High Performance THz Photonic Crystal band-edge Quantum Cascade Lasers

Hua Zhang[1], Giacomo Scalari[2], L. Andrea Dunbar[1] †,
Romuald Houdré[1], Jérôme Faist[2]

[1]*Institute of Quantum Electronics and Photonics*
Swiss Federal Institute of Technology Lausanne (EPFL)
[2]*Institute for Quantum Electronics*
Swiss Federal Institute of Technology Zurich (ETHZ)
†Now with: **Centre Suisse d'Electronique et de Microtechnique SA (CSEM)**

What we want from Terahertz (THz) Quantum Cascade Lasers (QCLs)…

- ↗ Operation temperature (Current highest 178 K[1]).
- ↗ Single mode tuneablity (30 GHz[2]).
- ↗ Gain enhancement.
- ↗ Clean far field .
- ↗ Output power.
- ↘ Threshold current density.
- ↘ Device Size.
- ↘ Losses.

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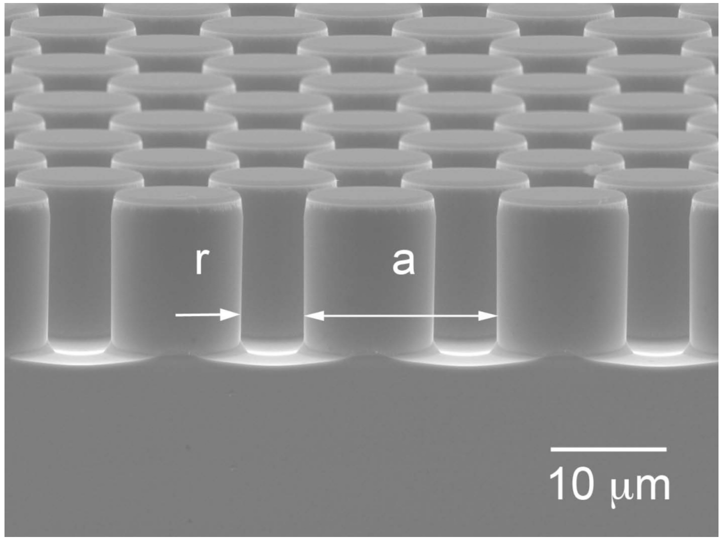
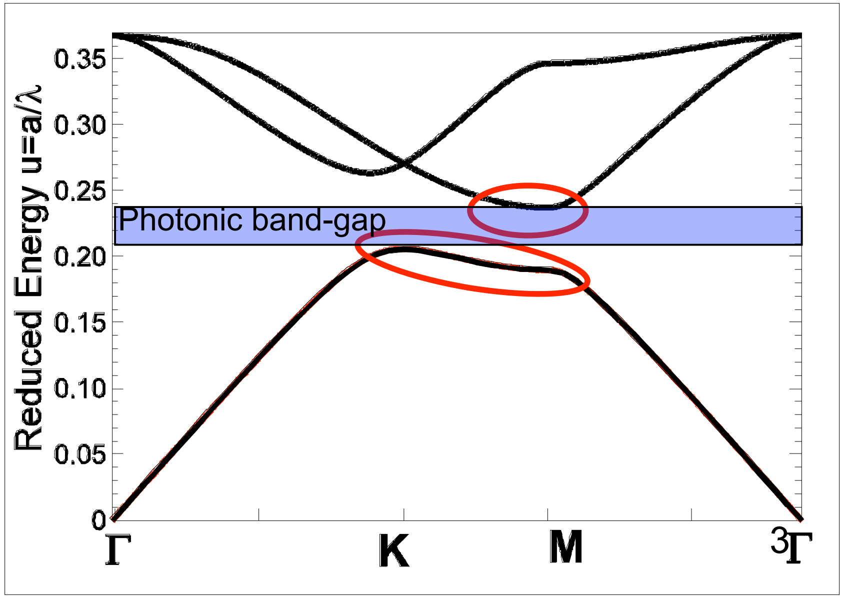
[1] *M.A. Belkin, J.A. Fan, S. Hormoz, F. Capasso, S.P. Khanna, M. Lachab, A.G. Davies, and E.H.Linfield, 'Terahertz quantum cascade lasers with copper metal-metal waveguides operating up to 178K', Optics Express, Vol. 16, Issue 25, 3242, 2008*

[2] *H. Zhang, L. A. Dunbar, G. Scalari, R. Houdré, J. Faist, 'Terahertz photonic crystal quantum cascade lasers', Optics Express, Vol. 15, 16818, 2007.*

