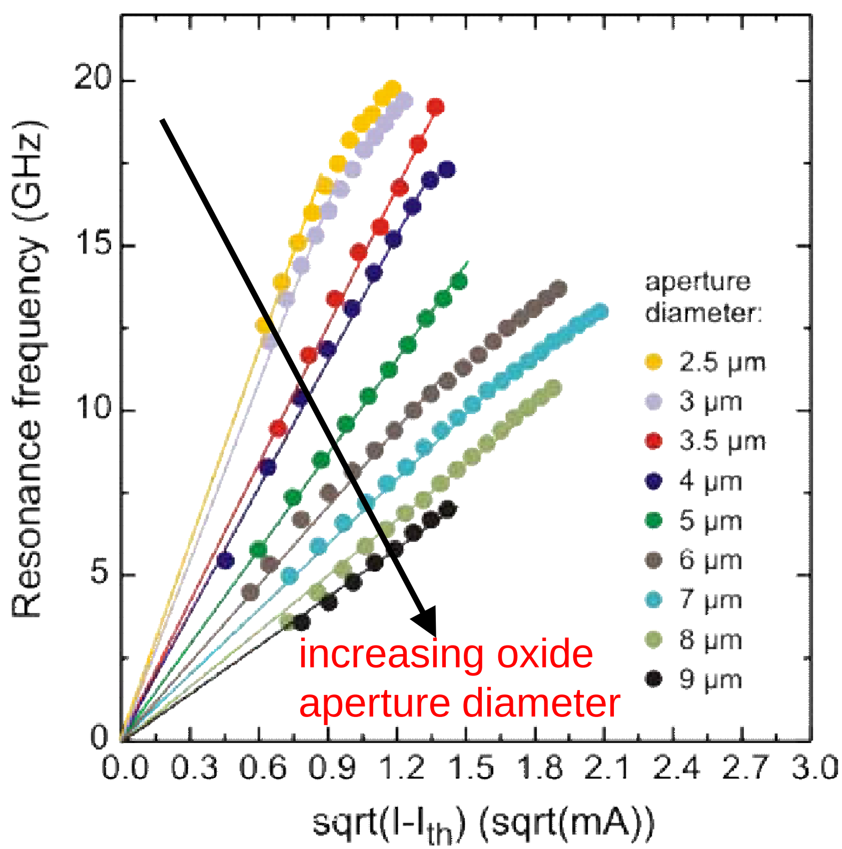
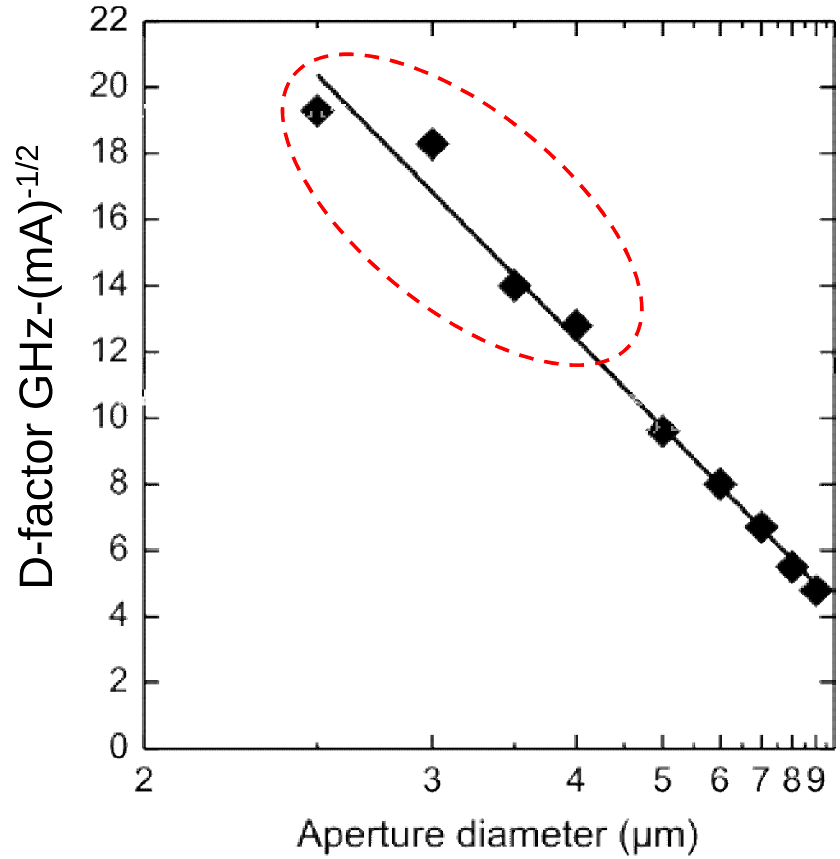
The D-factor versus the oxide aperture diameter





