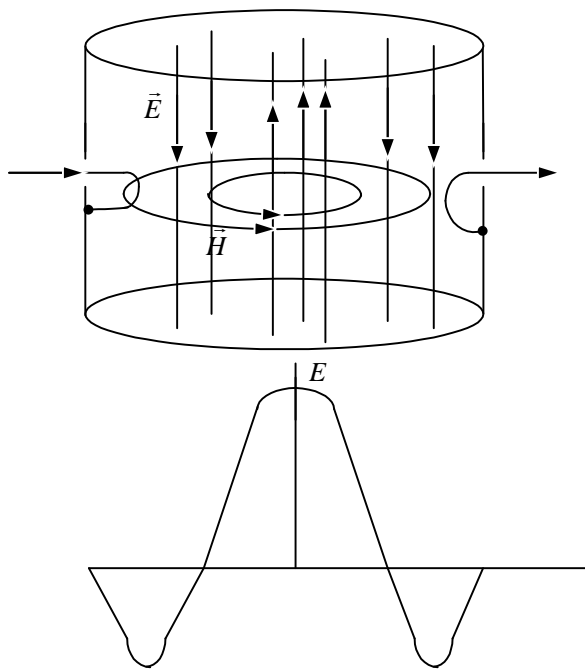
$$\vec{B} = \vec{E} \left(\text{rot} \vec{H} = \frac{\partial \vec{D}}{\partial t} \right) \quad \vec{B} \left(\text{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t} \right),$$

. 5.21.

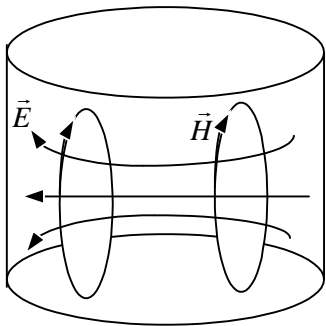
. 5.22.



. 5.21.

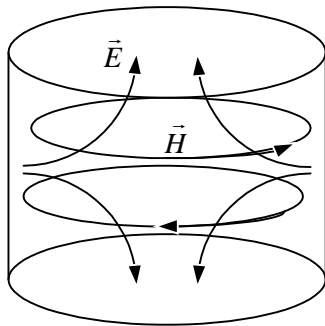


. 5.22.



a

. 5.23.



$$\nabla^2 \vec{E} + \omega_0^2 \epsilon_a \mu_a \vec{E} = 0$$

$$\left[\vec{n}_0 \vec{E} \right]_s = 0,$$

s -
; \vec{n}_0 -

ω_0

$$\omega_0^2 = \frac{1}{\epsilon_a \mu_a} \frac{\int_V |\text{rot} \vec{E}|^2 dV}{\int_V |\vec{E}|^2 dV} = \frac{1}{\epsilon_a \mu_a} \frac{\int_V |\text{rot} \vec{H}|^2 dV}{\int_V |\vec{H}|^2 dV}$$

ω_0, \dots

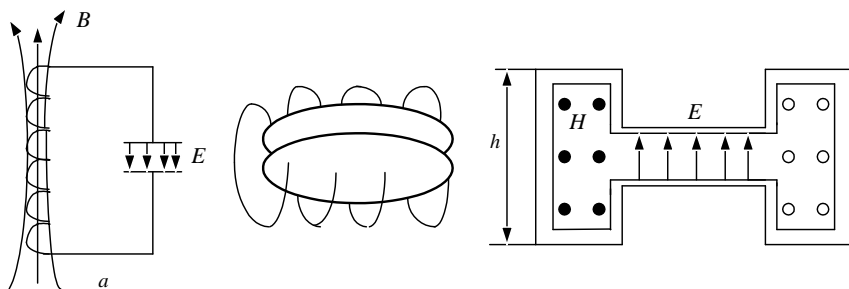
$\omega_{01}, \omega_{02}, \dots$

$\omega_{01},$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

LC (.5.24,)

L,



. 5.24.

5.24, .

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(h).

h

. 5.23.

LC –

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l .

$$l = n \frac{\lambda}{2} \quad (n - \quad),$$

(. 5.25),

$$l \neq n \frac{\lambda}{2},$$

().

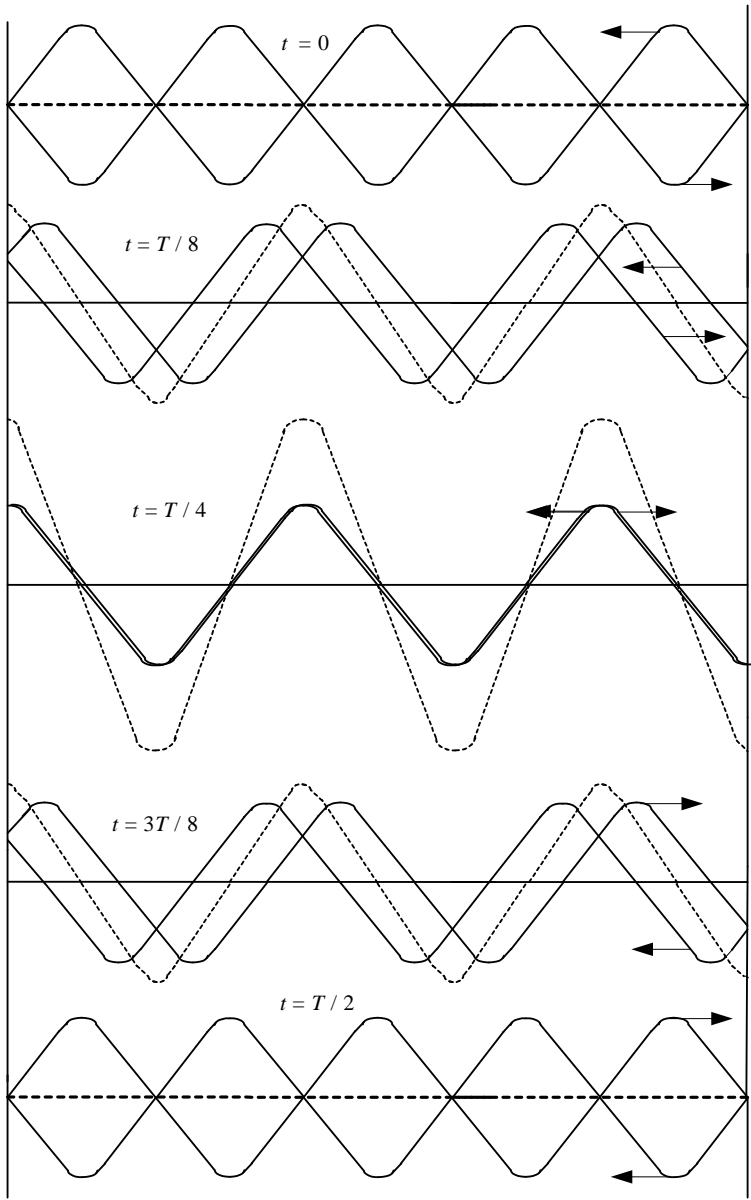
(),

. 5.25

$t = 0$

$$\Delta\phi = \pi, \quad t = \frac{T}{4} \quad \Delta\phi = 0$$

2 .



. 5.25.

→ ←

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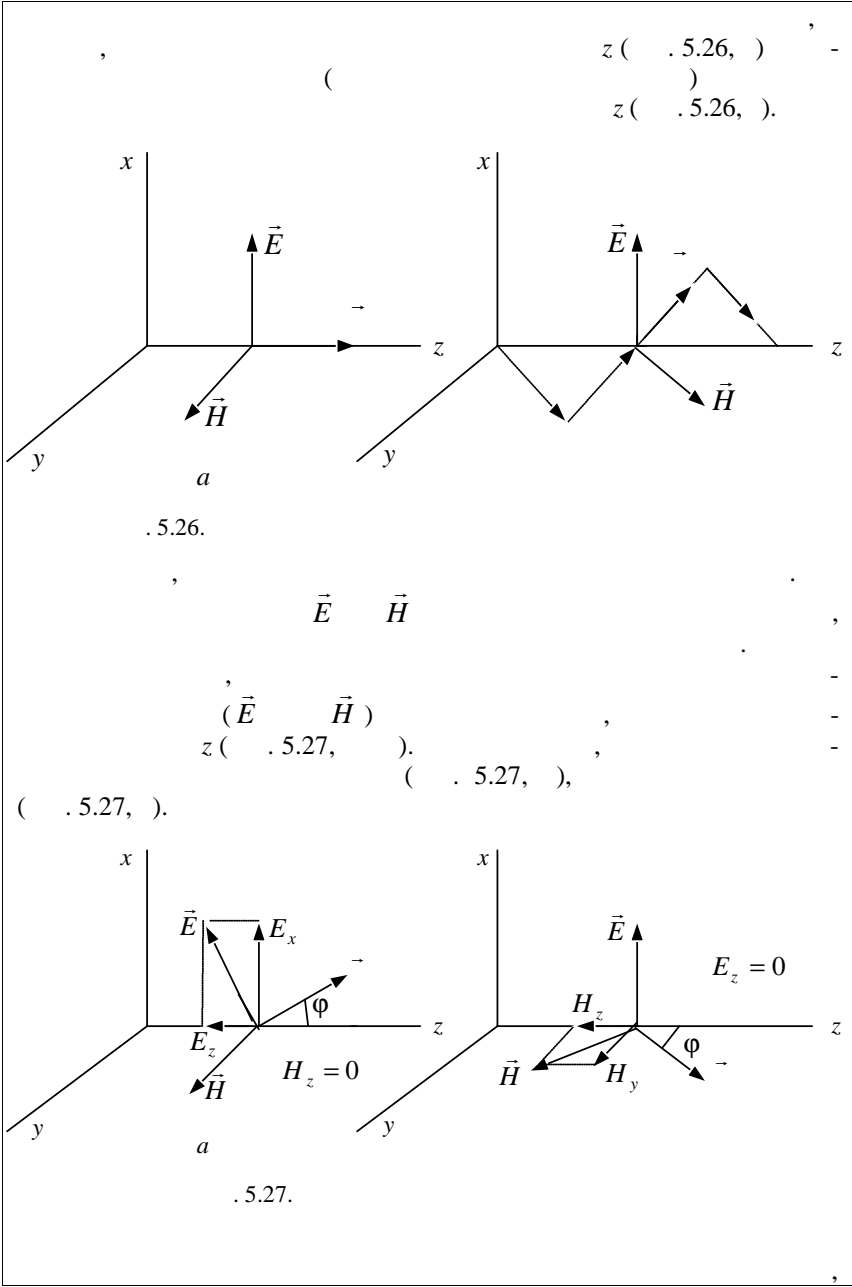
$$\vec{H} = \left(\begin{array}{c} \vec{E} \\ \vec{H} \end{array} \right), \quad \vec{E} = \left(\begin{array}{c} \vec{E} \\ \vec{H} \end{array} \right), \quad \dots$$

(Transverse Electric and Magnetic mode)

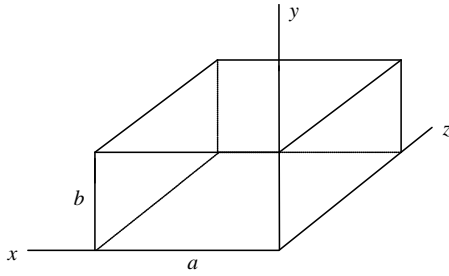
$\vec{E} = \vec{H} = 0$, $E_z = H_z = 0$.

$(H_z = 0, E_z \neq 0)$,

$(E_z = 0, H_z \neq 0)$,



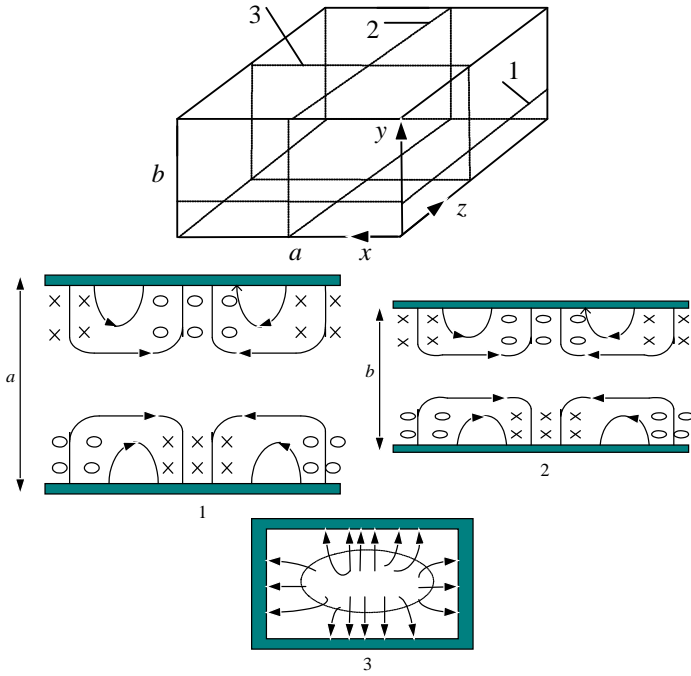
m
 n -
 .5.28.



. 5.28.

m n

E_{11}, E_{21} H_{10} -
 . 5.29 - 5.31



. 5.29.

E_{11}

E_{21}

()

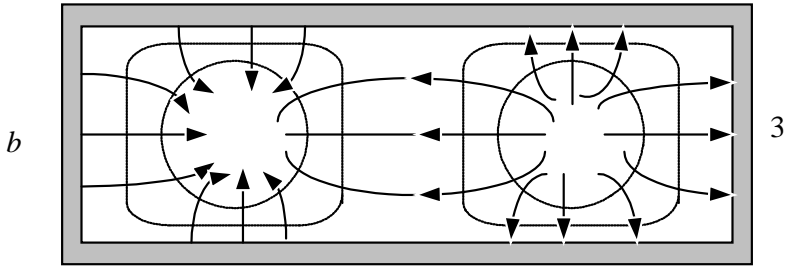
E_{11}

m

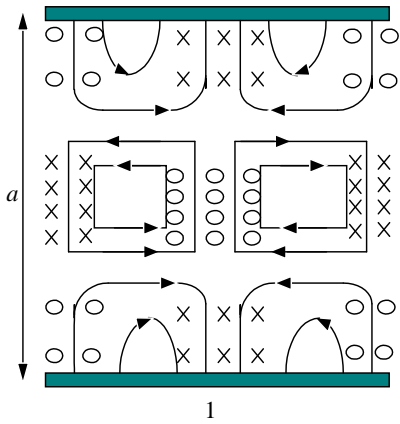
n

. 5.32

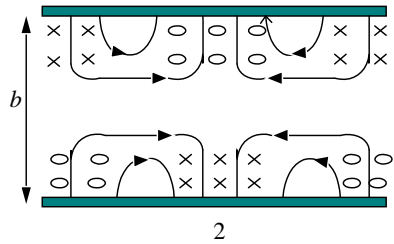
E_{01}



a

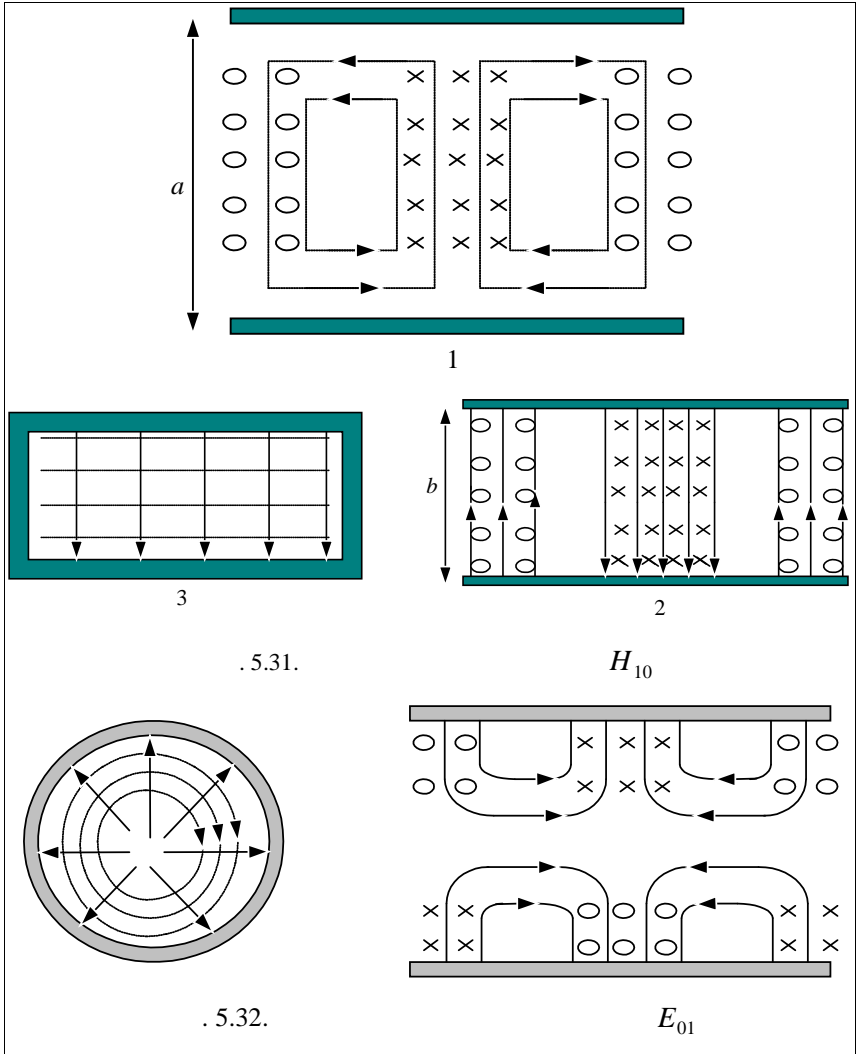


. 5.30.



— E
 — H

E_{21}



\vec{E} ,

(),
 \bar{H} ,
 ().

,
mnp,
 (, E_{mnp} H_{mnp}).

)
 .
 . 5.33 – 5.35

$E_{010}, H_{111}, H_{011}$

, –

,
 (),
 E_{010} H_{111}
 ().

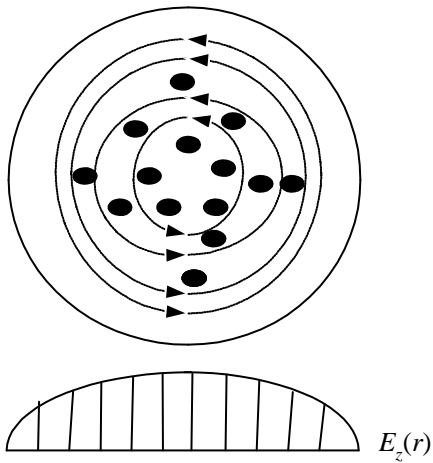
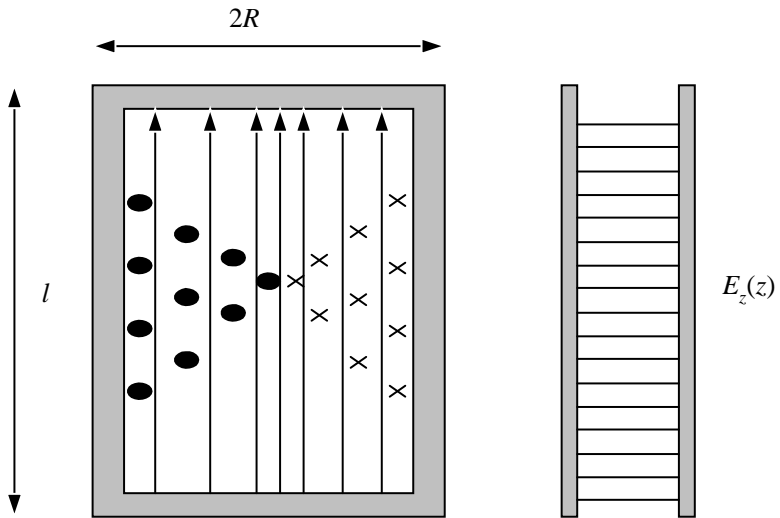
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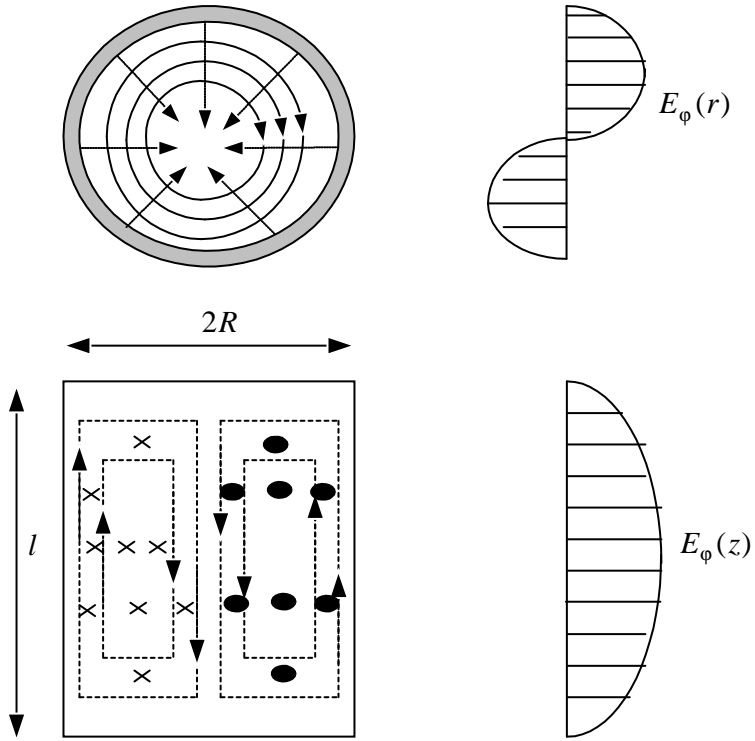
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. 5.33.

