

Mode Selectivity in Oxide-Confined Vertical-Cavity Surface-Emitting Lasers

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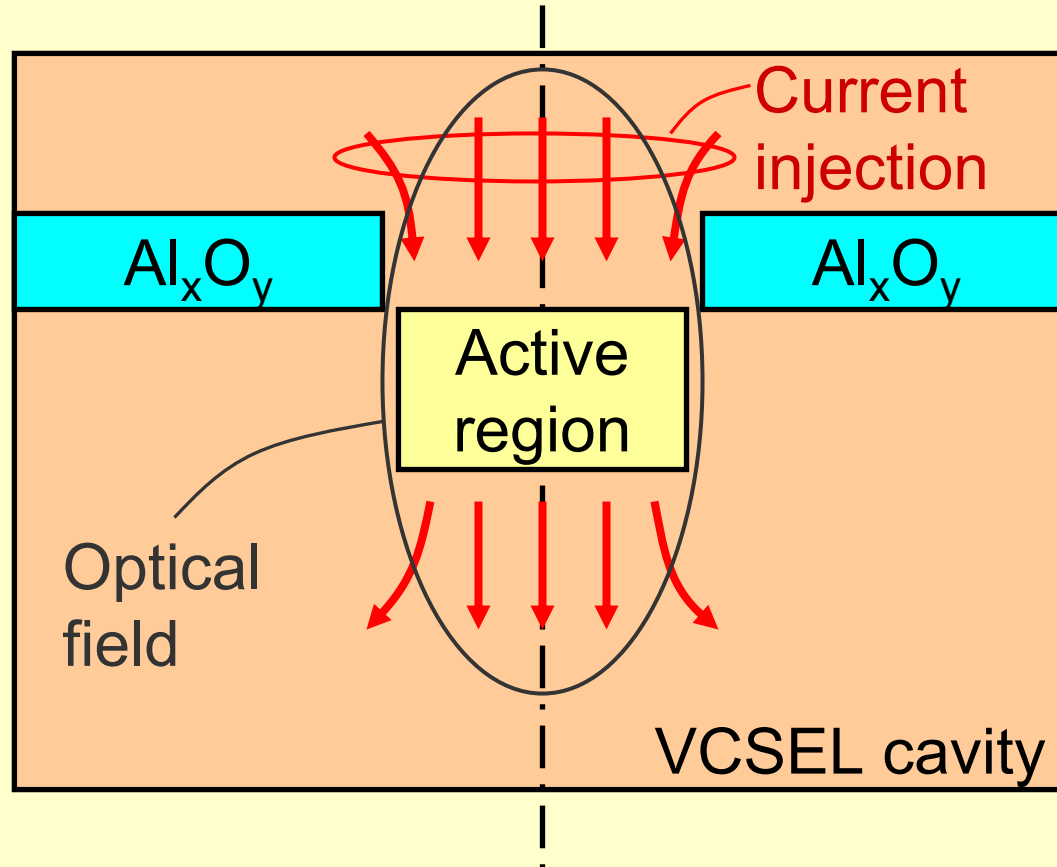
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Outline

- Radial electrical and optical VCSEL confinements
- Motivation
- The model
- VCSEL with a single oxide aperture
- VCSEL with two oxide apertures
- The SCO (Separate Confinement Oxidation) VCSEL
- Conclusions

Radial confinements of both a current injection and an optical field in GaAs-based VCSELs



Al_xO_y layer – high electrical resistivity
low index of refraction
high thermal conductivity (probably)

Motivation

During the presentation, the designing strategy to enhance mode selectivity (i.e. to ensure the single fundamental LP_{01} mode operation) in oxide-confined high-power VCSELs is presented.

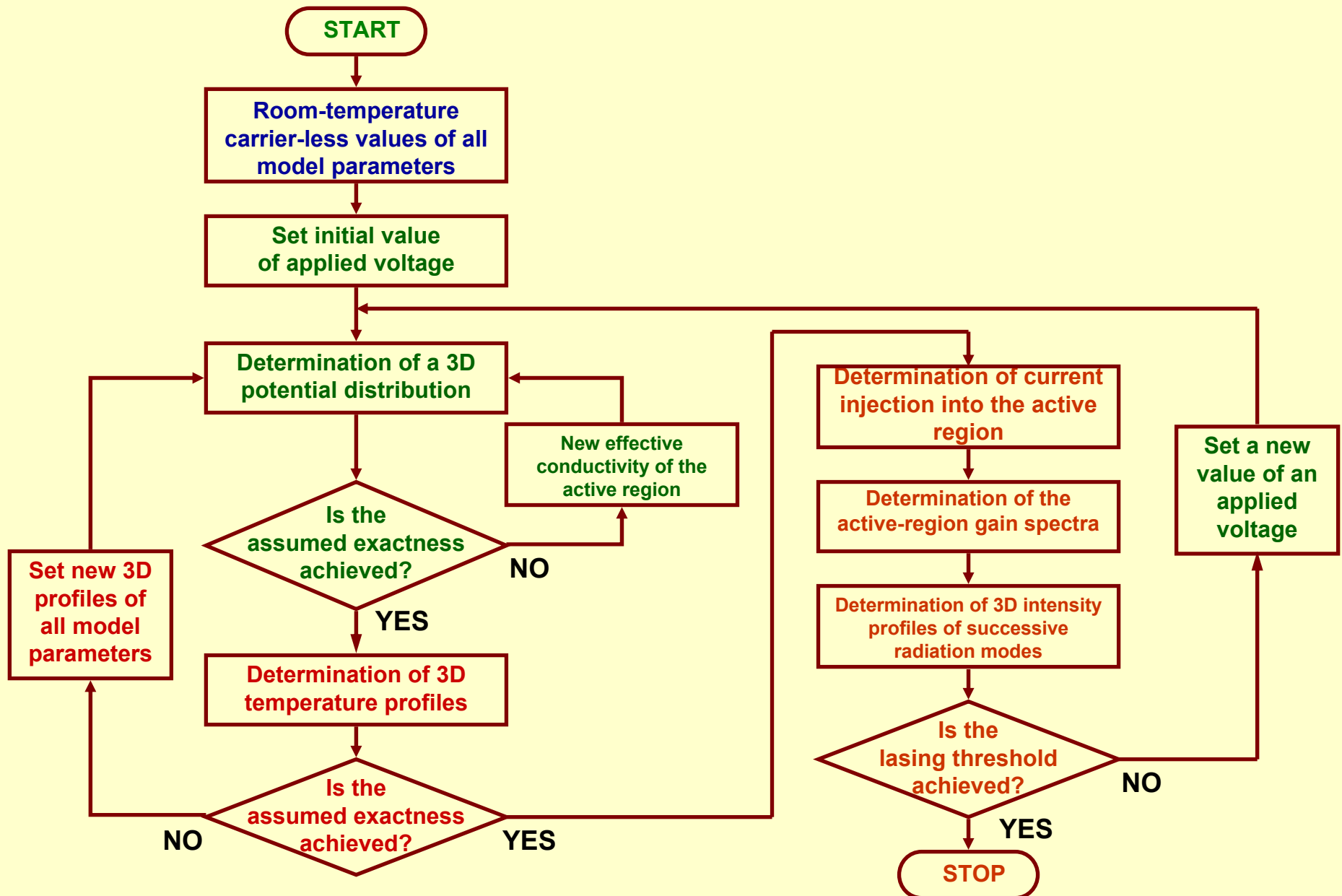
The three-dimensional fully self-consistent model

The model is composed of four interrelated parts:

- **the optical model** describing for successive modes a distribution of an optical field within the resonator and enabling determination of its lasing threshold,
- **the electrical model** characterizing both the current spreading between the top and bottom contacts and injection of carriers of both kinds into the active region,
- **the thermal model** characterizing generation of a heat flux and its spreading from heat sources towards heat sink and
- **the gain model** enabling determination of gain spectra within the active region.

