In-plane Semiconductor Membrane Lasers for Photonic Integrated Circuits

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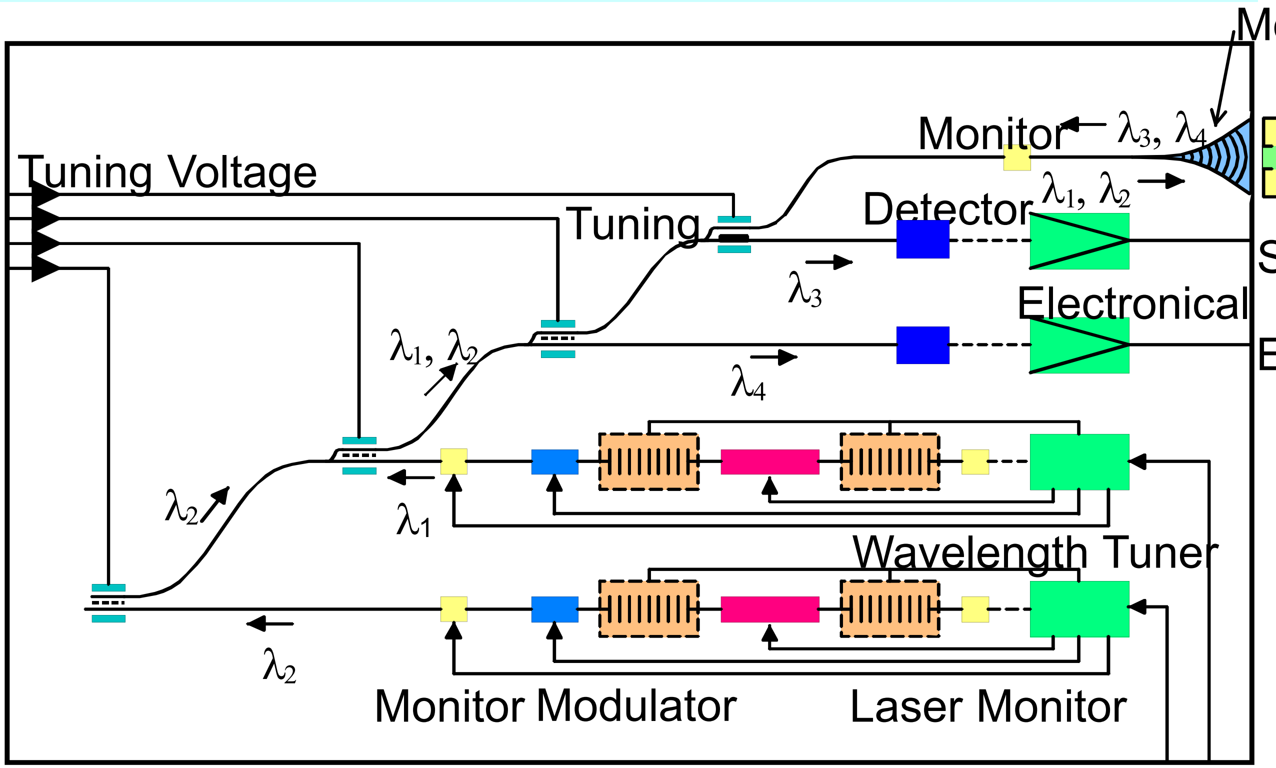
Outline

1. Background
    - Looking back Our In-plane Lasers
    - Optical Interconnects
2. Semiconductor Membrane Lasers
    - Design, Fabrication Process
    - Lasing properties of DFB & DR lasers
    - High-speed modulation of DFB lasers
3. Summary

Photonic Integrated Circuits (1)

In-plane Photonic Integrated Circuits

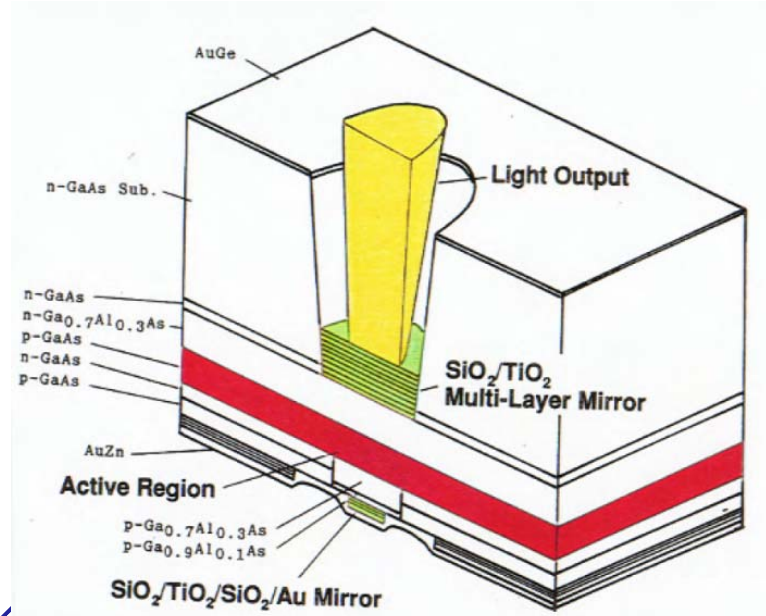


(Y. Suematsu, "Monolithic Integration of Optical Circuits and Related Twin Guide Lasers," IOOC'77, Tokyo, paper B1-1, pp. 185-188, July 1977.)

Photonic Integrated Circuits (2)

Stacked Photonic Integrated Circuits

(K. Iga, memo of VCSEL, 22nd March, 1977.)

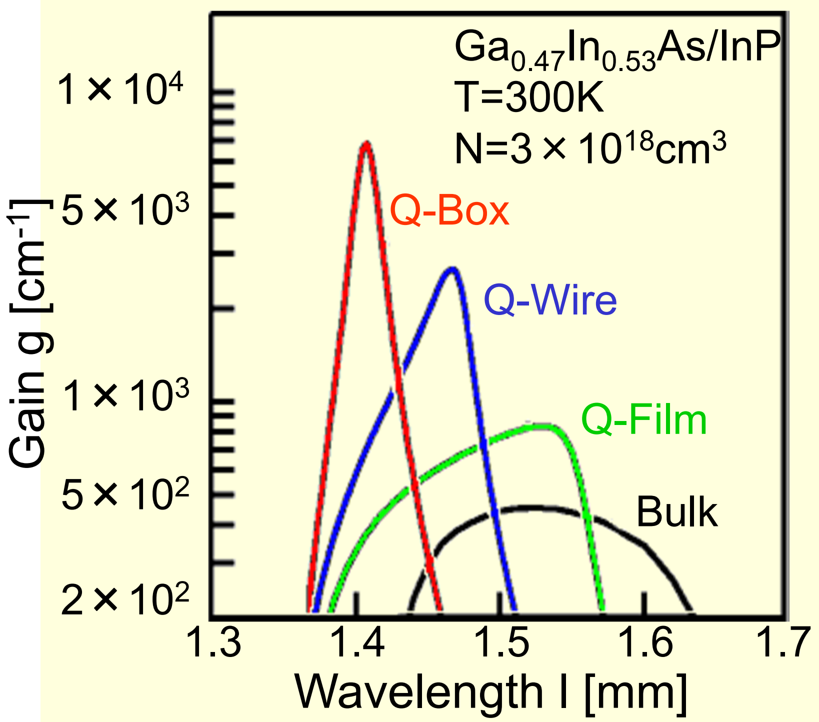


(K. Iga, “Stacked planar optics: an application of the
plana . 3456-3460,
Oct.

(F. Koyama, S. Kinoshita, and K. Iga, “RT-CW operation of VCSELs,” Trans. IEICE, **B71**, pp. 1089–1090, Nov. 1988.)

Low-threshold In-plane Laser

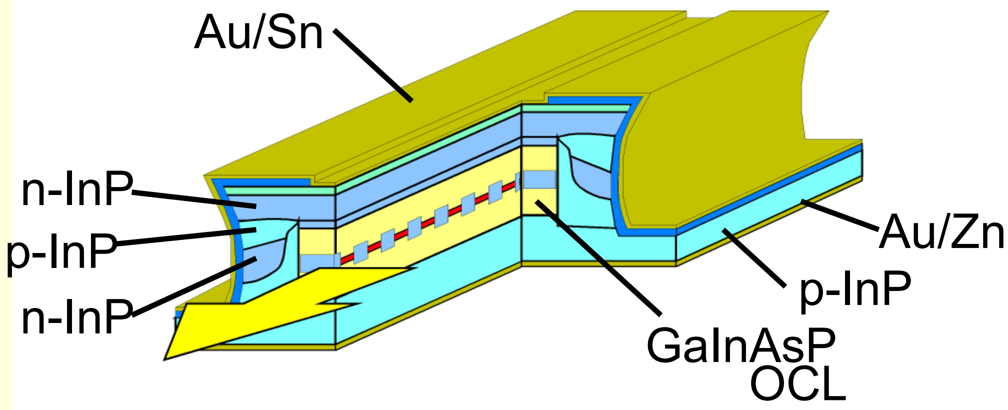
Low-dimensional structure



(M. Asada, Y. Miyamoto, and Y. Suematsu, IEEE J. Quantum Electron., **QE-22**, pp. 1915-1921, Sep. 1986.)

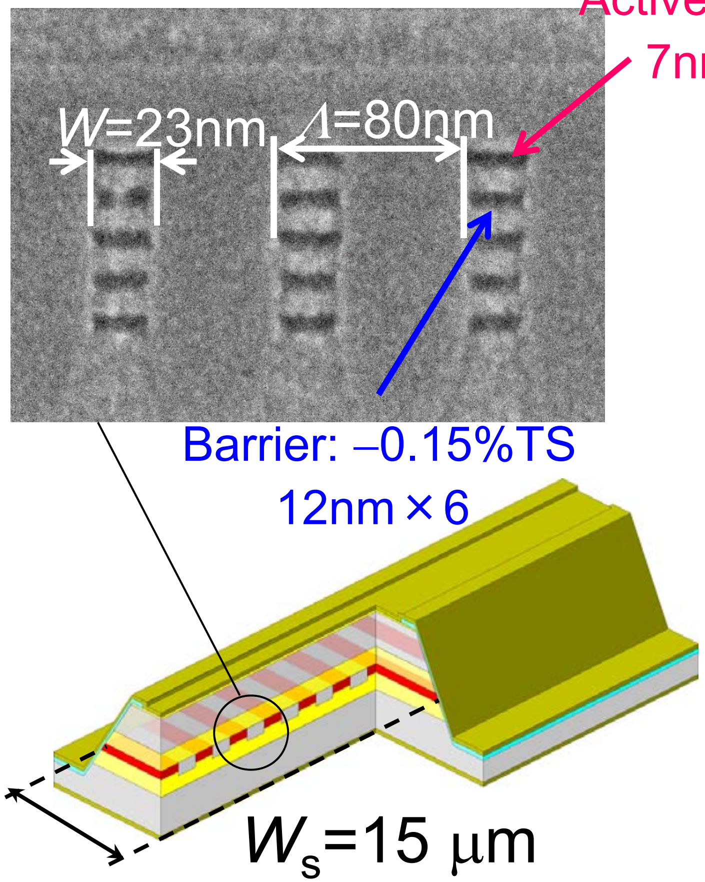
High-κ grating DFB with wire-like active regions

- High reflectivity mirror
- Small volume

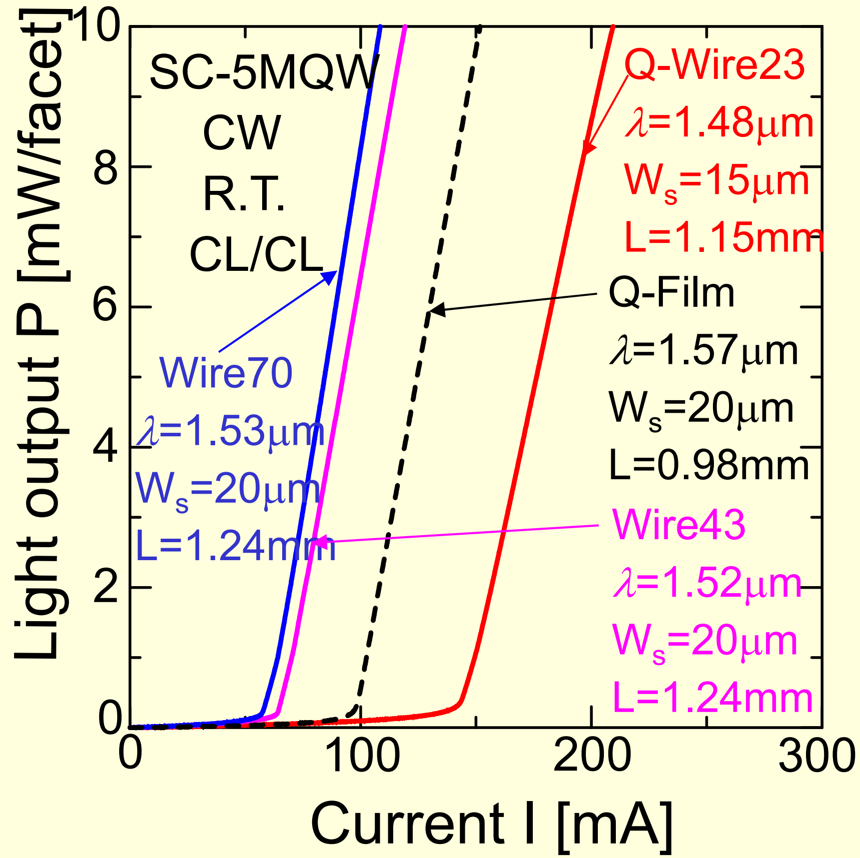


(N. Nunoya, M. Nakamura, M. Morshed, S. Tamura, and S. Arai, IEEE J. IEEE J. Select. Top. Quantum Electron., **7**, pp. 249-258, 2001.)

Quantum-wire Laser

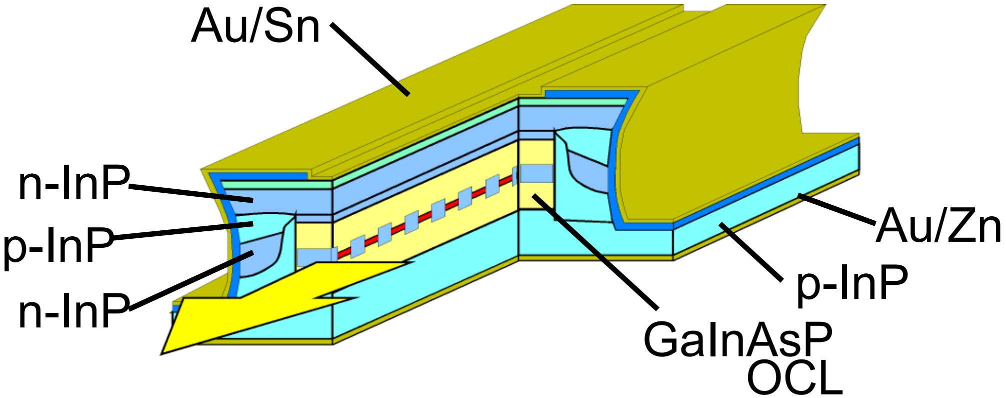


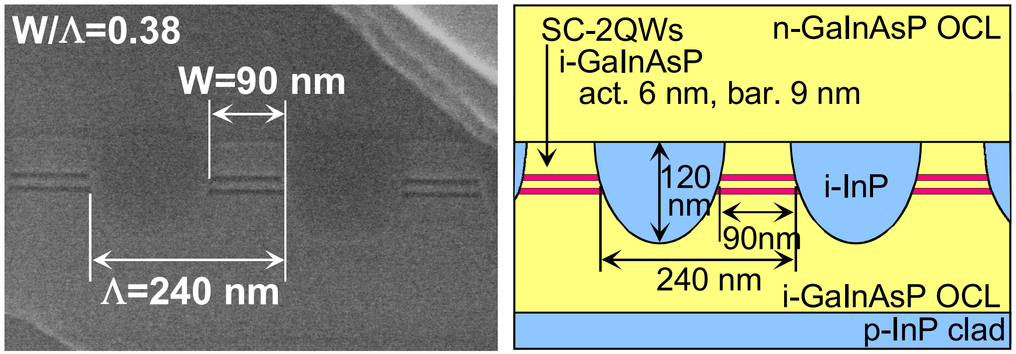
(H. Yagi, T. Sano, K. Ohira, T. Maruyama, A. Haque and S. Arai, Jpn. J. Appl. Phys., **42**, pp. L748-L750, July 2003.)

