Penrose QCLs

IQCLSW2014 - Policoro

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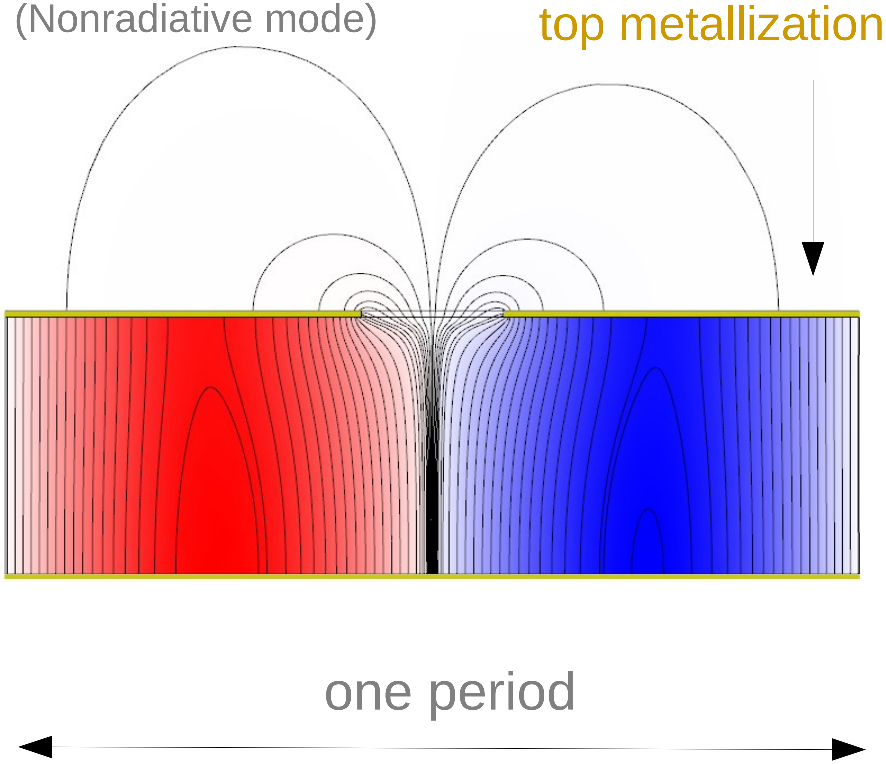
DFB in DM-QCLs

Color: H-field
Lines: E-field
(Nonradiative mode)

double-metal ridge
longitudinal cut

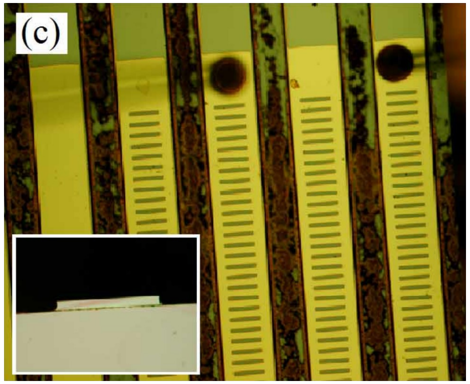


When a hole is opened in the top metallization, inhomogeneous boundary conditions are at play.

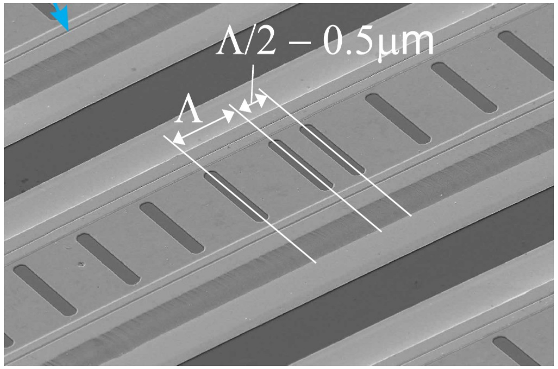
This affects the EM fields inside the waveguide, meaning that the patterning tailors the shape, symmetry and frequency of the lasing eigenmodes.

DFB patterns

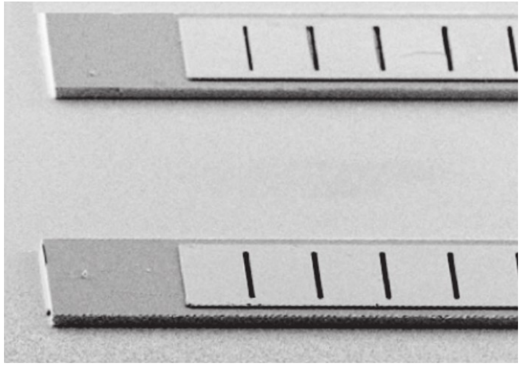
Fan *et al.*
Optics Express
14, 11673 (2006)



Kumar *et al.*
Optics Express
15, 113 (2006)



Amanti *et al.*
Nature Photonics
3, 586 (2009)

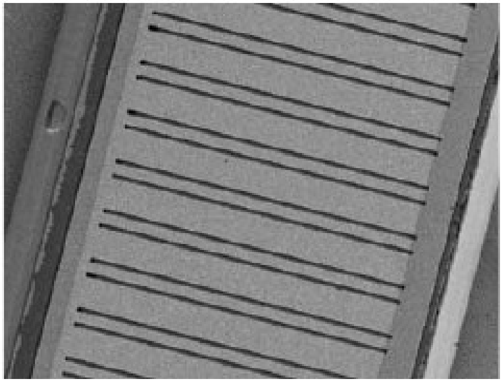


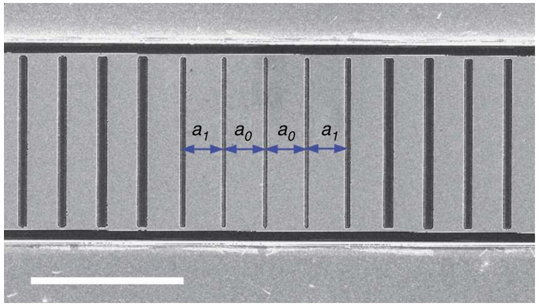
DFB patterns

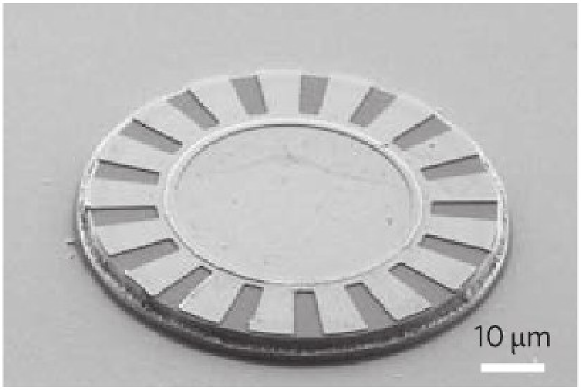
Mahler *et al.*
Appl. Phys. Lett.
96, 191109 (2010)

Xu *et al.*
Nature Communications
3, 952 (2012)

Mahler *et al.*
Nature Photonics
3, 46 (2009)

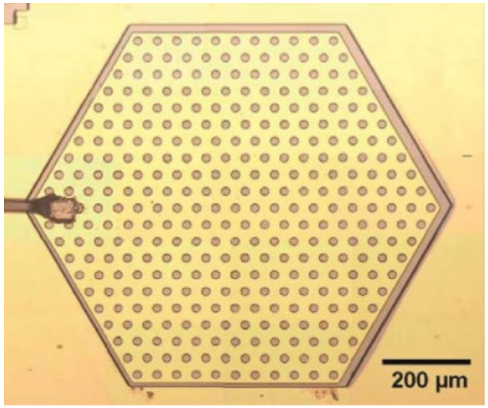




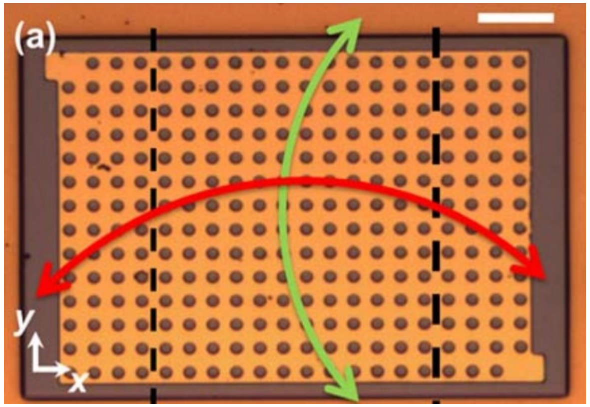


DFB patterns

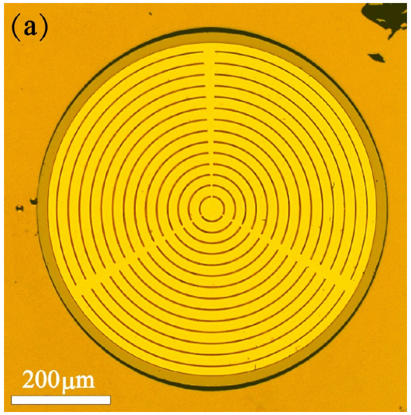
Chassagneux *et al.*
Nature
457, 174 (2009)



