

Типы резонаторов полупроводниковых лазеров

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Владимир Уточкин, аспирант 2-го года обучения

16 декабря 2021

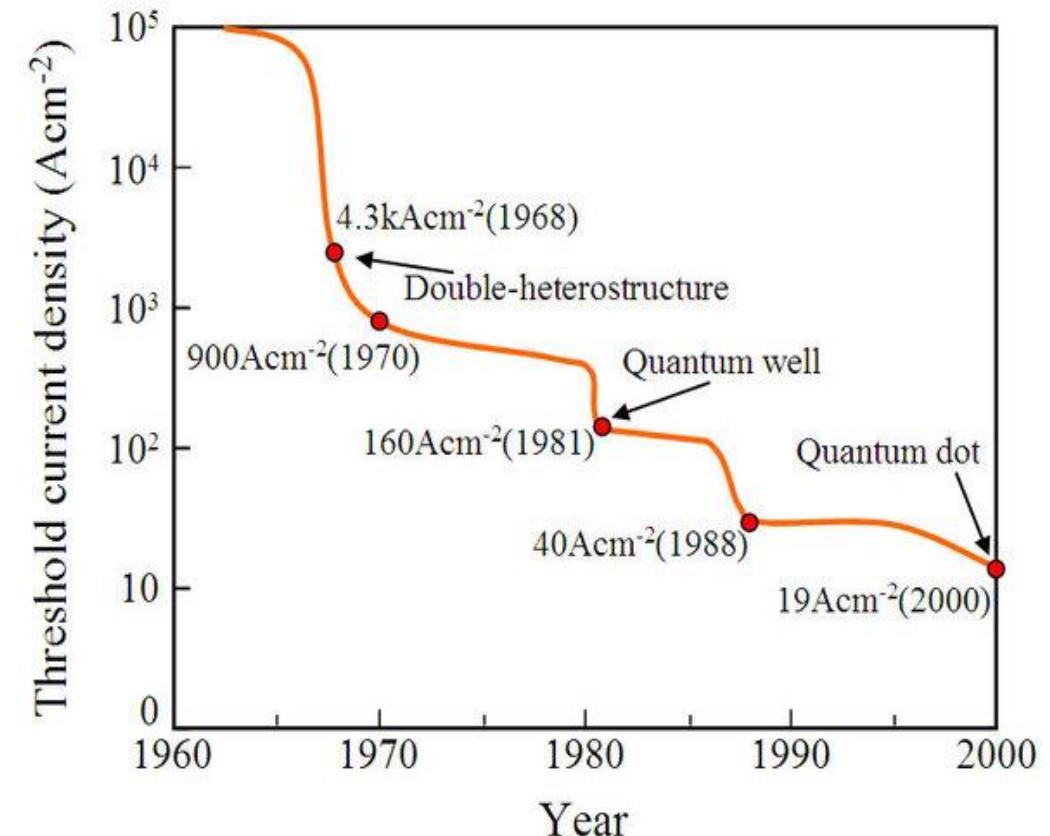
Краткое введение

1962 – первая демонстрация лазерного диода на GaAs (Р. Н. Холл в General Electric, Н. Маршалл в IBM T. J. Watson)

1963 – первый лазерный диод на GaAs в СССР Н. Басов

1970 – первые лазерные диоды на двойном гетеропереходе (Ж. Алферов в СССР и Кремер в США)

1977 - первый инжекционный лазер с квантовыми ямами (П. Д. Дапкусом и Р. Д. Дююи из Rockwell International в сотрудничестве с Н. Холоньяком)

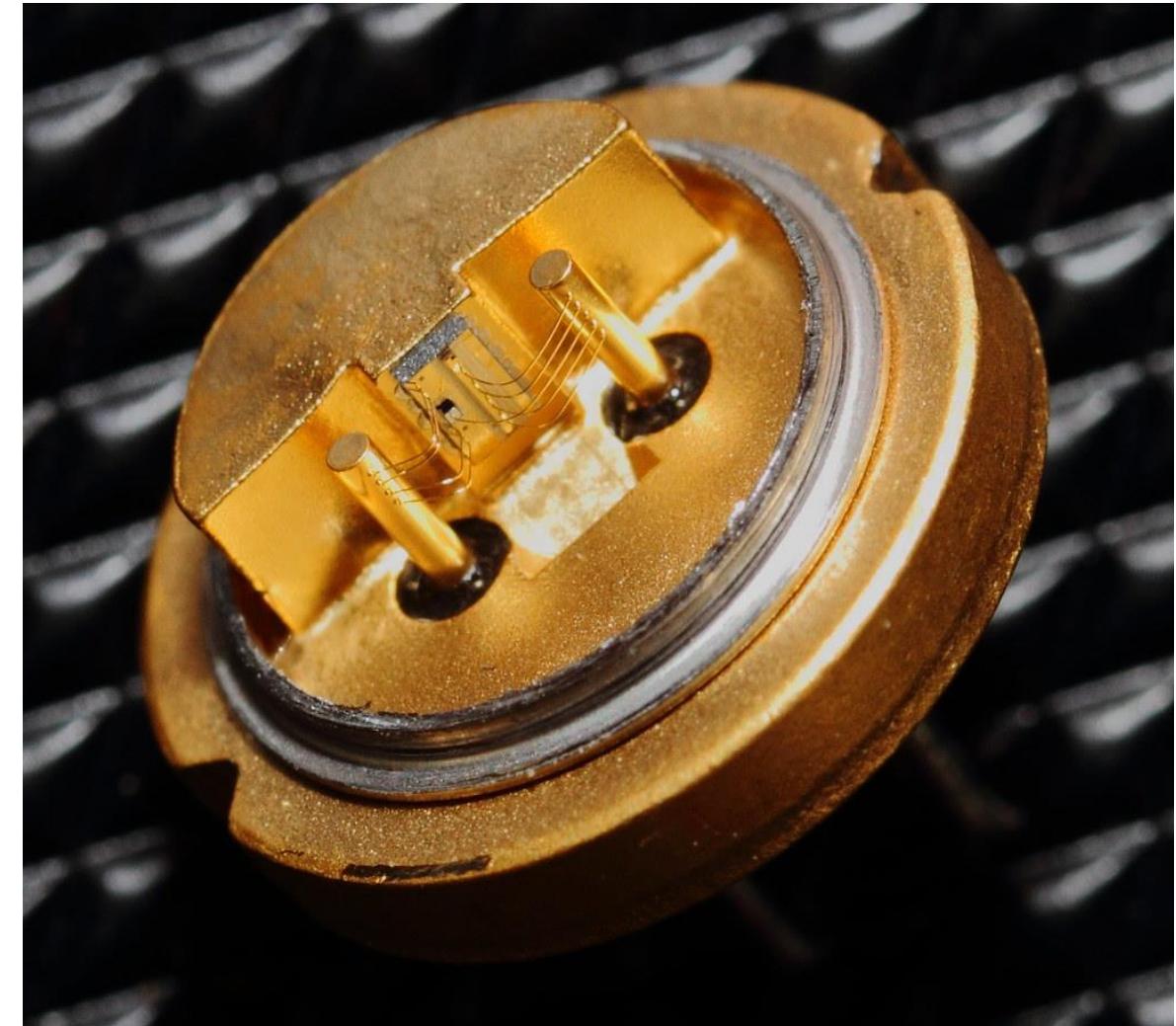
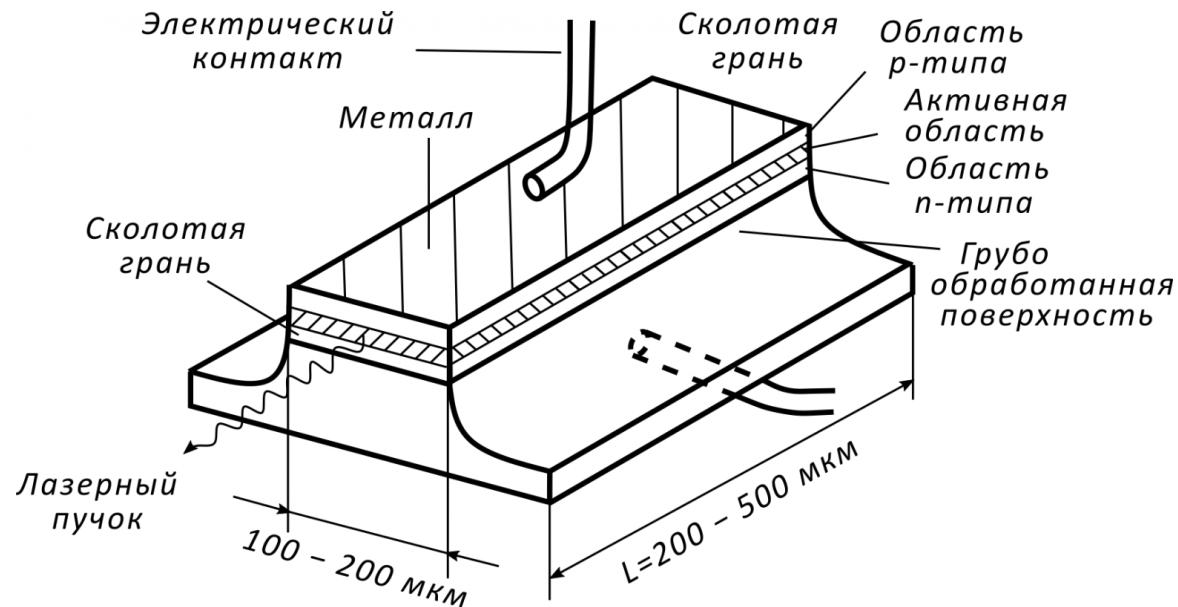


Эволюция значений пороговой плотности тока при комнатной температуре в межзонных инжекционных полупроводниковых лазерах

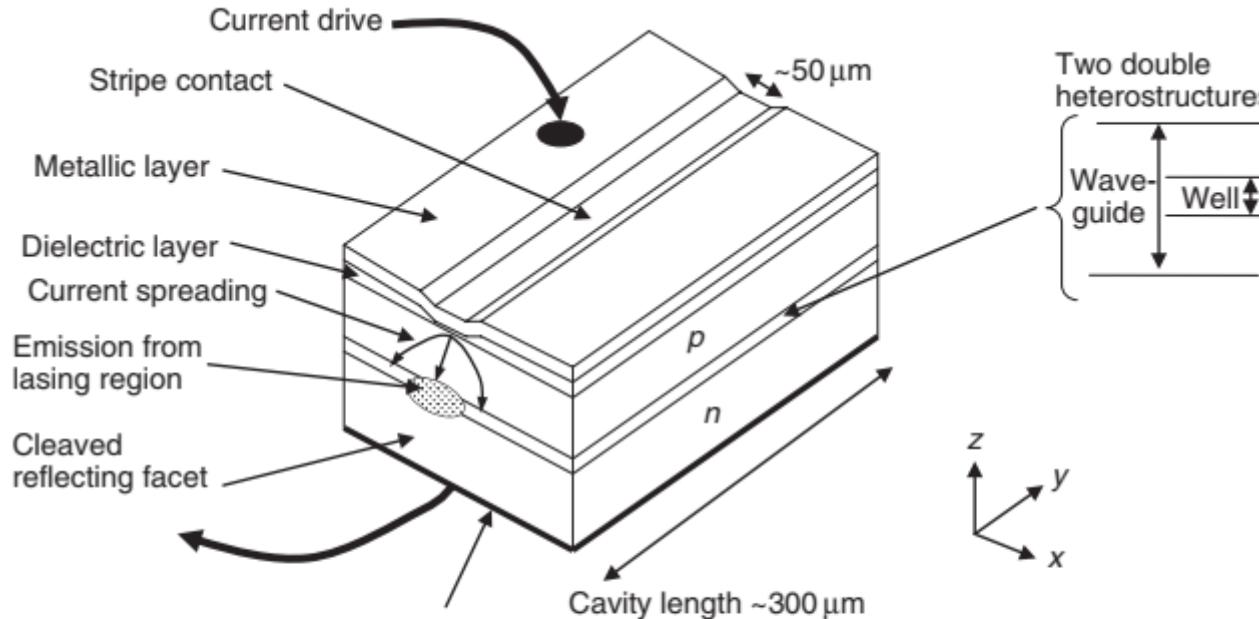
Лазеры с полосковыми резонаторами

Edge-emitting ridge lasers

Общий вид



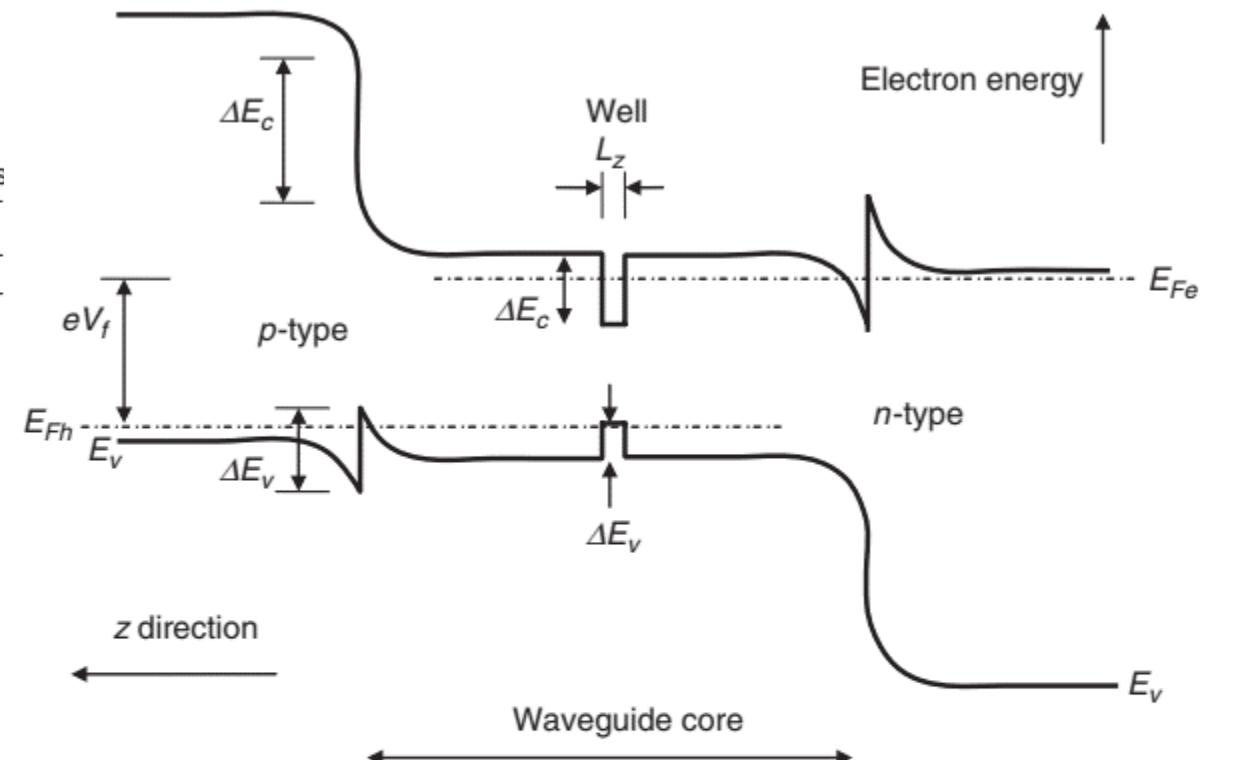
Базовые принципы работы



1.1 Illustration of a generic diode laser chip, with active region comprising two double heterostructures forming the waveguide and well. The width of the contact between the metal and *p*-type semiconductor is restricted by a stripe in the dielectric layer. The active region is pumped by a *p*-*n* junction in the region below the contact stripe with some current spreading.