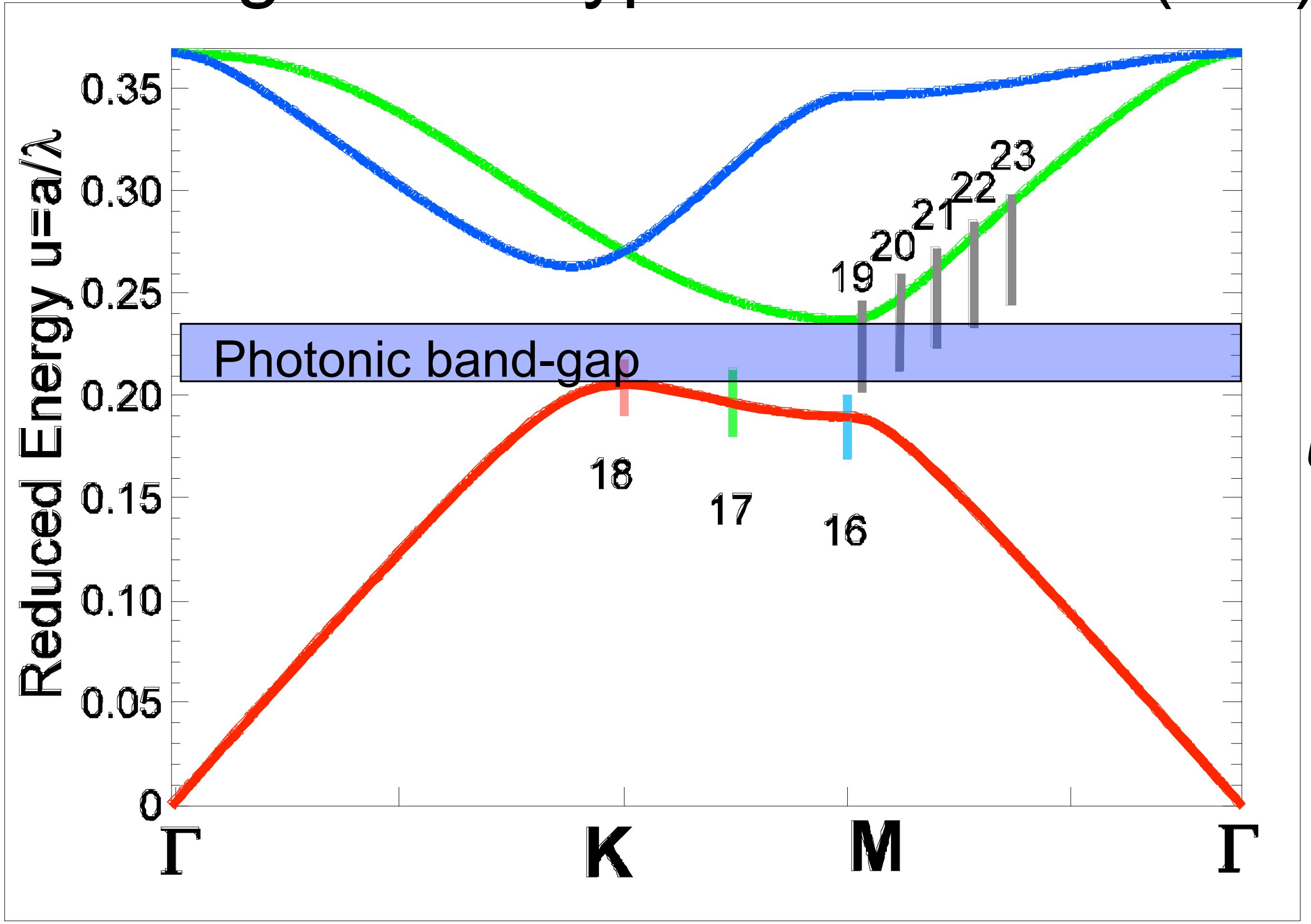
Features of pillar type deeply etched Photonic crystal (PhC) THz QCLs

- ✓ Complete photonic band-gap (PBG) for TM polarization.
- ✓ High mode confinement with double metal configuration.
- ✓ In dispersion, the slow light regime enhances the PhC gain.
- ✓ Mode selection between M saddle point and K band-edge.
- ✓ Emission direction selectable between in-plane & surface.





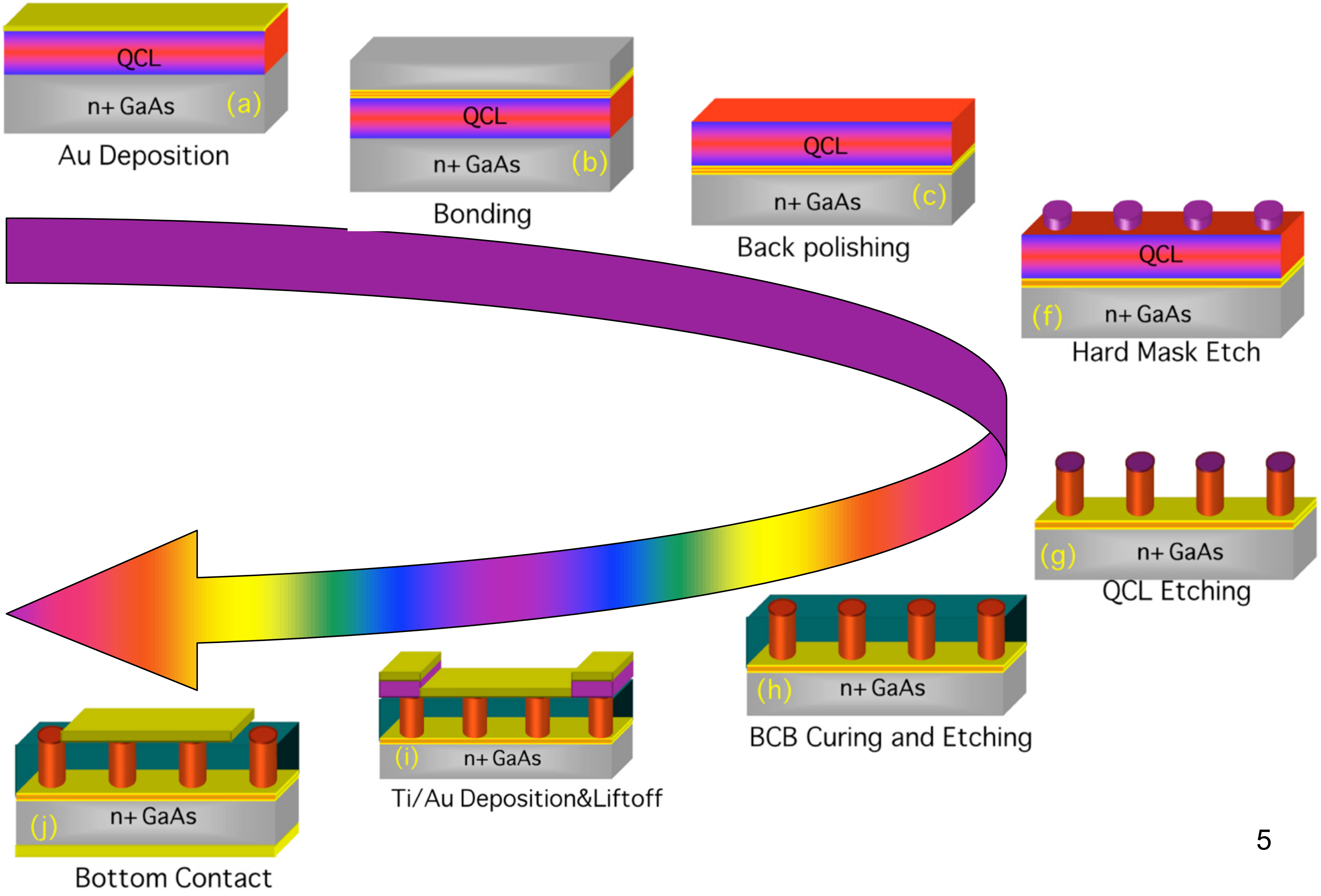
Design-Pillar type PhC QCLs (TM)