Halioua *et al.*
Optics Letters
39, 3962 (2014)



Liang *et al.*
Optics Express
21, 31872 (2013)



The goal

To tailor the resonating eigenmodes properties
via local phase control of the EM field

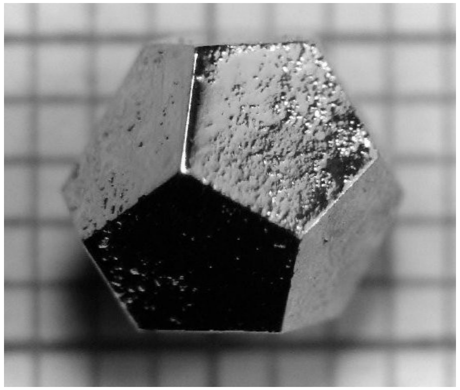
One needs to establish definite optic path length relations
in the DFB pattern (geometric order)

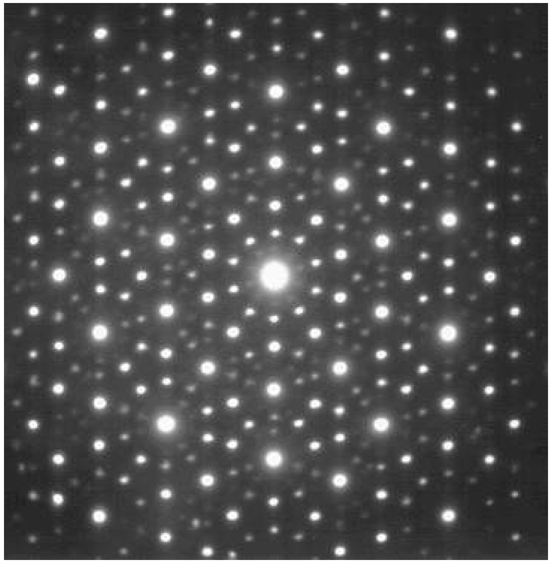
<u>Are periodic tilings the full story?</u>

Quasicrystal

"A structure that is ordered but not periodic."

Dan Shechtman

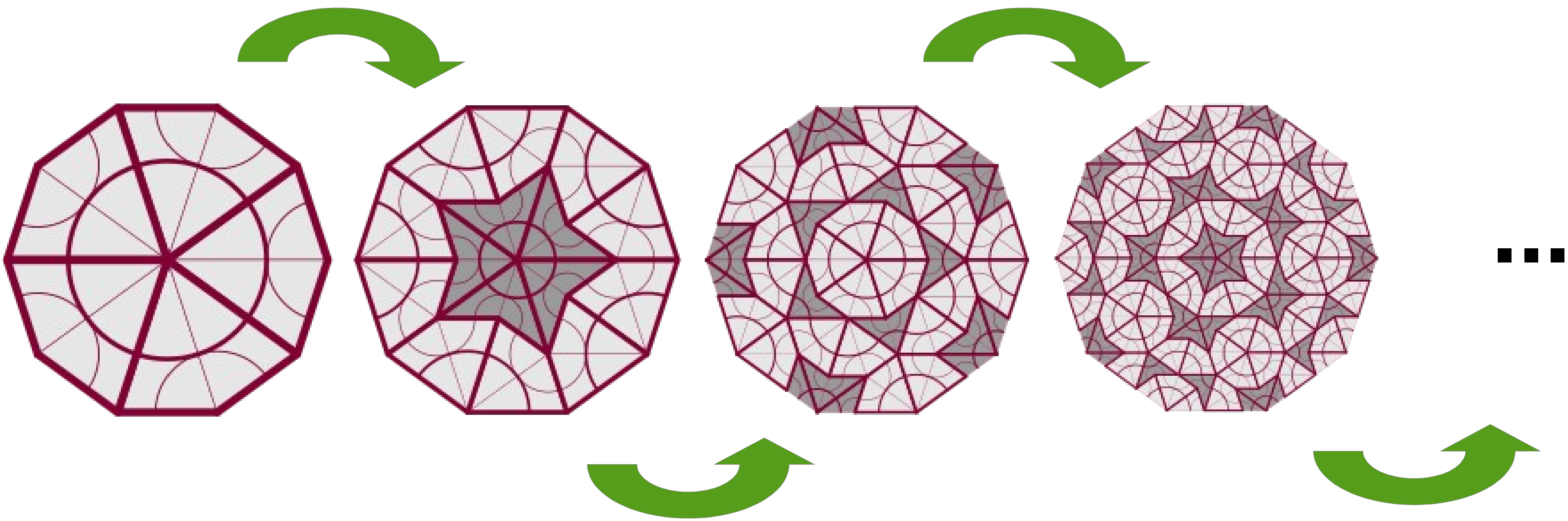




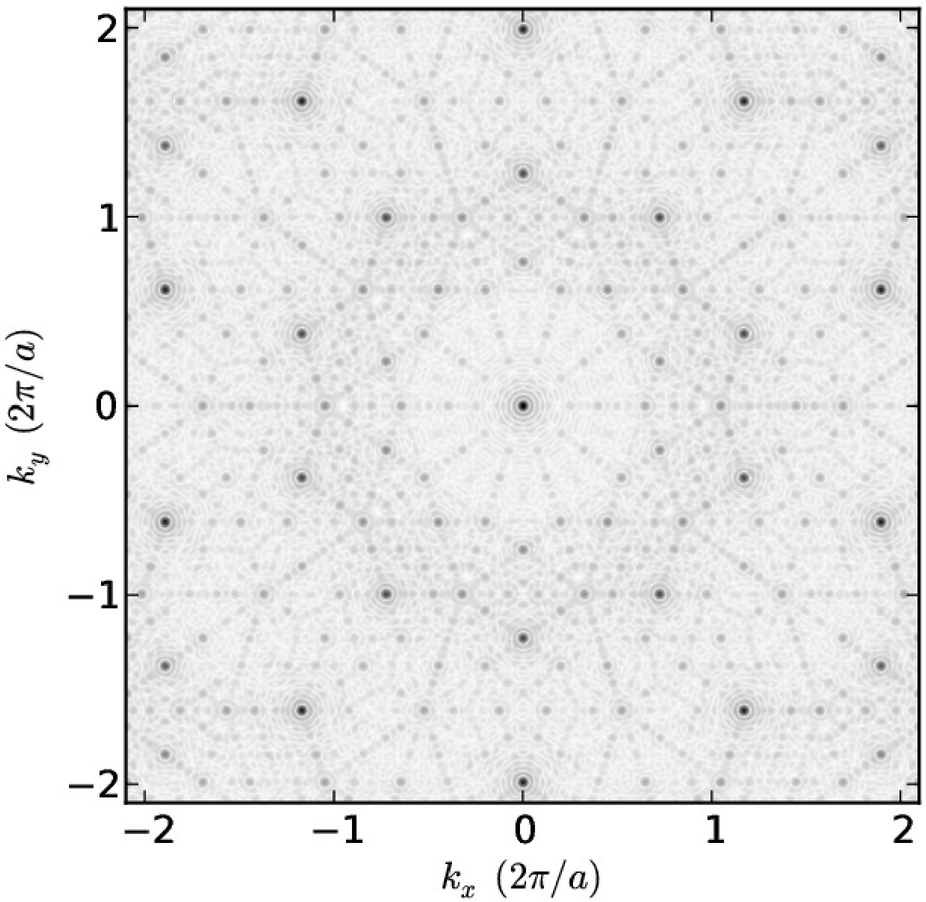
Nobel Prize in Chemistry (2011)

Penrose tiling

Just as crystals are obtained by repeated translations, a Penrose tiling can be obtained by repeated “deflations”, operations in which each element of the tiling changes into multiple smaller elements, following fixed rules.