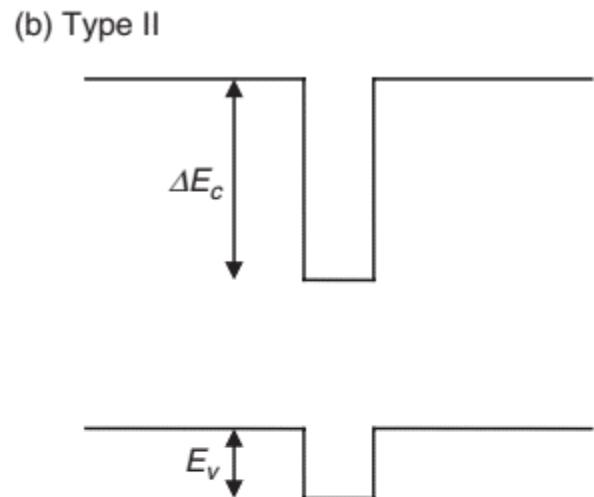
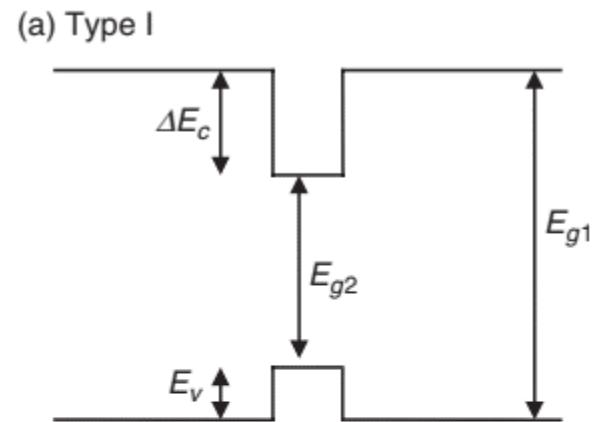
$$G_{th} = \alpha + \frac{1}{2L_c} \ln(R_1 R_2)^{-1}$$

$$Q = \frac{\sqrt{\mathcal{R}}}{1 - \mathcal{R}} kd,$$



1.2 Energy band diagram of the conduction and valence band edges (E_c and E_v , respectively) through the active region in the direction normal to the plane of the layers, drawn under forward bias, V_f , necessary for population inversion in the quantum well, width L_z . The structure comprises two double heterostructures forming the waveguide and the quantum well with band offsets ΔE_c and ΔE_v , which may be different for the waveguide and well. The layer thicknesses are not drawn to scale; band-bending in the well and adjacent barrier material has been neglected.

Базовые принципы работы

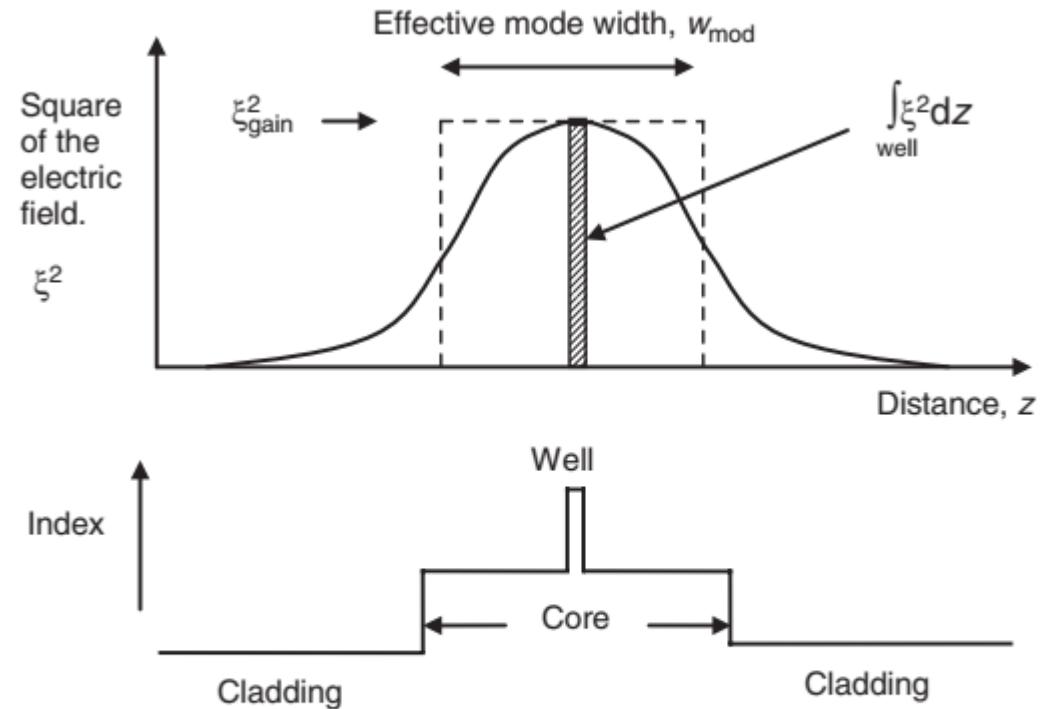


1.3 Energy band diagrams of (a) type I and (b) type II quantum wells formed of materials with band gaps E_{g1} and E_{g2} . The difference between the two structures is the magnitude and sense of the band offsets such that in the type I well electrons and holes have potential minima in the same spatial regions whereas in the type II well the potential minima for electrons and holes are in the narrow gap and wide gap material respectively.

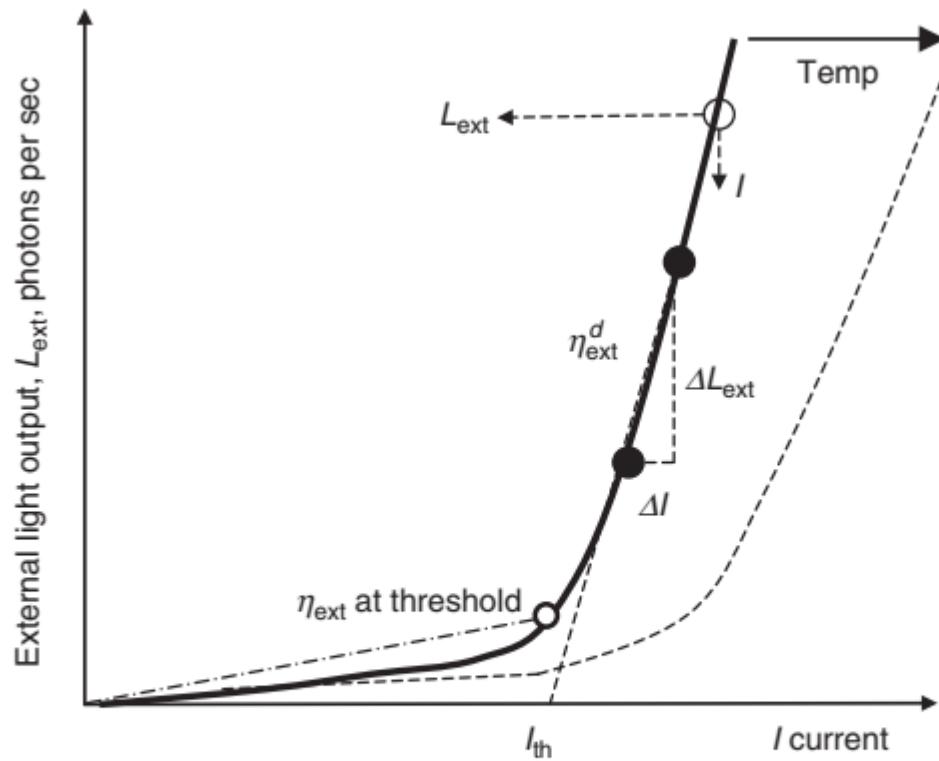
$$G = \frac{\Delta U}{\Delta L} \frac{1}{U}$$

$$\Gamma = \frac{\int_{\text{gain}} \xi^2 dz}{\int_{\text{mod}} \xi^2 dz}$$

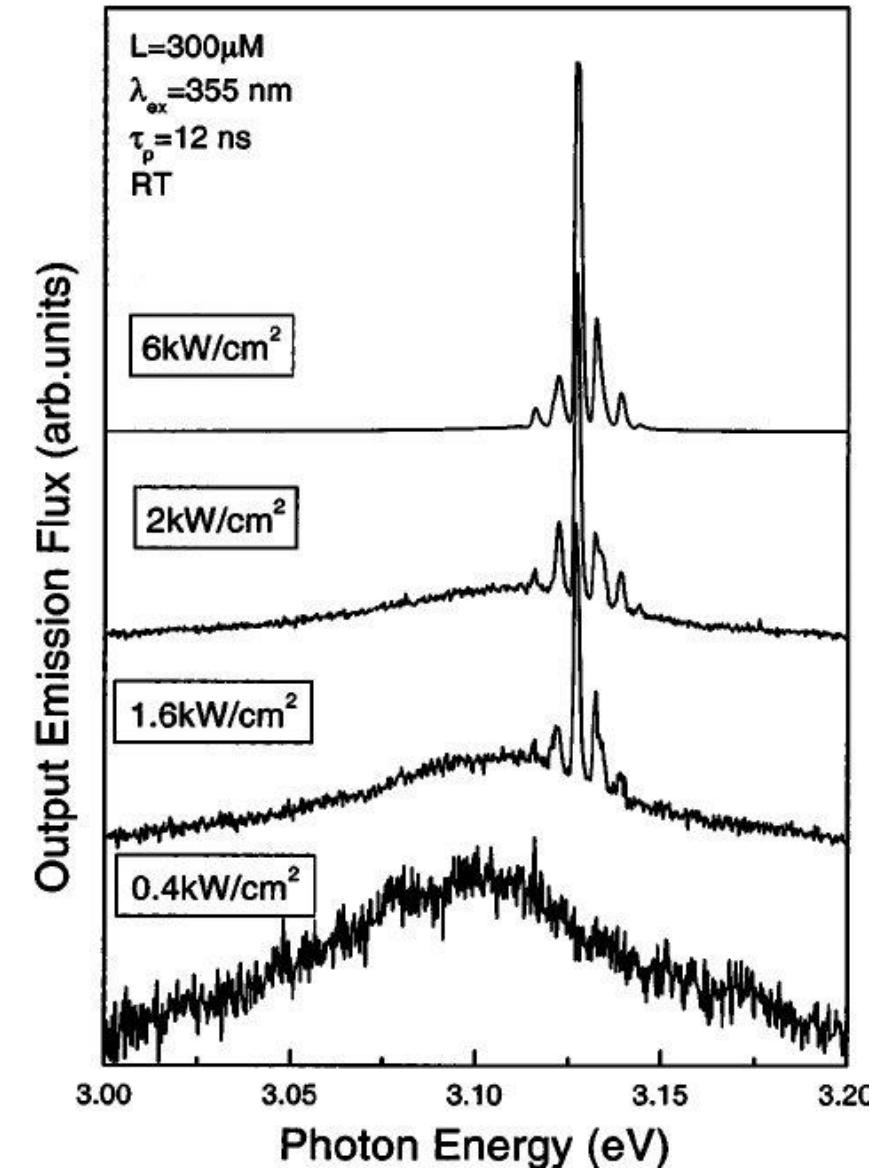
$$w_{\text{mod}} = \frac{\int_{\text{mod}} \xi^2(z) dz}{\xi_{\text{gain}}^2}$$



