MATERIALS THAT MATTER

Directly Modulated Lasers in a 3.2 Tb Era

Yasuhiro Matsui, Ph. D
II-VI Inc.
InP Business Unit, Fremont CA, USA

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Supports:

VPIphotonics
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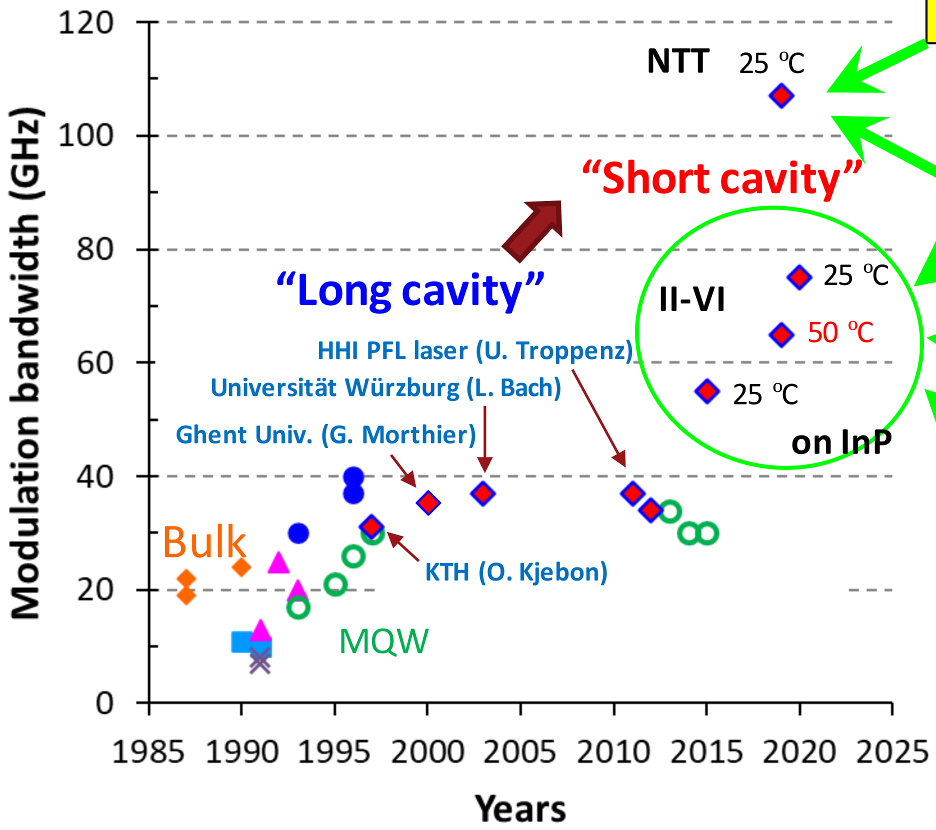
List of topics

- **3.2 Tb DML system prospect**
- **DML performance enhancement effects**
  - Detuned-loading effect
  - In-cavity FM-AM conversion for high-pass filter effect
  - Photon-photon resonance (PPR) effect
- **Three 70-GHz BW DML designs and comparison**
  - Short-cavity **split-contact DR laser** for tunable PPR frequency
  - Short-cavity **two-kappa DBR laser** and uniform modulation with SOA
  - **DFB+R laser**
  - LaserMatrix design simulator live demo
- **Experimental results and paper review**
  - Self-pulsation and pulse generation
  - Chirp reduction
  - Isolator-free operation
  - 400Gb/lane transmission by Sub-carrier multiplexing (SCM)
- **Reach extension by Chirp Managed Laser (CML)**
  - CML principles – optical duobinary effect, dispersion supported transmission, FM-AM conversion
- **Stability and reliability of DFB+R laser**
- **Conclusions**

Recent progress of DML and bandwidth enhancement effects



High index contract confinement

2010 S. Matsuo (PhC laser)
2019 S. Yamaoka (108GHz Membrane DML **on SiC**)
2021 N. Pandelis Diamantopoulos (60 GHz **on Si**)

Photon-Photon Resonance effect 1993 A. A. Tager

"High-pass" effect in response

In-cavity FM-AM conversion 2016 Y. Matsui

Detuned-loading effect 1984 K. Vahala

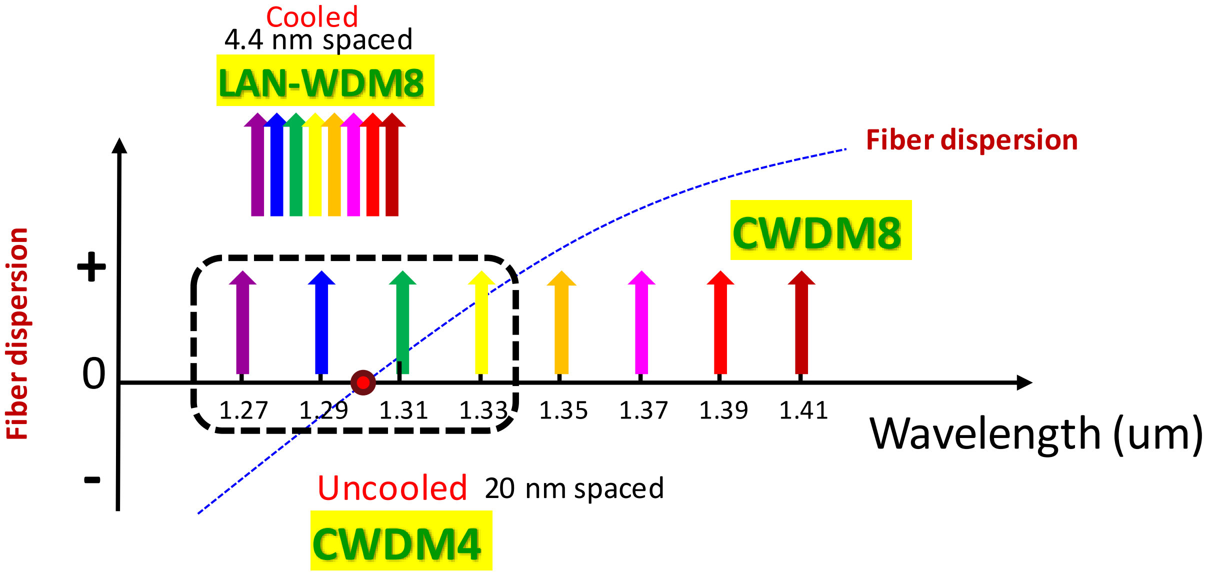
- **Isolator-free**
- **Chirp parameter reduction**

400Gb/lane 4km at 1330nm at 25 °C using SCM (2 carriers)

2020 Di Che, Optics Letter

3.2 Tb IMDD requires cooled tight spacing channels

- 400Gb/lane x 8 ch is a good candidate.
- Uncooled CWDM8 is not an option due to dispersion.
- Tighter channel spacing (5-10 nm spacing) reduces fiber dispersion. This requires cooling.



400G Transceiver today

	4 x 100G DML	4 x 100G EML	400G Coherent
Format	100G x 4λ PAM4	100G x 4λ PAM4	400G x λ DP 16QAM
Power consumption (7nm CMOS)	x 0.85 (cooled) x 0.82 (uncooled)	1 (cooled) x 0.92 (uncooled)	x 2.1
Market price (relative)	x 0.7	1	x 5 (400ZR)

*isolator-free lowers the cost

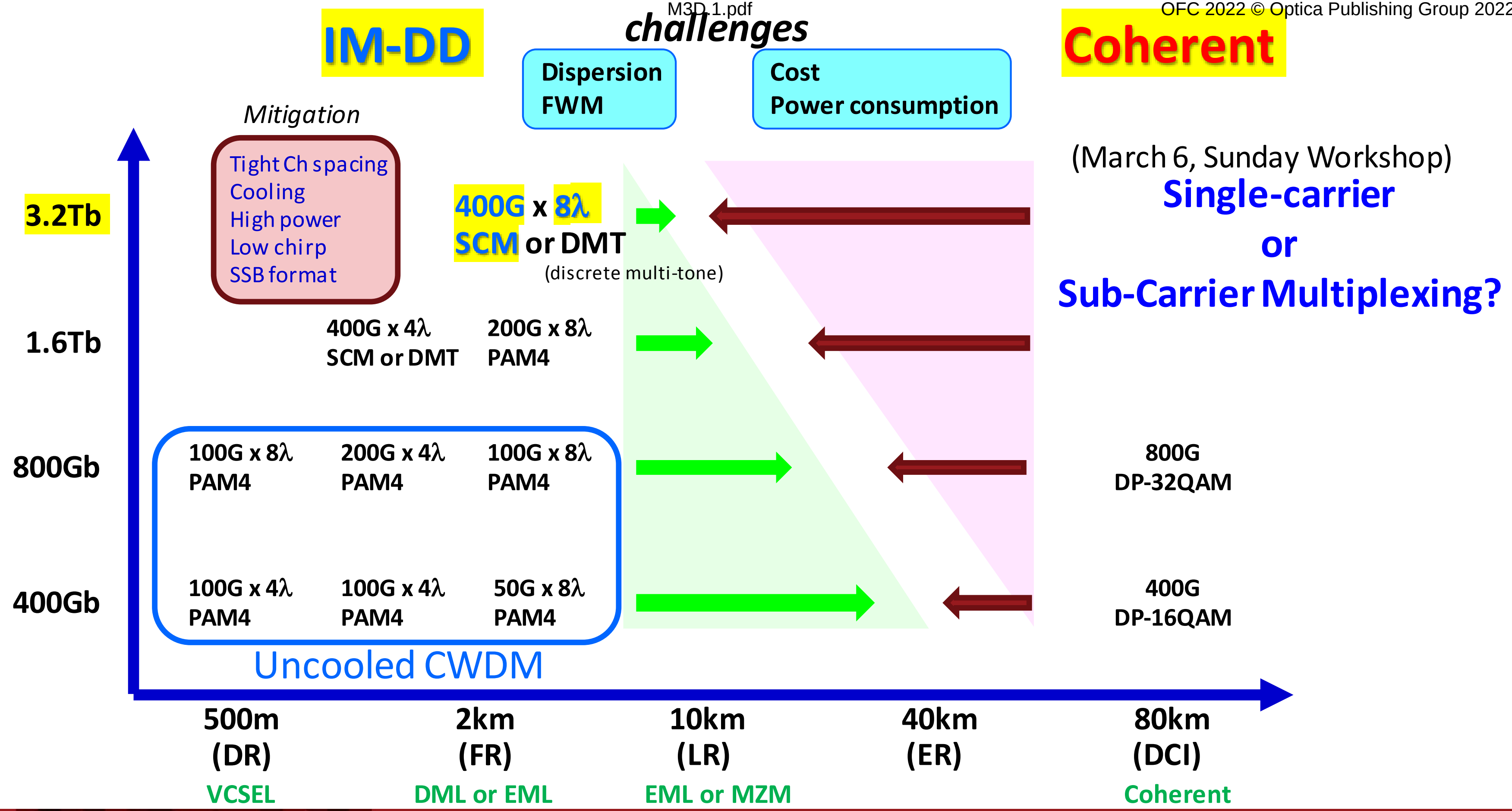
Benefit of uncooled:

- lower power consumption
- **Non-hermetic packaging**

Benefit of cooled:

- High output power
- Good reliability

Challenges to fill the gap in 3.2 Tb system



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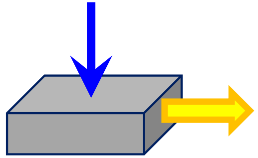
Chirp plays a key role in speed enhancement

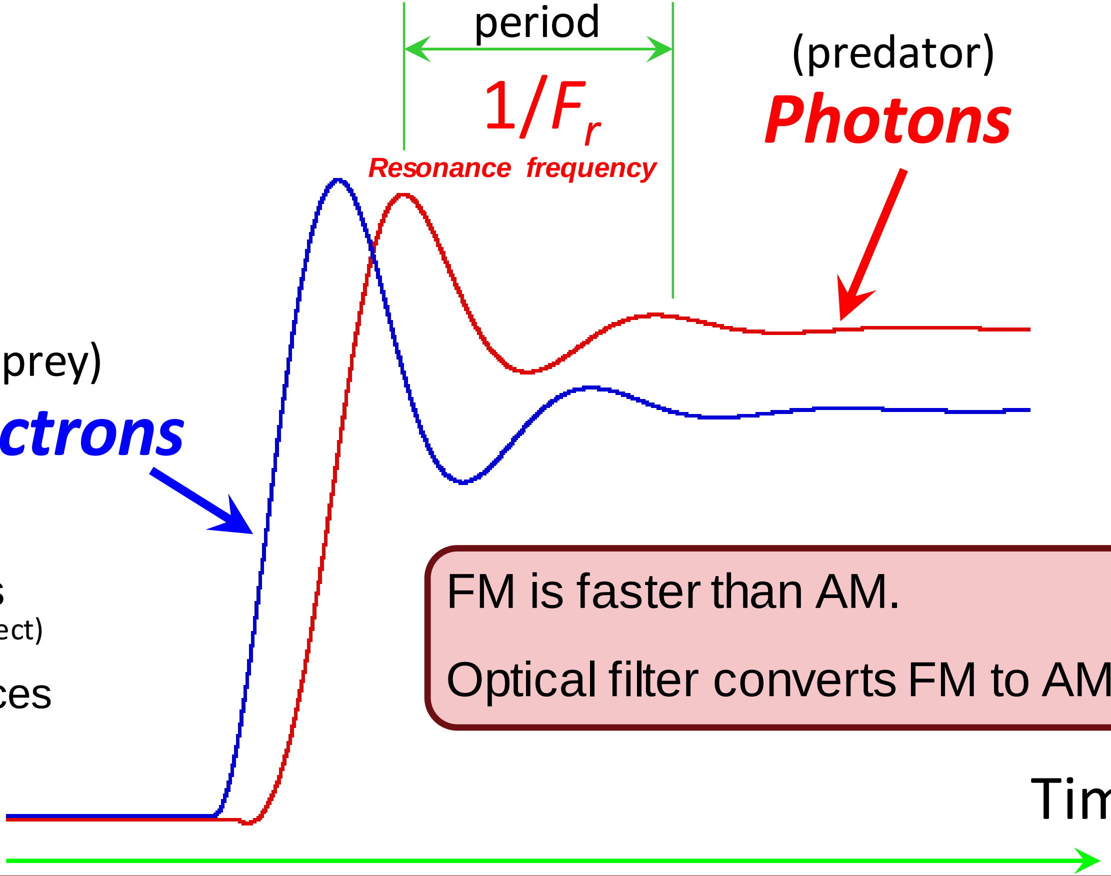
Laser Rate Equation

Current
(electrons)



Light
(photons)

Laser diode



\# of electrons increases

Refractive index reduces
(plasma effect)

Lasing wavelength reduces

$\propto$ Chirp!

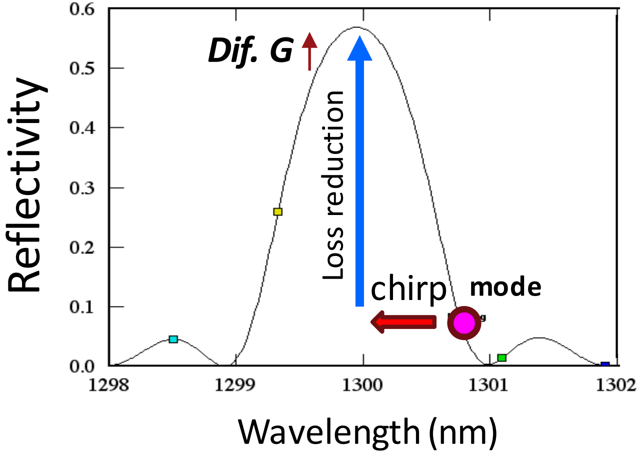
FM is faster than AM.

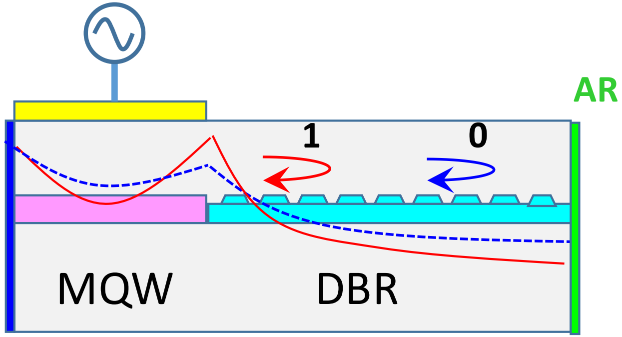
Optical filter converts FM to AM!

Detuned-loading effect on speed and chirp/linewidth

Works better for short cavity!

DBR mirror





Filter in the cavity converts chirp to effective differential gain

Lasing mode shifted on the edge

Due to chirp, mirror reflectivity goes up

Cavity loss reduces

Effective increase in differential gain

- Enhancement of resonance frequency

$$F_r \propto \sqrt{dif.G}$$

- Reduction of chirp parameter

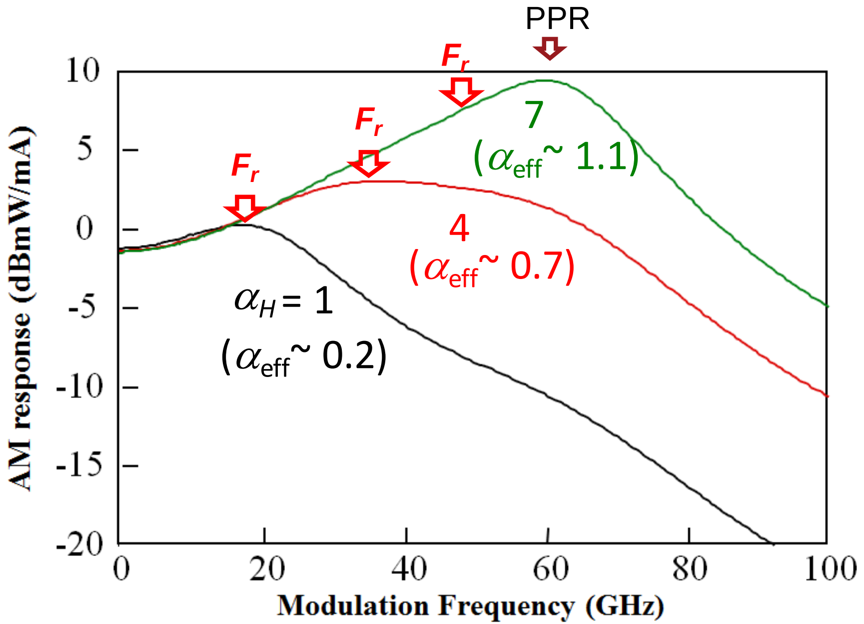
$$\alpha_{eff} \propto 1/(dif.G)$$

- Isolator-free operation

$$f_{ext} < \left[\boxed{\frac{\sqrt{1+\alpha_e^2}}{\alpha_e^2}} \frac{\gamma S}{2\sqrt{K_z P_{out}}} \right]^2$$

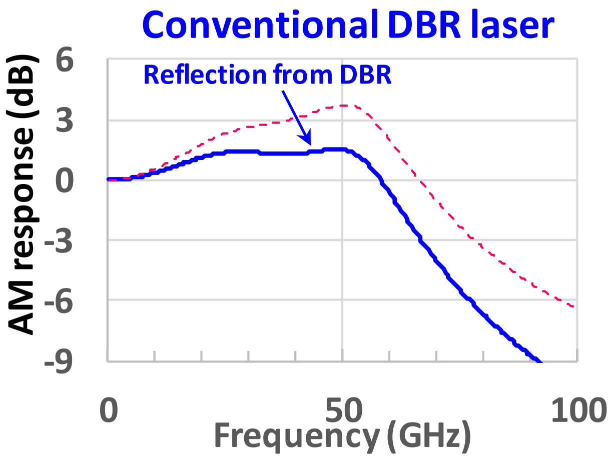
Large "material" alpha parameter improves the speed

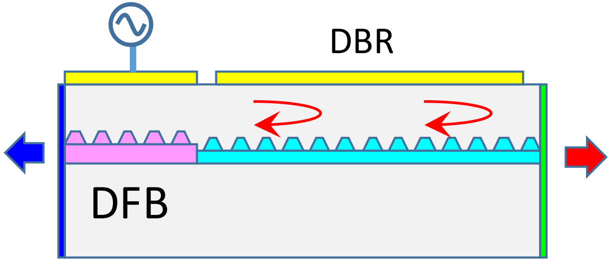
Effective alpha parameter (α_{eff}) can be ~ 1/5 of material alpha parameter due to detuned-loading effect.