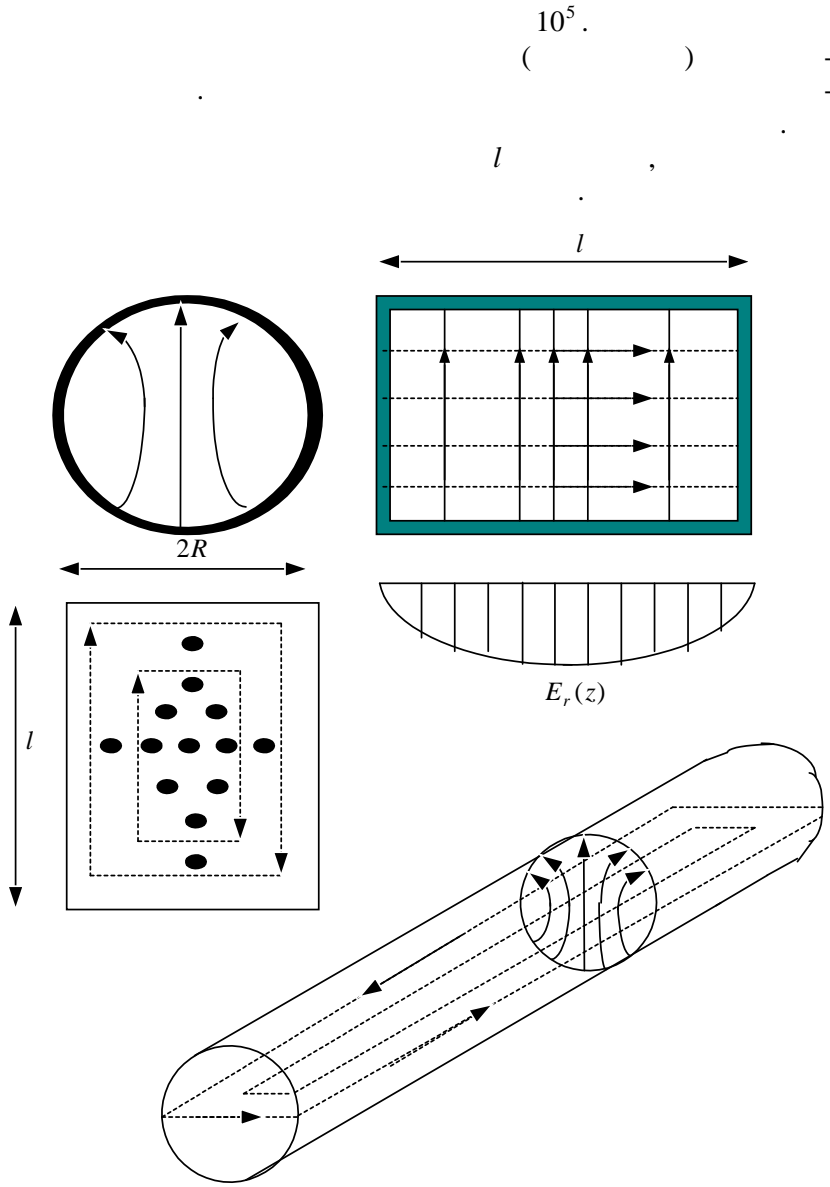
E_{010}



. 5.34.

H_{011}

$10^3 \cdot H_{011}$



. 5.35.

H_{111}

$$H_{mn0} \quad E_{010}, \quad E_{mn0}$$

$$\left(\dots \right) \quad (\dots) \quad \dots$$

5.7.

$$\dots$$

$$\begin{cases} \nabla^2 \vec{E} + \omega^2 \underline{\epsilon}_a \underline{\mu}_a \vec{E} = 0 \\ \nabla^2 \vec{H} + \omega^2 \underline{\epsilon}_a \underline{\mu}_a \vec{H} = 0. \end{cases}$$

$$\vec{E} \quad \vec{H} \quad z \left(e^{\pm j\beta z} \right) \quad (\beta - \dots)$$

$$\begin{aligned} \vec{E} &= \vec{E}(\xi, \eta) e^{\pm j\beta z} = \vec{E}_s e^{\pm j\beta z}, \\ \vec{H} &= \vec{H}(\xi, \eta) e^{\pm j\beta z} = \vec{H}_s e^{\pm j\beta z}, \end{aligned}$$

$$s \quad (\dots) \quad \dots$$

$\xi \quad \eta -$

$$\begin{cases} \nabla^2 \underline{\underline{E}} + (\omega^2 \underline{\underline{\epsilon}}_a \underline{\underline{\mu}}_a - \beta^2) \underline{\underline{E}} = 0 \\ \nabla^2 \underline{\underline{H}} + (\omega^2 \underline{\underline{\epsilon}}_a \underline{\underline{\mu}}_a - \beta^2) \underline{\underline{H}} = 0. \end{cases}$$

k

$$k_{\perp} = \omega^2 \epsilon_a \mu_a - \beta^2,$$

β

$$v = \frac{\omega}{\beta},$$

$$\lambda = \frac{2\pi}{\beta}.$$

β

$$k_{\perp} \leq \omega \sqrt{\epsilon_a \mu_a} = 2\pi f \sqrt{\epsilon_a \mu_a},$$

$$k_{\perp} > 2\pi f \sqrt{\epsilon_a \mu_a}.$$

$$k_{\perp} = 2\pi f \sqrt{\epsilon_a \mu_a}$$

$f :$

$$f = \frac{k_{\perp}}{2\pi \sqrt{\epsilon_a \mu_a}}$$

$$\lambda = \frac{c_0}{f} = \left| c_0 = \frac{1}{\sqrt{\epsilon_a \mu_a}} \right| = \frac{2\pi}{k_{\perp}},$$

$c_0 -$

$\epsilon_a, \mu_a .$

$$k_{\perp} = \sqrt{\omega^2 \epsilon_a \mu_a - \beta^2},$$

$\beta :$

$$\begin{aligned} \beta &= \sqrt{\omega^2 \epsilon_a \mu_a - \left(\frac{2\pi}{\lambda}\right)^2} = \omega \sqrt{\epsilon_a \mu_a} \sqrt{1 - \left(\frac{2\pi}{\lambda \omega \sqrt{\epsilon_a \mu_a}}\right)^2} = \\ &= \left| f = \frac{v}{\lambda} = \frac{1}{\lambda \sqrt{\epsilon_a \mu_a}} \right| = \omega \sqrt{\epsilon_a \mu_a} \sqrt{1 - \left(\frac{\lambda}{\lambda}\right)^2}. \end{aligned}$$

$, \dots f > f \quad \lambda < \lambda .$

Λ

$z,$

$2\pi .$

$$e^{-j\beta z},$$

z

$$\Lambda = \frac{2\pi}{\beta} = \frac{2\pi}{\omega\sqrt{\varepsilon_a\mu_a}\sqrt{1-\left(\frac{\lambda}{\lambda}\right)^2}} = \left| \omega = 2\pi f = \frac{2\pi}{\lambda\sqrt{\varepsilon_a\mu_a}} \right| = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda}\right)^2}}.$$

()

$$(E_z \neq 0, H_z = 0)$$

$$\frac{\partial^2 \underline{E}_z}{\partial x^2} + \frac{\partial^2 \underline{E}_z}{\partial y^2} + k_z^2 \underline{E}_z = 0.$$

$$\underline{E}_z = A(x)B(y)e^{-j\beta z},$$

() -

$$; B(y) -$$

$$A(x) = C_1 \cos k_x x + C_2 \sin k_x x,$$

$$B(y) = C_3 \cos k_y y + C_4 \sin k_y y,$$

$$k_x^2 + k_y^2 = k_z^2.$$

() ()

$$\underline{E}_z = E_{0z} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} e^{-j\beta z},$$

$$; E_{0z} = C_2 C_4 -$$

$$; k_x = \frac{m\pi}{a}, k_y = \frac{n\pi}{b}, m, n -$$

$$k_{\perp} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}.$$

$$\lambda = \frac{2\pi}{k_{\perp}} = \frac{2\pi}{\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}}.$$

E_{mn} ,

E_{11} .

$$(H_z \neq 0, E_z = 0)$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + k_{\perp}^2 H_z = 0,$$

$$k_x = \frac{m\pi}{a}, \quad k_y = \frac{n\pi}{b},$$

(r, φ, z) ,

$$(E_z \neq 0, H_z = 0)$$

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r} \frac{\partial E_z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 E_z}{\partial \varphi^2} + k_{\perp}^2 E_z = 0.$$

k_{\perp} ,

$$k_{\rightarrow} = \frac{v_{m,n}^E}{a},$$

n — m ; v_{mn}^E —

$$k_{\rightarrow} = \frac{v_{m,n}^H}{a},$$

H_{mn} E_{mn} E_{mnp}
 H_{mnp} .

$$l = p \frac{\Lambda}{2},$$

$$l \quad z = 0,$$

Λ :

$$l = \frac{p}{2} \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\Lambda}\right)^2}}.$$

λ

:

$$\lambda_{0p}^2 [4l^2 + p^2 \lambda^2] = 4l^2 \lambda^2,$$

$$\lambda_{0p}^2 = \frac{4l^2 \lambda^2}{4l^2 + p^2 \lambda^2} = \frac{4l^2 \lambda^2}{4l^2 \lambda^2 \left[\frac{1}{\lambda^2} + \frac{p^2}{4l^2} \right]} = \frac{1}{\frac{1}{\lambda^2} + \frac{p^2}{4l^2}},$$

$$\lambda_{0p} = \frac{1}{\sqrt{\lambda^2 + \frac{p^2}{4l^2}}}.$$

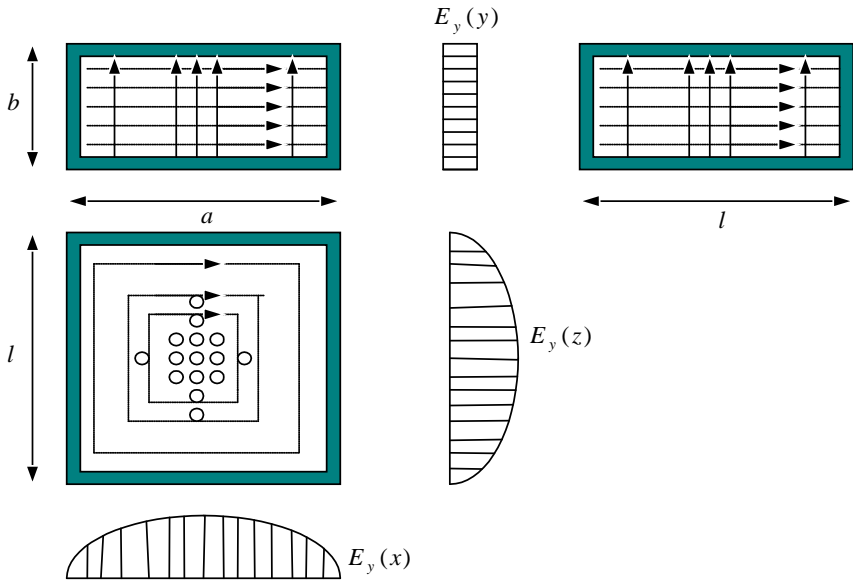
$$\lambda_{0p} \begin{matrix} E_{mnp} & H_{mnp} \end{matrix}$$

$$\lambda = \frac{2\pi}{\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}}.$$

$$\lambda_{0p} = \frac{1}{\sqrt{\left(\frac{p}{2l}\right)^2 + \frac{\pi^2 \left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 \right]}{4\pi^2}}} = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{l}\right)^2}}.$$

$$\begin{matrix} E_{mnp} & m, & E_{01} & E_{10} \\ & & H_{mnp} & m \\ n & & & \\ & E_{mnp} & & H_{mnp} \end{matrix} \left(\begin{matrix} \lambda_{0p} \\ m, n \end{matrix} \right).$$

$H_{101},$
 $H_{10} \text{ (. 5.36).}$



. 5.36.

H_{101}
()

$$\lambda_{0p} = \frac{1}{\sqrt{\lambda^2 + \frac{p^2}{4l^2}}}$$

$$\lambda = \frac{2\pi}{k_{\perp}} = \left| k_{\perp} = \frac{v_{m,n}^E}{R} \right| = \frac{2\pi R}{v_{m,n}^E}$$

E_{mnp} ($p \geq 0$),

$$\lambda = \frac{2\pi R}{v_{m,n}^H}$$

$$H_{mp} \quad (p \geq 1), \quad R - \quad , \quad v_{m,n}^{E,H} -$$

$$\lambda \quad , \quad \vdots$$

$$\lambda_{0p}^E = \frac{1}{\sqrt{\frac{1}{4}\left(\frac{p}{l}\right)^2 + \frac{1}{4}\left(\frac{v_{m,n}^E}{\pi R}\right)^2}} = \frac{2}{\sqrt{\left(\frac{p}{l}\right)^2 + \left(\frac{v_{m,n}^E}{\pi R}\right)^2}},$$

$$\lambda_{0p}^H = \frac{2}{\sqrt{\left(\frac{p}{l}\right)^2 + \left(\frac{v_{m,n}^H}{\pi R}\right)^2}}.$$

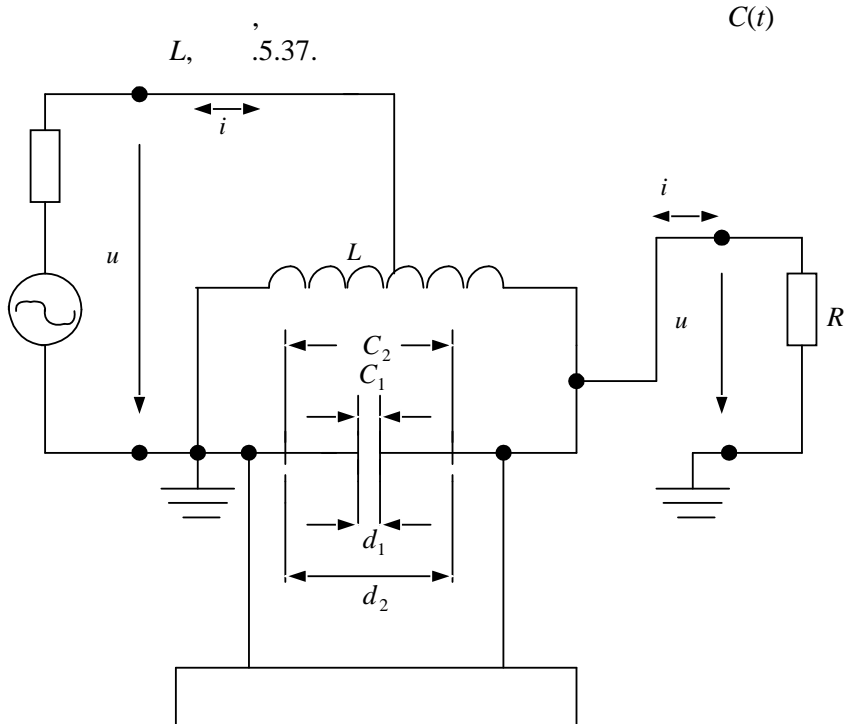
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10⁷ - 10⁹.
-
-

(= 4, 2).

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-
10³ - 10⁶.
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5.8.

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(, -
) -
,



$$u_c = \frac{q}{C}.$$

q

u_c

$$C = \frac{\epsilon_a S}{d},$$

$$u_c = \frac{q}{\epsilon_a S} d.$$

$$\begin{aligned}
 & \text{,} \quad q \quad - \\
 & \text{.} \quad d, \quad u_c \quad - \\
 & \text{.} \quad \text{,} \quad - \\
 & \text{.} \quad d \quad - \\
 & \text{.} \quad - \\
 & \text{.} \quad u_c \quad - \\
 & \text{.} \quad - \\
 & p - n \quad - \\
 & \quad \quad \quad (\quad \quad \quad). \quad -
 \end{aligned}$$

$$u = U \sin \omega_0 t, \quad q = uC = UC \sin \omega_0 t$$

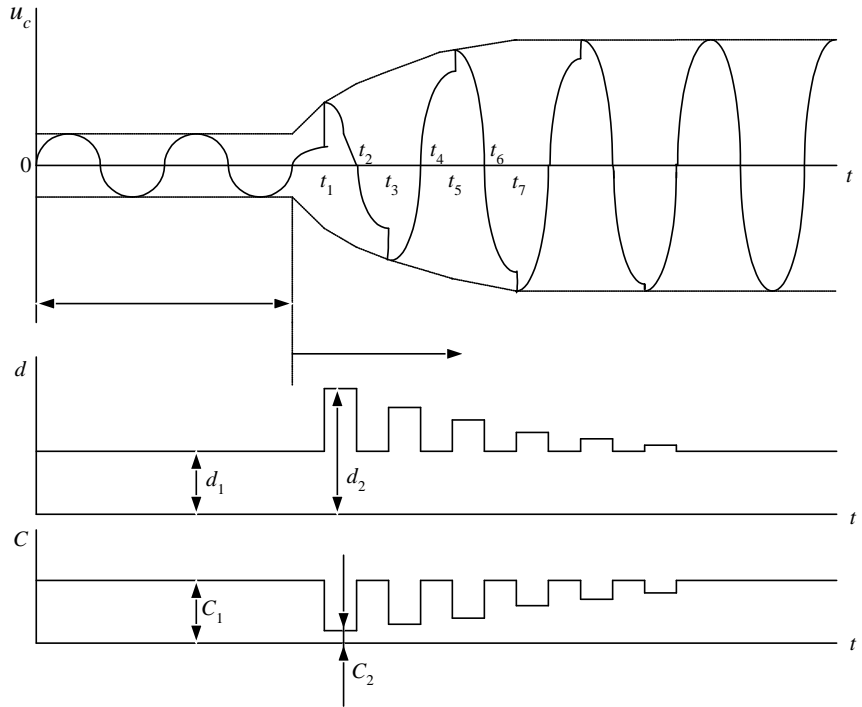
$$W = \frac{1}{2} C_1 U^2 = \frac{1}{2} \frac{C_1^2 U^2}{C_1} = \frac{q^2}{2C_1}.$$

$$\begin{aligned}
 & \text{,} \quad q, \quad \text{,} \quad \text{,} \\
 & \quad \quad \quad \text{,} \quad \quad \quad - \\
 & \quad \quad \quad \text{.} \quad \quad \quad \text{,} \\
 & \quad \quad \quad \text{.} \quad \quad \quad \text{.} \\
 & \text{,} \quad \quad \quad \text{.} \quad \quad \quad \text{.} \\
 & \quad \quad \quad d_1 \quad \quad \quad \text{.} \\
 & \quad \quad \quad (\quad \quad \quad , \quad \quad \quad). \quad \text{.}
 \end{aligned}$$

$$\begin{aligned}
 & \text{,} \quad \text{,} \\
 & \text{,} \quad \text{.} \quad \text{,} \\
 & \quad \quad \quad d \quad \text{,} \quad \text{.}
 \end{aligned}$$

$t_1, t_3, t_5 \dots$

(, . 5.38.



. 5.38.

, , t_1 d_2 .

, u_C .
 u_C -
 $L($
 $t_2, t_4, t_6 \dots$. .),
 d_1 .
 , , , -
 .

$$t_1 = \frac{T}{4} \quad (5.38),$$

$$d_1 \quad d_2,$$

$$C = \frac{\epsilon_0 \epsilon S}{d}$$

$$C_1 \quad C_2.$$

$$\Delta w = \frac{q^2}{2} \left[\frac{1}{C_2} - \frac{1}{C_1} \right] = \frac{q^2}{2} \frac{C_1 - C_2}{C_1 C_2} = \frac{q^2}{2C_1} \frac{C_1 - C_2}{C_2} = mW,$$

$$m = \frac{C_1 - C_2}{C_2}, \quad W =$$

$$\frac{T}{4}$$

$$t_2,$$

$$),$$

$$\frac{T}{4}$$

$$2\omega_0 \left(\frac{T}{2} \right),$$

$$U$$

$$u_C$$

W , -

Q , -

$$Q = \frac{P}{P}$$

P_p - , P -

$$P_{pL} = P_{pC} = \frac{I_m^2 x_L}{2} = \frac{I_m^2 x_C}{2} = P_p$$

$$W_{\max} = \frac{LI_m^2}{2} = \frac{CU_{mC}^2}{2}$$

$$I_m^2 = \frac{2W_{\max}}{L}$$

$$P_p = \frac{I_m^2 x_L}{2} = \frac{2W_{\max}}{L} \cdot \frac{\omega L}{2} = \omega W_{\max}$$

$$Q = \frac{P_p}{P} = \frac{\omega W_{\max}}{P} = \left| \omega = 2\pi f = \frac{2\pi}{T} \right| = \frac{2\pi W_{\max}}{P T} = 2\pi \frac{W_{\max}}{W}$$

W - , :

$$W = 2\pi \frac{W_{\max}}{Q}$$

() , -

ω_0

.
, ...
:

$$\Delta W - W = 2mW - 2\pi \frac{W}{Q} = 2 \left(m - \frac{\pi}{Q} \right) W,$$

$$\left(m - \frac{\pi}{Q} \right).$$

U

$$U \propto \exp \left(m - \frac{\pi}{Q} \right) \frac{t}{T}.$$

$$m > \frac{\pi}{Q}$$

$$m = \frac{\pi}{Q} \quad \frac{mQ}{\pi} = 1.$$

Q ,

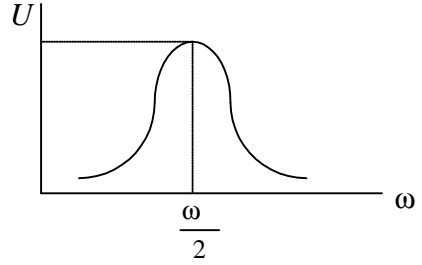
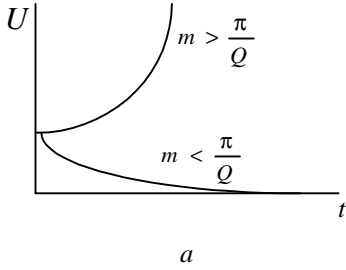
$$m < \frac{\pi}{Q},$$

(.5.39,)

U

(.5.39,), Q ,
 Q ,

$$Q = \frac{Q}{1 - \frac{mQ}{\pi}}.$$



. 5.39.
-

; -

$$K = \frac{Q}{Q} = \frac{1}{1 - \frac{mQ}{\pi}}$$

$$m > \frac{\pi}{Q}$$

$\frac{3}{2}$, , $\frac{3}{2}$, 2, . . .

$$\frac{\omega_0}{\omega} = \frac{N}{2}, \quad N = 1, 2, 3, \dots$$

$N \geq 2$

, , ,

$$\omega = 2\omega_0 .$$
$$\bar{\omega} = 2\bar{\omega}_0 .$$

•

;

•

. 5.37

(5.7).