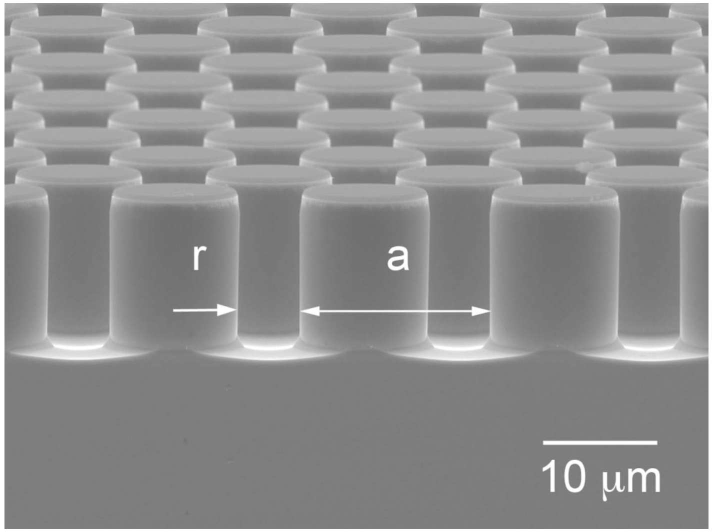
$u = a/\lambda$

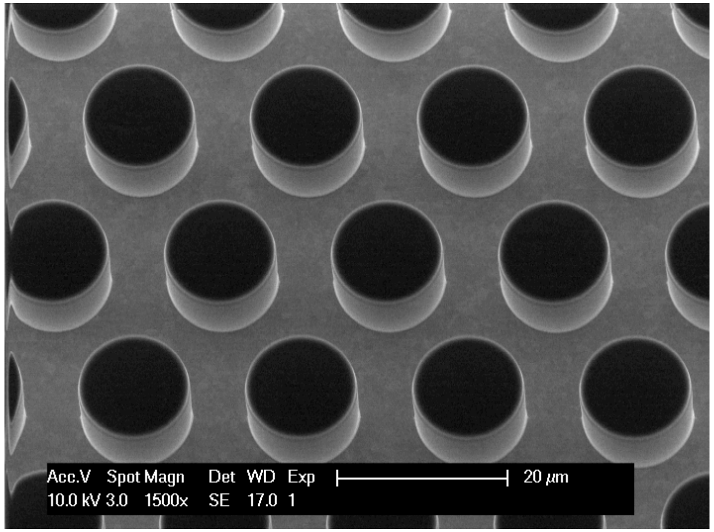
- λ: 77→94 μm (from EL, "gain bandwidth")
- *a* : 14→23 μm
- r/a = 0.33, 0.37 (Pillar filling factor: ff = 40%, 50%)