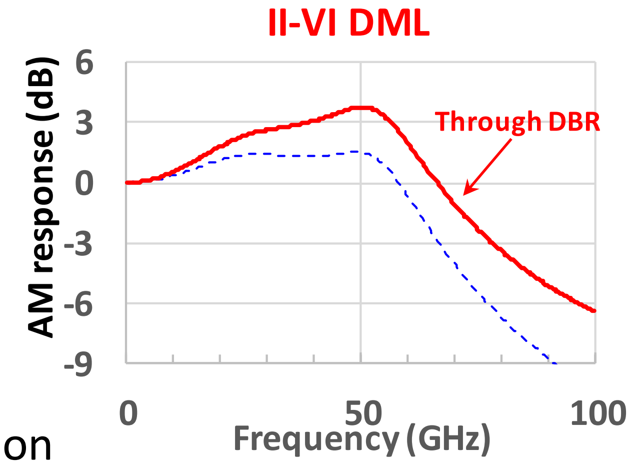


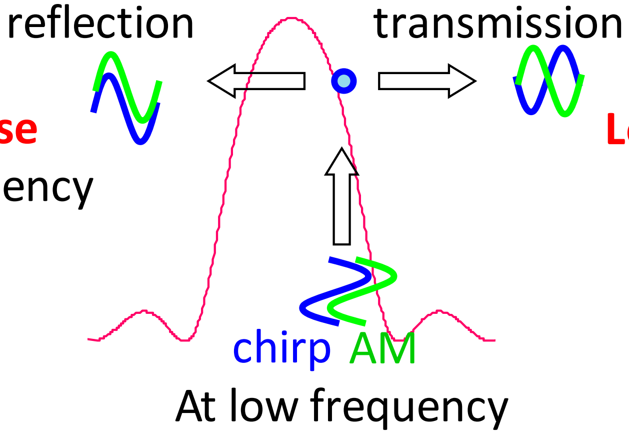
High-pass effect through DBR filter

Speed from two facets are not the same









High AM response

Only at low frequency

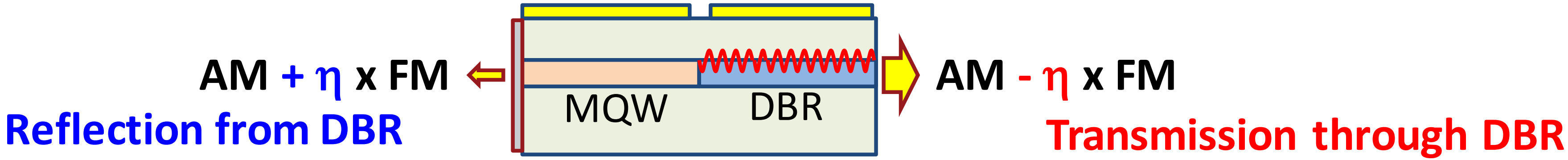
LPF effect

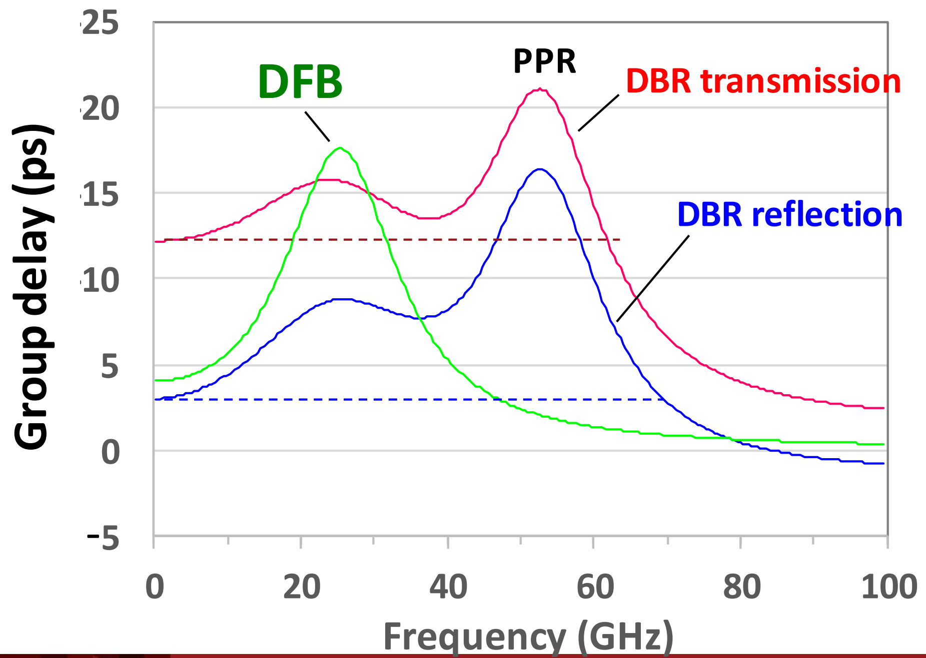
Low AM response

Only at low frequency

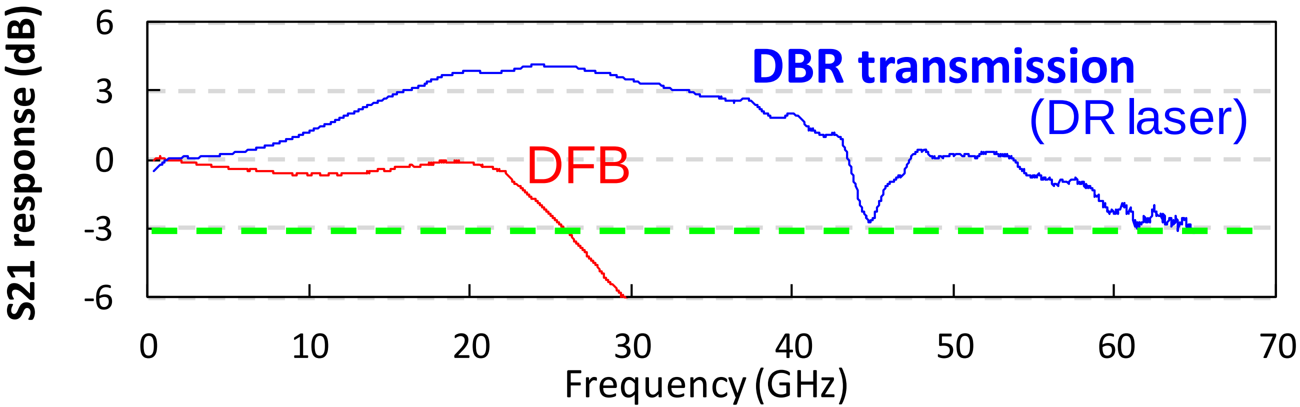
HPF effect

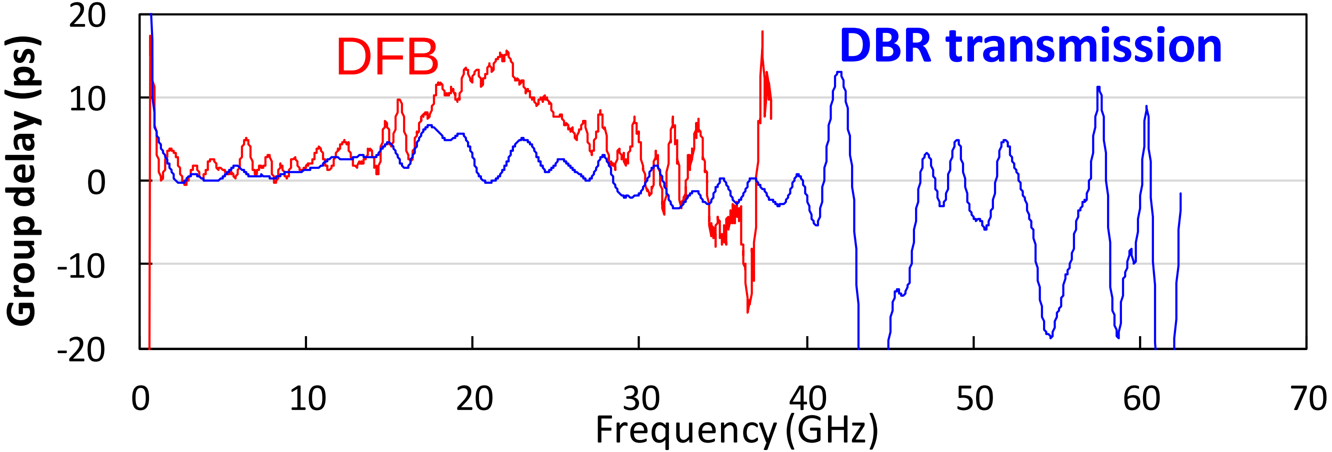
Flatter group delay for DBR transmission



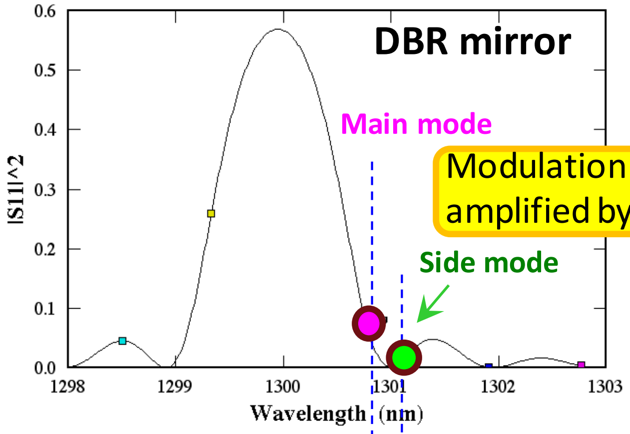


Measured group delay



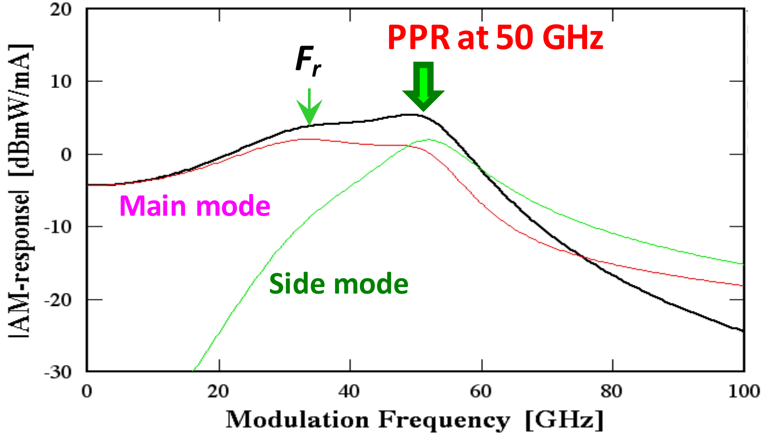


Photon-Photon Resonance (PPR)



Modulation sideband amplified by side mode

LaserMatrix simulation, developed by Richard Schatz (KTH)



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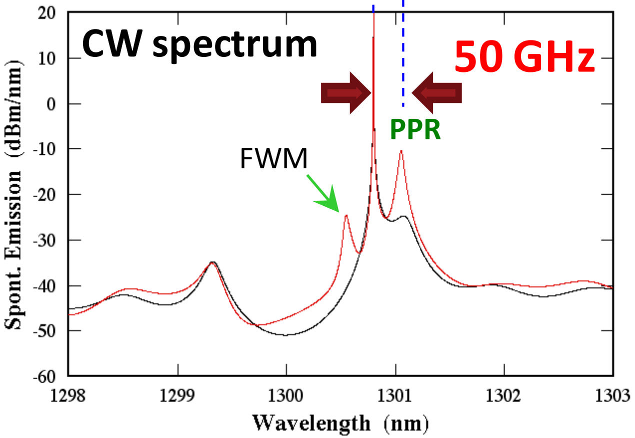
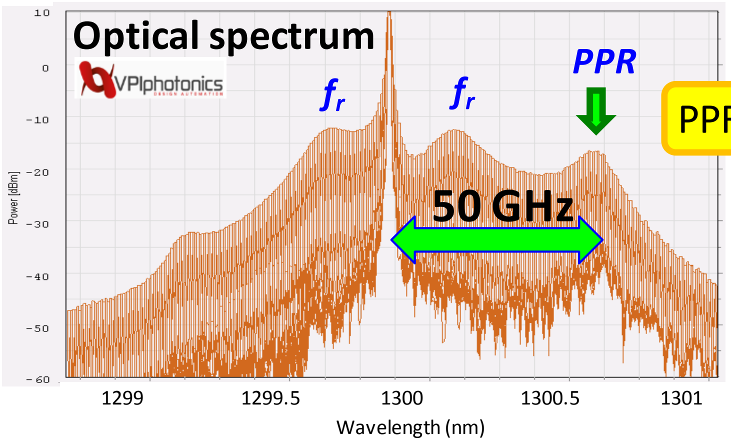


modulated



PPR is SSB

Necessary prerequisites for side-mode enhancement

PPR response

$$\Delta S_{a,m,(+\omega)} = v_g |U_0| \mathrm{Re}\left[\frac{\omega \left\langle \Phi_m \Phi_0^* \right\rangle_a \left\langle \Phi_m | \Phi_0 \right\rangle_a}{(\omega - \Omega_m)\Omega_m} (1 + i\alpha_H) \frac{\partial g}{\partial N} \Delta N_\omega e^{j\omega t} \right]$$

No PPR in FP laser

Coupled cavity required

- Laser cavity needs to be inhomogeneously modulated for the effect to occur, e.g. active-passive cavity or multielectrode active cavity (since modes are orthogonal over entire cavity)

$$\left\langle \Phi_m | \Phi_0 \right\rangle_a = \int_{active} \Phi_m^+ \Phi_0^- + \Phi_0^+ \Phi_m^- dz$$

- Both modes need to have good confinement in the modulated section

$$\left\langle \Phi_m \Phi_0^* \right\rangle_a = \int_{active} \Phi_m^+ \Phi_0^{+*} + \Phi_0^{-*} \Phi_m^- dz$$

- The modulation frequency needs to be close to the side mode beat frequency

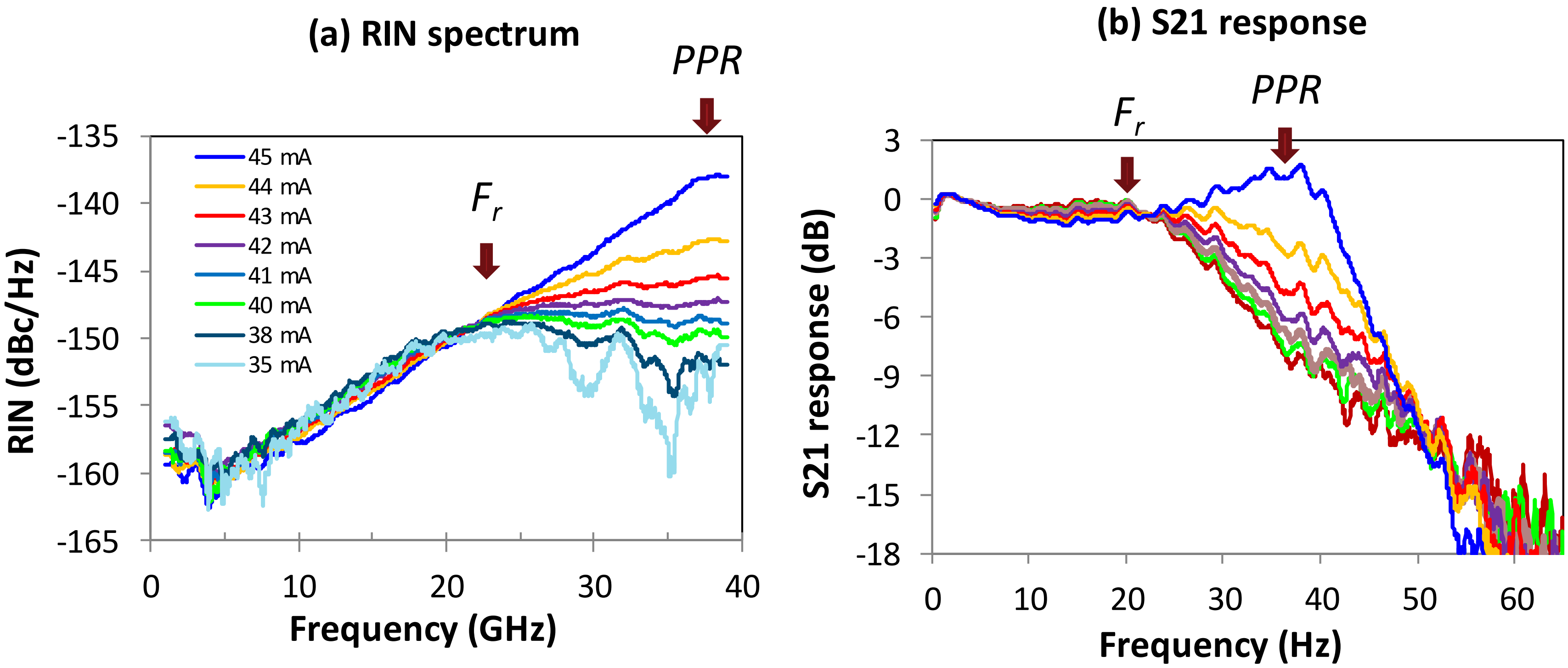
$$(\omega - \Omega_m)$$

- For a certain group delay, the induced spatio-temporal fluctuations in the carrier distribution and the intensity distribution will enforce each other. This enhances the effect and can lead to reduced side mode suppression of the PPR mode (a.k.a. asymmetric gain compression) and also self pulsations at mode beating frequency (mode locking)

OFC 20180315
Richard Schatz
Royal Institute of Technology
rschatz@kth.se

Relative Intensity noise (RIN) in PPR

- RC roll-off can be counteracted by PPR to achieve flat S21. However, it comes with noise.



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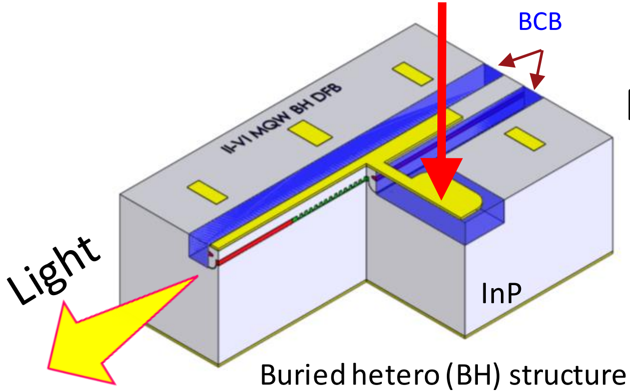
Distributed Feedback (DFB) laser OFC Postdeadline 2015

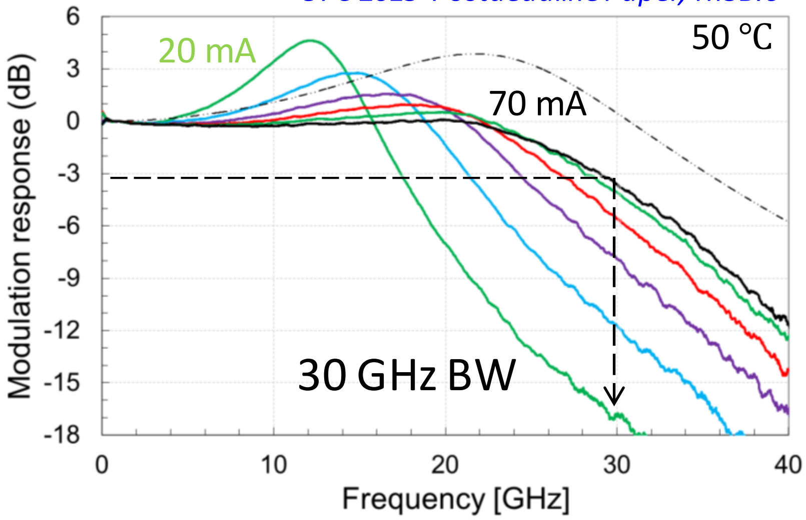
Current modulation

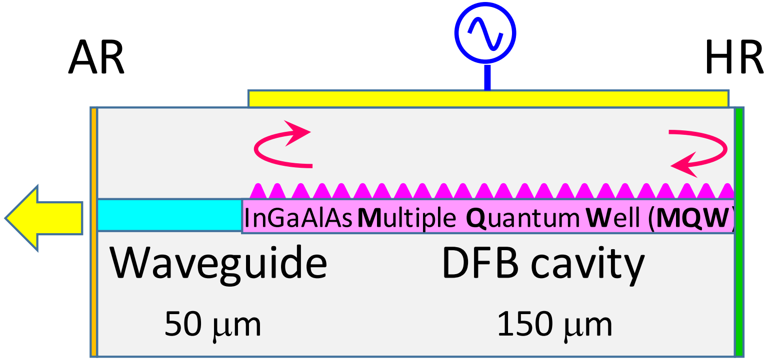


Buried hetero (BH) structure

PN-blocking
Cutoff ~ 22 GHz

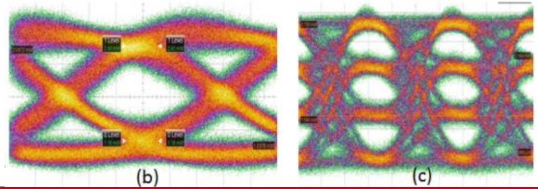
OFC 2015 Postdeadline Paper, Th5B.6



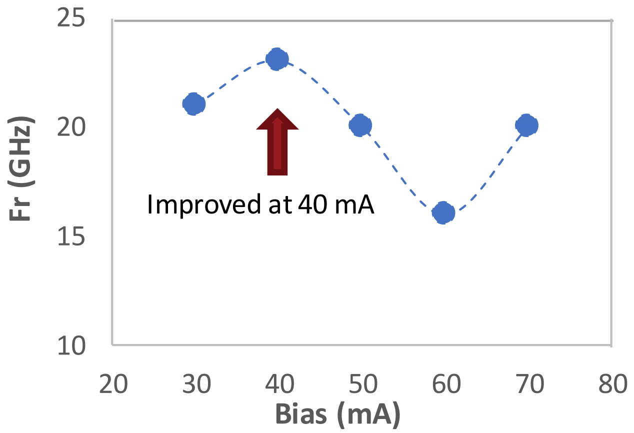


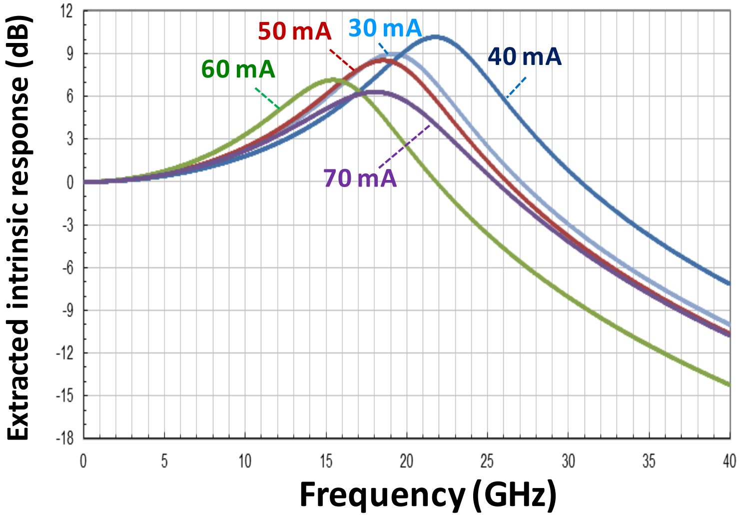
- 50um passive waveguide added for handling purpose.

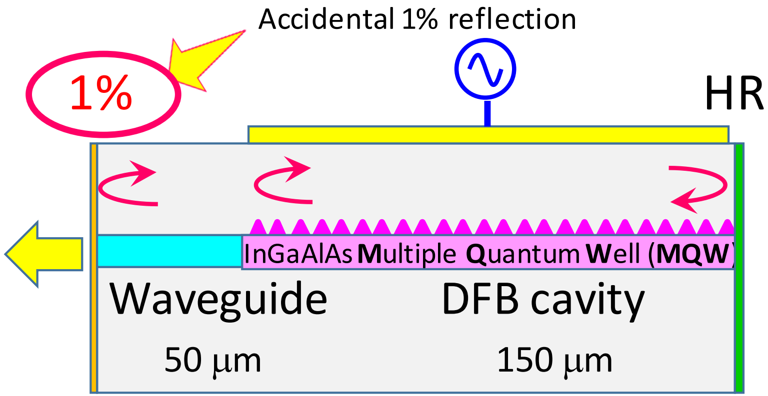
56 Gb NRZ 56 Gb PAM4



Accidental 1% reflection improved the speed in 2015





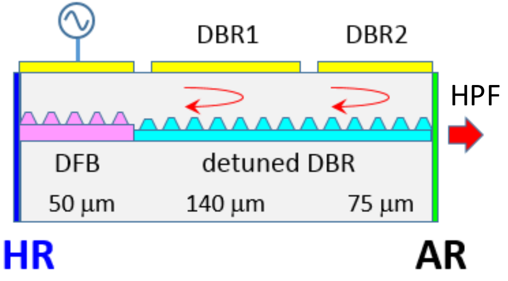


- 1% reflection at the end of passive waveguide improved the speed at 40 mA, degraded at 60 mA.
- It was explained by detuned-loading effect.

Three *short-cavity* DML implementations

2016 OFC PDP

(Split-contact) DR



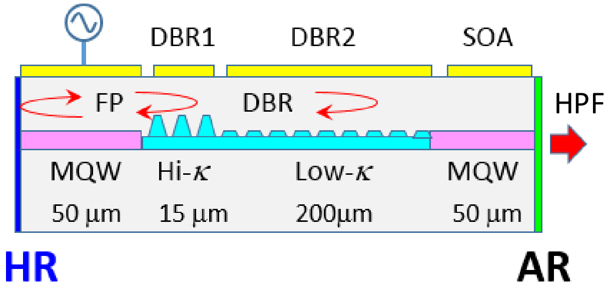
BW ~ 65 GHz

Reflection tolerance ~ 40%

Power ~ 4.5 mW

PPR tuning 20-80 GHz

Two-κ DBR laser with SOA



BW ~ 65 GHz

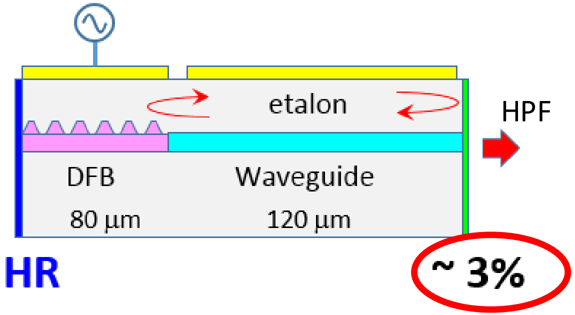
Chirp parameter ~ 1.0

Reflection tolerance ~ 20%

Power ~ 4.5 mW
Power ~ 15 mW (SOA *co-mod*)

2020 OFC PDP

DFB+R



BW ~ 75 GHz

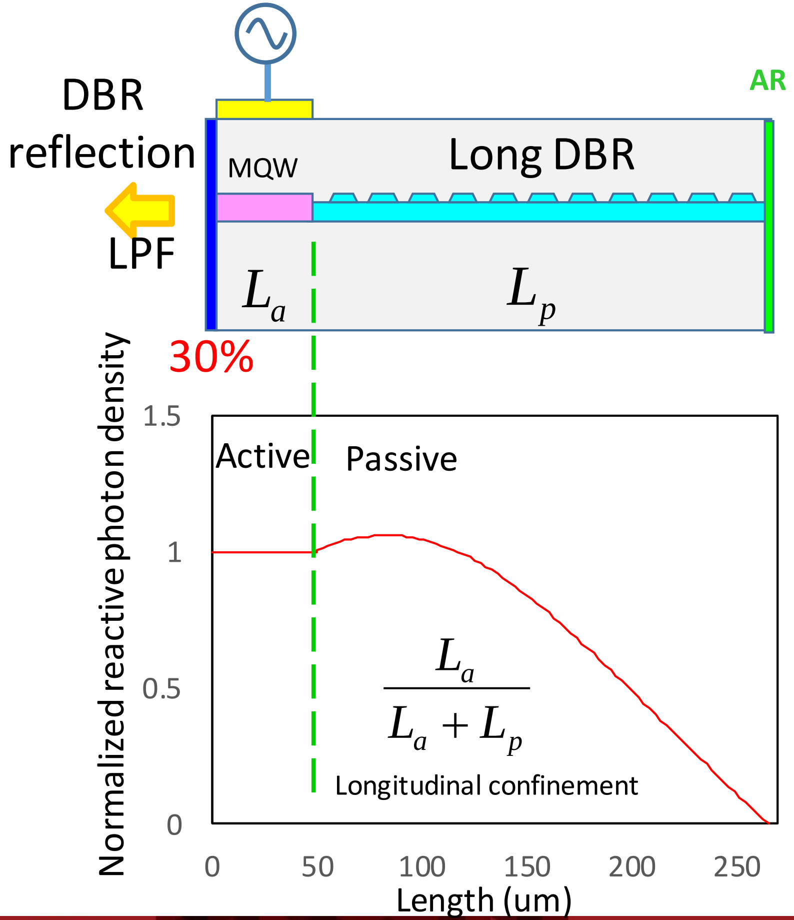
Chirp parameter ~ 0.6

Reflection tolerance ~ 12%

Power ~ 23 mW

Y. Matsui et al., Nature Photon. 15, 59 (2021).

Long cavity DML to use PPR effect diminishes detuned-loading



Conventional DML issues

- Light coupled for DBR reflection

✓ Creates low-pass response effect

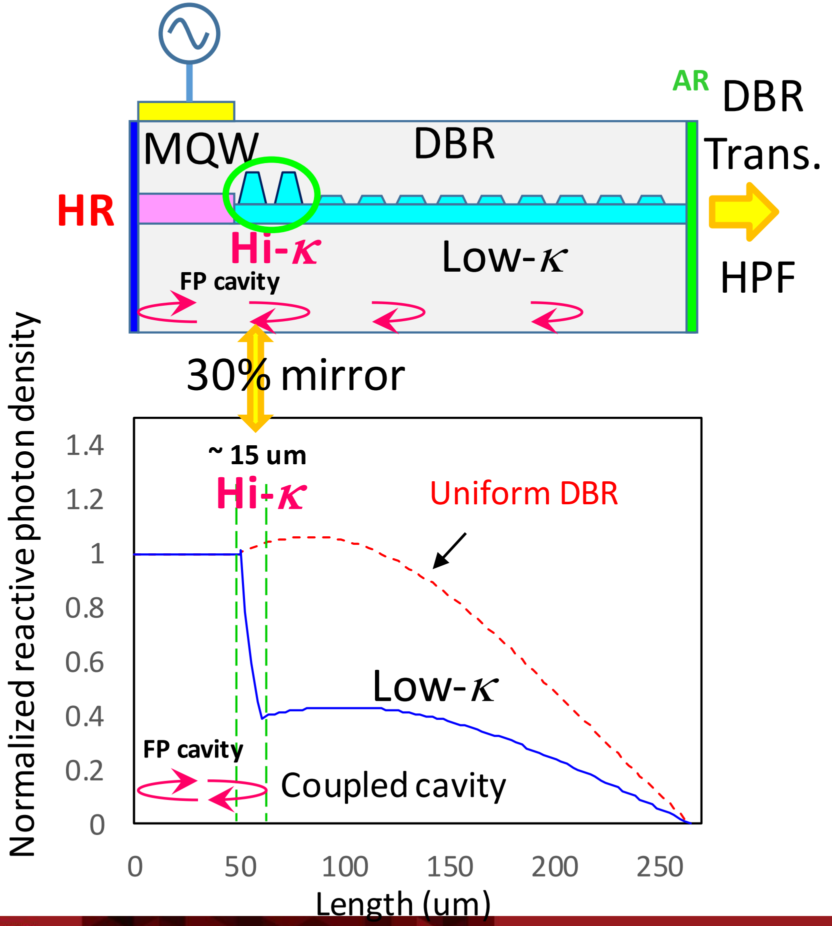
- 30GHz PPR frequency achieved using long cavity