. 5.40.

1.

$p-n-$

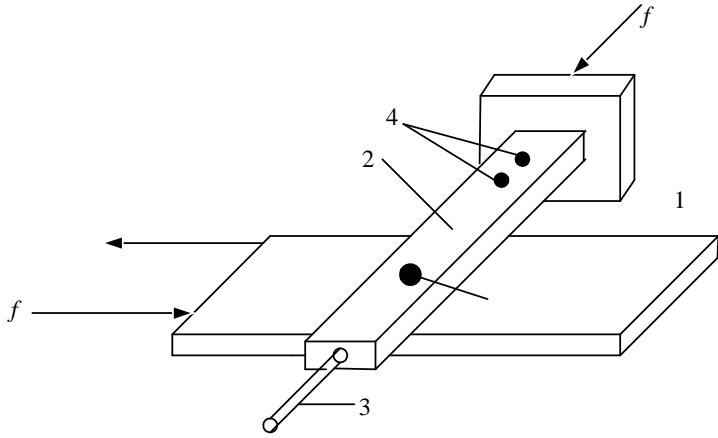
$(p-n-)$

2.

3

4

2.



1 - ; 2 - ; 3 - ; 4 -

($T \approx 80 K$),

$$\omega = 2\omega_0$$

$$\omega_0$$

$$\omega_1$$

$C(t)$

ω

$$: \omega + \omega_1 \quad \omega - \omega_1 .$$

$$\omega_2 = \omega - \omega_1 , \quad -$$

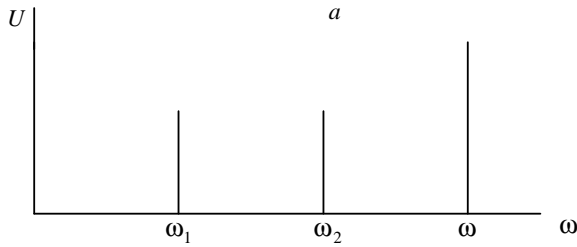
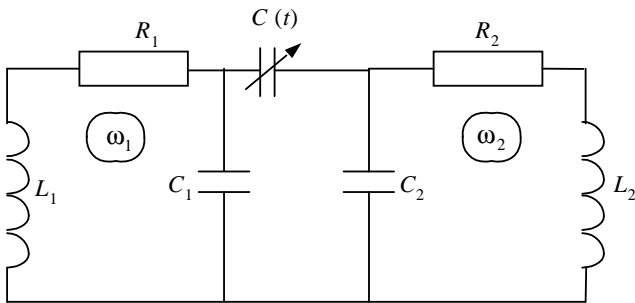
$$\omega_1 \quad \omega_2 , \quad -$$

$$\omega = \omega_1 + \omega_2 , .$$

$$\omega_1 \quad \omega_2$$

$$\omega , \quad . 5.40, \quad . \quad -$$

$$m > \frac{\pi}{\sqrt{Q_1 Q_2}} .$$



. 5.41.

, ...

$$m \leq \frac{\pi}{\sqrt{Q_1 Q_2}} .$$

ω_2

$$C = \frac{\epsilon\epsilon_0 S}{d}$$

d

ϵ

$p-n$

90

(InSb).

90

100 – 1000

T

L

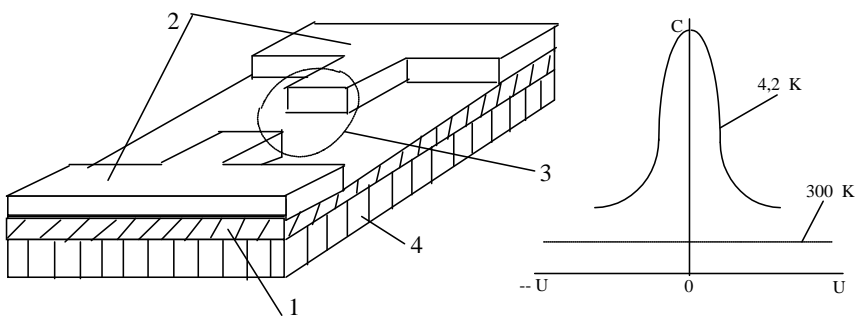
L

, n , $L = \frac{1}{n}$.

(CrTiO_3) ()
80

. 5.42.

, = 4, 2 . 300 .



. 5.42. :
- : 1 -
2 - , 3 -
4 - ;
-

6.

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-
-

6.1.

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 (,)
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 ,
 ,
 :

$$\vec{E}(t, z) = \vec{i} A \cos(\omega t - kz),$$

$$\vec{E} - , \vec{i} -$$

$$), - , z -$$

$$, k = \frac{\omega}{c} n -$$

$$, n -$$

$$I = \frac{cn\epsilon_0 A^2}{2} \left[\frac{1}{2} \right]$$

$$P = I\pi a^2,$$

« »

$$10^8 - 10^{10} \frac{\text{---}}{2},$$

« »
(6.4).

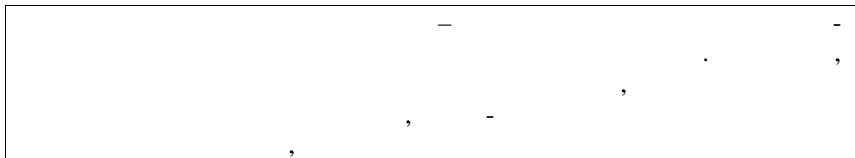
() ,

$$R = \frac{ka^2}{2},$$

R

$$\theta = \frac{1,22\lambda}{2an_0},$$

$n_0 -$



$$\theta = \lambda/d$$

$d = 1$ $\theta = 10^{-4}$ $\lambda = 1$

. 6.1.

$$\lambda = 6943 \text{ \AA}$$

$P = 0,5$

(. 6.1,).

(. 6.1,)

θ

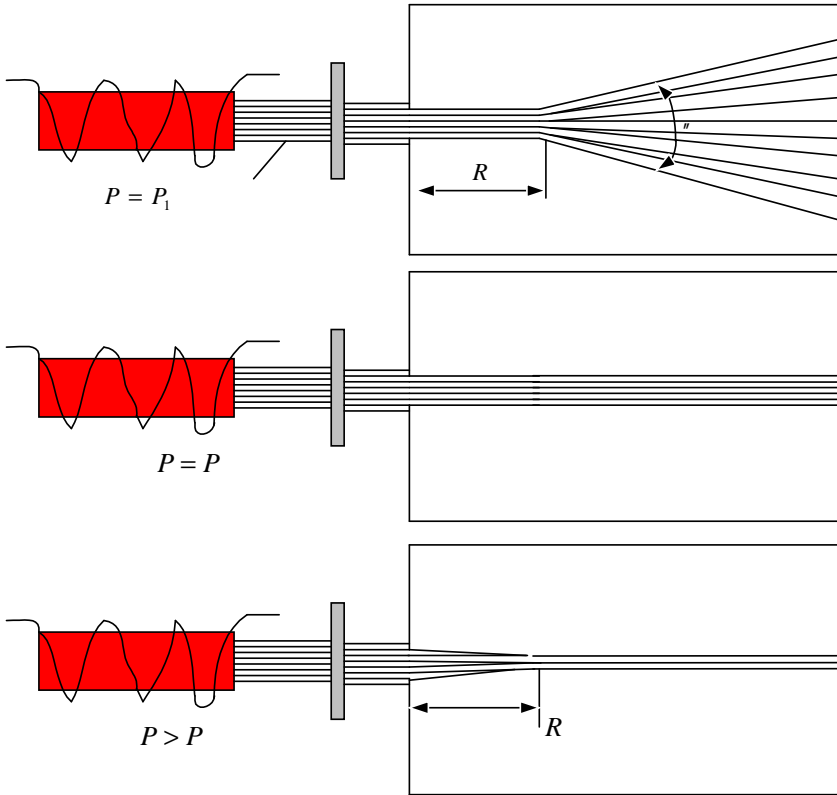
$P > P$ (. 6.1,)

$$R \sim \frac{1}{\sqrt{P}}$$

6.5). . 6.1

).
 ω

$\omega \pm \Omega$.

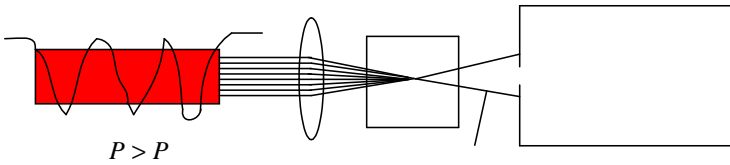
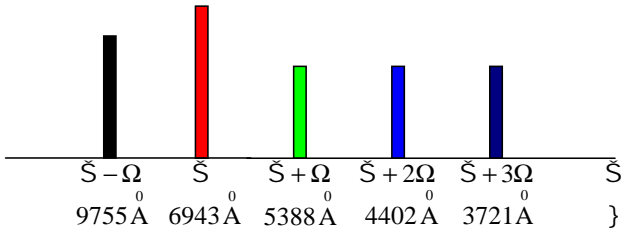
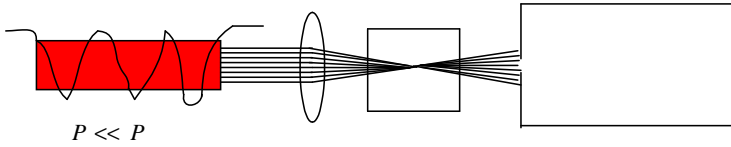
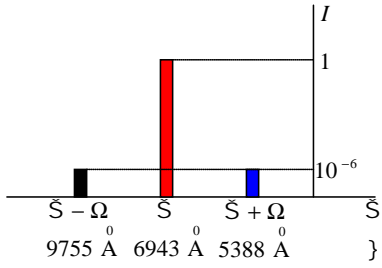


. 6.1.

(,).

, Ω -

... , , KDP (-) .



. 6.2.

($\lambda = 6943 \text{ \AA}$)

... 3471 \text{ \AA} .

6.2.

$$n = \frac{c}{v},$$

$v -$

$\delta,$

$$I = I_0 e^{-\delta t}, \delta > 0.$$

\bar{E}

6.1,

χ ,

ε

$$n = \sqrt{\varepsilon}$$

	n	$\sqrt{\varepsilon}$
	1,33	9,0
	1,34	5,7
	1,36	5,0

$$D = \varepsilon \varepsilon_0 E$$

$$n = \sqrt{\varepsilon}$$

(. . .)
 (. . .)
 (. . .)
 $\mu = 1.$
 $v = \frac{c}{\sqrt{\epsilon\mu}}$
 (5.2)
 μ
 χ

$\omega \pm \Omega$

$\vec{P} \quad \vec{E}$

$$\omega_0 = 2\pi\nu_0$$

$$\nu_0 = \frac{1}{2\pi\sqrt{LC}}, \quad \nu_0 = \sqrt{\frac{k}{m}}$$

):

$$m \frac{d^2 x}{dt^2} + R \frac{dx}{dt} = eE - F,$$

$m -$

$$(\quad , R - \quad), \quad (\quad , F - \quad).$$

F

:

$$F = kx,$$

$$m \frac{d^2 x}{dt^2} + R \frac{dx}{dt} + kx = eE$$

$$\frac{d^2 x}{dt^2} + \delta \frac{dx}{dt} + \omega_0^2 x = \frac{e}{m} E,$$

$$\delta = \frac{R}{m}, \quad \omega_0 = \sqrt{\frac{k}{m}}$$

$$E = A \cos(\omega t - kz):$$

$$x(t) = \frac{e}{m} A \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \delta^2 \omega^2}} \cos(\omega t - kz + \varphi),$$

$$\varphi = \arctan \frac{\delta \omega}{\omega^2 - \omega_0^2}.$$

$$p = qx = ex,$$

$$Nex = N\alpha E,$$

$$\alpha = \frac{ex}{E} = \left| x = \frac{eA}{m} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \delta^2 \omega^2}}, e = A \right| =$$

$$= \frac{e^2}{m} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \delta^2 \omega^2}}.$$

$$, \dots \quad |\omega - \omega_0| \gg \delta \quad ($$

$$\delta^2 \omega^2$$

$$\alpha = \frac{e^2}{m} \frac{1}{\omega^2 - \omega_0^2},$$

$$\epsilon_0 \chi = N\alpha = \frac{Ne^2}{m(\omega^2 - \omega_0^2)}; \quad n = \sqrt{1 + \frac{Ne^2}{\epsilon_0 m(\omega^2 - \omega_0^2)}}; \quad P = \epsilon_0 \chi E.$$

$$\omega \quad ; \quad n \quad (\quad \checkmark_0, \dots$$

(\quad , \quad)	(\quad , \quad)
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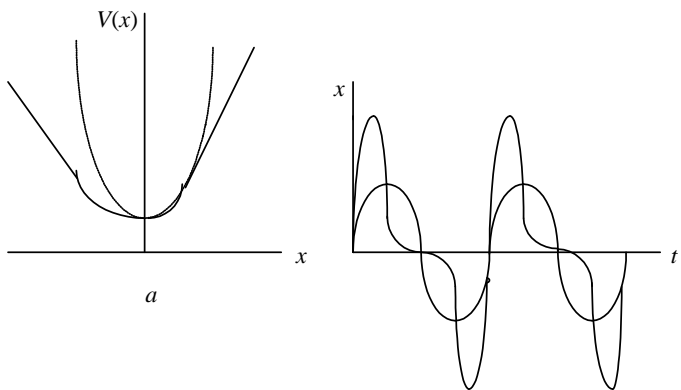
$$\vec{P} = \epsilon_0 \chi \vec{E}, \dots$$

(\quad) , F , \vec{E} , $(\quad .6.3,)$.

$$V(x)$$

$(\quad .6.3,)$:

$$V(x) = \frac{kx^2}{2} + \frac{\beta}{3}x^3.$$



. 6.3.

— , ;
 — , F ;

$$F = \frac{dV(x)}{dx} = kx + \beta x^2 .$$

) : , — (—

$$\frac{d^2x}{dt^2} + \delta \frac{dx}{dt} + \omega_0^2 x + \frac{\beta}{m} x^2 = \frac{e}{m} E .$$

, . 6.3, . —
 F x^3 .

$$\vec{P} = \epsilon_0 \chi \vec{E} ,$$

, -
 , -
 , -
 , -
 (-)
 E_a , -
 E_a
 :

$$E_a = \frac{e}{4\pi\epsilon_0 r_0^2},$$

$r_0 = 10^{-10}$ -
 $e = 1,6 \cdot 10^{-19}$ -
 $E_a \approx 5 \cdot 10^9$ —. -

$$I \approx 10^8 - 10^{10} \text{ —}_2$$

$$\approx 10^5 - 10^7 \text{ —},$$

E_a .

, $\approx 5 \cdot 10^9$ — — -

$$\approx 10^7 - 10^8 \text{ —}.$$

$$E_a, \dots E_a \gg E.$$

E_a .

6.3.

(...)

()

$$P = aE + a_1E^2 + a_2E^3 + \dots$$

$$P = P + \dots$$

$$P = aE,$$

$$\sim \frac{1}{\dots}$$

$$P = aE$$

k

$$= A \cos(\omega t - kz),$$

$\omega,$

$2\omega, 3\omega \dots$

$$a_1 E^2,$$

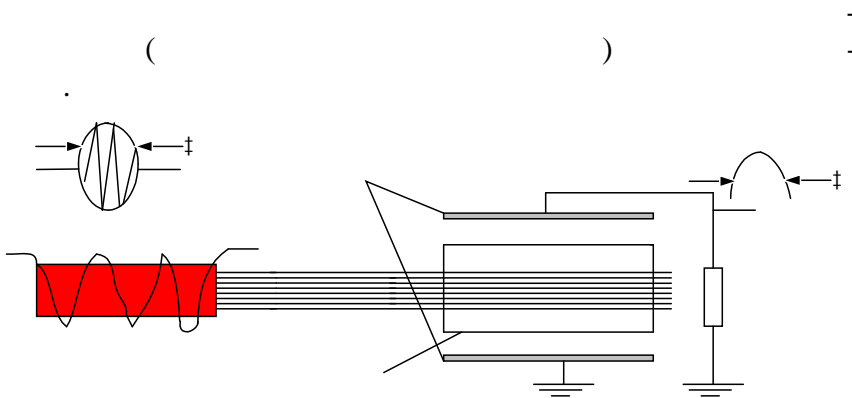
$$a_1 E^2 = a_1 A^2 \cos^2(\omega t - kz) = \left| \cos^2 \alpha = \frac{1 + \cos 2\alpha}{2} \right| =$$

$$= \frac{a_1 A^2}{2} + \frac{a_1 A^2}{2} \cos 2(\omega t - kz).$$

$$\frac{a_1 A^2}{2}$$

. 6.4.

()



. 6.4.

\mathbf{K}_2 4).

KDP (

$$P = aE + a_1 E^2 .$$

()

, (z)
 , ox oy

45^0

$$U = U_0 \sin^2 \gamma, \quad \gamma -$$

$$(U = U_0),$$

(,)

$$a_1 E^2,$$

$$\frac{1}{2} a_1 A^2 \cos 2(\omega t - kz),$$

$$a_2 E^3,$$

$$\begin{aligned} a_2 E^3 &= a_2 A^3 \cos^3(\omega t - k_1 z) = \left| \cos^3 \alpha = \frac{3}{4} \cos \alpha + \frac{1}{4} \cos 3\alpha \right| = \\ &= \frac{3}{4} a_2 A^3 \cos(\omega t - k_1 z) + \frac{1}{4} a_2 A^3 \cos 3(\omega t - k_1 z). \end{aligned}$$

$$a_2 E^3$$

$$\cos(\omega t - k_1 z)$$

$$a_2 A^3.$$

v (

ε ,

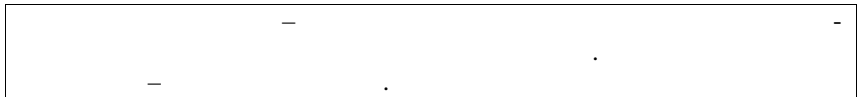
$$v = \frac{1}{\sqrt{\epsilon_a \mu_a}},$$

A^2 .

. 6.1).

(. 6.1,

6.4.

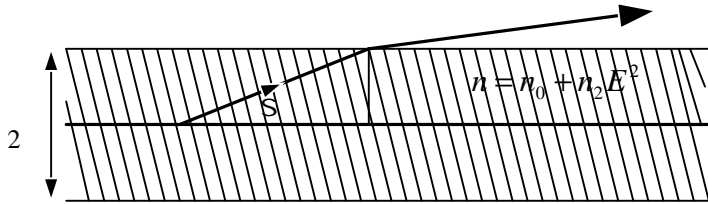


$$n_2 E^2 \quad n_2 > 0$$

$$n_2 > 0$$

$$n_2 > 0$$

. 6.5.



. 6.5.

(, ,)

$$n = n_0,$$

$$n = n_0 + n_2 E^2.$$

90° -

$$\beta_0 = \arccos \frac{n_0}{n_0 + n_2 E^2}.$$

$$\beta > \beta_0$$

$$\beta < \beta_0$$

)
β

$$\beta = \frac{0,61\lambda}{2an_0}.$$

β .

β₀

$\beta_0 < \beta$

« » ,

$\beta_0 = \beta$

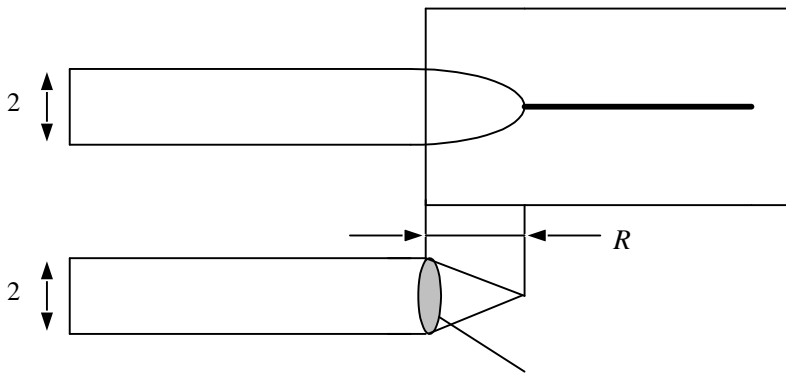
β_0

$$P = \frac{c\lambda_0^2 1,22^2}{256n_2}$$

$\beta_0 > \beta$

$P > P$

. 6.6.



. 6.6.

$P > P$,

$$P = 1 \quad ,$$

6.5.

5.8

$$\left(\quad \right) \quad \left(\quad \right)$$

ω

$$\omega = \frac{\omega}{2} .$$

$$\left(\quad \right) \quad \varepsilon$$

E

$$E = E_0 \sin(\omega t - k z) ,$$

$$k = \frac{\omega}{v} \quad , \quad \omega = \omega_1 + \omega_2 -$$

(. . .)
 .6.7, .

ε ,

z

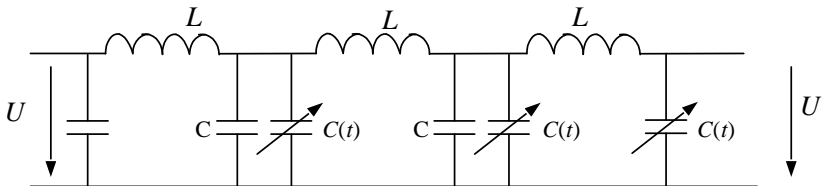
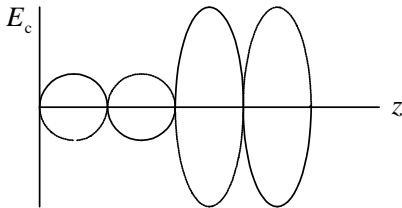
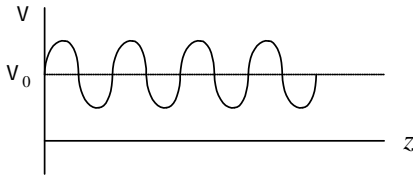
-

.6.7, .

$$\omega = \frac{\omega}{2},$$

()

, .6.7, .