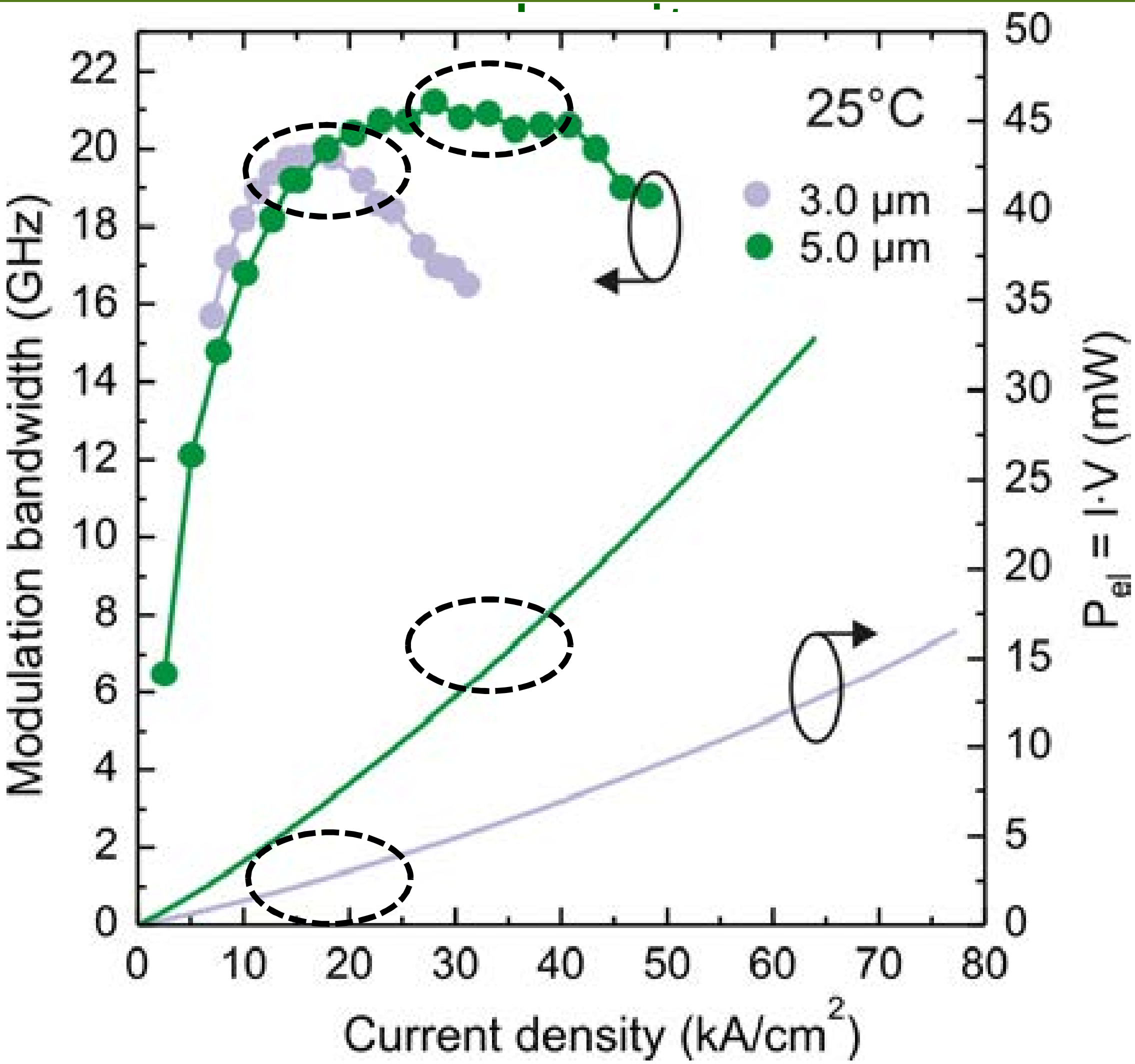
$$f_r = D\sqrt{I - I_{th}}$$

$$f_{3dB\max} = \sqrt{1+\sqrt{2}}\, f_r \approx 1.55\, f_r$$

$$D \propto \frac{1}{d_{aperture}}$$

P. Moser, …, D. Bimberg, IEEE JSTQE, 19 (4), 2013.

-3 dB modulation bandwidth and current



5 µm aperture dia.

J = 33 kA/cm^2
f_{3dB} = 21 GHz
P_{el} = 15 mW

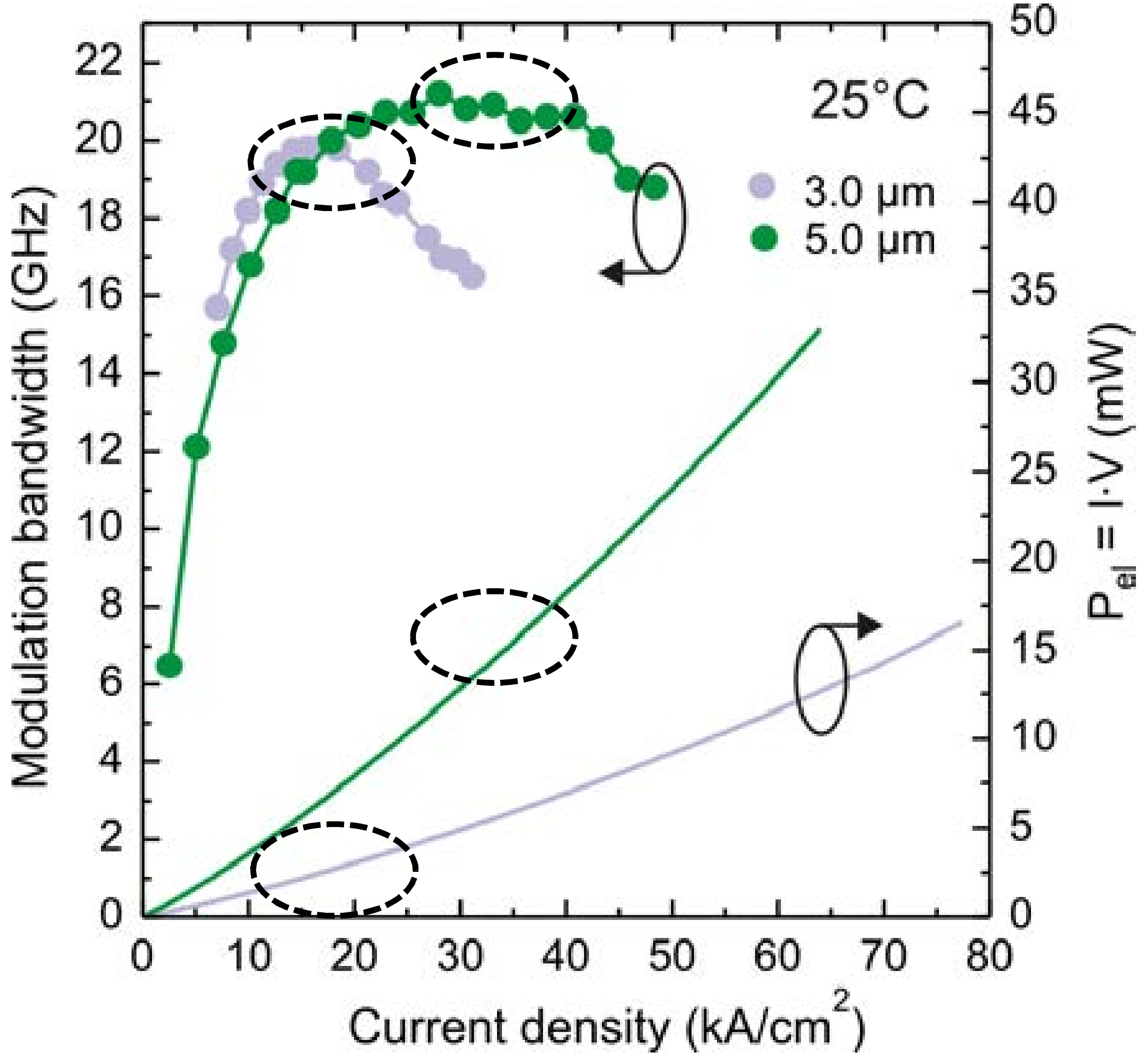
3 µm aperture dia.

J = 17 kA/cm^2
f_{3dB} = 20 GHz
P_{el} = 8 mW

smaller aperture VCSELs ⟶ have a slightly smaller maximum f_{3dB}
⟶ at a much smaller electrical power
⟶ at a smaller current density

P. Moser, …, D. Bimberg, Invited Talk Photonics West, San Francisco, CA, USA, SPIE 9001-2 (2014).

Modulation bandwidth and current density



5 µm aperture dia.

J = 33 kA/cm^2
f_{3dB} = 21 GHz
P_{el} = 15 mW

3 µm aperture dia.