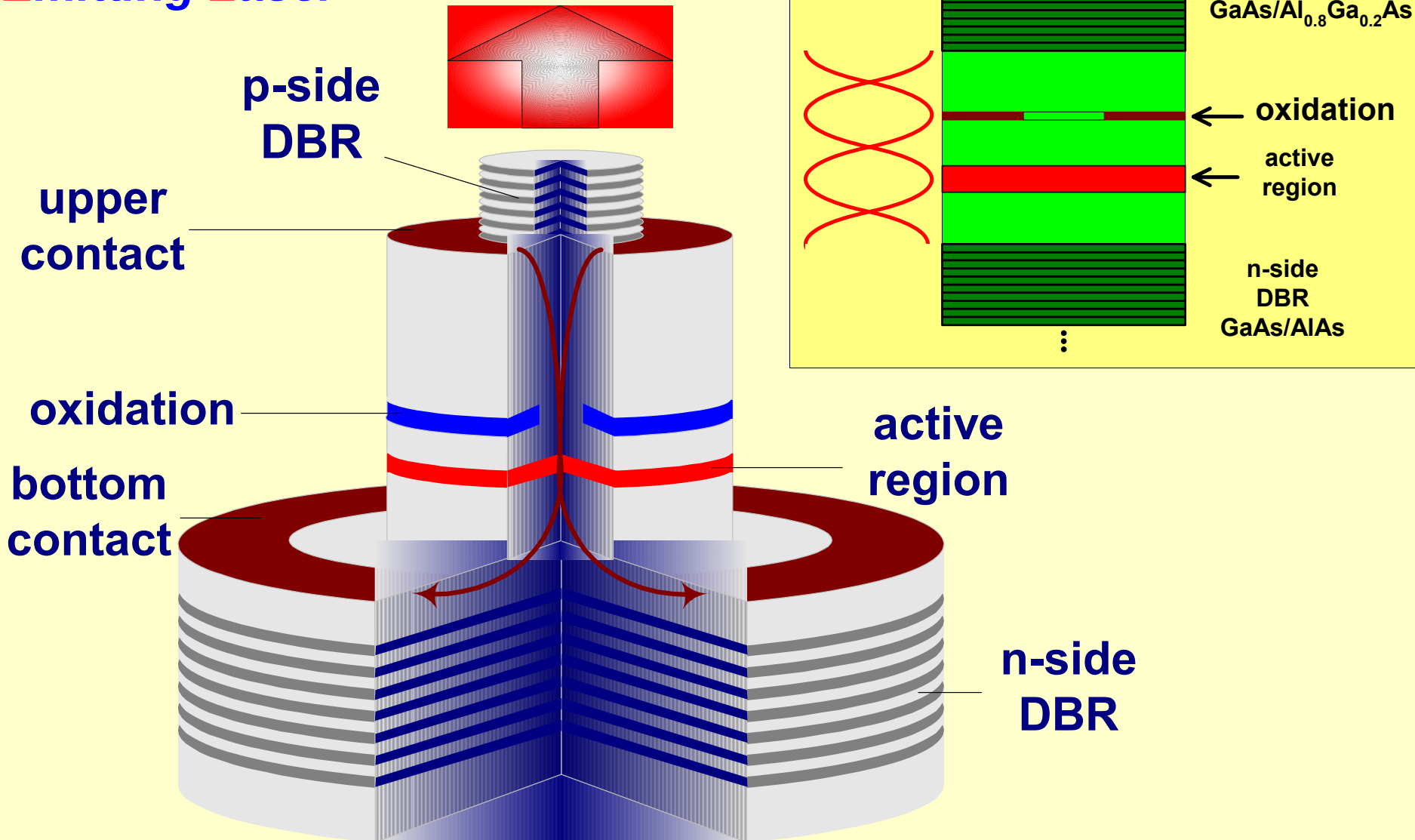
R.P. Sarzała and W. Nakwaski, J. Phys.:Condens. Matter
16 (2004) S3121-S3140

The calculation algorithm



VCSEL with a single oxide aperture

**Vertical Cavity Surface
Emitting Laser**



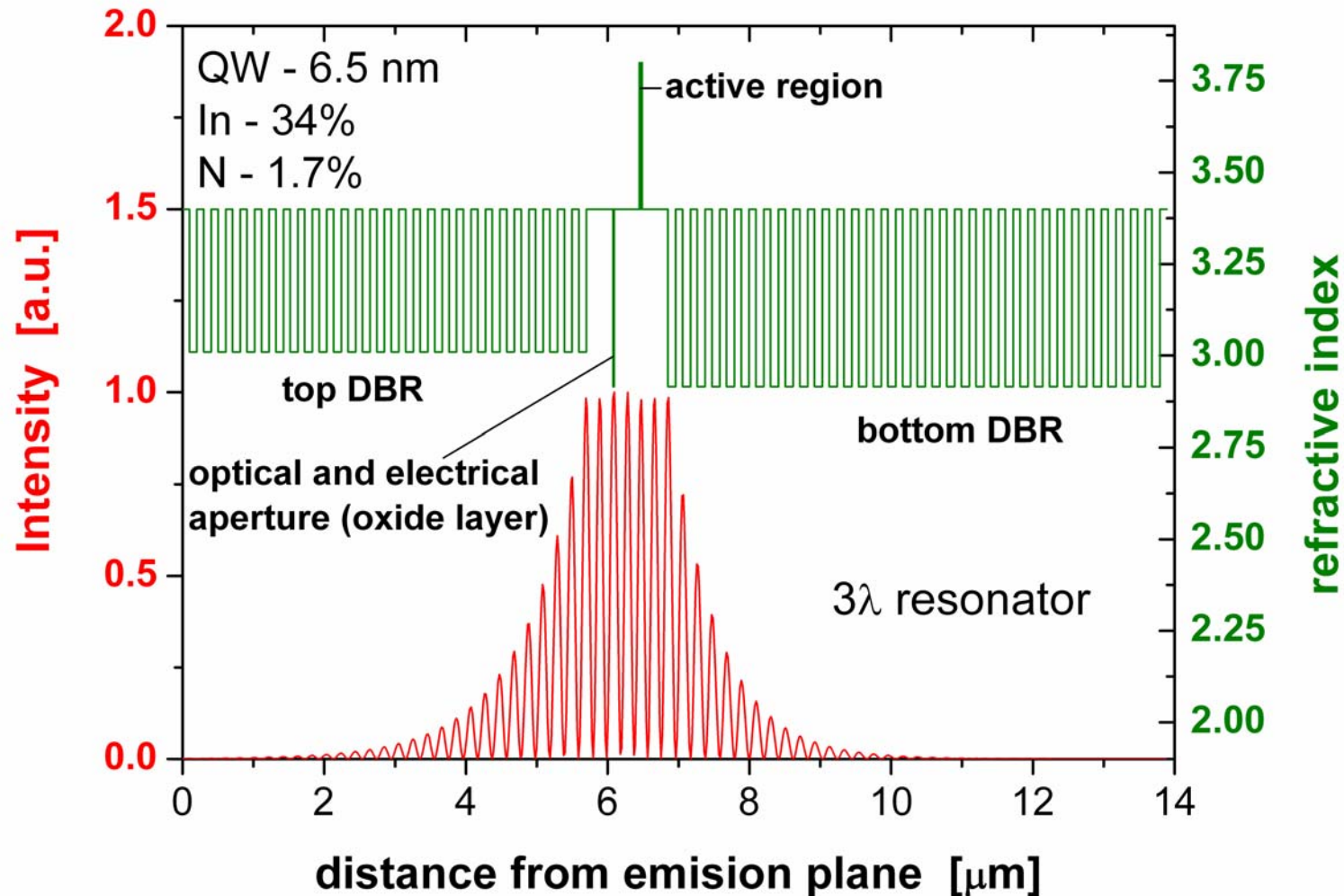
The GaInNAs/GaAs 1.3- μm VCSEL with a single oxide aperture