.6.7. -

; -

(... $N\lambda_c = z$),

$$\varphi_c = 0,$$

. 6.7,

$$\tau = \frac{z}{v_c},$$

$v_c -$

τ

z

:

$$\varphi = \omega \tau - k z = \omega \frac{z}{v_c} - \frac{\omega}{v} z = z \left[\frac{\omega}{v_c} - \frac{\omega}{v} \right].$$

$$\varphi = 0,$$

$$v = v_c.$$

().

$$\frac{\omega}{2}$$

$$\frac{\omega}{2}.$$

ω

$$\frac{\omega}{2}.$$

$$E_0$$

$$k = \frac{\omega}{v} = \frac{2\omega_c}{v}, \quad k_c = \frac{\omega_c}{v_c}, \quad v = v \quad -$$

$$k = 2k_c, \quad -$$

$$(\quad), \quad -$$

,
 ,

$$(\quad \quad \quad 5.8) \quad -$$

,
 :

$$\omega = \omega_1 + \omega_2.$$

$$\varphi = \varphi_1 + \varphi_2.$$

$$E^2 (\quad \quad \quad 6.3),$$

$$\S (\quad \quad \quad):$$

$$E = A \cos(\omega t - k z)$$

:

$$E_1 = A_1 \cos(\omega_1 t - k_1 z), \quad E_2 = A_2 \cos(\omega_2 t - k_2 z)$$

,

$$\omega = \omega_1 + \omega_2.$$

,

$$P = aE + a_1 E^2,$$

$$\omega_1 \quad \omega_2 \quad E \quad E_2$$

$$a_1 E^2 = a_1 [A \cos(\omega t - k z) + A_2 \cos(\omega_2 t - k_2 z)]^2 =$$

$$= a_1 A^2 \cos^2(\omega t - k z) + a_1 A_2^2 \cos^2(\omega_2 t - k_2 z) +$$

$$+ 2a_1 A A_2 \cos(\omega t - k z) \cos(\omega_2 t - k_2 z).$$

$\cos^2 \alpha$

$$(2\omega \quad 2\omega_2).$$

$$\omega + \omega_2 \quad \omega - \omega_2$$

$$\cos \alpha \cos \beta = \frac{1}{2} [\cos(\alpha + \beta) + \cos(\alpha - \beta)].$$

$$\omega_1 \quad \omega_2$$

$$\cos(\omega t - k z - \omega_2 t + k_2 z) = \cos[(\omega - \omega_2)t - (k - k_2)z],$$

\check{S}_1

E_2

$$P_1 = a_1 A A_2 \cos[\omega_1 t - (k - k_2)z].$$

ω_2 :

$$P_2 = a_1 A A_1 \cos[\omega_2 t - (k - k_1)z].$$

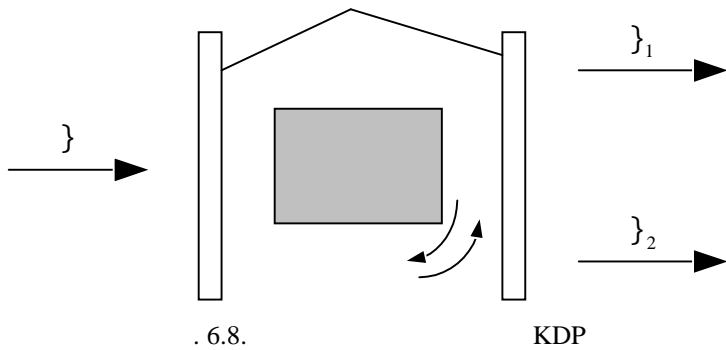
ω_2

ω_1 ,

$\omega \quad \omega_1 -$

ω_2 .

$\omega_1 \quad \omega_2$ -
-
 $P_1 \quad P_2$.
, -
 $\omega_1 \quad \omega_2$,
, . . .
Z:
 $k - k_2 = k_1$,
 $k - k_1 = k_2$.
, -
:
 $k_1 + k_2 = k$.
, -
, $\omega_1 \quad \omega_2$, -
, , -
, . . . , -
 $\omega_1 \quad \omega_2$, -
 $\omega_1 \quad \omega_2$.
 $\lambda_1, \quad \lambda_2$ -
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, ω (-
,) -
 $\omega_1 \quad \omega_2$, . 6.8. -



KDP

$$\} = 0,53 \quad ($$

$$\omega = \omega_1 + \omega_2,$$

$$k_1 + k_2 = k .$$

$$m > 4 \sqrt{\frac{\delta_1 \delta_2}{k_1 k_2}},$$

$$\delta_1 \quad \delta_2 -$$

$$\omega_1 \quad \omega_2 .$$

$$E_1 \quad \omega_1$$

E_2

$$\omega_2 = \omega - \omega_1,$$

6.6.

($\lambda \sim 10^4 - 10^5$)

$$L (\quad , \quad),$$

$\lambda.$

$$a_1 E^2 = a_1 A^2 \cos^2(\omega t - k_1 z) = \frac{a_1 A^2}{2} + \frac{1}{2} a_1 A^2 \cos(2\omega t - 2k_1 z)$$

$L \gg \}$

$$P(2\omega) = \frac{1}{2} a_1 A^2 \cos(2\omega t - 2k_1 z).$$

$$E_2 = A_2 \cos(2\omega t - 2k_2 z).$$

()

$$P(2\omega),$$

$$\Delta\varphi$$

$$\Delta\varphi$$

$$L:$$

$$\Delta\varphi = L(k_2 - 2k_1).$$

$$\Delta\varphi = 0, \quad 2k_1 = k_2$$

$$v(\omega) = v(2\omega).$$

$$v(\omega) \neq v(2\omega).$$

$$\Delta\varphi \geq \pi, \quad \Delta\varphi = \pi, \quad L$$

$$L = \frac{\Delta\varphi}{k_2 - 2k_1} = \frac{\pi}{k_2 - 2k_1} = \left| k_2 = \frac{2\omega}{v(2\omega)}, 2k_1 = \frac{2\omega}{v(\omega)} \right| =$$

$$\frac{\pi}{2\omega \left\{ \frac{1}{v(2\omega)} - \frac{1}{v(\omega)} \right\}} = \left| v = \frac{c}{n(\omega)} \right| = \frac{\pi}{2\omega \left(\frac{n(2\omega)}{c} - \frac{n(\omega)}{c} \right)} =$$

$$= \left| \omega = 2\pi f, \lambda = \frac{c}{f} \right| = \frac{\lambda}{4(n_2 - n_1)}.$$

, L - ,
 , L . ,
 P_2 .
 « » ()
 $L = 10^{-3}$. L .
 :

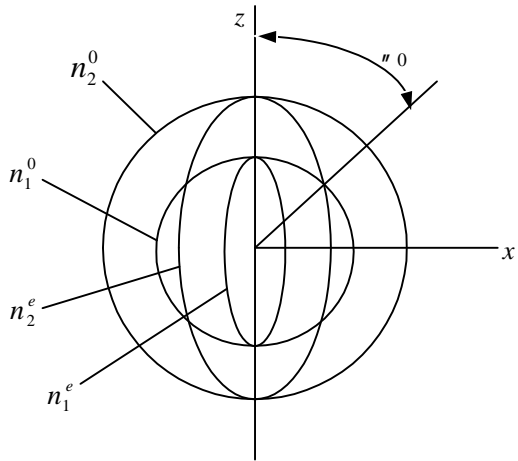
$$P_2 \sim P_1^2 k_1 a_1 \frac{\sin^2 \left[\frac{k_2 - 2k_1}{2} L \right]}{(k^2 - 2k_1)^2} .$$

L ,
 P_1 ,
 a_1 .
 , $300 - 400 \frac{1}{2}$.

$L = 10^{-3}$,
 L .

(, $n(\omega) = \frac{c}{v(\omega)}$)

L) (, ,
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 n , ,
 v ω ,
 , ...
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), ()
 $= \epsilon_0 \chi$
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 oz (, . 6.9.),
 (,),
 , ω
 ,
 n^0 n^e
 $n_2^0 - n_1^0$ $n_2^e - n_1^e$
 , ,
 (L^0 L),



. 6.9.

:

(n^0)

(n^e)

n_1^0 .

KDP.

n_2^e

θ_0

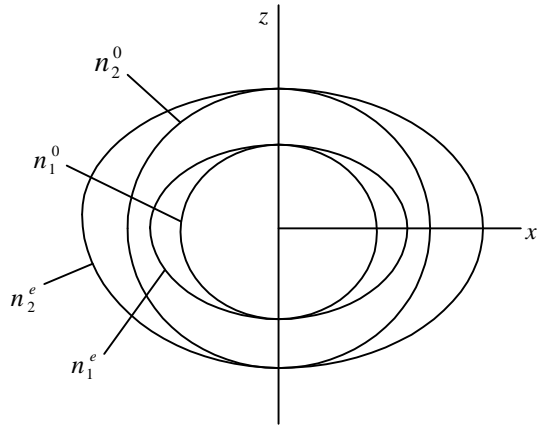
oz

$n_2^e = n_1^0$.

L

θ_0

. 6.10.



. 6.10.

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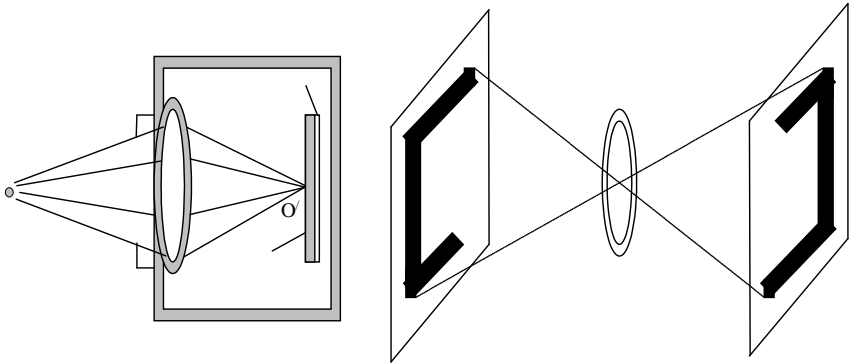
7.

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7.1.

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7.1.

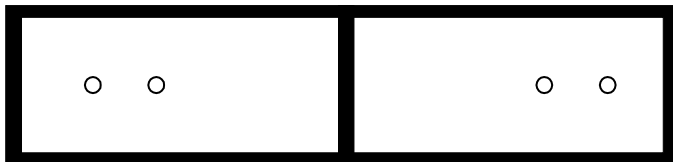


7.1.

— — ; — ; — () ; ;
 O' — ;

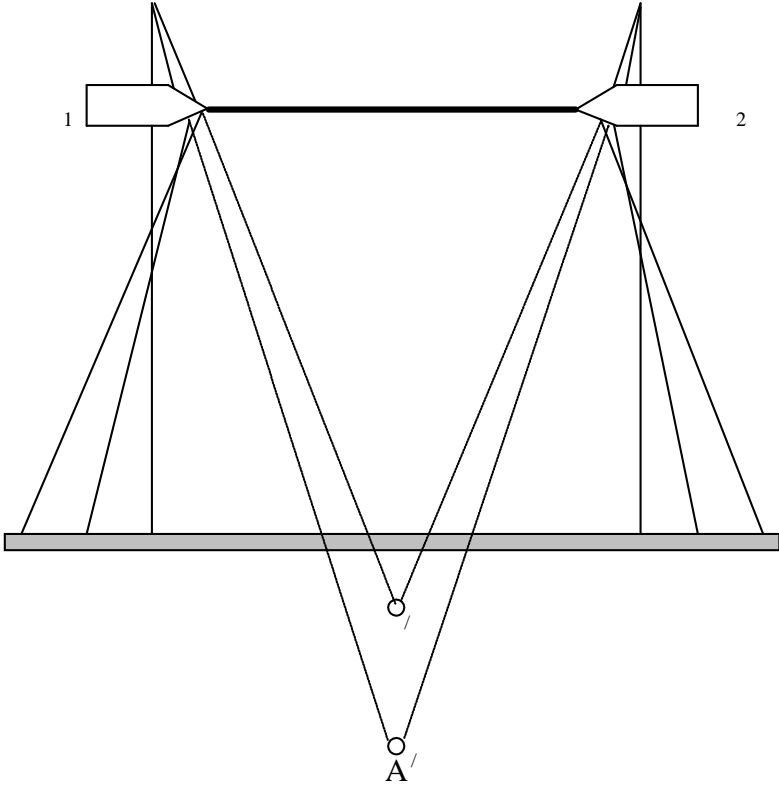
7.1.

— — ; — ; — () ; ;
 O' — ;



.7.2.

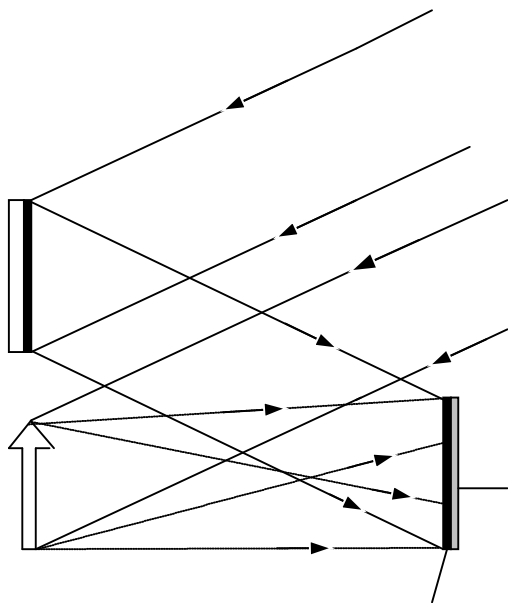
), .7.3.



.7.3.

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), (,) .7.4. , - - - -

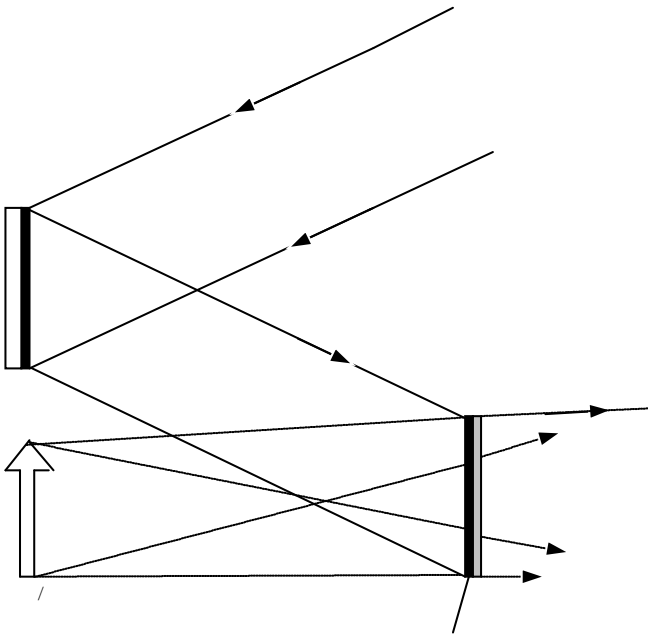


. 7.4.

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.7.5. :

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7.2.

$S \ S' \ (\ .7.6).$

SS'

,
 , $S \ S'$,

E'

o_1

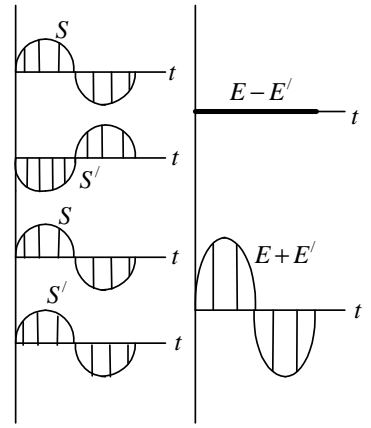
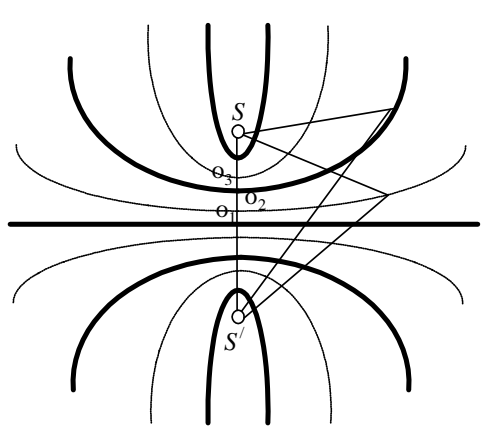
SS' ,

$\frac{\lambda}{4}$

$(\lambda -$

$$o_1 \quad S \quad S' \quad \left(- \frac{T}{4} \right),$$

$$S' - E' \quad o_1 \quad \varphi' - \varphi = \frac{T}{2} = \pi.$$



. 7.6.

()
 o_1 S
 S' ,
 o_1
 $S \quad S' \quad \frac{\lambda}{2}$
 $o_2, \quad \frac{\lambda}{2} \quad o_1,$
 $\varphi' - \varphi = 2\pi.$

SS' ,

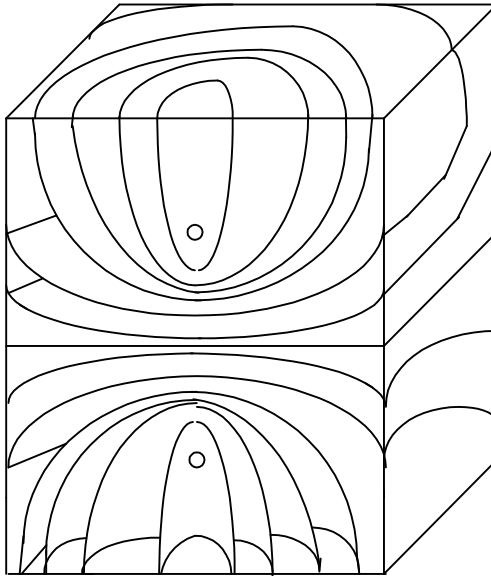
$\frac{\lambda}{2}$,
0,35

. 7.6.

$S S'$.

($S S'$),

. 7.7.

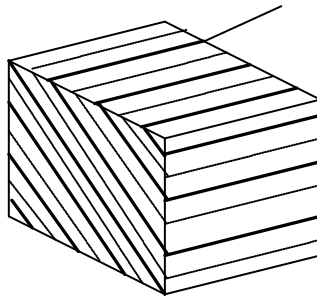
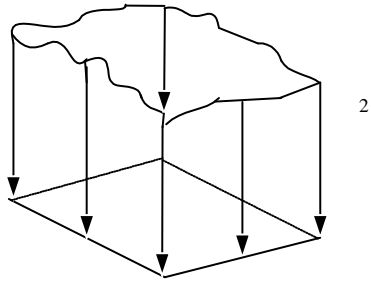
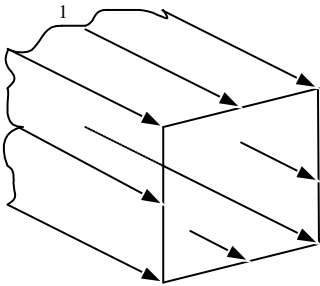


. 7.7.

$S S'$

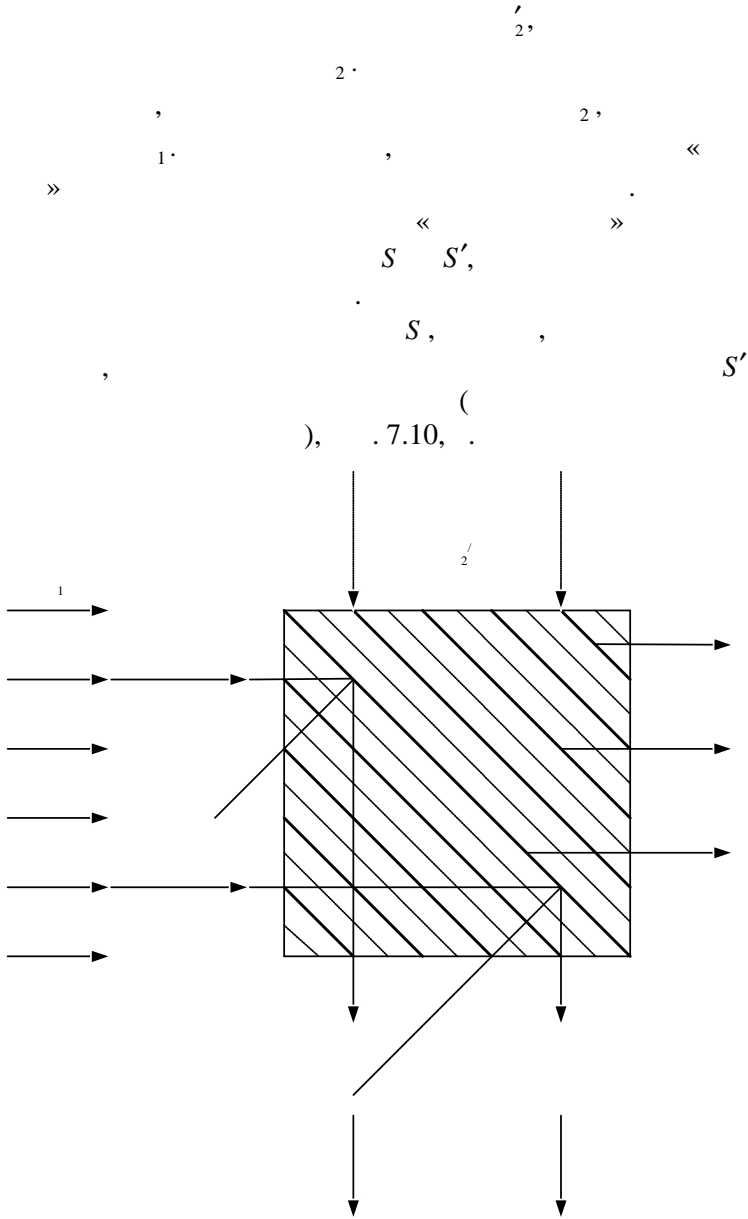
2 (), , . 7.8.

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. 7.8.