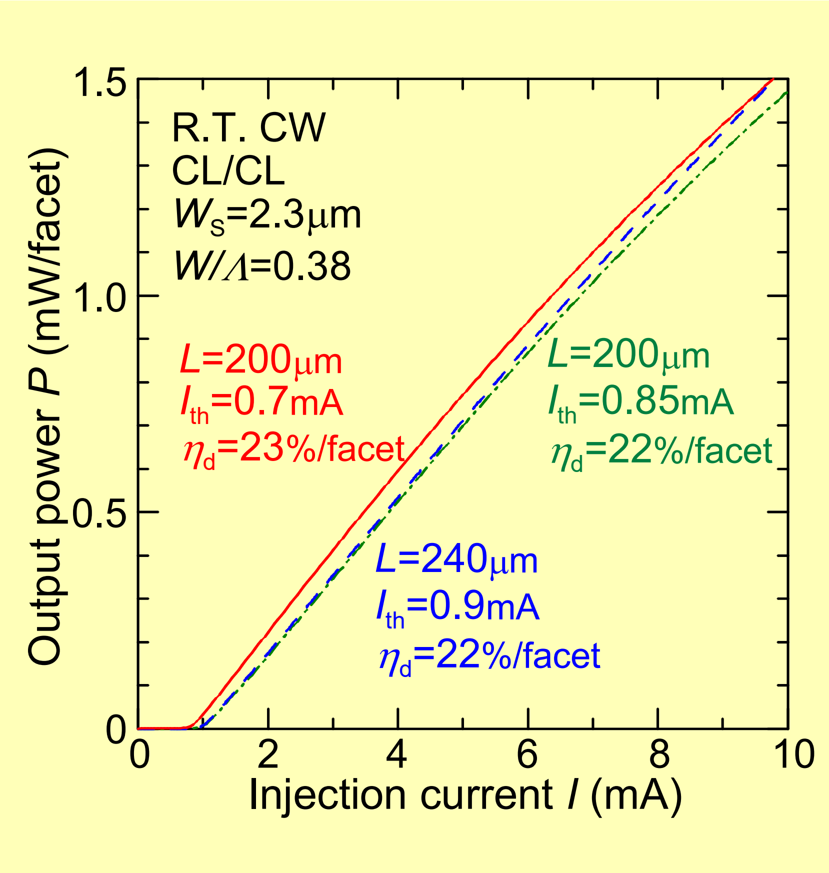


- **Similar gain spectrum**
- **Lifetime > 41,600 h**

DFB Lasers with Wire-like Active Regions







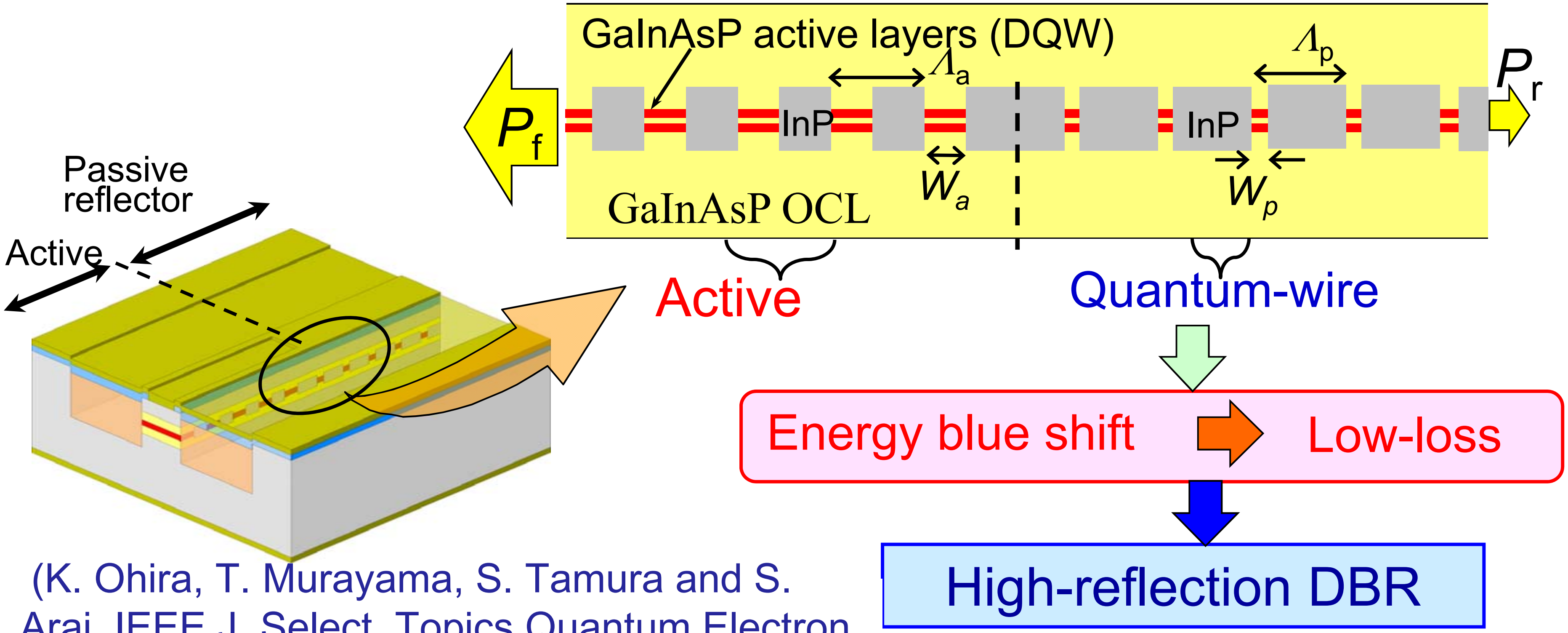
(N. Nunoya, M. Nakamura, M. Morshed, S. Tamura, and S. Arai, IEEE J. Select. Top. Quantum Electron., 7, pp. 249-258, 2001.)

- I_{th} < 1 mA
- η_{df} = 22 % (front facet)

DR Lasers with Wire-like Active Regions

Application of integration using energy blue shift

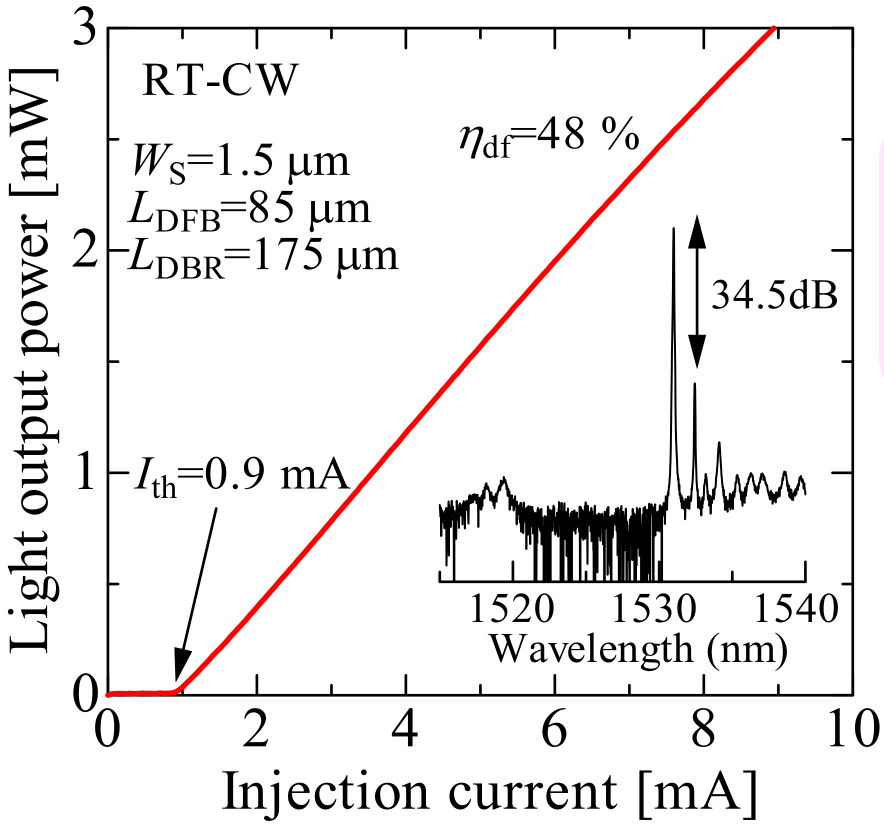
- Integration of active and passive sections



(K. Ohira, T. Murayama, S. Tamura and S. Arai, IEEE J. Select. Topics Quantum Electron., 11, pp. 1162-1168 , Sept./Oct. 2005.)

For low-threshold and high-efficiency lasers

Low-threshold & High-efficiency DR Lasers



(T. Shindo, S. Lee, D. Takahashi, N. Tajima, N. Nishiyama, and S. Arai, IEEE Photon. Technol. Lett., **21**, pp. 1414-1416 , Oct. 2009.)

- I_{th} = 0.9 mA
- η_{df} = 48 % (front facet)
- SMSR = 34.5 dB @ 2I_{th}

Low-threshold and high-efficiency operation

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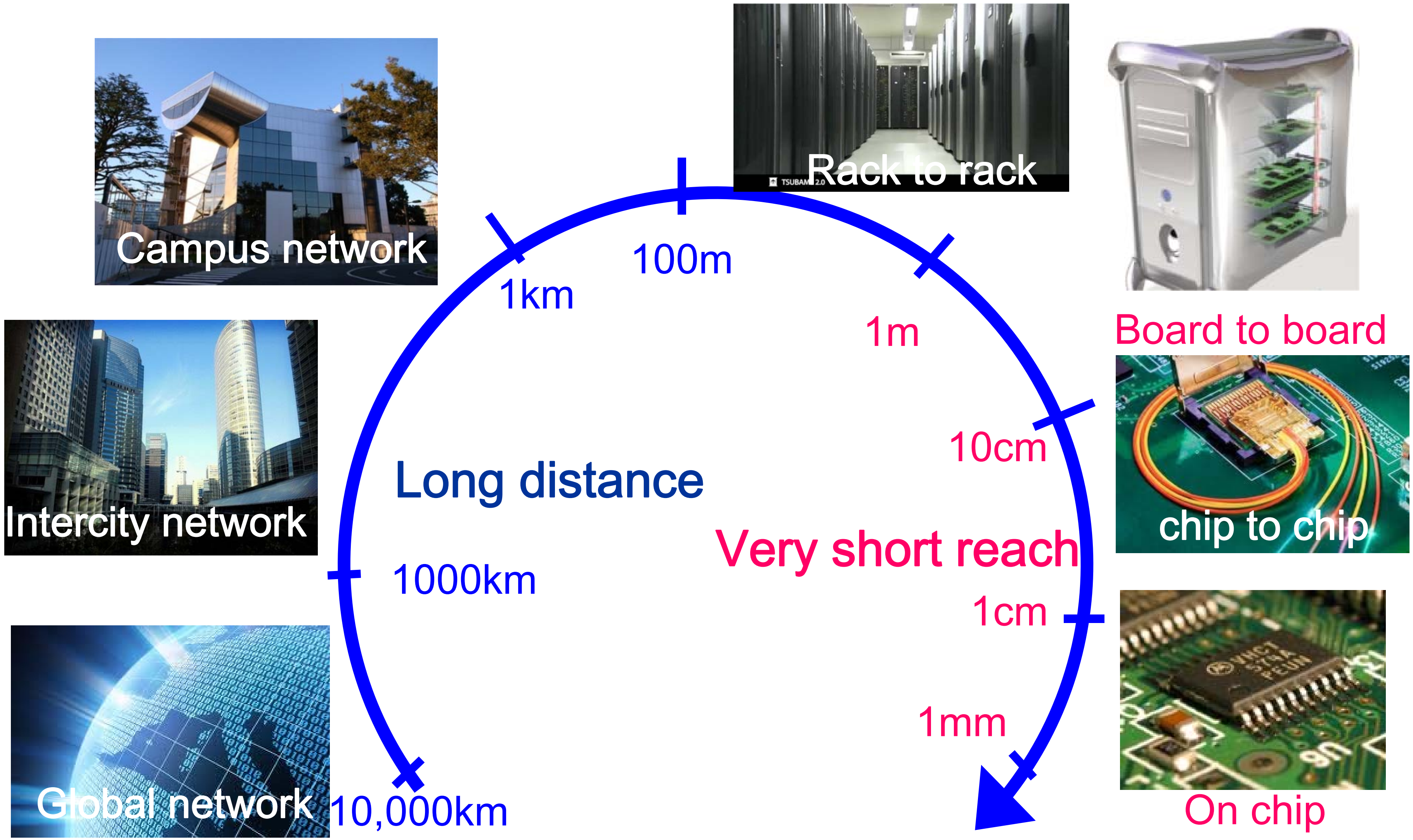
Various Photonic Networks



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Optical Interconnect

Optical Interconnections for VLSI Systems

Proc. of IEEE , 72, 7, p. 850, 1984.

JOSEPH W. GOODMAN, FELLOW, IEEE, FREDERICK J. LEONBERGER, SENIOR MEMBER, IEEE, SUN-YUAN KUNG, SENIOR MEMBER, IEEE, AND RAVINDRA A. ATHALE

problem becomes further exacerbated. As a consequence of these considerations, it has been estimated that by the late 1980s, chip speeds will be limited primarily by interconnect delays [11]. The tantalizing possibilities for bringing optics to bear on this interconnection bottleneck are prime motivating factors for the considerations of this paper.

noncleaved mirrors for more compact devices. Although surface-emitting GaAs lasers have seen limited development, both distributed feedback [30] and heterointerface-mirror [31] types have been reported. These devices are to date relatively inefficient and in the latter case require cryogenic cooling.

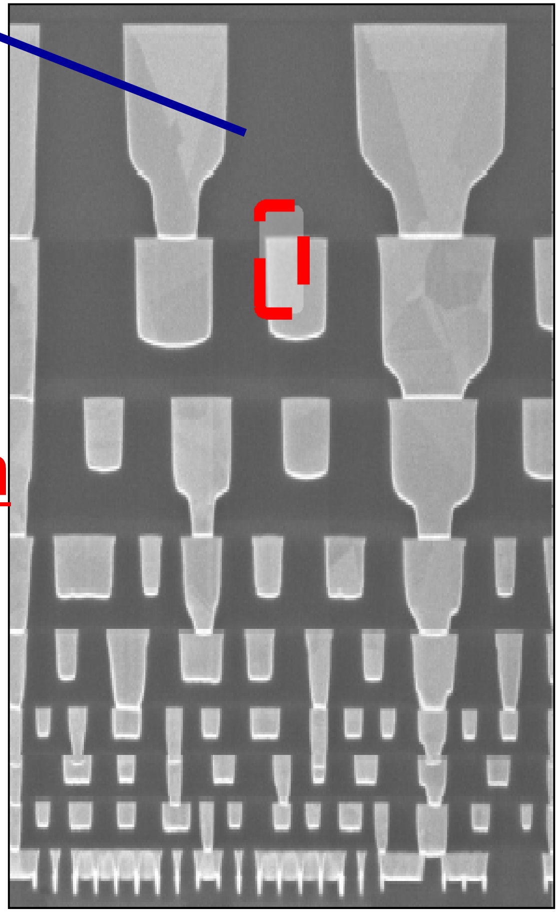
Optical Interconnect

Copper Global Wiring

Problems
- RC delay
- Joule Heating

On-chip Optical Interconnection

Cross section of LSI

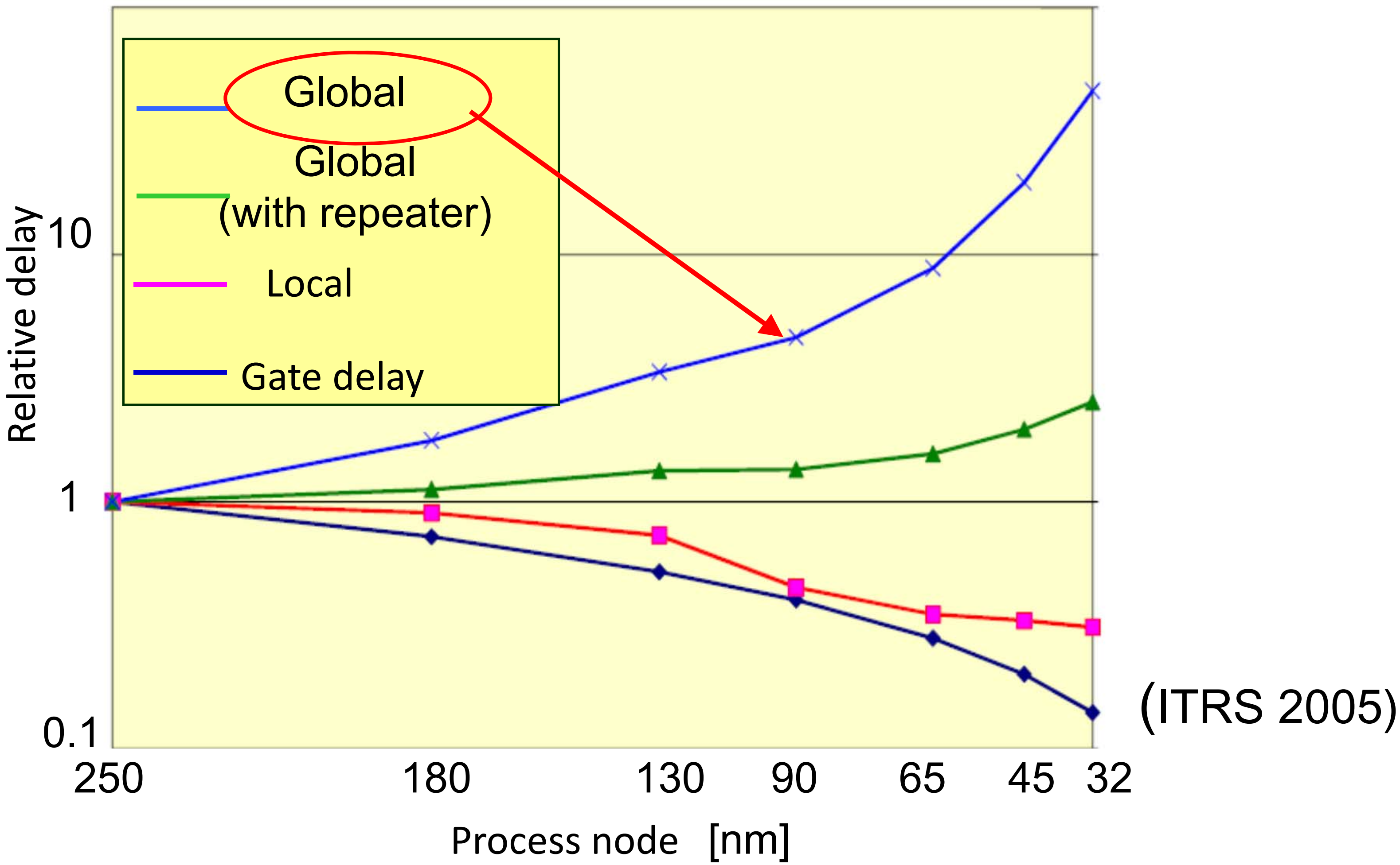


(ref : Intel®)