Layer	Thickness nm	Refractive index n_R	$\frac{dn_R}{dT}$ $10^{-4}/\text{K}$	Group refractive index n_G	Absorption coefficient α cm^{-1}	$\frac{d\alpha}{dT}$ $1/10^3\text{cmK}$
GaAs upper DBR	28* 95.6	3.4	3.0	3.654	1	1.28
$\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ upper DBR	28* 108	3.01	1.47	3.198	1	1.28
<i>p</i> -GaAs	184.7	3.4	3.0	3.654	20	1.28
Al_xO_y	15	1.61	0	1.681	20	0
<i>p</i> -GaAs	165.2	3.4	3.0	3.654	5	1.28
$\text{Ga}_{0.66}\text{In}_{0.34}\text{N}_{0.017}\text{As}_{0.983}$ quantum well	2* 6.5	3.8	3.0	4.62	0	0
GaAs barrier	25	3.4	3.0	3.654	0	0
<i>n</i> -GaAs	171.6	3.4	3.0	3.654	2.5	1.28
GaAs bottom DBR	34* 95.6	3.4	3.0	3.654	0.5	1.28
AlAs bottom DBR	34* 111.5	2.915	1.34	3.056	0.5	1.28

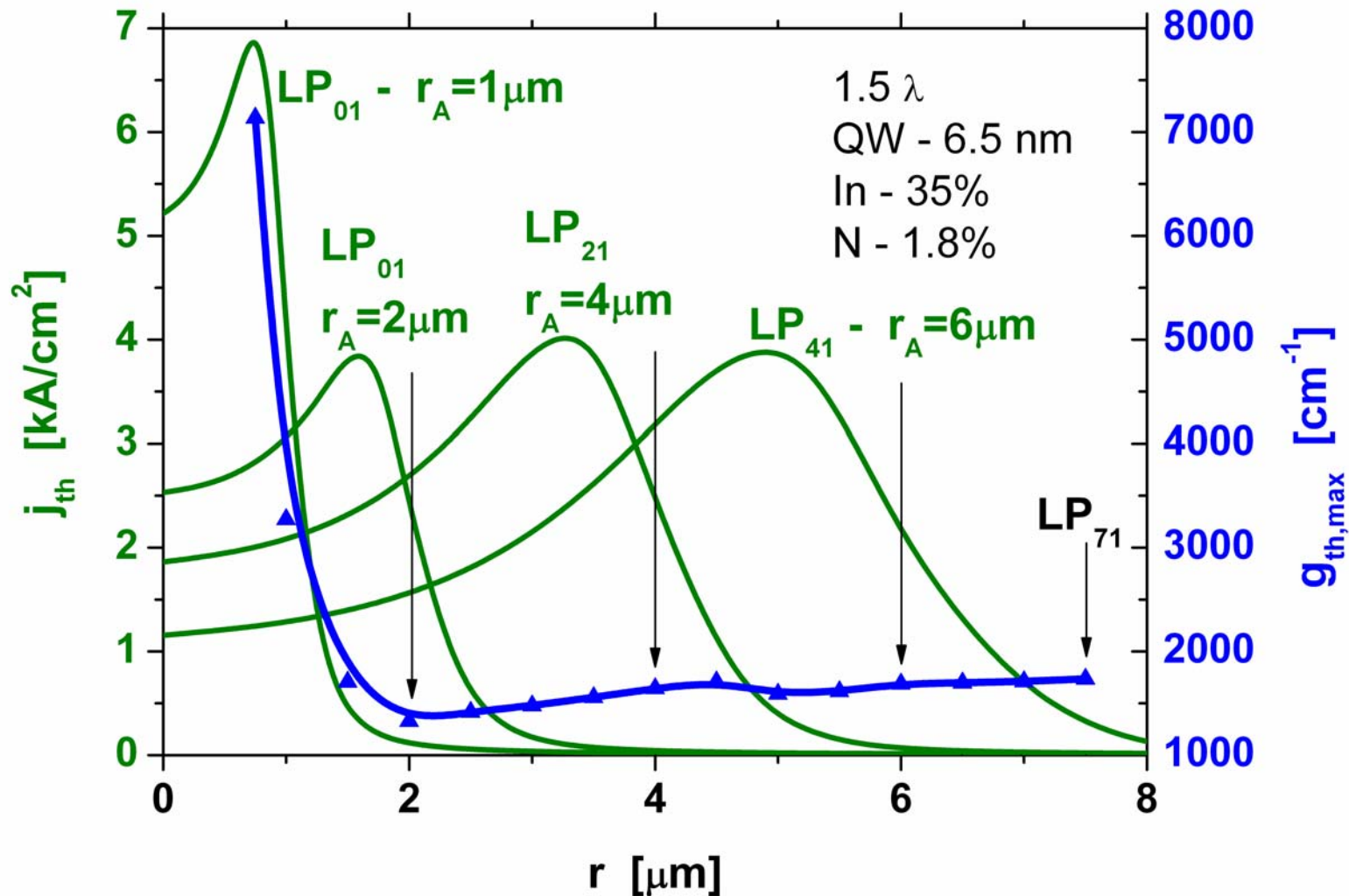
The VCSEL structure is similar (but not identical) to the one reported by Infineon in

A. Ramakrishnan et al., J. Cryst. Growth **248** (2003) 457

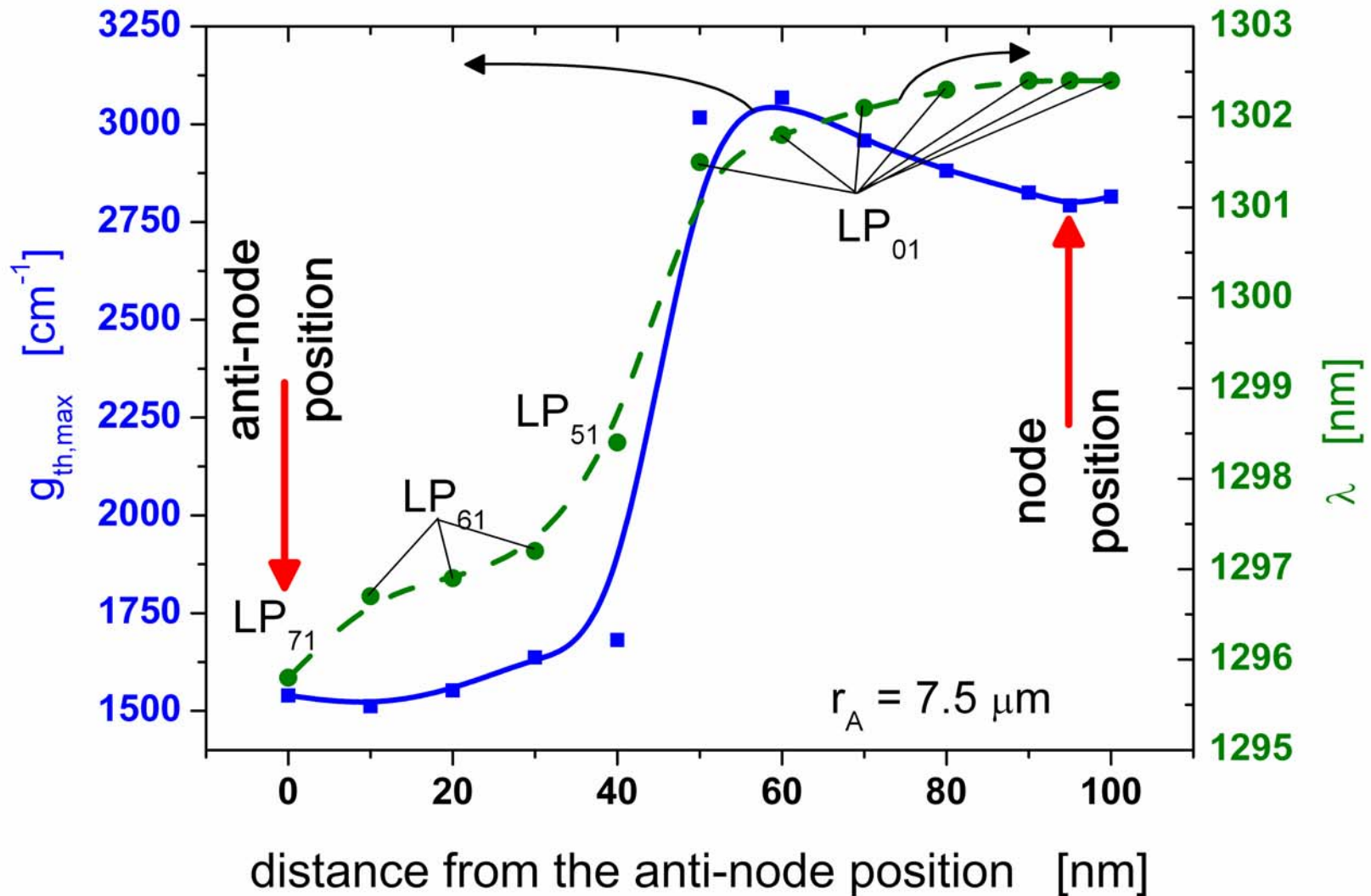
VCSEL with a single oxide aperture at the anti-node position