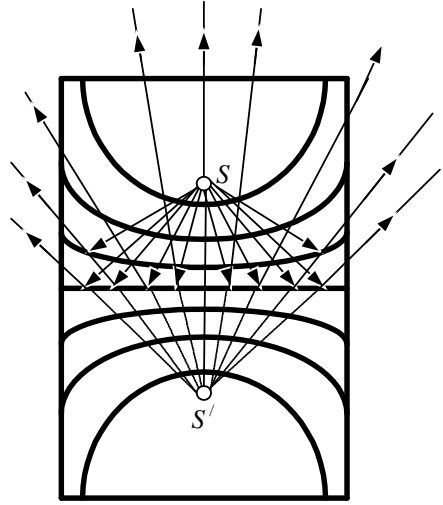
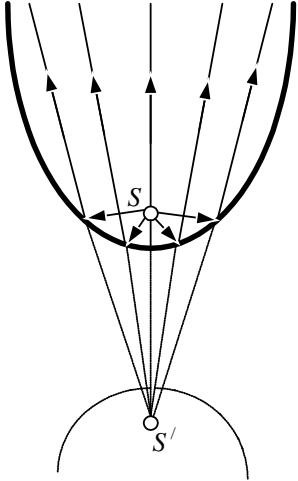
1 2



.7.9.

2

S S' , , S , ,
 S' , . 7.10, .



. 7.10. -
 S .

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S'

S'

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S'
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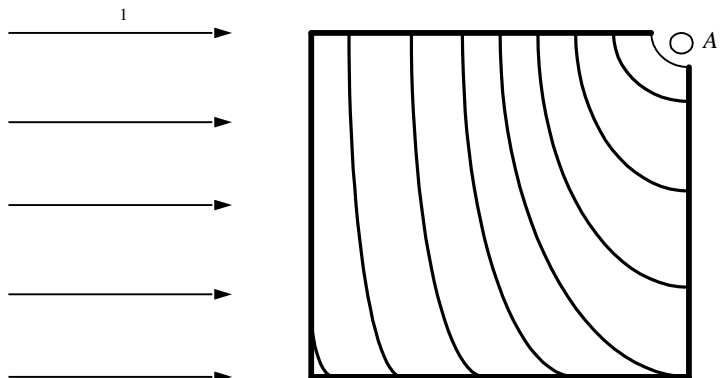
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. 7.11.



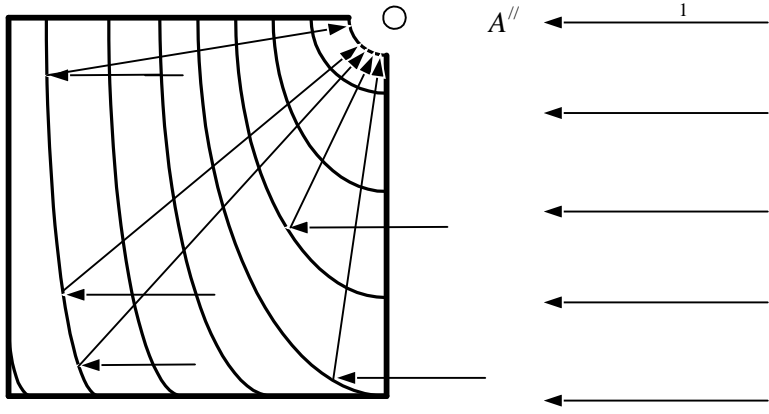
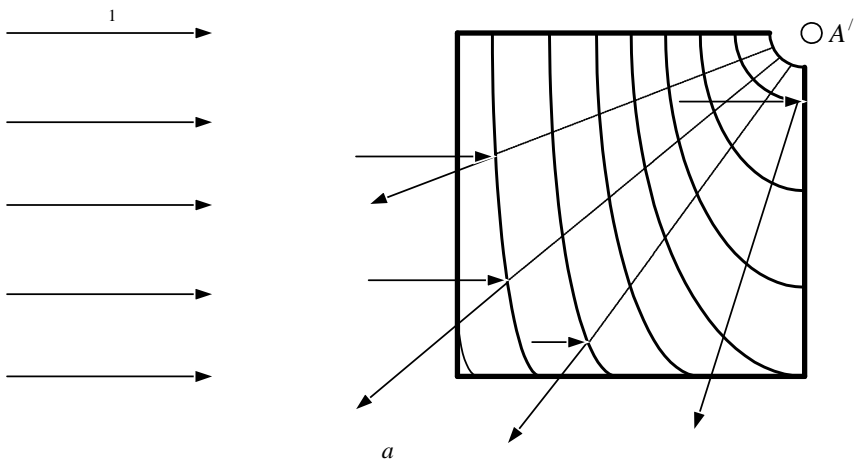
. 7.11.

, . 7.12, .

, . 7.12, .

" .

7.3.

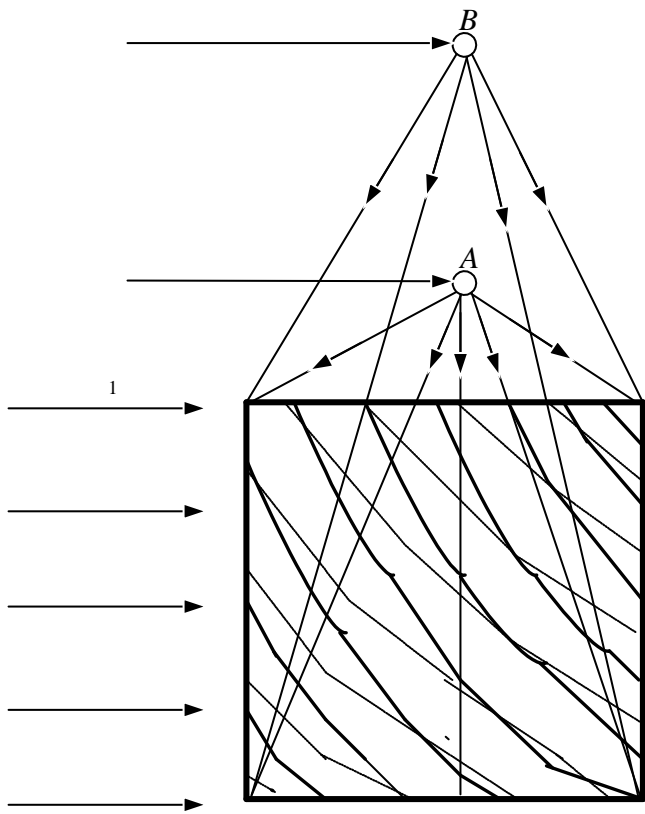


. 7.12.

' ()

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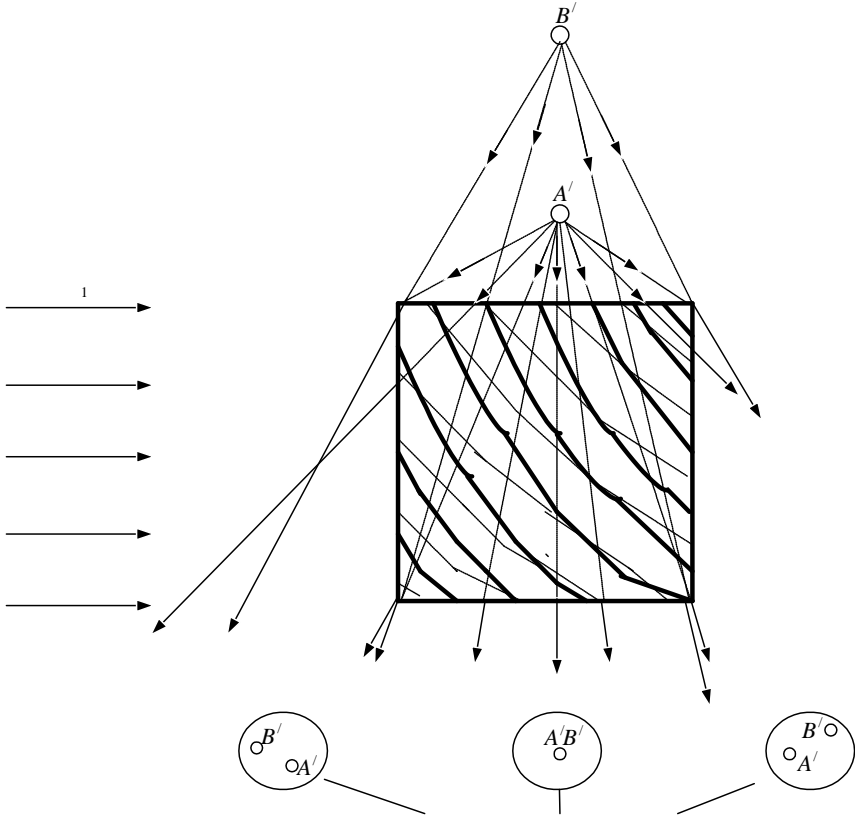
. 7.13.



. 7.13.

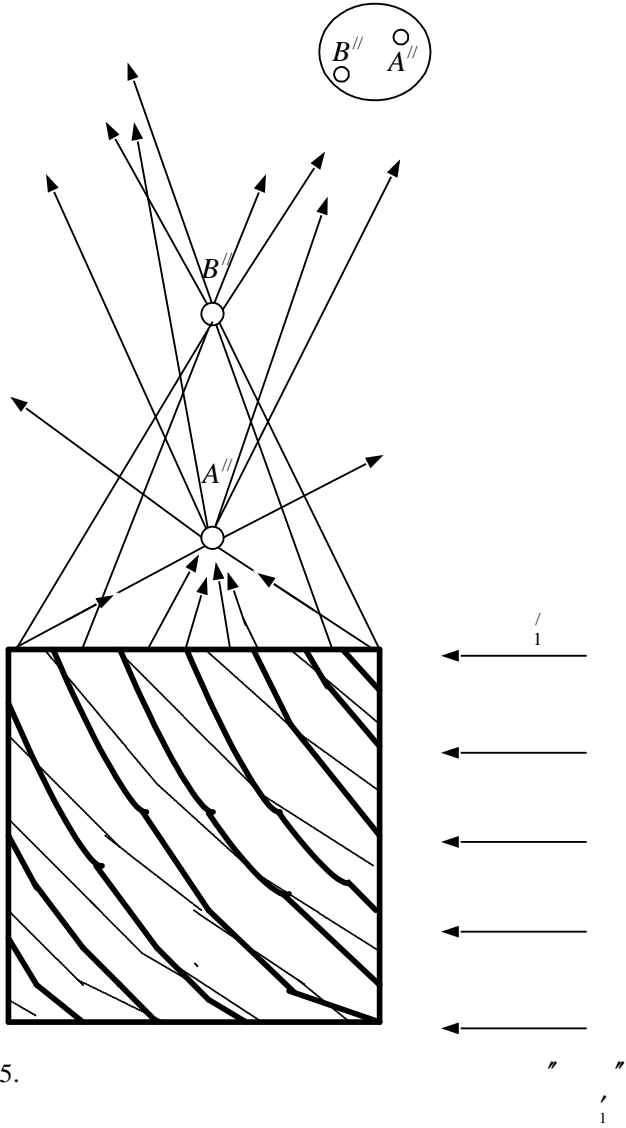
(- , -)

. 7.14.



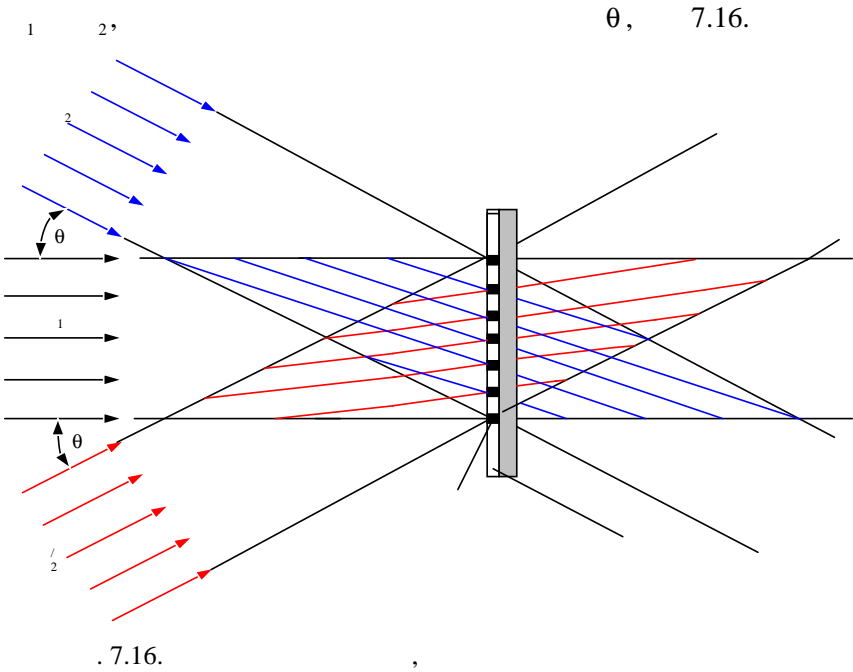
. 7.14.

" " , . 7.15.



.7.15.

7.4.



. 7.16.

$$2 \sin \theta = m \lambda$$

()

$$2 \sin \theta = m \lambda$$

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. 7.17.

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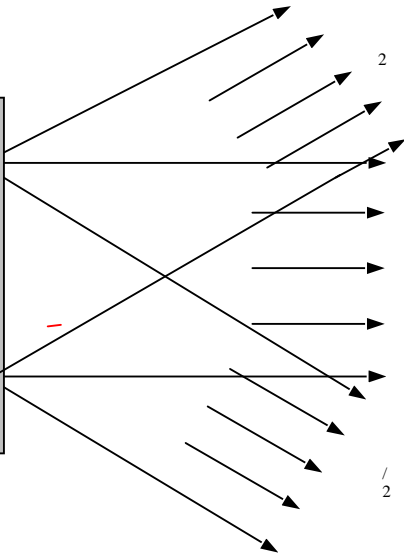
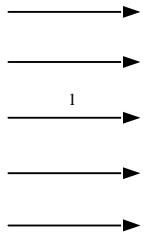
2

2

,

,

,

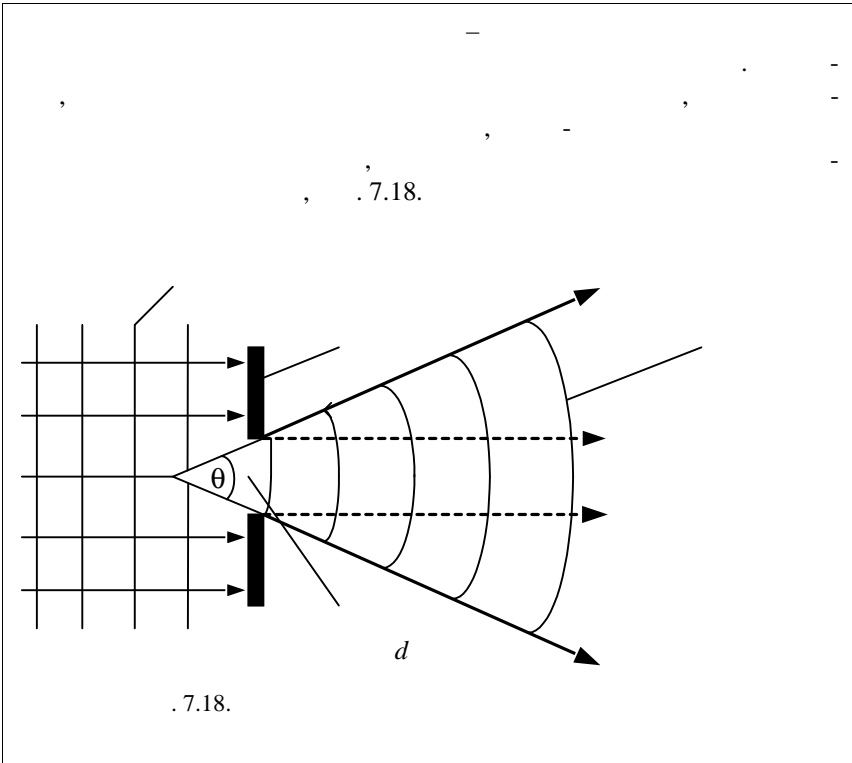


. 7.17.

2

2 ()
 / 2 ()

1



$$\theta = \frac{\lambda}{d},$$

$\lambda -$; $d -$ () .

$= 1$, $d \approx 1$ $\theta \approx 10^{-4}$. $\lambda =$

$$a < \lambda \quad (7.19), \dots$$

$$\pm\theta, \pm 2\theta, \pm 3\theta \dots (7.19), \quad \sin \theta \approx \frac{\lambda}{a}$$

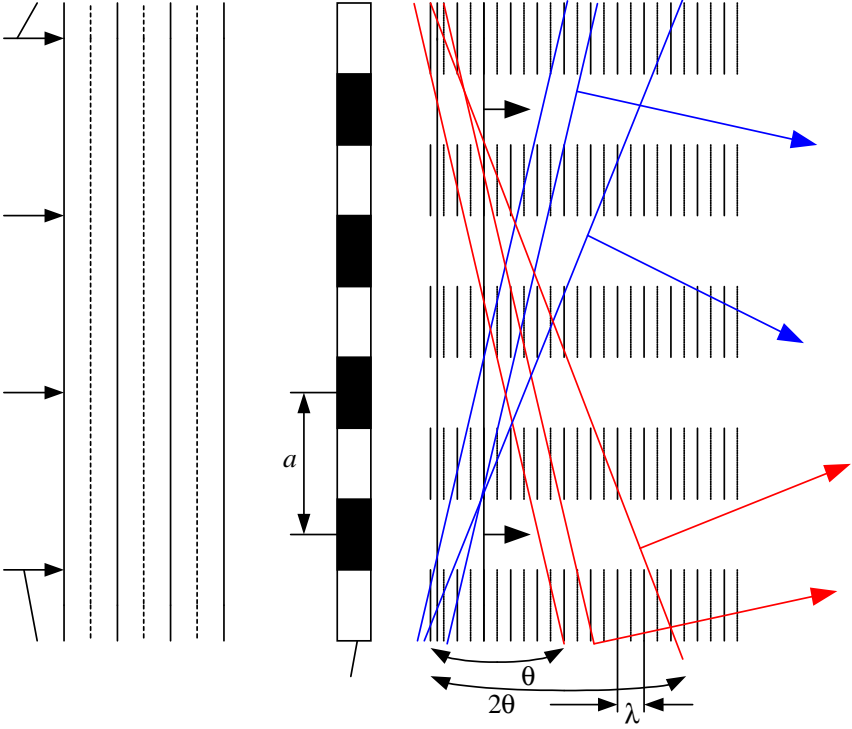
$\pm\theta,$

2, 7.17.

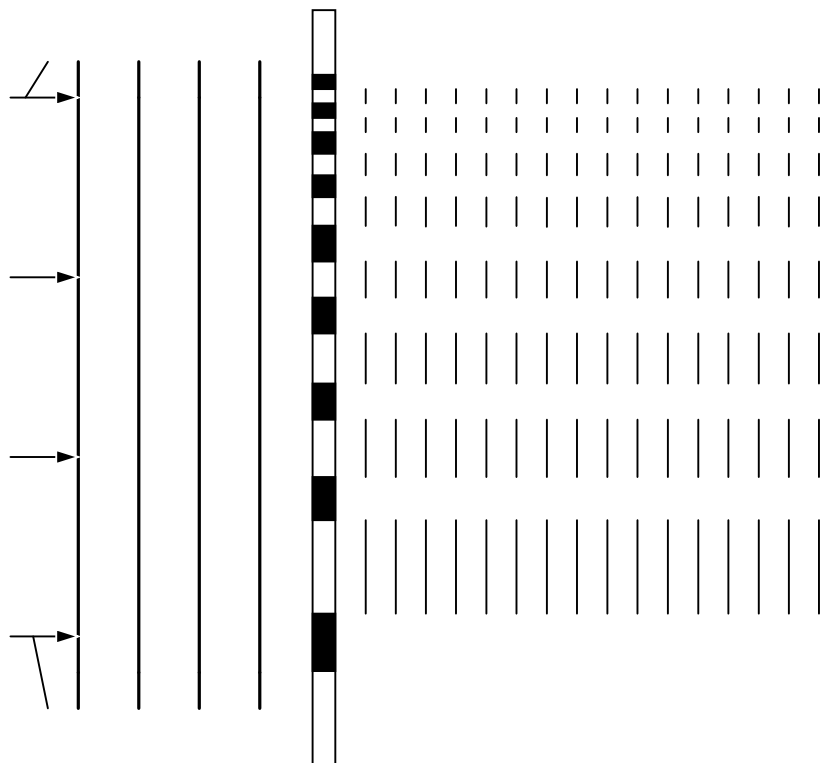
. 7.20.

()

;

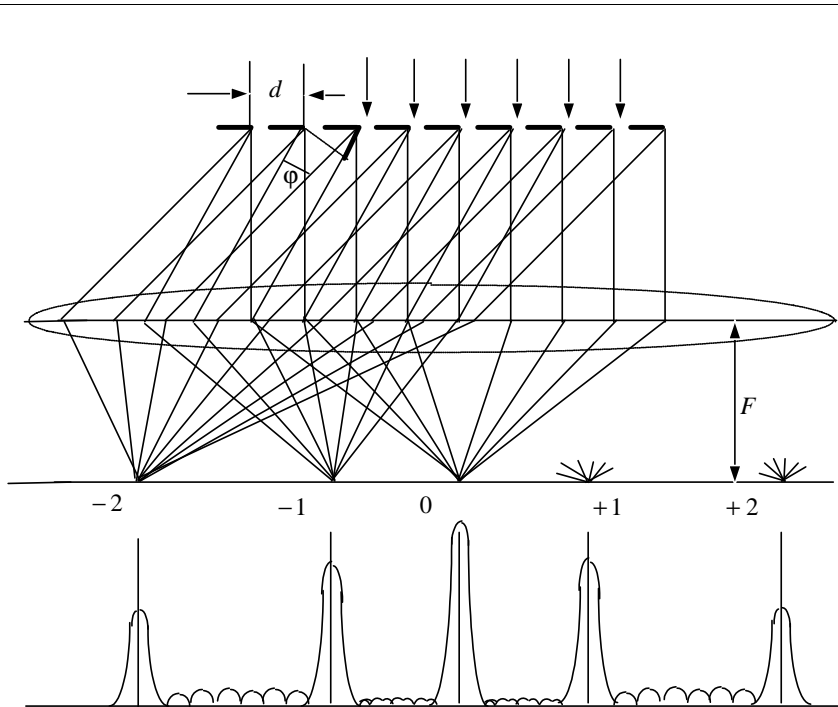


. 7.19.



. 7.20.