Requirements

- Small size
- Ultra-low power consumption

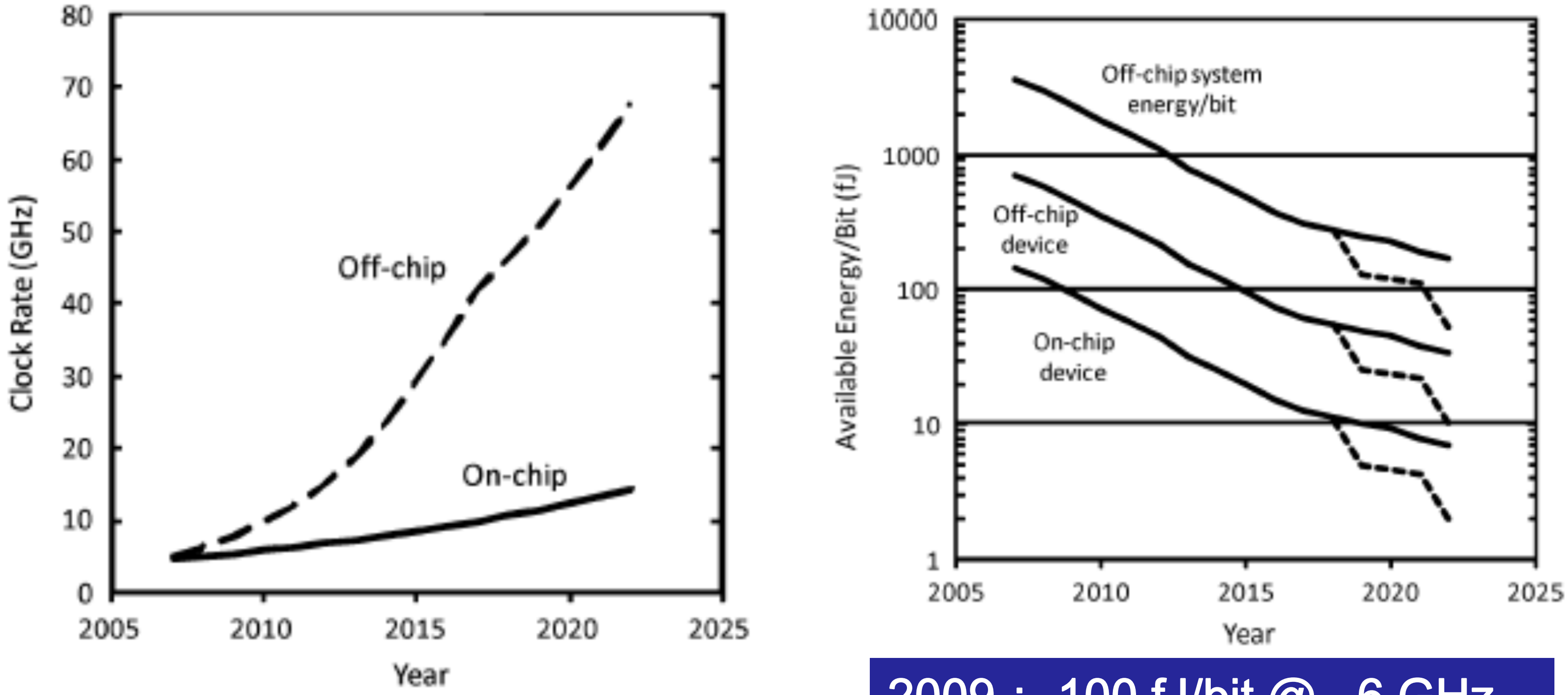
Transmission Delay in LSI



Operation speed of LSI: Electrical wiring limit

Prospect for On-chip Optical Interconnects

Requirements for high-speed and low power-consumption

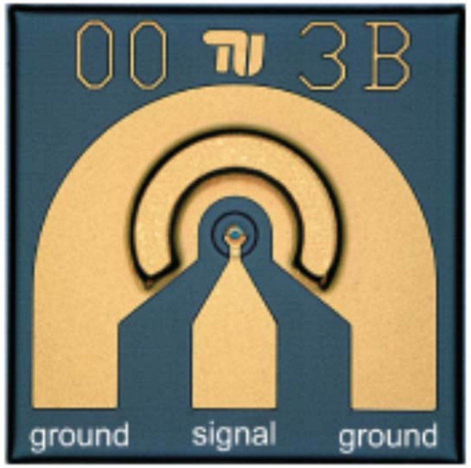


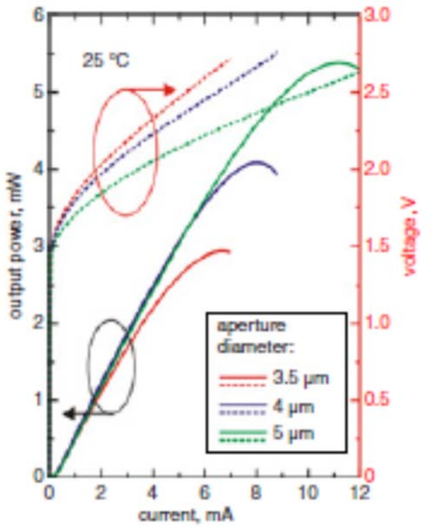
2009 : 100 fJ/bit @ 6 GHz
2020 : 10 fJ/bit @ 12 GHz

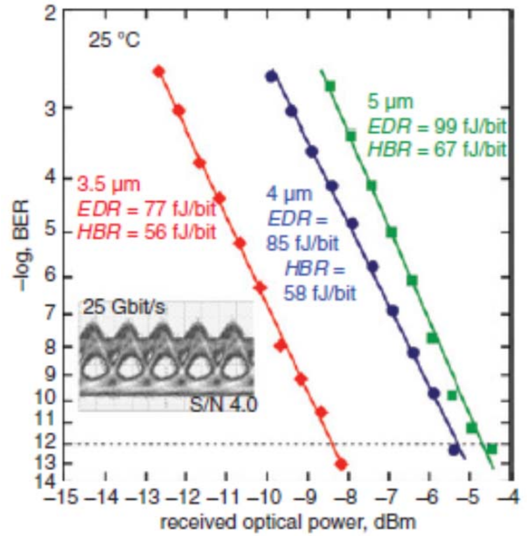
D. A. B. Miller, Proc. IEEE 97, 1166 (2009)

Ultra Low Power Consumption Lasers (1)

VCSEL







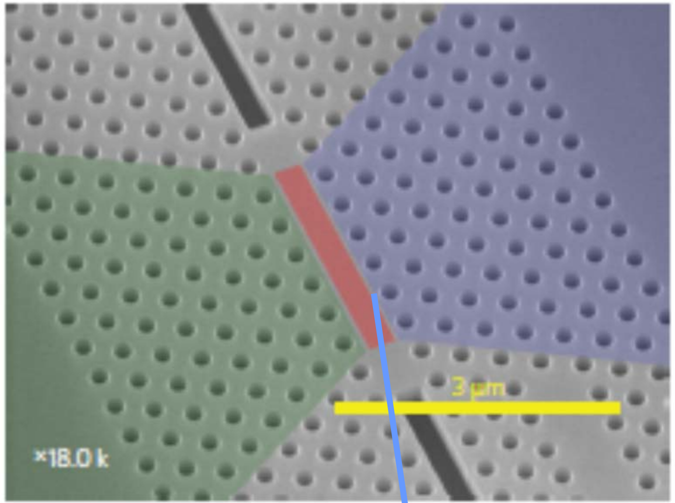
I_{th} : 150 μA (λ= 850 nm)
Energy Cost: 77 fJ/bit @25 Gb/s

Short reach data com.
1 km @17 Gb/s
600 m @25 Gb/s

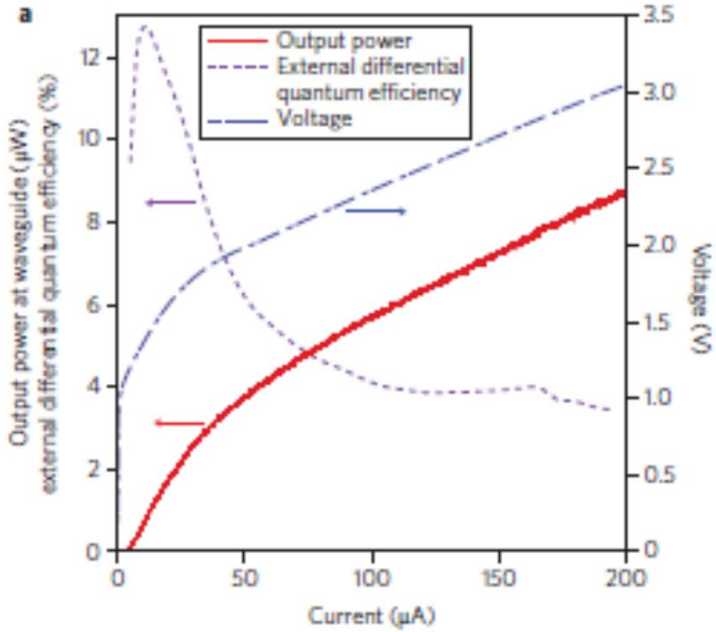
P. Moser et al., JSTQE. 19, 2, 7900406, (2013).
P. Moser et al., Electron. Lett. 48, 1292, (2012).

Ultra Low Power Consumption Lasers (2)

LEAP (Lambda-scale embedded active region photonic-crystal) LD



Active Region Volume
2.6 μm (L) × 0.3 μm (W)× 0.15 μm (H)



I_{th} : 4.8 μA
Energy cost : 4.4 fJ/bit @10 Gb/s (APD)

K. Takeda et al., Nature Photonics, vol. 7, p. 569, 2013.

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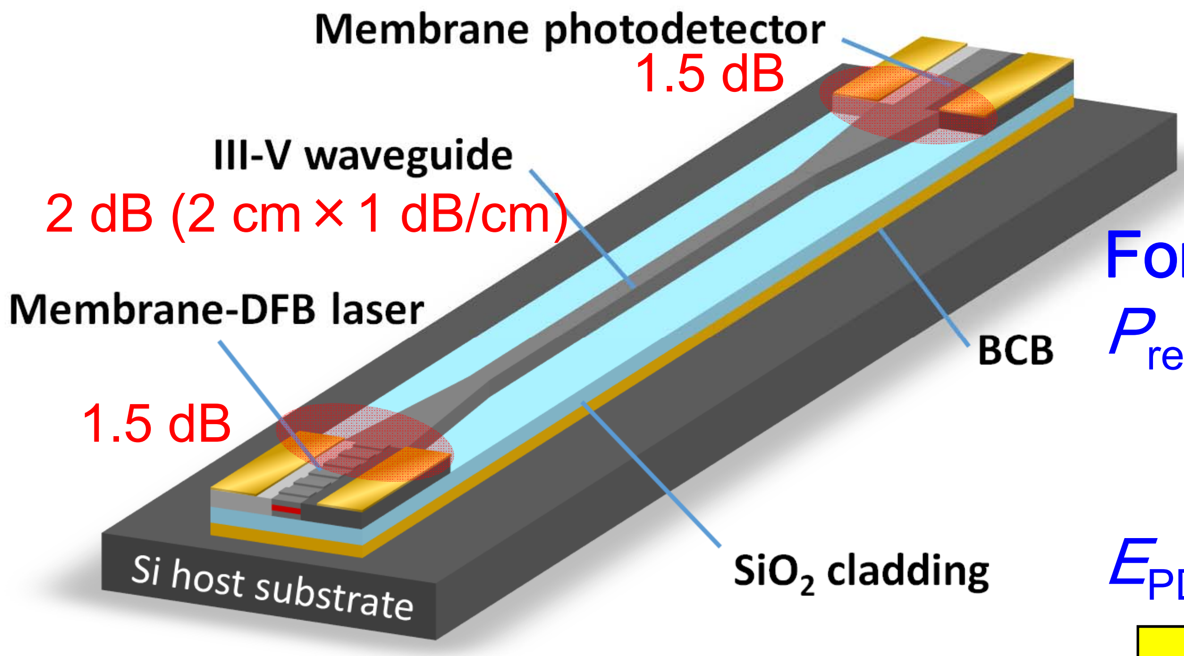
Energy Cost of Optical Link



For PIN-PD

P_{rec} = -13 dBm (0.05 mW) @ BER < 10^{-9} 10 Gb/s

E_{PD} = 5 fJ/b

When the link loss is 5 dB

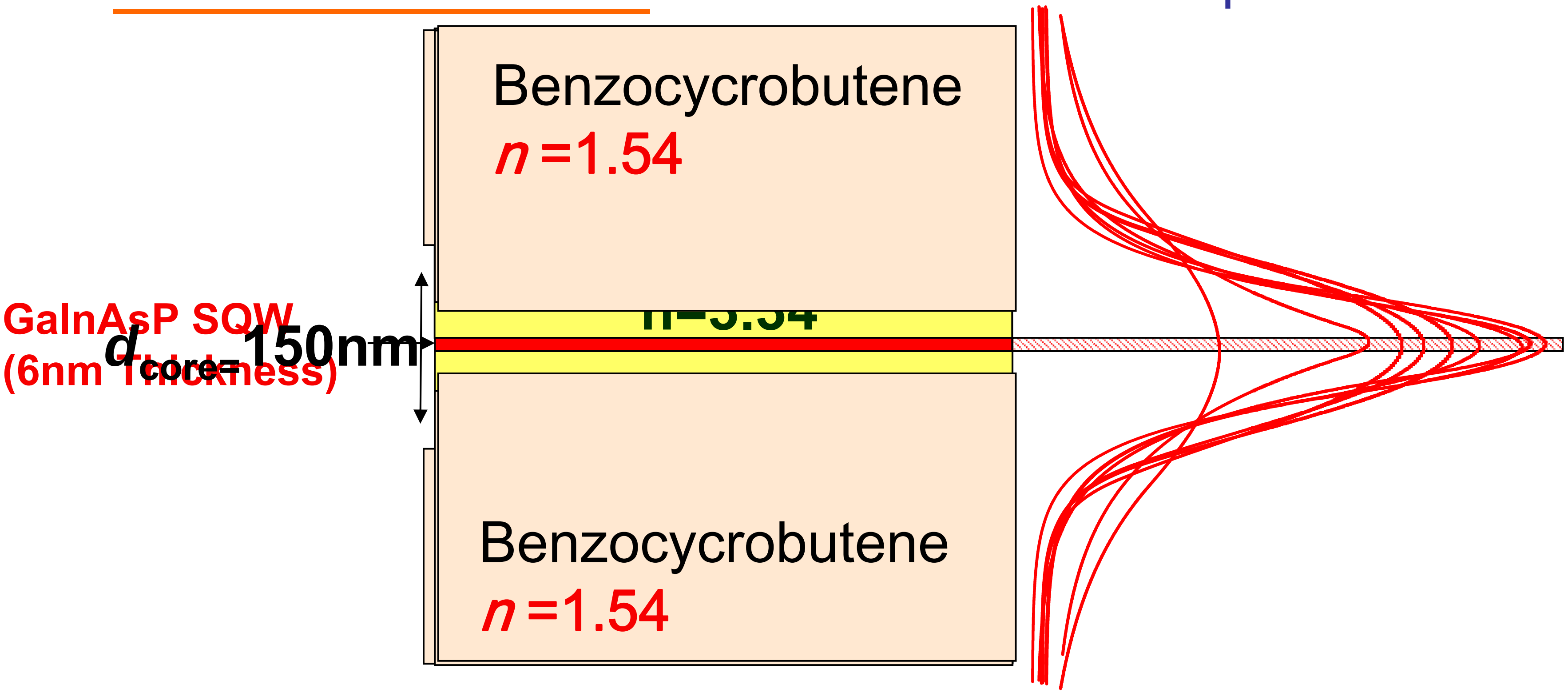
P_{out} > - 8 dBm (160 μW) @ BER < 10^{-9}, 10 Gbps

Hiratani et al., IPRM 2014, Montpellier, France.