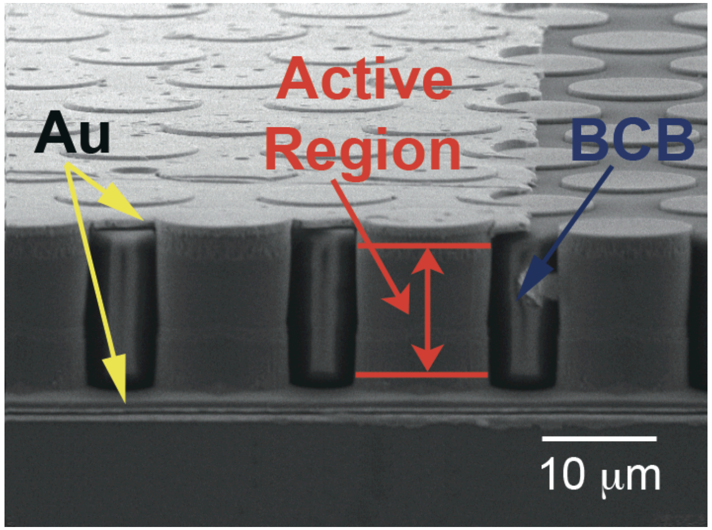
Process flow of THz PhC QCLs

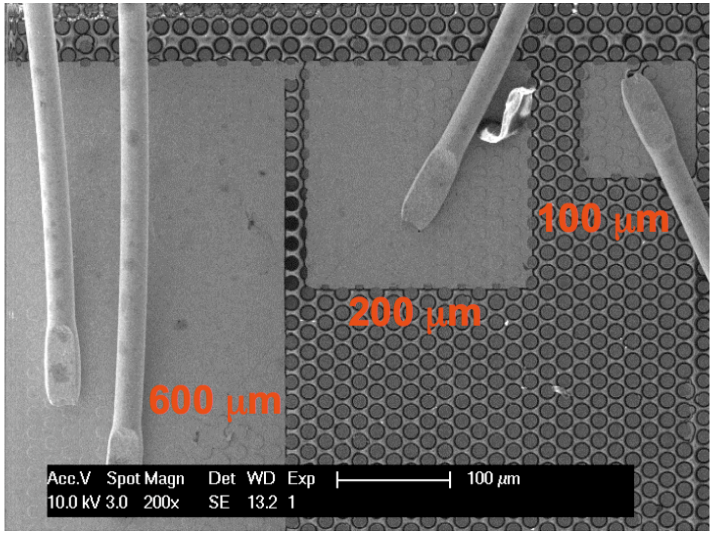


Fabrication results of THz PhC QCLs





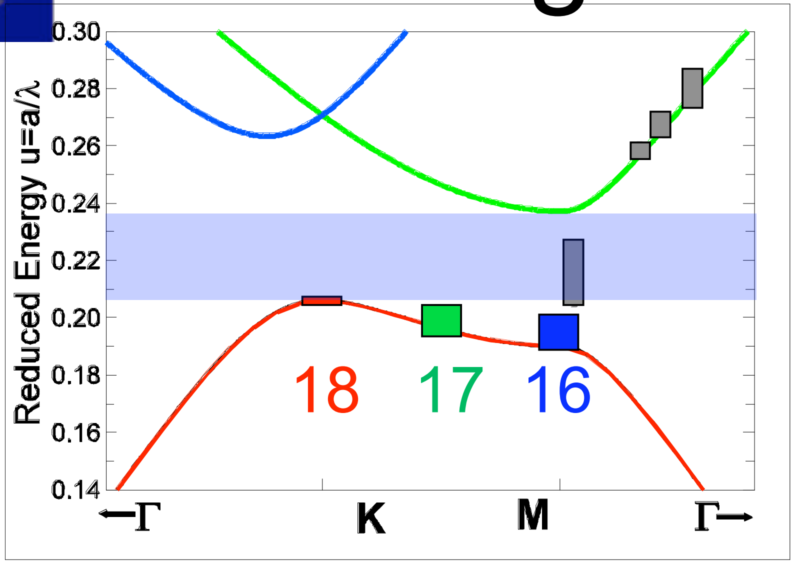




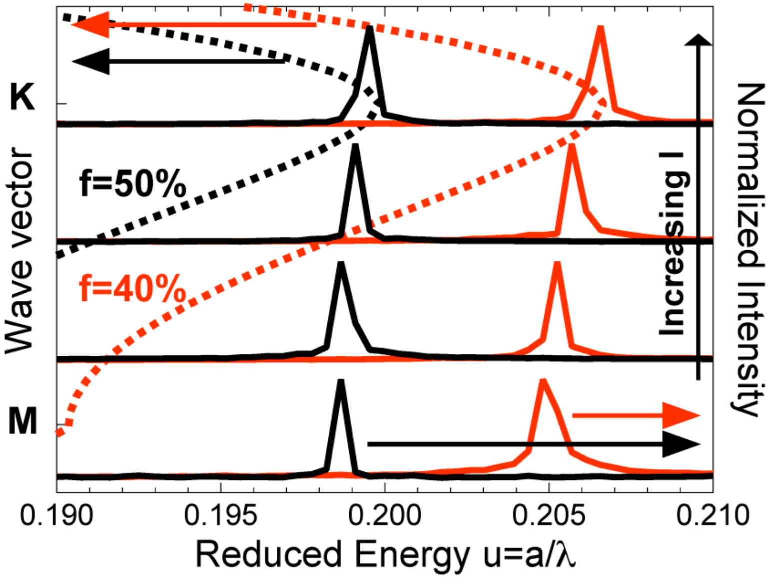
In-plane emission

Compact size in λ scale (2.2 λ) can lase!!!

Band edge lasing Spectra



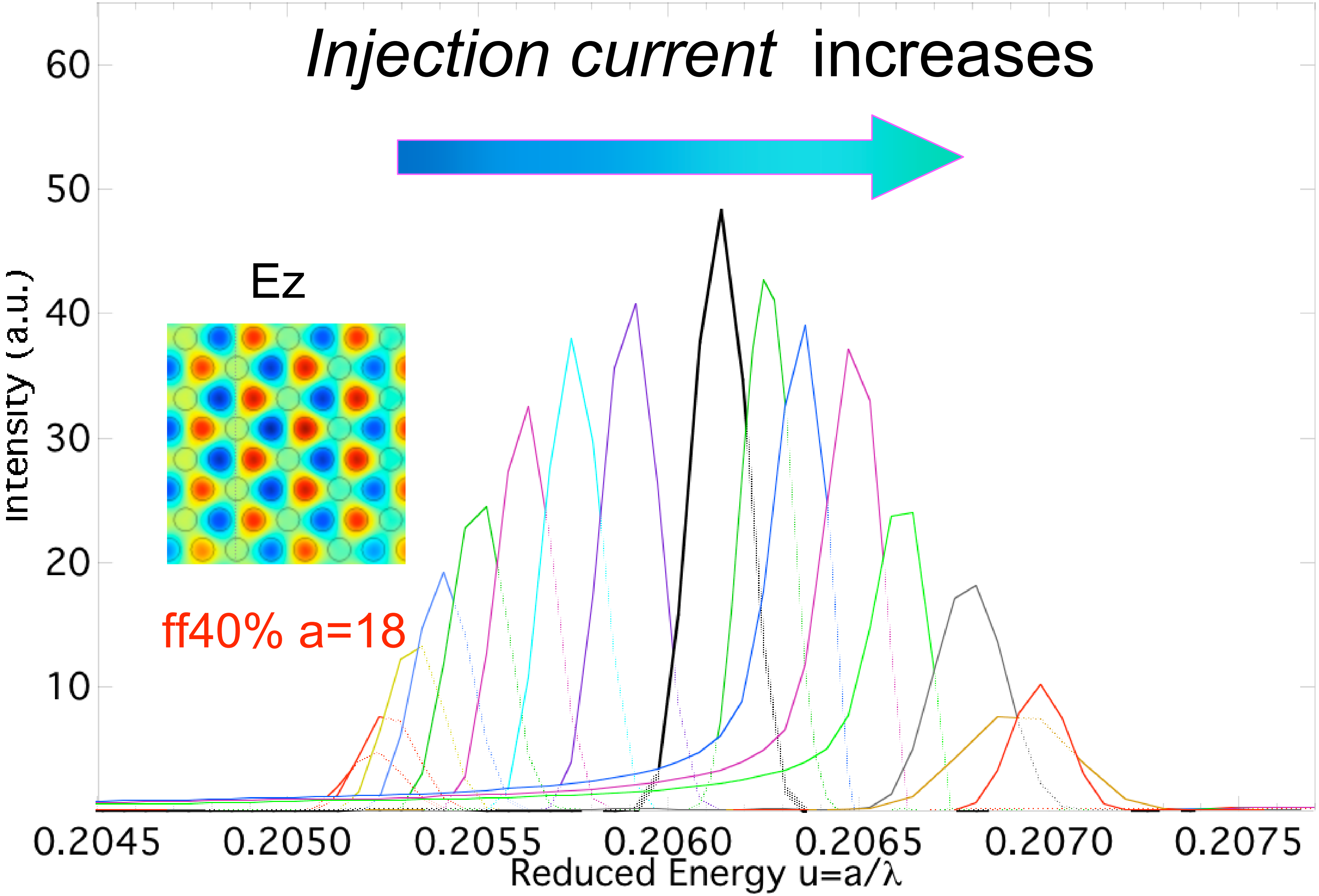
❖Pure band edge lasing devices at different r/a ratio (ff 40%,50%)