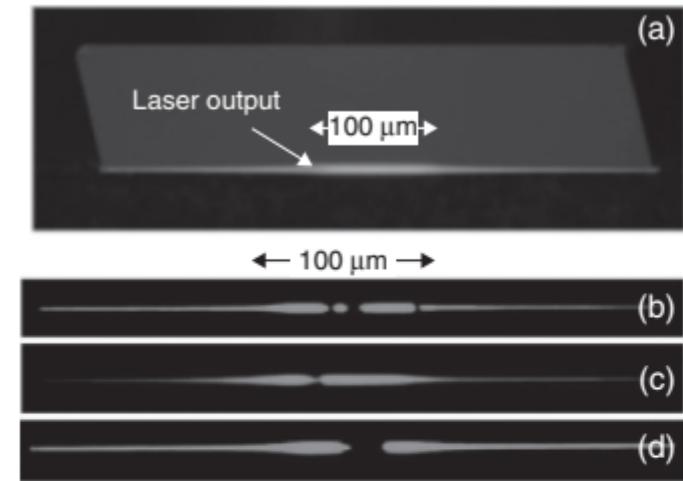
Пороговый характер генерации



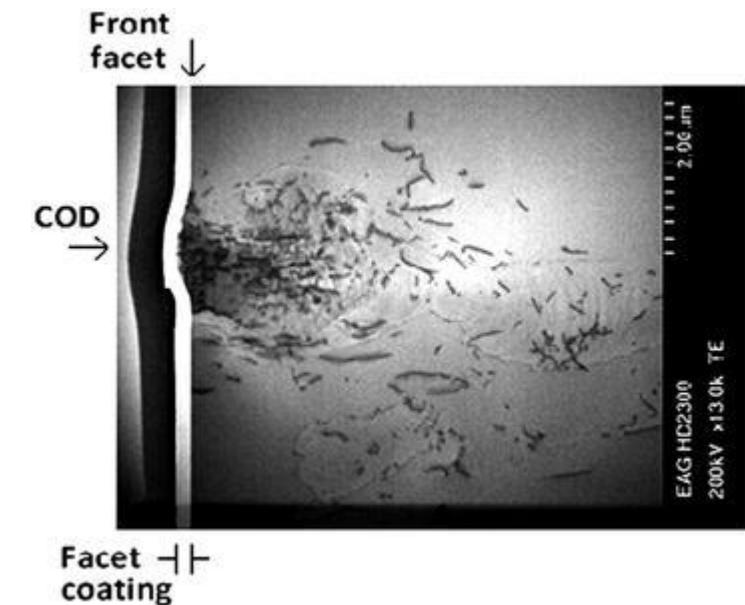
1.7 Schematic light-current curve illustrating identification of the threshold current, I_{th} . The overall external efficiency, η_{ext} at threshold is illustrated, as is the differential external efficiency above threshold. The effect of temperature on the light-current curve is also shown.



Оптическая катастрофическая деградация зеркал (COMD)



3.2 Electroluminescence from the output facet of an AlGaInP broad-area laser (a) before, and (b), (c), (d) after a COMD event. Source: Reprinted with permission from SPIE.¹⁴ (e) COMD data for 806-nm laser diodes before operation. N²-IBE is native-nitride ion-beam epitaxy. Source: Reprinted from the November 2003 edition of *Laser Focus World*, Copyright 2003 by PennWell.²¹



Пути увеличения мощности полосковых лазеров

- Minimizing internal loss and threshold current.
- Minimizing thermal resistance between the active layer and the heat sink. A very low thermal resistance helps in efficient heat dissipation from the active region through the heat sink.
- Maximizing conversion efficiency of the laser by reducing internal loss and carrier leakage and minimize non-radiative recombination.
- minimizing R_1 ,
- increasing w ,
- maximizing d/Γ .

$$P_{\max} = W \cdot \left(\frac{d}{\Gamma} \right) \cdot \left(\frac{1 - R_1}{1 + R_1} \right) \cdot P_{\text{COMD}}$$

where d is the thickness of the active QW layer, Γ is the transverse confinement factor, and P_{COMD} is the internal optical power density at COMD

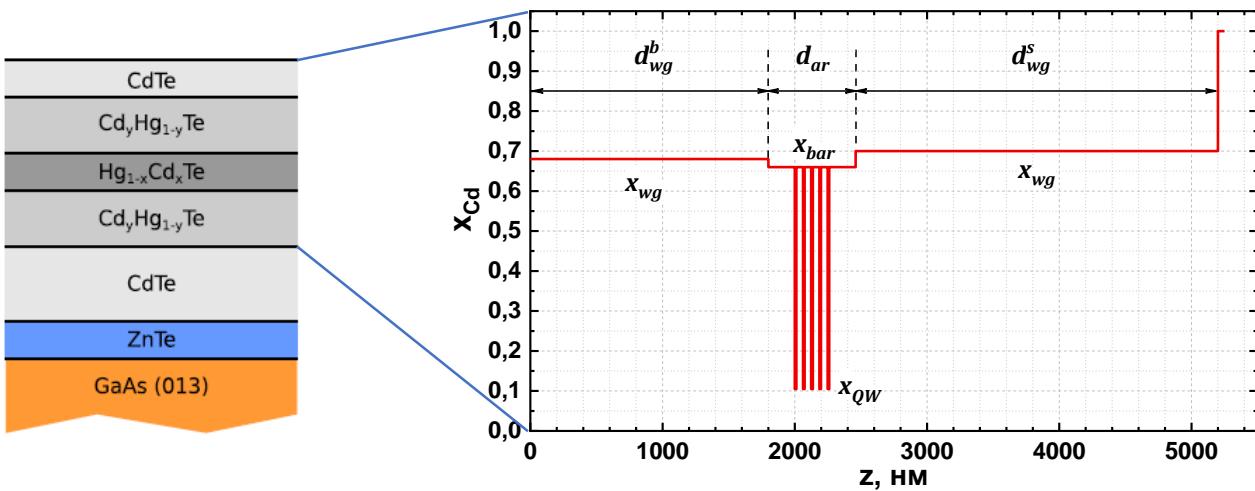
Table 3.1 Approximate power densities necessary to cause COMD in different QW materials

Active-region material	P_{COMD} (MW/cm ²)
InGaAs (0.92–0.98 μm)	18–19
InGaAsP (0.81 μm)	18–19
InAlGaAs (0.81 μm)	13–14
GaAs (0.81–0.87 μm)	10–12
Al _{0.07} GaAs (0.81 μm)	8–9
Al _{0.13} GaAs (0.78 μm)	5

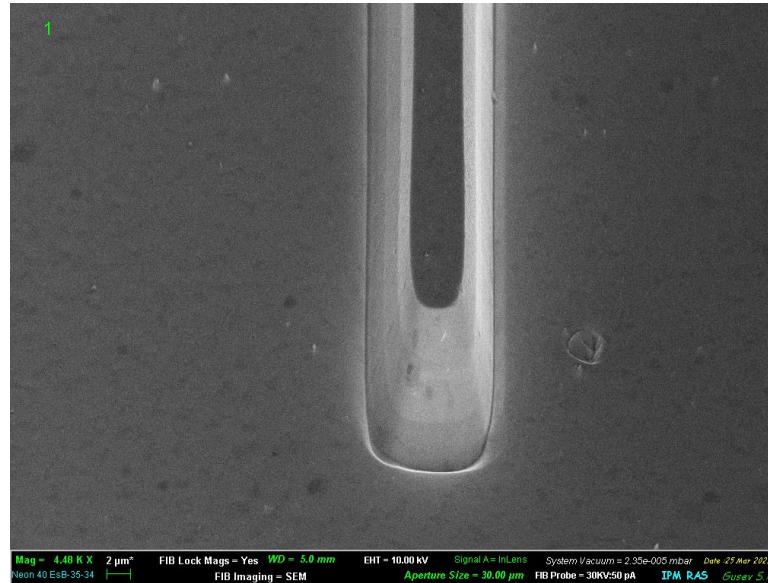
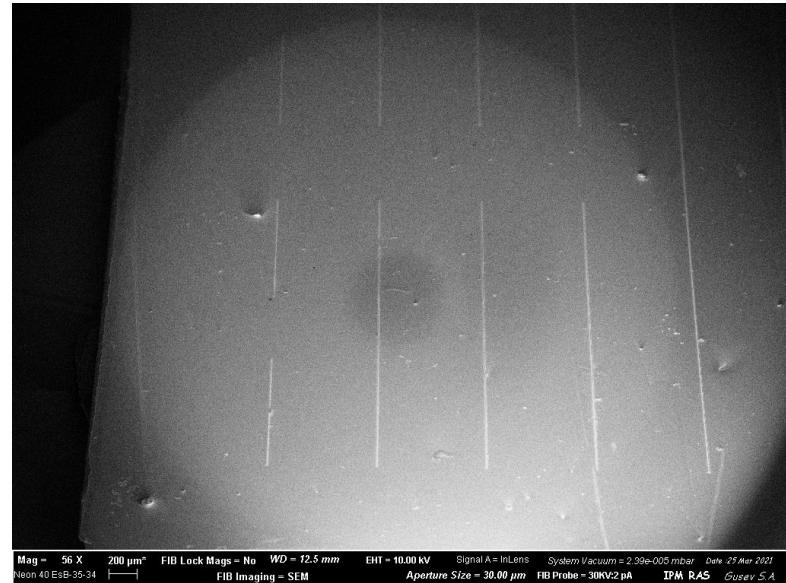
- (a) Removal of surface states resulting from dangling bond imperfections.
 - (b) Removal of surface oxides.
 - (c) Minimize optical absorption at the facet by formation of large bandgap interface.
 - (d) Creation of a diffusion barrier against oxygen incorporation from the atmosphere.
-
- Ultrahigh-vacuum (UHV) cleaving followed by *in situ* passivation.¹⁶
 - Selective area growth for producing non-absorbing mirror lasers.¹⁷
 - Quantum well intermixing (QWI).²⁰
 - Air-cleaving followed by ablation under unreactive ions (e.g. argon or nitrogen).²¹
 - Nitridization to reduce surface-state carrier recombination, prevent surface contamination and provide a higher bandgap surface layer.²²
 - Sulphation²³ followed by a dielectric layer deposition.
 - Hydrogenation and silicon hydride barrier layers.²⁴

- Исторически первый тип резонатора полупроводникового лазера
- Относительно простая технология изготовления зеркал
- Высокая мощность излучения одиночного лазера (до ~ 30 Вт в непрерывном режиме)
- Хорошая диаграмма направленности
- Преимущественно эллиптическая, вытянутая форма пятна лазера
- Торцевая генерация лазерного излучения

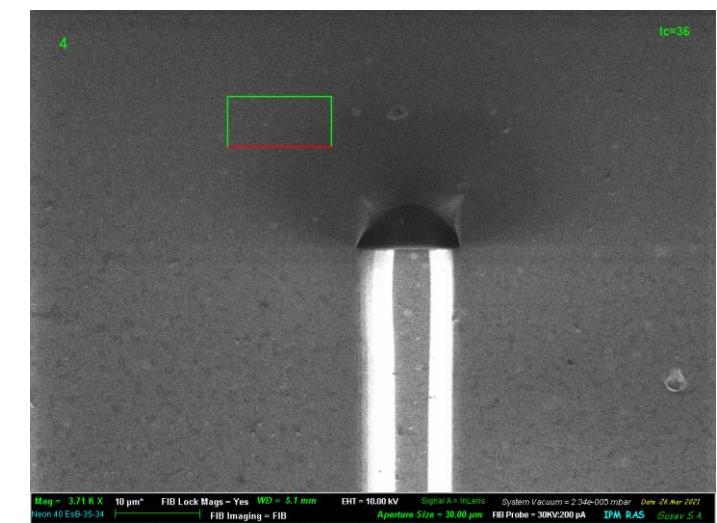
Методика эксперимента и исследованный образец