Membrane Semiconductor Lasers

Membrane Structure

Optical Field

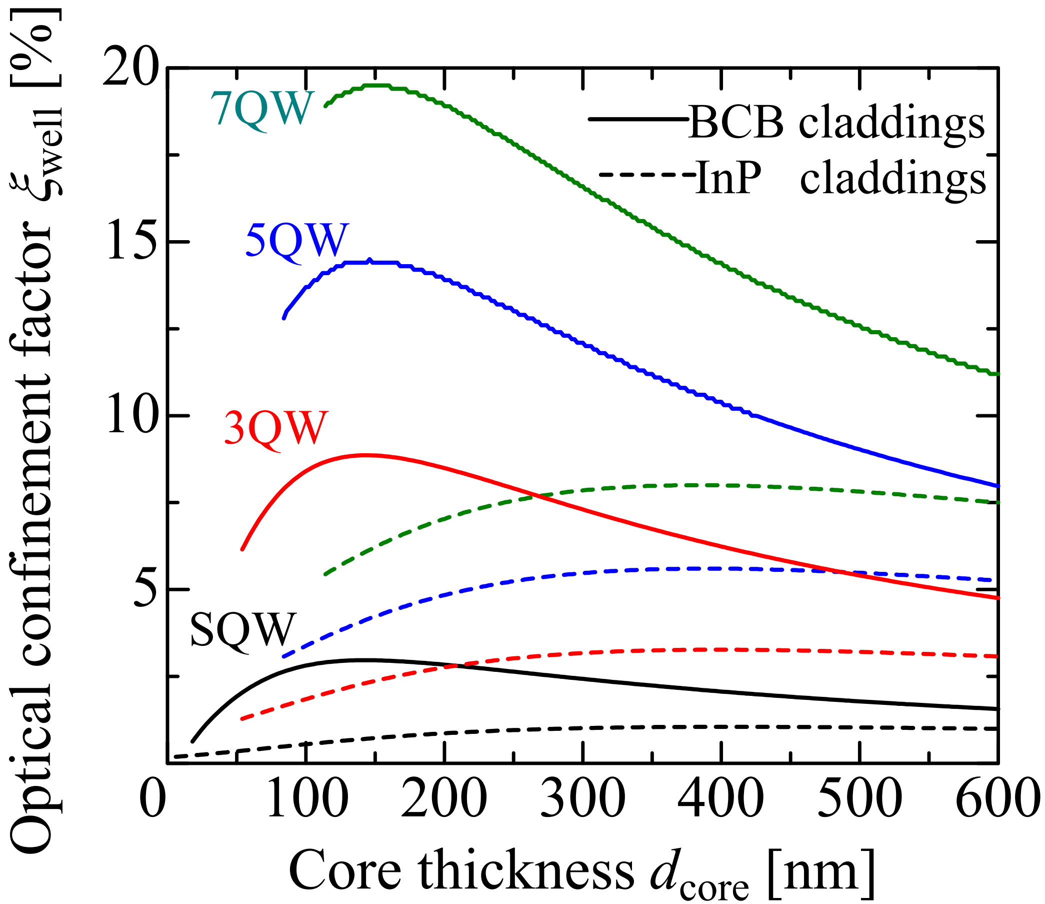


Optical confinement factor

$\xi_{Mem} \fallingdotseq 3\xi_{Conv}$

T. Okamotoet al., Electron. Lett., vol. 38, p. 1444, 2002.

Optical Confinement in Membrane Lasers



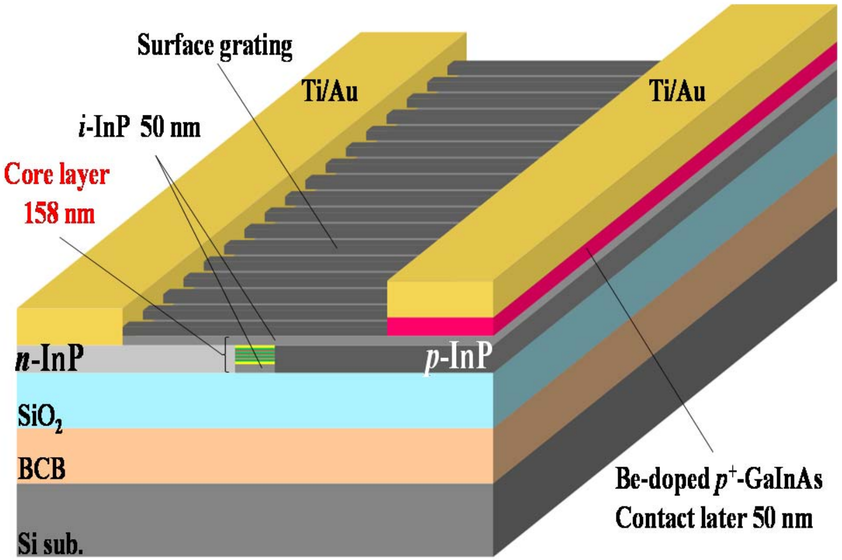
Optical confinement

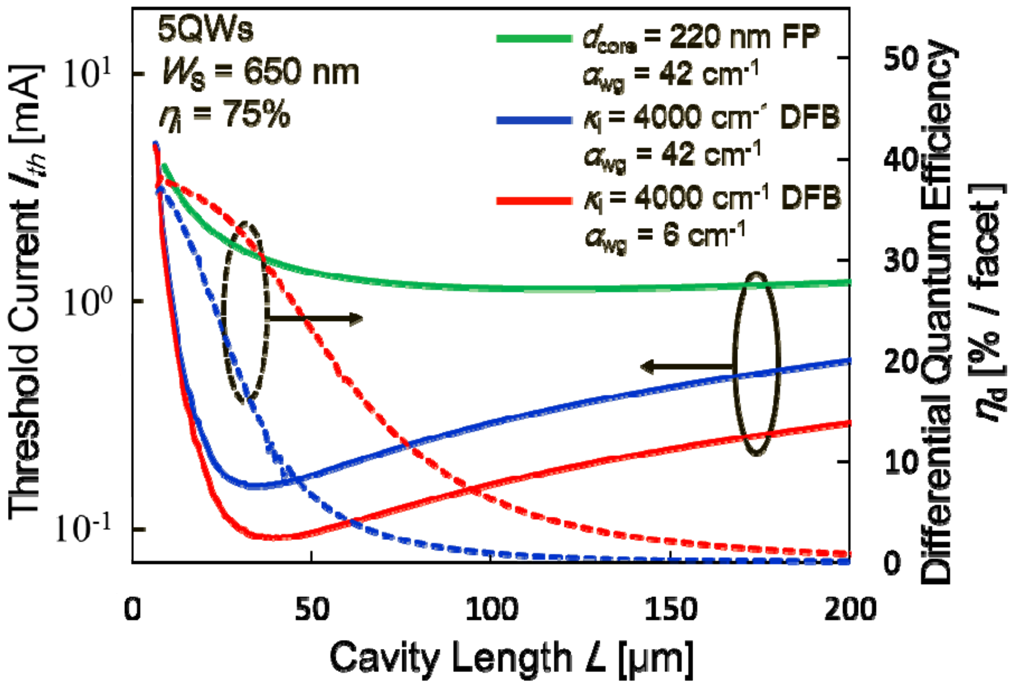
$\xi_{Mem} \fallingdotseq 3\xi_{Conv}$
$@d_{core} = 150$ nm

$\xi_{Mem} \fallingdotseq 2.2\text{-}2.4\,\xi_{Conv}$
$@d_{core} = 300$ nm

T. Okumura al., Appl. Phys. Express, vol. 4, 042101, 2011.

Threshold Current Estimation





High index-coupling κ_i
Short cavity DFB L_{DFB}

Very low $I_{th} << 1$ mA
Enough high η_d

Power Consumption for Required Light Output

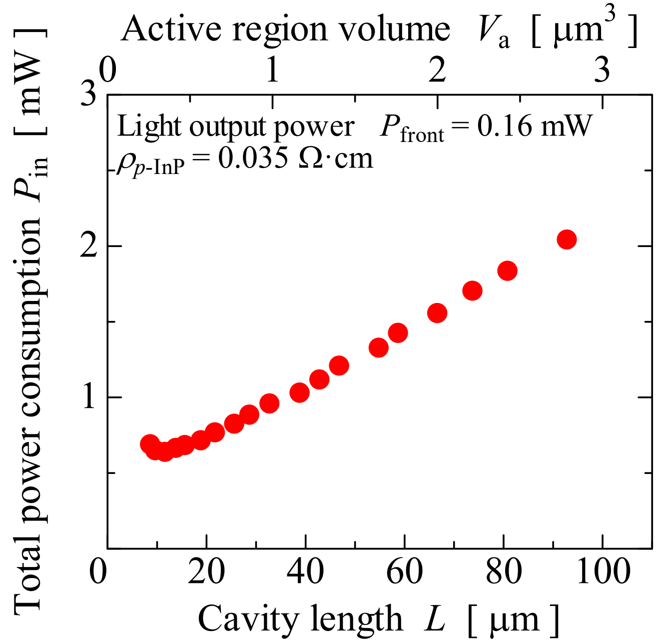
Light output

$$P_{\text{front}} = \frac{h\nu}{e}\eta_{\text{df}}(\boxed{I_{\text{b}}} - I_{\text{th}})$$

0.16 mW

$$P_{\text{in}} = \boxed{I_{\text{b}}} V_{\text{turn-on}} + R\boxed{I_{\text{b}}^{2}}$$

Power consumption for P_{front} = 0.16 mW



Power Consumption for Required Modulation Speed

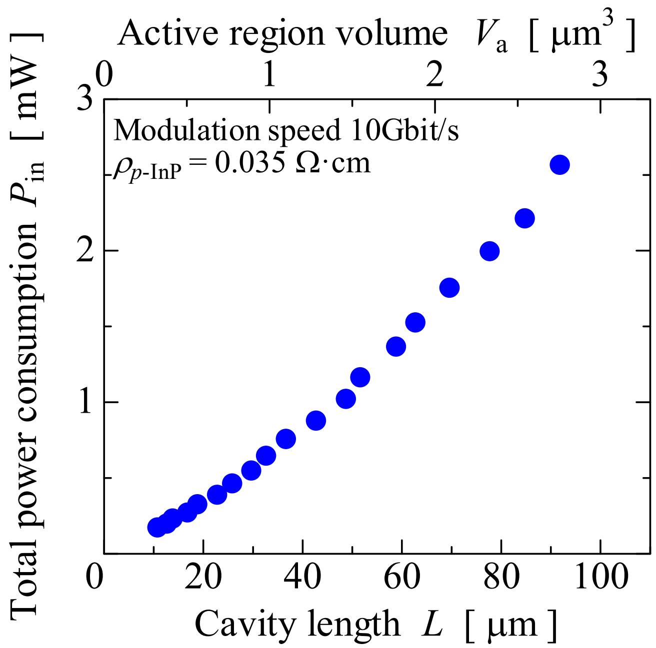
3dB band width

$$f_{3\mathrm{dB}} \approx \frac{1.55}{2\pi}\sqrt{\frac{\xi G'\eta_{\mathrm{i}}}{eV_{\mathrm{a}}}}\sqrt{\boxed{I_{\mathrm{b}}}-I_{\mathrm{th}}}$$

7.7 GHz (10Gbps)

$$P_{\mathrm{in}} = \boxed{I_{\mathrm{b}}}V_{\text{turn-on}} + R\boxed{I_{\mathrm{b}}^2}$$

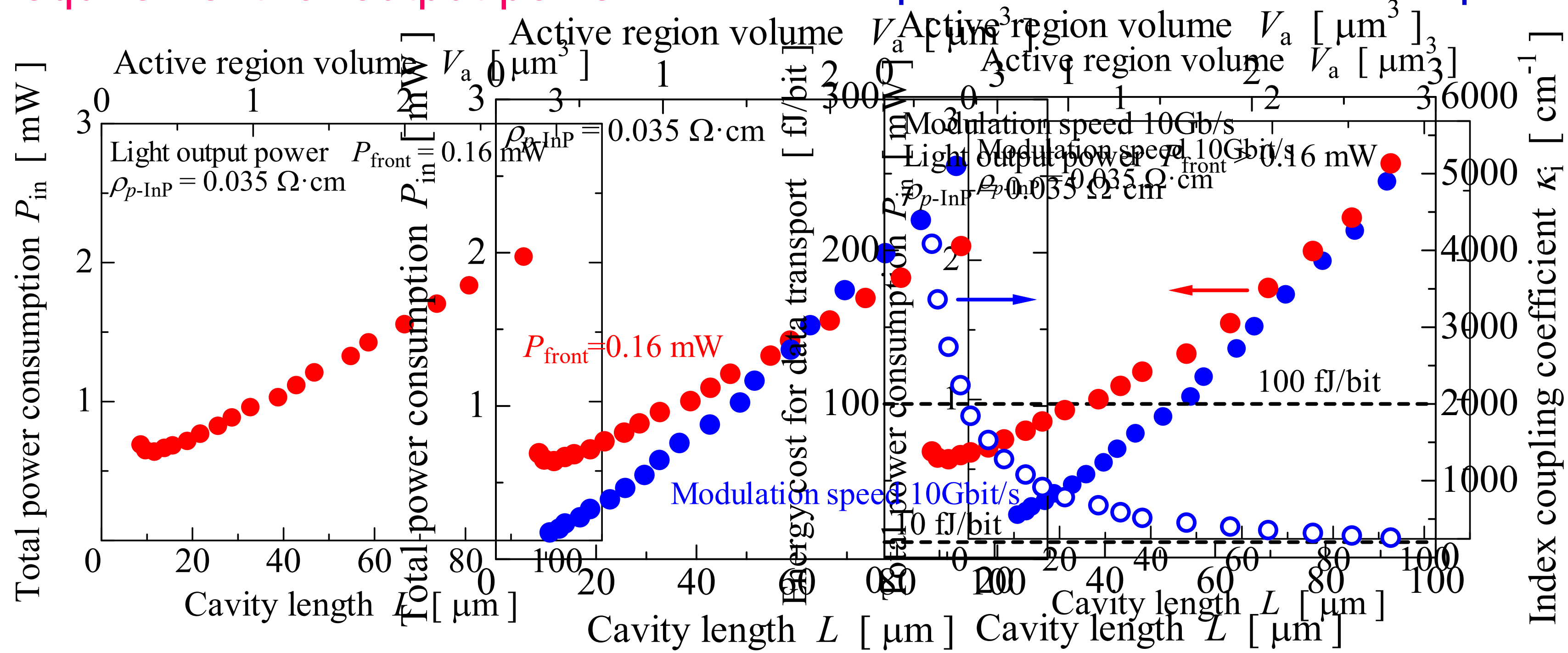
Power consumption for 10Gbps operation



Energy Cost Estimation

Requirement for output power

Requirement for modulation speed

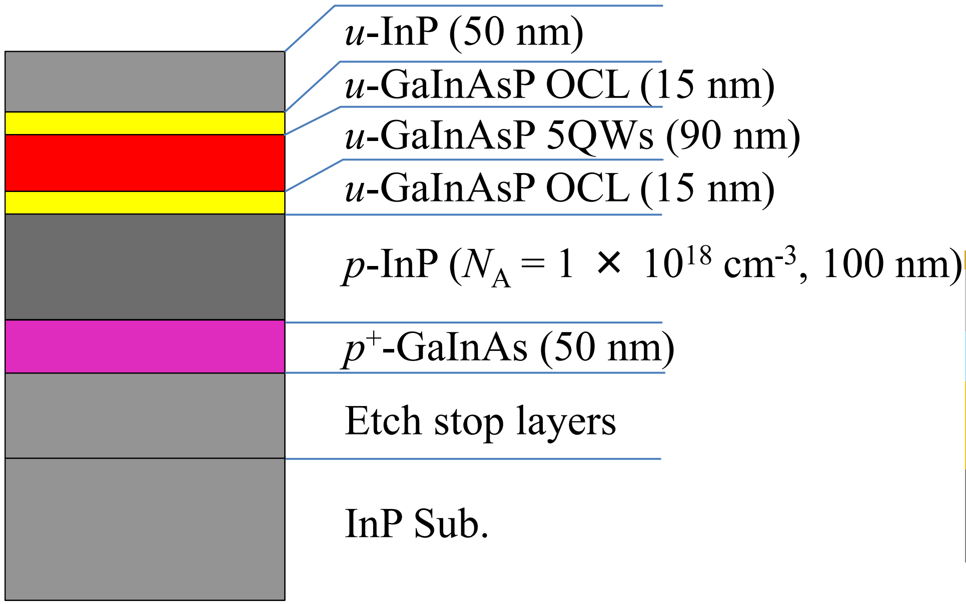


T. Hiratani et al., JSTQE, vol. 21, 1503410, 2015.

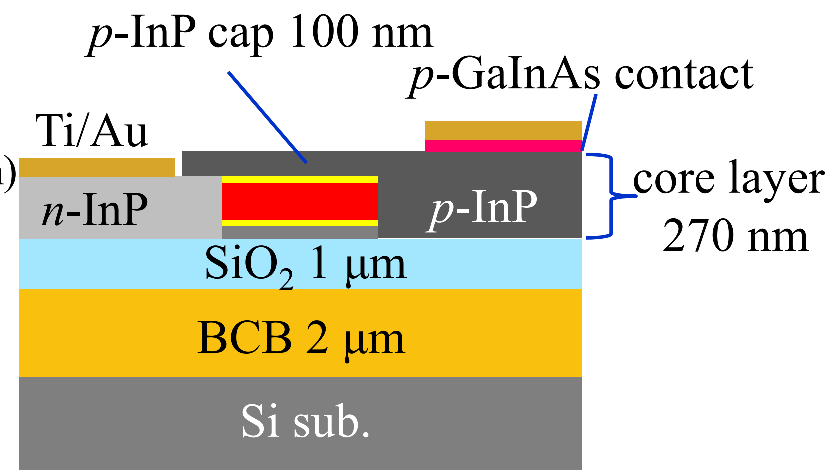
Optimum cavity length : power consumption for required output power and modulation bandwidth.