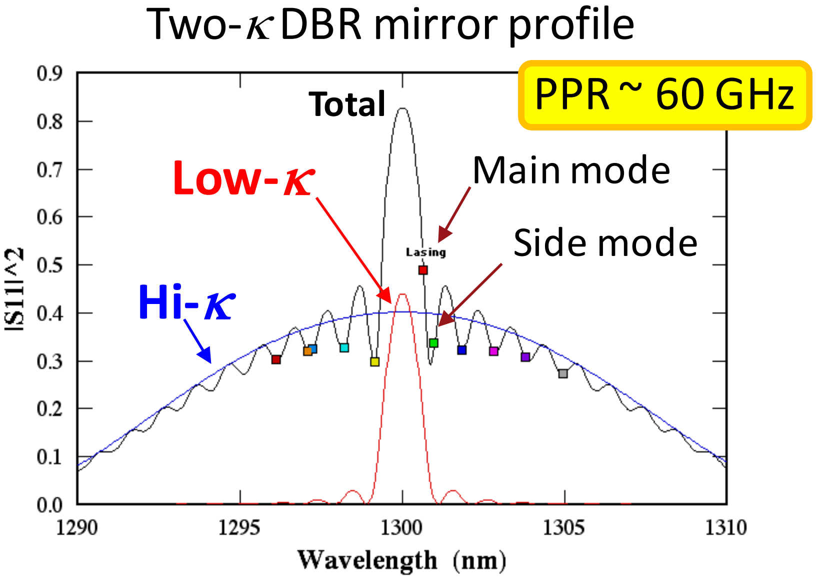
✓ Frequent mode hopping diminished the detuned-loading effect.

✓ Passive section dilutes differential gain.

Short-cavity Two-κ DBR laser concept

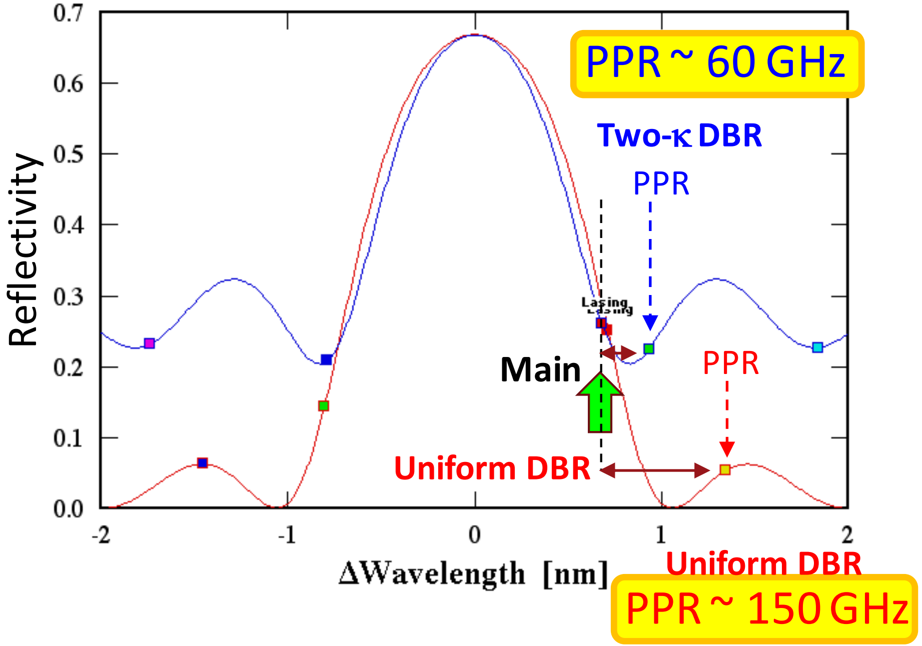
- Very short (15um) Hi-κ DBR forms FP cavity and confine photons effectively in the MQW region.
- Low-κ DBR forms a complex-cavity and excite PPR effect while generating detuned-loading effect.

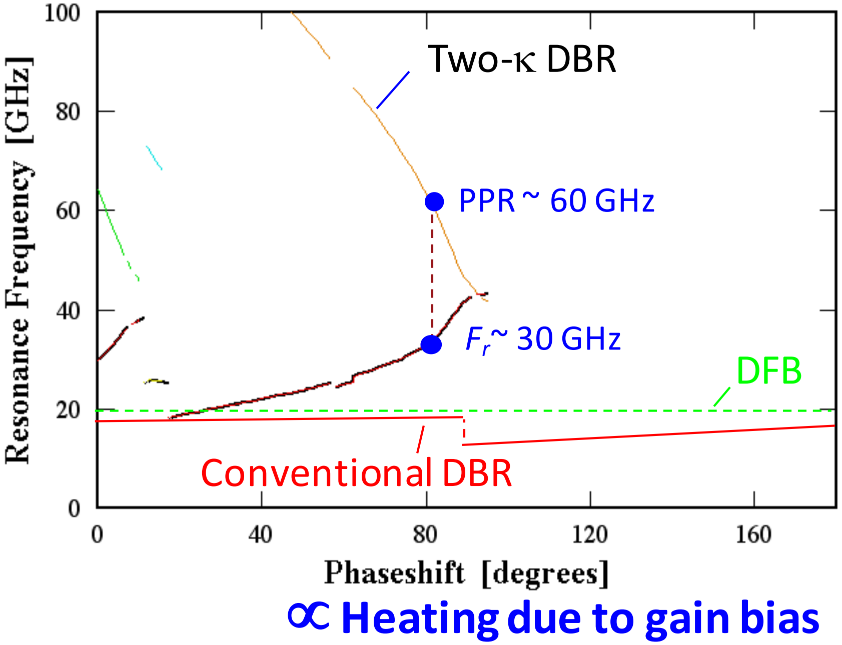




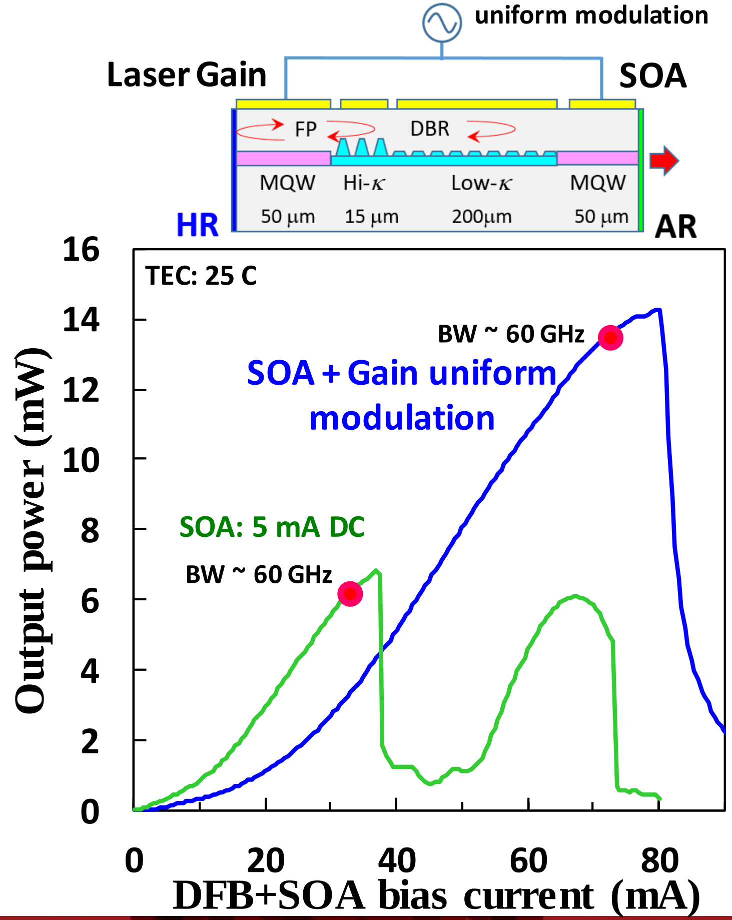
Another benefit of Two-κ DBR laser

- PPR frequency for conventional short-cavity DBR laser is ~150 GHz.
- Two-κ DBR short-cavity design brings down the PPR frequency to ~ 60 GHz.

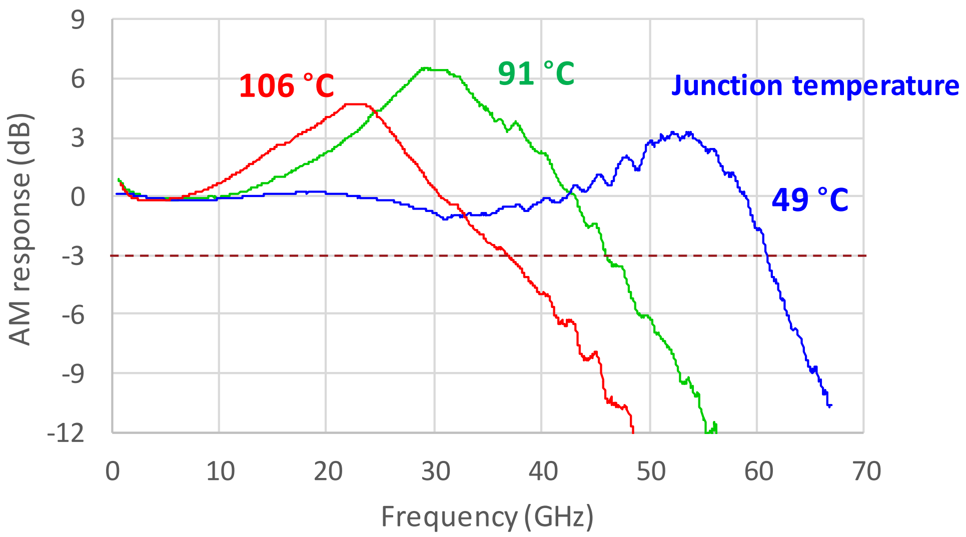




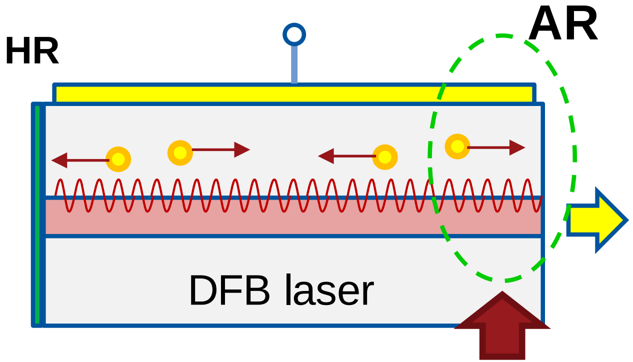
Output power for uniform modulation including SOA



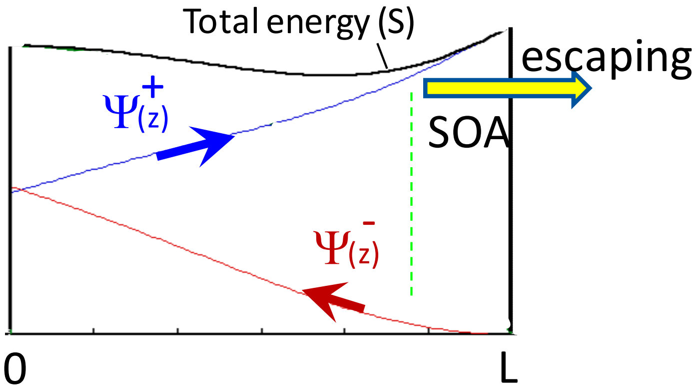
For > 200 Gb/s transmission, it is important to couple > 10 dBm power.

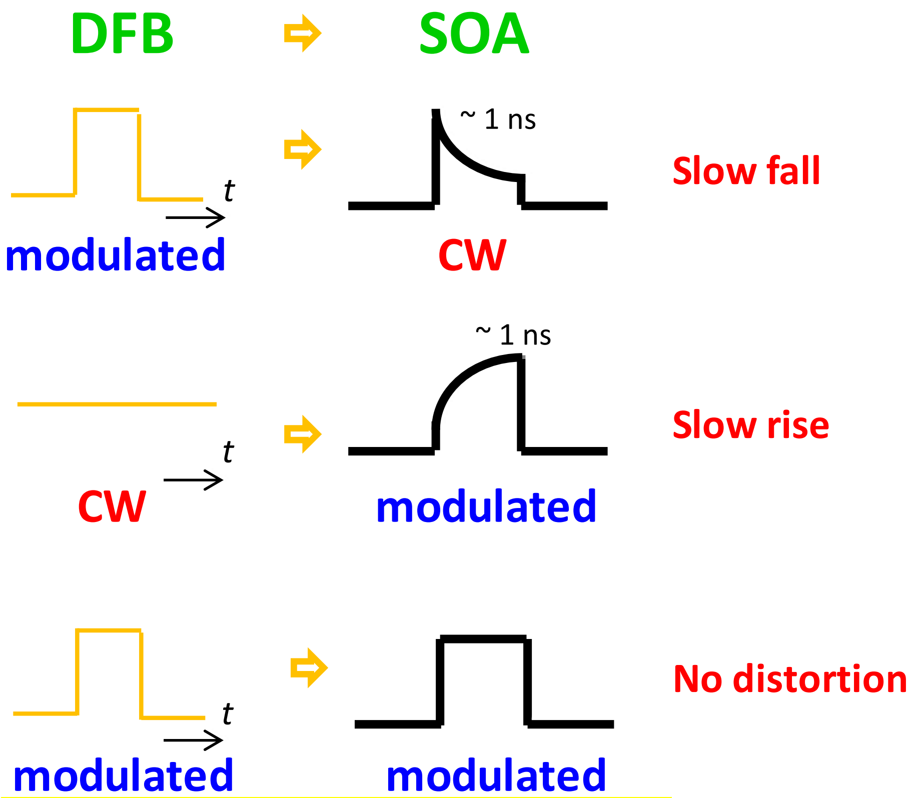


AR-coated DFB laser does not show distortion in uniform modulation



This section acts like "SOA"

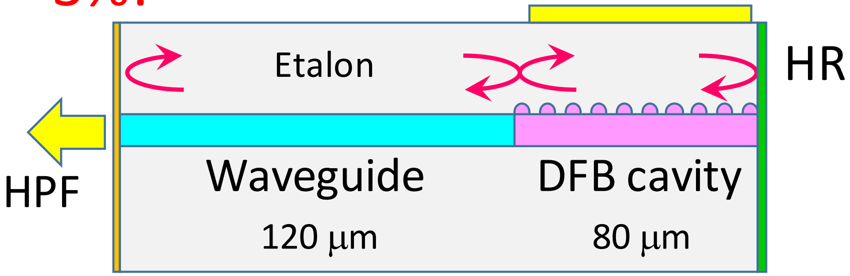


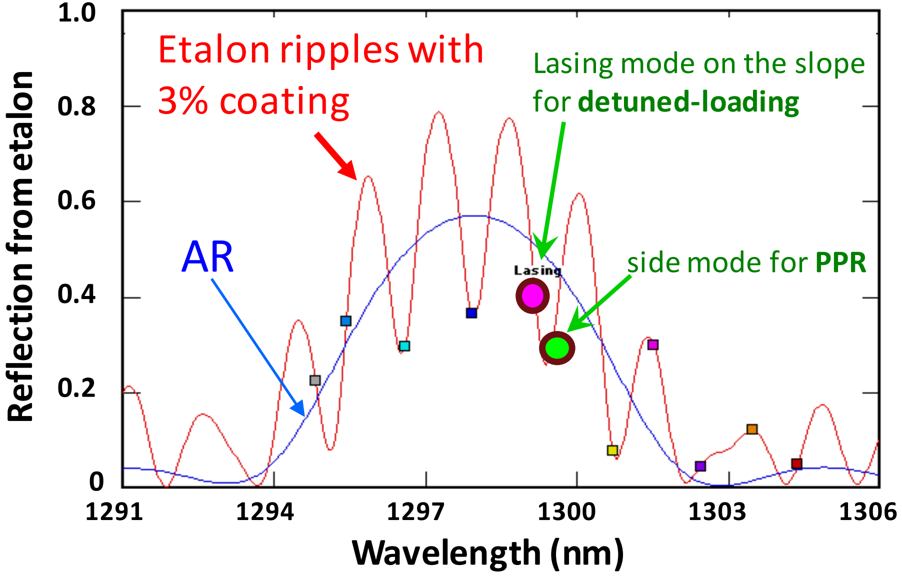


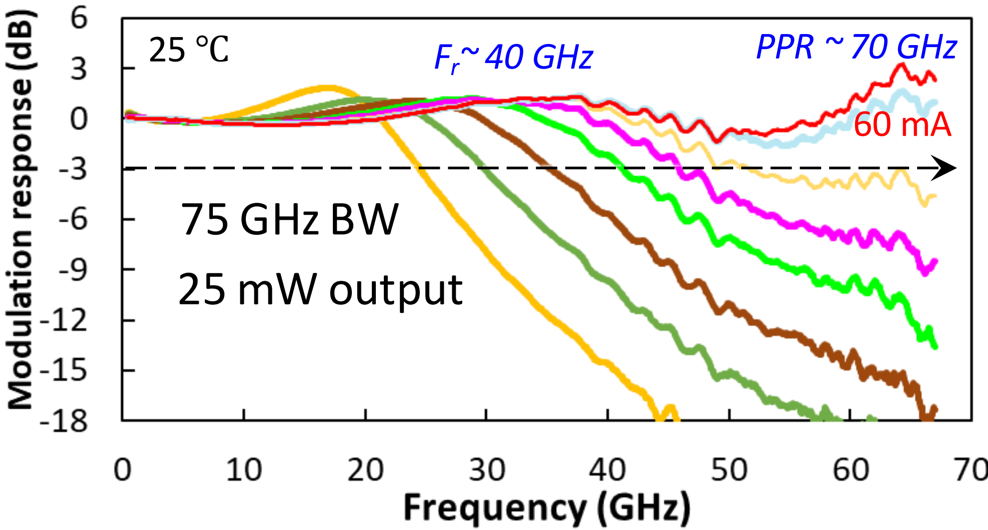
No distortion in "co-modulation"

DFB+R laser operation principle

3%!



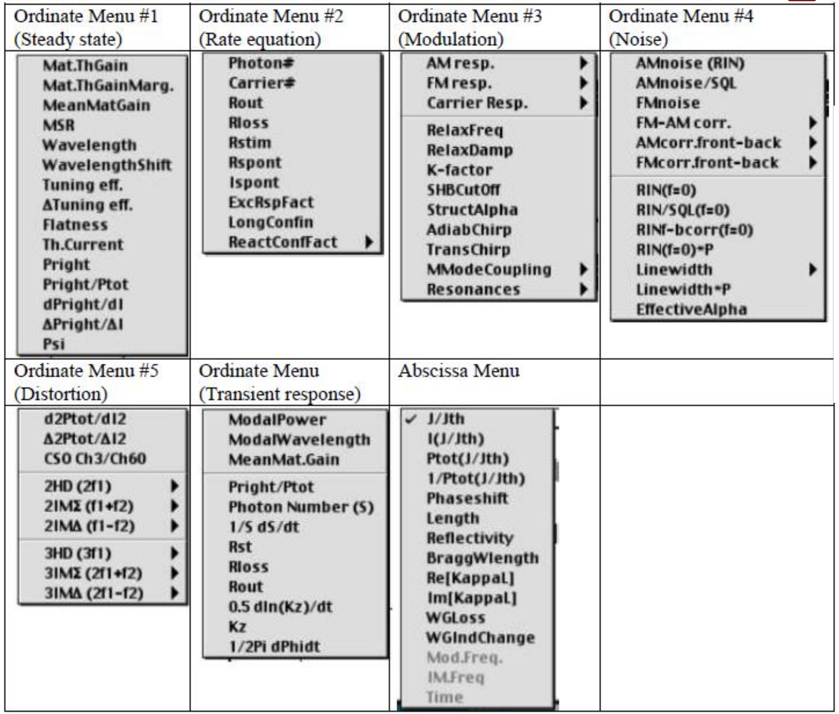




- ✓ **75GHz bandwidth**
- ✓ **Chirp parameter ~ 0.6**
- ✓ **Isolator-free**
- ✓ **25 mW output power**
- ✓ **Based on reliable DFB laser**

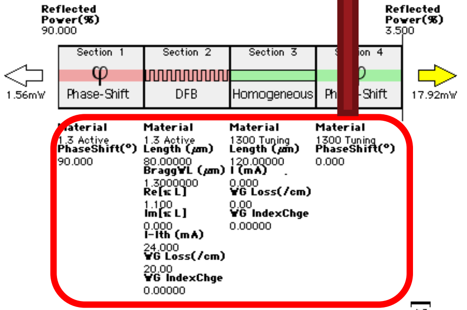
LaserMatrix simulation – "This vs That" function

Pulldown menu for Y axis

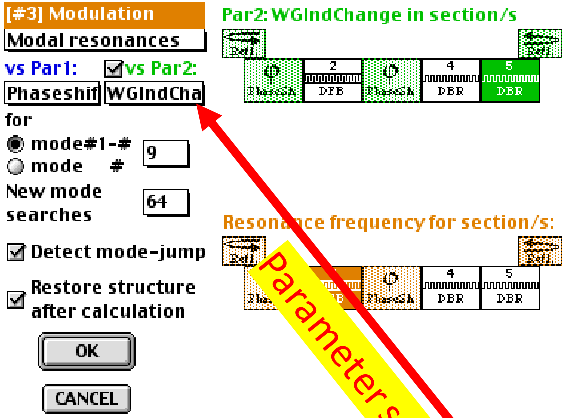


Y axis

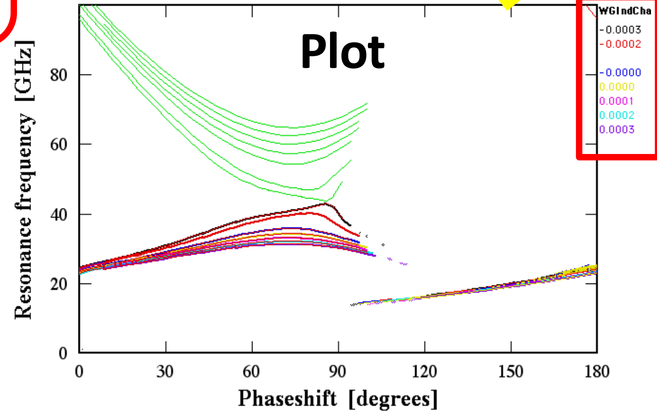
X axis



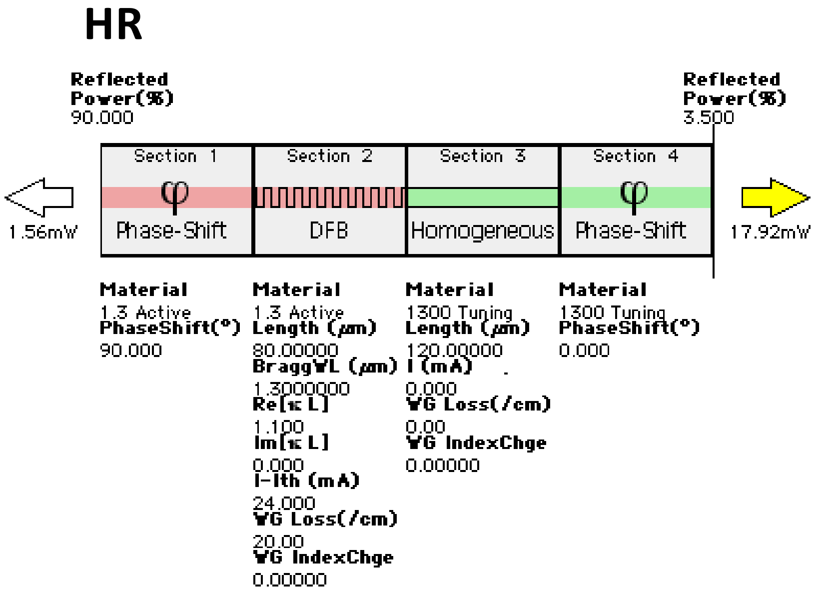
Any of cavity and material parameters can go to X axis