) (, (), -
 , .7.21. , -



. 7.21. $x = d \sin \varphi$; $d -$;
 F ; - ; -
 ,
 ,
 ,
 $x = d \sin \varphi$; $d \sin \varphi = m\lambda$, $m -$
 m : λ
 $m -$.
 $\alpha -$,

$m, l -$, $7.21:$

$$\sin \alpha_{\max} = m \frac{\lambda}{d},$$

α

$$\operatorname{tg} \alpha = \frac{a}{l}.$$

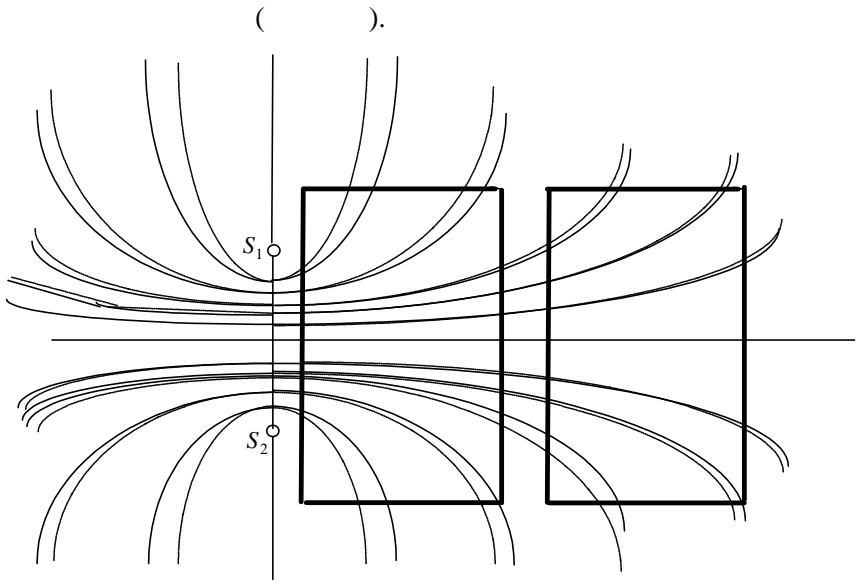
1000,

300.

7.5.

$$\lambda \approx 0,5$$

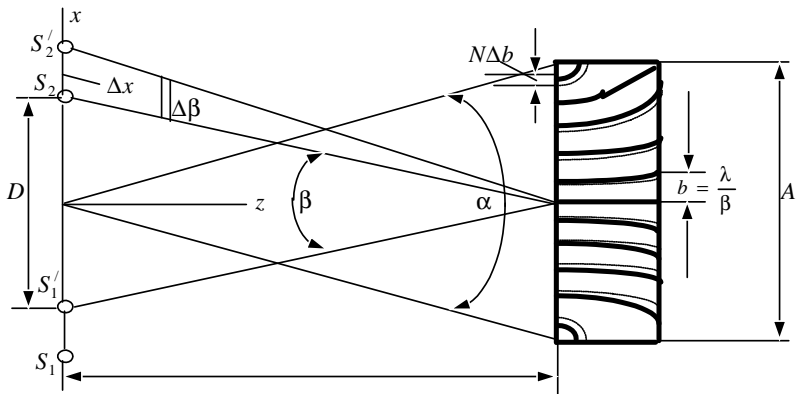
λ ,
 $\Delta\lambda$,
 λ



. 7.22.

N , $S_1 S_2$,
 N , λ .
 λ
 N ,
 (. 7.22). λ N
 $\frac{\Delta\lambda}{\lambda_0} = \frac{2\Delta\lambda}{\lambda + \lambda}$
 $\frac{1}{N}$, $N -$
 $\therefore \frac{\lambda}{\Delta\lambda} \geq N$

S_2 ,
 $S_1, S_1' \quad S_2, S_2'$, . 7.23.



. 7.23.

x

S_2' .

$S_1 \quad S_2$,

S_1'

$$b = \frac{\lambda}{\beta}, \quad \beta -$$

$S_1' \quad S_2$,

Δx

$$\Delta x \ll \frac{\lambda}{\beta}.$$

$$\alpha = \beta, \quad D \approx A.$$

$$N = \frac{A}{\lambda/\beta} = A \frac{\beta}{\lambda}$$

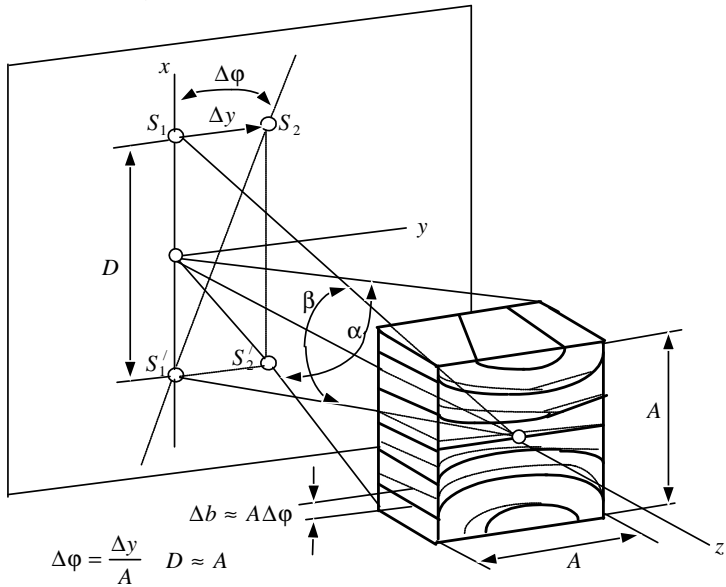
, ... , β , Δx

y z :

$$\Delta y \ll \frac{\lambda}{\beta}, \quad \Delta z \ll \frac{1}{\alpha} \frac{\lambda}{\beta} = |\alpha = \beta| = \frac{\lambda}{\beta^2},$$

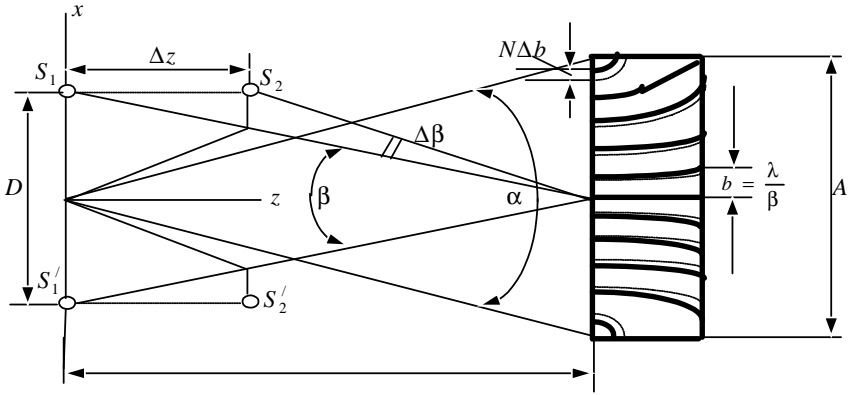
... (z)

$\frac{1}{\alpha}$, x
 y (. 7.24, 7.25).



. 7.24.

y



. 7.25.

z

,
 ,
 ,
 :
 • ,
 • ,
 ,
 ($\lambda \approx 0,5$)
 , 3×3 2 ,
 30 , $\beta = \frac{1}{10}$ « » , « »
 () , :
 $\Delta x \ll \frac{\lambda}{\beta} = 5$, $\Delta y \ll \frac{\lambda}{\beta} = 5$, $\Delta z \ll \frac{\lambda}{\beta^2} = 50$.

5 ,

, $\frac{A}{\alpha}$, ... 100 .

10^{-8} .

7.6.

. 7.26.

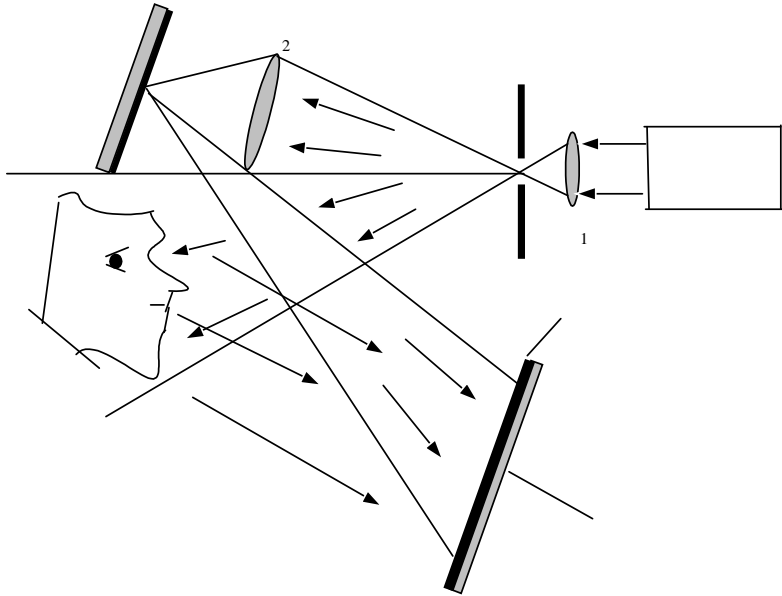
1

2

$dx, dy, dz,$

(

).



. 7.26.

$$\beta = \frac{1}{10}$$

$$\frac{\lambda}{\beta} \text{ (. . .)},$$

$$\lambda = 0,5$$

$$10\lambda \approx 5$$

$$200$$

Δ

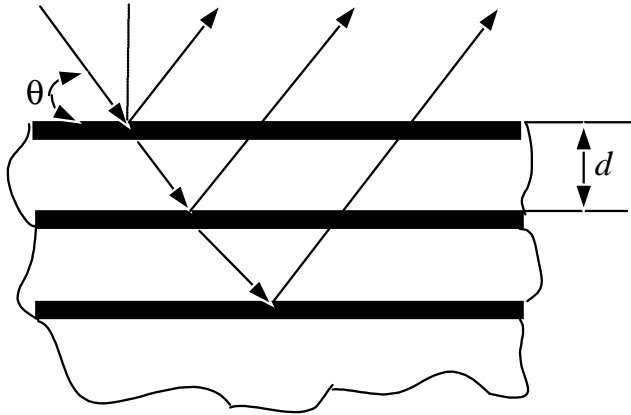
$$\Delta = 2d \sin \theta, \quad \theta -$$

. 7.27.

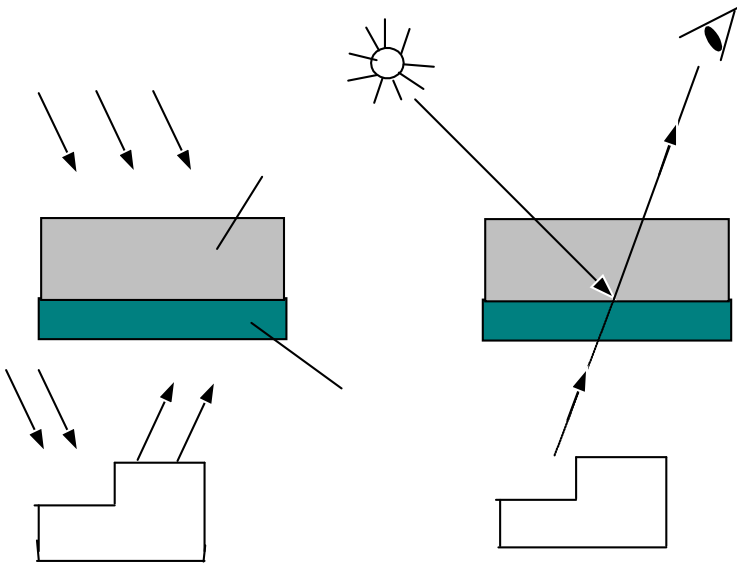
$$2d \sin \theta = m\lambda \text{ (} m - \text{ . . .)}.$$

λ

. 7.28.



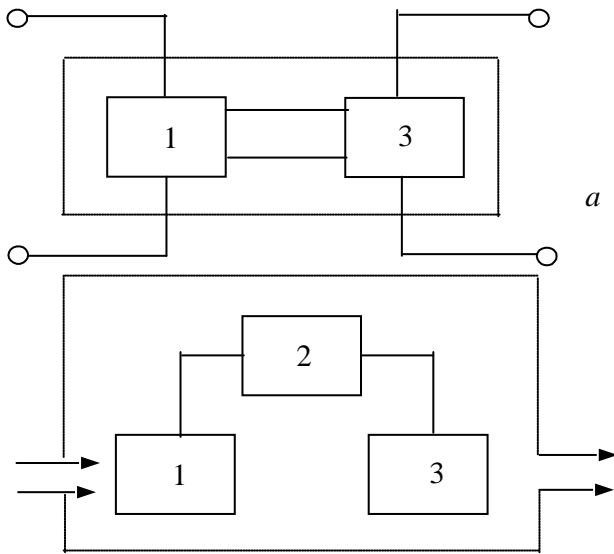
. 7.27.



. 7.28.

- () ;

),
 », (optoelectronic couple).
 3, .8.1, .



.8.1. ; -

$10^{13} - 10^{16}$

, .8.1, .

,

1

2

3,

(light emitting diode (LED))

$p-n-$

3.3.1 - 3.3.3).

(

$p-n-$

$p-n-$

L_n L_p .

(), ().

— , —), ;

,

,

,

$\Delta\epsilon$

,

,

GaAs, GaSb, GaP, InAs, InSb . . .

()

,

.

), . . . — . (-

,

,

, .8.2.

,

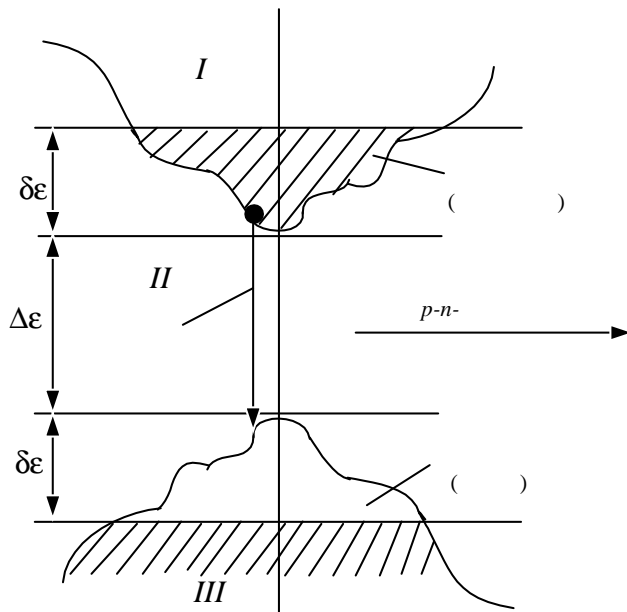
$\Delta\epsilon + 2\delta\epsilon$,

,

$\Delta\epsilon$.

, **ZnO** , **ZnO** N—

, N— , N— . .



. 8.2. $II-$ $I-$,

$p-n-$,

(GaP).

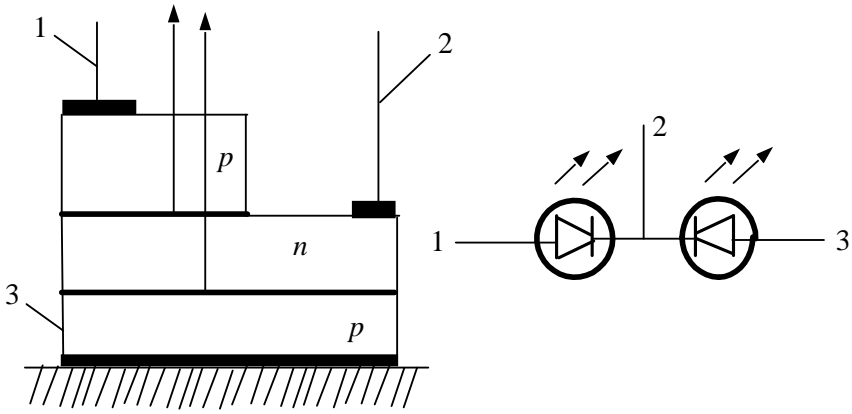
GaP, . 8.3.

$p-n-$.

(1, 2, 3),

$p - n -$

3 / 2). (60



. 8.3.

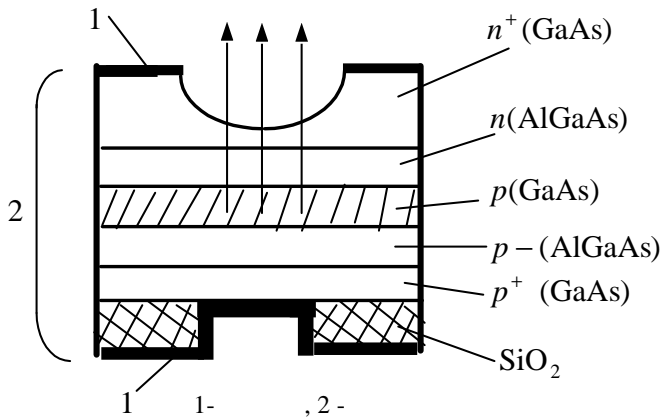
10 - 100

$$B = bl^\gamma,$$

$I -$, $b -$, $\gamma = 0,5 - 0,9$ GaAs. GaP, $\gamma = 1 - 3$

. 8.4.

(photoresistor, light resistor)



. 8.4.

() .

σ_0 ,

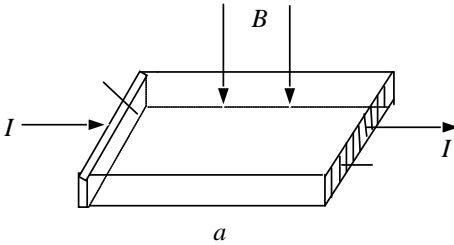
$$\sigma_0 = q(n_0\mu_n + p_0\mu_p),$$

$q -$, $n_0, p_0 -$

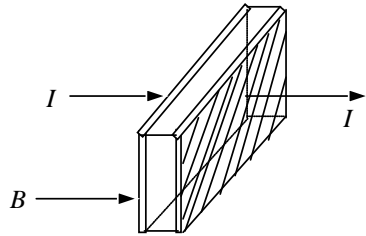
3.3.1, 3.3.2).

$\Delta n \quad \Delta p$

$$\sigma = q[(n_0 + \Delta n)\mu_n + (p_0 + \Delta p)\mu_p].$$



. 8.5.



: -

(photodiode)

. 8.6. .

$n-$

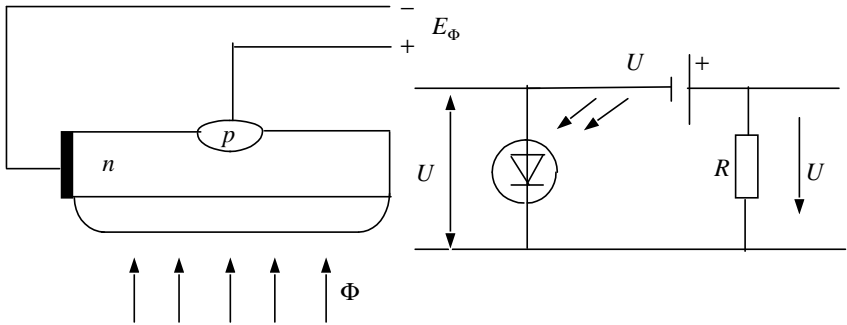
, $p- n-$

$p-n-$

$p-n-$

$p-$

$p-$



. 8.6.

();

()

$p-n-$

$p-n-$

$n-$

$p-$

$p-n-$

E_{Φ}),

$p-n-$

(phototransistor)

$p-n-$

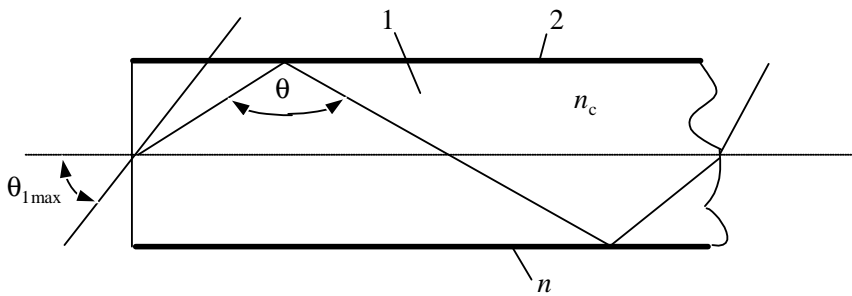
1,8 – 1,9
2,4 – 2,6.

(optical fiber).

(),

(1);

. 8.7.



. 8.7.

n .
 90° ,
 $\theta_{1\max}$.

$$\sin \theta_{1\max} = \sqrt{n_c^2 - n^2} = A_0 .$$

A_0

$\varphi > \theta_{1\max}$ (

« »

$$1 \quad 10^{-9} - 10^{-10} .$$

() .
 (6.4),

(selfoc fiber).

() .

« »

()

« »

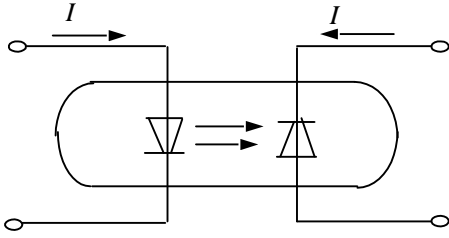
$$10^{-9} - 10^{-10} /$$

$$10^{14} \quad 10^{20}$$

/

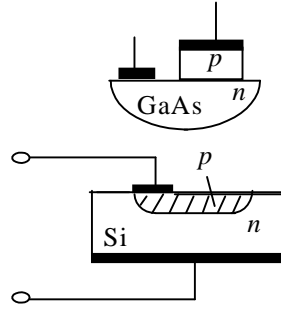
. 8.8, , .

$$10^6 - 10^7$$

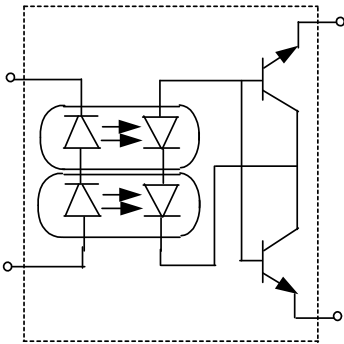


. 8.8.

()

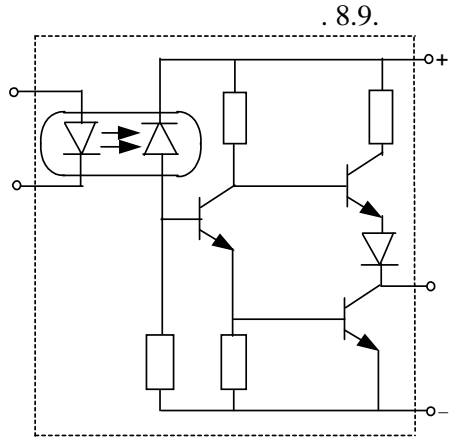


()



. 8.9.