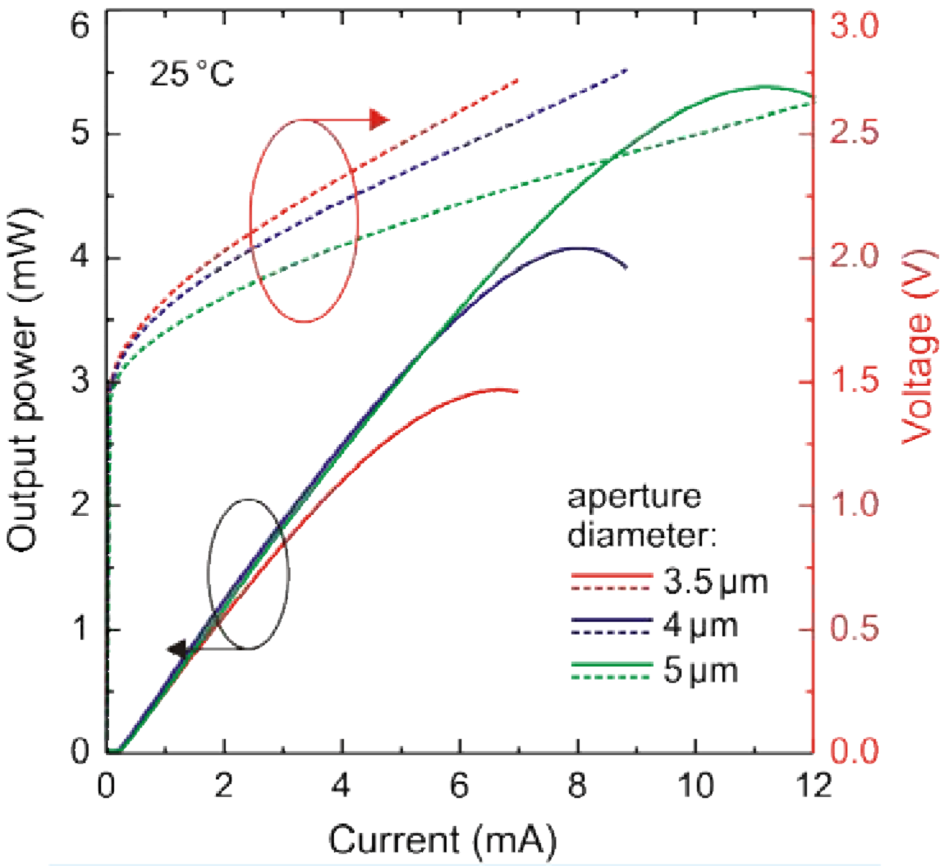
J = 17 kA/cm^2
f_{3dB} = 20 GHz
P_{el} = 8 mW

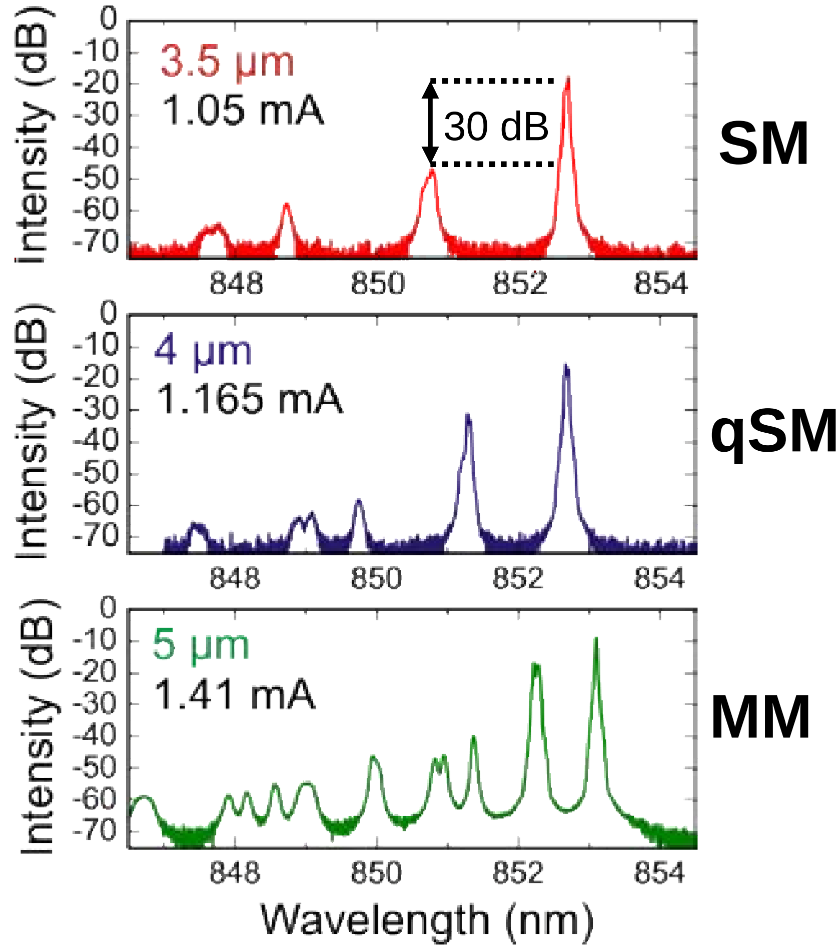
	5 µm	3 µm
$\frac{f_{3dB}}{P_{el}}$ (GHz/mW)	1.4	**2.5**

79% more bandwidth per mW!

P. Moser, …, D. Bimberg, Invited Talk Photonics West, San Francisco, CA, USA, SPIE 9001-2 (2014).

850 nm VCSELs





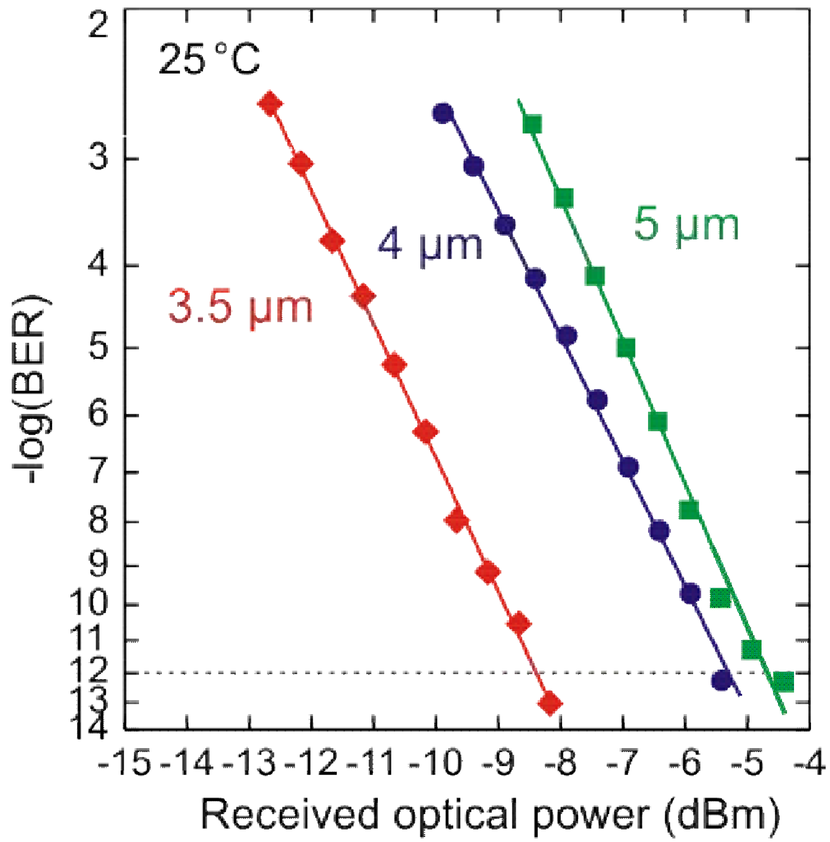
	P_{th}	R_d
3.5 µm:	240 µW	220 Ω
4 µm:	310 µW	190 Ω
5 µm:	380 µW	140 Ω