ИФП СО РАН Н.Н. Михайлов - рост структур

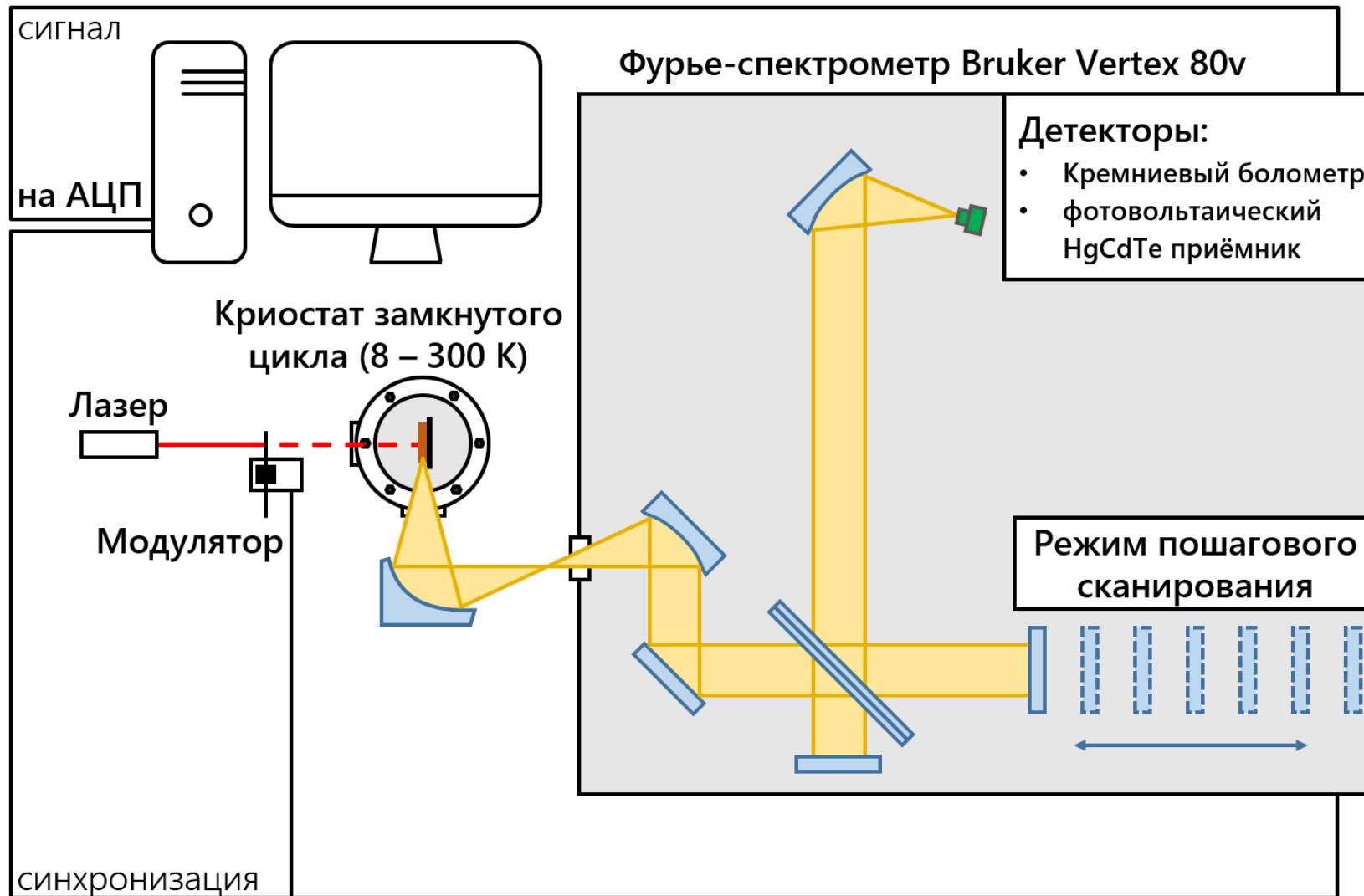


ИФМ РАН
С.А. Гусев
FIB

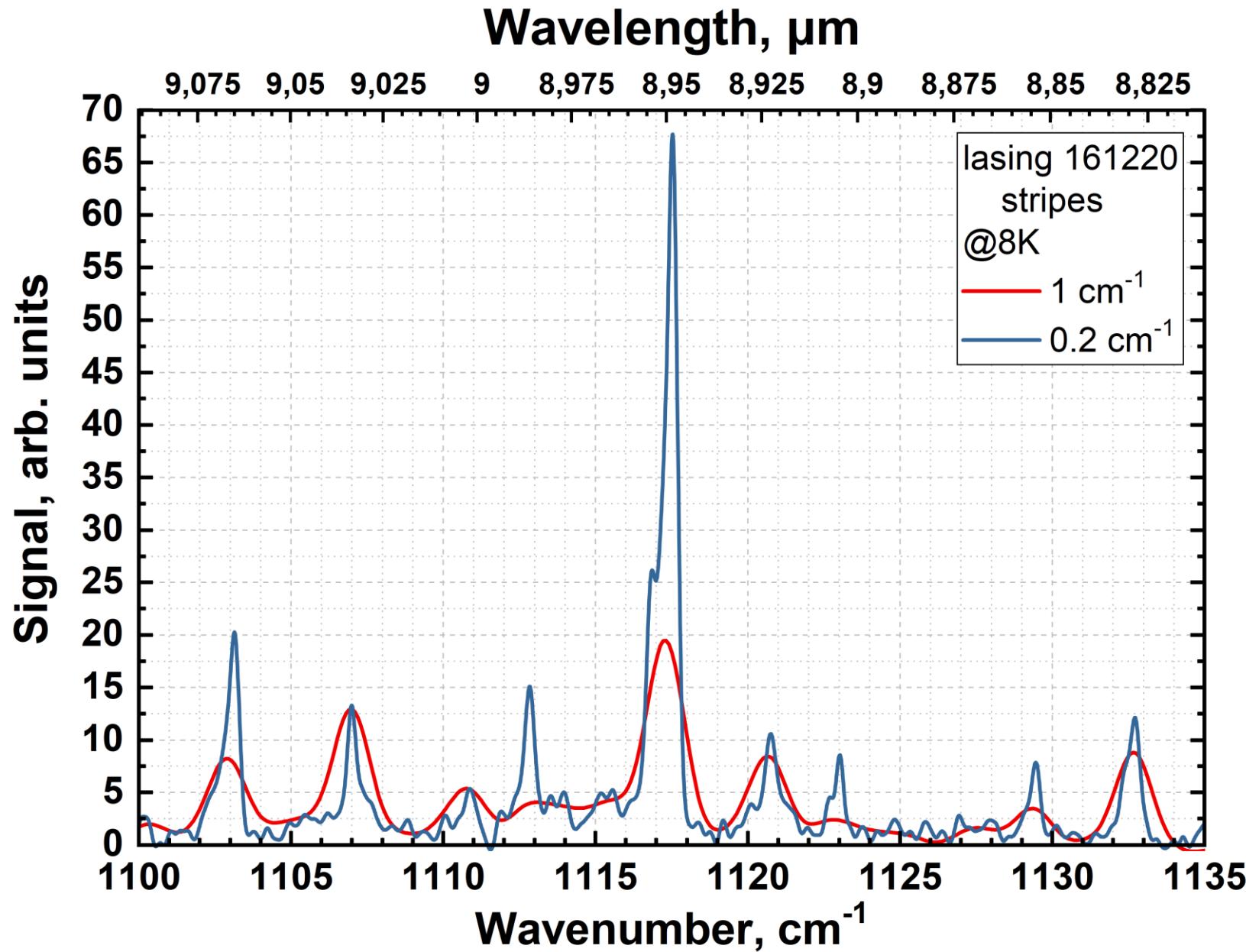


ИФМ РАН Д.В. Шенгуров, Е.Е. Морозова - процессинг полосков

Методика эксперимента и исследованный образец



Первые результаты

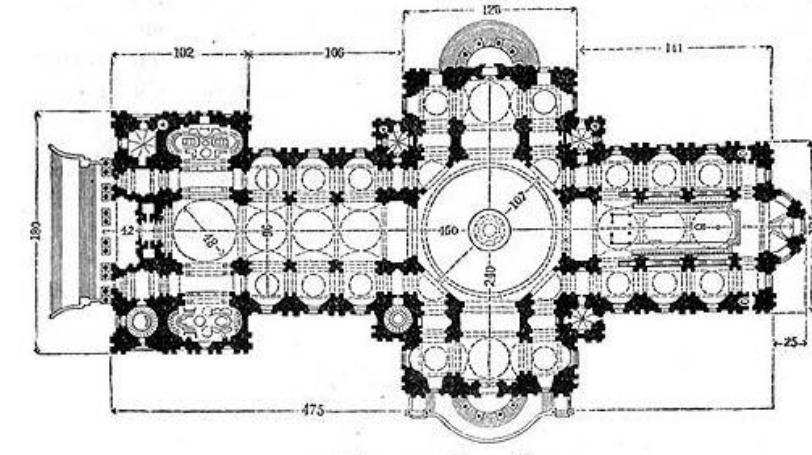


Микродисковые лазеры на модах шепчущей галереи (МШГ, WGM)

Моды шепчущей галереи



Акустический резонатор мод шепчущей галереи - стена эха в Храме Неба, Пекин: изображение на плане и фотография (вставка).



Rayleigh , L. 1910 . The problem of the whispering gallery. *Philosophical Magazine*, 20, 1001–1004

Моды шепчущей галереи

$$\Delta F + \frac{\omega^2}{c^2} F = 0$$

$$F|_{\partial\Omega} = 0$$

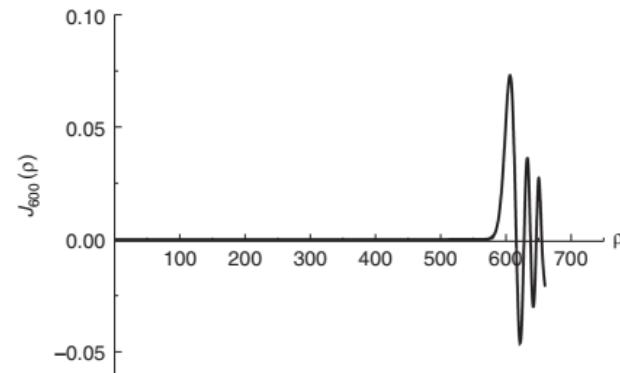
$$F = F_0 J_m(\alpha r) \sin(m\phi + \psi_m) \cos(kz) e^{\pm i\omega t},$$

where ϕ is the polar angle, $k = \frac{\pi n}{h}$, $n = 0, 1, 2, \dots$, $\alpha = \frac{\alpha_{mp}}{R}$, $\omega^2 = c^2(\alpha^2 + k^2)$,

R is the radius of the resonator, h is the height and α_{mp} is the p^{th} root of the equation

$$J_m(\alpha_{mp}) = 0$$

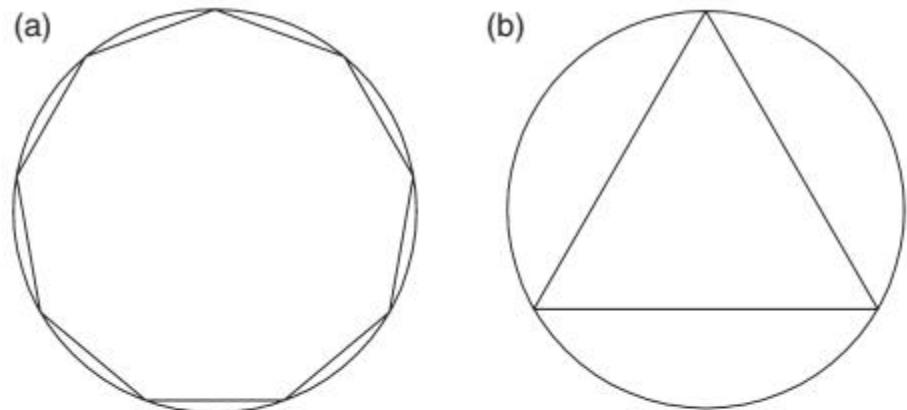
$$\alpha_{mp} = \frac{2\pi R}{\lambda} \gg 1.$$



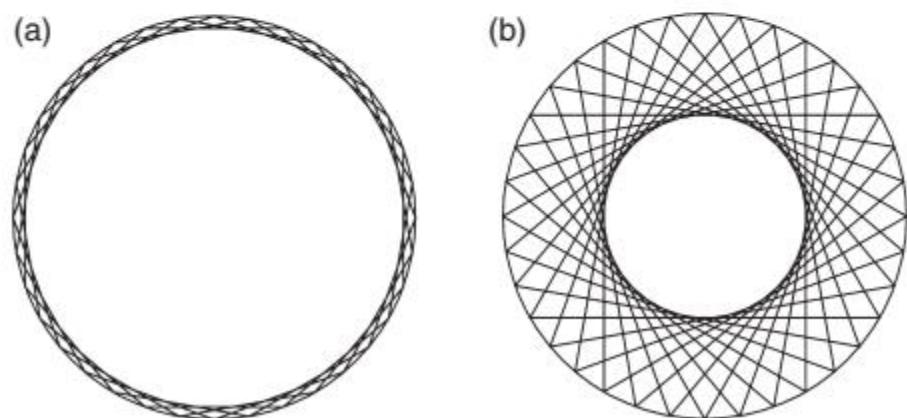
14.1 Bessel function for index $m = 600$.

$$\lambda_m = \frac{2\pi R n}{m},$$

$$\Delta\lambda = 2\pi R \left(\frac{1}{m} - \frac{1}{m+1} \right) \approx \frac{2\pi R}{m^2} = \frac{\lambda^2}{2\pi R},$$

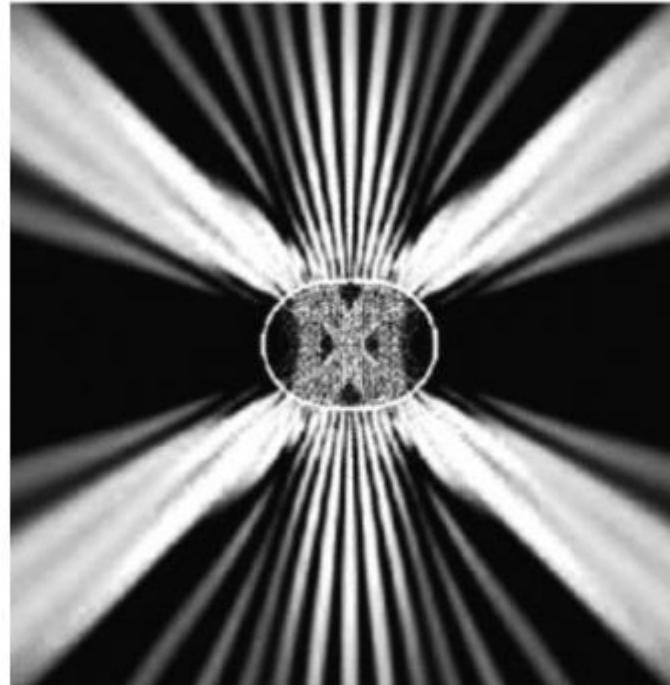
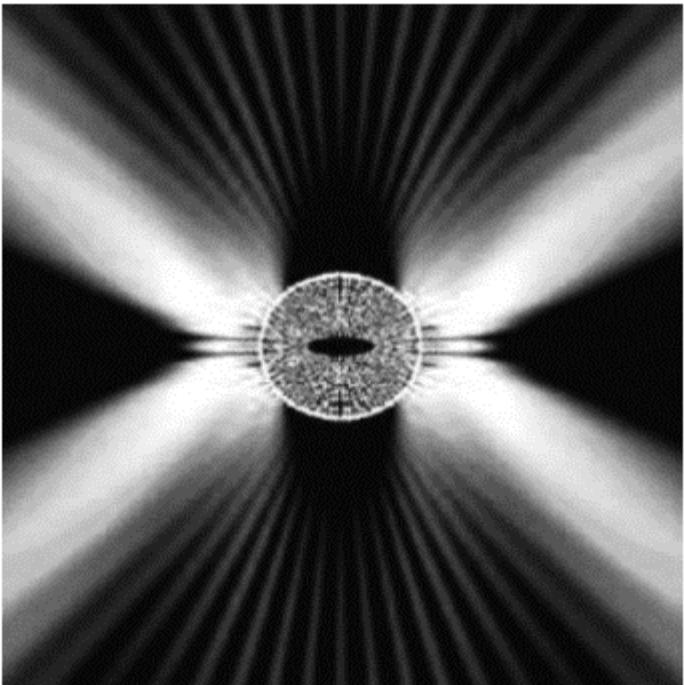