Structure factor

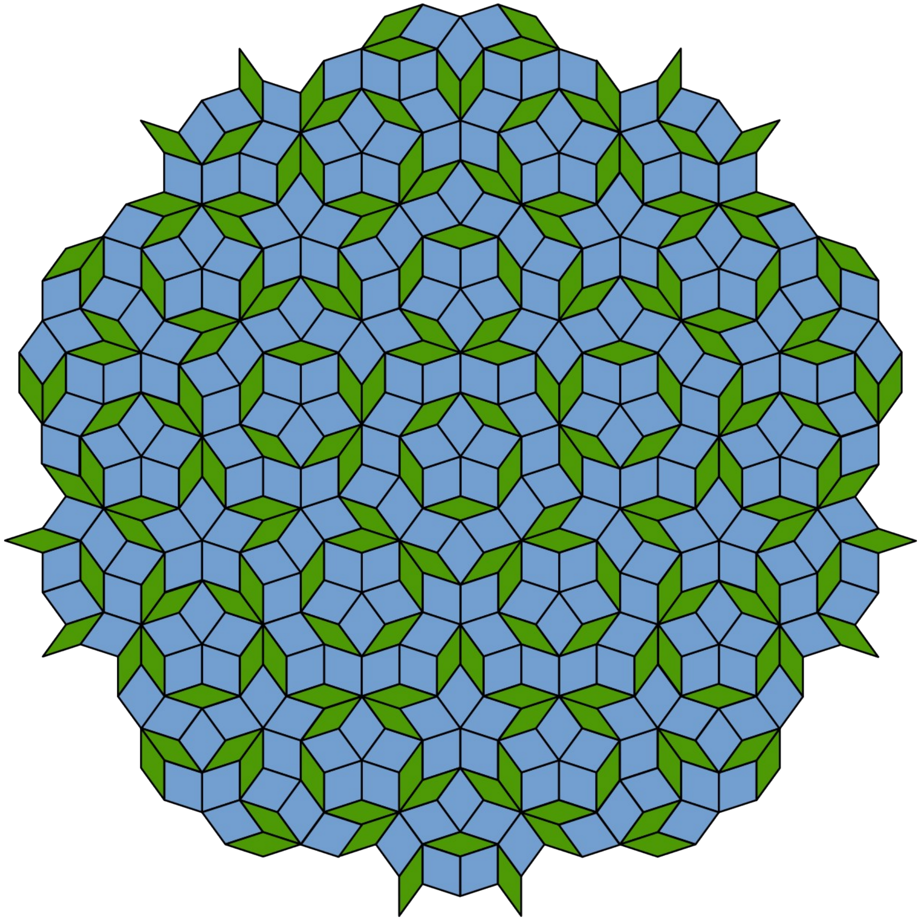


Striking properties:

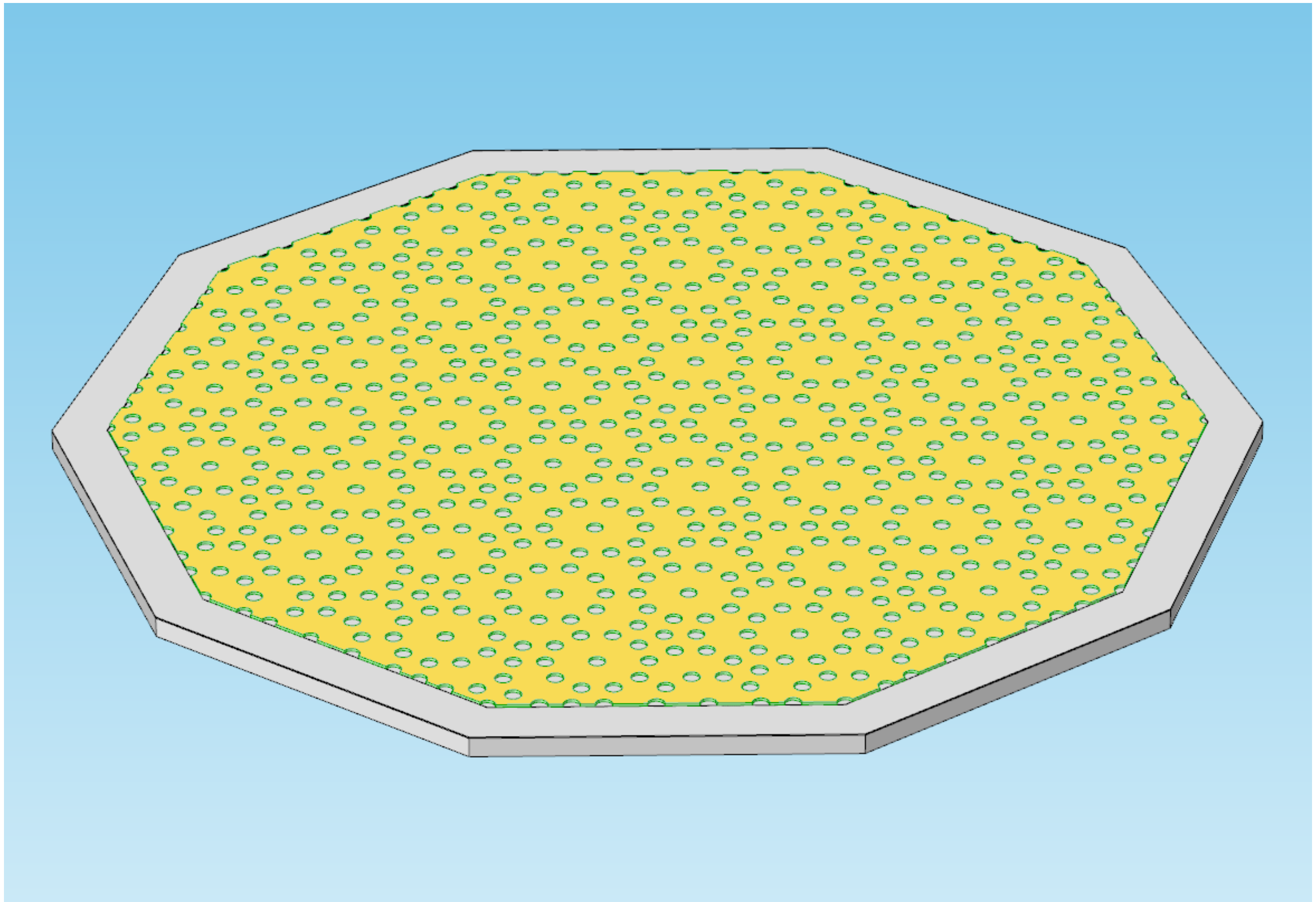
The long-range order is evident from the **dense set** of Bragg peaks in the Fourier transform of the Penrose lattice.

A **10-fold** rotational symmetry axis is present in reciprocal space.