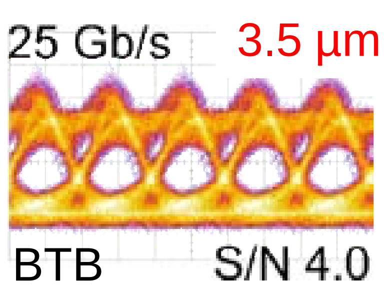
	$\Delta\lambda_{RMS}$
3.5 µm:	0.08 nm
4 µm:	0.22 nm
5 µm:	0.42 nm

P. Moser, …, D. Bimberg, Electronics Letters, vol.48, no.20, pp. 1292-1293, 2012.

25 Gbit/s back-to-back (BTB) operation

25 Gbit/s, BTB, V_{PP} = 420 mV





3.5 µm:
- *EDR* = 77 fJ/bit
- *HBR* = 56 fJ/bit

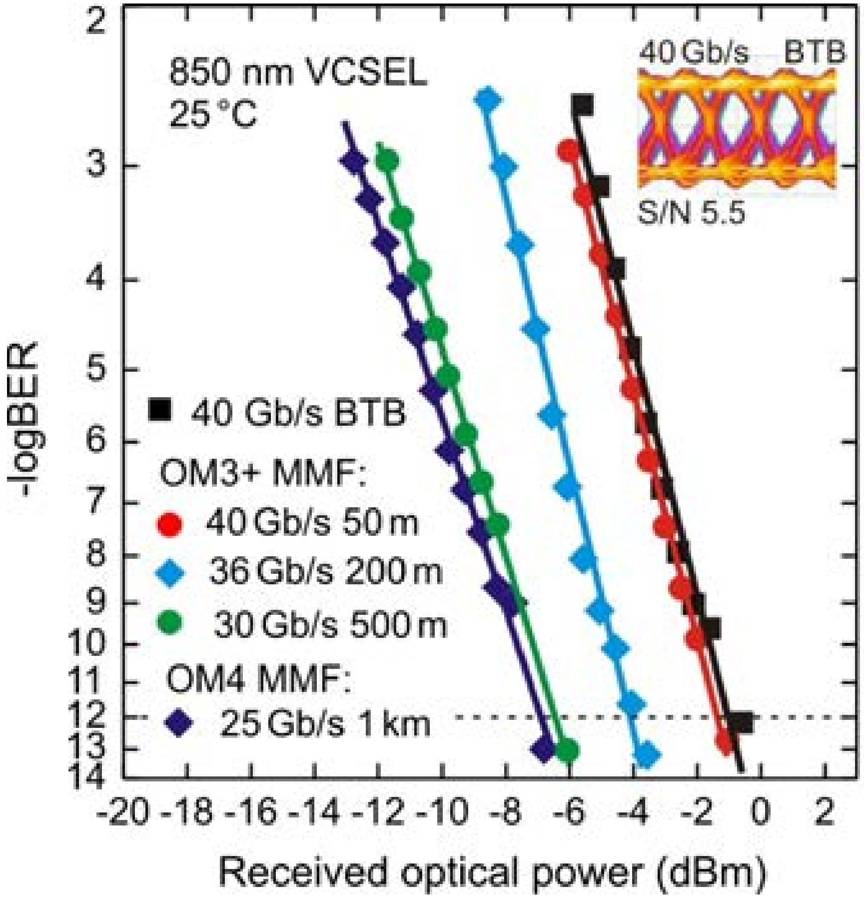
4 µm:
- *EDR* = 85 fJ/bit
- *HBR* = 58 fJ/bit

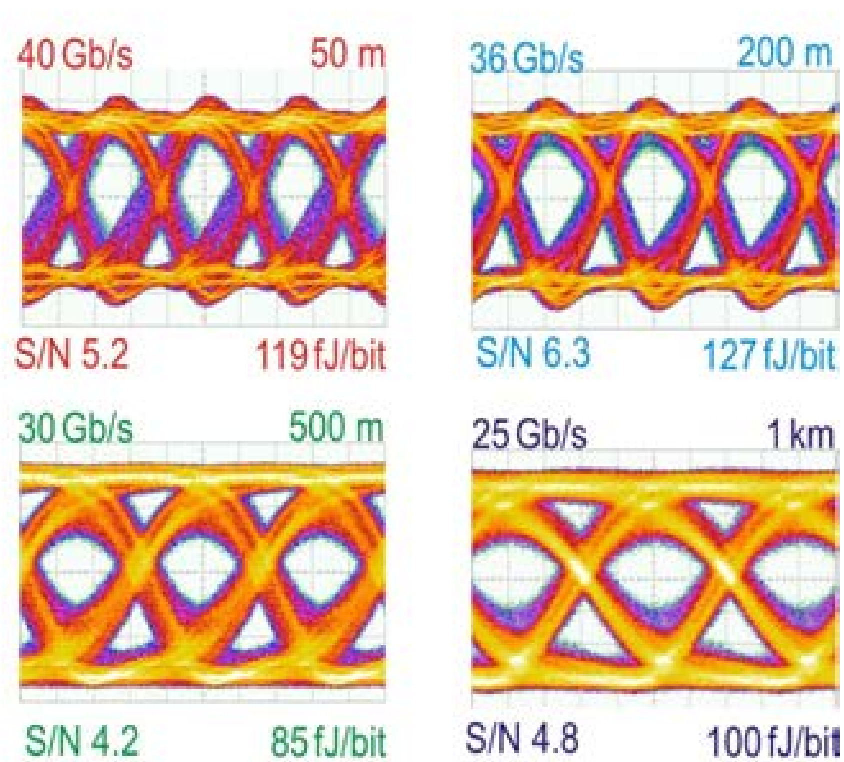
5 µm:
- *EDR* = 99 fJ/bit
- *HBR* = 67 fJ/bit