14.2 Basic ray pictures for two modes in a circle.



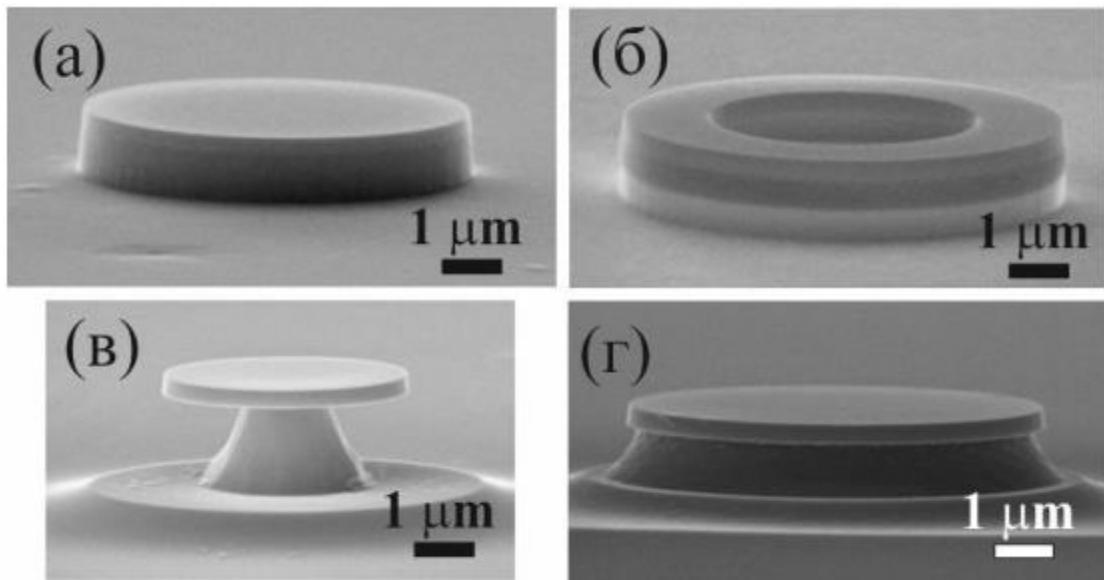
14.3 Family of rays forming WGM (a) and a common mode (b).

Другие моды в микродисковых резонаторах

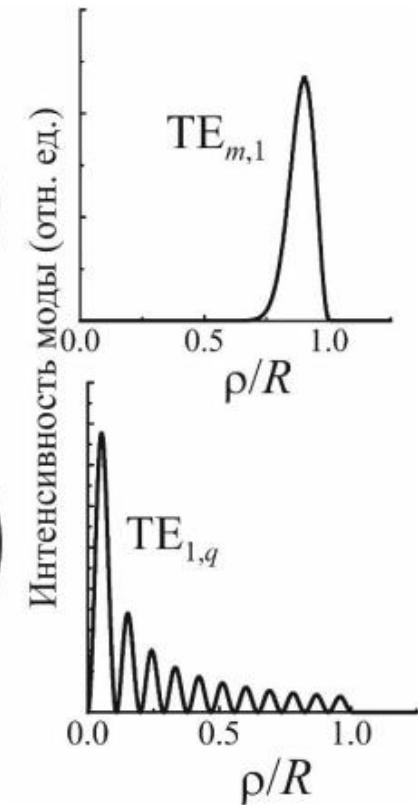
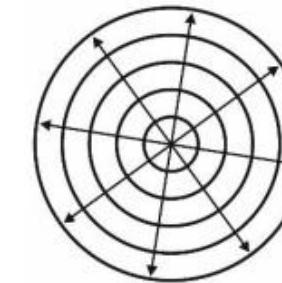
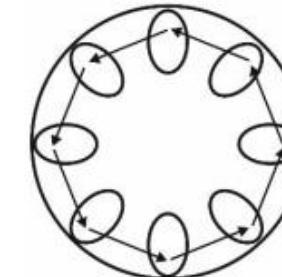
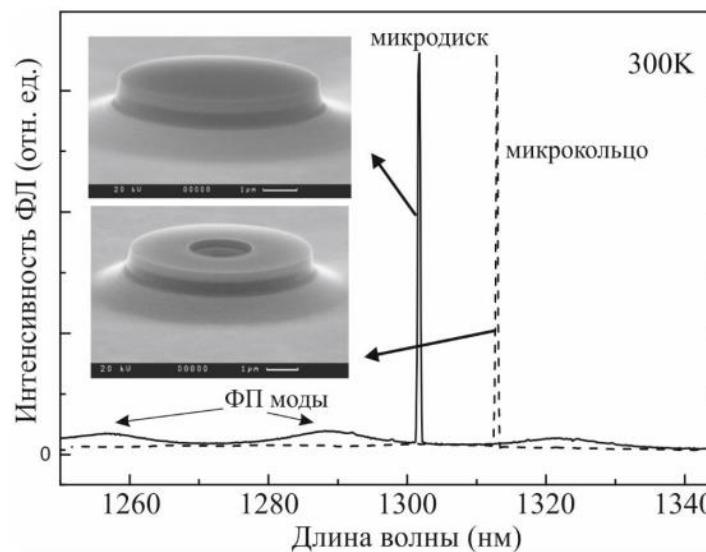


14.4 Chaotic mode (upper plot) and bouncing-ball bow-tie mode (lower plot). Directed light beams are seen. Image from Gmach *et al.* (1998).

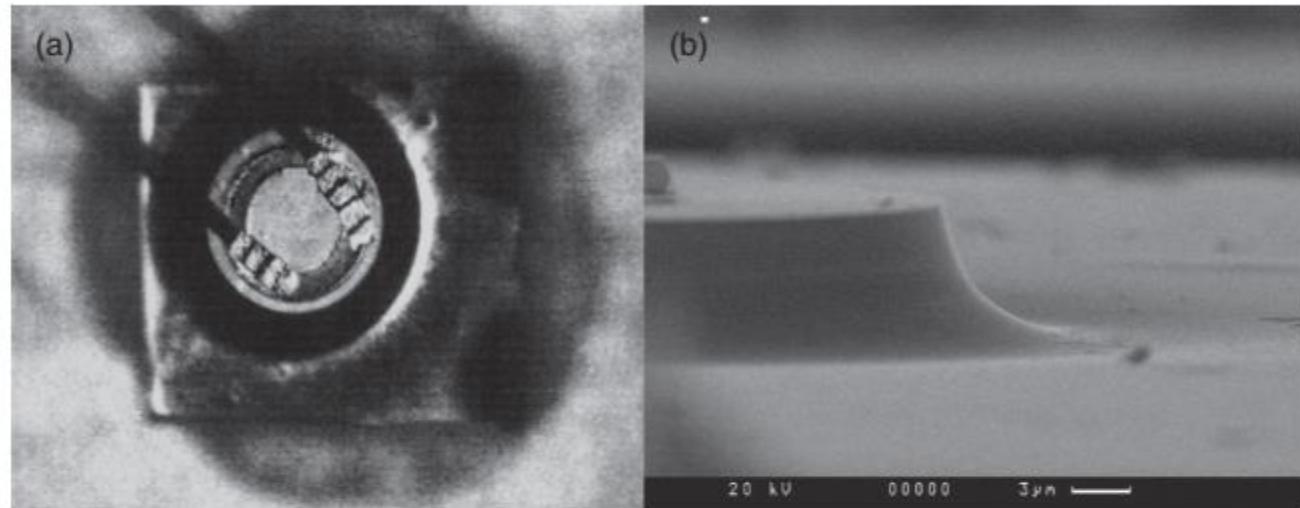
Резонаторы на МШГ



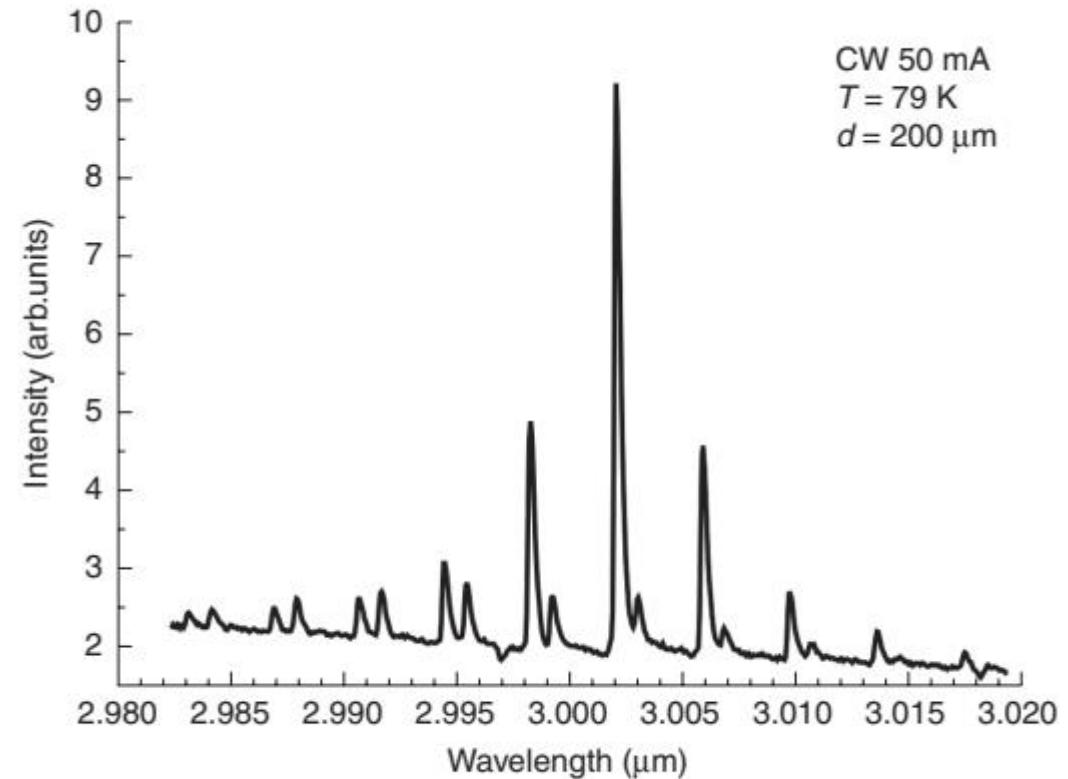
Изображения микрорезонатора в форме
микродисковой мезы (а),
микрокольцевой мезы (б),
подвешенного диска (в),
микродисковой мезы с подтравленным пьедесталом (г).



Модовый состав МШГ



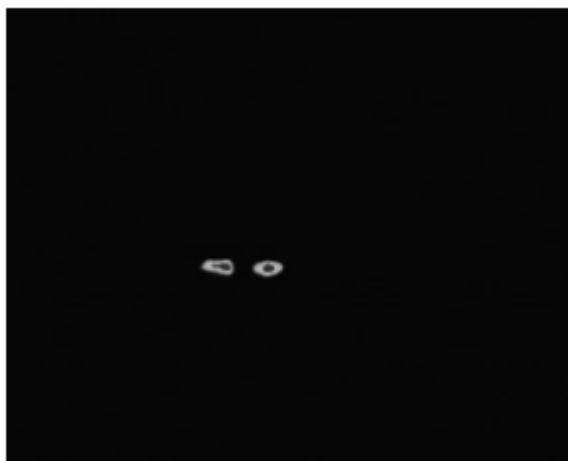
14.9 Micrographs of a disk WGM laser: (a) a side view and (b) a top view of the laser diode.