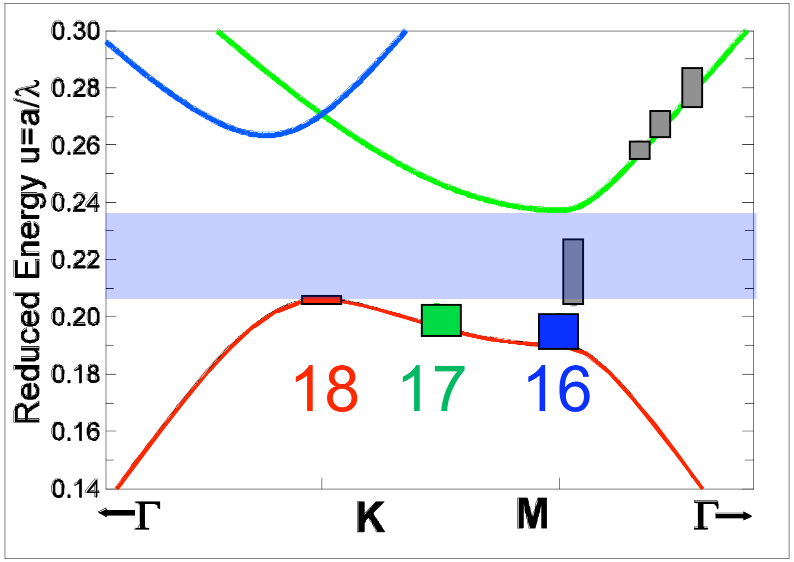
❖Single mode continuously tunes (field assisted gain shift and cavity pulling) over 30 GHz.

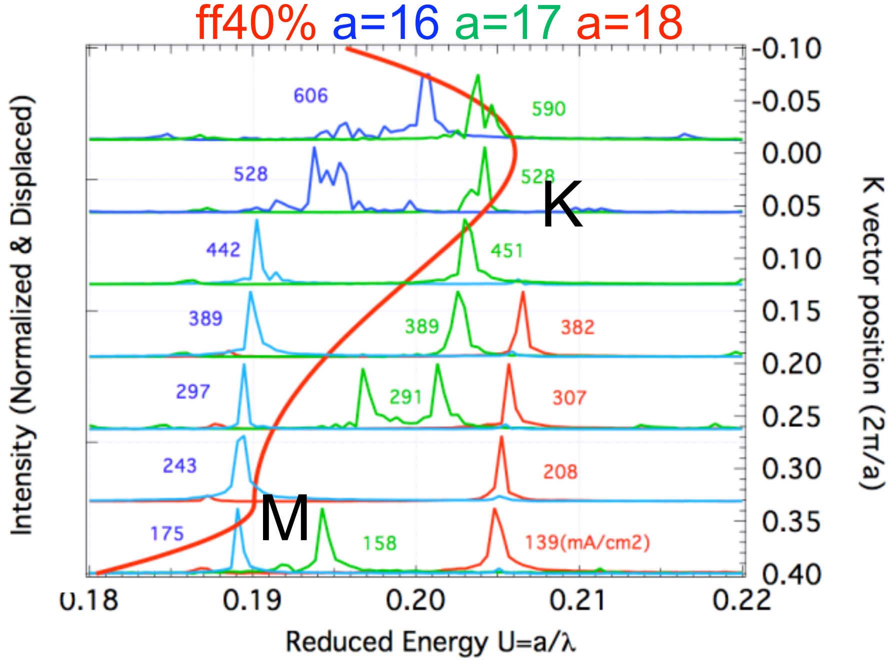
a=18 μm

Single Mode Tuning for 30 GHz!