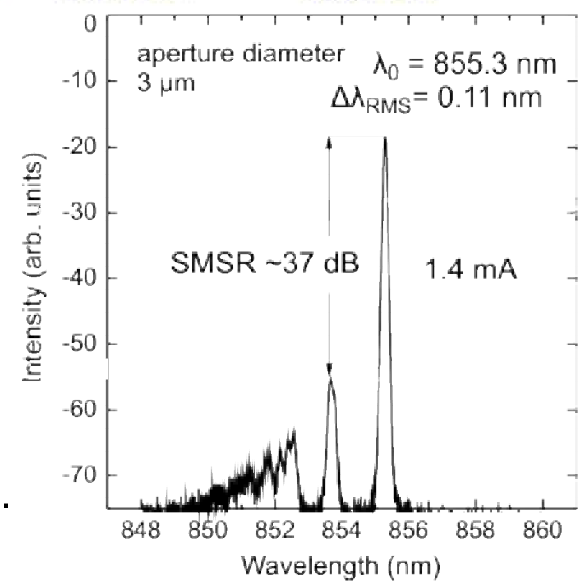
Record **energy-efficient** directly modulated VCSELs

P. Moser, …, D. Bimberg, Electronics Letters, 48(20), 2012.

High bit rates, toward long MMF distances







25 Gbit/s [1]
1 km MMF
100 fJ/bit

30 Gbit/s [1]
500 m MMF
85 fJ/bit

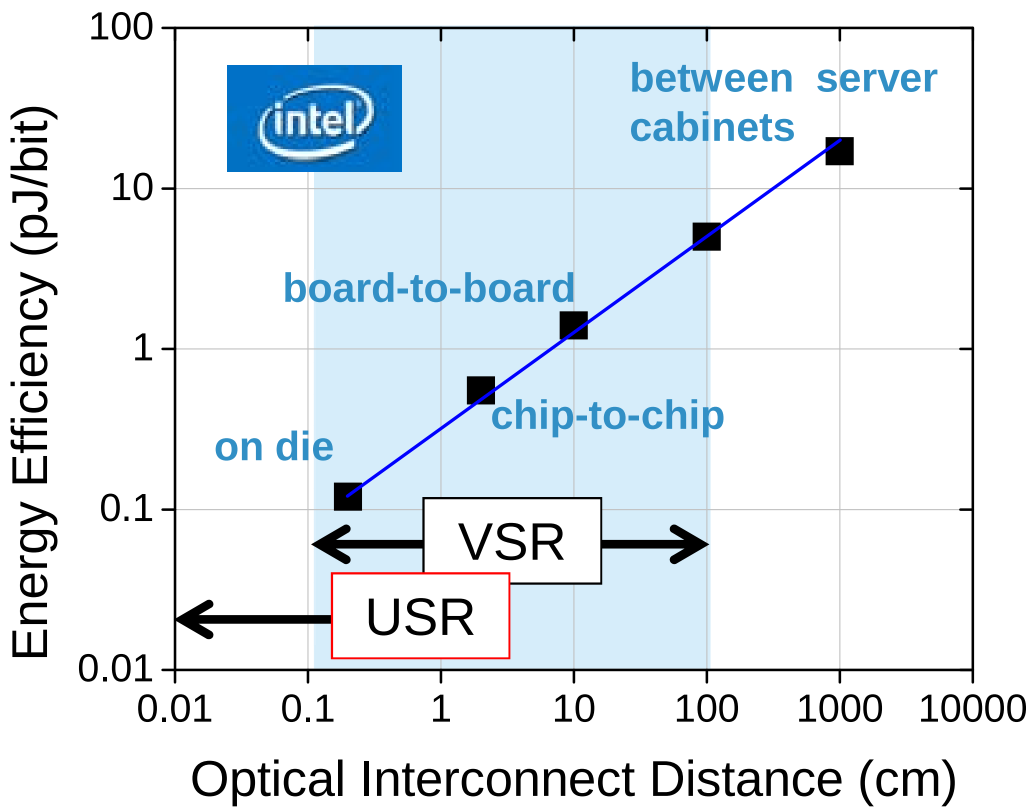
40 Gbit/s [2]
BTB
108 fJ/bit

[1] P. Moser, …, D. Bimberg, IEEE Photonics Technology Letters, 25(6), 2013.
[2] P. Wolf, …, D. Bimberg, Electronics Letters, 49(10), 2013.

optical interconnect **opportunities**

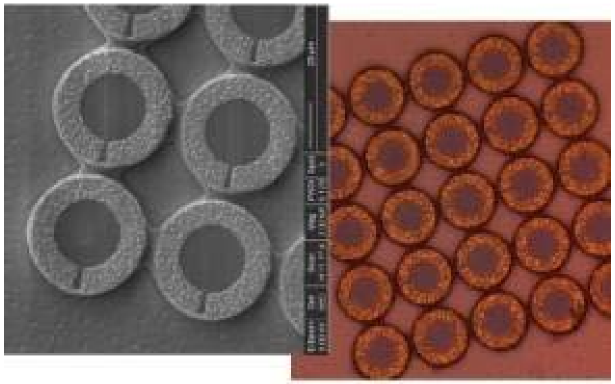
very-short-reach (VSR) optical interconnects: < 2 m

ultra-short-reach (USR) optical interconnects: < 20 mm



after: S. Borkar, Proc. IEEE Optical Interconnects conference, Santa Fe, NM USA (08 May 2013)