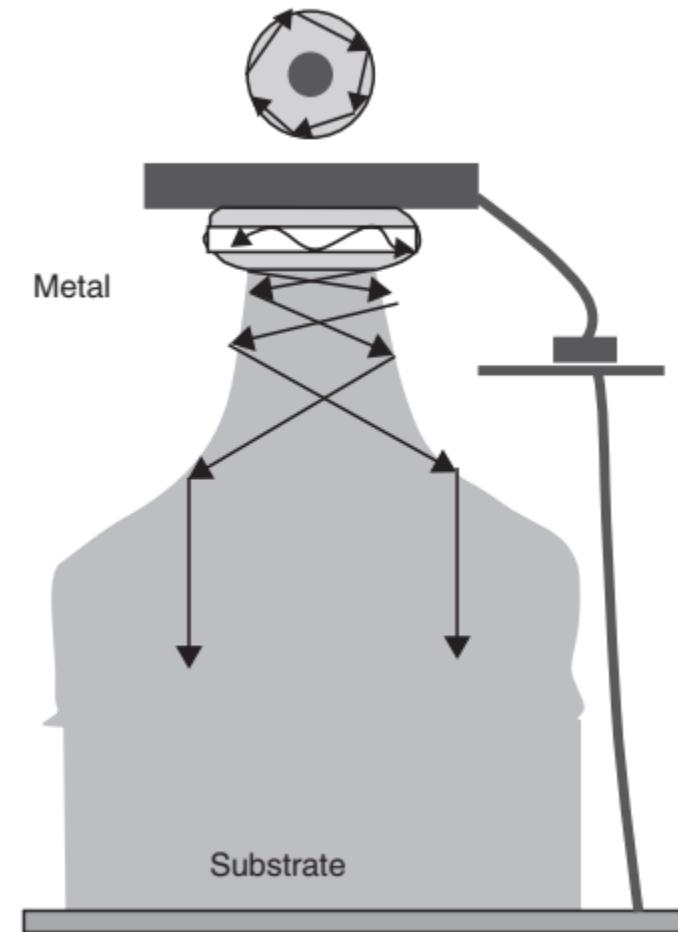
14.10 Lasing spectra of the device in Fig. 14.9.

$$\Delta\lambda = 2\pi R \left(\frac{1}{m} - \frac{1}{m+1} \right) \approx \frac{2\pi R}{m^2} = \frac{\lambda^2}{2\pi R},$$

Проблема вывода излучения

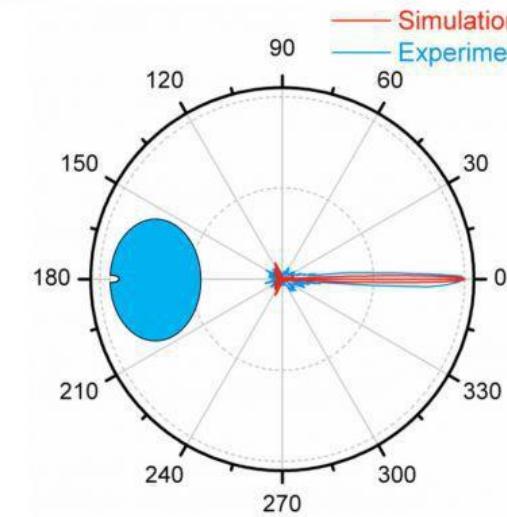
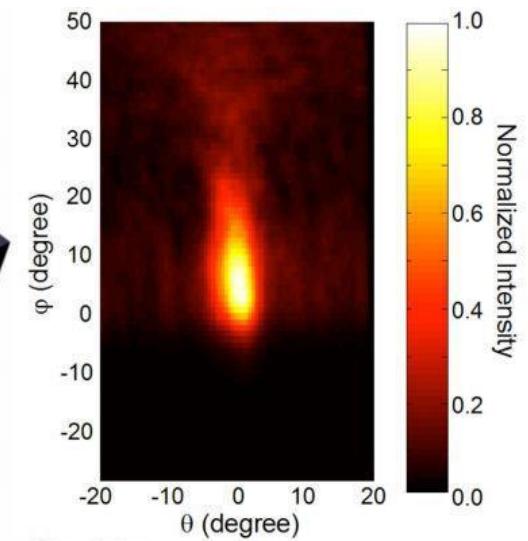
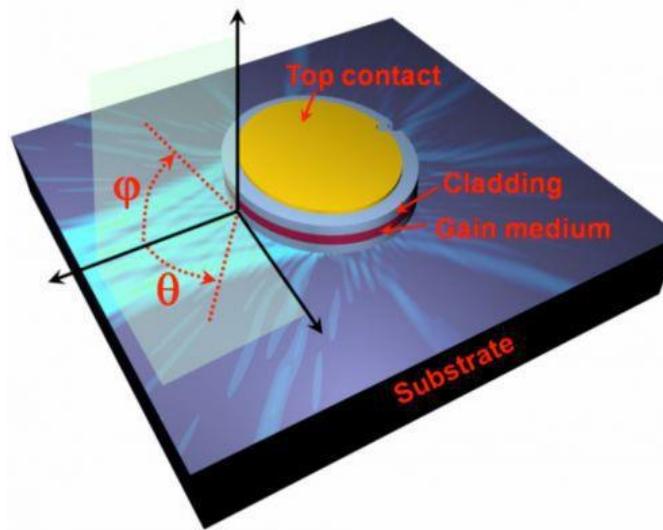
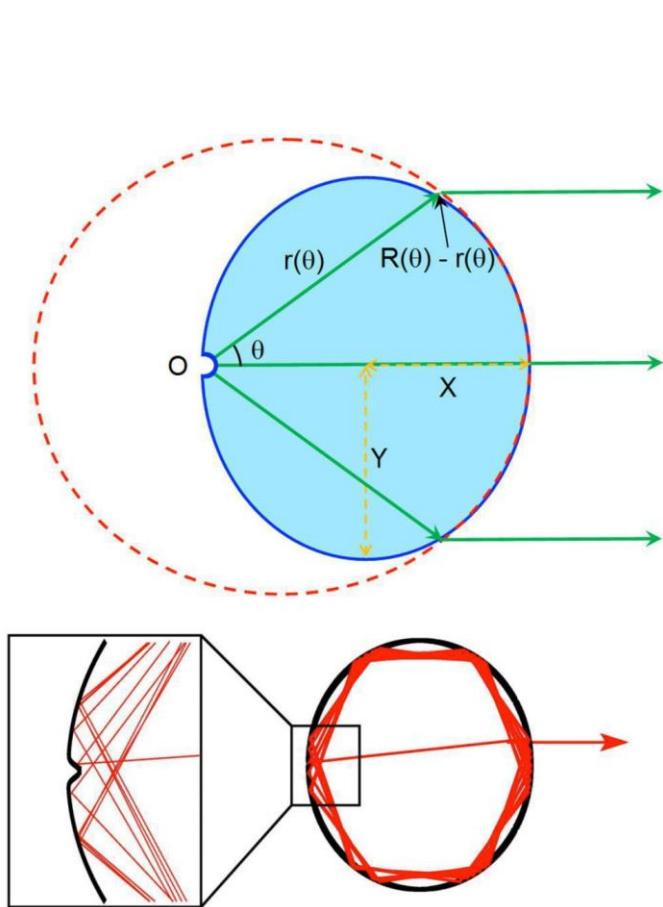
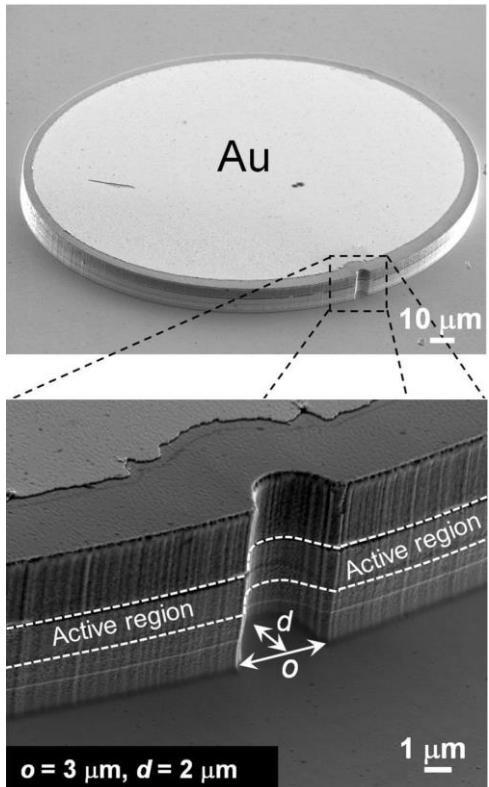


14.17 IR image of an operating half-disk QWGM laser.



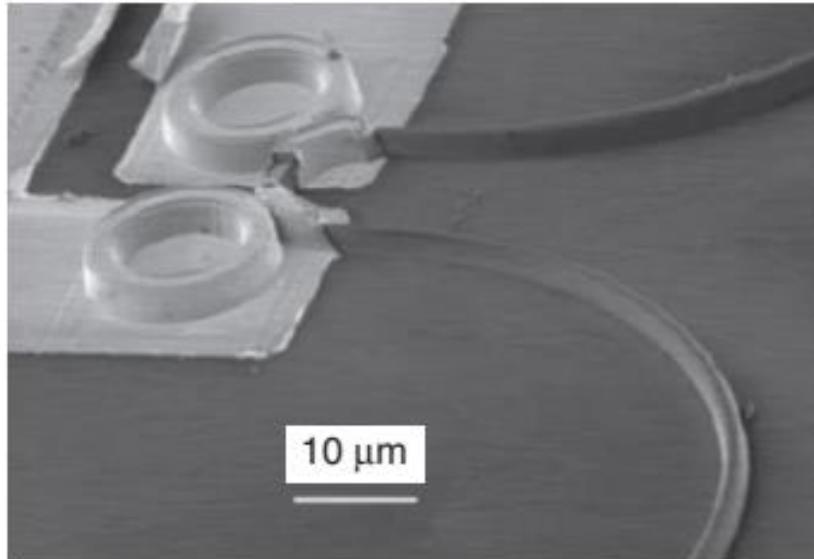
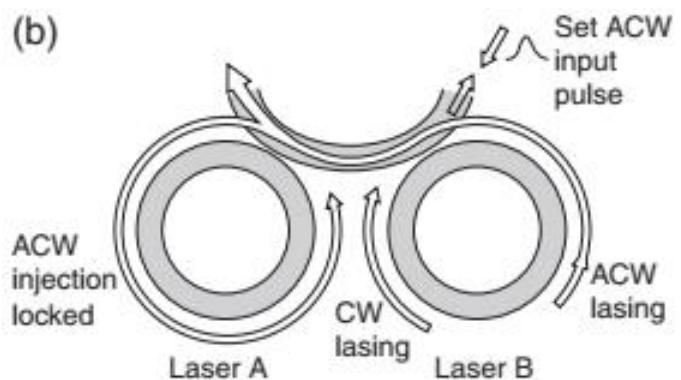
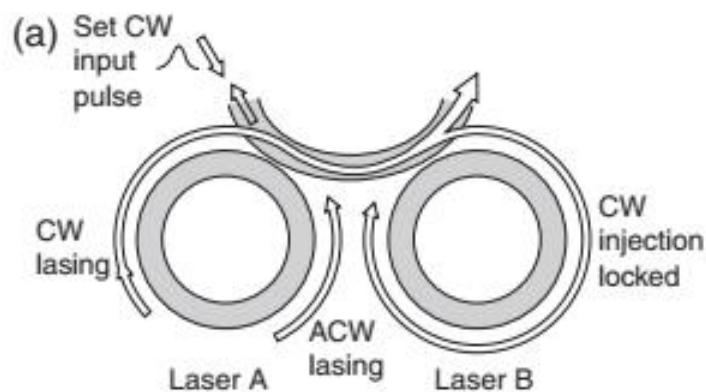
14.19 Vertically emitting WGM laser with the matched waveguide.