VCSEL with a single oxide aperture at the anti-node position



VCSEL with a single oxide aperture



VCSEL with a single oxide aperture

Number and structure symbol	r_A [μm]	U_{th} [V]	I_{th} [mA]	$T_{A,max}$ [K]	$g_{th,max}$ [cm^{-1}]	mode	λ [nm]
1 SN	10	3.65	21.13	316.83	4432	LP_{01}	1303.2
2 SA	10	2.09	8.24	304.28	1644	$LP_{11\ 1}$	1295.1
3 SN	7.5	2.55	10.22	308.16	2792	LP_{01}	1302.4
4 SA	7.5	1.94	5.72	303.76	1539	LP_{71}	1295.8
5 SN	5	1.99	5.11	305.18	2174	LP_{01}	1302.1
6 SA	5	1.68	3.22	302.91	1311	LP_{31}	1297.1
7 SN	2	2.75	4.85	315.68	6890	LP_{01}	1302.3
8 SA	2	1.27	0.86	301.50	1189	LP_{01}	1298.2

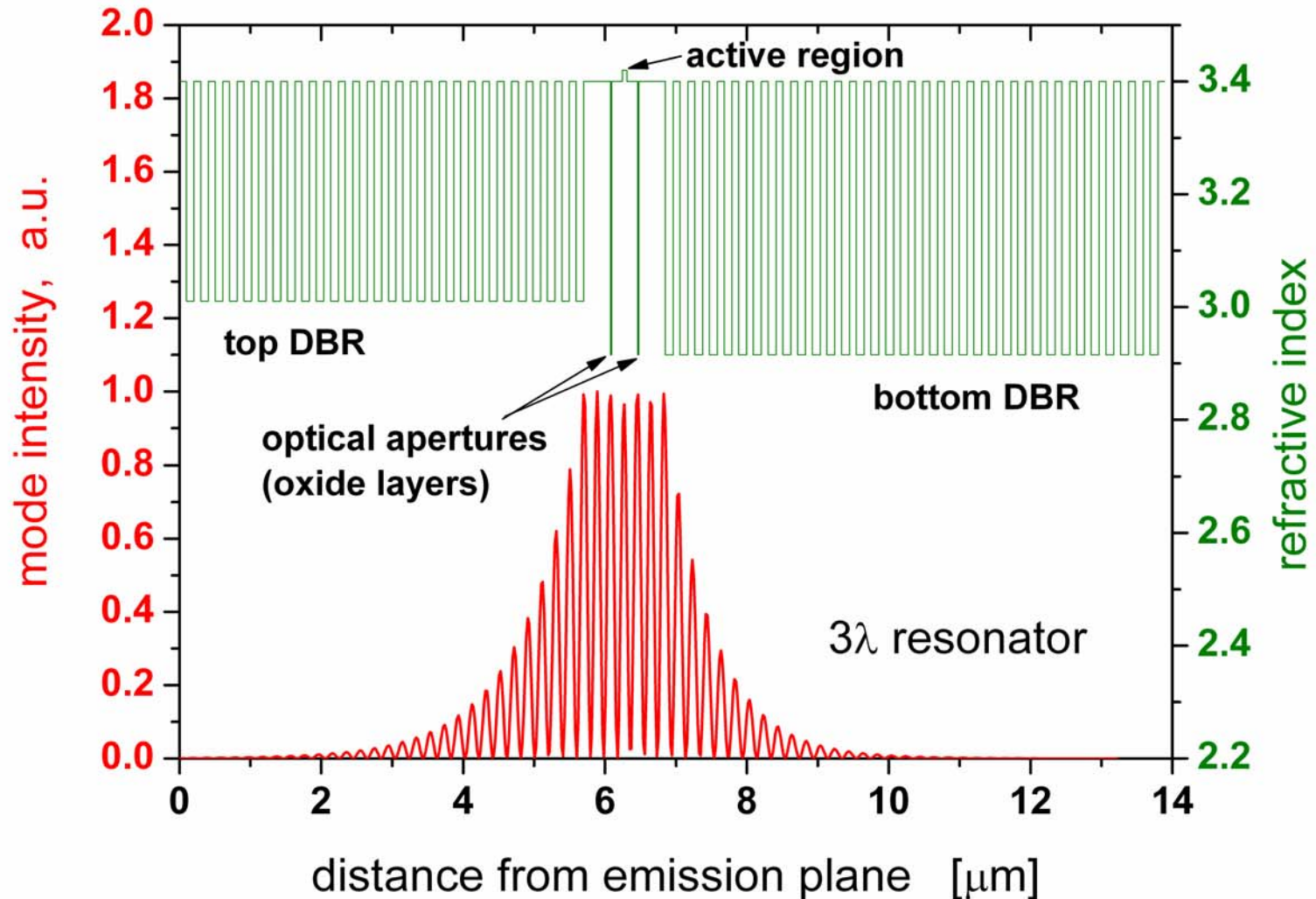
VCSEL with a single oxide aperture

No further improvements are available in VCSELs with a single oxide aperture. Then two extreme cases are possible:

- **Index-guided VCSELs:** To reduce a VCSEL threshold current, the radial index-guiding is necessary achieved with the aid of the oxide aperture located at the anti-node position of the resonator standing wave. But then, in the case of higher-output large-size VCSELs, higher-order transverse modes exhibit the lowest thresholds.
- **Gain-guided VCSELs:** To ensure the fundamental-mode LP_{01} operation, the radial gain-guiding should be used realized in the VCSEL design with the oxide aperture located at the analogous node position. Then its threshold current is considerably higher.

Further improvements may be possible in VCSELs with two oxide apertures.

VCSEL with two oxide apertures



VCSEL with two oxide apertures

Layer	Thickness nm	Refractive index n_R	$\frac{dn_R}{dT}$ $10^{-4}/K$	Group refractive index n_G	Absorption coefficient α cm^{-1}	$\frac{d\alpha}{dT}$ $1/10^3 cmK$
GaAs upper DBR	28* 95.6	3.4	3.0	3.654	1	1.28
Al _{0.8} Ga _{0.2} As upper DBR	28* 108	3.01	1.47	3.198	1	1.28
p-GaAs	360.9	3.4	3.0	3.654	20	1.28
Al _x O _y	50	1.61	0	1.681	20	0
p-GaAs	341.2	3.4	3.0	3.654	5	1.28
Ga _{0.66} In _{0.34} N _{0.017} As _{0.983} quantum well	2* 6.5	3.8	3.0	4.62	0	0
GaAs barrier	25	3.4	3.0	3.654	0	0
n-GaAs	260.5	3.4	3.0	3.654	2.5	1.28
Al _x O _y	15	1.61	0	1.681	2.5	0
n-GaAs	89.2	3.4	3.0	3.654	2.5	1.28
GaAs bottom DBR	34* 95.6	3.4	3.0	3.654	0.5	1.28
AlAs bottom DBR	34* 111.5	2.915	1.34	3.056	0.5	1.28

The VCSEL structure is similar (but not identical) to the one reported by Infineon in
A. Ramakrishnan et al., J. Cryst. Growth **248** (2003) 457

General strategy

Much more improvements may be expected in the oxide-confined VCSEL when:

- one of its oxide apertures is localized in a VCSEL cavity at the antinode position of the optical standing wave, where it is working as both the electrical aperture confining radially the current injection into the active region and the optical aperture introducing the built-in radial optical confinement mechanism,
- the second oxide aperture on the opposite side of the active region is shifted to the analogous standing-wave node position, where it is working as the electrical aperture only.