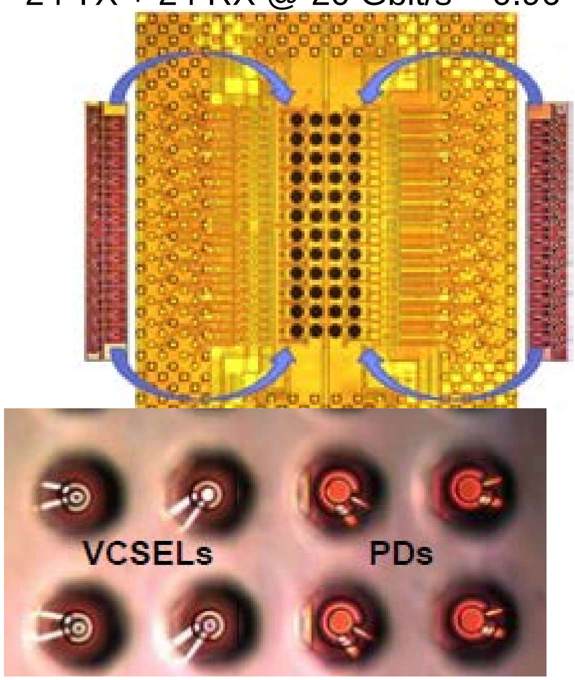
optical interconnect **opportunities**

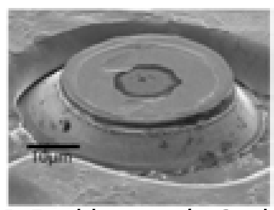


J. A. Lott *et al.*, Proc. IEEE Summer Topical (July 2002).

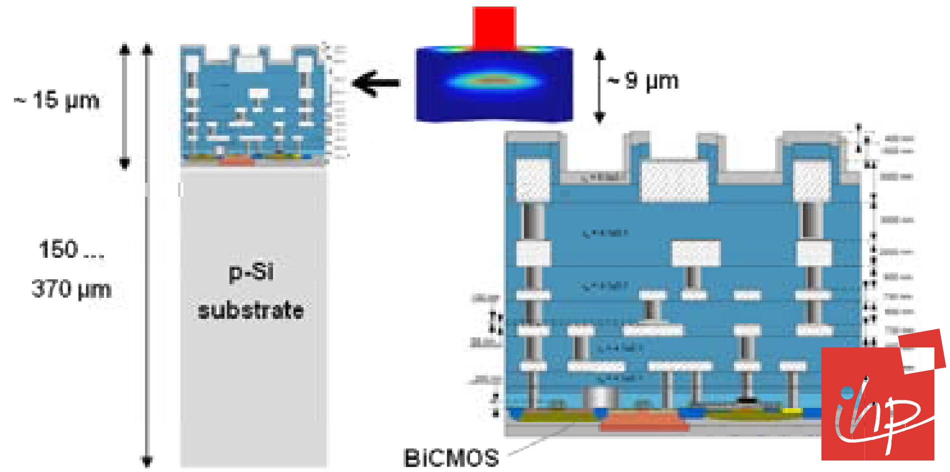
VCSELs on
CMOS
MEMS
silicon
flexible plastic
fabrics
and more