Parameter scan

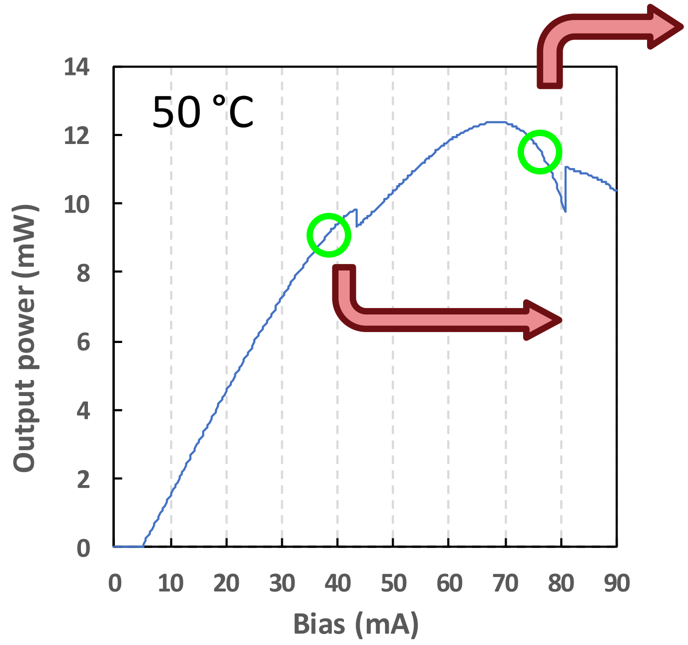


LaserMatrix design simulation for DFB+R laser

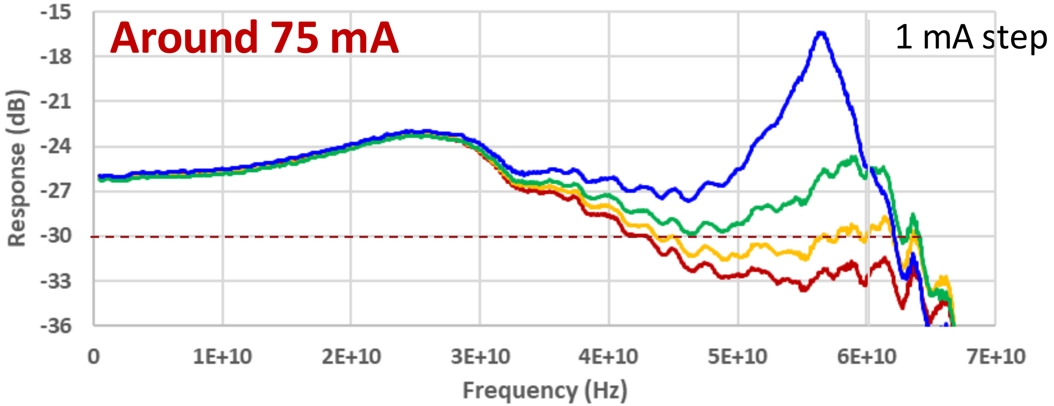


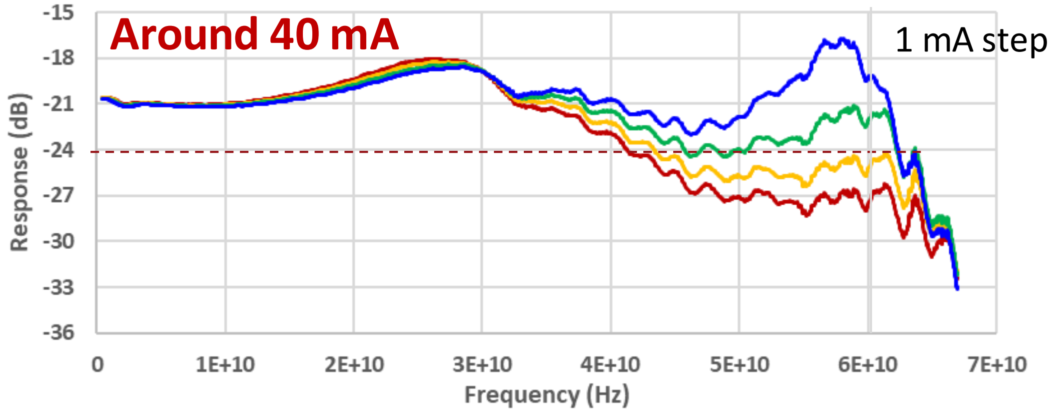
> 60 GHz BW at 50 °C

BW is always ~ 60 GHz for > 40 mA bias.

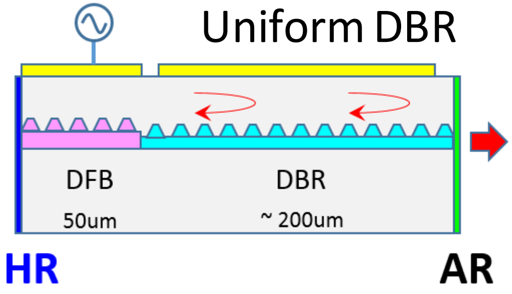


DFB+R laser



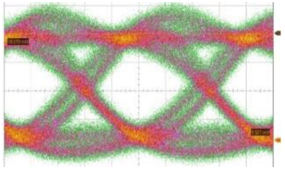


Distributed Reflector (DR) laser in 2016

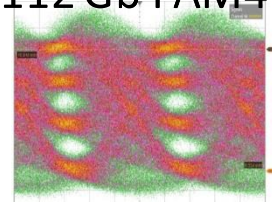


Photon confinement by DFB grating

56 Gb NRZ

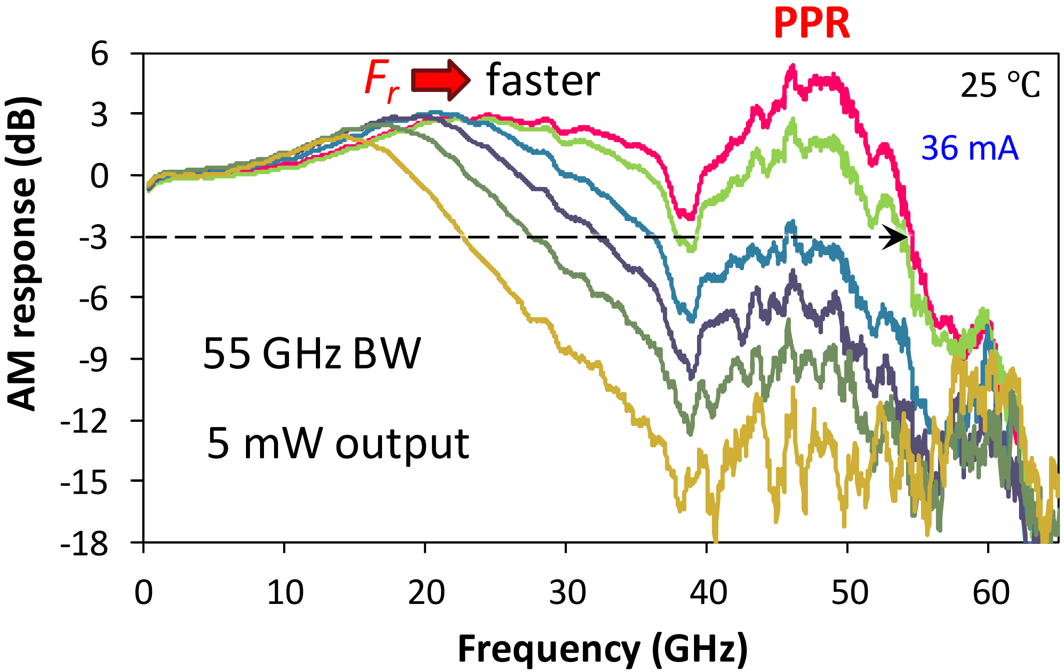


112 Gb PAM4

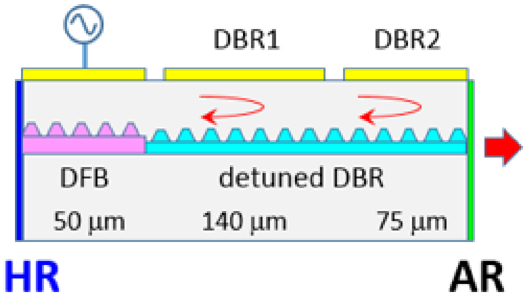


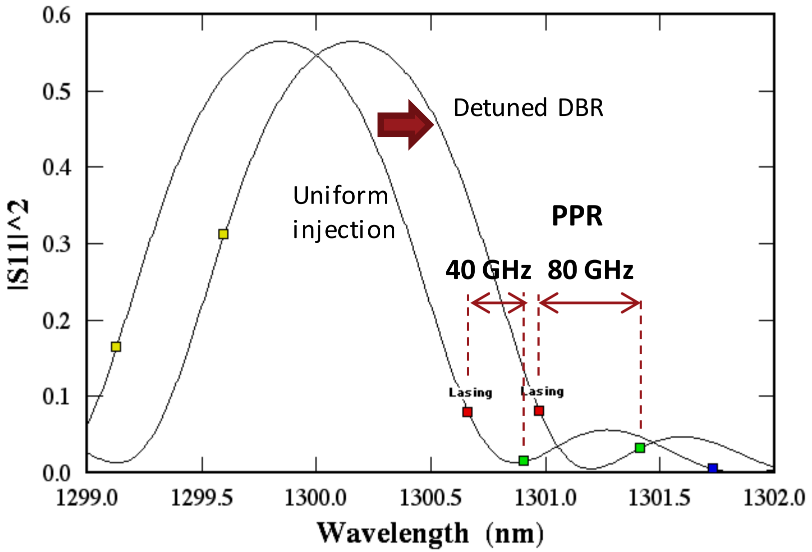
(No equalizer)

OFC 2016 Postdeadline Paper, Th5B.4

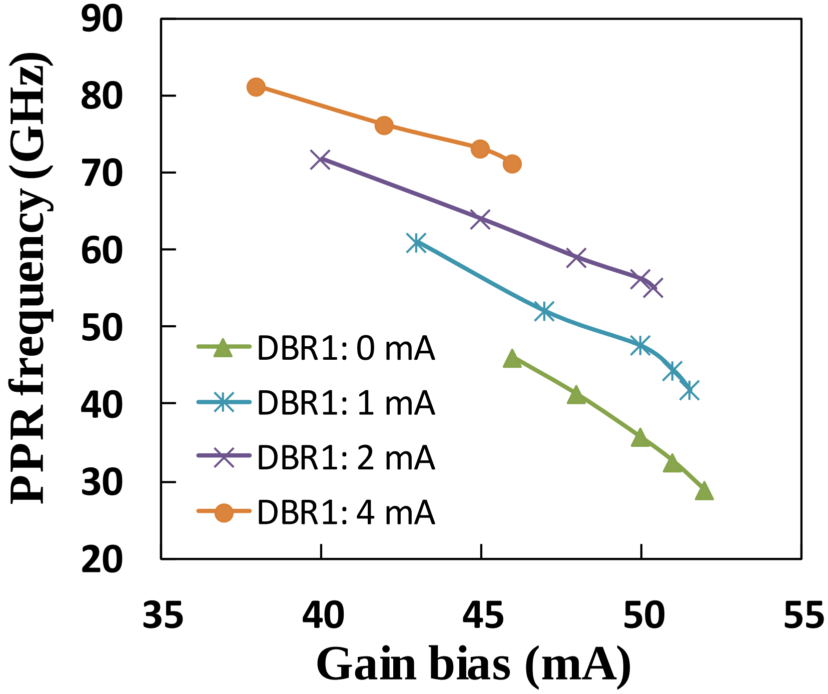


Split-contact DR laser for PPR tuning

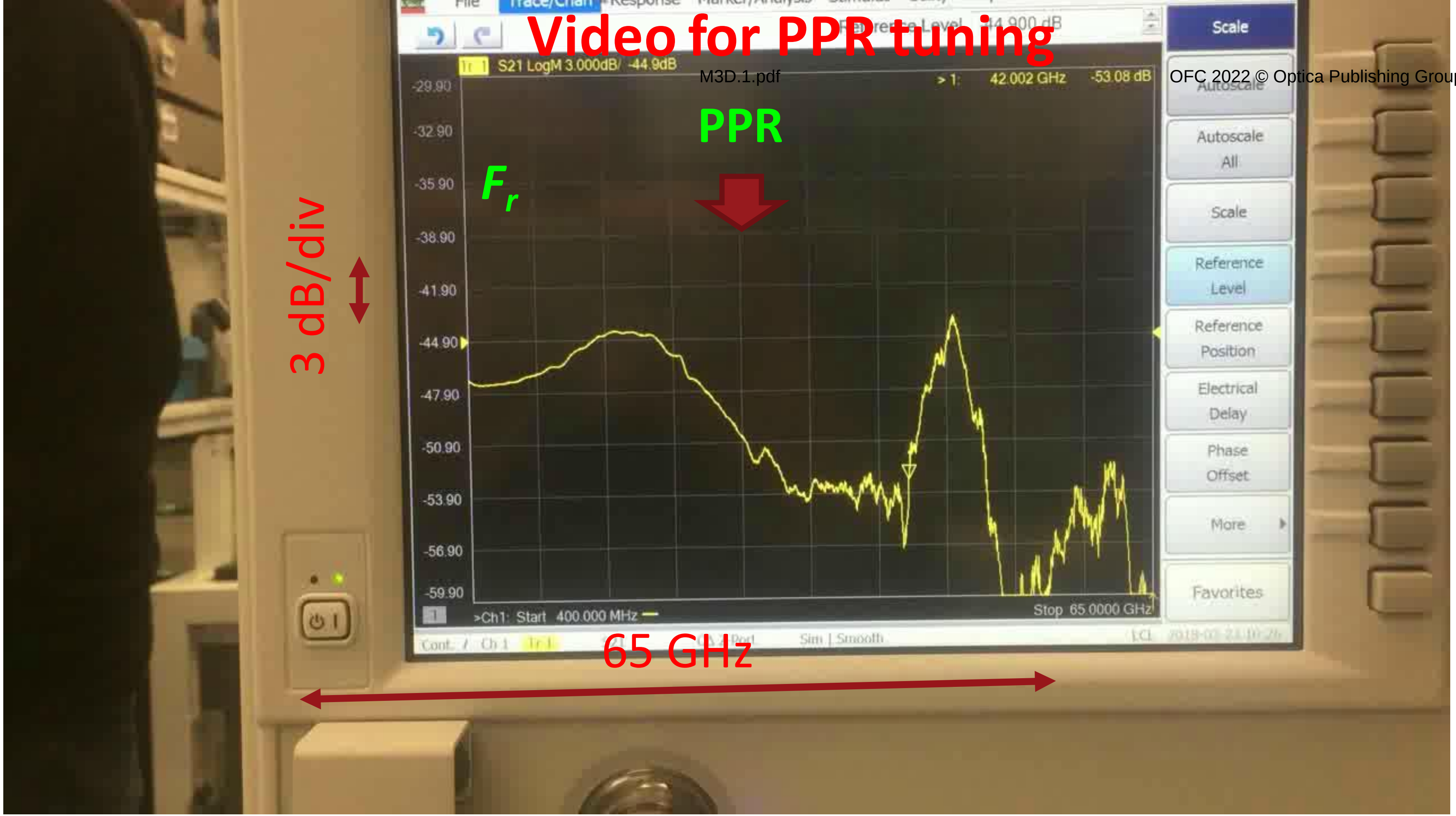




Slight detuning between DBR1 and DBR2 can tune the PPR frequency over wide range.



Video for PPR tuning



List of topics

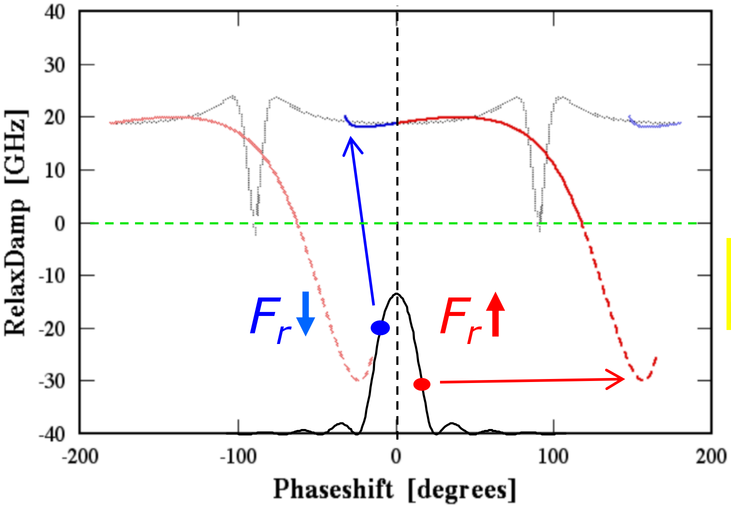
- ❑ **3.2 Tb DML system prospect**
- ❑ **DML performance enhancement effects**
  - ➢ Detuned-loading effect
  - ➢ In-cavity FM-AM conversion for high-pass filter effect
  - ➢ Photon-photon resonance (PPR) effect
- ❑ **Three 70-GHz BW DML designs and comparison**
  - ➢ Short-cavity split-contact DR laser for tunable PPR frequency
  - ➢ Short-cavity two-kappa DBR laser and uniform modulation with SOA
  - ➢ DFB+R laser
  - ➢ LaserMatrix design simulator live demo
- ❑ **Experimental results and paper review**
  - ➢ Self-pulsation and pulse generation
  - ➢ Chirp reduction
  - ➢ Isolator-free operation
  - ➢ 400Gb/lane transmission by Sub-carrier multiplexing (SCM)
- ❑ **Reach extension by Chirp Managed Laser (CML)**

  CML principles – optical duobinary effect, dispersion supported transmission, FM-AM conversion
- ❑ **Stability and reliability of DFB+R laser**
- ❑ **Conclusions**

Reduced damping factor by detuned-loading effect

Relaxation damping reduced on long wavelength flank of Bragg peak (if high DBR WGloss)

$$\boxed{\gamma_d = \frac{1}{\tau_d} + \frac{S}{\tau_p} \frac{d}{dN} \ln\left[g\Gamma_z \sqrt{K_z} \right]}$$



Detuned-loading is opposite to "gain compression"

Gain compression: $\text{Gain} = \dfrac{G}{1+\varepsilon S}$

$\varepsilon > 0$ Damping

Detuned-loading: $\varepsilon < 0$ Self-pulsation

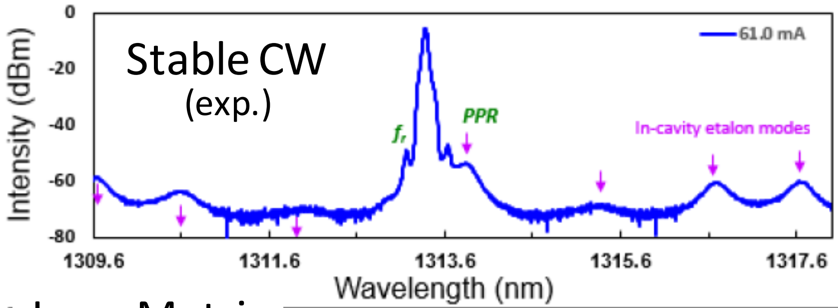
Negative damping factor means "self-pulsation"

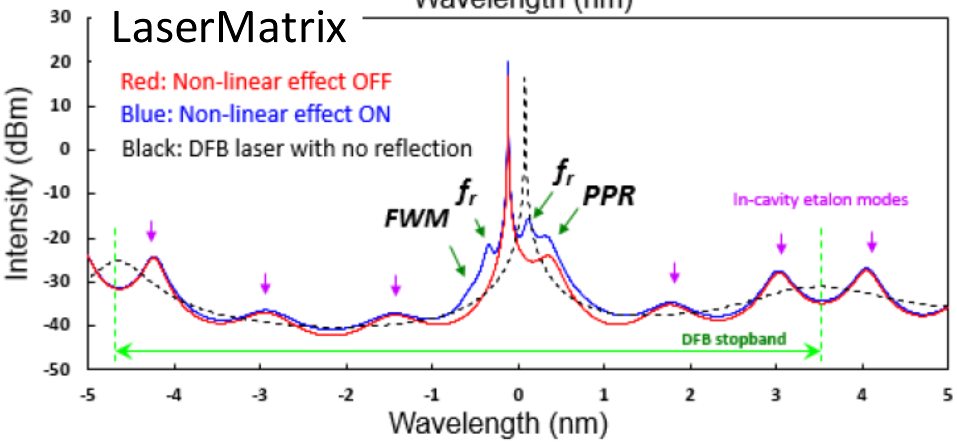
Similar to saturable absorber for mode locking

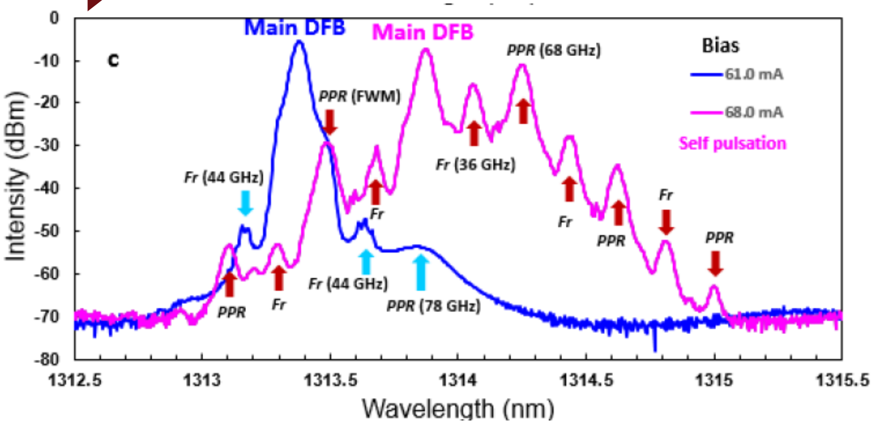
OFC 20180315
Richard Schatz
Royal Institute of Technology
rschatz@kth.se

Self-pulsation and 50-GHz Gain switching

Stable CW operation → Self-pulsation in CW







Alternating peaks for F_r and PPR induced by FWM.

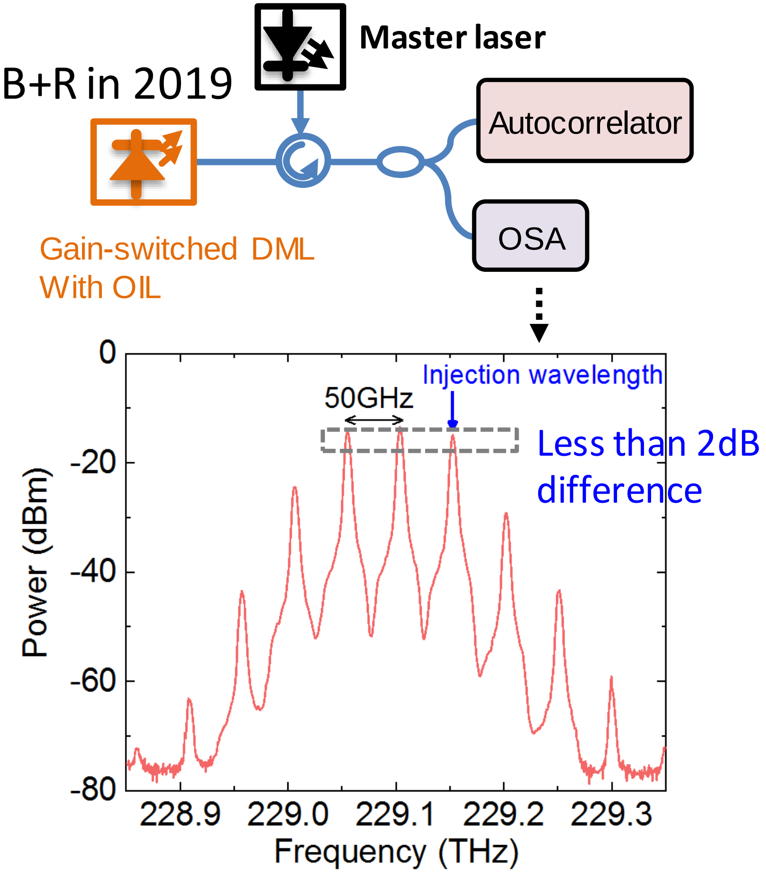
F_r peaks can be clearly seen at 44 GHz!