E_{pulse} = 63 fJ/bit for L = 12 μm

Initial Wafer

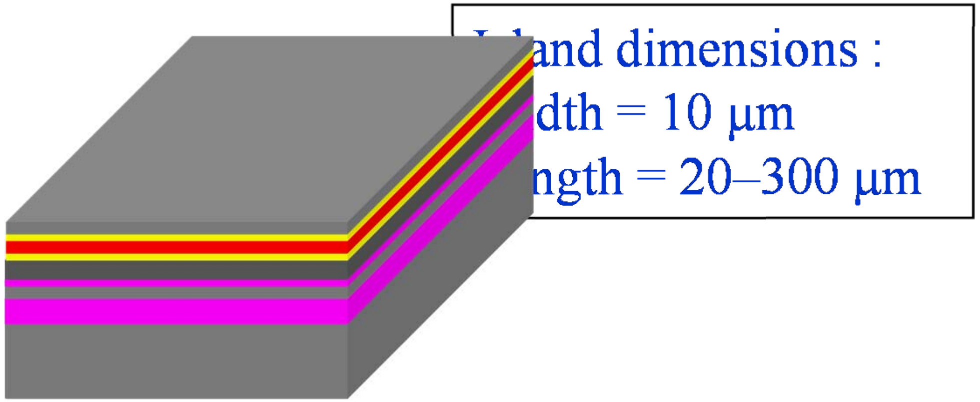


Initial wafer

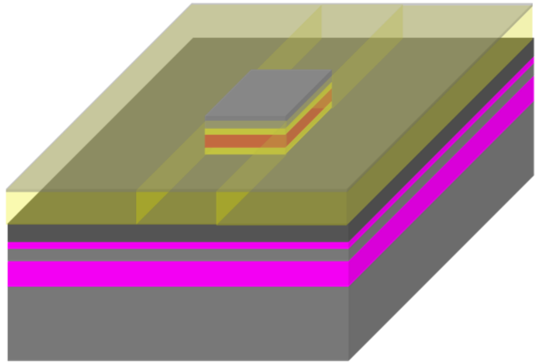


Cross section
of laser region

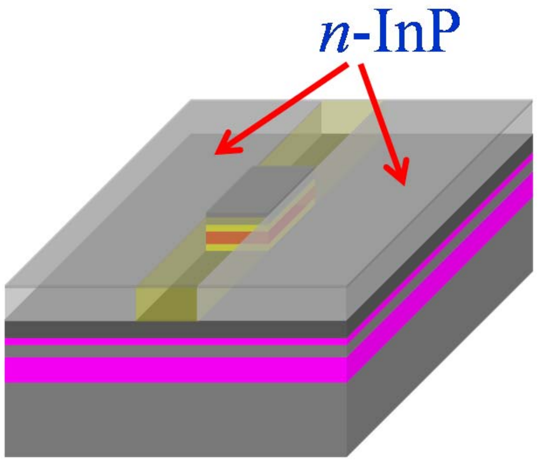
Fabrication Process (1)



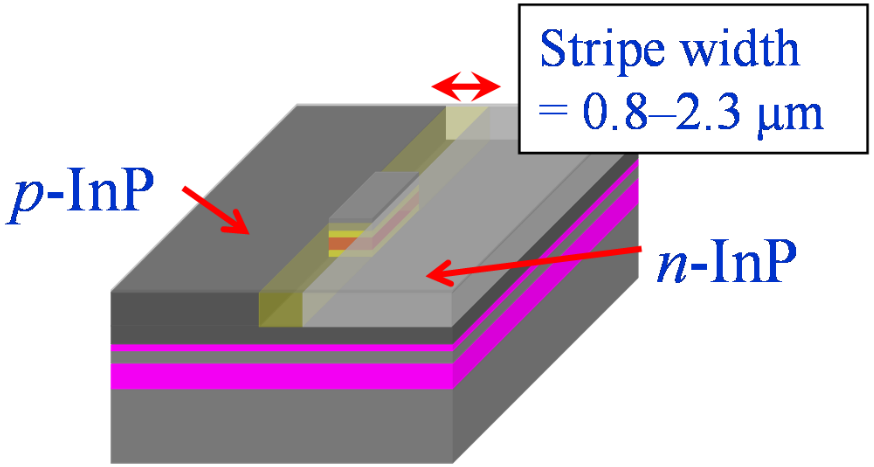
1. Island formation



2. 1st regrowth of *u*-GaInAsP waveguide layers



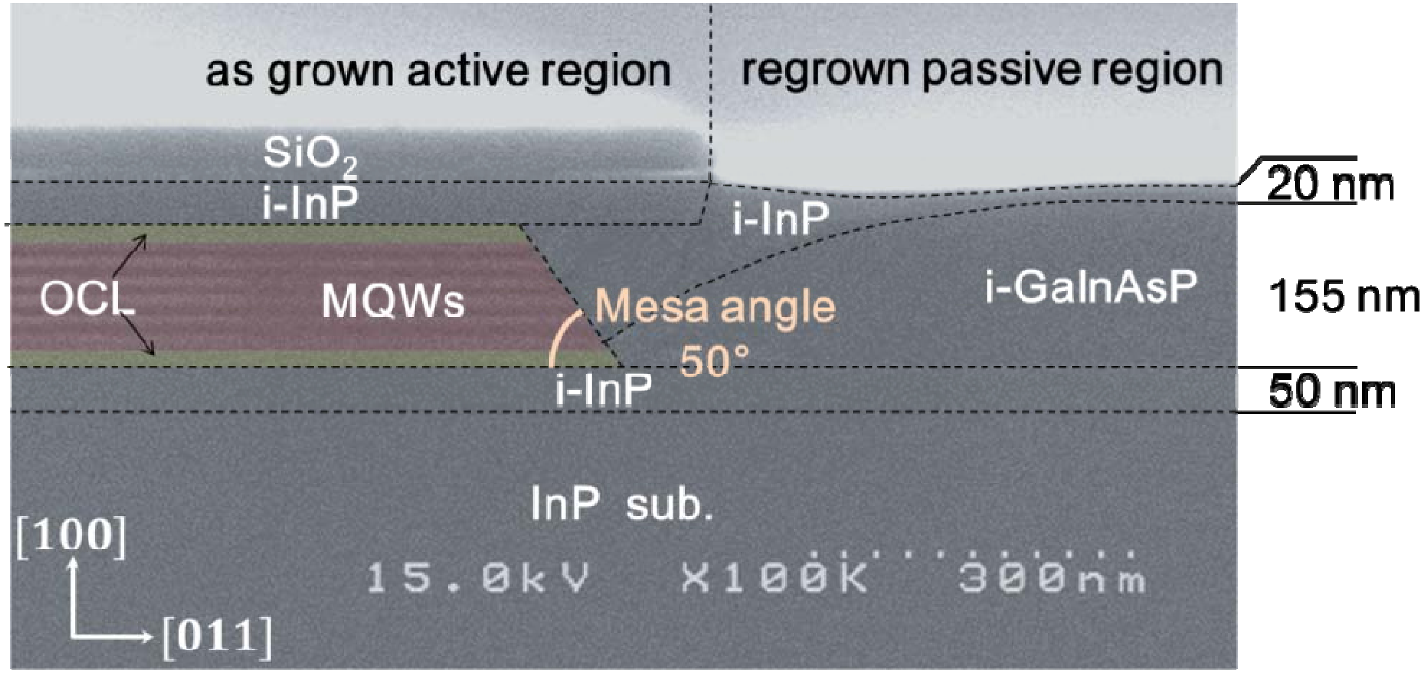
3. 2nd regrowth of *n*-InP



4. 3rd regrowth of *p*-InP

Towards Integration- Selective Regrowth

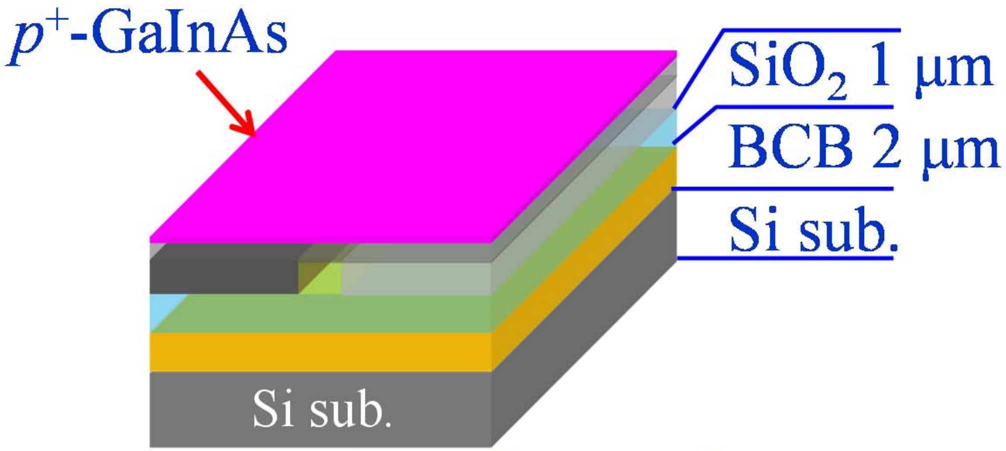
Selective growth by MOCVD with thin thickness



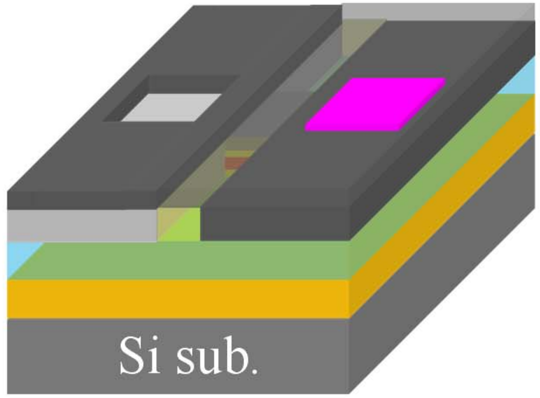
D. Inoue et al., JSTQE, vol. 21, 1502907, 2015.

Flat surface even with the regrowth thickness of 175 nm
Simulation results indicate the coupling efficiency of 98% and reflection of -36dB

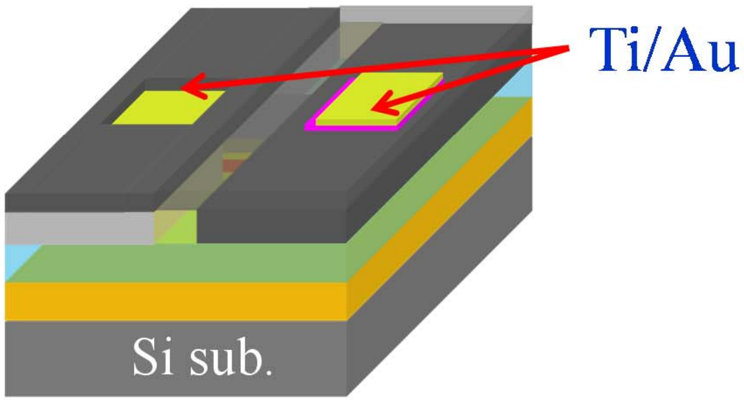
Fabrication Process (2)



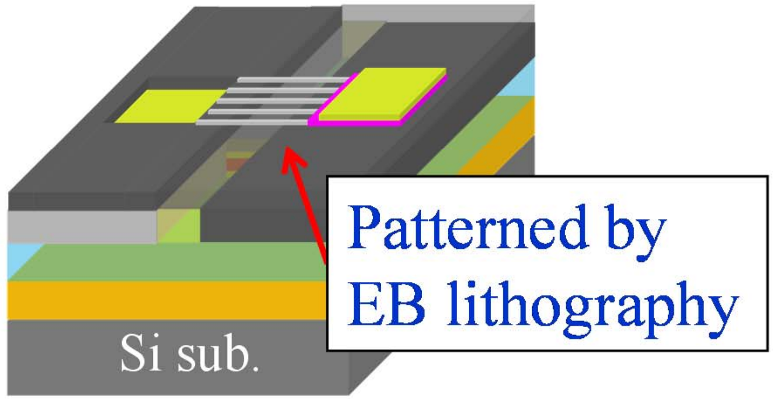
5. BCB bonding and removing InP sub.



6. Removing contact and cap layer



7. Electrode deposition



8. Formation of surface grating

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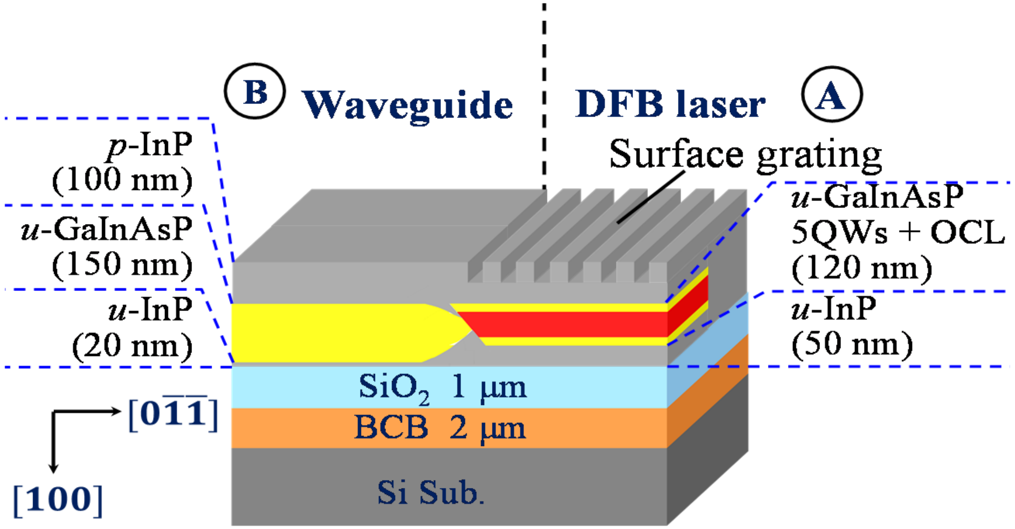
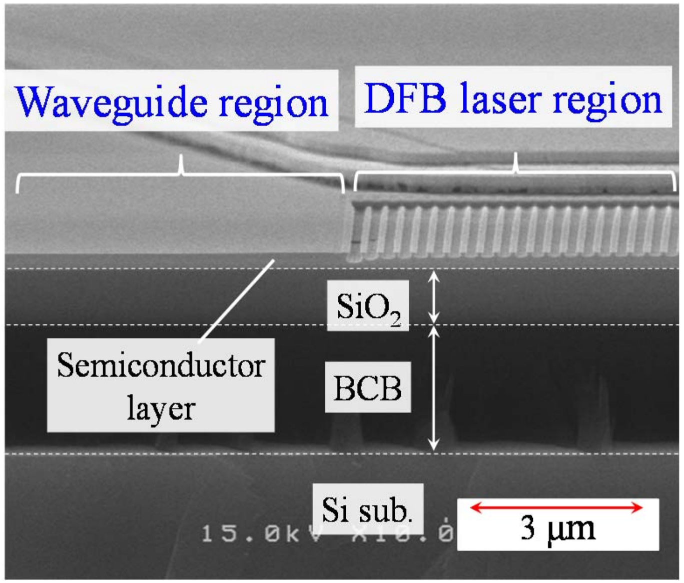
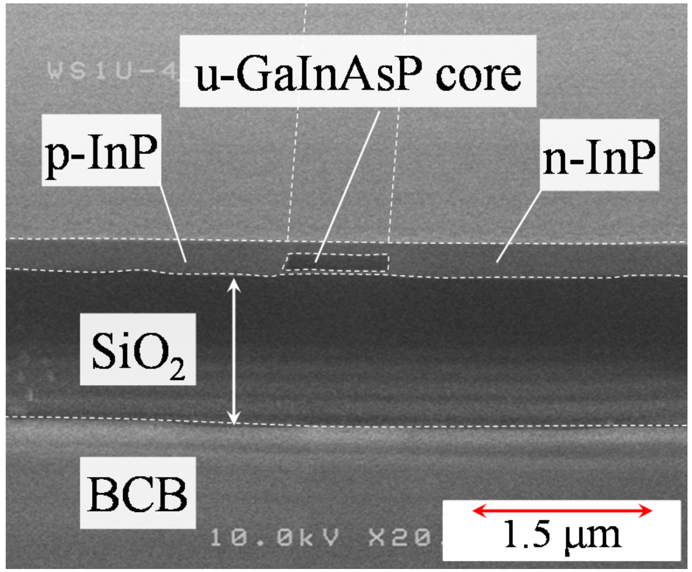
III - V/Si DFB Laser by BCB Bonding (1)