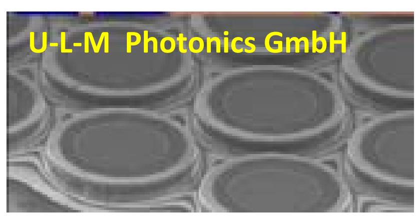
24 TX + 24 RX @ 20 Gbit/s = 0.96 Tb/s





J. Perkins *et al.*, Optics Express, 16(8) (Aug 2008).

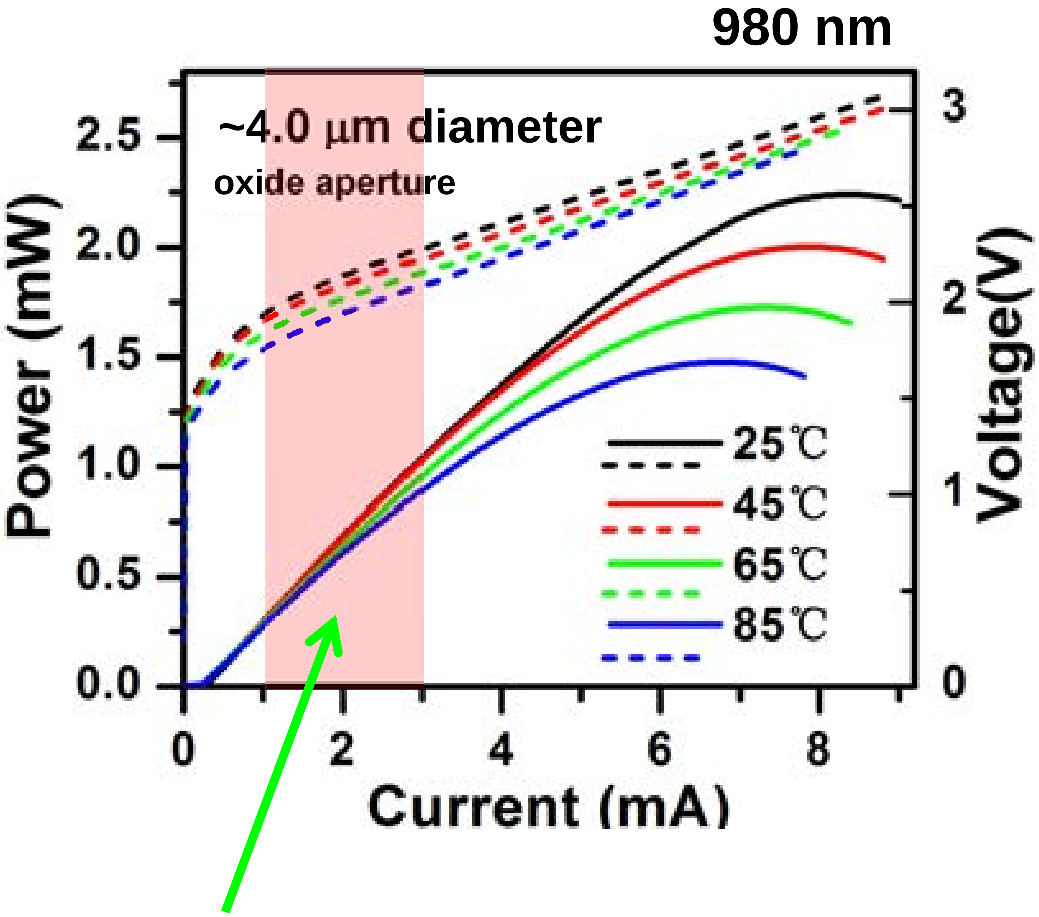


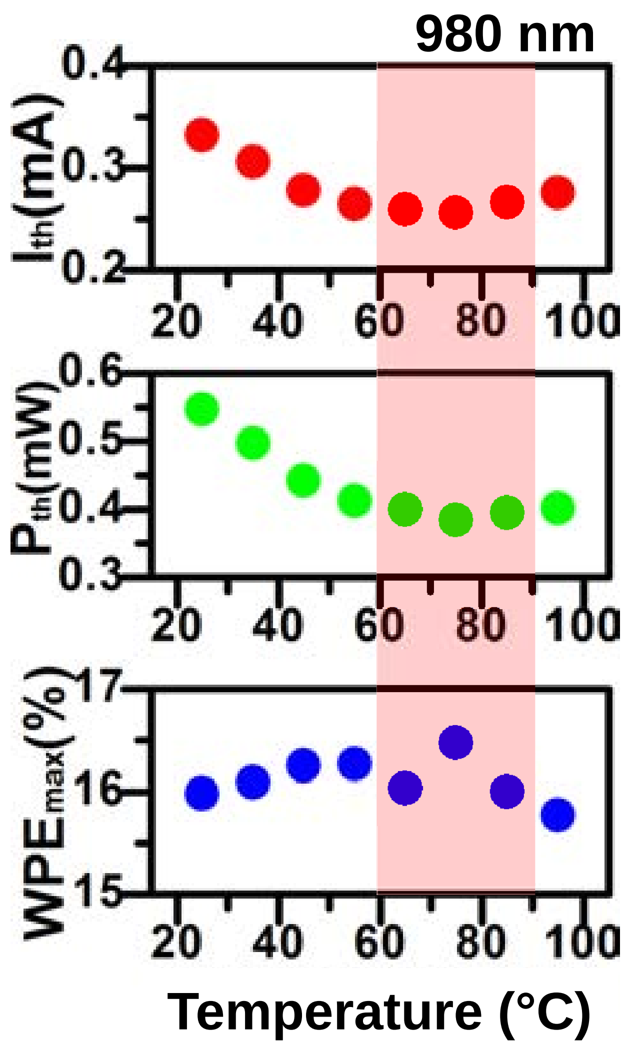


BiCMOS
Photonics
BiCMOS
BiCMOS

N. Li *et al., (IBM) OFC 2010, paper OTuP2.*

Temperature stable L-I with minimum I_{th} at ~70°C





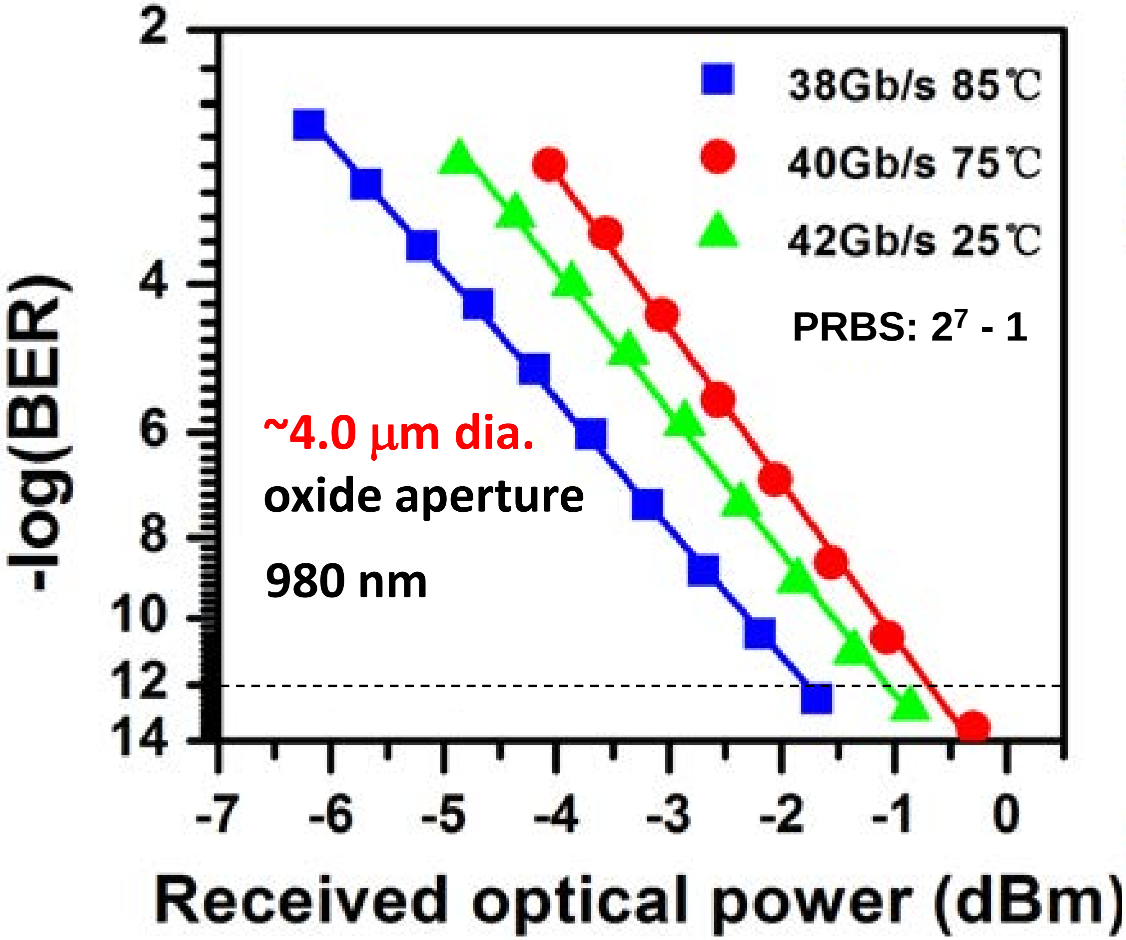
the L-I characteristics are ~constant with temperature from 25 to 85°C near threshold

H. Li, P. Moser, …, D. Bimberg, Photonics West, San Francisco, CA, USA, SPIE 9001-10 (2014).

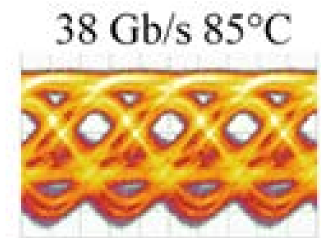
up to 42 Gbit/s error free transmission

non-return-to-zero (NRZ) modulation

best optical eyes

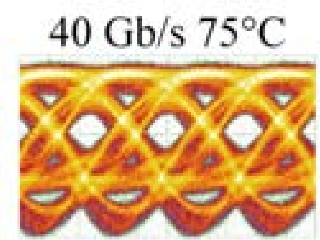


5.4 mA; 2.45 V; 1.39 mW



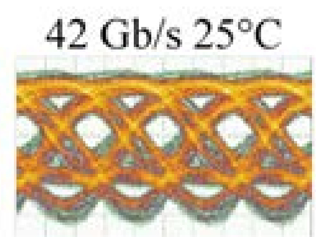
38 Gbit/s at 85°C:
- *EDR* = 348 fJ/bit
- *HBR* = 312 fJ/bit
- *J* = 43.0 kA/cm²