DFB design



DFB design



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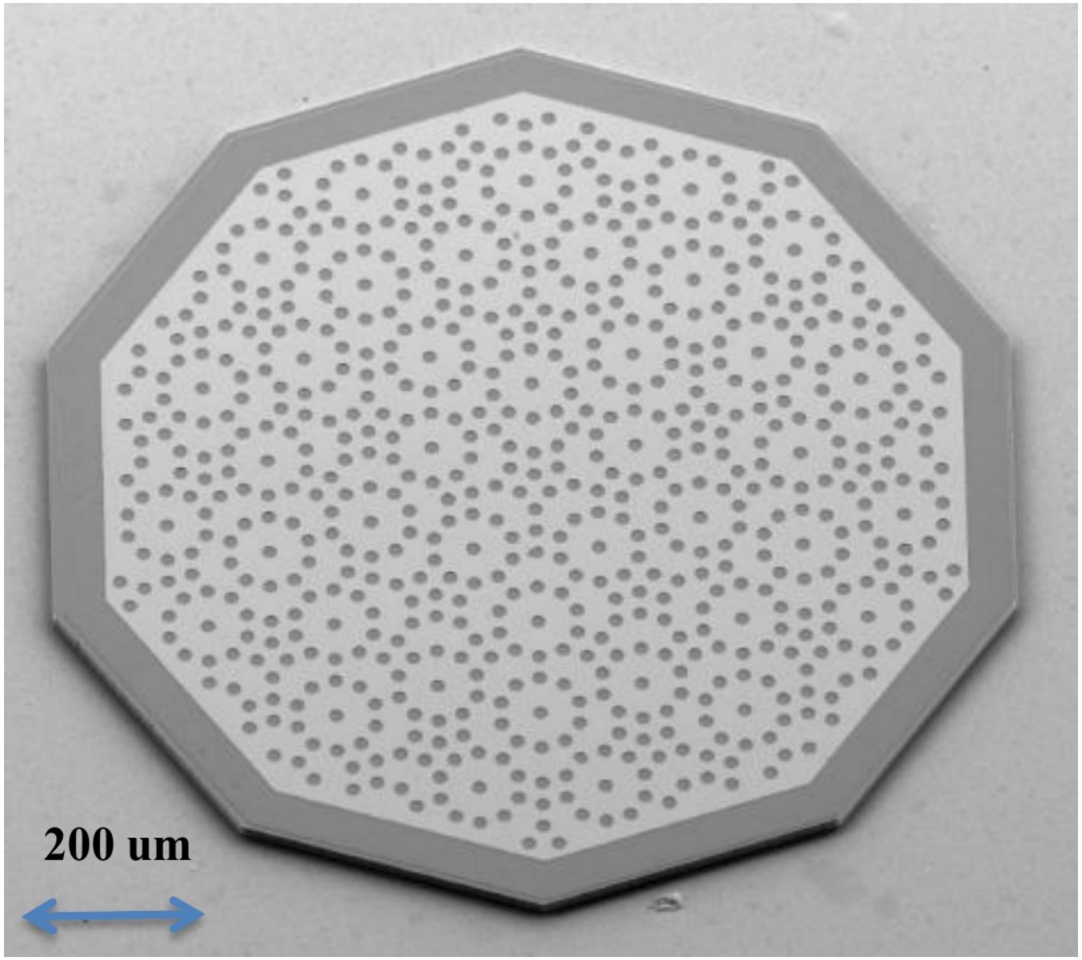
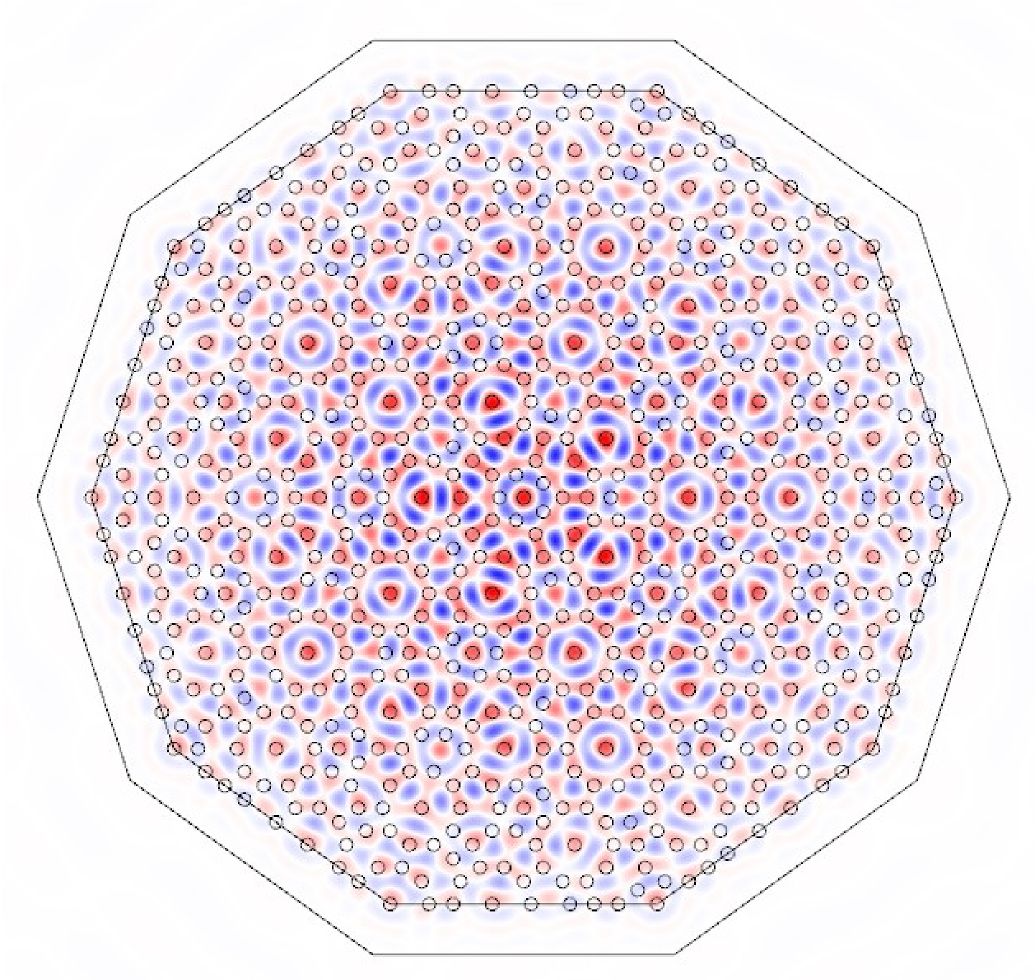
DFB design



Penrose eigenmode



From 2D FEM

Effective index approx.

Standing wave mode

- spans the whole device
- holes in phase

Colorscale: $E_z(t)$ in the waveguide

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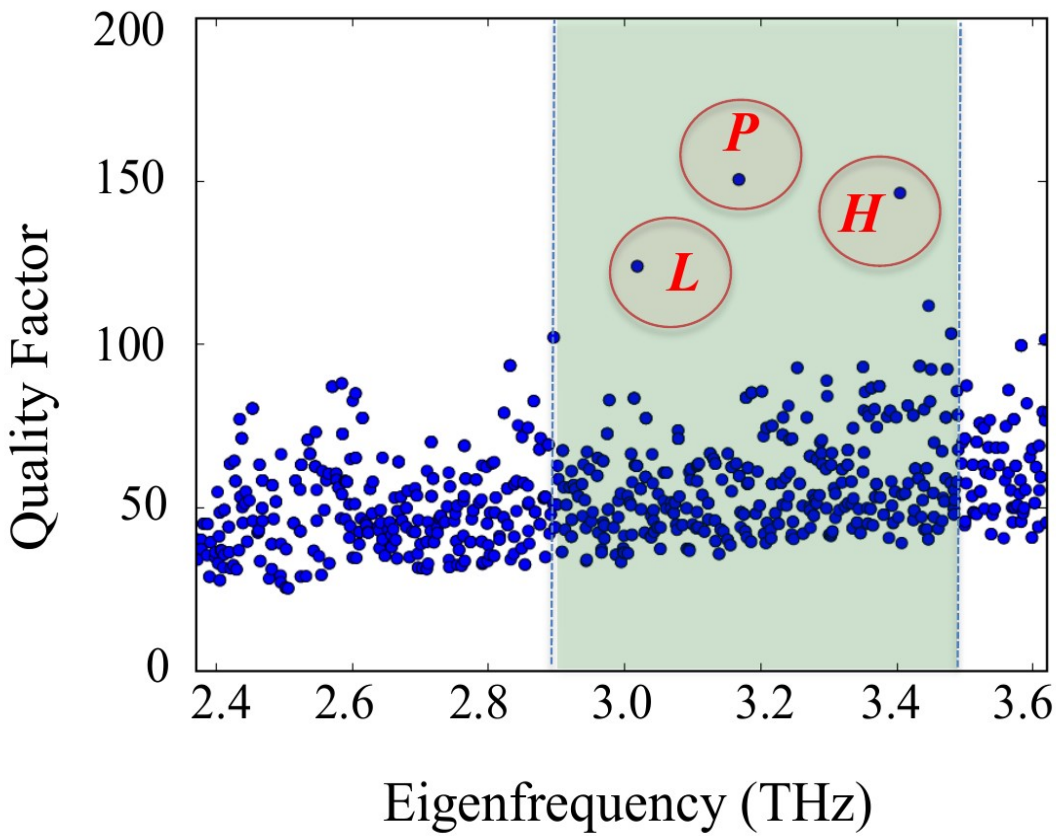
Penrose eigenmode



From 2D FEM

Effective index approx.

Standing wave mode labeled “P”