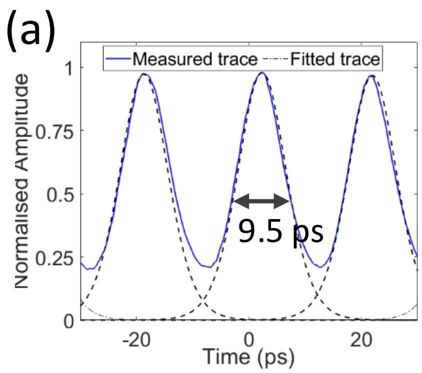
Y. Matsui et al., Nature Photonics 15 (1), 59-63, 2021, Supplementary information

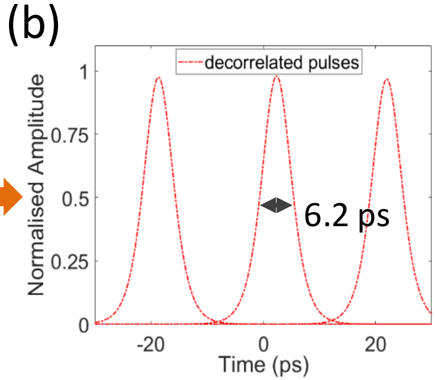
Gain-switching of DFB+R laser at 50 GHz with OIL

Possible new scheme: Self-pulsation and tunable repetition

DFB+R in 2019







Measured FWHM: 9.5 ps

Decorrelation (assuming Sech^2)

Decorrelated 6.2 ps

Time-bandwidth product: **0.81**

Assuming linear chirp,
pulse can be compressed to: **2.4 ps**

OIL further enhanced the relaxation, leading to **narrower pulse width**

Measured chirp parameter

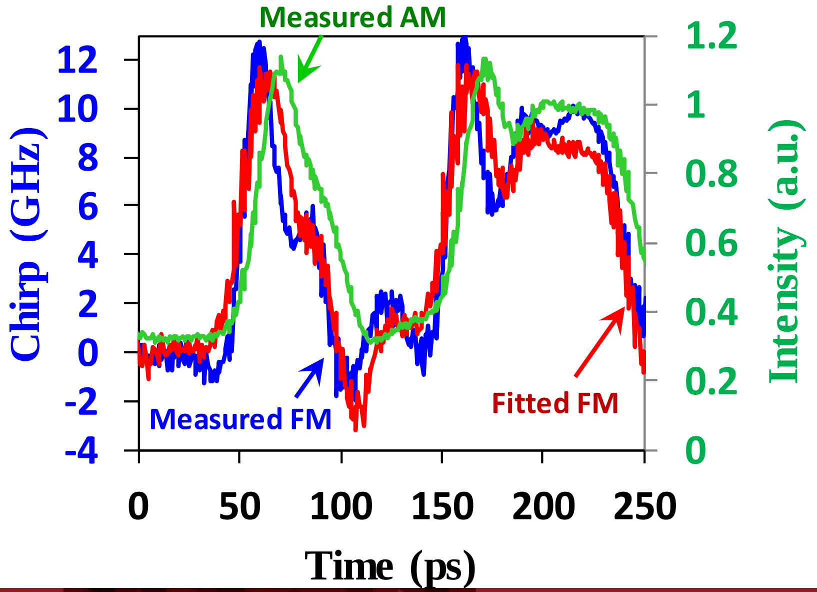
Conventional DFB:
α **= 3.5 (25GHz chirp)**

Fitting formula: $$\Delta\nu(t) = \frac{\alpha}{4\pi}\left(\frac{d}{dt}[\ln(P(t))] + \kappa P(t)\right)$$

FM **AM**

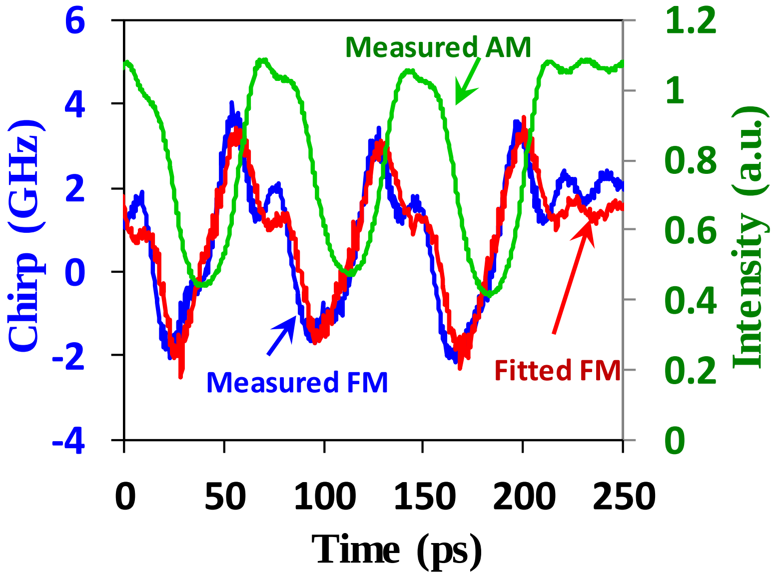
α = 1.0 (chirp ~ 9 GHz)

Two-κ DBR



α = 0.6 (chirp ~ 5 GHz)

DFB+R



Reflection tolerance - Expressions

DBR dispersion Slope x chirp

$$\alpha_{eff} = \alpha \frac{\tau_L + \boxed{\frac{d\phi_r}{d\omega}} - \boxed{\frac{1}{\alpha |r_m|}\frac{d|r_m|}{d\omega}}}{\tau_L - \boxed{\frac{d\phi_r}{d\omega}} + \boxed{\frac{\alpha}{|r_m|}\frac{d|r_m|}{d\omega}}}$$

Klaus Petermann, “Laser Diode Modulation and Noise,” Kluwer *Academic Publishers*, ISBN0-7923-1204-X (1988).

$$f_{ext,c} = \frac{\tau_L^2}{4(1-R)^2/R}\left(Kf_r^2 + \gamma_0\right)\boxed{\left[\frac{1+\alpha_{eff}^2}{\alpha_{eff}^4}\right]}$$

Jochen Helms *et. al.*, “A simple analytic expression for the stable operation range of laser diodes with optical feedback,” *IEEE J. Quantum Electron.*, **26**, 833-836 (1990).

Slope x chirp

$$\alpha_e = \frac{\frac{d}{dN}\mathrm{Re}(\Omega)}{\frac{d}{dN}\mathrm{Im}(\Omega)} = \frac{\mathrm{Im}\left[\boxed{\tilde{\Gamma}_z}\left(1+\boxed{i\alpha}\right)\right]}{\mathrm{Re}\left[\boxed{\tilde{\Gamma}_z}\left(1+\boxed{i\alpha}\right)\right]}$$

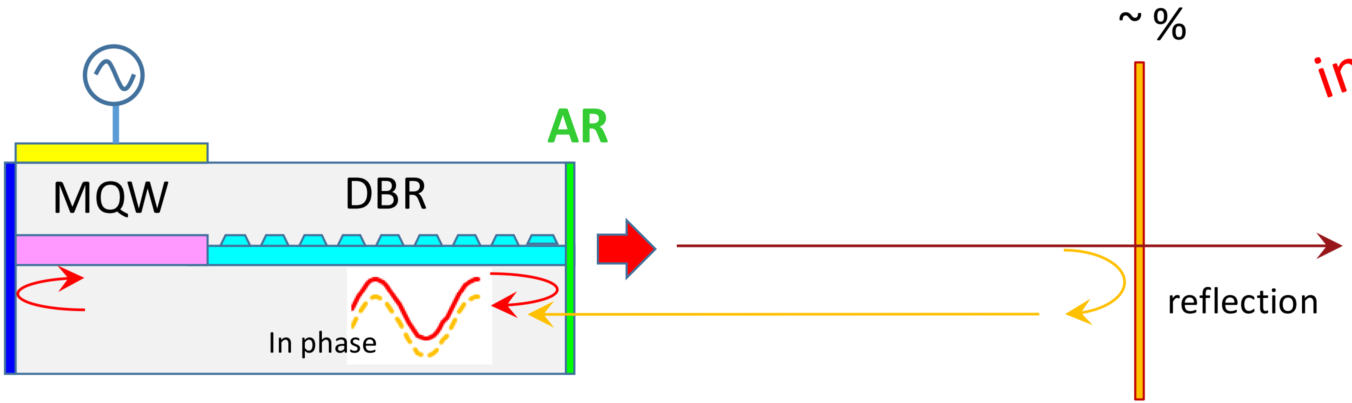
Marek Chacinski *et. al.*, “Impact of Losses in the Bragg Section on the Dynamics of Detuned Loaded DBR Lasers,” *IEEE J. Quantum Electron.* **46**, 1360–1367 (2010).

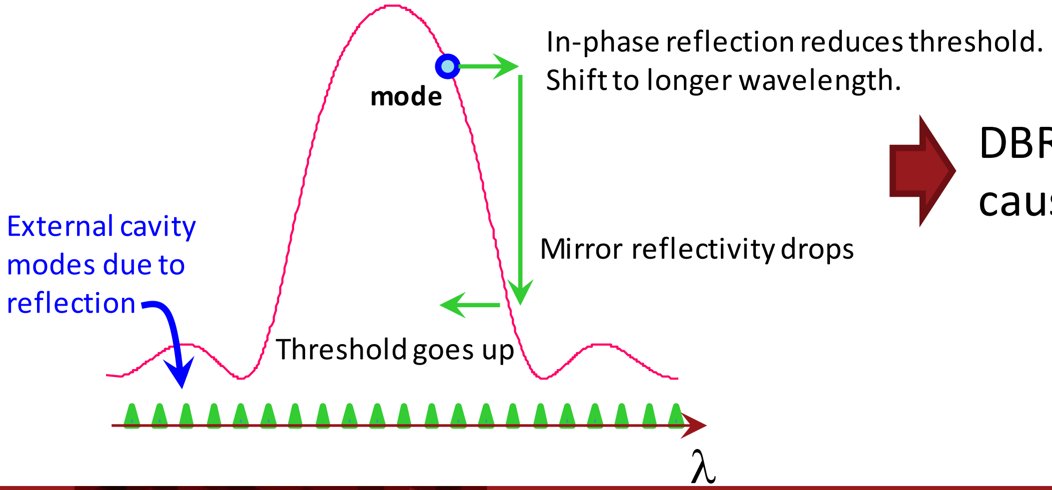
$$f_{ext} < \left[\boxed{\frac{\sqrt{1+\alpha_e^2}}{\alpha_e^2}}\frac{\gamma S}{2\sqrt{K_z P_{out}}}\right]^2$$

O. Nilsson and J. Buus, "Linewidth and feedback sensitivity of semiconductor diode lasers," *IEEE J. Quantum Electron.*, **26**, 2039-2042 (1990).

Theory for isolator-free operation

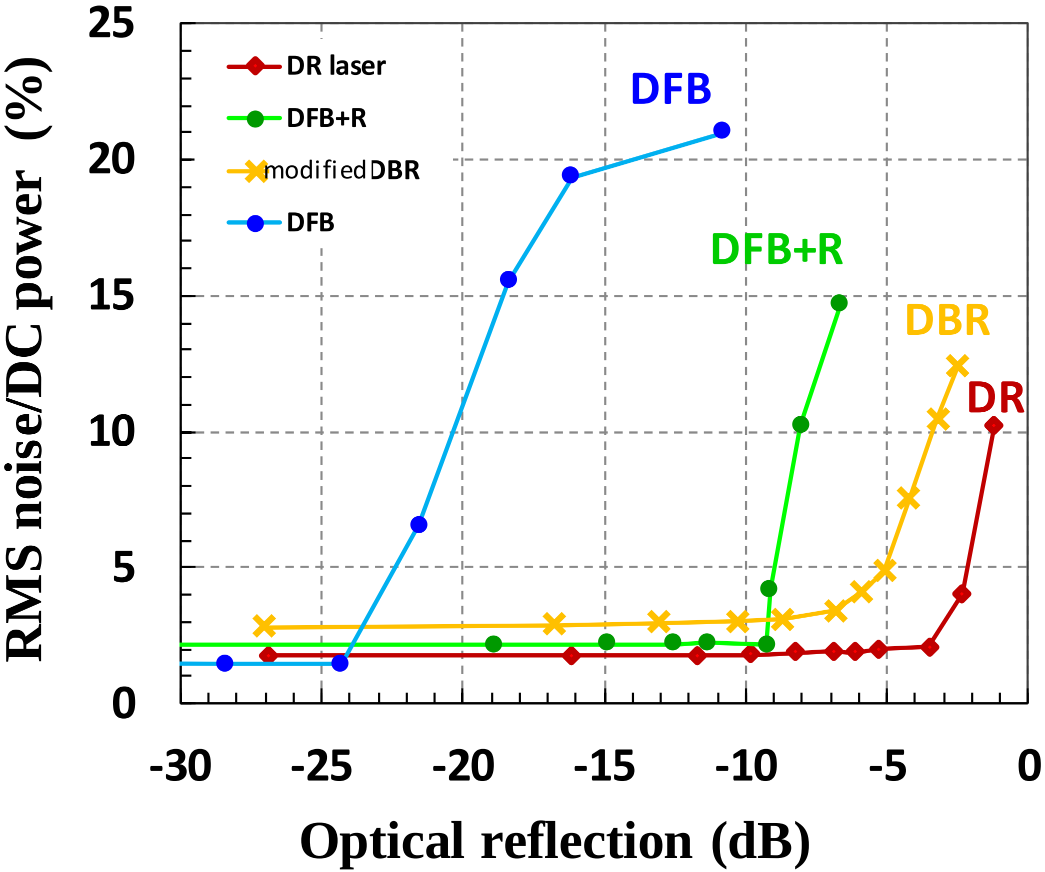
intuitive version



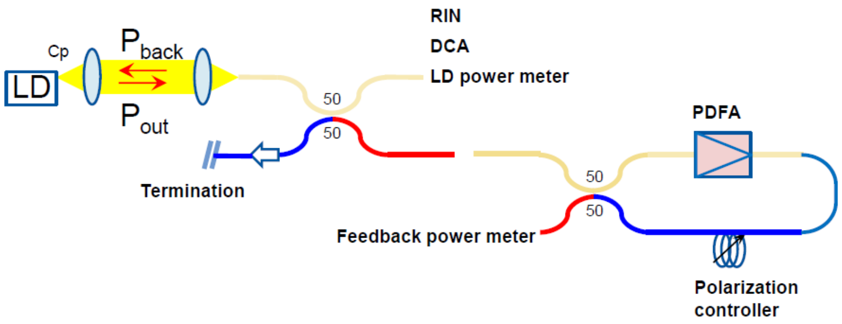


DBR mirror counteracts to the perturbation caused by external reflection.

Reflection tolerance



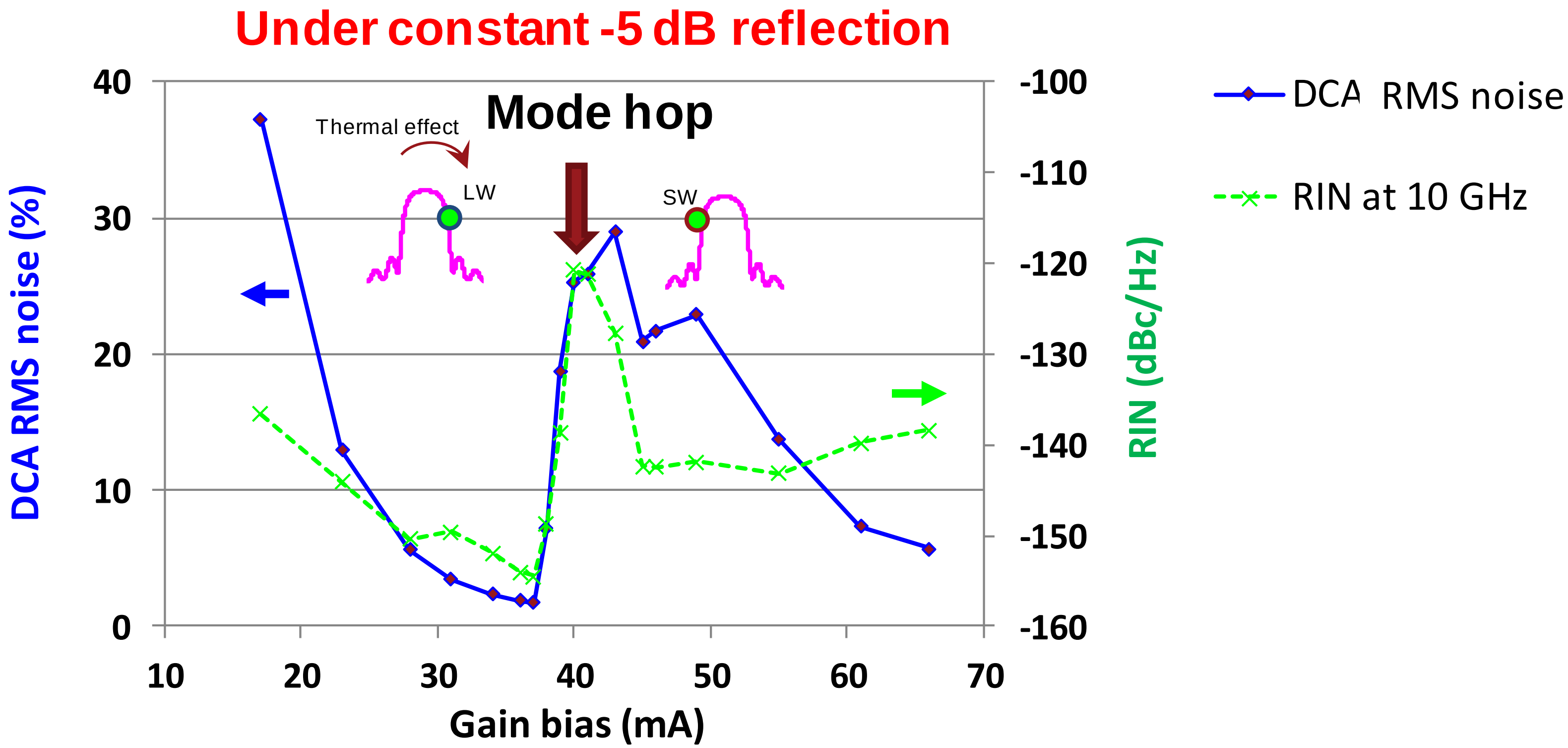
Setup (fiber loop mirror with fiber amplifier)



- Loop mirror with PDFA inside
- Coupling loss is excluded. If coupling loss is 2 dB, there is 4 dB additional tolerance.

➢ 40% reflection tolerance for DR laser!

DR laser Reflection tolerance before/after mode hop



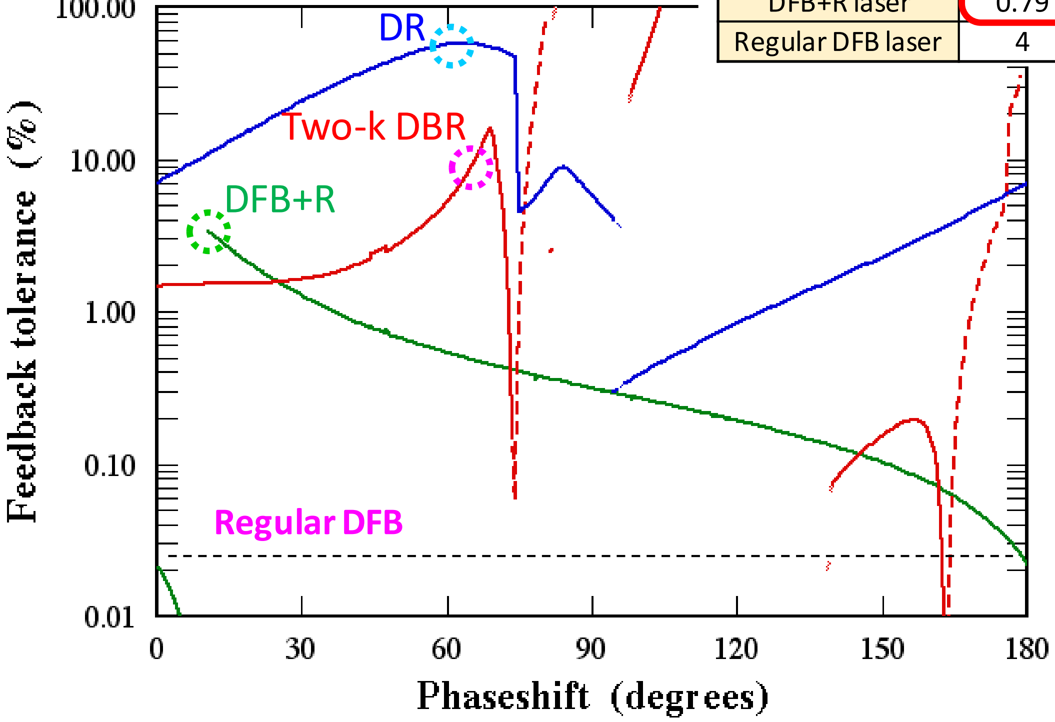
Reason for superior reflection tolerance of DR laser

Reflection tolerance:

$$f_{ext} < \left[\frac{\sqrt{1+\alpha_e^2}}{\alpha_e^2} \frac{\gamma S}{2\sqrt{K_z P_{out}}} \right]^2$$

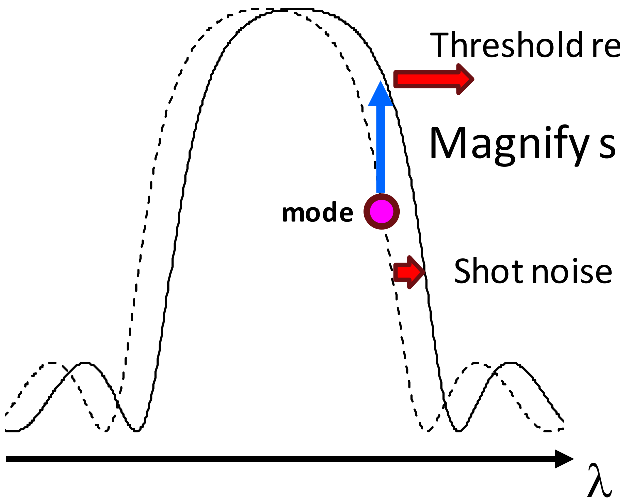
(by LaserMatrix)

	alpha	Kz	Damping, 1/ns	S/Pout	Relative improvement, dB
DR laser	0.5	6.5	193	32.58	-32
Two-κ DBR laser	0.83	5	97	33.75	-20
DFB+R laser	0.79	10.7	160	21.92	-18
Regular DFB laser	4	1.48	65	20.56	**0**

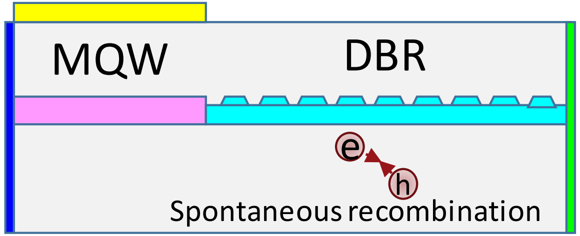


- DR laser excels in all four parameters.
- DFB+R is not as tolerant because of high output coupling.