()



. 8.9.

80

()

60 -

	<p> $R = \frac{pV}{T}$ $N_a = (6,02486 \pm 0,00016)10^{23}$ $k = \frac{R}{N_a} = (8,6167 \pm 0,0004)^{-5}$ </p>
()	<p> $\frac{N_m}{N_n} = \exp\left[-\frac{\epsilon_m - \epsilon_n}{kT}\right]$ </p>
	<p> $N_m = N_n -$ </p>

$\rightarrow \infty$

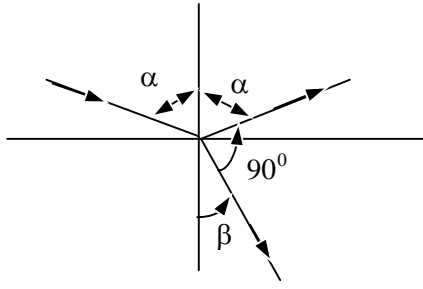
$0 \quad \infty$

$$v = \frac{\varepsilon_m - \varepsilon_n}{h}$$

, [. 30].

), (

, . 1.1.



. 1.1

$\beta = 90^\circ - \alpha$

	$\frac{\sin \alpha}{\sin(90^\circ - \alpha)} = \frac{\sin \alpha}{\cos \alpha} = n,$ $\operatorname{tg} \alpha = n \Rightarrow \alpha = \operatorname{arctg} n.$
	<p>() , . . , : , , .) (,) (, , ... () . () $E_{m,n}, H_{m,n}$. , $m \quad n -$, , , 0,2 50 , [. 184].</p>

	<p> , (:), (, -) : - , - , [.272]. </p>
	<p> (,). , , , , [.45]. </p>
<p>-</p>	<p> . - . - , ε_2, - $h\nu = \varepsilon_2 - \varepsilon_1$, , - ε_1, . , . - , - . - , , . - , [.14-16]. </p>

	<p>, . , , - . , - , [. 121-137].</p>
	<p>, () - , , , [. 255, 264, 269].</p>
	<p>, - . , - . , , [. 251].</p>
	<p>- () - (), - () - . - , (= 0). - , - , , - , . . . , [. 243].</p>

	<p style="text-align: right;">-</p> <p style="text-align: right;">.</p> <p style="text-align: right;">,</p> <p style="text-align: right;">.</p> $\frac{\sin \alpha}{\sin \beta} = \frac{c}{v_2} = n,$ <p>α – , β – , v_2 – , n</p> <p style="text-align: right;">.</p> <p style="text-align: right;">, ...</p> <p style="text-align: right;">-</p> <p style="text-align: right;">-</p> <p style="text-align: right;">.</p> <p style="text-align: right;">-</p> <p style="text-align: right;">[]:</p> <p style="text-align: center;">390 435 495</p> <p style="text-align: center;">— — —</p> <p>570 590 630 770</p> <p style="text-align: center;">[228].</p>
	<p style="text-align: right;">-</p> <p style="text-align: right;">.</p> <p style="text-align: right;">-</p> <p style="text-align: right;">-</p> <p style="text-align: right;">,</p> <p style="text-align: right;">[. 218, 271].</p>
	<p style="text-align: right;">,</p> <p style="text-align: right;">-</p> <p style="text-align: right;">.</p> <p style="text-align: right;">,</p> <p style="text-align: right;">[. 48, 228].</p>

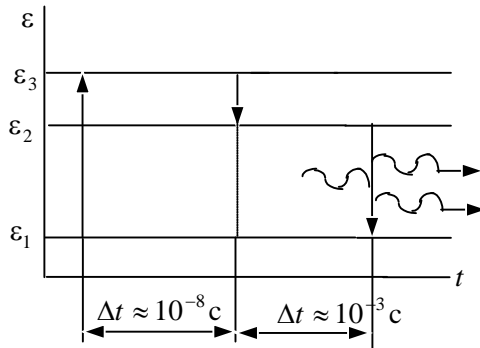
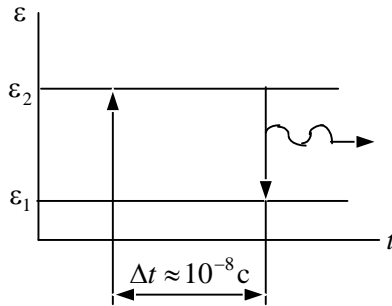
	<p> τ $a = c\tau$ [.277]. </p>
	<p> [.94]. </p>
-	<p> [.76]. </p>
	<p> [.151]. </p>
-	<p> $(1-2) \cdot 10^7$ 10^{-9} $(1-2) \cdot 10^4$ 10^{14} [7]. </p>
	<p> [14-16]. </p>

	<p>()</p> <p>(50 -70 %)</p> <p>[.91].</p>
	<p>φ:</p> $A = \sqrt{A_1^2 + A_2^2 + 2A_1A_2 \cos \varphi} .$ <p>$\varphi = 2\pi(r_1 - r_2) / \lambda , \quad r_1 \quad r_2$</p> $\Delta = r_1 - r_2$ <p>2 ,</p> <p>[.69, 254].</p>

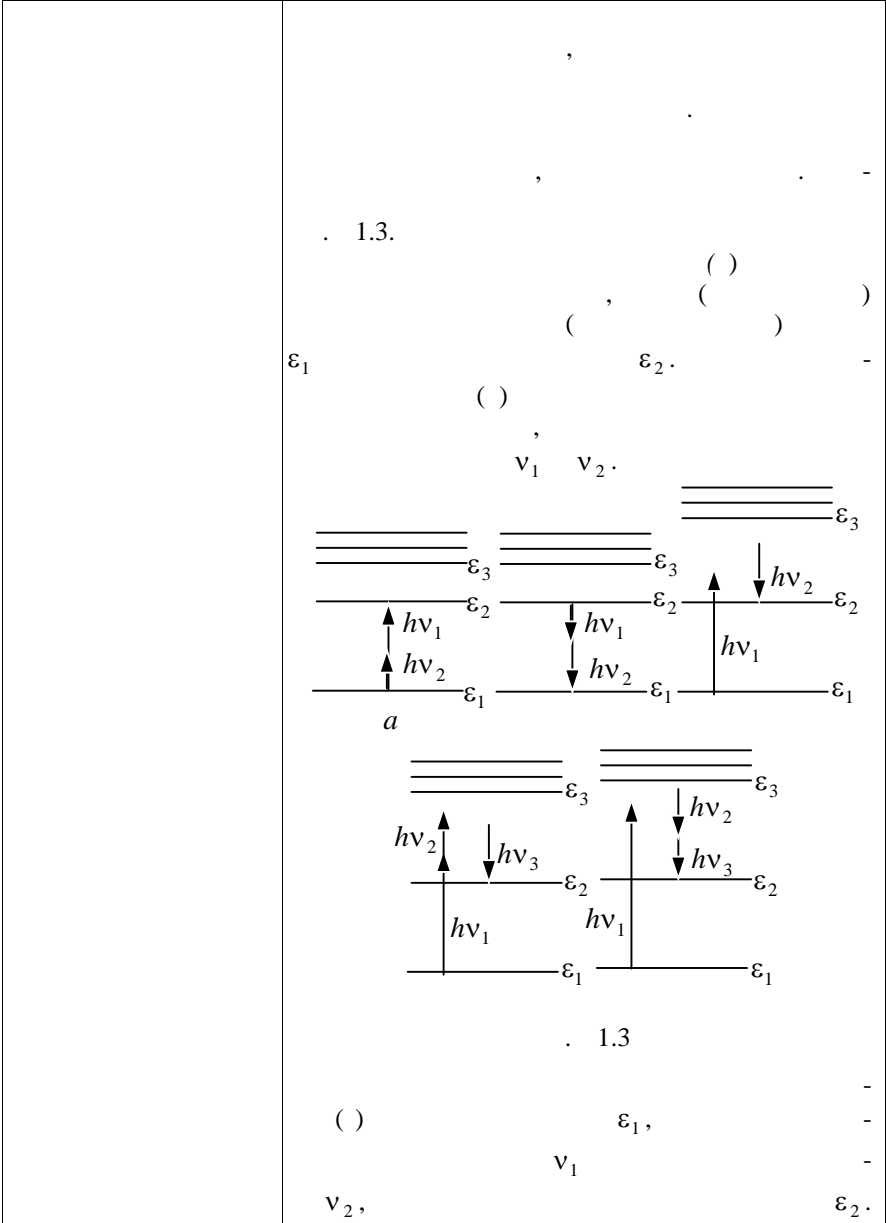
-	<p>, (), , , , . - - - - [.75].</p>
	<p>, (Xe, Kr, Ar, Ne), , . - [131].</p>
	<p>- « ». - - - - $h\nu$, ν - , h - [14].</p>
	<p>, - (, , , , ,); (,); (,); (,);) [14].</p>
-	(,)

	<p> ω' (ω), $h(\omega - \omega')$, Ω, [. 118, 218]. </p>	- - - - - -
	<p>[. 75].</p>	- -
	<p>), [. 120]. </p>	- - -
- -	<p> , . . . , [. 115]. </p>	- -
	<p> 10^{-8} . 10^{-3} . </p>	- - - -

125].



. 12.

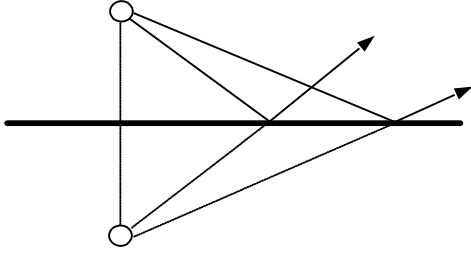


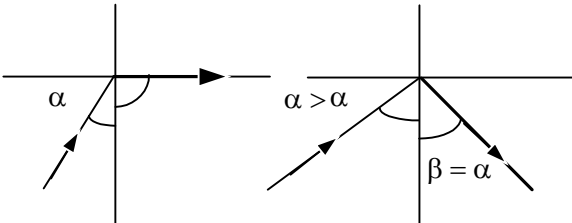
	<p style="text-align: right;">ε_1 ε_2 -</p> <p style="text-align: right;">() ()</p> <p style="text-align: right;">·</p> <p style="text-align: right;">-</p> <p style="text-align: right;">,</p> <p>[. 162].</p>
	<p style="text-align: right;">-</p> <p style="text-align: right;">(</p> <p style="text-align: right;">), [38].</p>
	<p style="text-align: right;">-</p> <p style="text-align: right;">$E = A \sin(\omega t + \varphi)$,</p> <p style="text-align: right;">ω φ</p> <p style="text-align: right;">(</p> <p style="text-align: right;">).</p> <p style="text-align: right;">« »</p> <p style="text-align: right;">« » « »,</p> <p>[. 46, 71].</p>
	<p style="text-align: right;">-</p> <p style="text-align: right;">(,)</p> <p style="text-align: right;">·</p> <p style="text-align: right;">-</p> <p style="text-align: right;">,</p> <p style="text-align: right;">,</p> <p style="text-align: right;">,</p> <p style="text-align: right;">, [. 43, 90].</p>

	<p>()</p> <p>« » ()</p> <p>$\Delta N = 0$.</p> <p>[. 31, 173].</p>
	<p>($P = k\varepsilon_0 E$).</p> <p>($E \ll E_a$),</p> <p>$P = a_2 E^2 + a_3 E^3 + \dots$</p> <p>[. 232, 242].</p>
-	<p>[. 235].</p>
	<p>,</p>

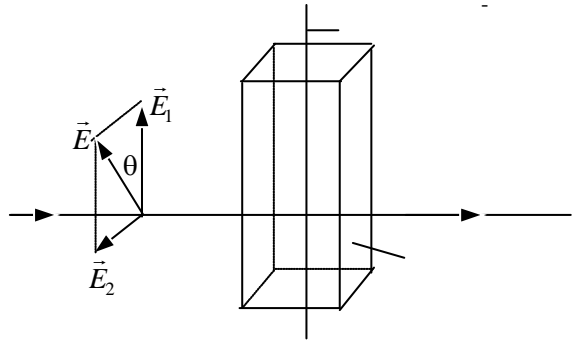
	<p> E_a. $E_a \approx 5 \cdot 10^9$ —, [216]. </p>
	<p> , [. 21]. </p>
-	<p> , (-), [. 277]. </p>
-	<p> , λ λ, [. 33, 174]. </p>
-	<p>), (- - , [. 28, 75]. </p>

	<p> α </p> <p> β </p> <p> , [. 216]. </p>
	<p> $\frac{N_1}{N_2} = \exp\left(\frac{h\nu_2}{kT}\right)$ </p> <p> , [. 112]. </p>
-	<p> , [. 154]. </p>
	<p> , [. 146]. </p>

	<p>,</p> <p>, [. 236].</p>
	<p>,</p> <p>, [. 53].</p>  <p>. 1.4</p>
	<p>,</p> <p>, [. 167-172].</p> <p>,</p> <p>,</p> <p>,</p> <p>, [. 18, 184].</p>

	<p> α . α , v_1 v_2 - n - $n = \frac{\sin \alpha}{\sin 90^\circ} = \sin \alpha$, $\sin \alpha = \frac{v_1}{v_2} = n$. $\alpha > \alpha$, (. 1.5), [. 234]. </p>  <p> . 1.5 </p>
	<p>[230].</p>
	<p>[. 167,222].</p>

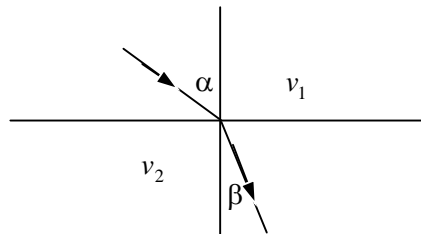
-	<ul style="list-style-type: none"> • (• ; • (; • (<p>).</p> <p>,</p> <p>,</p> <p>,</p> <p>, [.167, 222].</p>
-	<p>(,) .</p> <p>,</p> <p>, [.18, 63].</p>
	<p>,</p> <p>,</p> <p>(() , ,</p> <p>()),</p> <p>,</p> <p>,</p> <p>.</p> <p>\vec{E} θ</p> <p>,</p> <p>: $\vec{E}_1 = \vec{E} \cos \theta$ $\vec{E}_2 = \vec{E} \sin \theta$ (. 1.6).</p> <p>,</p> <p>\vec{E}_1.</p> <p>,</p> <p>, [.63].</p>



. 1.6

, v , , ...
 ()
 :

$$\frac{\sin \alpha}{\sin \beta} = \frac{c}{v_2} = n,$$
 $n -$, α $\beta -$ ()
), . 17.



. 1.7

1

2:

	$\frac{\sin \alpha}{\sin \beta} = \frac{v_1}{v_2} = n_{12}.$ $v_1 > v_2 (n > 1), \quad 1$ $(\beta < \alpha),$ $v_1 < v_2 (n < 1)$ $(\beta > \alpha) \quad 1$ <p>[233].</p>	- - -
	<p>,) (</p> <p>) (</p> <p>.</p> <p>,</p> <p>,</p> <p>.</p> <p>, [. 30].</p>	- - - - - -
	<p>[. 233].</p> <p>-</p> <p>,</p>	- - -
	<p>,</p> <p>.</p> <p>,</p> <p>, [. 235].</p>	- - - -
	<p>.</p>	-

	$n = n_0 + n_2 E^2,$ $n_0 = \dots$ <p>[. 216, 233].</p>
	<p>[. 19].</p>
	<p>()</p> $\frac{h}{2\pi} \sqrt{s(s+1)},$ <p>$s = \dots$</p> <p>() $s = \frac{1}{2},$ $s = 1.$</p> <p>$s = 0,$ [. 152].</p>

	<p> , , , [.69, 183]. </p>
	<p> (,) Nd , [.55]. Cr </p>
	<p> , [.138]. </p>

2

1.

ε –

v –

h –

$$, \quad h = 6,626 \cdot 10^{-34} \quad .$$

λ –

m_e –

$$, \quad m_e = 9,11 \cdot 10^{-31}$$

c –

p –

v –

e –

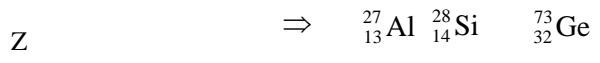
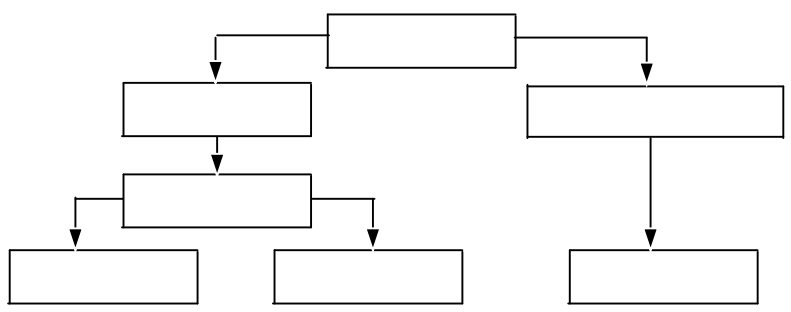
$$, \quad e = 1,602 \cdot 10^{-19}$$

μ_0 –

$$, \quad \mu_0 = 4\pi \cdot 10^{-7} \text{ —}$$

$\epsilon_0 -$, $\epsilon_0 = \frac{1}{36\pi} 10^{-9} -$
 $r -$
 $\epsilon_m -$ $m -$
 $n -$
 $R -$, $R = 3,2898 \cdot 10^{15}$

2.



$Z -$, $A = Z + N -$,
 () .
 .
 $Z ($, $($) ,
 () .

		-	-
${}_{92}^{234}\text{U}$	92	142	92
${}_{92}^{234}\text{U}$	92	143	92
${}_{92}^{234}\text{U}$	92	146	92

Z (),

().

		-	-
${}_{81}^{210}\text{Tl}$	81	129	81
${}_{82}^{210}\text{Pb}$	82	128	82
${}_{83}^{210}\text{Bi}$	83	127	83
${}_{84}^{210}\text{Po}$	84	126	84

3.

, (, , , ...),

, (, , , ...),

, ε (, , ...),

($\varepsilon_1 < \varepsilon_2 < \varepsilon_3 \dots$).

$$\begin{aligned}
 \varepsilon &= \int_{\infty}^r F dr = \int_{\infty}^r \frac{e^2}{4\pi\varepsilon_0 r^2} dr = \frac{e^2}{4\pi\varepsilon_0} \int_{\infty}^r \frac{dr}{r^2} = \frac{e^2}{4\pi\varepsilon_0} \int_{\infty}^r r^{-2} dr = \\
 &= -\frac{e^2}{4\pi\varepsilon_0 r} = \left| r_n = \frac{h^2 \varepsilon_0 n^2}{\pi m_e e^2} \right| = -\frac{m_e e^4}{4n^2 \varepsilon_0^2 h^2} = -\frac{27,21}{n^2} \text{ eV} .
 \end{aligned}$$

$$\varepsilon = \frac{m_e v^2}{2} = \left| v = \frac{e^2}{2n\varepsilon_0 h} \right| = \frac{m_e e^4}{8n^2 \varepsilon_0^2 h^2} .$$

$$\varepsilon = -\frac{\varepsilon}{2} = \frac{|\varepsilon|}{2} ,$$

$$\begin{aligned}
 &n - \\
 \varepsilon_n &= \varepsilon + \varepsilon
 \end{aligned}$$

$$\varepsilon_n = -\frac{m_e e^4}{8n^2 \varepsilon_0^2 h^2} = -\frac{13,6}{n^2}$$

$$\frac{1}{n^2}$$

ε_n

(2.1).

$n = \infty,$

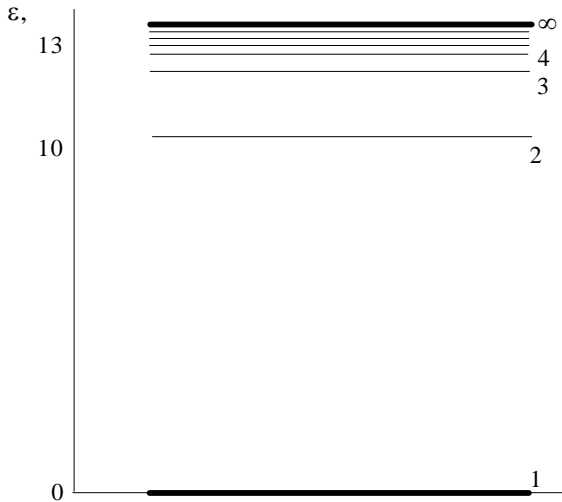
$n = 1$

$n(n \rightarrow \infty)$

ε_n

: $\varepsilon_\infty = U_\infty$. $\varepsilon > U_\infty$ ()

().



. 2.1.

$$\varepsilon \rightarrow \varepsilon_\infty$$

$m,$

n

$$\varepsilon_m - \varepsilon_n = h\nu.$$

$$h\nu = \frac{m_e e^4}{8\varepsilon_0^2 h^2} \left(\frac{1}{n^2} - \frac{1}{m^2} \right) = \left(\frac{1}{n^2} - \frac{1}{m^2} \right) \cdot 2,1799 \cdot 10^{-18} \quad ,$$

$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2} \right) \cdot 3,2898 \cdot 10^{15} \quad .$$

R, \dots

$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2} \right) \cdot R.$$

$l \quad s \quad (\quad) ,$

$L,$

$$\Delta l = 1 \quad \Delta s = 1.$$

$($

$)$

3.

ε

()

ε ,

$\frac{1}{2} (\quad h/2\pi).$

$\frac{1}{2}$

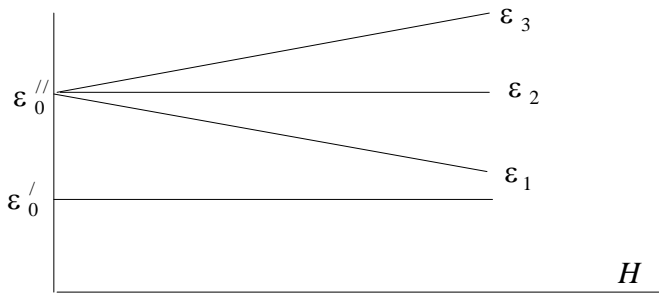
0 1,

$\frac{1}{2} - \frac{1}{2} = 0,$

$\frac{1}{2} + \frac{1}{2} = 1.$

ε_0'

« », « » « » . -
 ε_0'' . -
 ε_0' 0 -
 ε_0'' 1
 ε_3
 ε_1
 ε_2
 . 2.2.