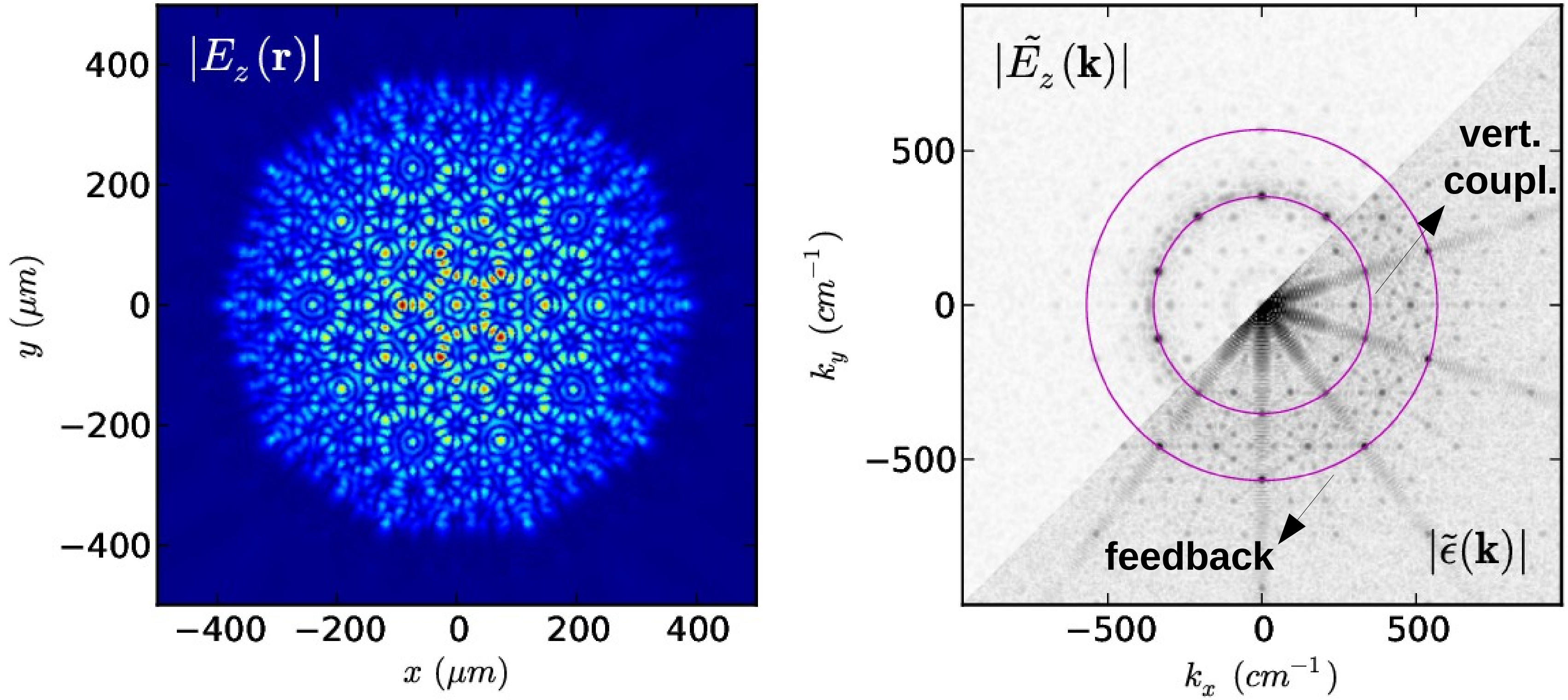
F = 3.17 THz

Q_{2D} = 145

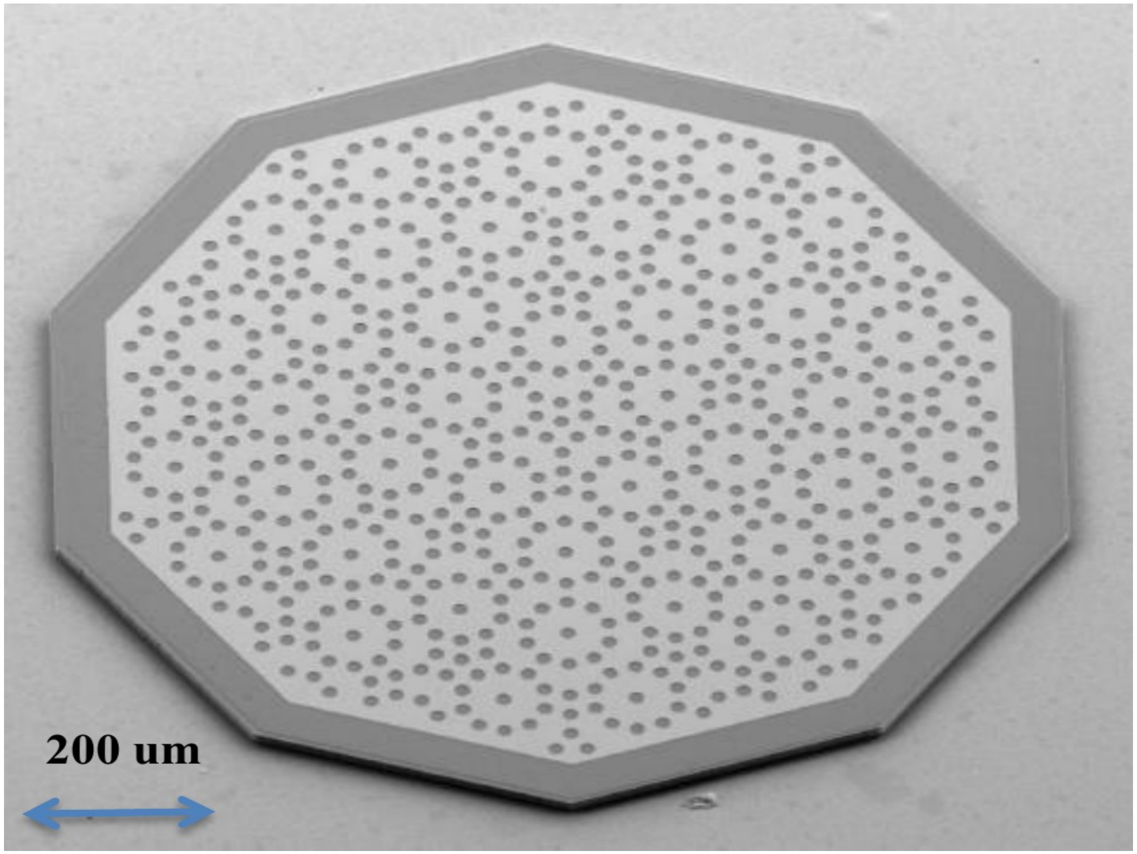
Penrose eigenmode

Real space

Reciprocal space



Fabricated devices



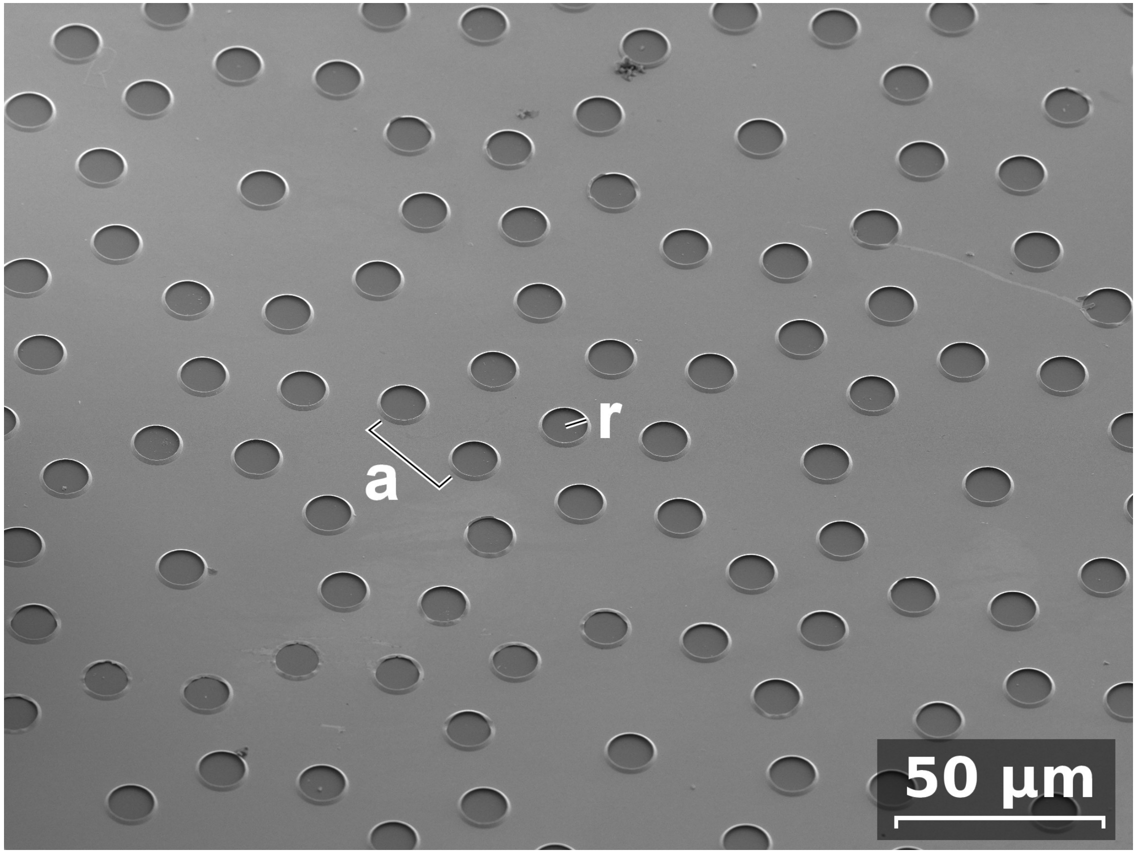
Gain band:
2.9 - 3.4 THz

Pattern tuning

Nearest neigh.
a = 21-23 um

Hole radius
r/a = 0.26-0.33

Fabricated devices