Detuned-loading magnifies noise in passive DBR



Shot noise in DBR

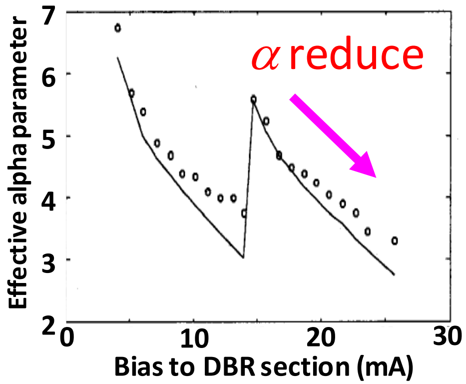


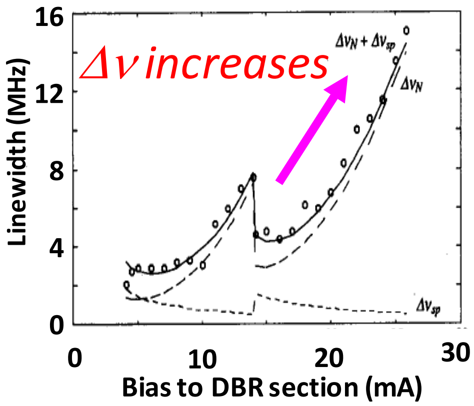
Detuned loading can reduce the alpha parameter

But, the linewidth broadens if the noise source is in the passive DBR section

Thermally tunable DBR laser (DBR shorted) is useful

IEEE Photonics Technology Letters, 1992
J.-M. Verdiel, U. Koren, T.L. Koch





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- **Conclusions**

Isolator-free operation in QD lasers

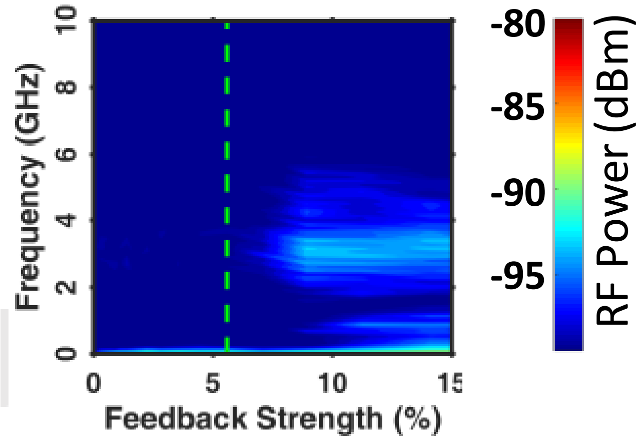
H. Huang et al., JOSA B, 2018

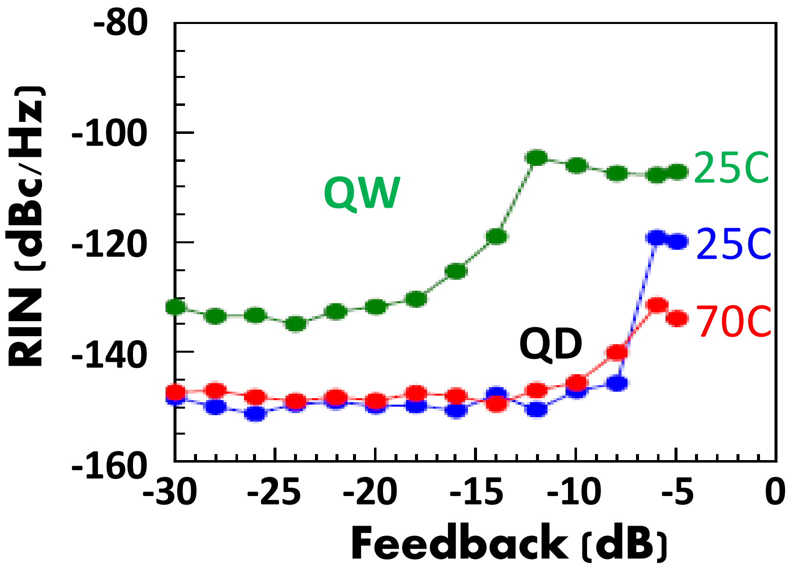
M. Matsuda et al., International Semiconductor Laser Conference (ISLC), 2018

Small alpha parameter

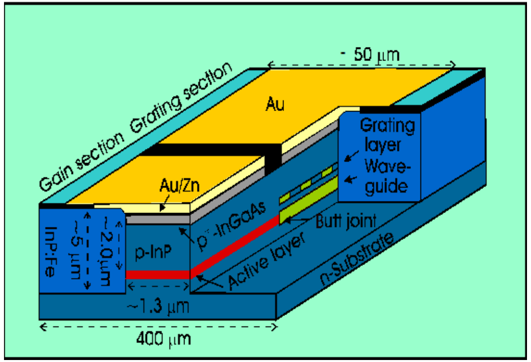
α ~ 0.5

High reflection tolerance (~ 5%)

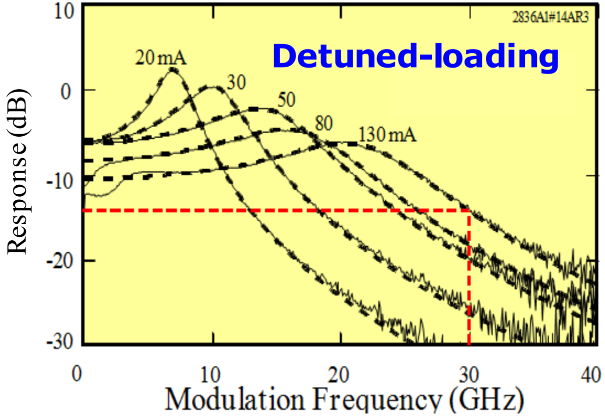




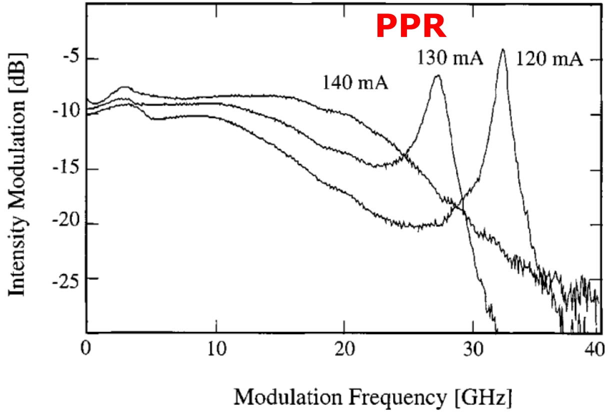
30 GHz/40Gbps DBR laser @ 1.55 µm using detuned loaded DBR lasers

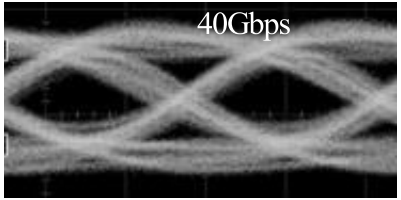


Gain: 100-200um
DBR: 300um



Gain: 120um
DBR: 700um





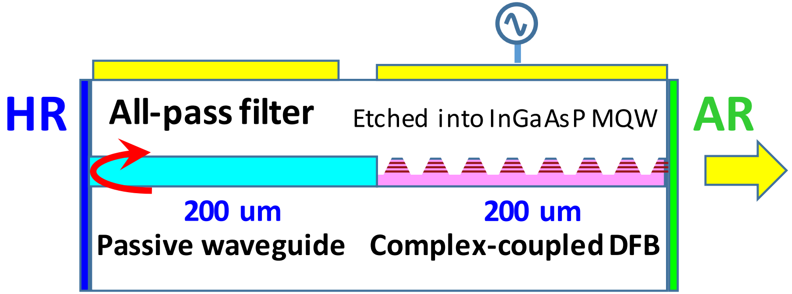
- Detuned loaded DBR lasers can be used to enhance the bandwidth (middle)
- Early observation of high-frequency PPR at 31 GHz (right)

O. Kjebon, R. Schatz, S. Lourdudoss *et al. Electronics Letters*, 33, (6), 1997 (middle)
G. Morthier, R. Schatz, O. Kjebon, *J. Quantum Electronics, 36, (12), 2000 (right)*

OFC 20180315
Richard Schatz
Royal Institute of Technology
rschatz@kth.se

Passive Feedback Laser (PFL)

Fraunhofer HHI



2005 M. Radziunas (simulations)

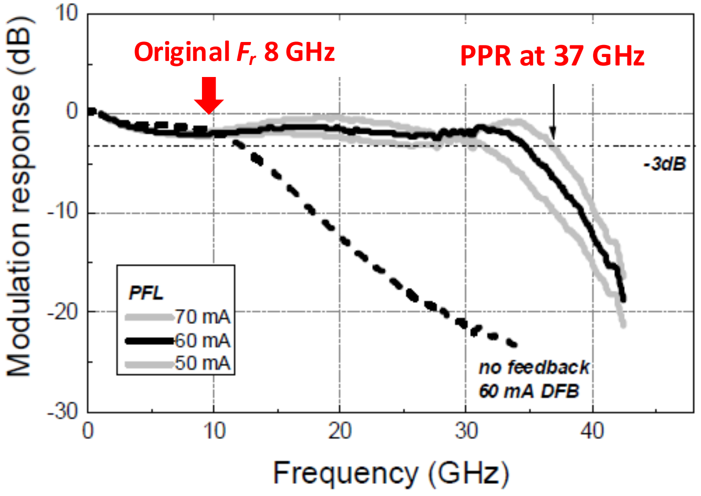
2006 U. Troppenz (1.55um, 30GHz)

2007 M. Radziunas (1.55 um, 30 GHz)

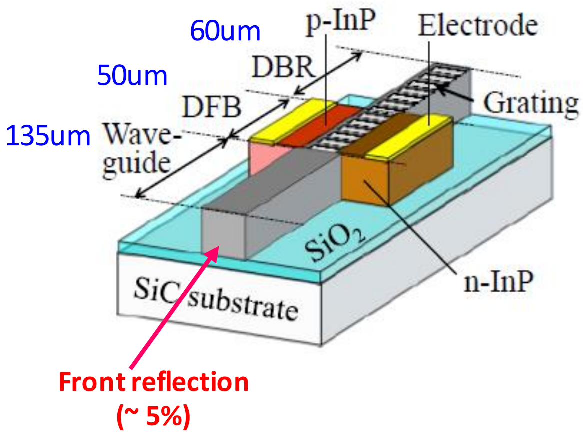
2011 J. Kreissl (1.55 um, 35 GHz)

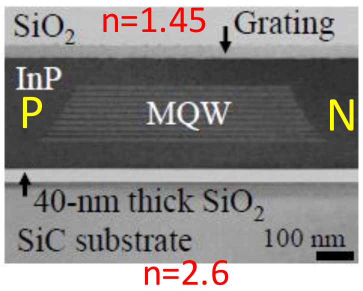
2011 U. Troppenz (1.3um, 37 GHz)

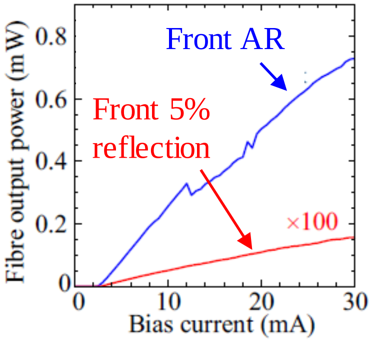
- HR coating on passive waveguide. This acts as "all-pass filter" and diminishes detuned-loading effect.
- DFB grating etched into InGaAsP MQW to stabilize the mode.
- Strong grating and long DFB length can diminish detuned-loading effect.
- PPR extended the BW to 37 GHz
- Detuned-loading was not discussed.
- Reduction of alpha parameter was experimentally observed, suggesting that detuned-loading existed.



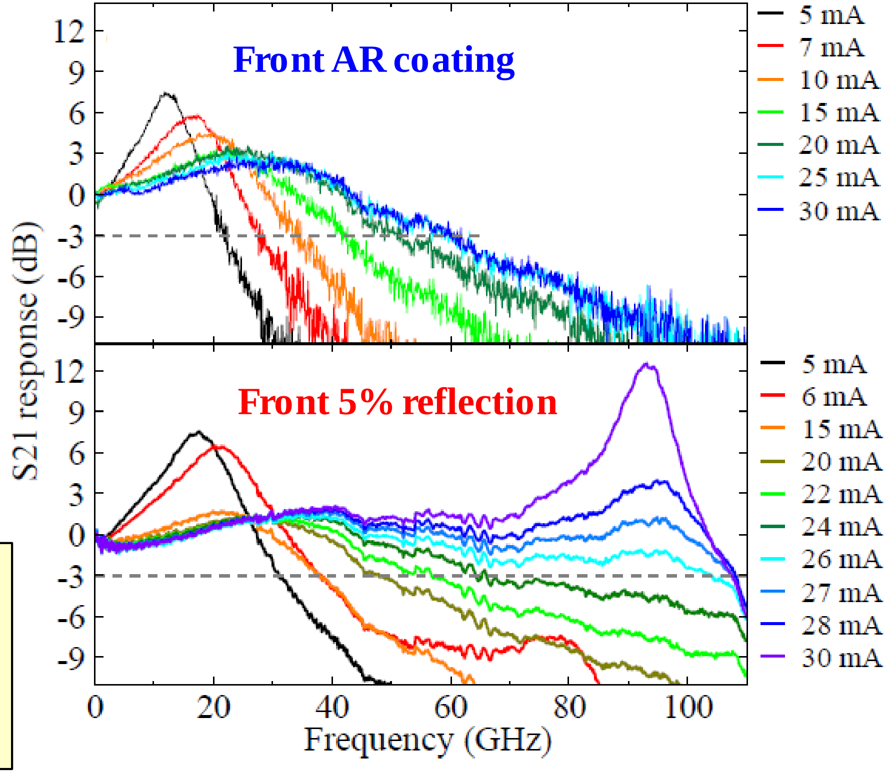
108-GHz BW membrane DML







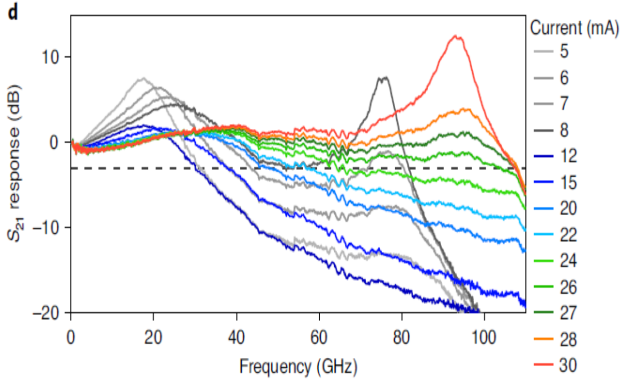
S. Yamaoka et al., ECOC 2019 PDP



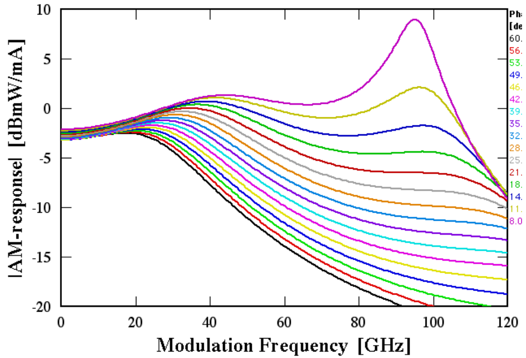
- Thin SiO2 layer (40nm) improved thermal dissipation.
- Strong optical confinement (SiC/MQW/SiO_2) improved F_r to 40 GHz
- PPR effect extended the BW to 108 GHz.
- 50um DFB design is x1.8 faster than 140um DFB design

Simulation analysis of NTT membrane DR laser

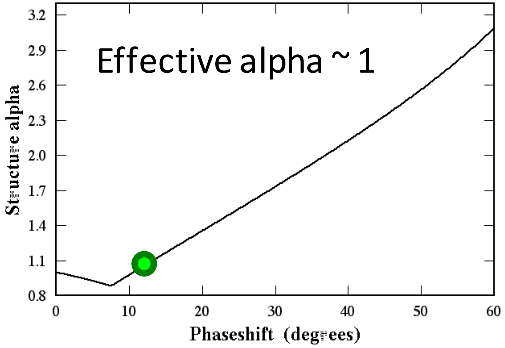
NTT data



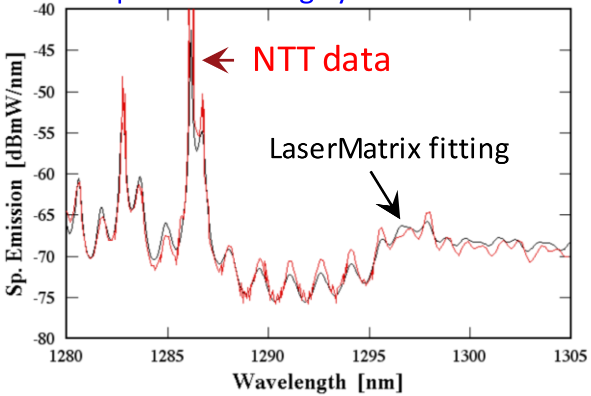
LaserMatrix simulation



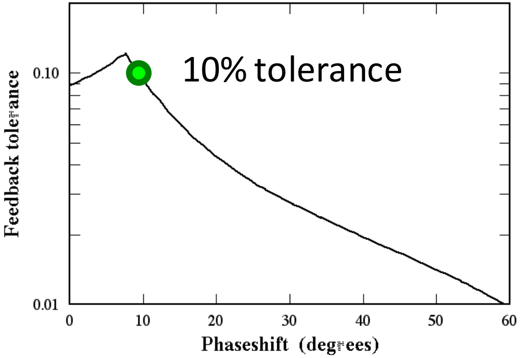
Alpha parameter



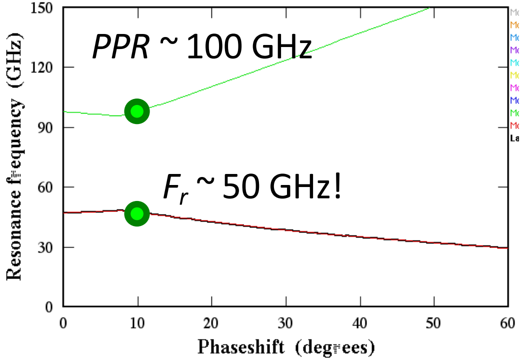
Spectrum fitting by LaserMatrix



Reflection tolerance



F_r and PPR frequency

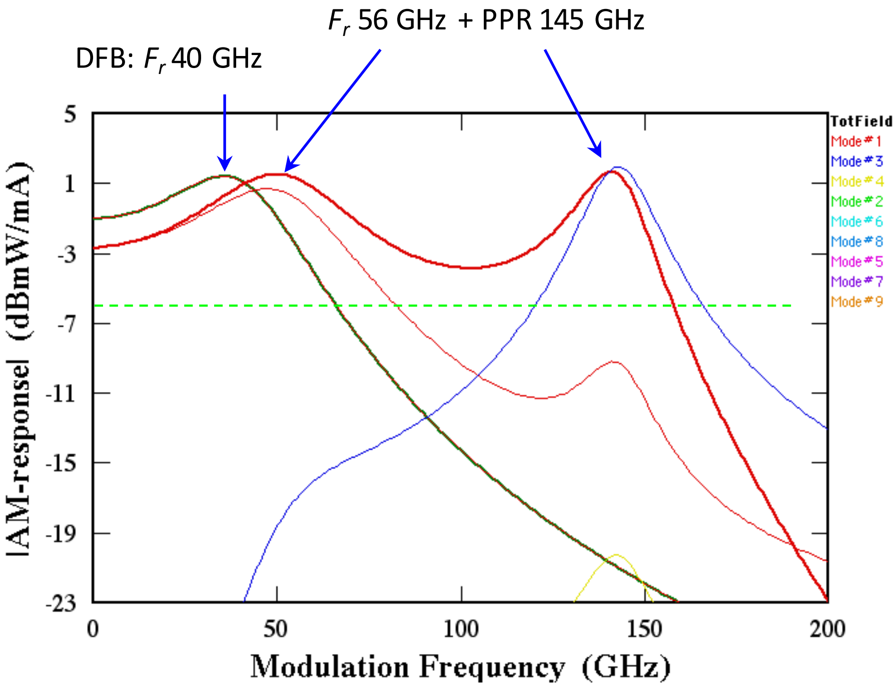


(presented with permission by Dr. Matsuo, NTT)

150 GHz BW DML by using all the BW enhancement effects

Assumptions:

- 40GHz Fr achieved for DFB laser by strong optical confinement by membrane structure
- Detuned-loading maximized by cavity optimization
- PPR frequency set at 150 GHz by cavity optimization



List of topics

- **3.2 Tb DML system prospect**

- **DML performance enhancement effects**
  - Detuned-loading effect
  - In-cavity FM-AM conversion for high-pass filter effect
  - Photon-photon resonance (PPR) effect

- **Three 70-GHz BW DML designs and comparison**
  - Short-cavity split-contact DR laser for tunable PPR frequency
  - Short-cavity two-kappa DBR laser and uniform modulation with SOA
  - DFB+R laser
  - LaserMatrix design simulator live demo

- **Experimental results and paper review**
  - Self-pulsation and pulse generation
  - Chirp reduction
  - Isolator-free operation
  - 400Gb/lane transmission by Sub-carrier multiplexing (SCM)

- **Reach extension by Chirp Managed Laser (CML)**

  CML principles – optical duobinary effect, dispersion supported transmission, FM-AM conversion

- **Stability and reliability of DFB+R laser**

- **Conclusions**

Adiabatic and transient chirp for DML

α parameter

$$\Delta\nu_{(t)} = \frac{\alpha}{4\pi}\left(\frac{d}{dt}\left[\ln\left(P_{(t)}\right)\right] + \kappa P_{(t)}\right)$$

Transient chirp — Adiabatic chirp

No adiabatic chirp for external modulators!

Transient chirp

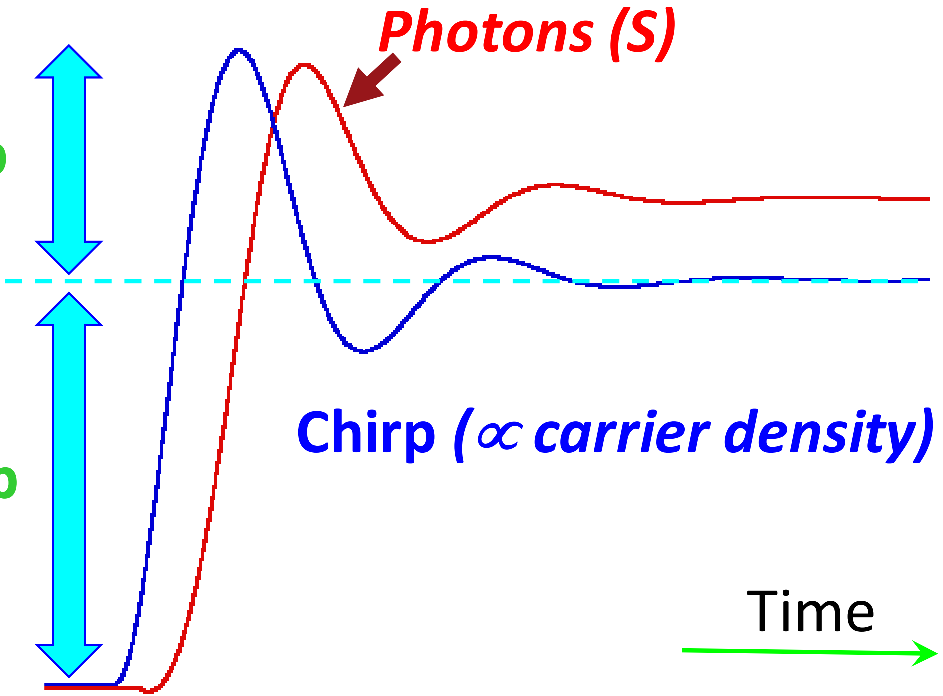
Time-derivative of # of Photons

$$\propto \frac{d}{dt}\left[\ln\left(P_{(t)}\right)\right]$$

Adiabatic chirp

Proportional to # of Photons

$$\propto \varepsilon P_{(t)}$$



Large gain compression factor increases damping and suppress transient chirp.