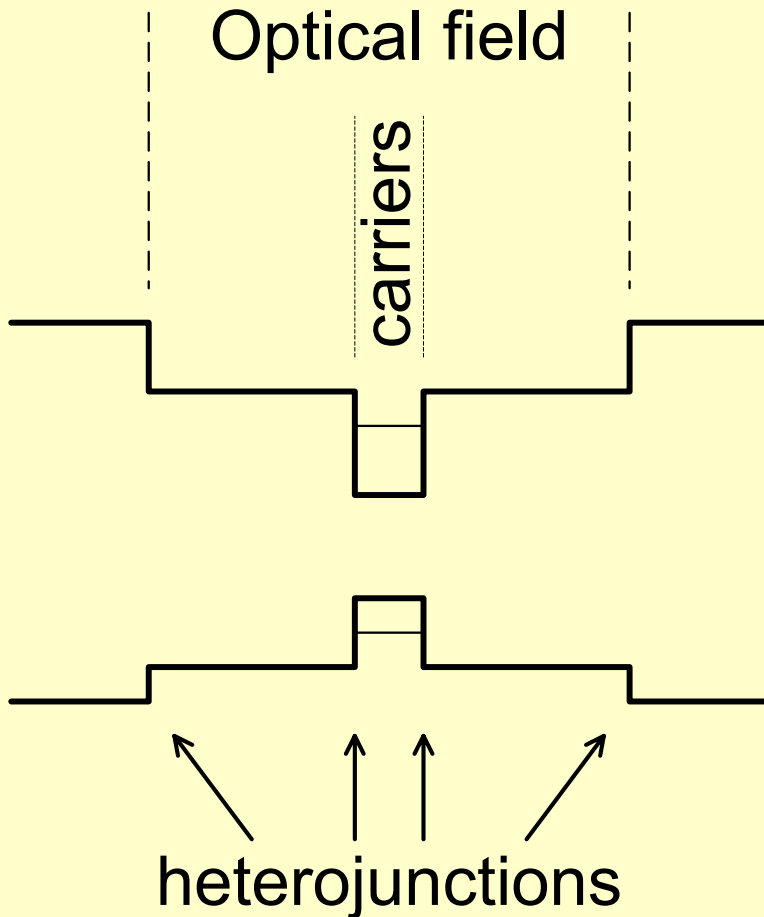
The **SCO** VCSEL – new concept

Diameters of both the apertures may be changed independently giving an additional degree of freedom for VCSEL designing. Then the second aperture, located at the node position, will influence the current spreading only, whereas the first one, in the anti-node position, will mostly introduce the radial waveguiding effect. Both radial confinements influencing the current spreading and the electromagnetic field may be achieved separately, analogously to their axial confinements in the SCH (Separate Confinement Heterostructure) diode lasers. That is why we call this laser structure the SCO (Separate Confinement Oxidation) VCSEL.

Different aperture diameters may be obtained taking advantage of the dependence of radial oxidation kinetics on a composition and a thickness of the oxidized layer (see W. Nakwaski et al. Semicond. Sci. Technol. **19** (2004) 333)