5.0 mA; 2.40 V; 1.40 mW



40 Gbit/s at 75°C:
- *EDR* = 300 fJ/bit
- *HBR* = 265 fJ/bit
- *J* = 39.8 kA/cm²

5.5 mA; 2.59 V; 1.81 mW



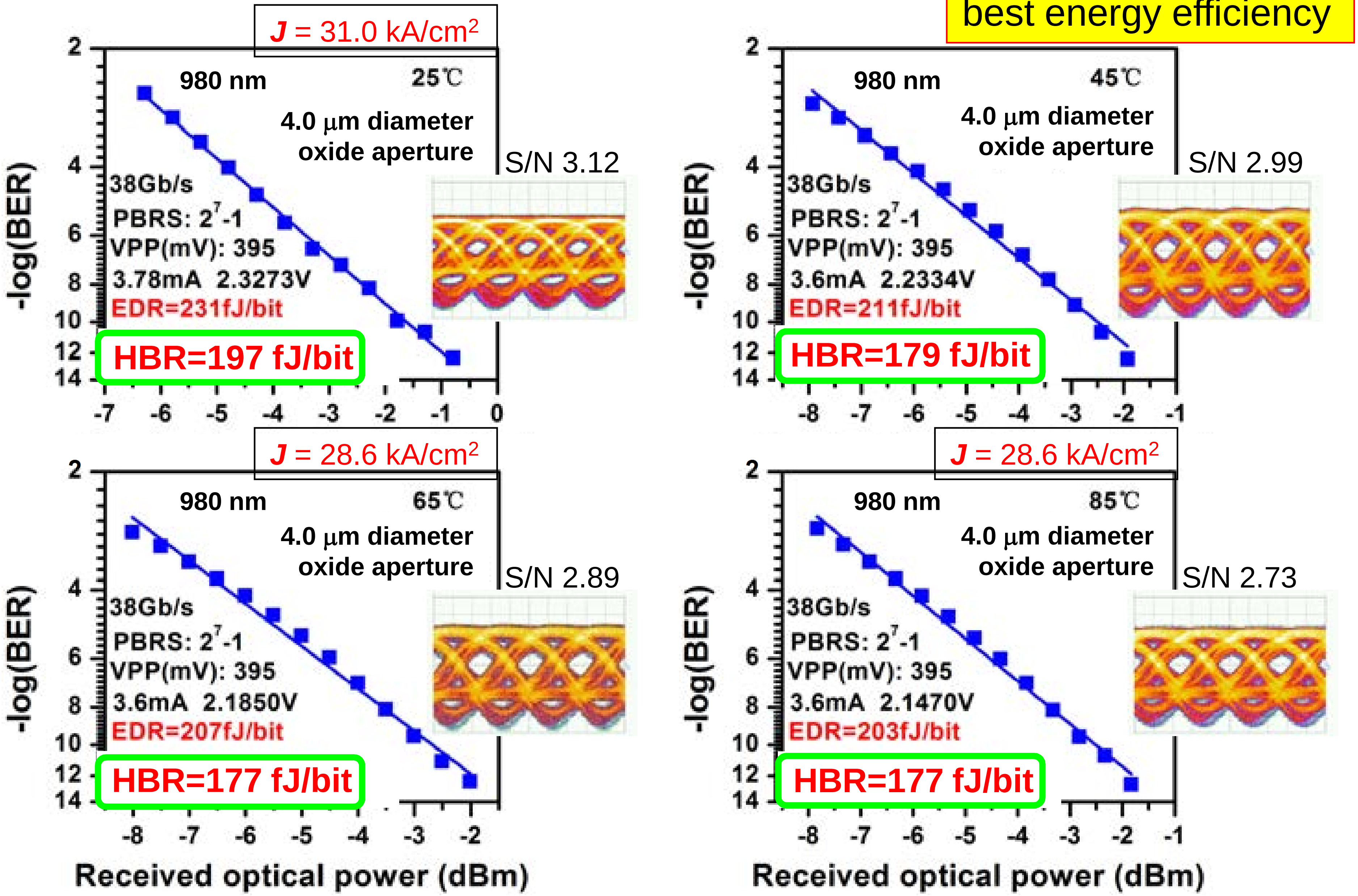
42 Gbit/s at 25°C:
- *EDR* = 339 fJ/bit
- *HBR* = 296 fJ/bit
- *J* = 43.8 kA/cm²

bit error ratio = BER
define “error-free“ as a BER < 1E-12

H. Li, P. Wolf, P. Moser, …, D. Bimberg, unpublished (2014).

38 Gbit/s error-free BER tests 25 to 85°C

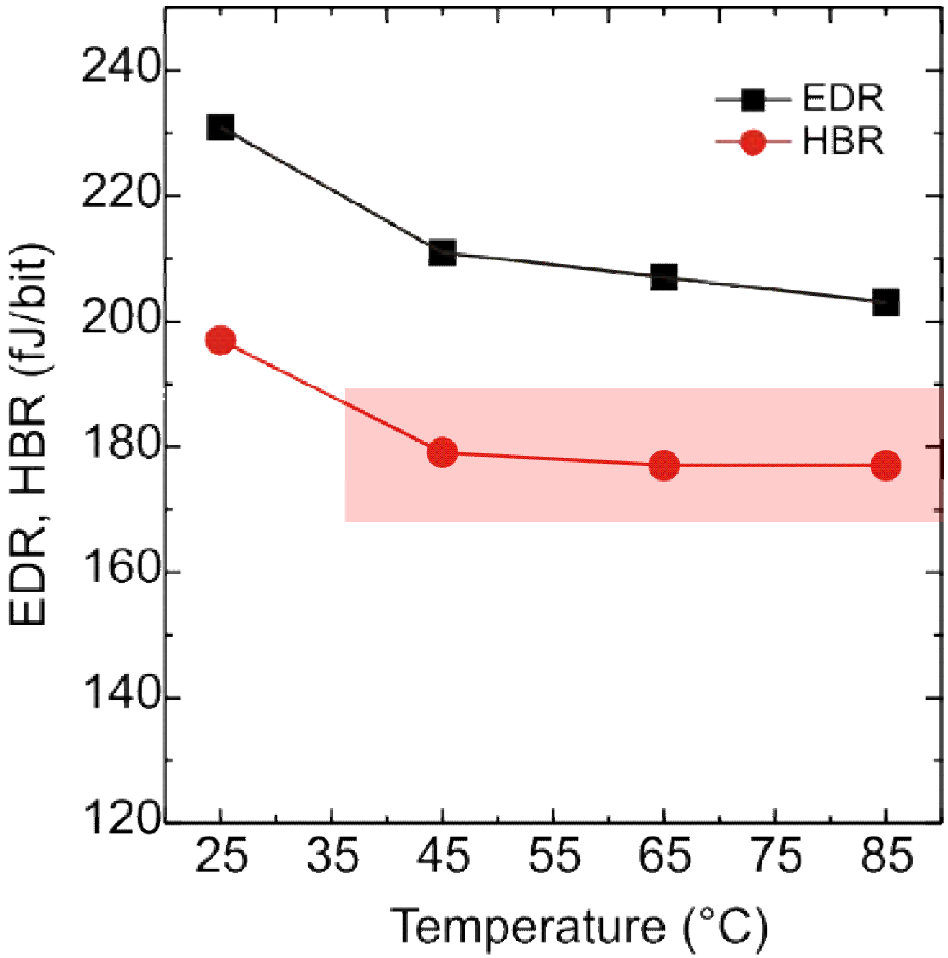
best energy efficiency



H. Li, P. Moser, …, D. Bimberg, Photonics West, San Francisco, CA, USA, SPIE 9001-10 (2014).

Energy efficiency vs. temperature

at 38 Gbit/s



Highly temperature stable energy dissipation per bit

H. Li, P. Moser, …, D. Bimberg, Photonics West, San Francisco, CA, USA, SPIE 9001-10 (2014).