Gain band:
2.9 - 3.4 THz

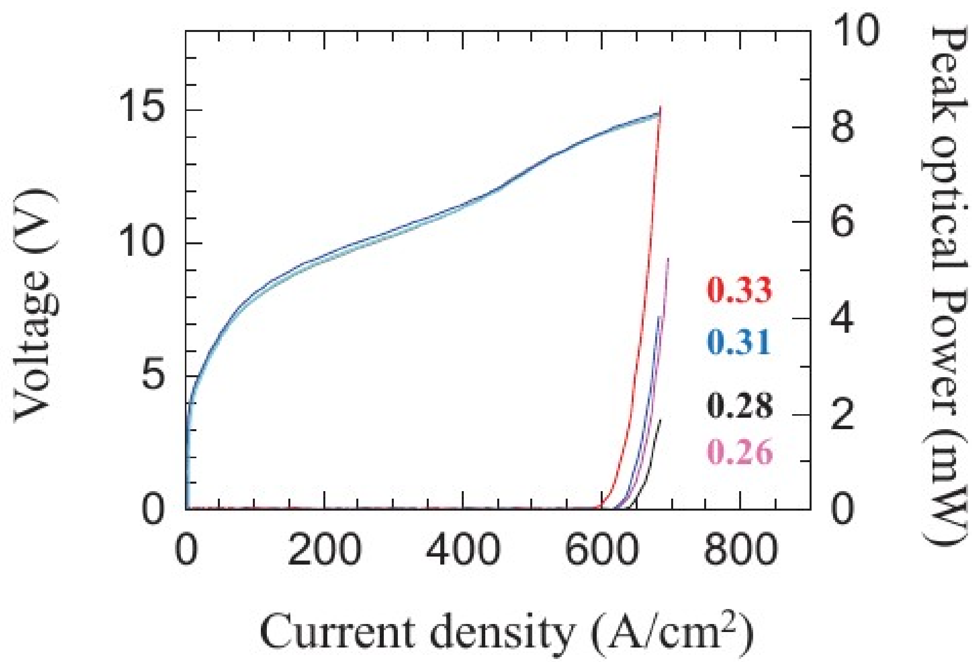
Pattern tuning

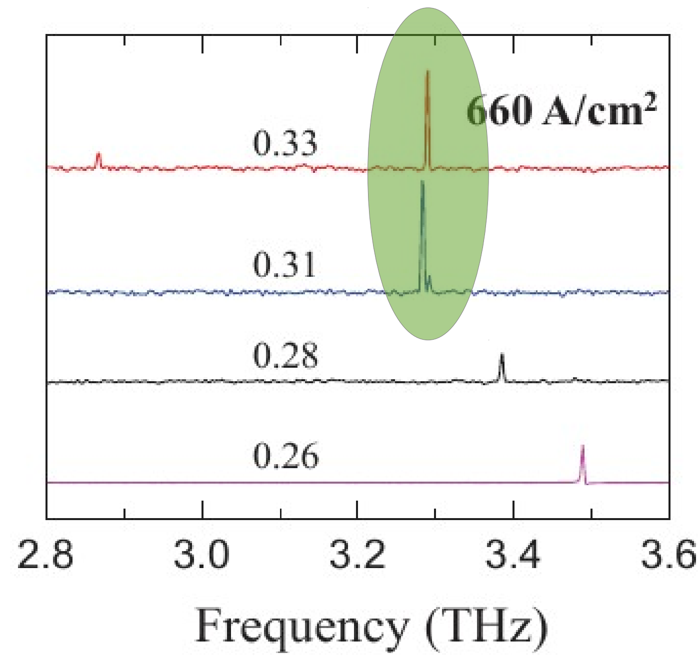
Nearest neigh.
a = 21-23 um

Hole radius
r/a = 0.26-0.33

Batch (a = 23 um)

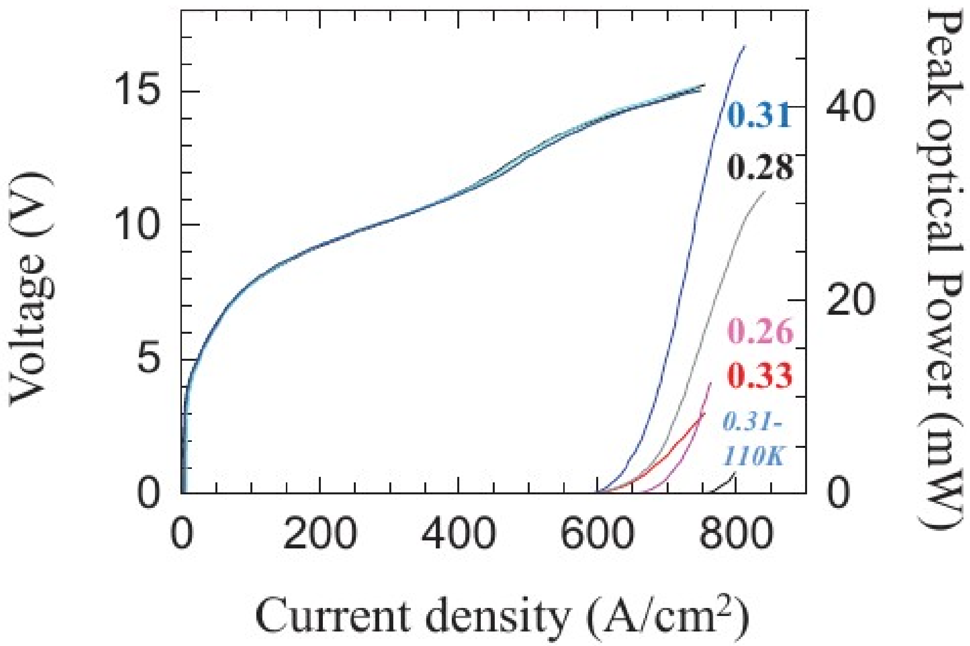
Moderate peak output power, single mode operation

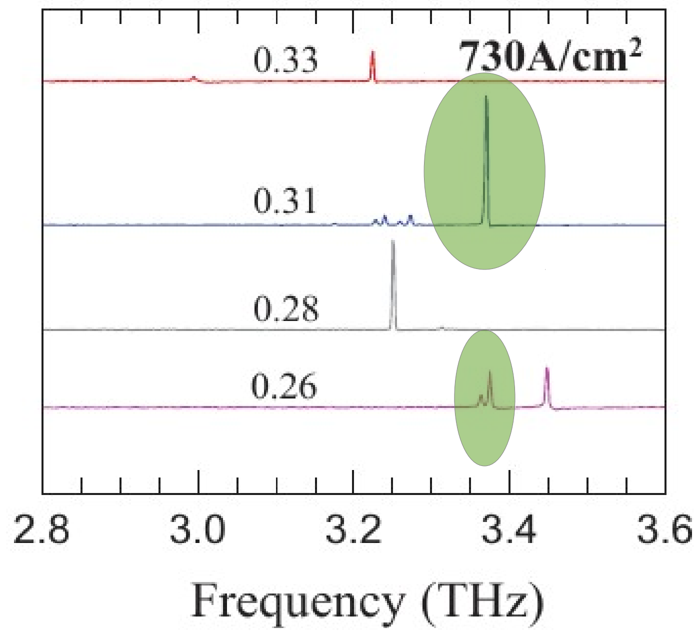




Batch (a = 22 um)