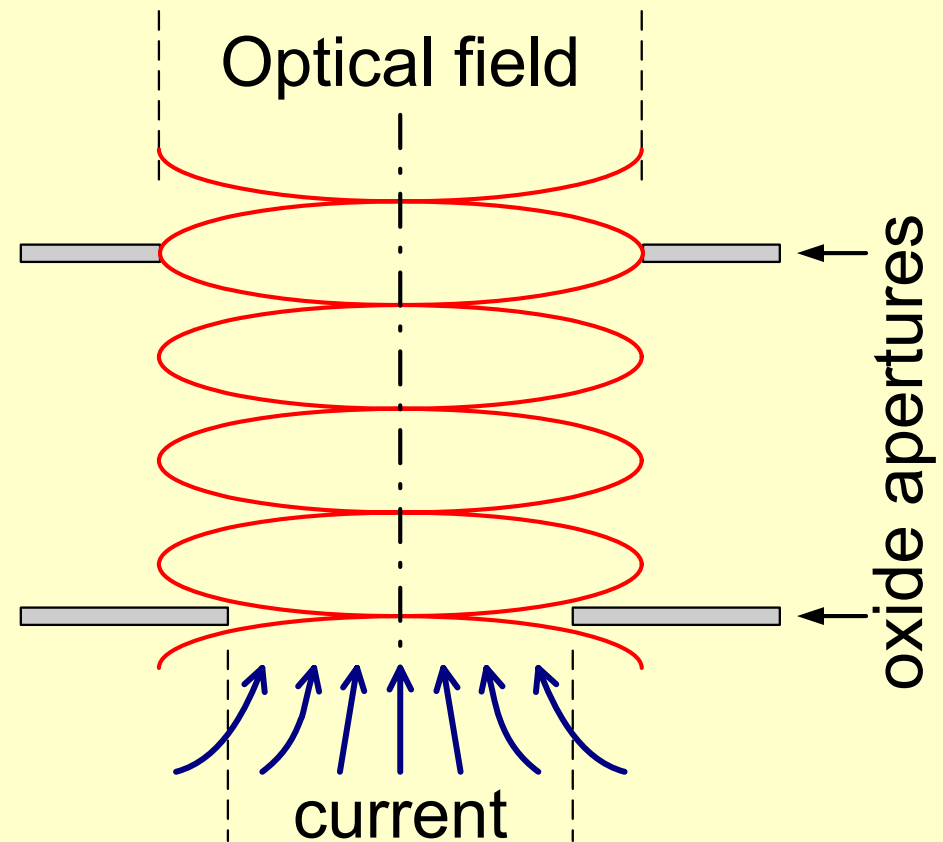
SCH

***Separate
Confinement
Heterostructure***



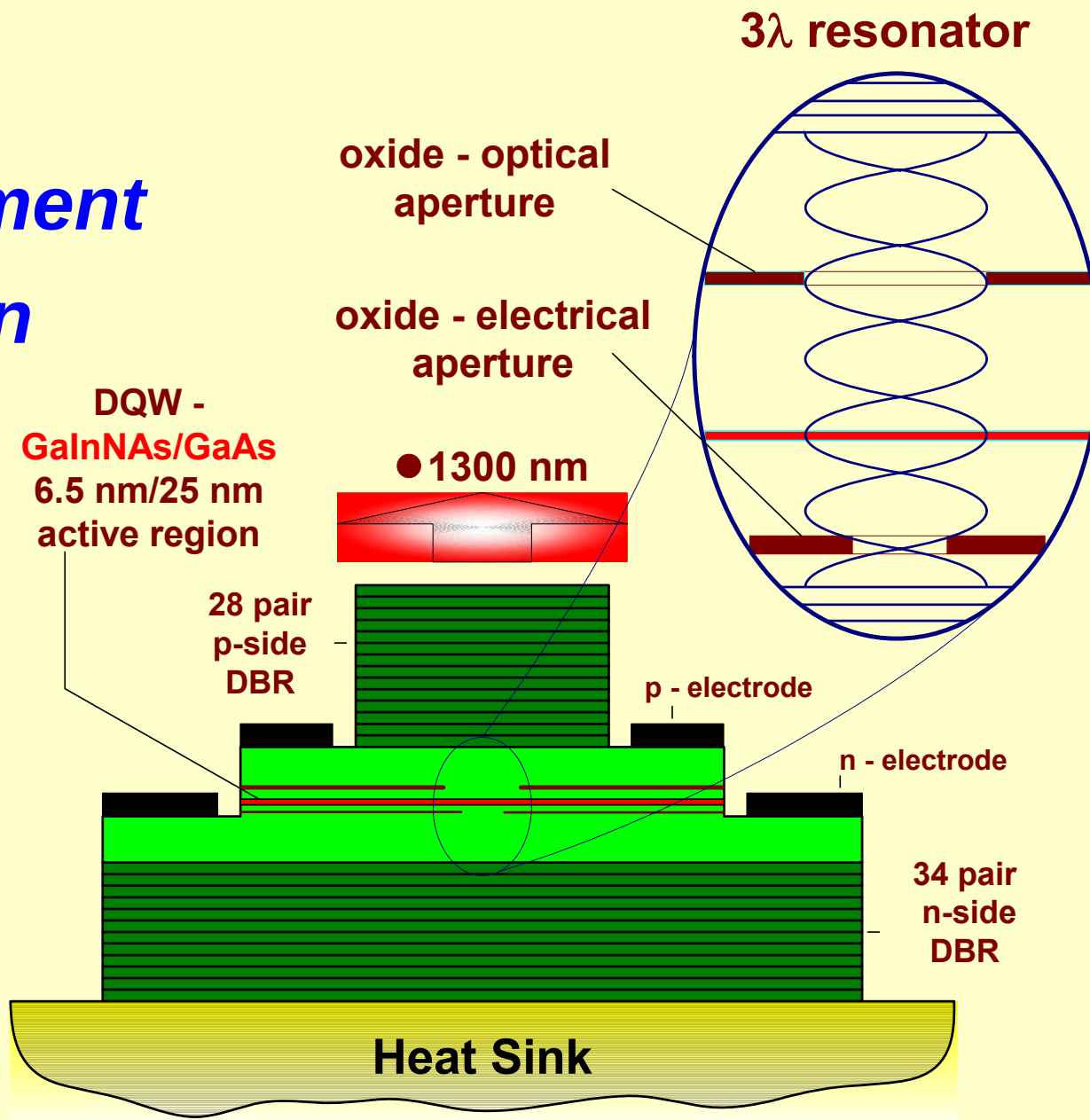
SCO

***Separate
Confinement
Oxidation***

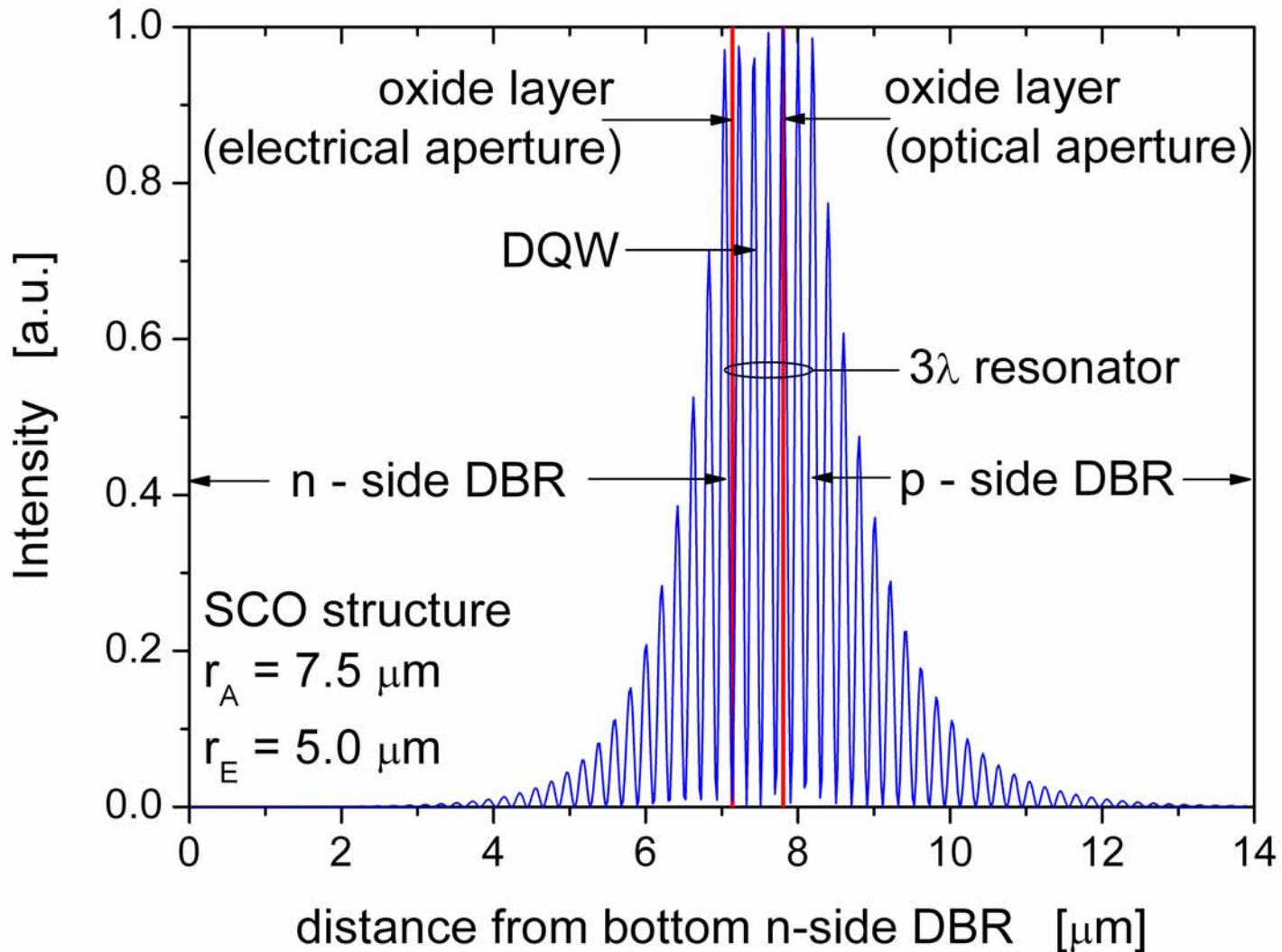


The **SCO** VCSEL

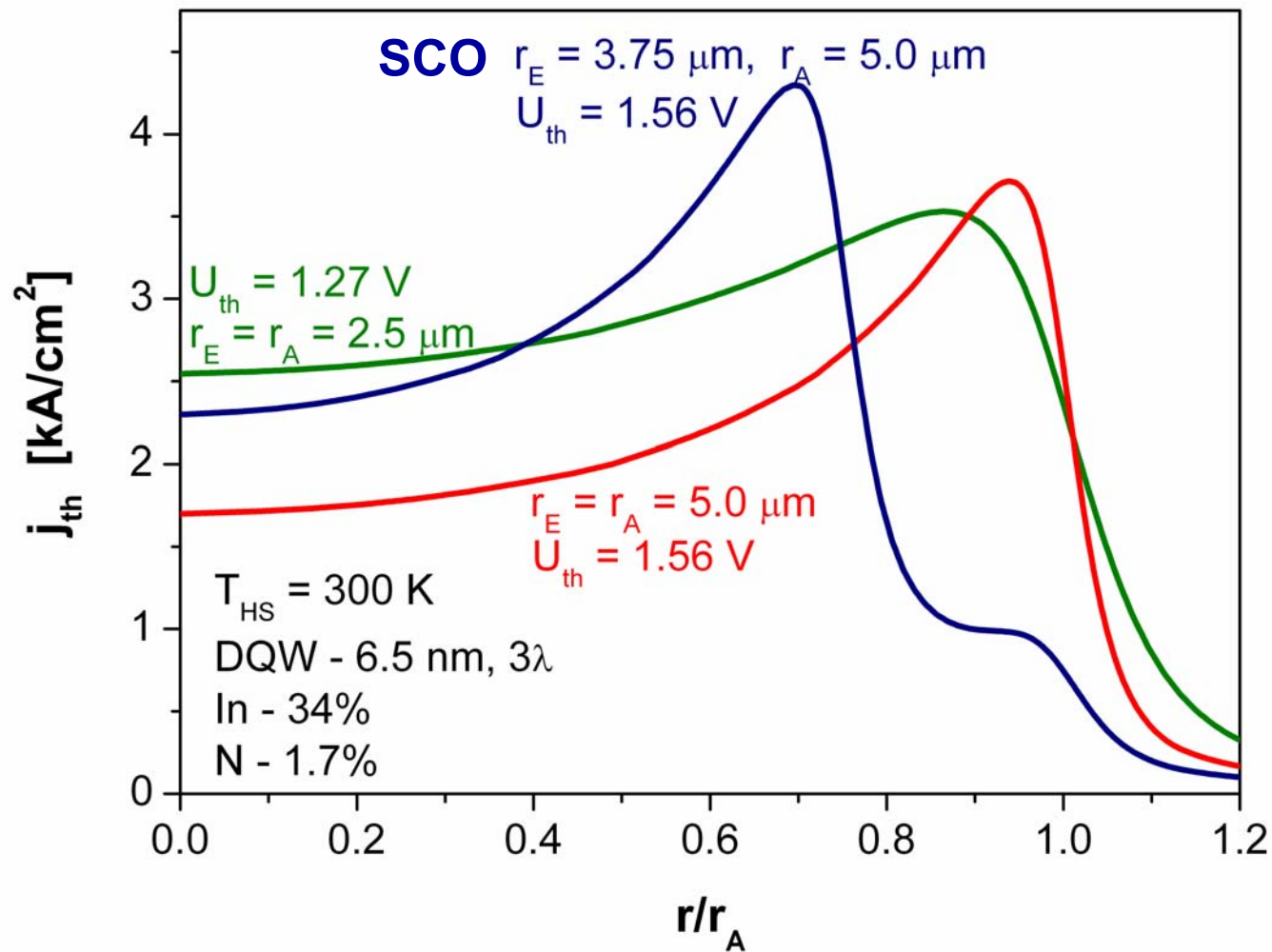
Separate
Confinement
Oxidation



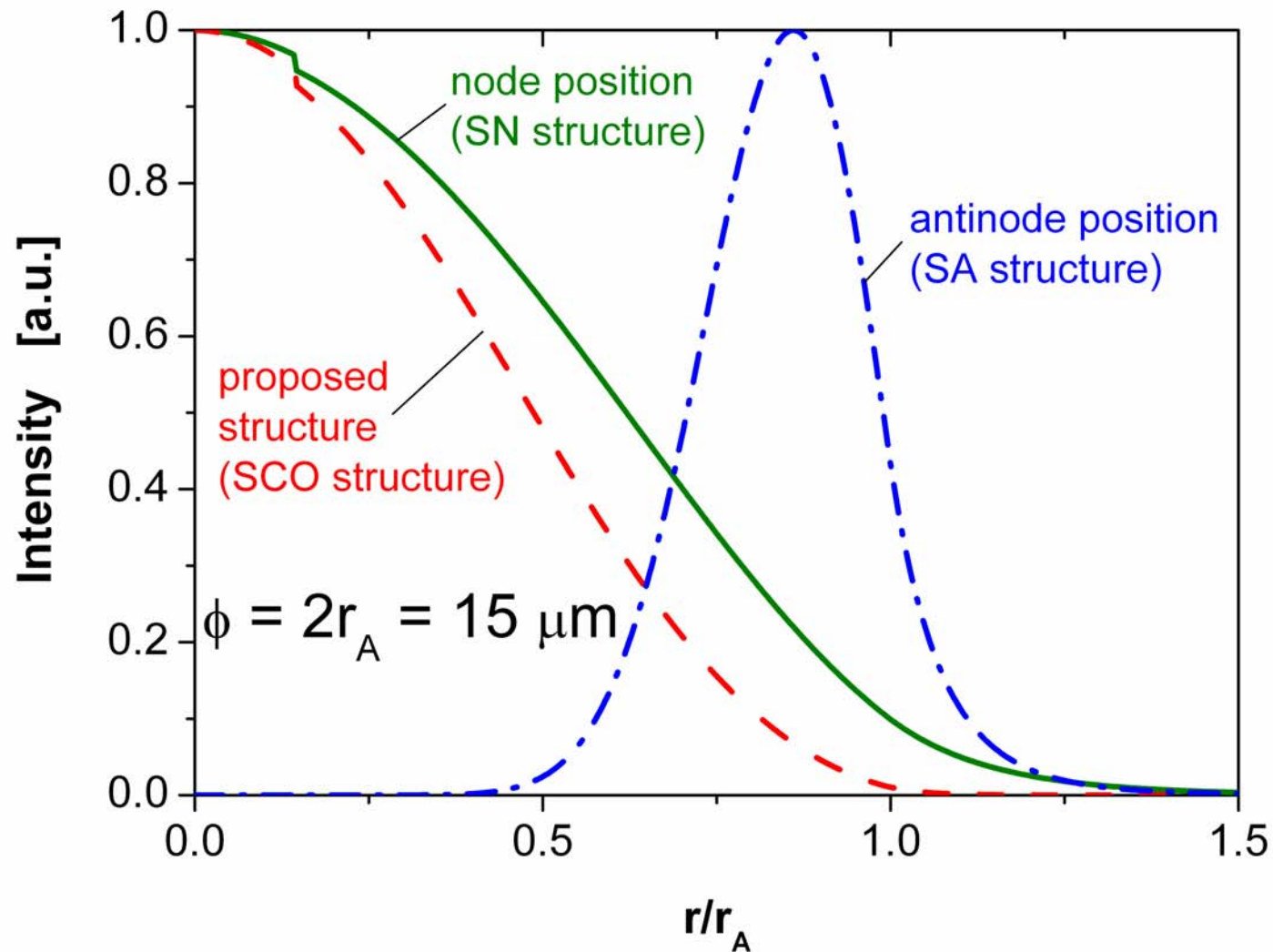
The SCO VCSEL



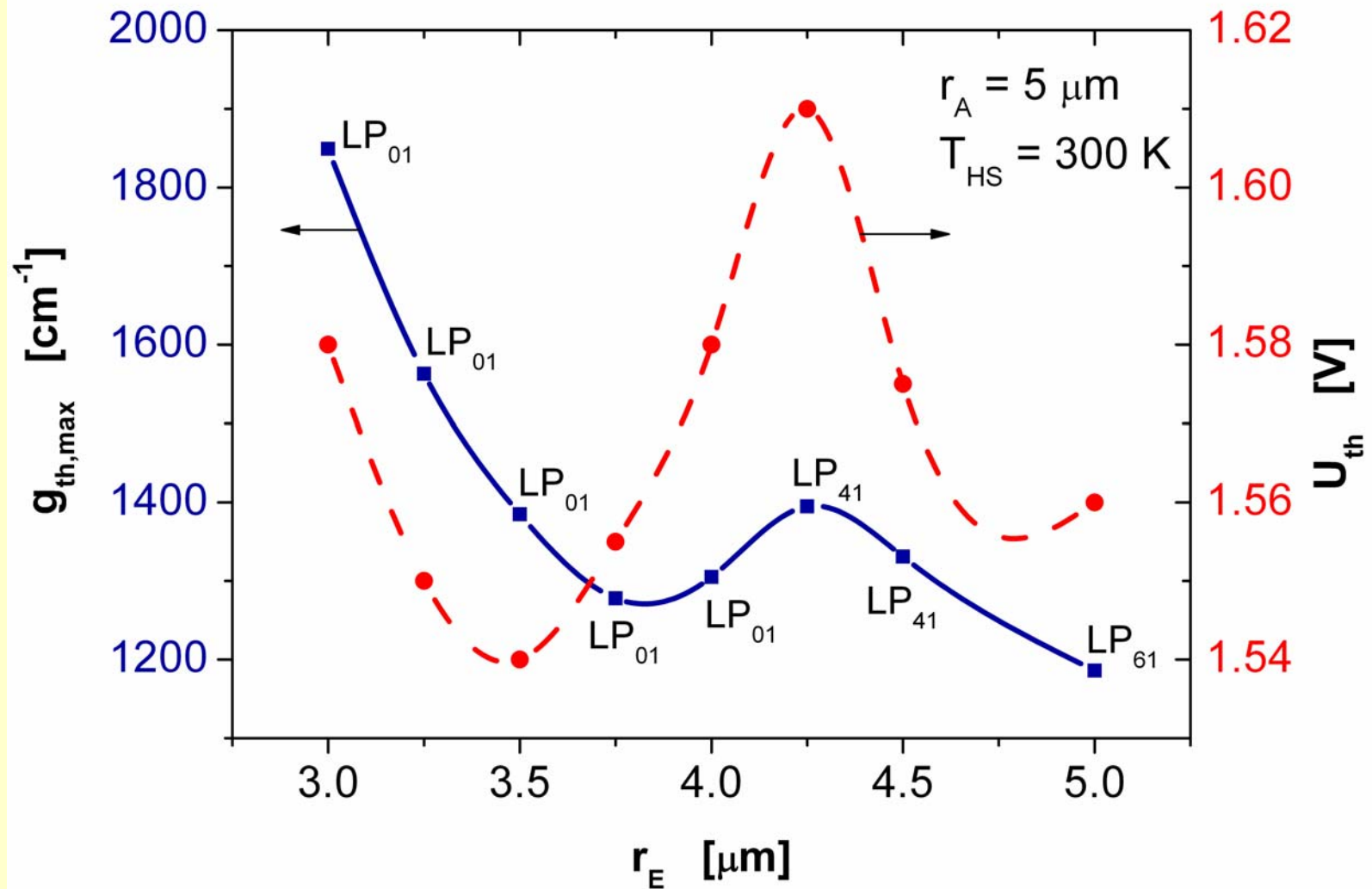
The SCO VCSEL



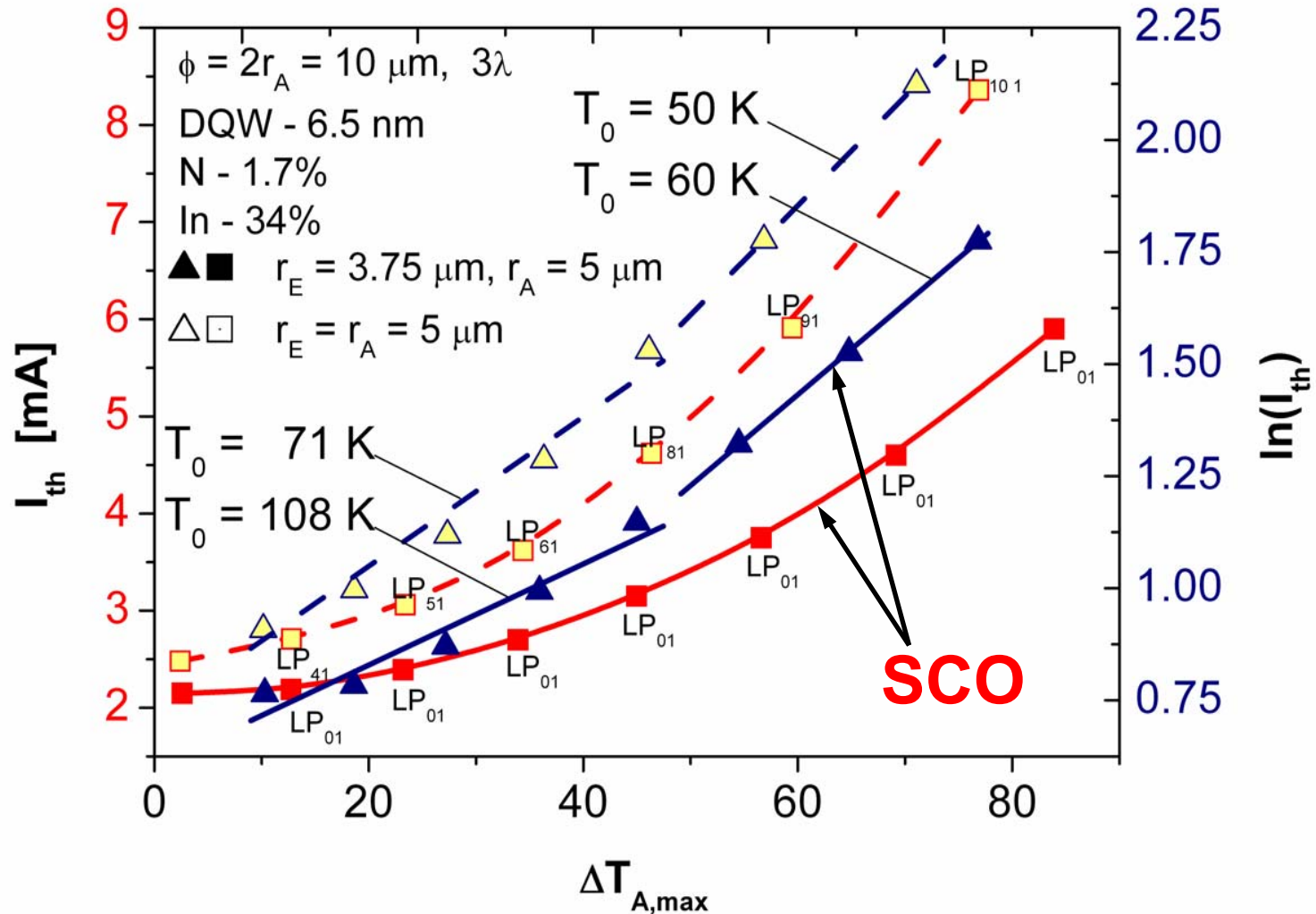
The SCO VCSEL



The SCO VCSEL



The SCO VCSEL



The SCO VCSEL

Name of structure	r_A [μm]	r_E [μm]	U_{th} [V]	I_{th} [mA]	$T_{A,max}$ [K]	$g_{th,max}$ [cm^{-1}]	MOD	λ [nm]
1 SN	10	-	3.65	21.13	316.83	4432	LP_{01}	1303.2