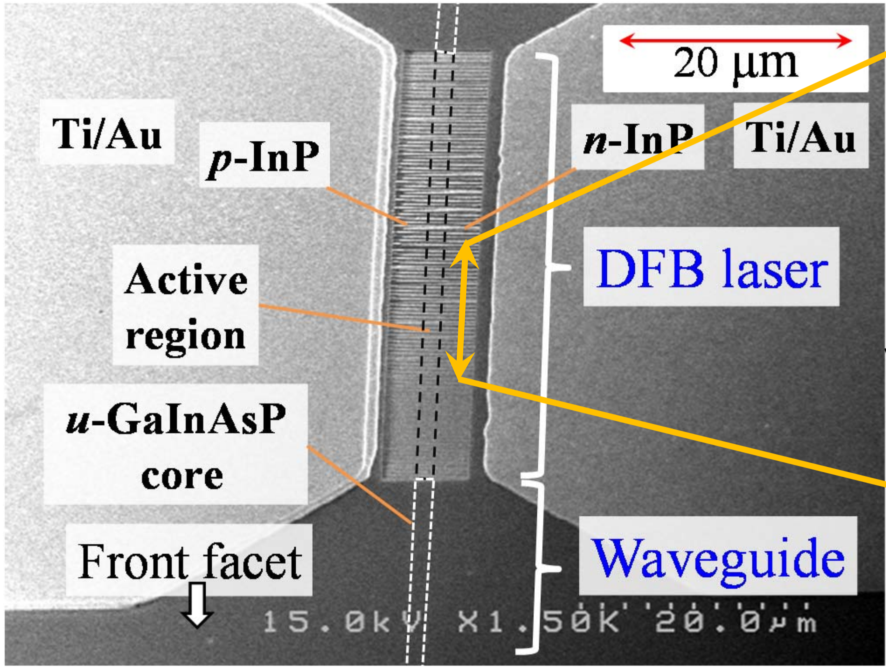


D. Inoue et al., Opt. Exp., vol. 23, 7771, 2015.

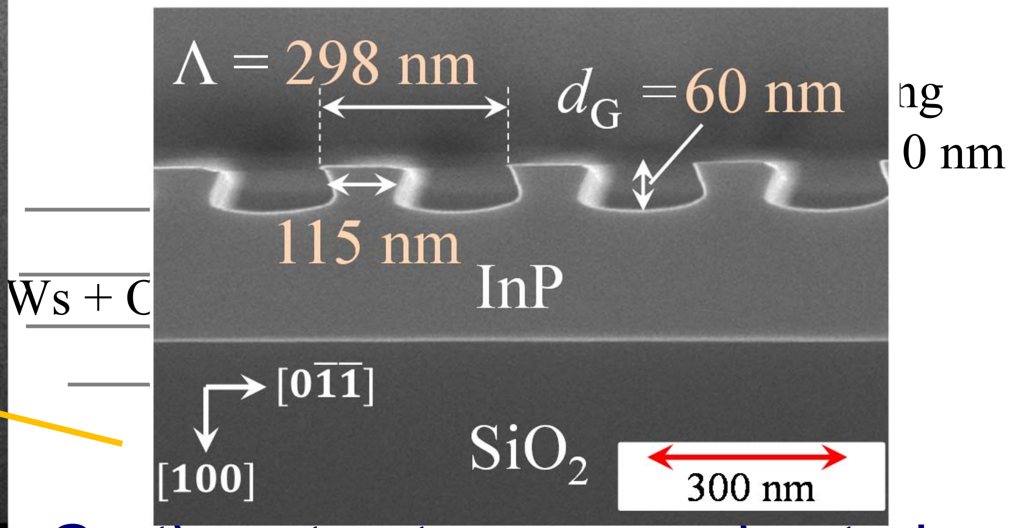




III - V/Si DFB Laser by BCB Bonding (2)



SEM image of top view



Grating structure approximated by square-shape

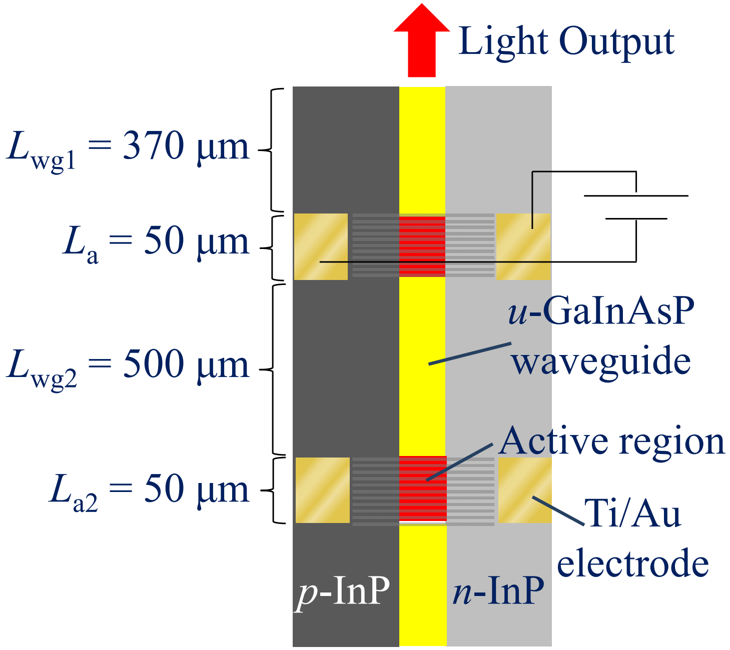
Cross section of surface grating at InP side cladding region

Λ = 298 nm
d_G = 60 nm

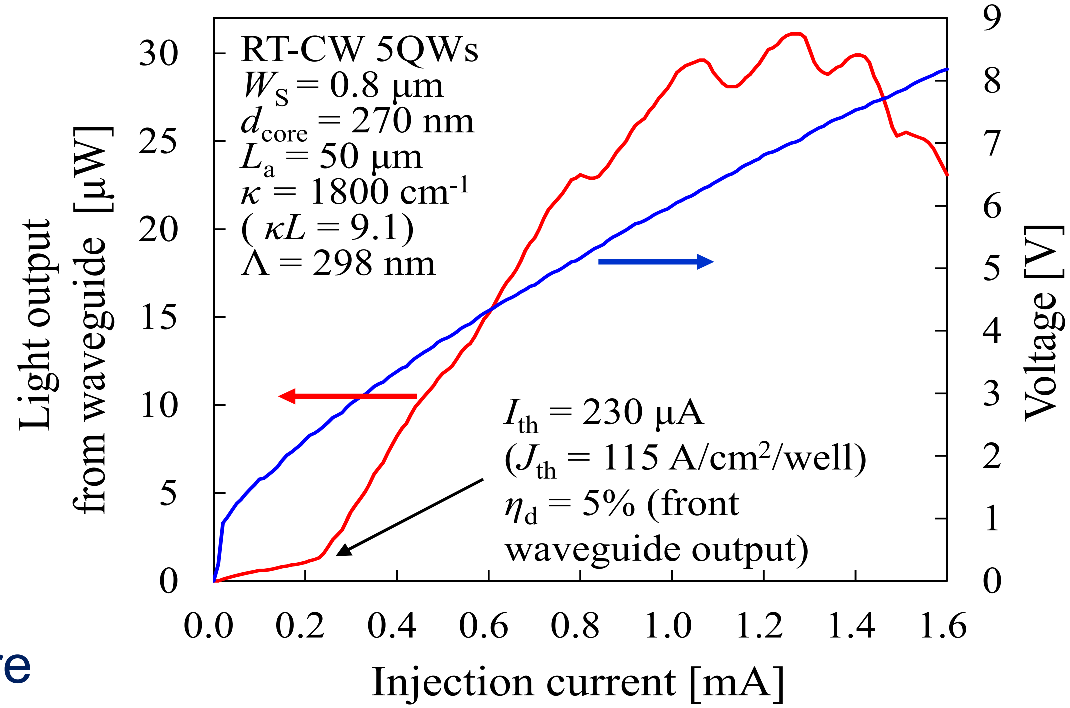
κ_i = 1800 cm^{-1}

D. Inoue et al., Opt. Exp., vol. 23, 7771, 2015.

III - V/Si DFB Laser by BCB Bonding (3)



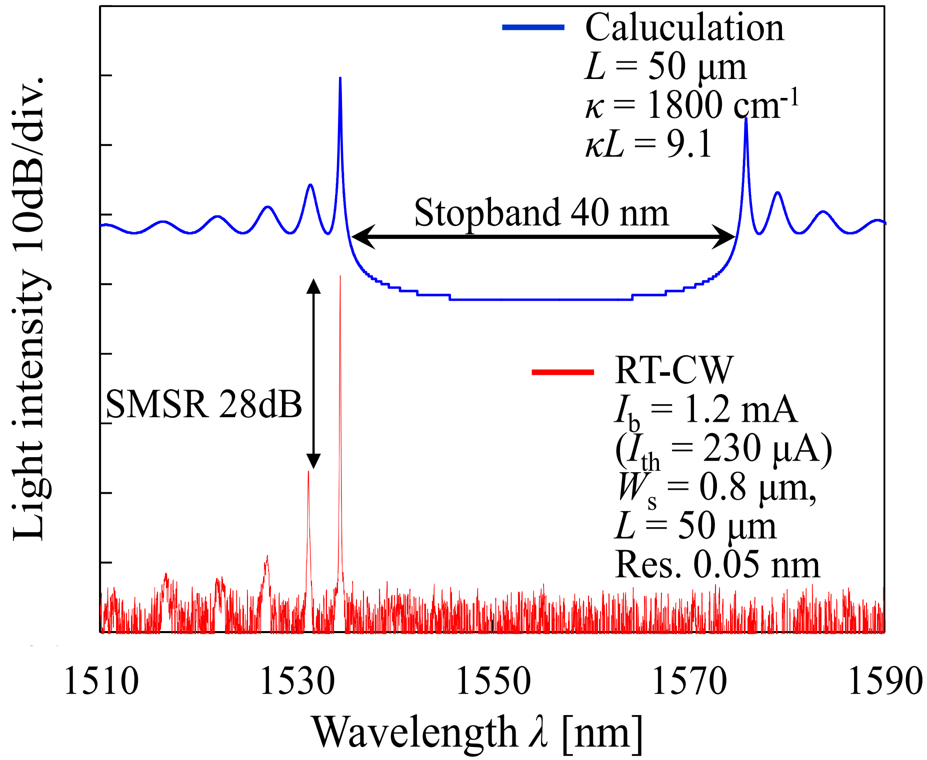
Measured device structure



I-*L* characteristic	*V*-*I* characteristic
I_{th} = 230 μA (J_{th} = 115 A/cm^2/well , 5QWs)	V_{th} = 4 V
η_d = 5% (front waveguide output) (W_S = 0.8 μm, L_a = 50 μm, κL = 9.1)	dV/dI = 6 kΩ @ $I = I_{th}$

D. Inoue et al., Opt. Exp., vol. 23, 7771, 2015.

III - V/Si DFB Laser by BCB Bonding (4)



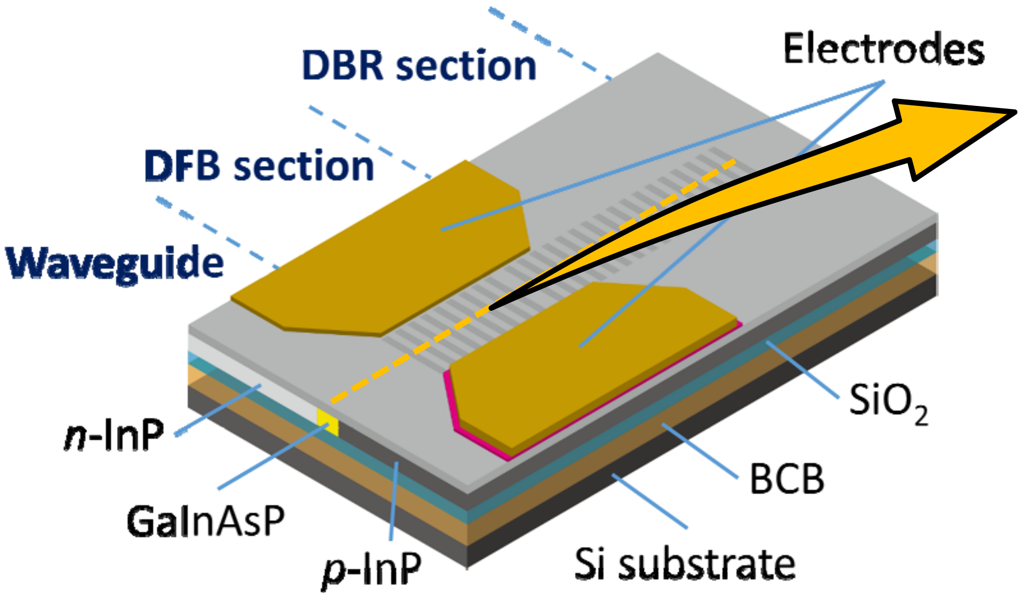
λ =1534 nm
SMSR: 28 dB
@I_b = 1.2 mA (5I_{th})

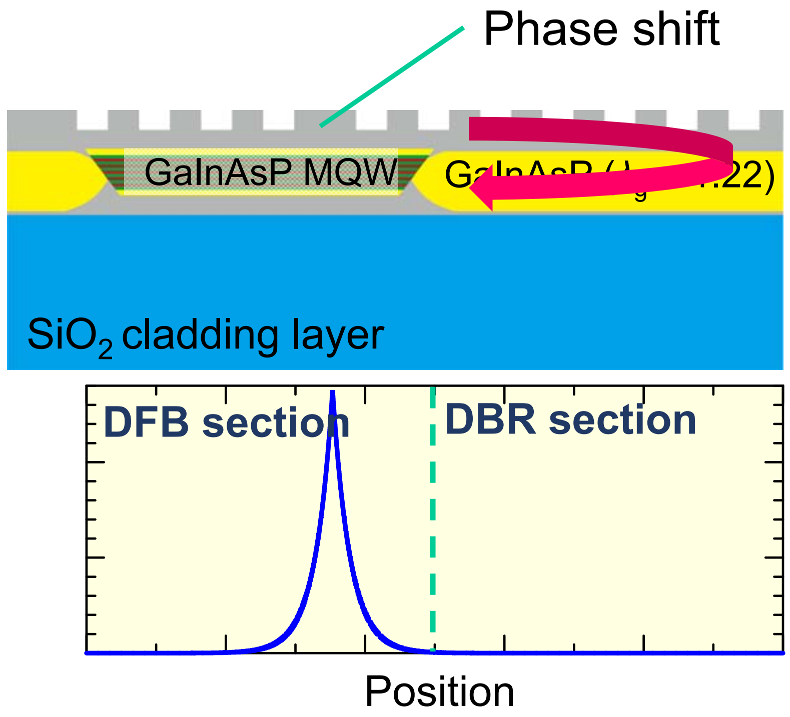
κ_i = 1800 cm^{-1}
n_{eq} = 2.61 @λ_B
Stopband width = 40 nm
> Gain width

D. Inoue et al., Opt. Exp., vol. 23, 7771, 2015.

Resonance modes were observed
in short-wavelength side of the stopband

Membrane Distributed Reflector (DR) Laser (1)