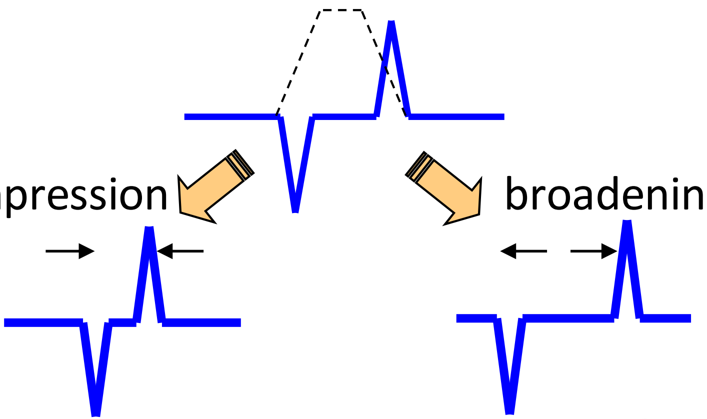
Benefit of adiabatic chirp

Transient chirp

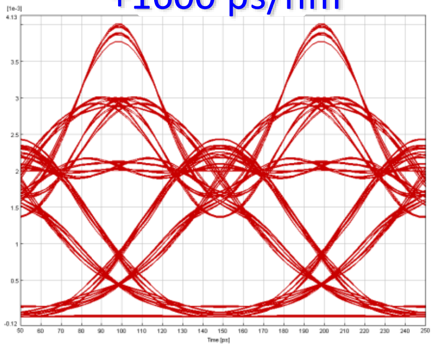
0 1 0

compression

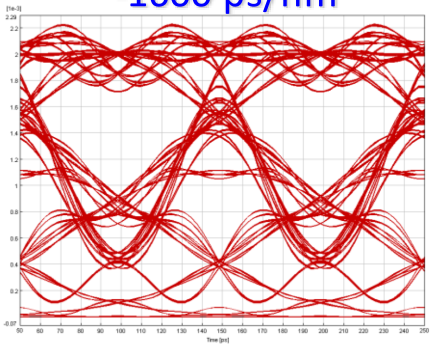
broadening



+1600 ps/nm



-1600 ps/nm

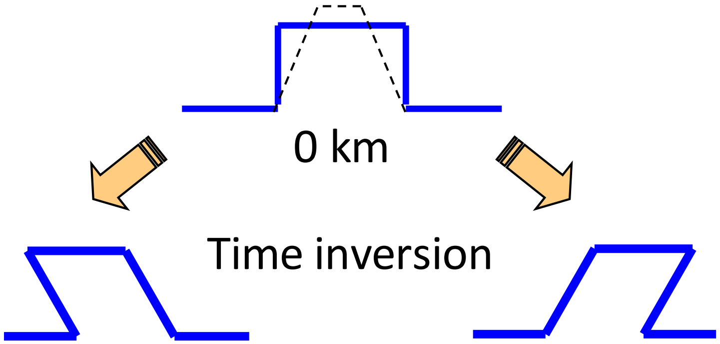


Adiabatic chirp

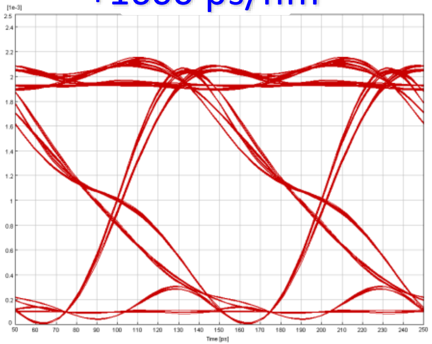
0 1 0

0 km

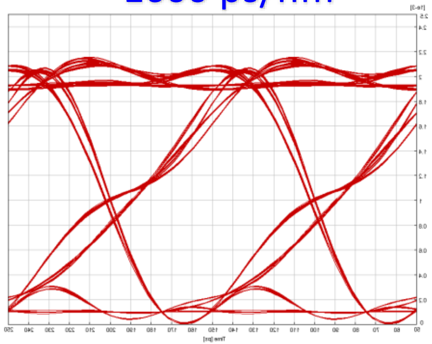
Time inversion



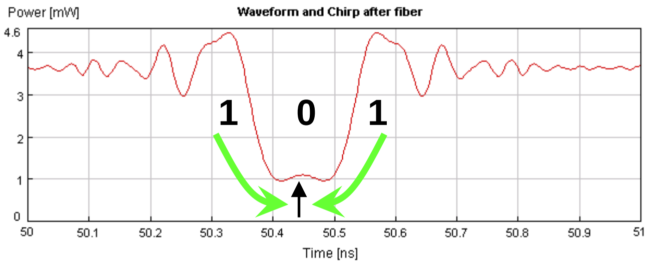
+1600 ps/nm



-1600 ps/nm

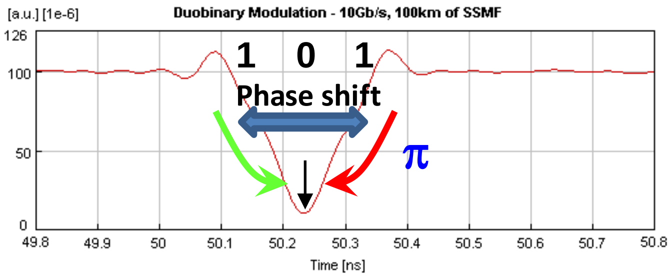


Similarity between ODB and CML



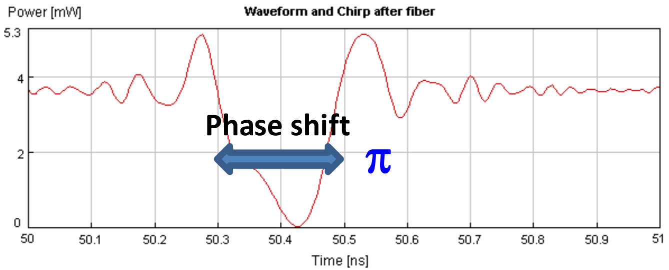
Un-chirped NRZ

0 bits are filled after fiber transmission



Duo binary

Destructive interference (π phase shift) open the eye in the middle of 0 bit.

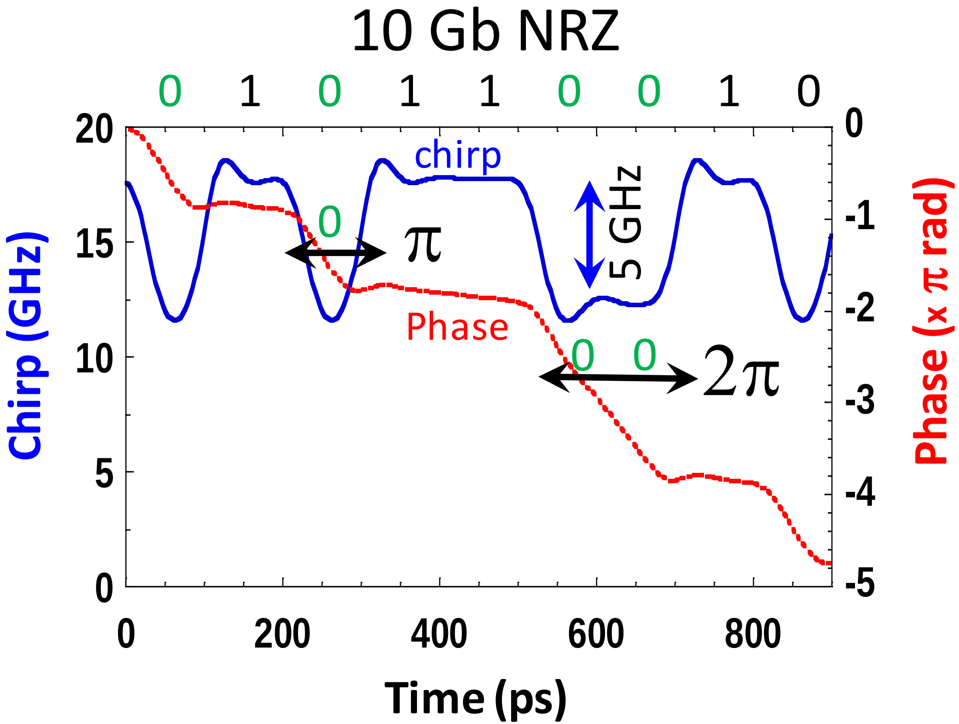


Chirp-Managed Laser (CML)

π phase shift between the bits is achieved.

$$2\pi \times \underbrace{5GHz}_{\text{Adiabatic chirp}} \times \underbrace{100\,ps}_{\text{Bit period}} = \pi$$

ODB effect – π phase shift between the bits



Bit period

Chirp

$$\Delta\phi = 2\pi \int_0^T \Delta f(t)\, dt$$

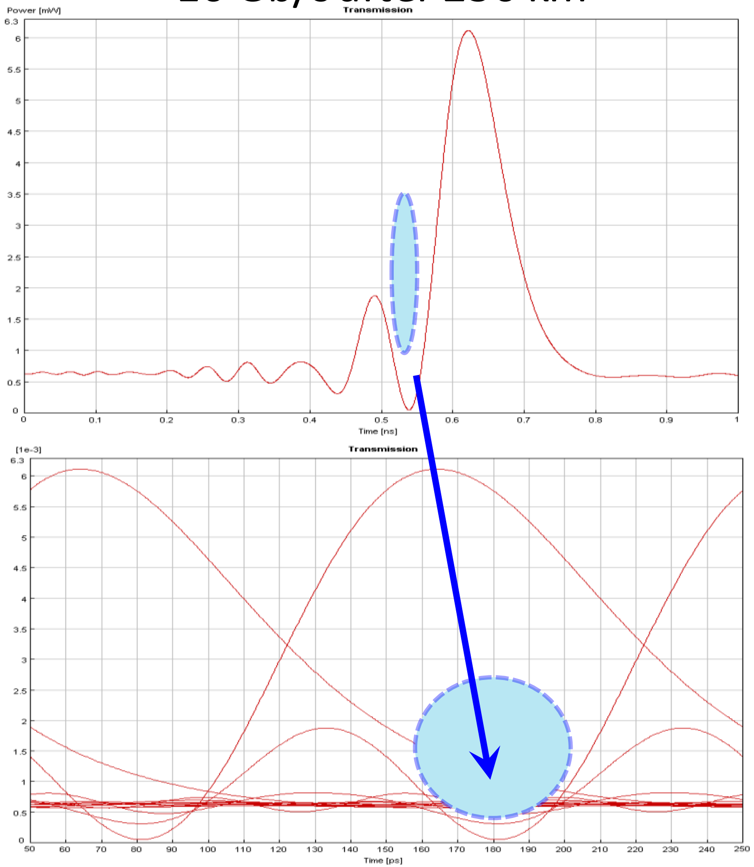
Phase shift

$$\pi = 2\pi \cdot 5GHz \cdot 100\,ps$$

Half bit rate

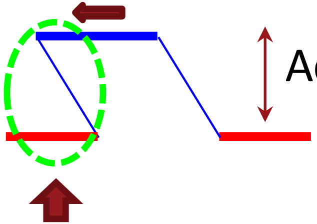
Dispersion Supported Transmission (DST)

10 Gb/s after 250 km



Blue travels faster

$$Shift, ps = Dispersion \cdot Length \cdot Chirp$$



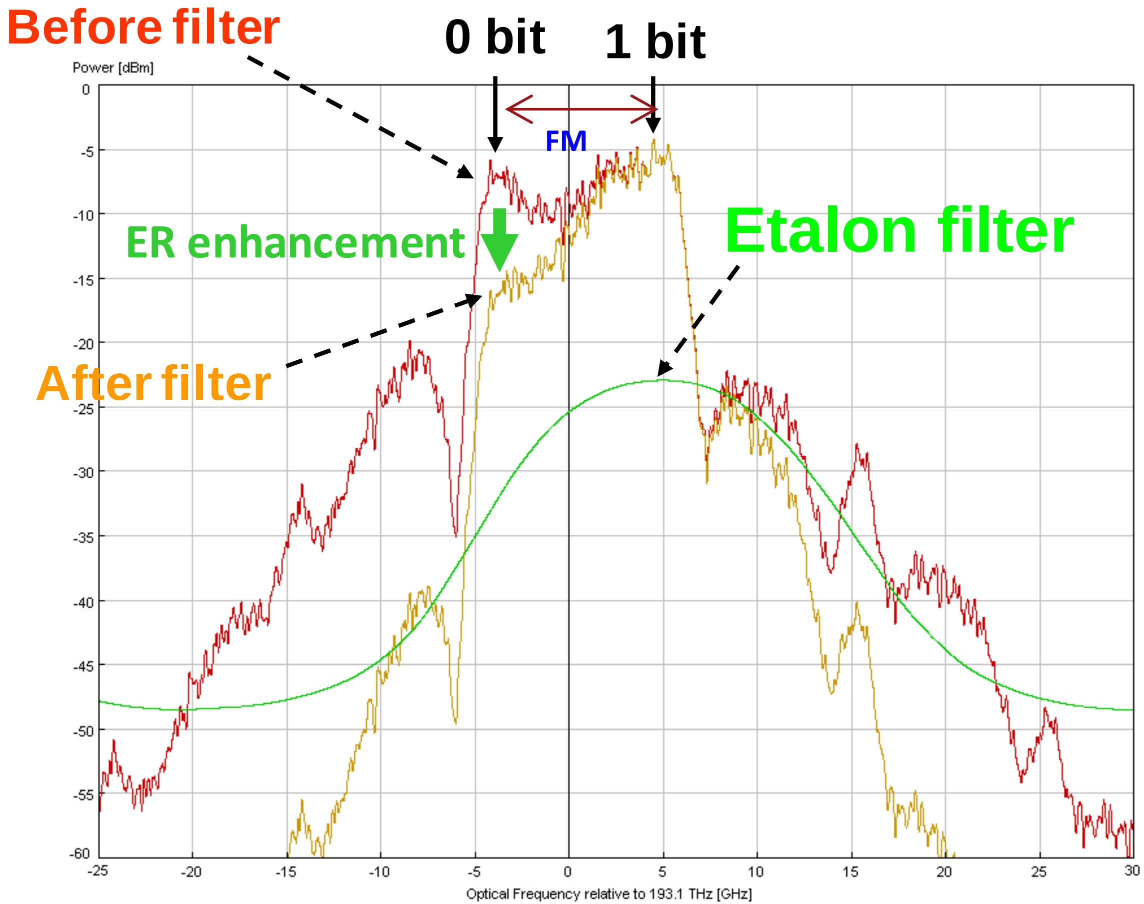
Interference fringe pattern in leading edge

This fringe pattern opens the eye as long as:

$$Shift, ps \quad < \quad Bit\ Period$$

(DST condition)

Edge of filter - ER enhancement and SSB generation



Transient chirp blocked

Adiabatic chirp passes through

Single-side band spectrum

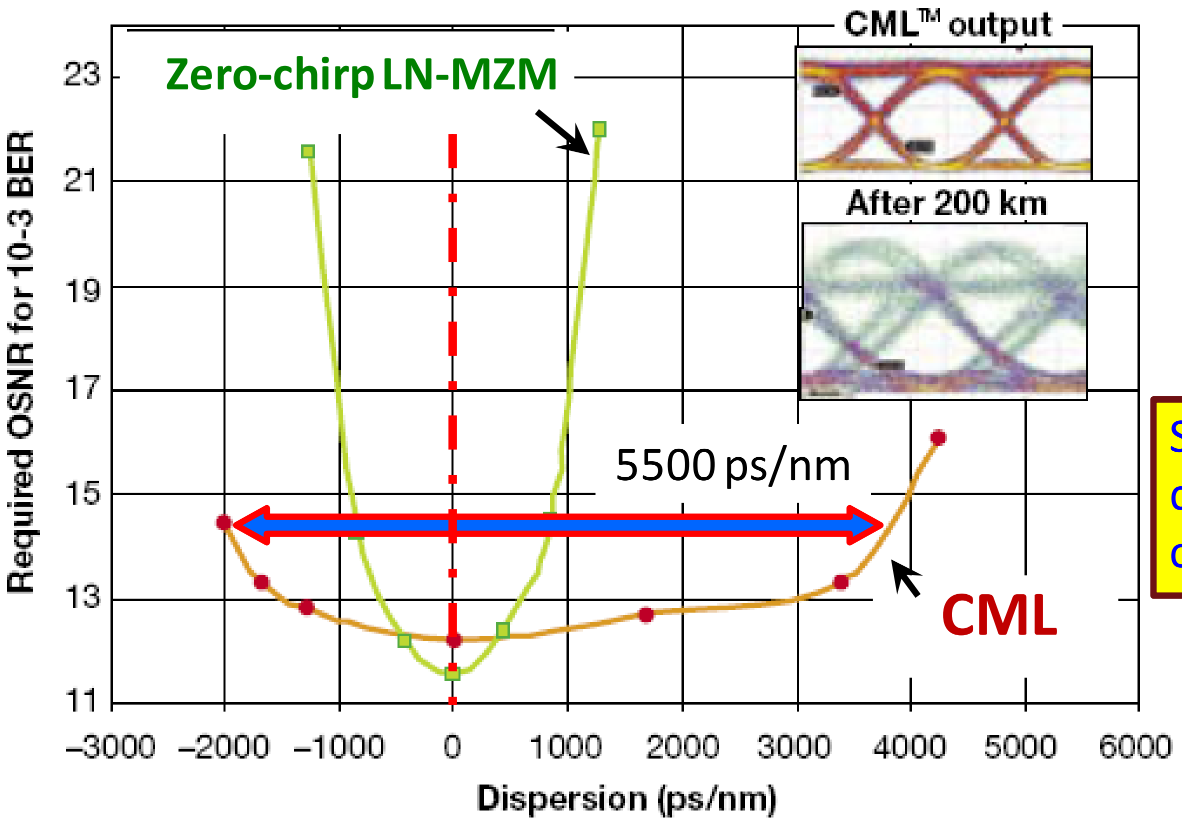
Reach extension

Blocks 0 bits, Passes 1 bits

ER enhancement

CML vs zero-chirp MZM dispersion tolerance

10Gb NRZ in C-band



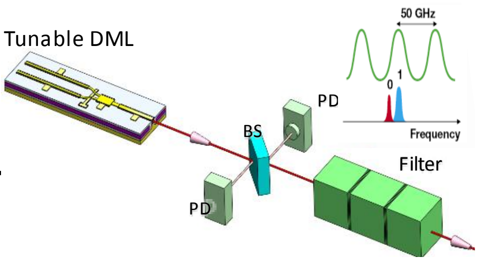
Stronger in positive dispersion due to AWG filter dispersion compensation effect.

How to extend the reach of DML

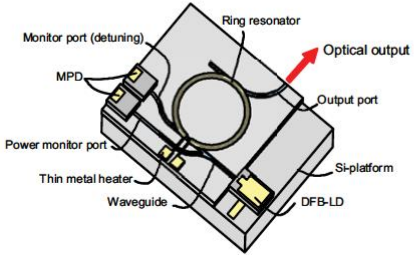
DML + optical filter = CML

Benefit of adiabatic chirp

- Optical duo-binary (ODB) effect
- Dispersion supported transmission (DST) effec
- Vestigial sideband effect (VSB)
- Symmetric wide dispersion window



Y. Matsui, PTL 2006

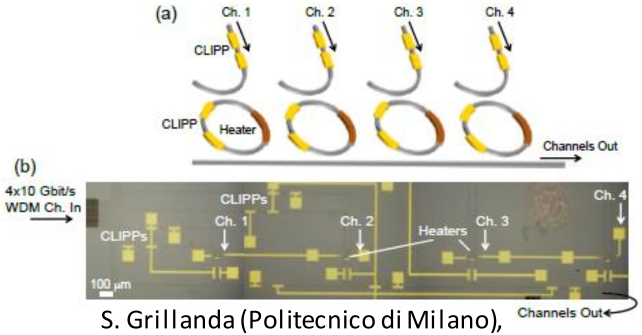


Y. Yokoyama (NEC), ECOC 2010

Benefit of Chirp Managed Laser (CML)

- Remove transient chirp
- Single-sideband (SSB) generation
- Improve extinction ratio (FM-AM conversion)
- Abrupt phase shift for ODB (AM-FM conversion)

λ-MUX by ring filters



S. Grillanda (Politecnico di Milano), JLT 2017 (used with permission)

(black: C band)

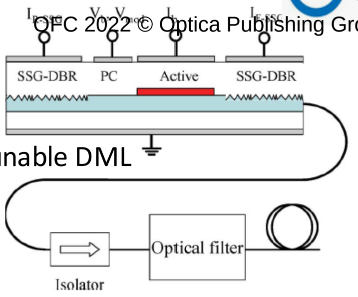
List of CML works

M3D.1.pdf

2004, Y. Matsui and D. Mahgerefteh co-invented CML at AZNA
2005, S. Chandrasekhar (Nokia-Bell Labs), 10Gb 675km with EDC
2005, S. Chandrasekhar (Nokia-Bell Labs), 10Gb 285km
2005, D. Mahgerefteh (AZNA), 10Gb 250km
2006, Y. Matsui (AZNA), 10Gb CML principle
2008, S. Matsuo (NTT), 25Gx4 array of <u>in-cavity phase mod (FM laser)</u>
2009, J. Yu (NEC America), 40Gb 20km CML
2009, S. Matsuo (NTT), 40Gb 30km CML by in-cavity phase mod
2010, Y. Matsui (Finisar), 10Gb 40nm Tunable CML
2010, Y, Yokoyama (NEC), 10Gb DFB+Si PLC hybrid integration
2014, A.S. Karar (Queens Univ/Finisar), <u>56Gb CML using 20GHz BW DML</u>
2022, Son Thai Le (Nokia-Bell Labs), 32km@1330nm or 28km@1270nm 100Gb PAM4

NTT

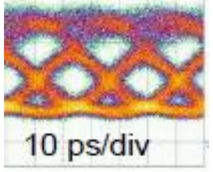
OFC 2022 © Optica Publishing Group 2022



20Gb Tunable DML

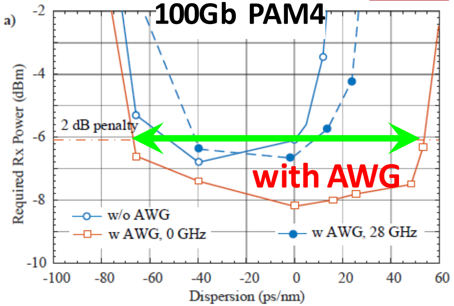
Intra-cavity phase modulation to generate FM and then convert into AM on the edge of filter.

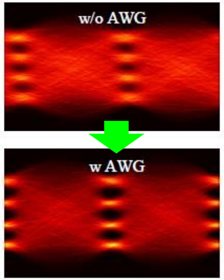
40Gb
20 km
x 6 of chirp-free MZM



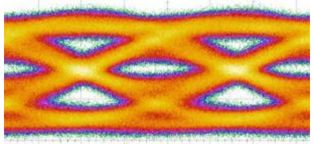
NOKIA Bell Labs   II-VI

100Gb PAM4



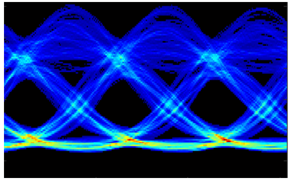


Queen's UNIVERSITY   II-VI



20GHz BW short-cavity DBR

After filter



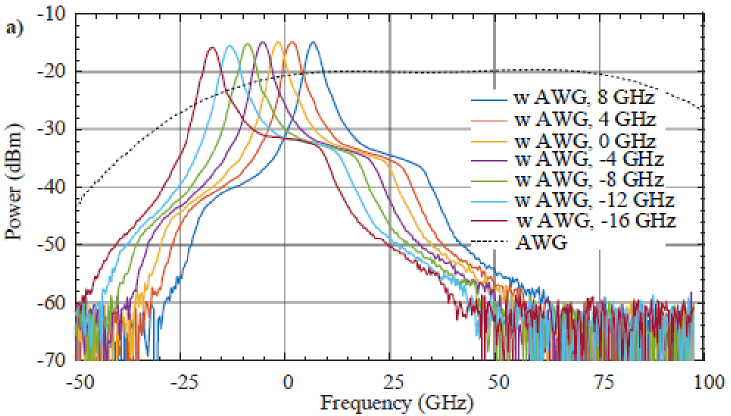
56Gb CML

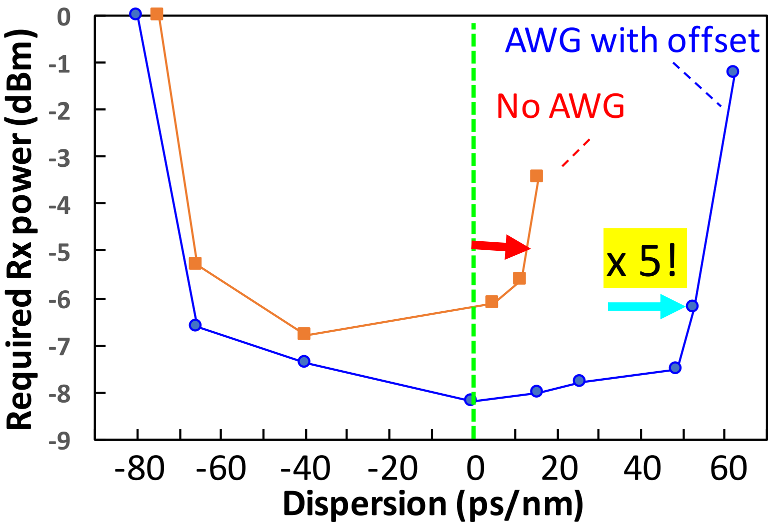
Reach extension of 100Gb/lane PAM4 by optical filtering

- Regular DFB laser was used
- 32km transmission at 1330nm
- 28km transmission at 1270nm
- Temperature 45C.
- AWG filter for λ-mux is used with an offset to extend the reach

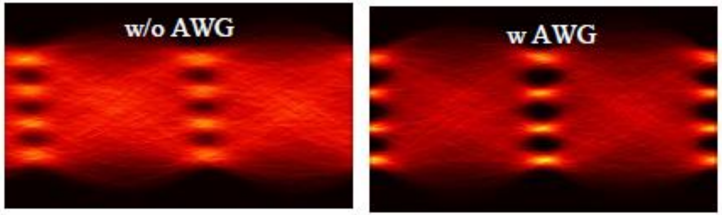
OFC 2022, Son Thai Le

AWG filter offset and spectrum





at 34 ps/nm dispersion



VPIphotonics Software Solutions

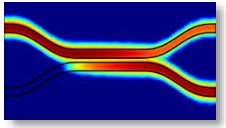
for Photonic Design & Analysis

Device Simulation

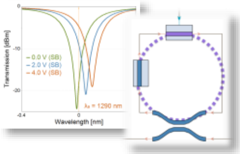
Component Design

Transmission Design

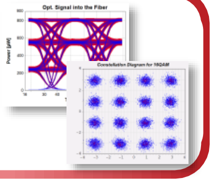
VPIdeviceDesigner



VPIcomponentMaker Photonic Circuits



VPItransmissionMaker Optical Systems



VPIphotonics Design Suite

VPIcomponentMaker Photonic Circuits:

- Extended library of fast and accurate analytical models for passive photonic devices (waveguides, ring-based devices, MMIs, Bragg gratings, AWGs).
- An advanced Photonics TLM model for designing of optoelectronic and active photonic devices (lasers, SOAs, modulators, photodetectors).
- Seamless integration with **VPItransmissionMaker Optical Systems** for investigating photonic integrated circuit impact in optical fiber systems.
- Cosimulation with 3rd party software tools for creating custom components, automatic chip layout generation and electronic-photonic co-design.