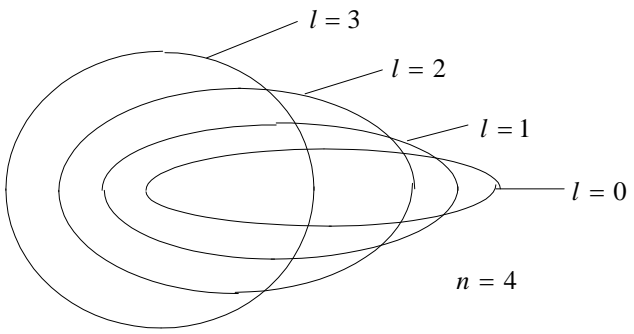


. 2.2.

3 4,
 7 9, .. 16
 -
 16
 -
 -
 -
 -
 -

4.

\bullet ; 4 ;
 \bullet ;
 \bullet ;
 \bullet ;
 n ;
 $(n=1)$, $(n=2) - L$,
 $(n=3) -$, $(n=4) - N$, $(n=5) -$, $(n=6) -$,
 $(n=7) - Q$.
 l ;
 n ;
 $(n-1)$, 2.3.



2.3.

$$: L = l\bar{h}, \quad \bar{h} = \frac{h}{2\pi} ($$

).

$$L = \sqrt{l(l+1)} \hbar.$$

0, 1, 2, 3 ... (n-1).

$$l = n - 1$$

:

0	1	2	3	4	5	6	7	...
s	p	d	f	g	h	l	k	

, .

.

•

•

;

().

,

$z -$
 $, n -$

$z = 2n^2$.

m

(2l+1)

,

,

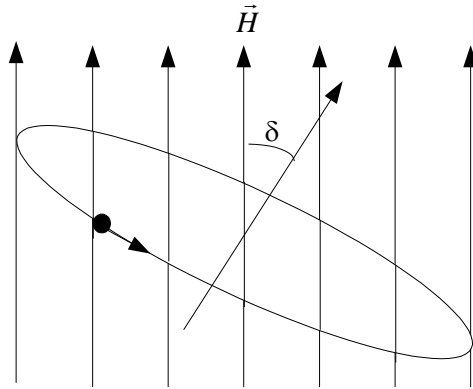
δ

2.4.

$$\pm 1, \pm 2, \pm 3, \dots, \pm l, \quad l - m$$

$$\cos \delta = \frac{m}{l}$$

$$\cos \delta = \frac{m}{\sqrt{l(l+1)}}$$



2.4.

$4d,$

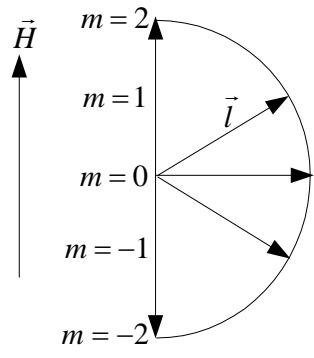
$l = 2,$

$2 \cdot 2 + 1 = 5$

m	-2	-1	0	+1	+2
$\frac{m}{l}$	$\frac{-2}{2}$	$\frac{-1}{2}$	$\frac{0}{2}$	$\frac{+1}{2}$	$\frac{+2}{2}$
$\cos \delta$	-1	-0,5	0	+0,5	+1
δ	180°	120°	90°	60°	0°

(\vec{L}), \vec{l}

2.5. s l $+$ $\frac{1}{2}$ $-$ $\frac{1}{2}$





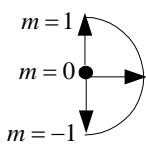
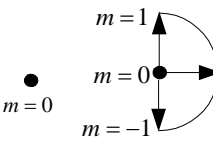
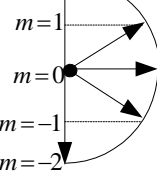
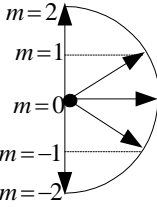






2.5.

$n = 1, 2, 3, \dots$ 2. 6.

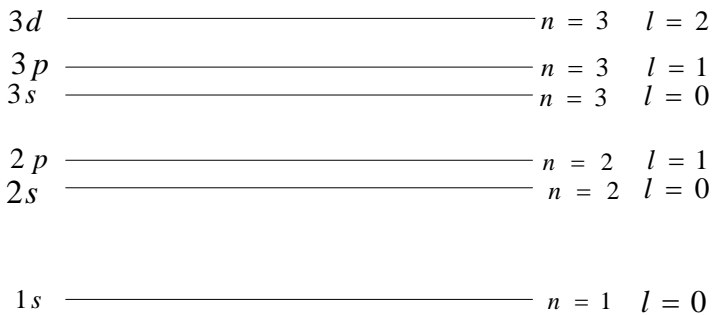
$\text{He}^+, \text{Li}^{2+}, \text{Be}^{3+}, \dots,$

n $l,$

n), l , n), l (. 2.7.

$n = 1$	$n = 2$		$n = 3$		
$l = 0$	$l = 0$	$l = 1$	$l = 0$	$l = 1$	$l = 2$
 $m = 0$	 $m = 0$	 $m = 1$ $m = 0$ $m = -1$	 $m = 1$ $m = 0$ $m = -1$	 $m = 1$ $m = 0$ $m = -1$ $m = -1$ $m = 1$	 $m = 2$ $m = 1$ $m = 0$ $m = -1$ $m = -2$ $m = -1$ $m = 0$
$s = 1/2$  $s = -1/2$	$s = 1/2$  $s = -1/2$	$s = 1/2$  $s = -1/2$	$s = 1/2$  $s = -1/2$	$s = 1/2$  $s = -1/2$	$s = 1/2$  $s = -1/2$

. 2.6.



. 2.7.

$$2(2l + 1)$$

n — номер квантового уровня, l — орбитальный квантовый момент, $2(2l+1)$ — количество орбитальных состояний с данным l .

$2(2l+1)$ — количество орбитальных состояний с данным l .

«...» — «...» ()

$l=0,1,2,\dots$ — $s-, p-, d-, f-$

$1s, 2s, 2p, 3s, 3p, 3d$ — n ,

l .

Z , $1s$,

$()$

$He (Z=2)$

$1s$. $1s^2$ ()

$(Ar) Z=18$

$1s^2 2s^2 2p^6 3s^2 3p^6$

He

$1s2s$

$1s$ $2s$, $1s3d$ $2s2p$

$1s$ $3d$

$1s$ $2s$ $2p$.

$z = 2n^2$, $n-$

$n=1,2,3$

2.1

4.

2.8

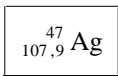
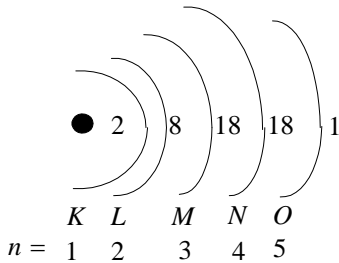
Ag ().

	n	l		m	s		
K	1	0	$1s$	0	$\pm 1/2$	2	2
L	2	0	$2s$	0	$\pm 1/2$	2	8
		1	$2p$	0	$\pm 1/2$	2	
				± 1	$\pm 1/2$	4	
M	3	0	$3s$	0	$\pm 1/2$	2	18
		1	$3p$	0	$\pm 1/2$	2	
				± 1	$\pm 1/2$	4	
		2	$3d$	0	$\pm 1/2$	2	
				± 1	$\pm 1/2$	4	
				± 2	$\pm 1/2$	4	
N	4	0	$4s$	0	$\pm 1/2$	2	32
		1	$4p$	0	$\pm 1/2$	2	
				± 1	$\pm 1/2$	4	
		2	$4d$	0	$\pm 1/2$	2	
				± 1	$\pm 1/2$	4	
				± 1	$\pm 1/2$	4	
		3	$4f$	± 2	$\pm 1/2$	2	
				0	$\pm 1/2$	4	
				± 1	$\pm 1/2$	4	
				± 2	$\pm 1/2$	4	
				± 3			

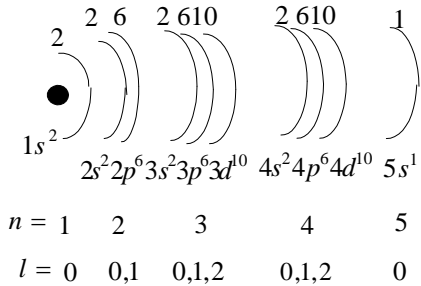
5.

$$\lambda = \frac{h}{m_e v}$$

$$2\pi r_n = n\lambda = \frac{nh}{m_e v_n}$$



. 2.8.



$n = 1 \quad 2 \quad 3 \quad 4 \quad 5$
 $l = 0 \quad 0,1 \quad 0,1,2 \quad 0,1,2 \quad 0$

:

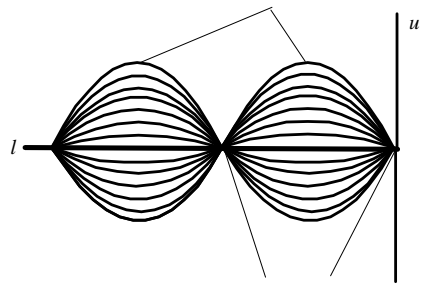
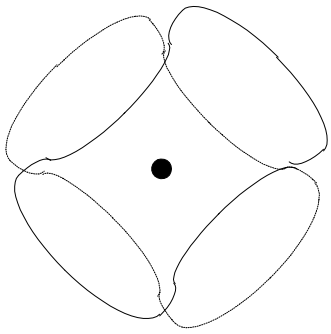
$$L = J\omega = m_e r^2 \omega = m_e r v = \frac{nh}{2\pi}$$

$L -$ () ,
 $\omega -$.
 (ε)
 () , . 2.9, .

»,

. 2.9,

)



. 2.9. -

; -

6.

« »

K, Cu, Ag, Au)
2.10.

I

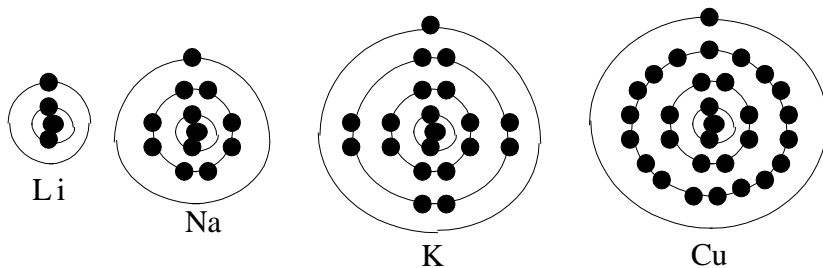
(Li, Na,

VII (F , Cl, Br, I)

7

8

2.11.



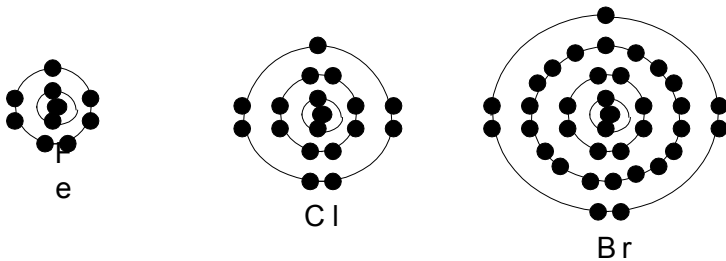
2.10.

I

(Cl),

(Na),

(Cl⁻).



2.11.

7

VII

, Na Cl

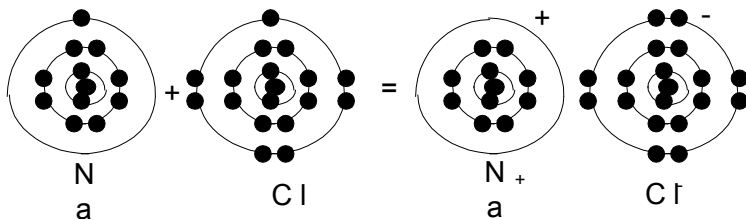
NaCl,
(Na⁺)

Na⁺Cl⁻,
(Cl⁻)

-

-

2.12.



2.12.

IV (C, Si, Ge)

4

), 2.13.

, 2.13

(
2D -
3D.

()

,

Na⁺ Cl⁻

-

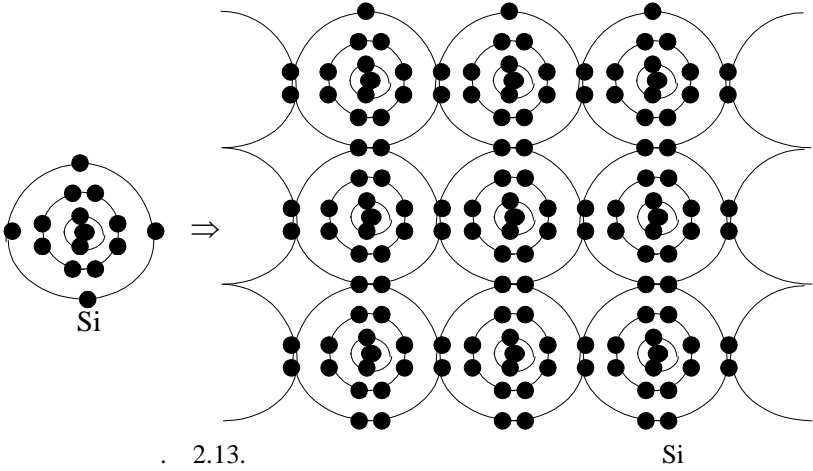
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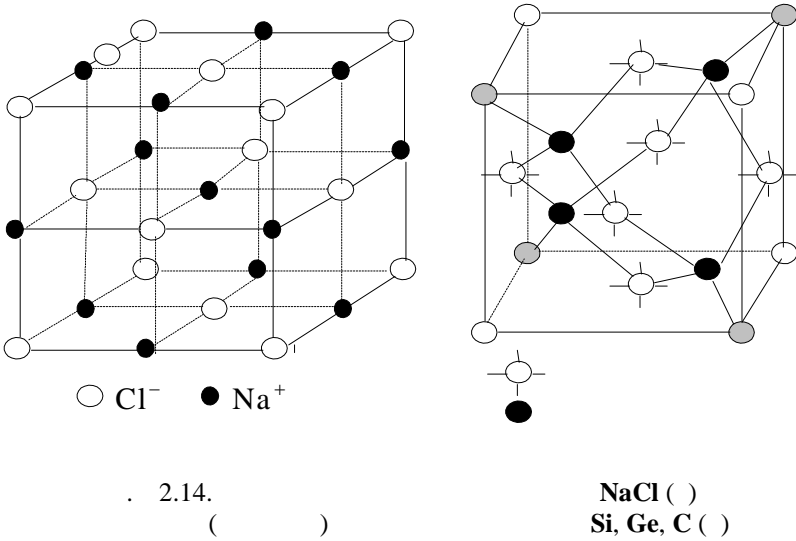
-

,

2.14,



IV
(Si, Ge, C)



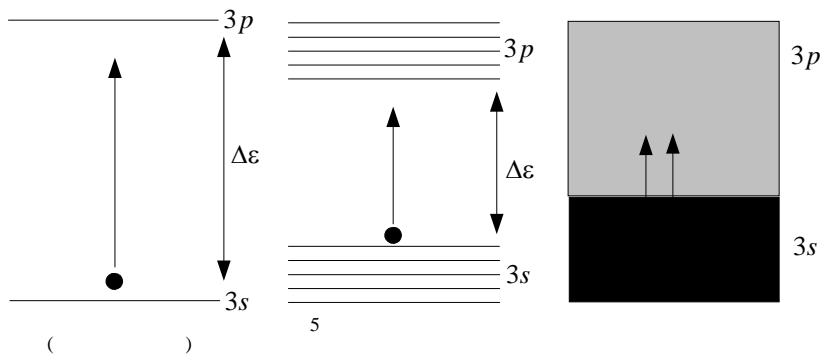
Si, Ge, C . 2.14, .

7.

(. 2.14,),

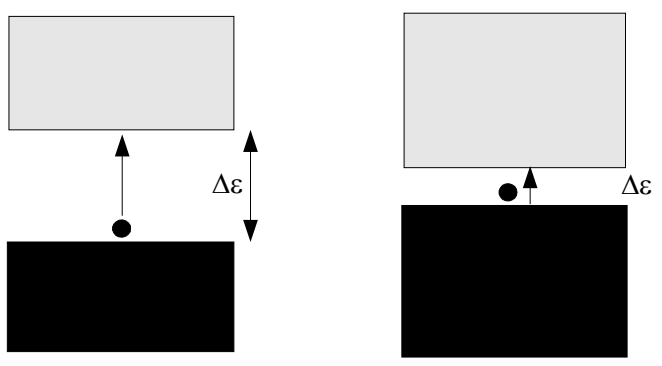
2.15.

« »,



2.15.

. , , -
 , « » , . 2.15.
 () .
 , -
 . 2.15.
 , -
 , -
 $\Delta\varepsilon$
 $\Delta\varepsilon \gg kT$ ($kT - \approx 0,04$) ,
 . 2.16, .



. 2.16: - ;
 -

$\Delta\varepsilon$ kT , (\quad) -
 (\quad) , (\quad)
 , 2.16, .
 , -
 (\quad, \quad, \quad) .
 s
 $(\quad, \quad, \quad 2.2)$. 2.2

	$\frac{\Delta\varepsilon}{kT}$	
(Ag)	0,016	$4d^{10} 5s^1$
(Cu)	0,0172	$3d^{10} 4s^1$
(Au)	0,022	$5d^{10} 6s^1$
(Al)	0,027	$3p^1$
(W)	0,052	$5d^4 6s^2$
()	0,054	$4d^5 5s^1$
(Zn)	0,059	$3d^{10} 4s^2$
(Ni)	0,087	$3d^8 4s^2$
(Fe)	0,1	$3d^6 4s^2$
(Pt)	0,107	$5d^9 6s^1$

3

3.1

(20° **101,3** n $\lambda = 589,3$)

n	n
2,4173	FK3 1,4644
1,325	BK1 1,5100
1,5014	BK7 1,5162
1,333	K 3 1,5181
1,4695	SK1 1,6101
() 1,4864	1,491
() 1,6583	1,588
1,4584	F 3 1,6128
	SF 4 1,7549
	1,3617

3.2

λ ,	λ ,
393,3666	535,048 Tl
396,8468	546,074 Hg
404,6561 Hg	576,9596 Hg
410,1735	579,0634 g
422,6728	587,5618 He
430,7905 Fe	588,9953 Na
434,0465	589,5923 Na
435,8343 Hg	610,3642 Li
438,3547 Fe	636,2347 Zn
441,463 Cd	643,84696 Cd
447,1477	656,2725
460,7331 Sr	667,8149 He
468,02983 Fe	670,7844 Li

479,9914	Cd	686,72	O
486,1327		706,5188	e
492,1929		760,82	O
508,5824	Cd	766,4907	K
527,03602	Fe	769,8979	K

3.3

ε

ε	ε
1,0	4,0...6,0
1,000594	4,0...10,0
2,2	4,5...6,5
2,2	5,0
2,2...2,9	5,0...15,0
2,3...2,5	21,4
2,5...3,0	25,1
2,5...4,0	33,5
3,0...4,0	81
3,0...5,0	10000
3,5...6,0	

3.4

μ

	μ
	50 000
»	15 000
»	10 000
»	5 000
»	600
»	300
»	200
	1,00026
»	1,000021
»	1,000014
»	1,000000 4
	0,9999904
»	0,999987
»	0,999843

	.....	3
	.....	4
1.	.....	12
1.1.	.....	12
1.2.	.....	16
1.3.	.....	19
1.4.	.....	22
1.5.	.....	33
1.5.1.	.....	37
1.5.2.	.....	41
1.5.3.	.....	43
1.5.4.	.....	44
2.	.....	44
2.1.	.....	44
2.2.	.....	49
2.3.	.....	52
2.3.1.	.....	63
2.3.2.	.....	70
2.3.3.	.....	72
2.4.	.....	73
3.	.....	75
3.1.	.....	75
3.2.	.....	84
3.3.	.....	87
3.3.1.	.....	87
3.3.2.	.....	93
3.3.3.	<i>p-n</i> ().....	100

3.4.	.....	109
3.5.	.....	112
3.6.	.....	115
4.	.....	116
4.1.	.....	116
4.2.	.....	118
4.2.1.	.....	121
4.2.2.	.....	125
4.2.3.	.....	127
4.3.	.....	131
4.4.	.....	132
5.	.....	134
5.1.	.....	134
5.2.	.....	140
5.3.	.....	148
5.4.	.....	156
5.5.	.....	164
5.6.	.....	166
5.7.	.....	185
5.8.	.....	193
6.	.....	206
6.1.	.....	206
6.2.	.....	212
6.3.	.....	221
6.4.	.....	225
6.5.	.....	228
6.6.	.....	235

7.	.....	240
7.1.	.....	240
7.2.	.....	246
7.3.	.....	252
7.4.	.....	257
7.5.	.....	264
7.6.	270
8.	274
	1288
	2311
	3335
	337
	340

1. /
 - : , 1985. - 176 .
2. / ;
 - : , 1991. - 544 .
3. / - : , 1981. -
 440 .
4. /
 - : « » , 1969. -
 500 .
5. / ,
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6. / -
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7. / -
 : , 1964. - 64 .
8. / ,
 - : , 1966. - 234 .
9. () /
 , - :
 , 1971. - 452 .
10. / , ,
 - : , 1973. - 450 .
11. (2-) /
 - : , 1982. - 778 .
12. / - : , 1964.
 - 360 .
13. -
 / - : , 1966. - 264 .
14.
 / - : , 1967. - 524 .
15. / - : , 1964.
 - 168 .
16. -
 / - : , 1966. - 376 .

17. . . . / -
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18. . . . / -
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19. . . . / -
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20. . . . / -
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E-mail: osvita2005@gmail.com, www.rambook.ru