Spectra coarse tuning



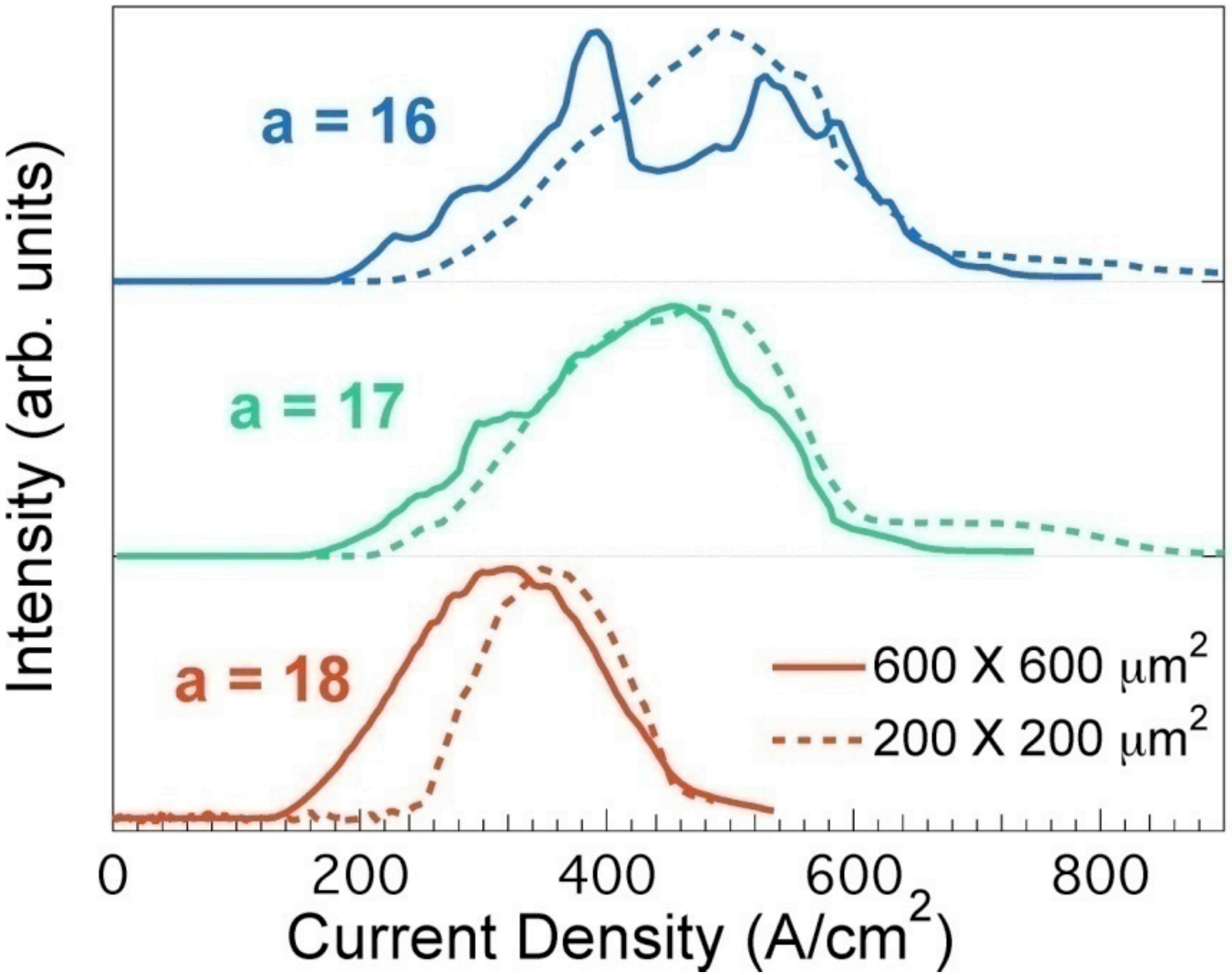


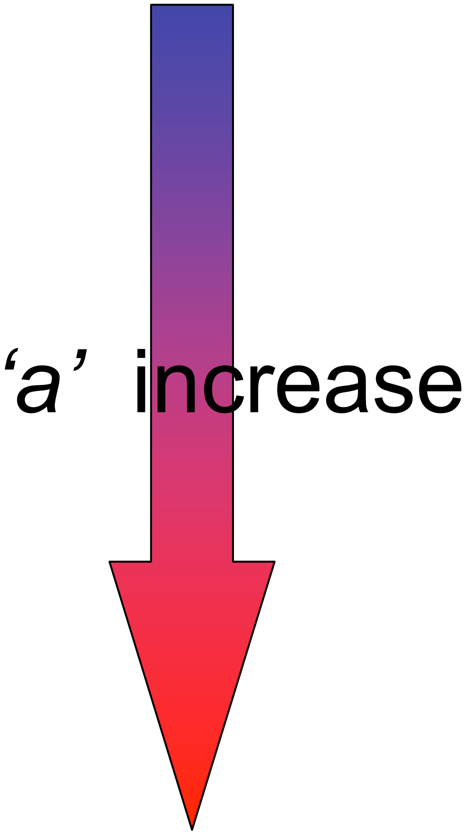
❖Single mode lasing at M and K.

❖Lasing between MK path in dispersion.

❖Coarse lithographic tuning range is 450 GHz.