2 SCO	10	6	2.34	7.24	306.26	3128	LP_{01}	1303.2
3 SA	10	-	2.09	8.24	304.28	1644	$LP_{11\ 1}$	1295.1
4 SN	7.5	-	2.55	10.22	308.16	2792	LP_{01}	1302.4
5 SCO	7.5	5	1.95	4.60	304.30	2094	LP_{01}	1300.0
6 SA	7.5	-	1.94	5.72	303.76	1539	LP_{71}	1295.8
7 SN	5	-	1.99	5.11	305.18	2174	LP_{01}	1302.1
8 SCO	5	3.75	1.55	2.36	302.59	1518	LP_{01}	1298.7
9 SA	5	-	1.68	3.22	302.91	1311	LP_{31}	1297.1
10 SN	2	-	2.75	4.85	315.68	6890	LP_{01}	1302.3
11 D	2	2	1.20	0.65	301.20	884	LP_{01}	1296.6
12 SA	2	-	1.27	0.86	301.50	1189	LP_{01}	1298.2

SN – single oxidation at the node position

SA – single oxidation at the anti-node position

D – two identical oxidations

SCO – new SCO VCSEL

Conclusions

The new SCO VCSEL structure demonstrates advantages of both the previous oxide-confinement VCSELs:

- **the stable single-fundamental-mode operation** of the gain-guided VCSEL with the oxide aperture located at the standing-wave node position, and
- **the low lasing threshold** of the index-guided VCSEL with the aperture shifted to the analogous anti-node position.

Therefore, the traditional VCSEL design with the oxide aperture located at the standing-wave node position may be recommended for the room-temperature operation of large-active-region VCSELs because of their relatively simple technology. In all other cases, the new SCO VCSEL structure ensures much better performance.