High peak output power, some mode competition

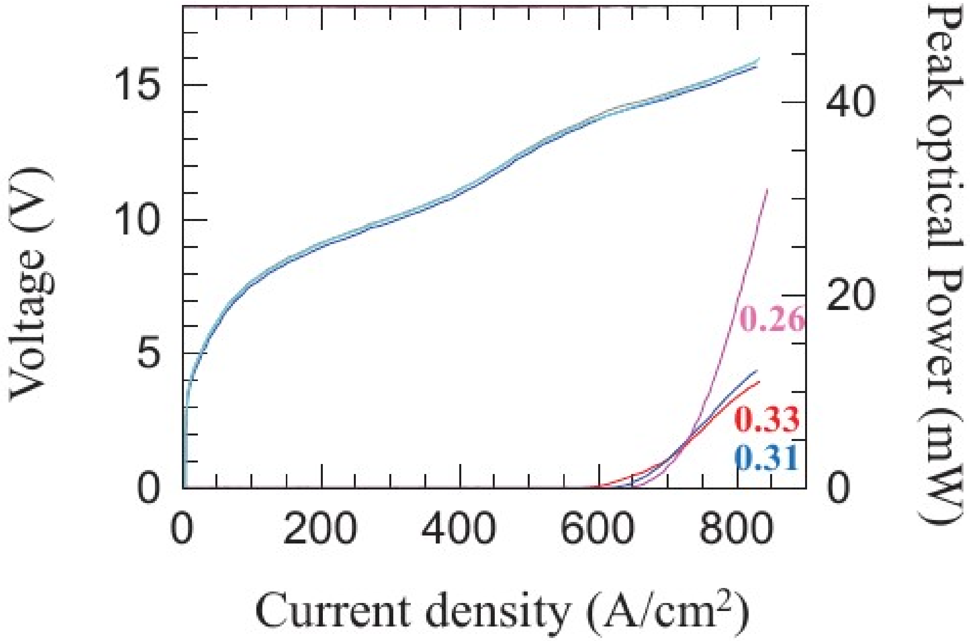


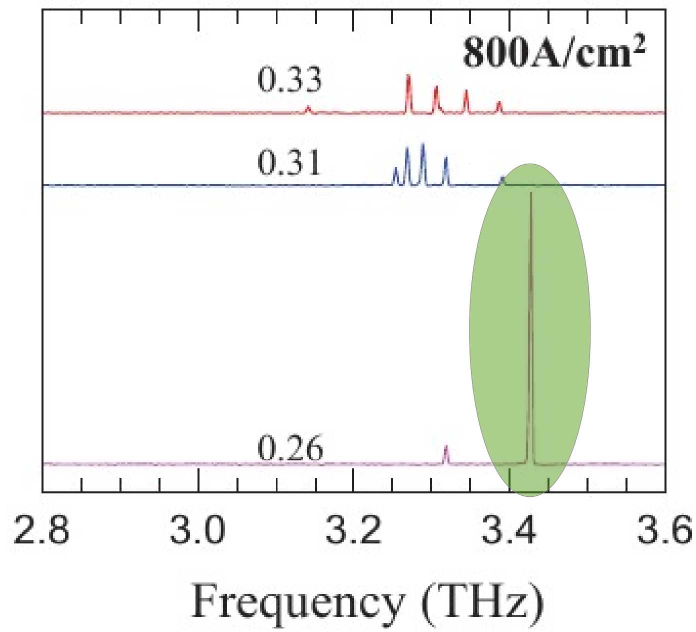


Batch (a = 21 um)

Just for the r/a = 0.26 device

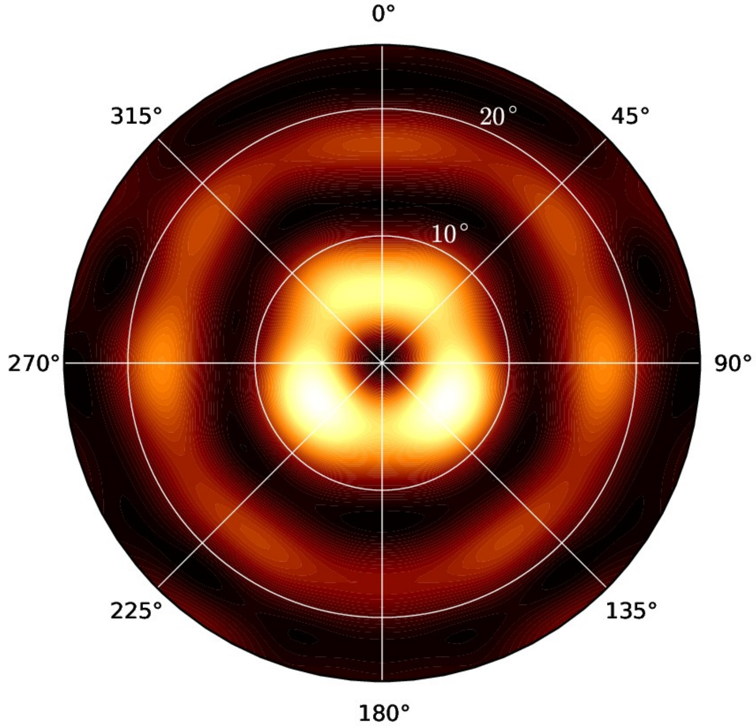
Considerable peak output power, ~single mode operation



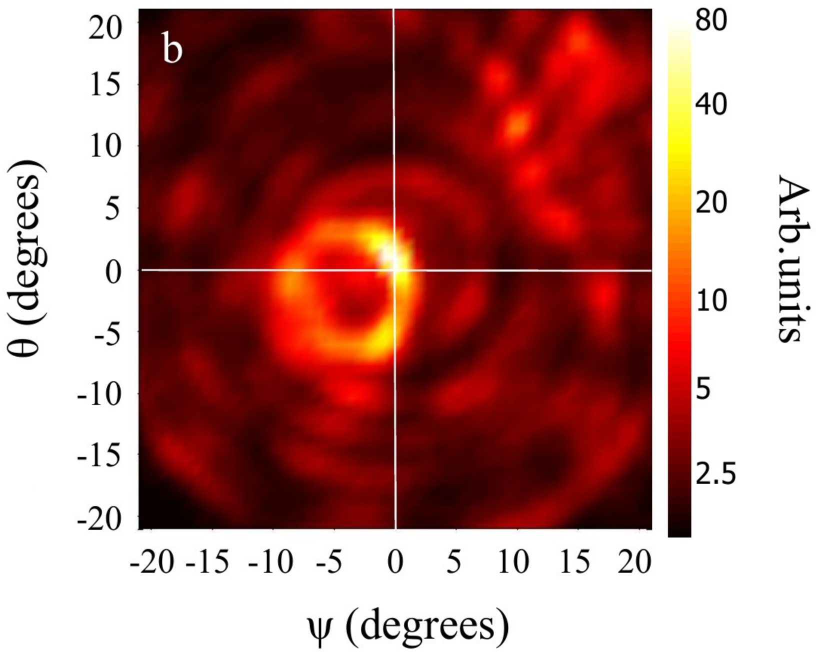


Far field

Numeric
(3D F.E.M.)



Measured far field
(a = 21, r/a = 0.26)



Summary

We designed, fabricated and characterized double metal THz QCLs based on quasiperiodic Penrose DFB pattern.

The Penrose design allows to reach sizeable output power, with radiative performance figures already comparable to the best vertical-emitting devices so far.

For our best device: P_{out} > 45 mW
W.P.E. ~ 0.6 ‰
T_{max} ~ 110K

Quasiperiodic lattices represent a robust design strategy for the realization of vertical emitting DFB resonators.

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Thank you for your attention

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FUTURO IN RICERCA
Starting Grant "FRONTera"

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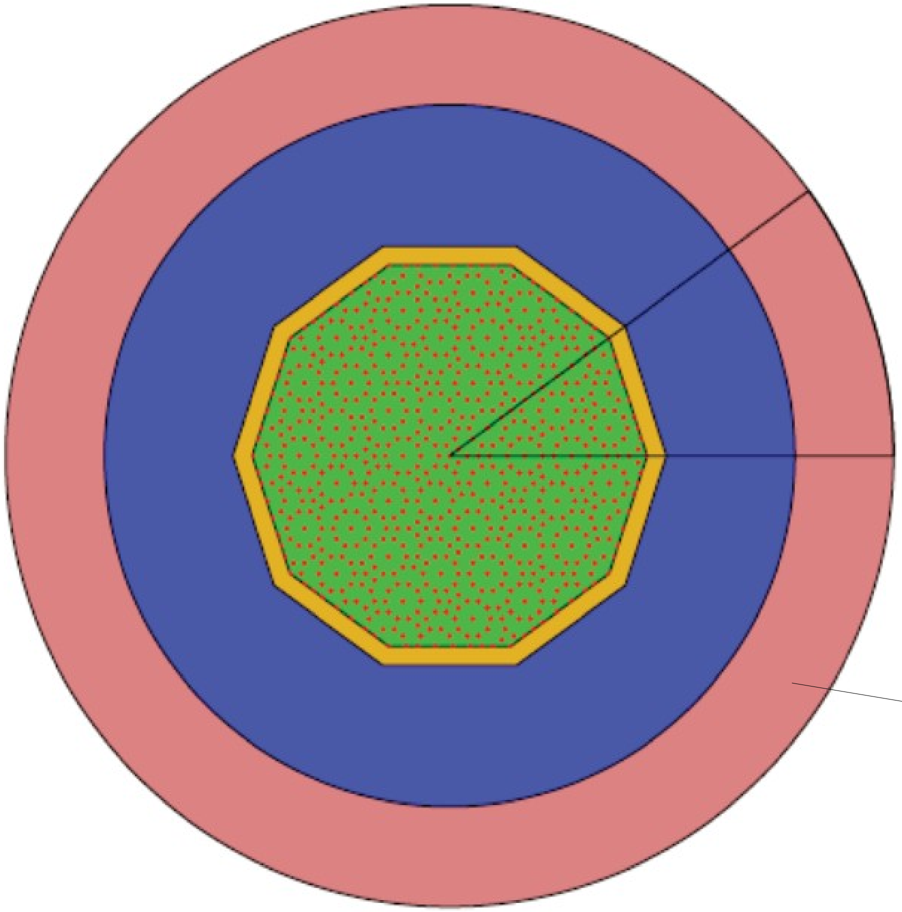
2D FEM calculation