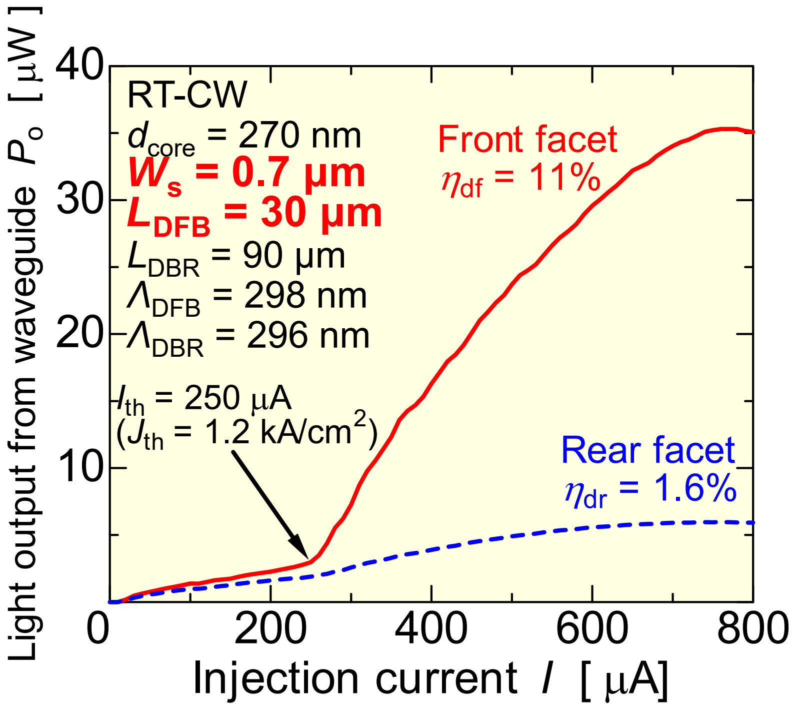


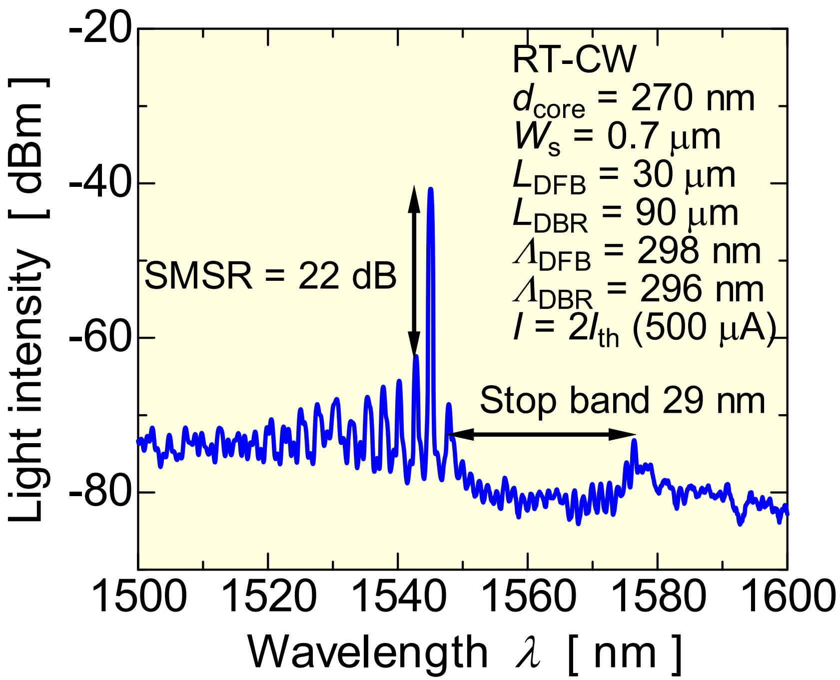
DR structure + phase-shifted grating

- ✓ High efficiency output from one side
- ✓ Low threshold by phase-shift region

T. Hiratani et al., Appl. Exp. , vol. 8, 150836, 2015.

Membrane DR Laser (2): uniform grating





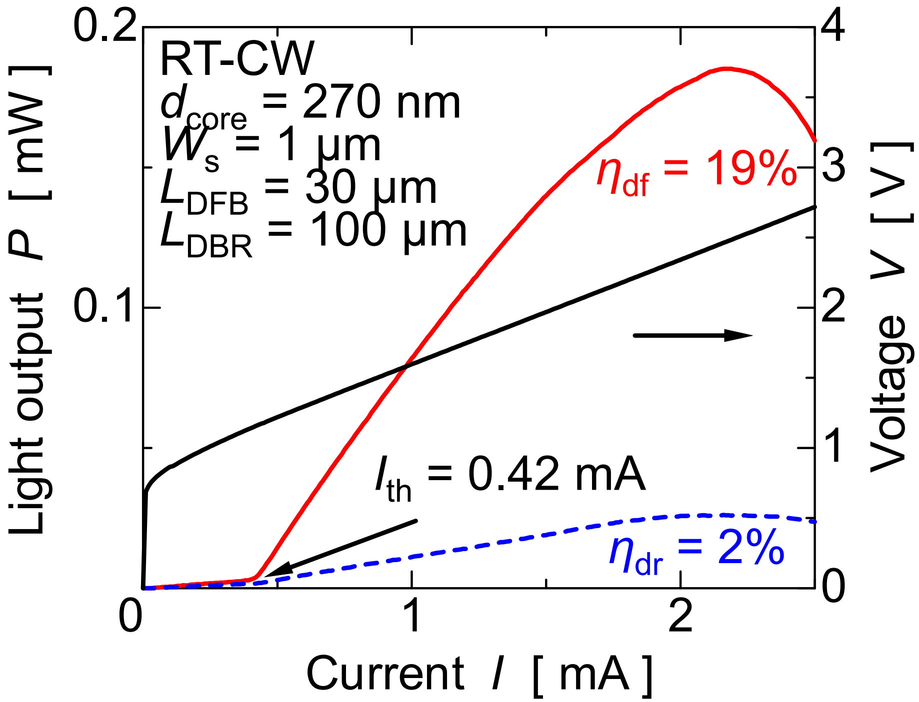
- I_{th} = 250 μA @ L_{DFB}= 30 μm
- J_{th} = 1.2 kA/cm^2
- η_{df}/η_{dr} = 6.7

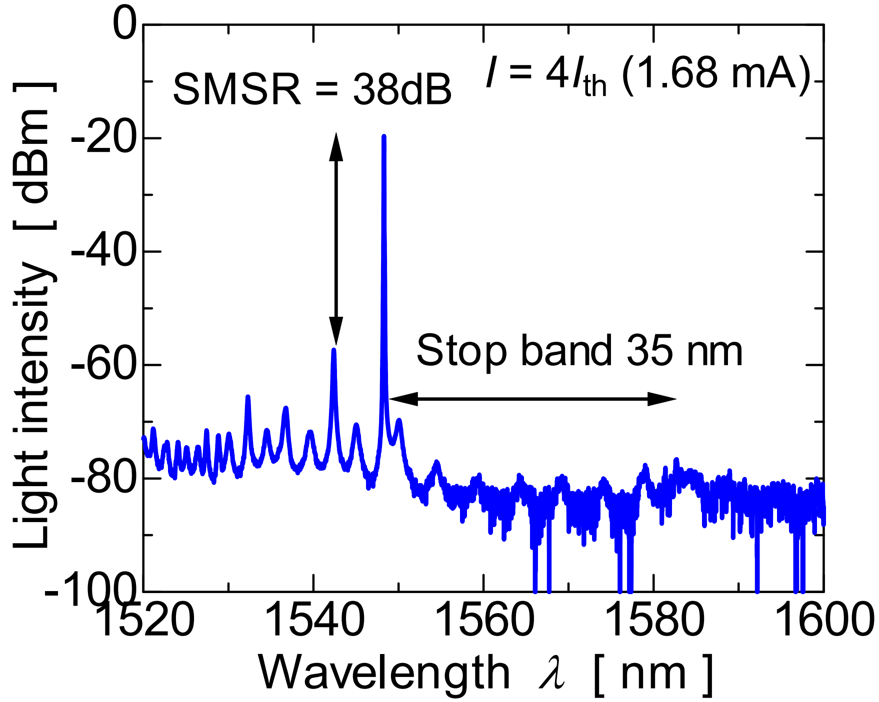
SMSR = 22dB @I = 2I_{th}

T. Hiratani et al., Appl. Exp. , vol. 8, 150836, 2015.

Low I_{th} with high output efficiency from 1-side

Membrane DR Laser (3): uniform grating





- I_{th} = 420 µA @ L_{DFB}= 30 µm
- η_{df}/η_{dr} = 9.5

SMSR = 38dB @ $I = 4 I_{th}$

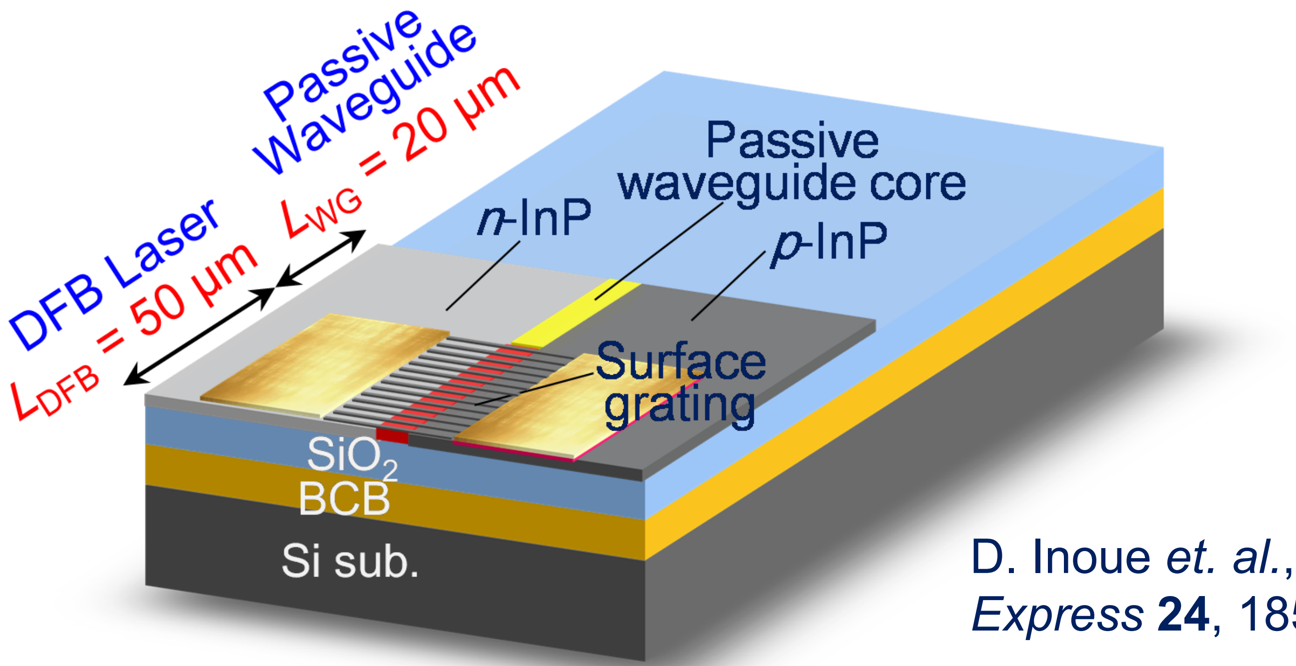
ThB3 T. Hiratani *et. al.*, ISLC 2016

Low I_{th} with high output efficiency from 1-side

Outline

1. Background
    - Optical Interconnects
2. Semiconductor Membrane Lasers
    - Design, Fabrication Process
    - Static lasing properties of DR laser
    - High-speed modulation of DFB lasers
3. Summary

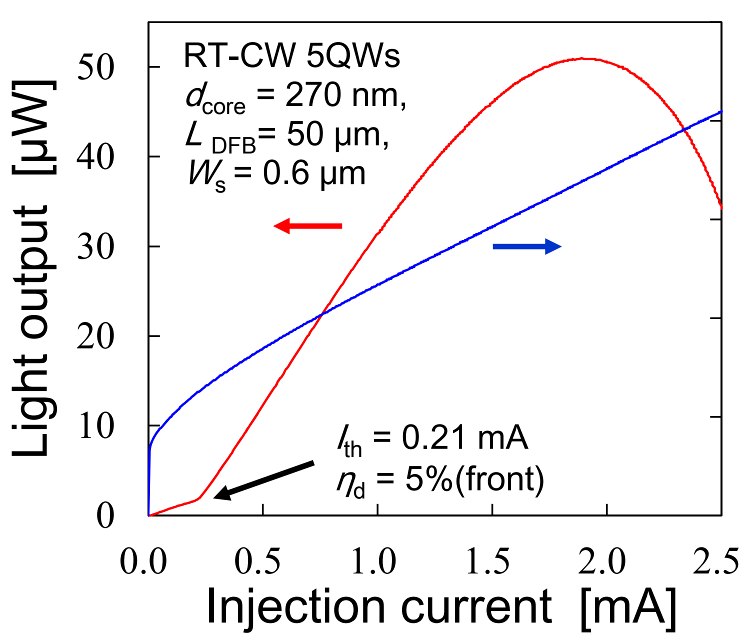
Direct Modulation of Membrane DFB Laser (1)

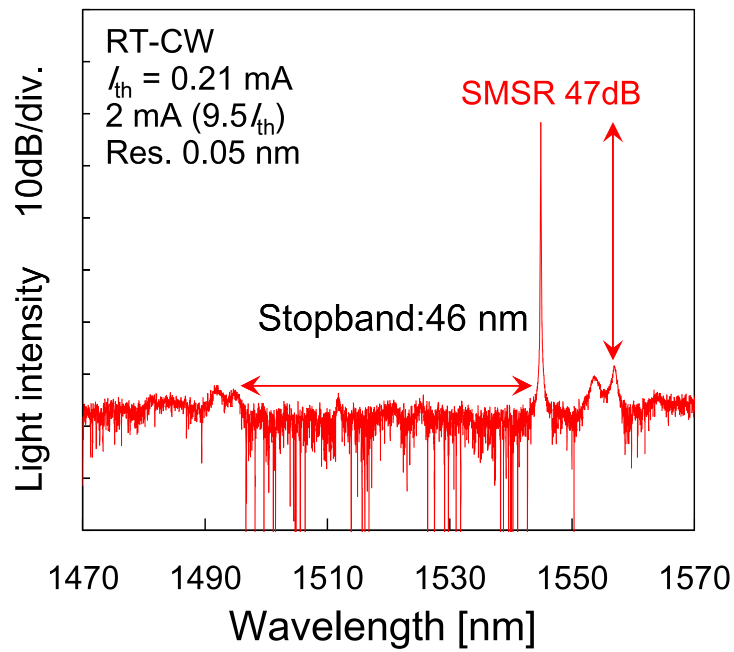


D. Inoue *et. al.*, *Optics Express* **24**, 18571 (2016)

- Membrane DFB laser
  - Core thickness 270 nm, • Cavity length 50 μm,
  - Surface grating : period 295 nm, depth 60 nm
- Waveguide-integrated structure

Direct Modulation of Membrane DFB Laser (2)





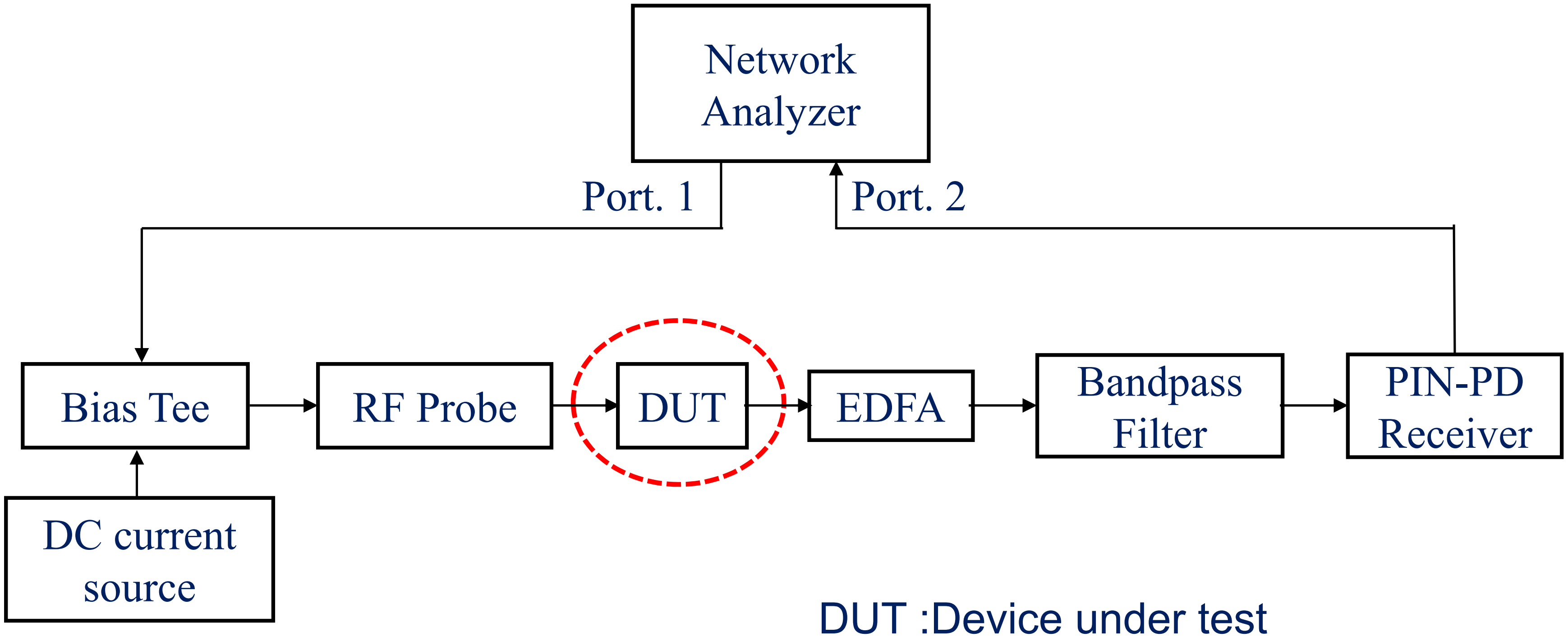
Lasing characteristics (RT-CW)