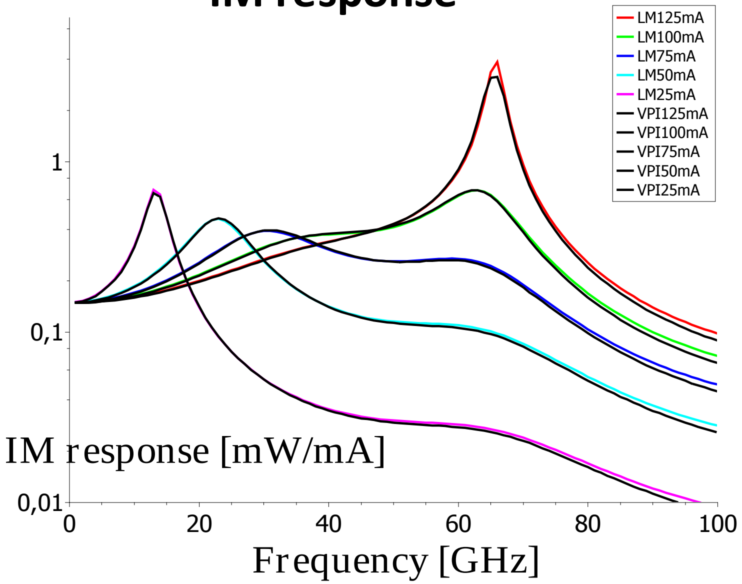
Interfaces with 3rd Party Tools and PDKs

KEYSIGHT TECHNOLOGIES, MATLAB, SMART PHOTONICS, HHI PDK, SYNOPSYS, python, LioniX INTERNATIONAL, Nazca design, LUCEDA PHOTONICS, LIGENTEC, SIEMENS, Infinera

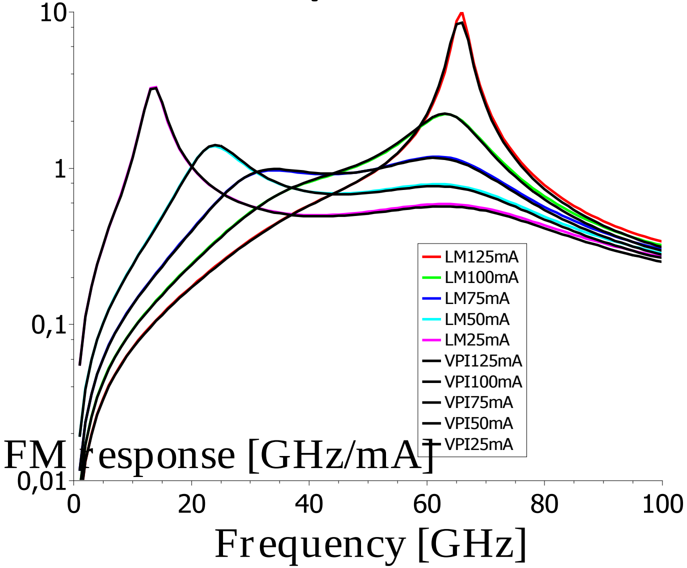
LaserMatrix and VPIcomponentMaker comparison

Dashed: VPIphotonics
Solid: LaserMatrix

IM response



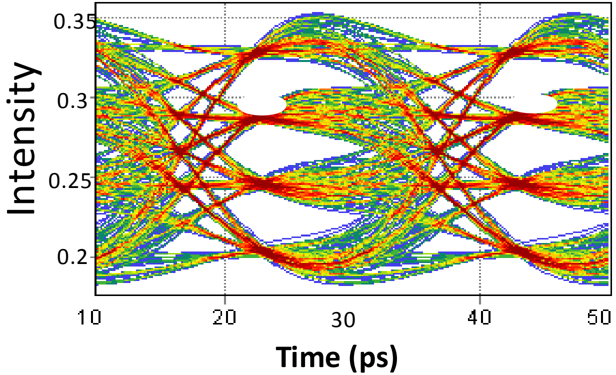
FM response

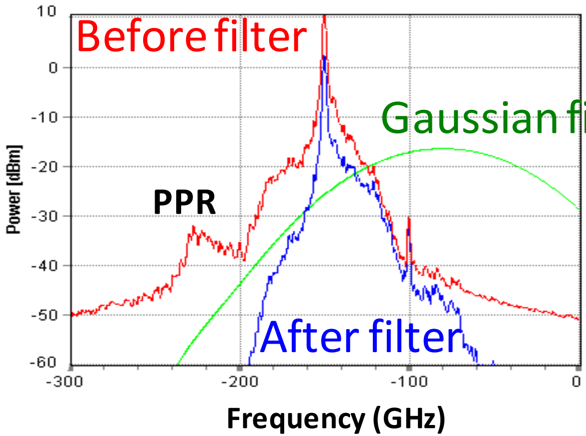


Confirmed by Richard Schatz, KTH

100Gb PAM4 transmission at 1330 nm

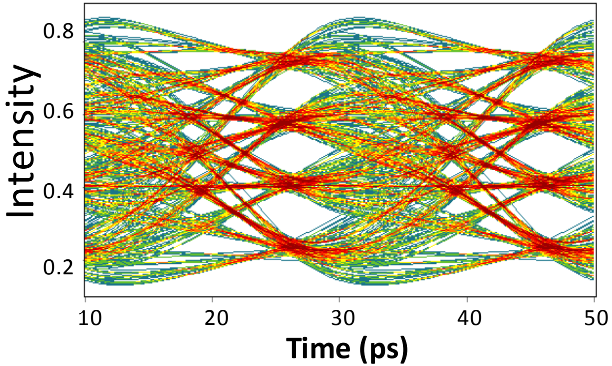
Back-to-back

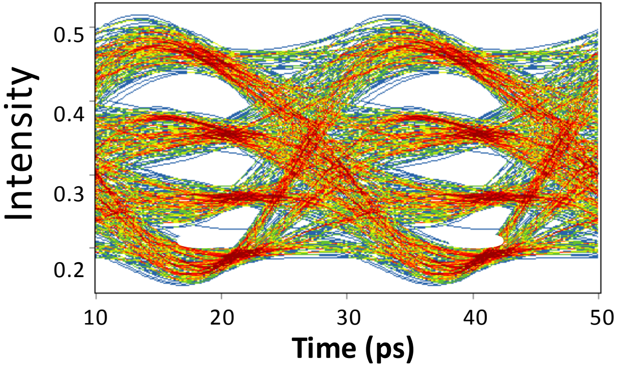




30

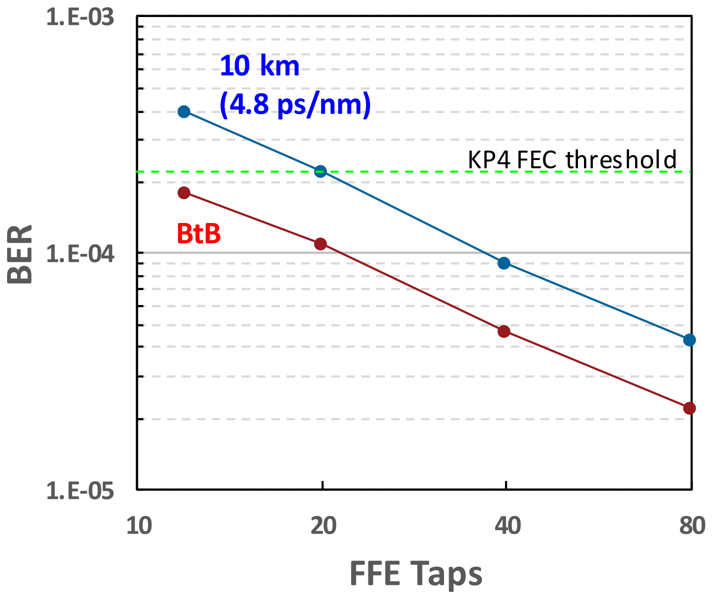
10 km **DFB+R** → **CML** 70 km



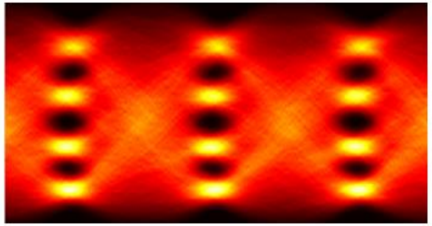


216 Gb/s PAM4 transmission using DFB+R laser

- DFB+R laser (BW ~ 70 GHz, α = 0.6, isolator-free)
- Simple 2-tap MLSE
- KP4 FEC threshold achieved with
  - 12 FFE taps for B2B
  - 20 FFE taps for +4.8 ps/nm CD (3km 1330nm)
- +10dBm fiber coupled power at 60 mA bias
- 280 Gbaud PAM2 achieved BER below 20% HD FEC



108 GBd PAM4 (12-tap FFE)



IEEE 802.3 Beyond 400 Gb/s Ethernet Study Group

By Di Che
Collaboration with NOKIA Bell Labs

411.6 Gb/s Transmission using DFB+R laser

NOKIA Bell Labs

Di Che, Optics Letters, 2020

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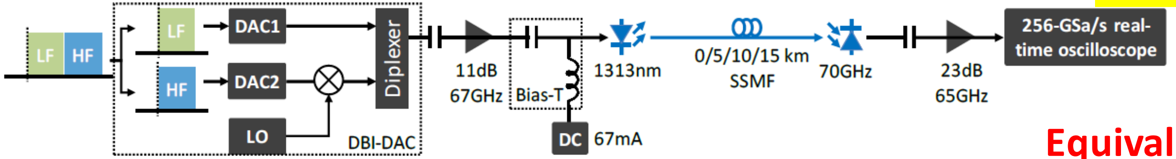
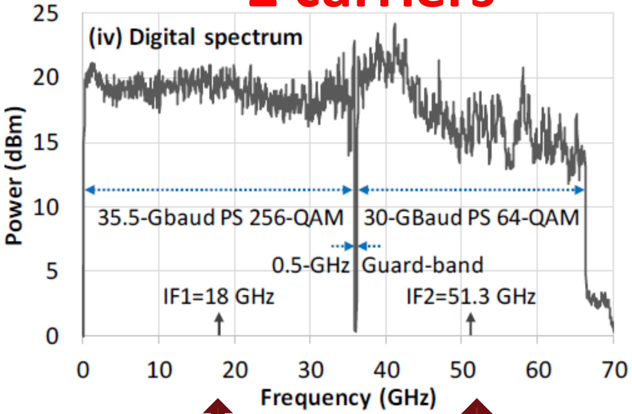
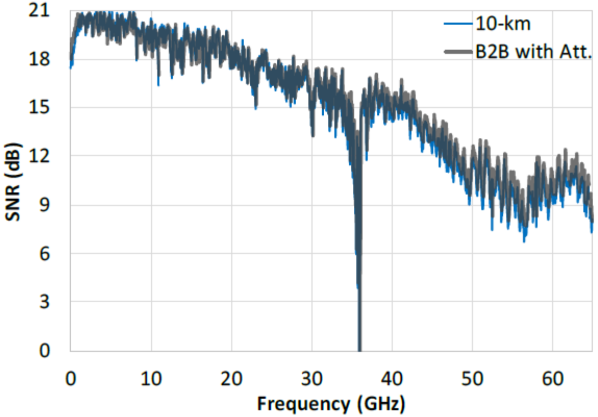
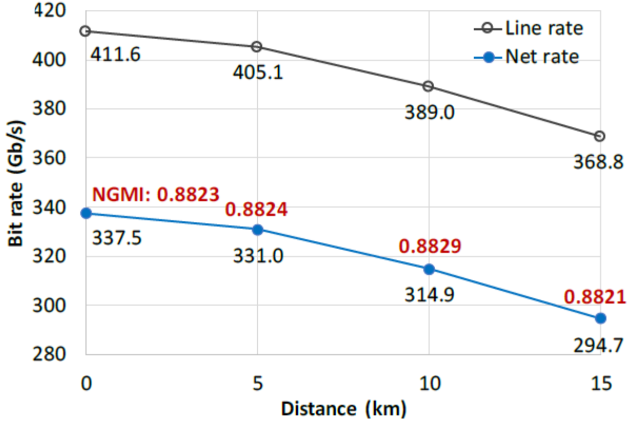


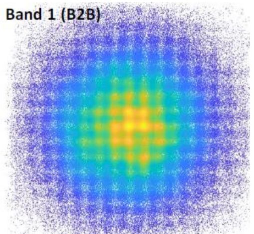
Equivalent to 4km at 1330nm

2 carriers

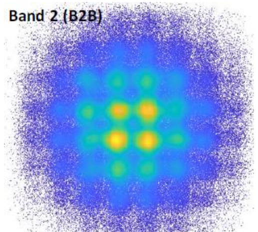




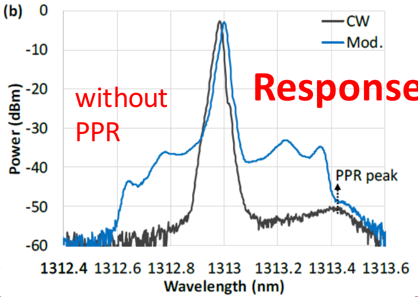




256-QAM



64-QAM



without PPR

Response with PPR SSB!

(iii) Entropy loading map

	Band 1	Band 2
	256-QAM	64-QAM
B2B	7.2	5.2
5 km	7.1	5.1
10 km	6.9	4.8
15 km	6.5	4.6

List of topics

❑ **3.2 Tb DML system prospect**

❑ **DML performance enhancement effects**

- Detuned-loading effect
- In-cavity FM-AM conversion for high-pass filter effect
- Photon-photon resonance (PPR) effect

❑ **Three 70-GHz BW DML designs and comparison**

- Short-cavity split-contact DR laser for tunable PPR frequency
- Short-cavity two-kappa DBR laser and uniform modulation with SOA
- DFB+R laser
- LaserMatrix design simulator live demo

❑ **Experimental results and paper review**

- Self-pulsation and pulse generation
- Chirp reduction
- Isolator-free operation
- 400Gb/lane transmission by Sub-carrier multiplexing (SCM)

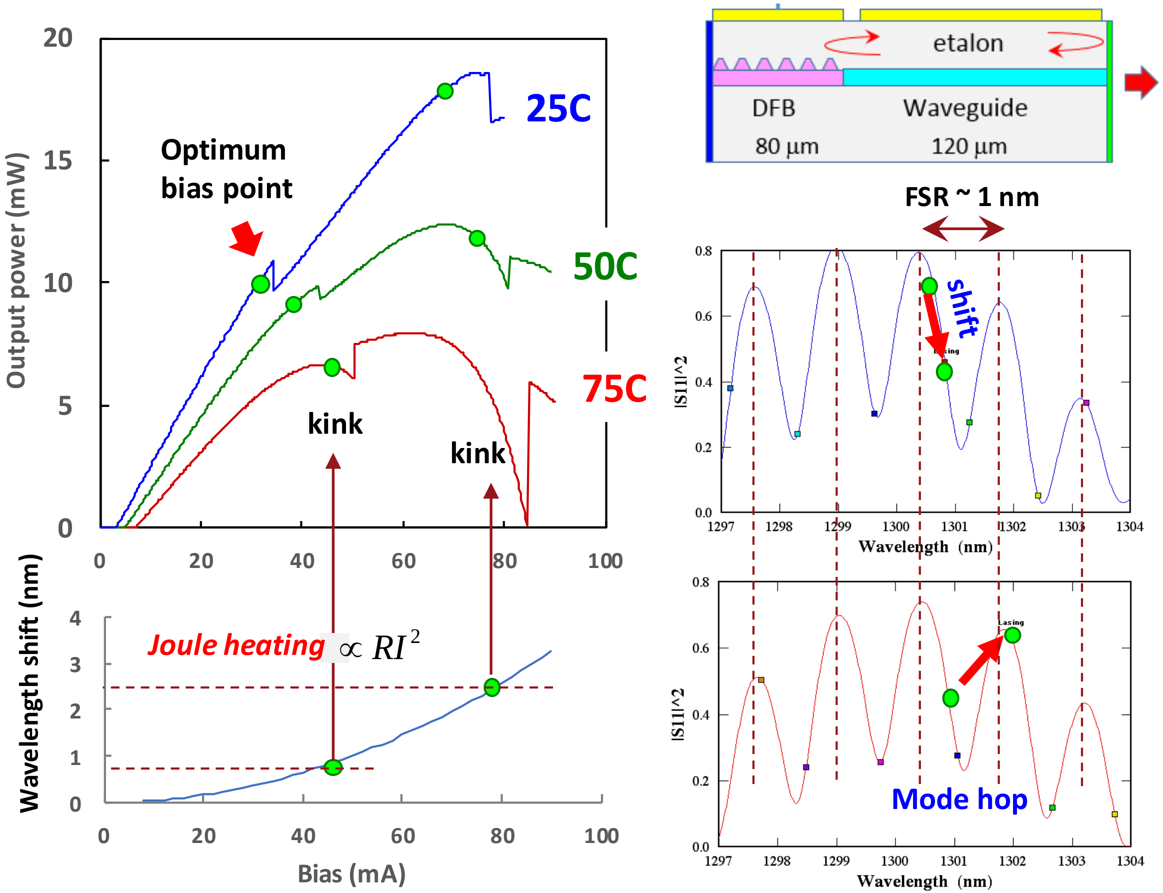
❑ **Reach extension by Chirp Managed Laser (CML)**

CML principles – optical duobinary effect, dispersion supported transmission, FM-AM conversion

❑ **Stability and reliability of DFB+R laser**

❑ **Conclusions**

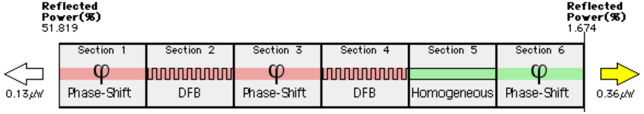
Stability and reliability



- Joule heating with bias shifts the mode toward the longer wavelength.
- Fastest speed obtained before mode hop
- After mode hop, etalon reflection peak increases.
- This can drop output power at lower temperature, but increase output power at high temperature by reducing threshold.

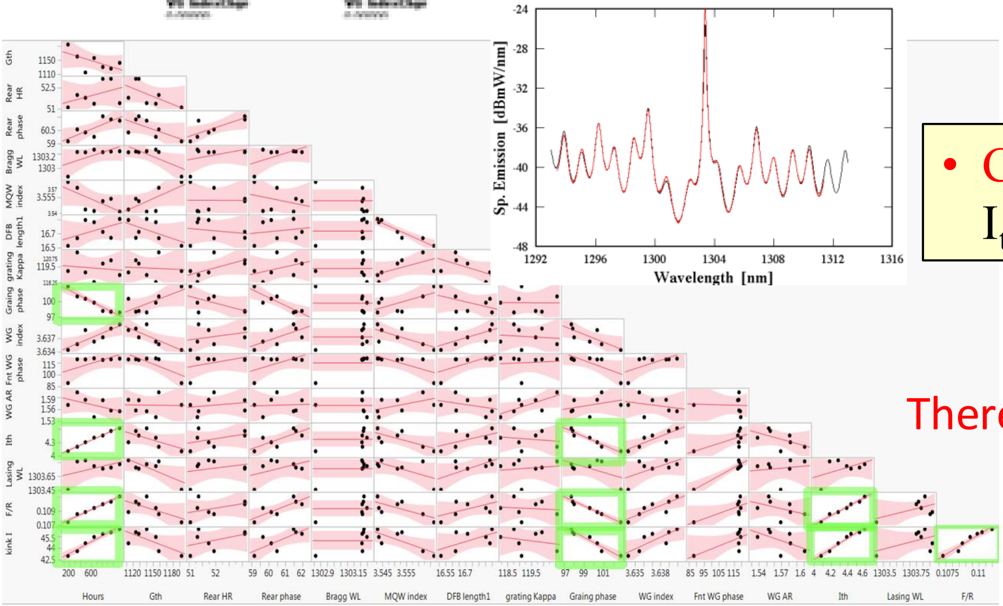
How kink bias moves with aging?

Rear



Front

Spectrum fitting



Facts:

- Extracted cavity parameters by spectrum fitting, then, plotted vs. aging time.
- Map out all the parameters and observed correlations.

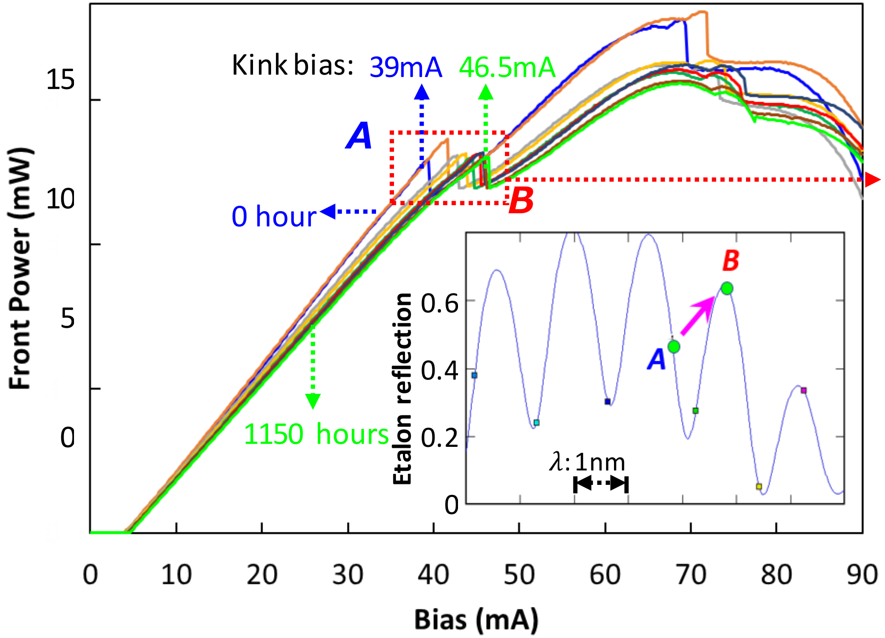
- Change in kink bias strongly correlates with I_{th} and Front/Rear power ratio.

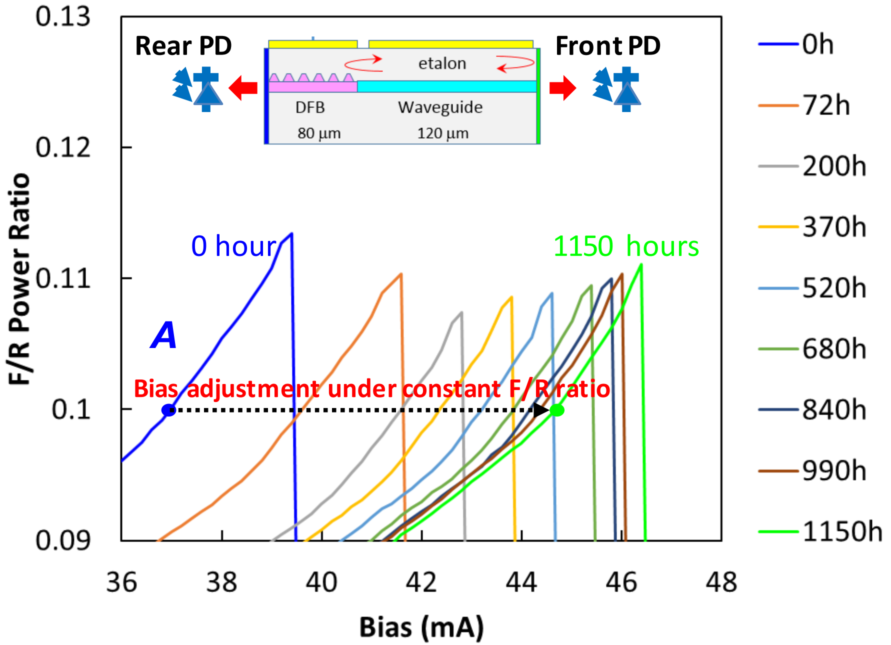
Therefore, F/R is good predictor of kink bias shift.

DFB+R laser: Long-term reliability

- ***A*** (below the kink) is the optimum bias condition.
- At higher bias, the mode hops to "***B***"
- Accelerated aging: 1150 h at 135°C junction
- Equivalent to 198 years at 25°C

- monitor the F/R ratio and adjust the bias current to maintain the optimum mode position "A".
- Similar to a wavelength locker using in-cavity filter





Conclusions

- **Present DML status**
  - 108GHz BW for membrane DR laser bonded on SiC (NTT) at 25C
  - 75GHz BW for DFB+R laser at 25C.
  - 55 - 60GHz at 50C for DR laser bonded on Si and DFB+R laser, respectively.
  - Chirp parameter of 0.7 and isolator-free operation reported for DFB+R laser
  - Stability under front/rear facet power monitor has been reported
  - Net rate of 338Gb in BtB and 320Gb after 2km equivalent at 1330nm were achieved at 25C.

- **Future DML challenges for 3.2Tb system - Assuming tight channel spacing (5-10nm) will be used to reduce the dispersion**
  - 400Gb net-rate sub-carrier multiplexing (SCM) at 50C to enable low-power consumption 3.2Tb system
  - 2km transmission should be possible, however 10km requires further dispersion tolerance.
  - SSB format by optical filtering may serve the purpose.

MATERIALS THAT MATTER