Проблема вывода излучения



$Q \sim 10^3$

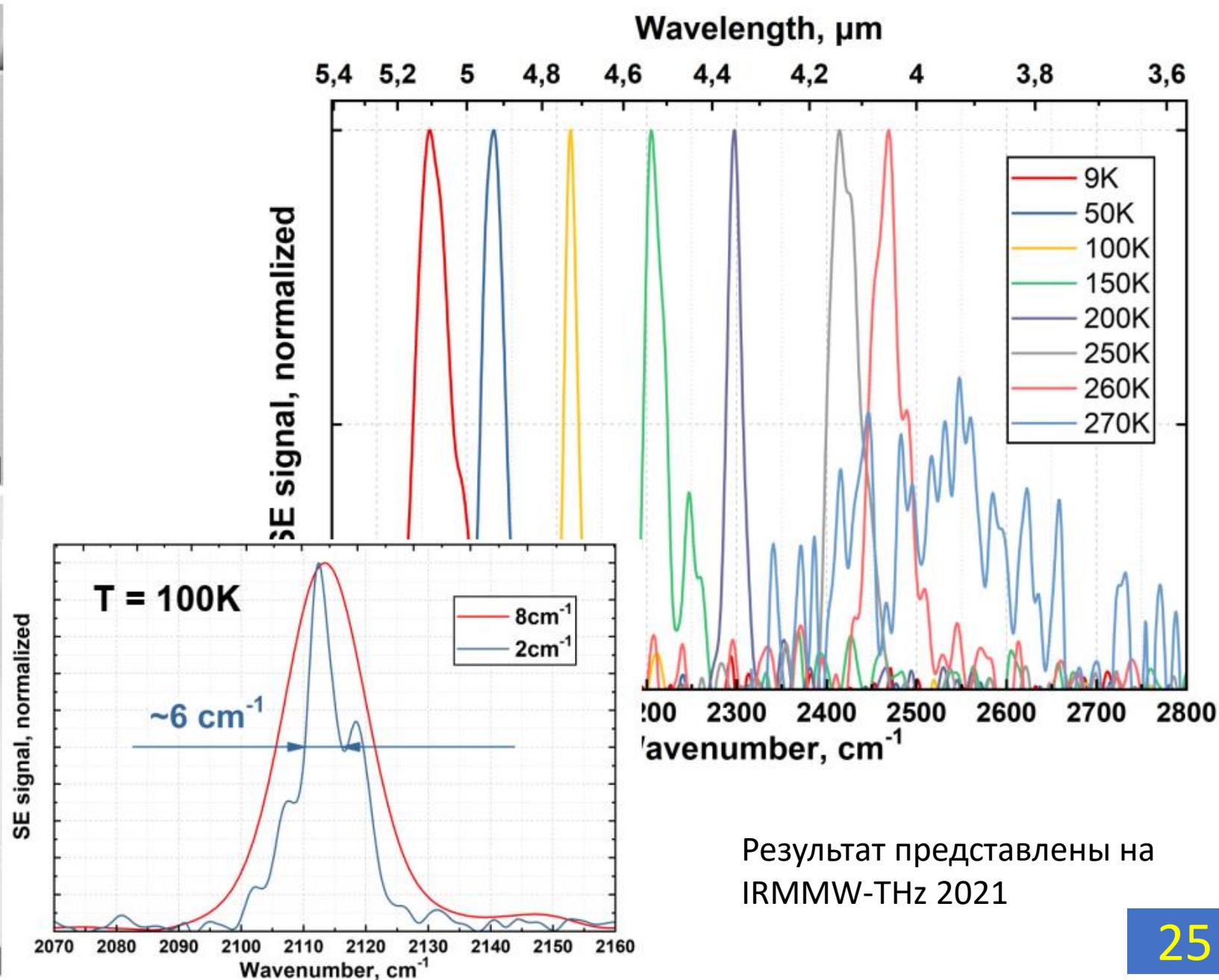
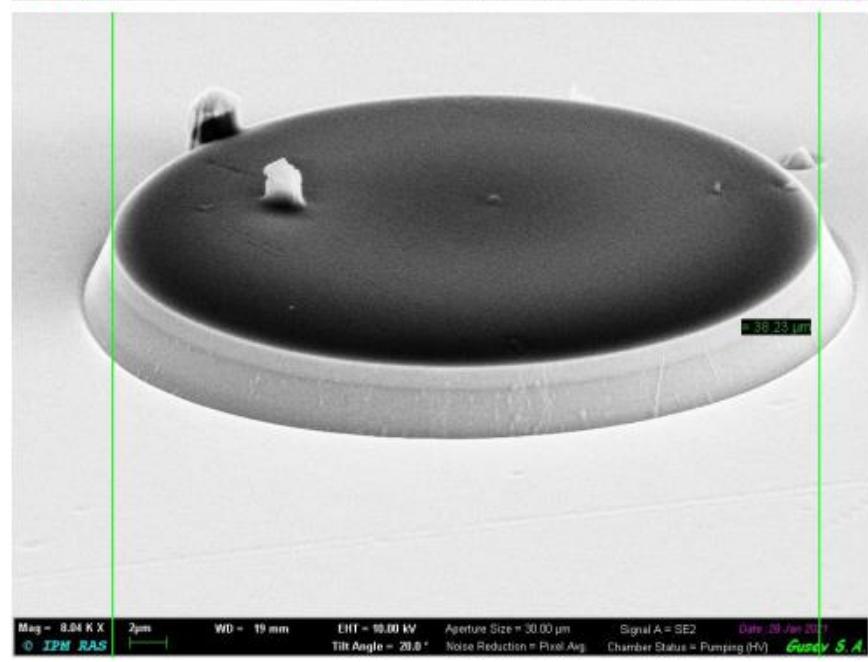
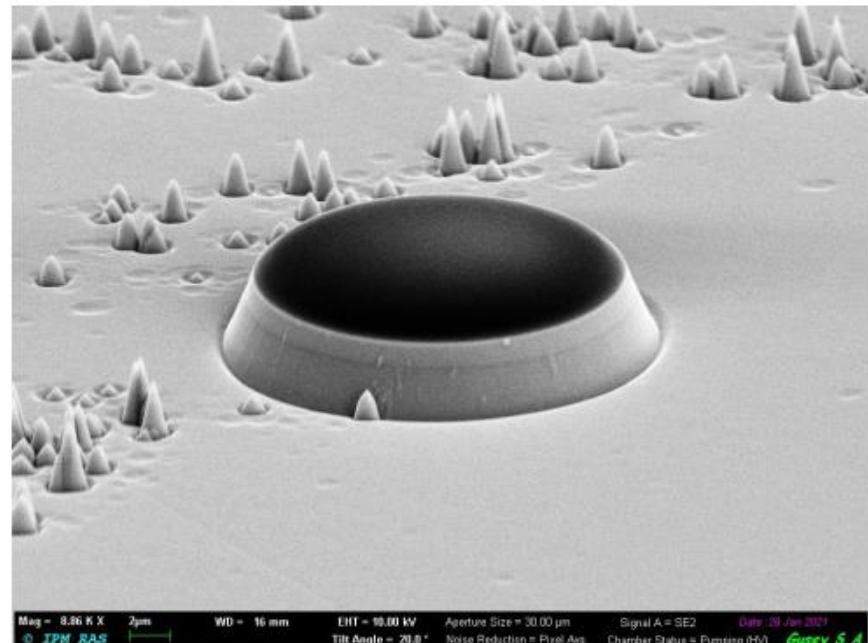
Оптический элемент памяти на резонаторах с МШГ



14.16 A memory element formed by two $16 \mu\text{m}$ diameter micro-ring lasers coupled via a waveguide on an InP/InGaAsP photonic integrated circuit (Hill *et al.*, 2004).

- Высокая добротность резонатора
- Малые размеры резонатора – единицы-десятки длин волн генерации
- Плохая диаграмма направленности
- Двукратное вырождение МШГ
- Торцевая генерация лазерного излучения

Микродисковые резонаторы на HgCdTe гетероструктурах

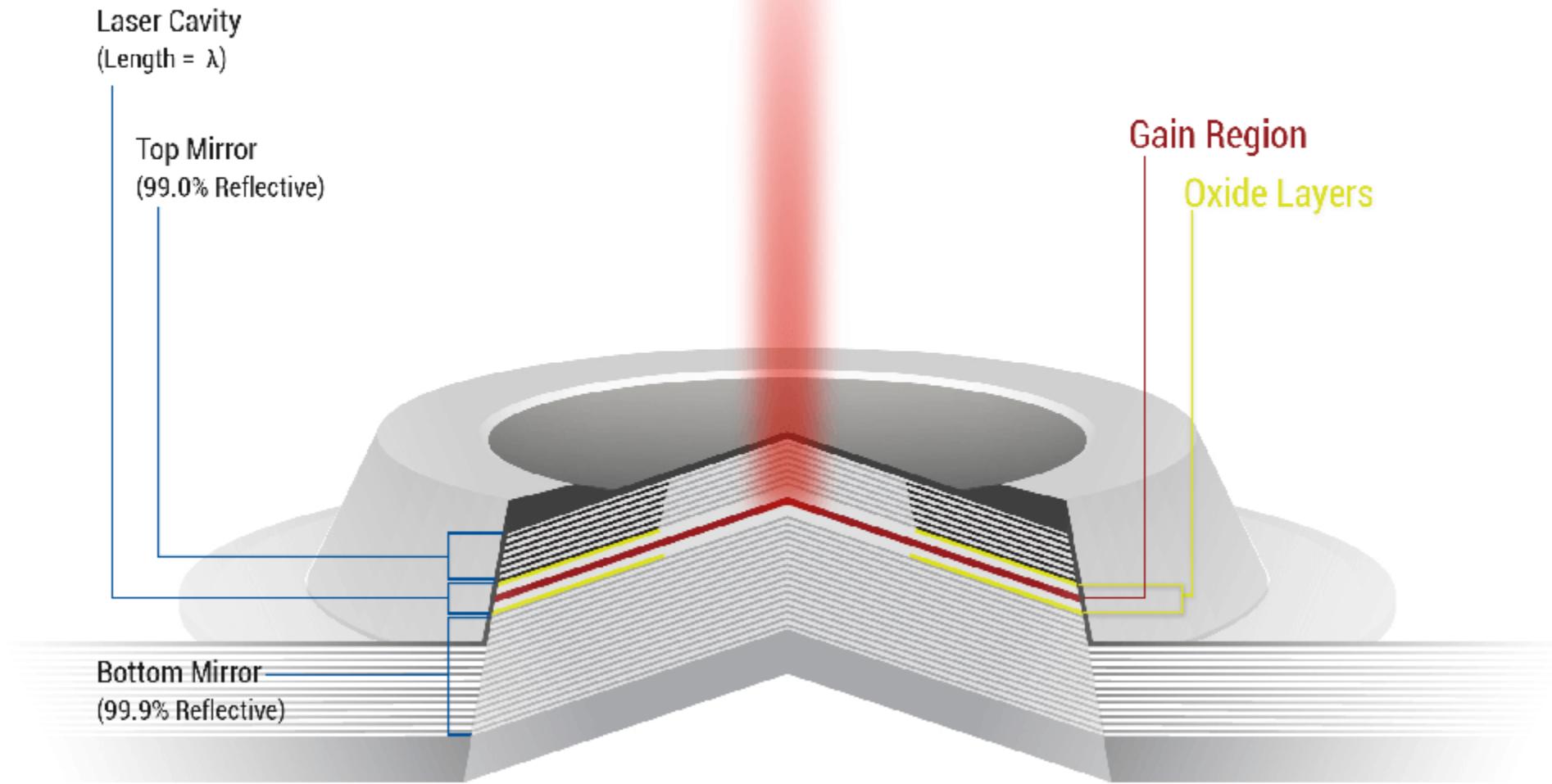


Результаты представлены на
IRMMW-THz 2021

Вертикально-излучающие микродисковые лазеры

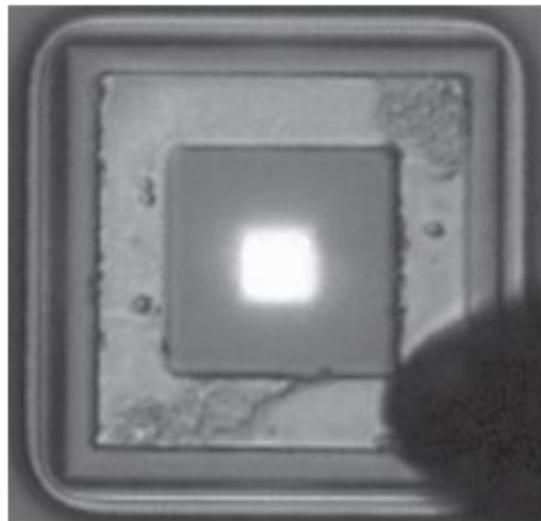
Vertical Cavity Surface Emitting Laser (VCSEL)

Общий вид

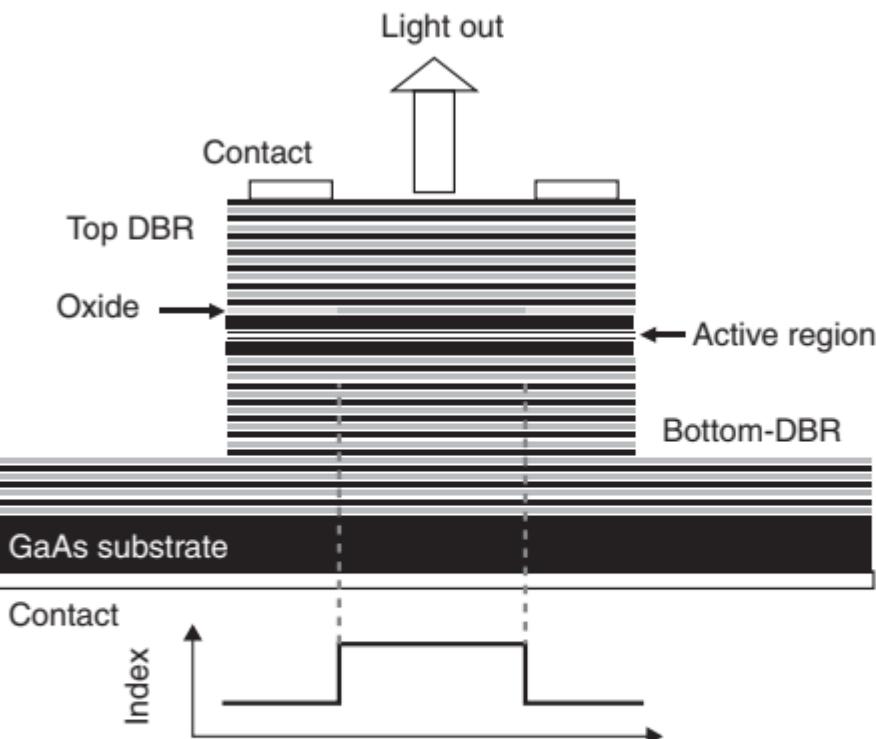


Общий вид

(a)

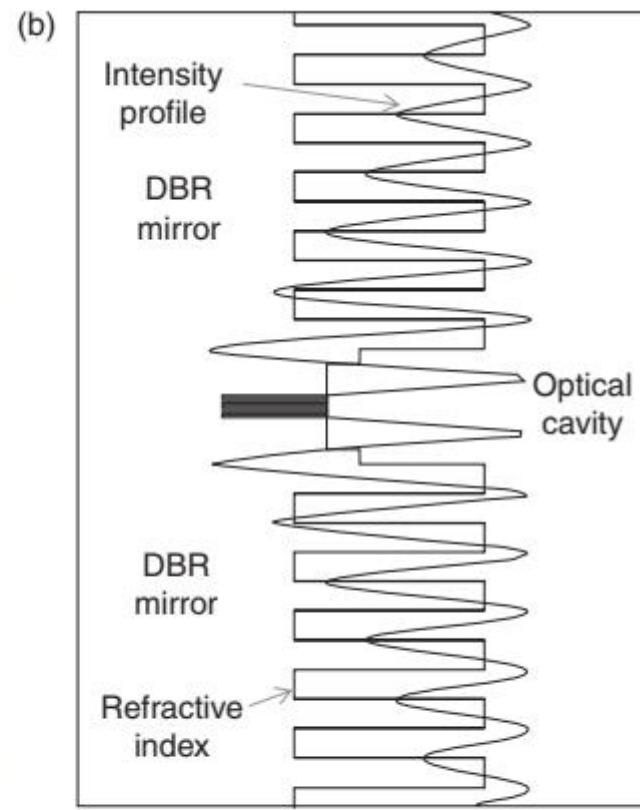
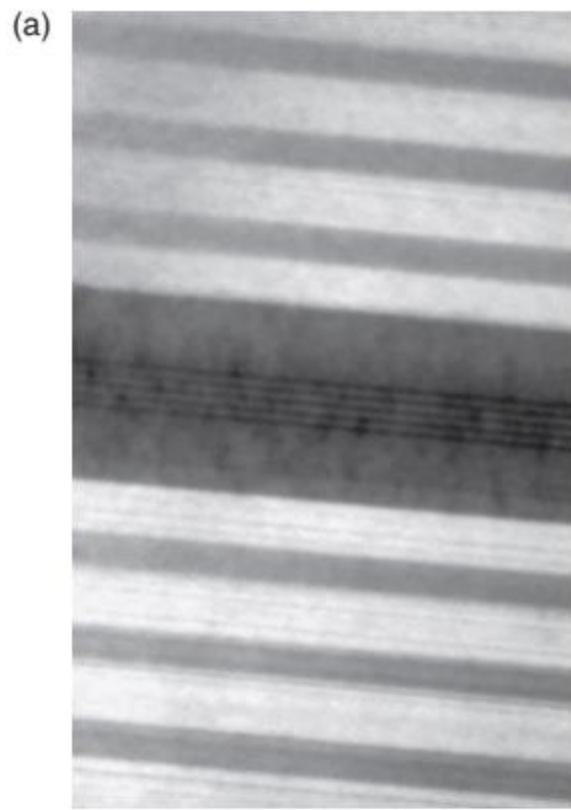