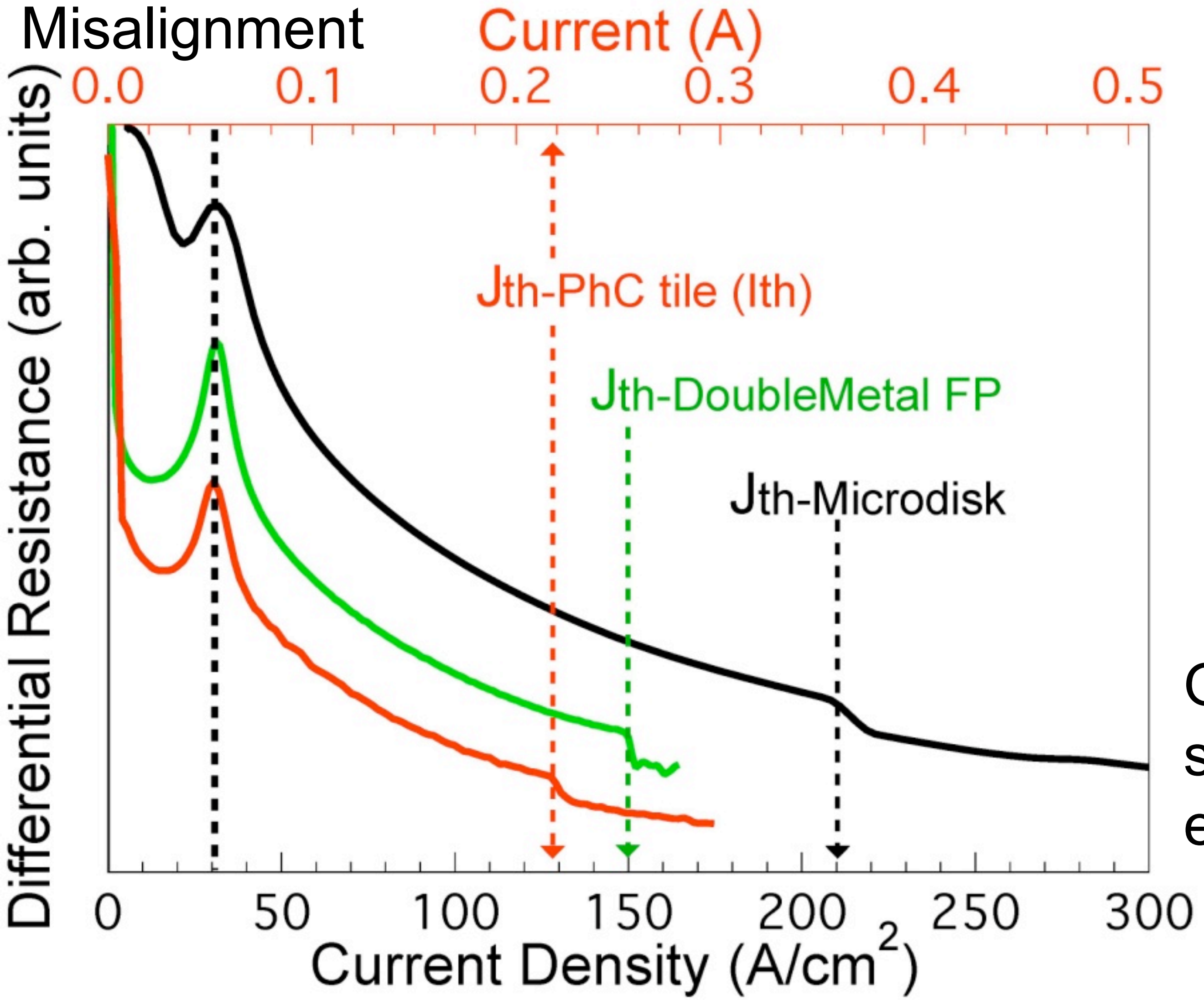
Light/Current at different *‘a’*





The lowest threshold current density (J_{th}) at a=18 μm shows the evidence of the strongest overlap between the material gain and the bandedge optical mode energy.

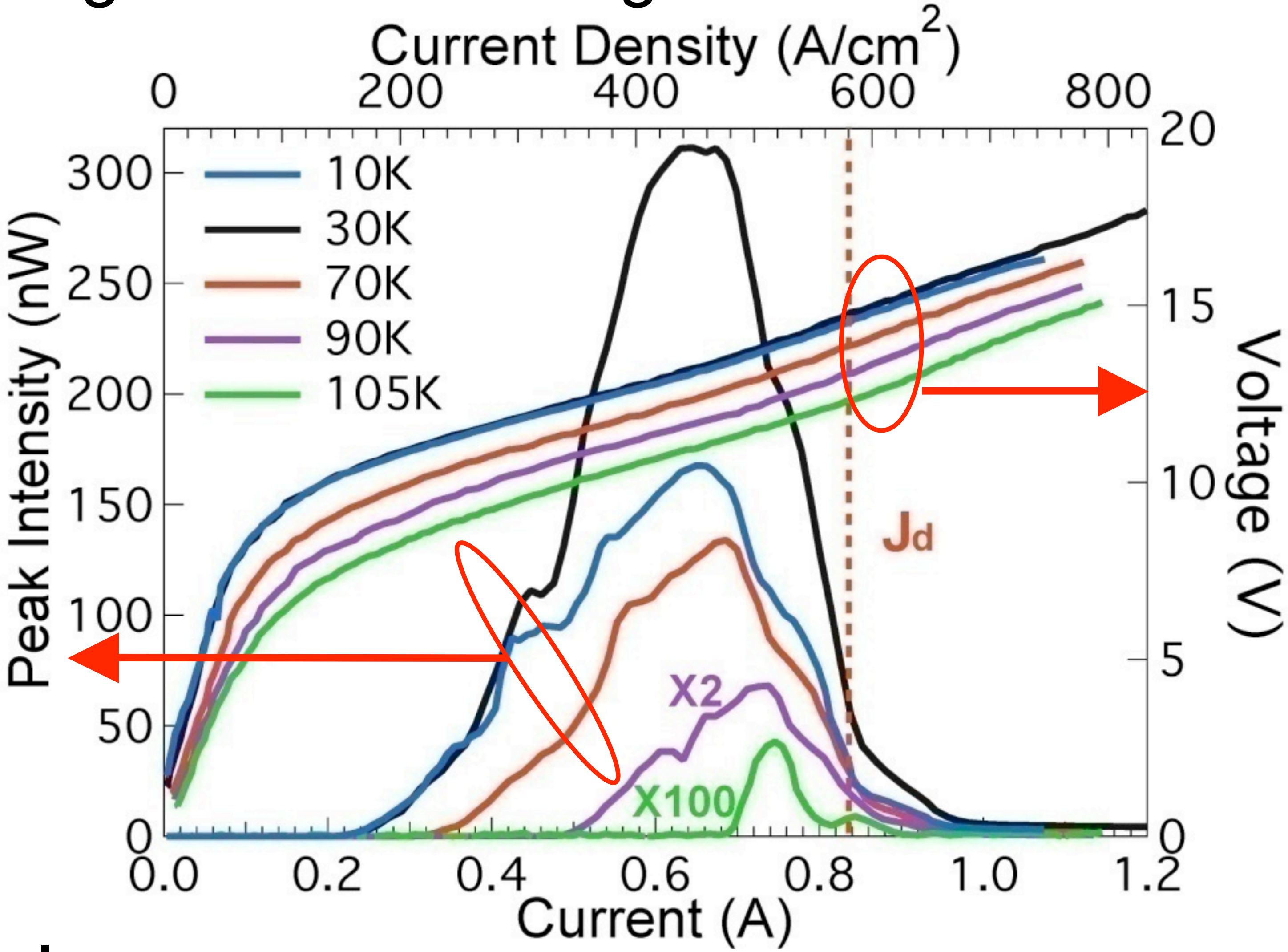
Differential Resistance of different devices