I_{th} = 210 μA
(J_{th} = 140 A/cm^2/well , 5QWs)
η_d = 5% (front facet)

λ = 1542 nm
@I_b = 1 mA (4.8I_{th})
$W_{Stopband}$: 46 nm
κ = 2100 cm^{-1}

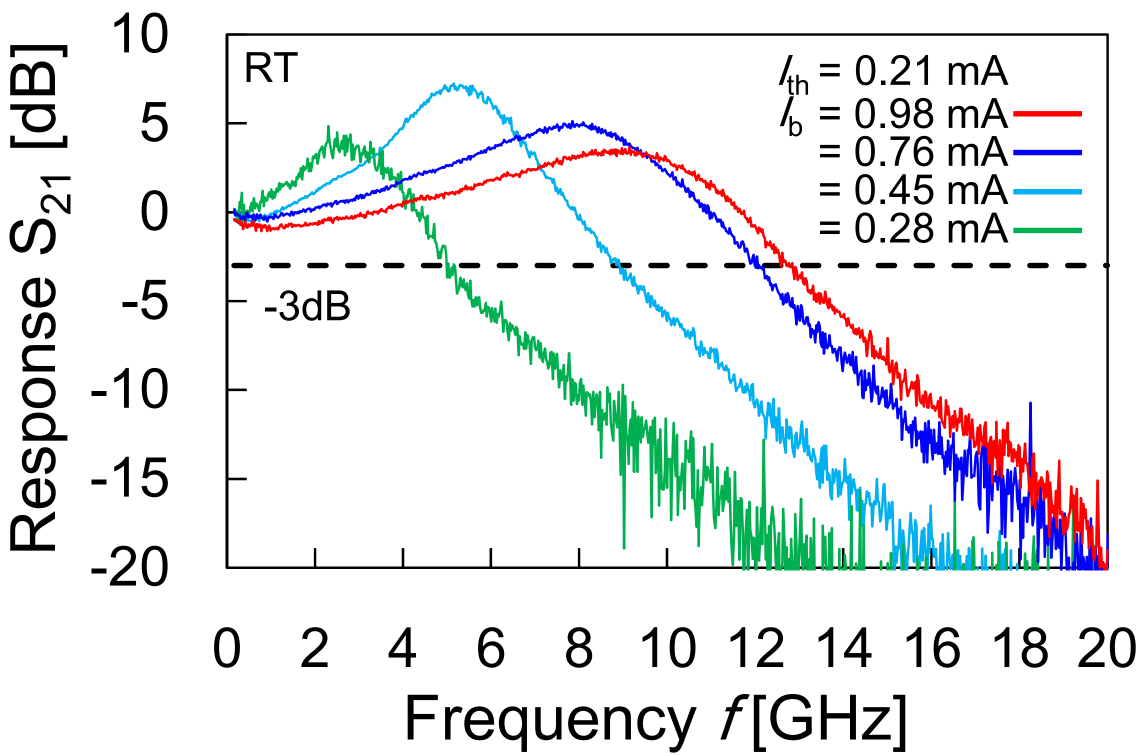
Measurement System

≪Small signal measurement by vector network analyzer≫



DUT :Device under test
EDFA :Erbium-doped fiber amplifiers

Small Signal Frequency Response



ThB8 D. Inoue *et. al.*, ISLC 2016

D. Inoue *et. al.*, *Optics Express* **24**, 18571 (2016)

- -3dB bandwidth : 12.8 GHz @ I_b = 0.98 mA

Sufficient bandwidth for 10 Gbps operation

Modulation Efficiency

Formula for relaxation oscillation frequency

$$f_r = \frac{1}{2\pi}\sqrt{\frac{\xi g' v_g \eta_i}{eV_a}}\sqrt{I_b - I_{th}}$$

Modulation efficiency

ξ : optical confinement factor
g' : differential gain
v_g : group velocity
η_i : internal quantum efficiency
e : electron charge
V_g : active volume

Membrane DFB structure

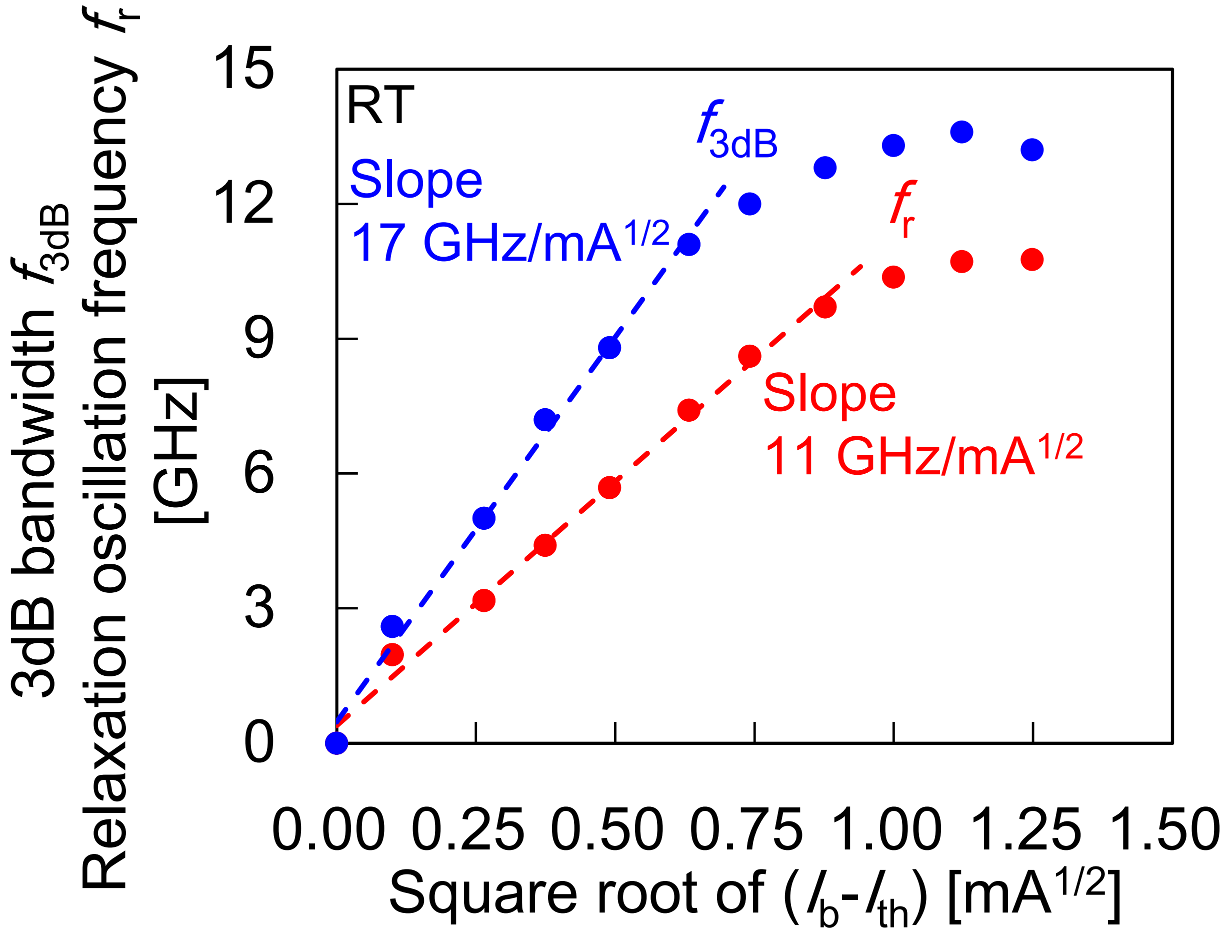
- High optical confinement factor

  $\xi g'$ ↗

- Strong index-coupling coefficient

  When κL is constant $\sqrt{1/V_a}$ ↗

Modulation Efficiency



Modulation efficiency of f_r = 11 GHz/mA$^{1/2}$

Modulation Efficiency of DFB Lasers

	Active layer	Cavity length	Modulation efficiency
This work	GaInAsP	50 μm	11 GHz/mA$^{1/2}$
[1] D. Inoue *et. al*. (Titech)	GaInAsP	80 μm	9.9 GHz/mA$^{1/2}$
[2] H. Nishi *et. al*. (NTT)	GaInAsP	50 μm	9.4 GHz/mA$^{1/2}$
[3] W. Kobayashi *et. al*. (NTT)	AlGaInAs	100 μm	4.8 GHz/mA$^{1/2}$
[4] S. Kanazawa *et. al*. (NTT)	GaInAsP	150 μm	2.3 GHz/mA$^{1/2}$

Membrane structure

[1] D. Inoue *et. al., Opt. Exp.* **23**, 29024, 2015. [2] H. Nishi *et. al.*, *ECOC* 2015.
[3] W. Kobayashi *et. al.*, *JSTQE* **19**, 2013. [4] S. Kanazawa *et. al.*, *ELEX* **12**, 2015.

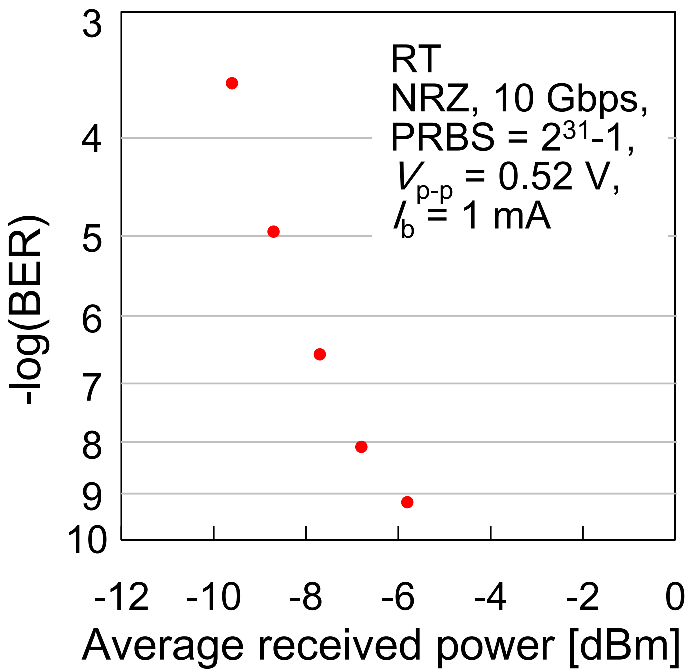
Compared with conventional DFB laser

2–4 times higher efficiency was realized

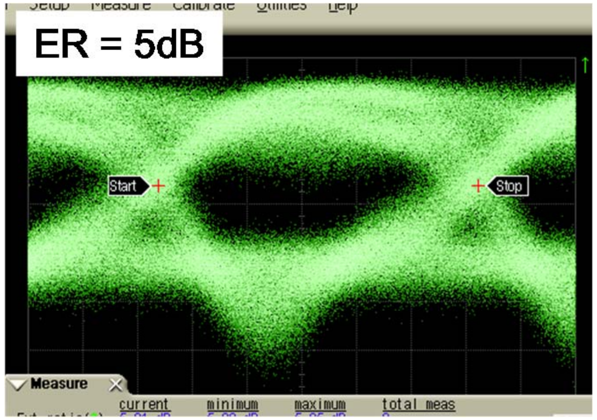
✓Strong optical confinement ✓Short cavity DFB laser

10 Gbit/s Direct Modulation

- 10 Gbit/s, NRZ signal, PRBS = 2^{31}-1, Voltage swing $V_{p\text{-}p}$ = 0.52 V
- Amplified by an EDFA, detected by 12 GHz band PIN-photoreciever



BER characteristics

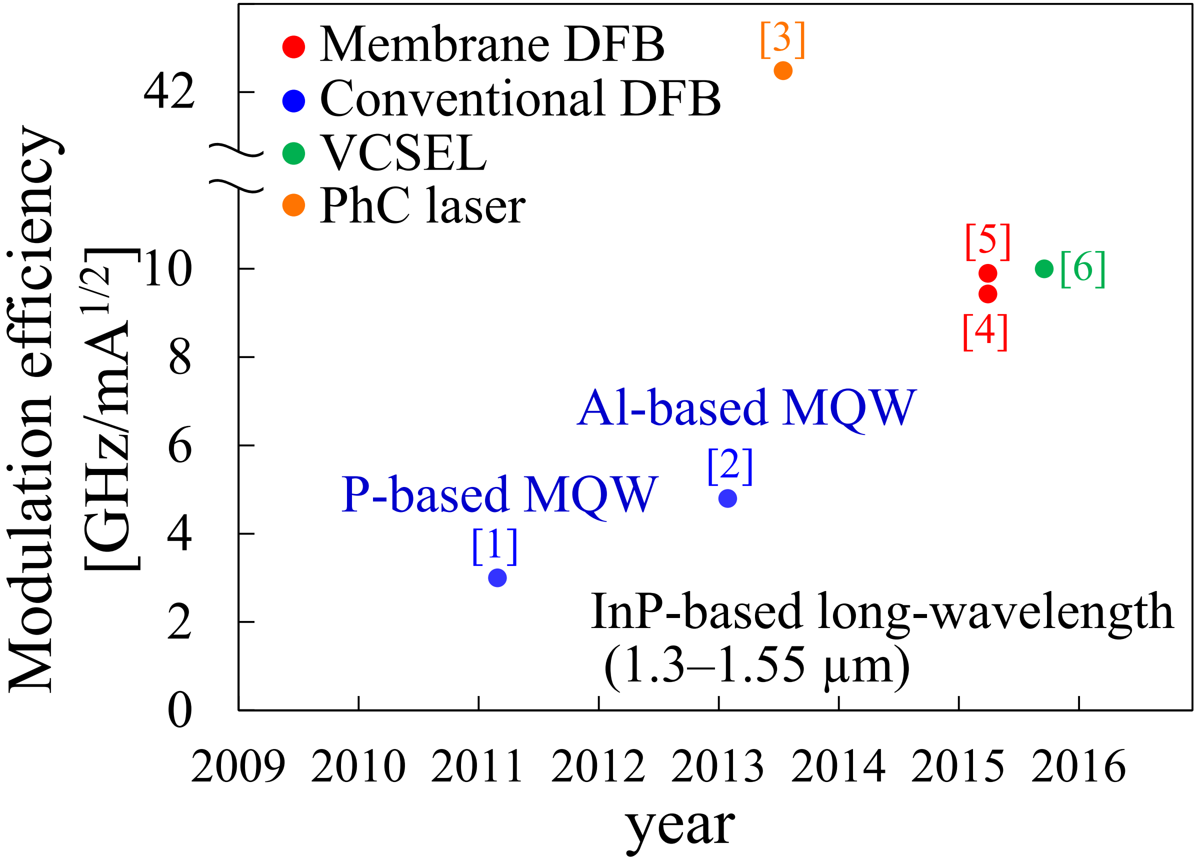


10 Gbit/s eye pattern
(inverted pattern)

<u>Need improvement of output power</u>

10 Gbit/s direct modulation (BER < 10^{-9})@I_b = 1 mA

Modulation Efficiency



[1] S. H. Lee et al., PTL, 1349 (2011).
[2] W. Kobayashi et al., JSTQE, 1500908 (2013).
[3] S. Matsuo et al., JSTQE, 4900311 (2013).
[4] H. Nishi et al., ECOC'2015, We.2.5.3.
[5] D. Inoue et al., Opt. Express, 29024 (2015).
[6] S. Spiga et al., OFC'2016, Tu3D.4.

Summary

Membrane Lasers

Enhanced Optical Confinement → Low Threshold
High Speed Modulation

1. DFB lasers:

   Low threshold I_{th}= 210 μA @L= 50 μm

   ▲ η_d = 5%/front side

   Record modulation efficiency 11 GHz/mA$^{1/2}$

   10 Gbps with BER < 10^{-9} @ I_b= 1 mA

2. DR lasers:

   Low threshold I_{th}= 250 μA @L= 30 μm

   ▲ η_d = 11%/front side, P_f/P_r = 6.7