(b)

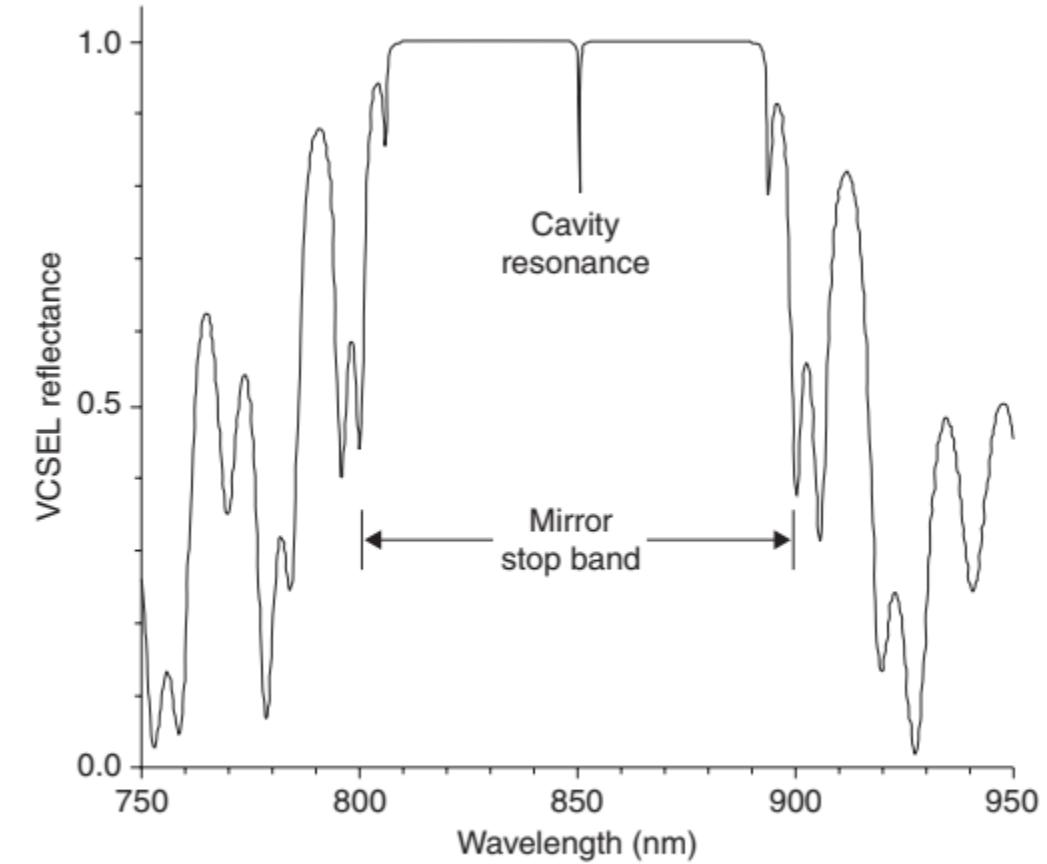


8.1 Side view sketch (b) of an oxide-confined VCSEL; the lower inset shows the refractive index profile across the cavity, while panel (a) shows a lasing mode confined by an oxide aperture inside a top electrical contact.

Устройство резонатора VCSEL



8.2 Transmission electron micrograph (a) and sketch (b) of the refractive index and optical intensity profiles in the optical cavity and surrounding regions of the top and bottom DBR mirror.

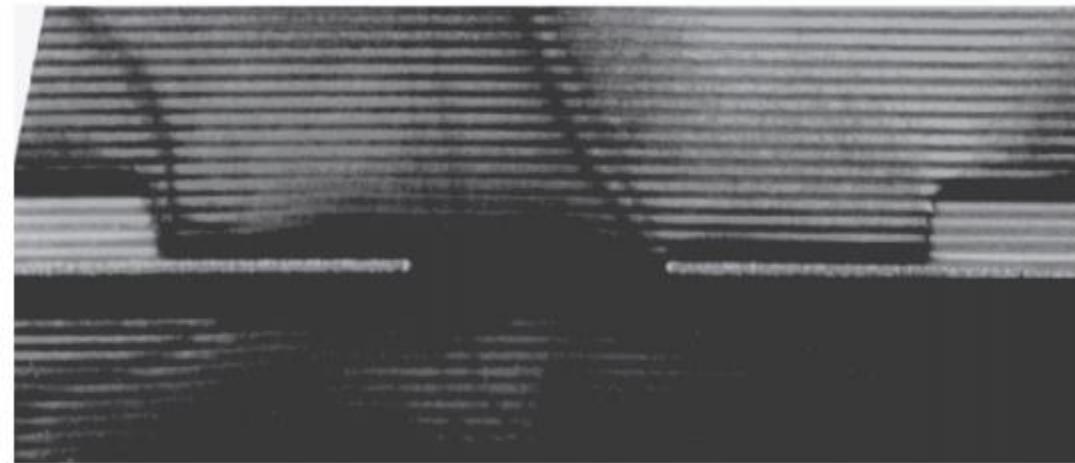


8.3 Calculated VCSEL reflectance spectrum showing the cavity resonance at 850 nm inside the DBR mirror stop band.

Полупроводниковые материалы для VCSEL

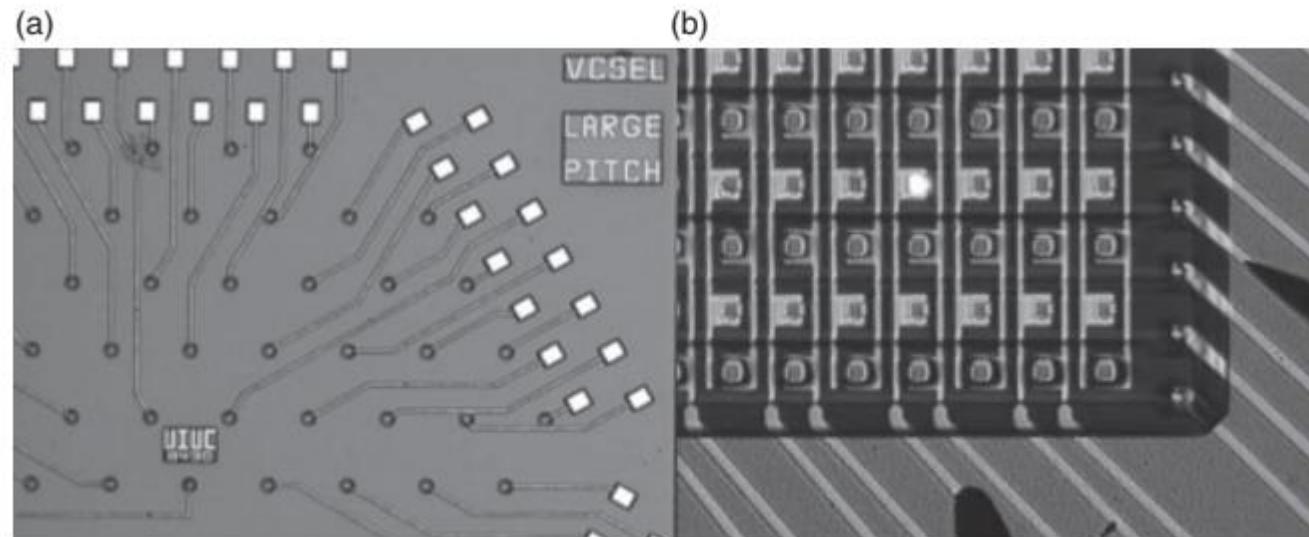
Table 8.2 VCSEL semiconductor materials

Wavelength (nm)	Quantum well	High index	Low index
450	$\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$	GaN	AlN
650	InGaP	$\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$	$\text{Al}_{0.96}\text{Ga}_{0.04}\text{As}$
780	$\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$	$\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$	$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$
850	GaAs	$\text{Al}_{0.16}\text{Ga}_{0.84}\text{As}$	$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$
980	$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$	GaAs	$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$
1300	$\text{Al}_{0.34}\text{Ga}_{0.46}\text{AsN}_{0.01}$ or GaAsSb	GaAs	$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$
1300 and 1550	InGaAsP	GaAs (wafer bonded)	$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ (wafer bonded)
1300 and 1550	InGaAsP	InGaAsP	InP
1500	AllnGaAs	AlAsSb	AlGaAsSb
2300	GalnAsSb	AlAsSb	GaSb

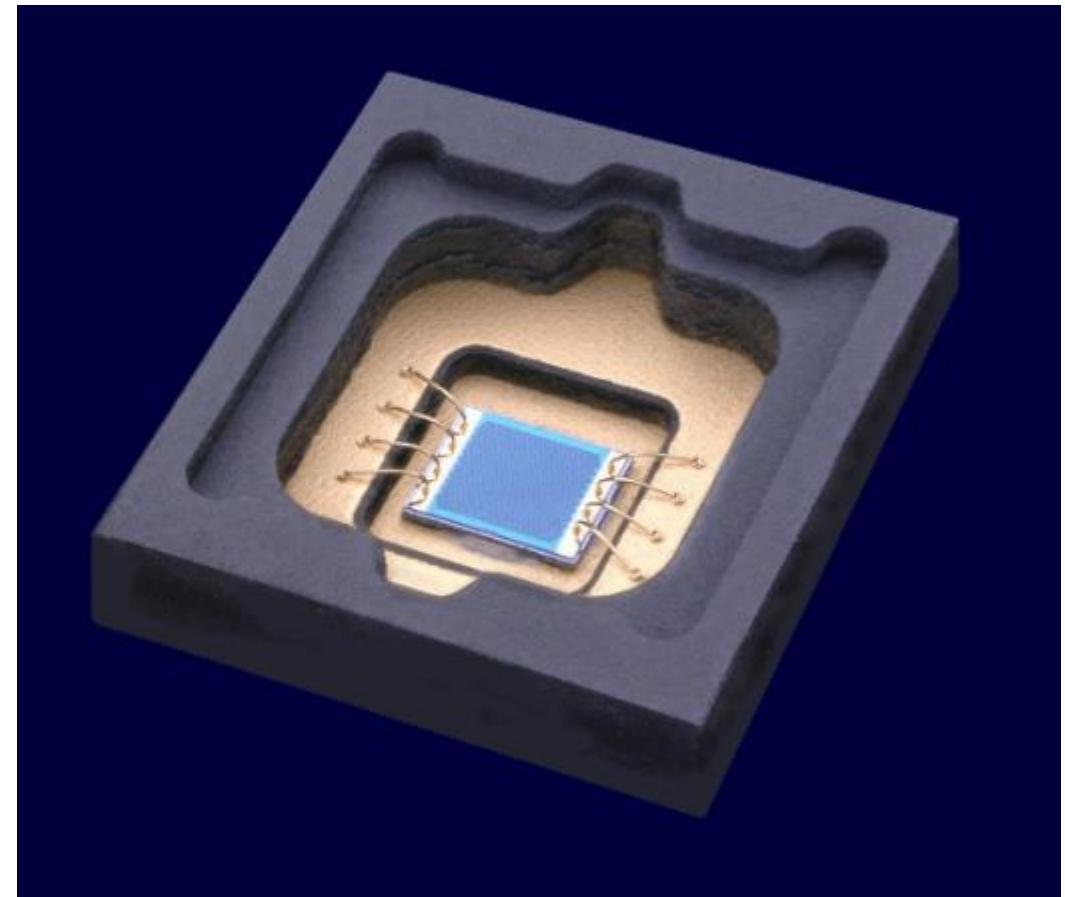


8.6 Transmission electron micrograph of an oxide-confined VCSEL aperture showing five oxide layers, with one layer defining a 1 μm aperture.

2D массивы VCSEL



8.12 (a) Hexagonal individually addressable VCSEL array and (b) square matrix addressable VCSEL array with a lasing element in the fourth column from the right and the fourth row from the bottom.



VCSEL – единственный тип резонаторов полупроводниковых лазеров, позволяющий формировать двумерные массивы лазеров

Table 8.1 VCSEL applications

	Multi-mode operation	Single-mode operation
Individual VCSEL	<ul style="list-style-type: none">• Local and storage area network• Server/router interconnect• Active cable• Plastic fiber links (automotive)	<ul style="list-style-type: none">• Position sensing (laser mice)• Chemical sensing• Encoder• Metro access networks
2D VCSEL array	<ul style="list-style-type: none">• Solid state pumps• Laser Imaging Detection and Ranging (LIDAR)• Medical therapy• Tailored heating	<ul style="list-style-type: none">• Laser printing• Parallel channel high speed links• Coherent arrays (high brightness)• Chip optical interconnects

Области применения VCSEL



Facial Recognition



3D Sensing



2D Imaging



LIDAR and Ranging

- Высокая технологичность изготовления
- Низкие пороги генерации
- Возможность быстрой модуляции генерации
- Вертикальная геометрия излучения
- Возможность создавать 2D массивы лазеров
- Достигимы высокие мощности излучения в 2D массивах
- Не требуют сложной оптики для получения пятна высокого качества