Onset of stimulated emission

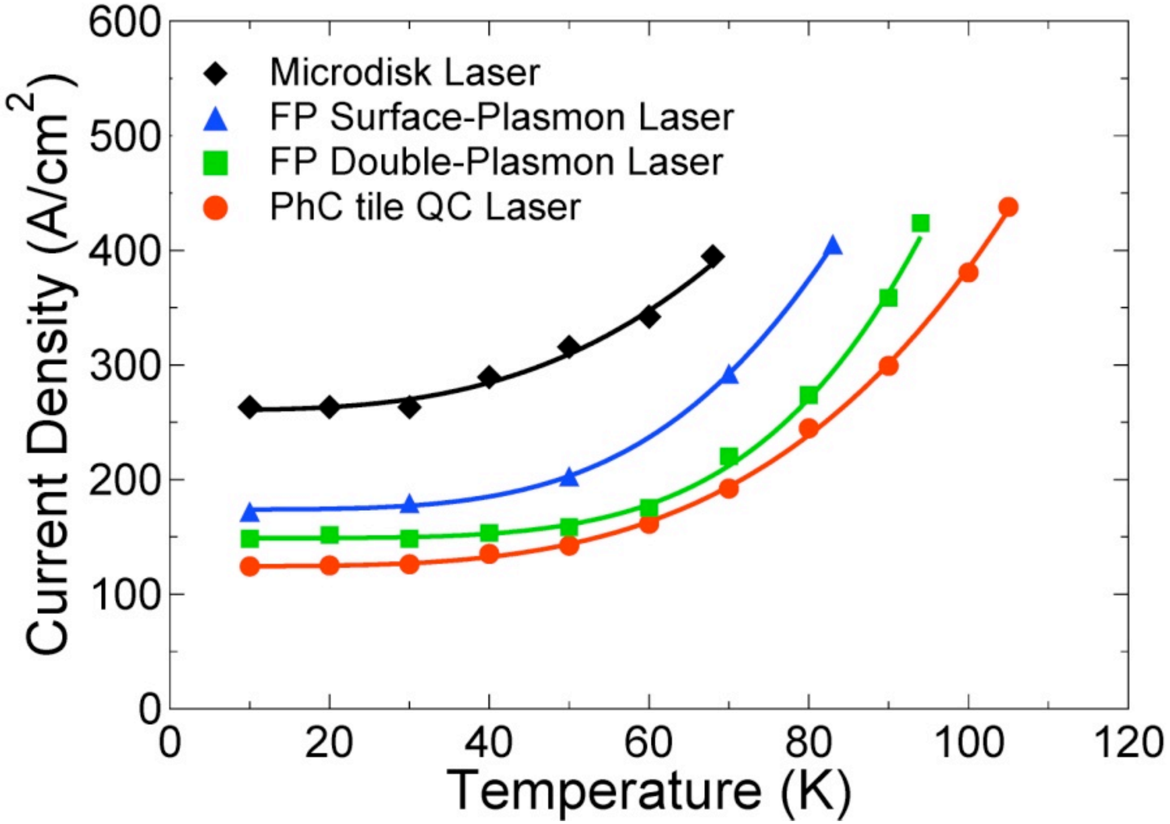
On the same QCL layer, the PhC tile laser reduces the J_{th} by 17 % compare to the lowest reported FP laser and 41% compare to μ-disk laser.

Light/Current/Voltage of THz PhC QCL



Same layer:
Maximum operating temperature was improved from 90K→105K.

Highest temperature performance!



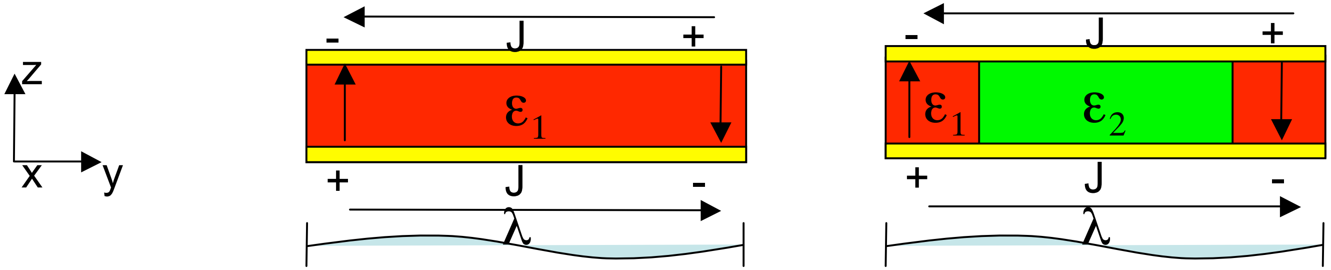
On the same layer, the PhC laser :

- Has the lowest Jth and the highest operating temperature.
- Substantially enhances the gain.
- Generates less heat due to the periodic patterning of the active region, hence, improves the temperature performance.

Reduction of $J_{th,}$ Reduction of losses

For double Plasmon WG:

- ➢ Vertical losses can be minimized by optimized intersubband structure design.
- ➢ **In plane** ohmic losses maybe reduced by PhC structure.
- ➢ For identical active region, ↘ J_{th} → ↘ waveguide losses by the same amount.



What happened if we replace part of waveguide by low ε material ?

❖Waveguide with the lower dielectric constant will have lower losses

---*Probably because the field is expelled better from the metal.*

❖Gain/losses peaks are no longer at the same place!

❖The in-plane field will be maximum between the maxima of the vertical one!

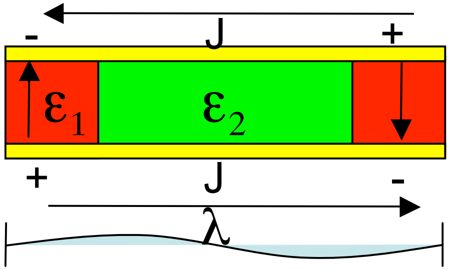
Less loss in BCB than in QCL(Loss-Gain)

TM mode, B field -------------------------------- $\vec{B} = (B_x(z)e^{i(\beta y - \omega t)}, 0, 0)$ (1)

E-field components (y, z) from -------------- $\nabla \times \vec{B} = \varepsilon\mu_0 \frac{\partial}{\partial t}\vec{E}$ (2)

$E_z(z) = -\frac{\beta}{\omega\varepsilon\mu_0} B_x(z)e^{i(\beta y - \omega t)}$ (3) $E_y(z) = \frac{i}{\omega\varepsilon\mu_0}\frac{\partial}{\partial z} B_x(z)e^{i(\beta y - \omega t)}$ (4)

y- and z- E components are proportional to each other, but with a **π/2** phase shift.



In our PhC laser, thanks to the patterning of the active medium the anti-node of the in-plane field occurs in the BCB, which, because it sustains a guided mode with a more rectangular profile, is intrinsically less lossy than the high-index section (QCL).

Summary

- No mirrors, no cavities, pure PhC 2D DFB laser.
- Pillar type PhC with complete PBG for TM polarization.
- BCB planarization enables free patterning to achieve double-metal confinement and uniform current injection.
- Broad single mode continuous tuneablity. (30GHz)
- Slow light gain enhancement lasing at M,K points and between.
- Lower threshold current density (17%).
- Higher operation temperature (17%).
- Reduction of the losses is a unique feature of deep etched, strongly confined PhC structure.

Thanks for your attention!