Metal $n_{eff} = 3.6$

Hole $n_{eff} = 2.8$

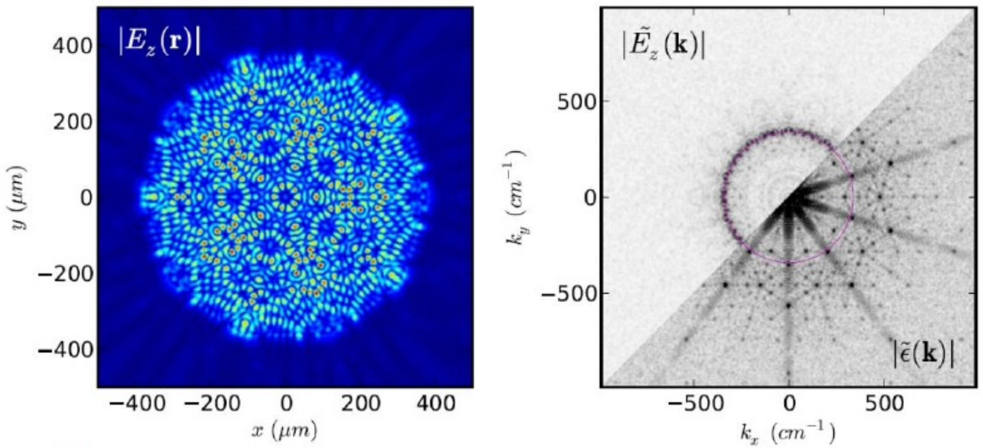
Border $n_{eff} = 3.6+i$

Air $n_{eff} = 1$

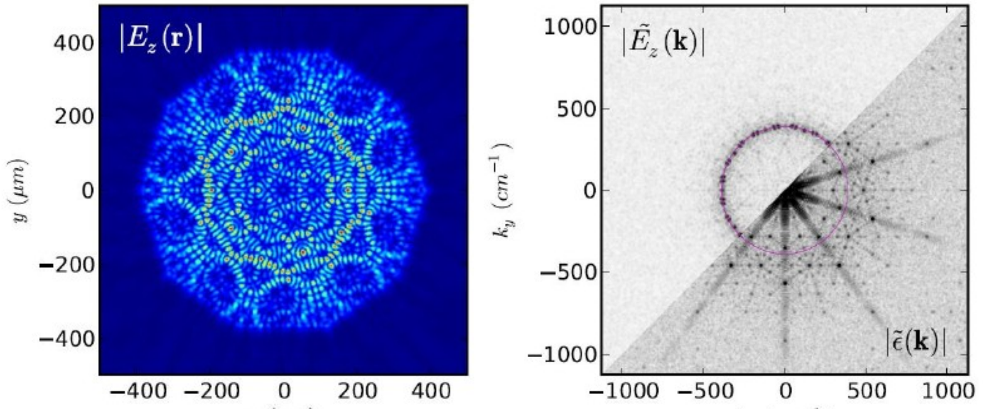
P.M.L.
(open boundary)

Other eigenmodes

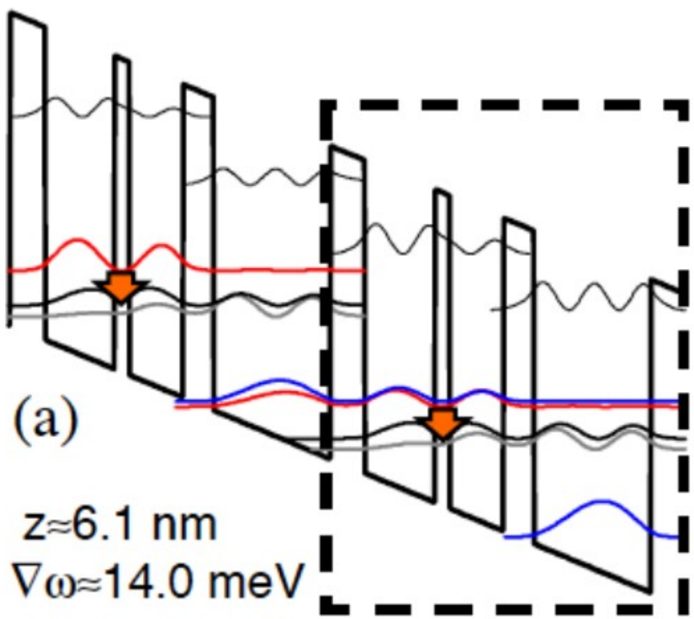
H mode



L mode



L341 active region



M. Belkin et al. Optics Express 16, 3242 (2008)

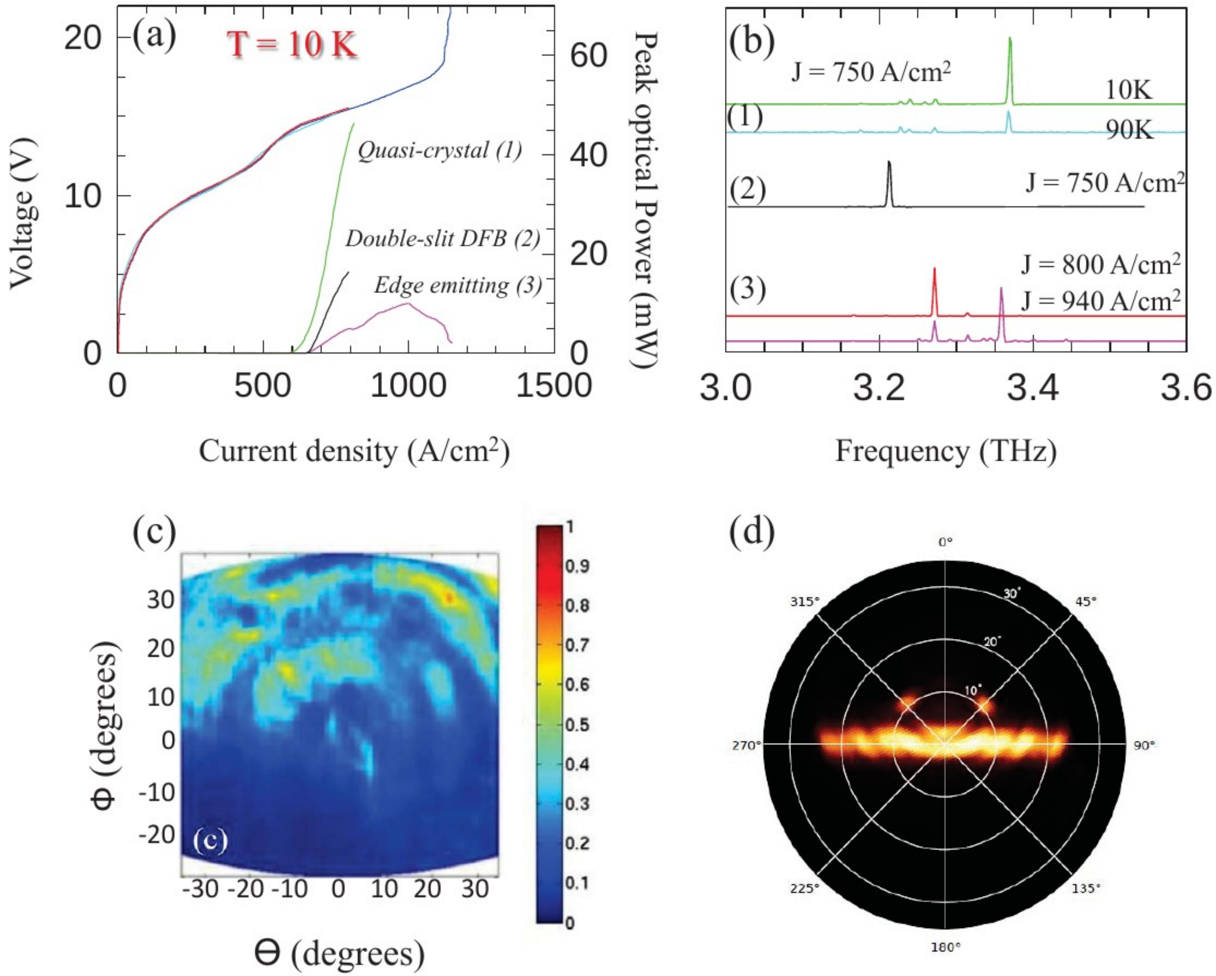
Three-well resonant-phonon QCL ➔

- Quite large gain bandwidth (600 GHz)
- Main optical mode can be easily tuned by ≈13% of its central frequency

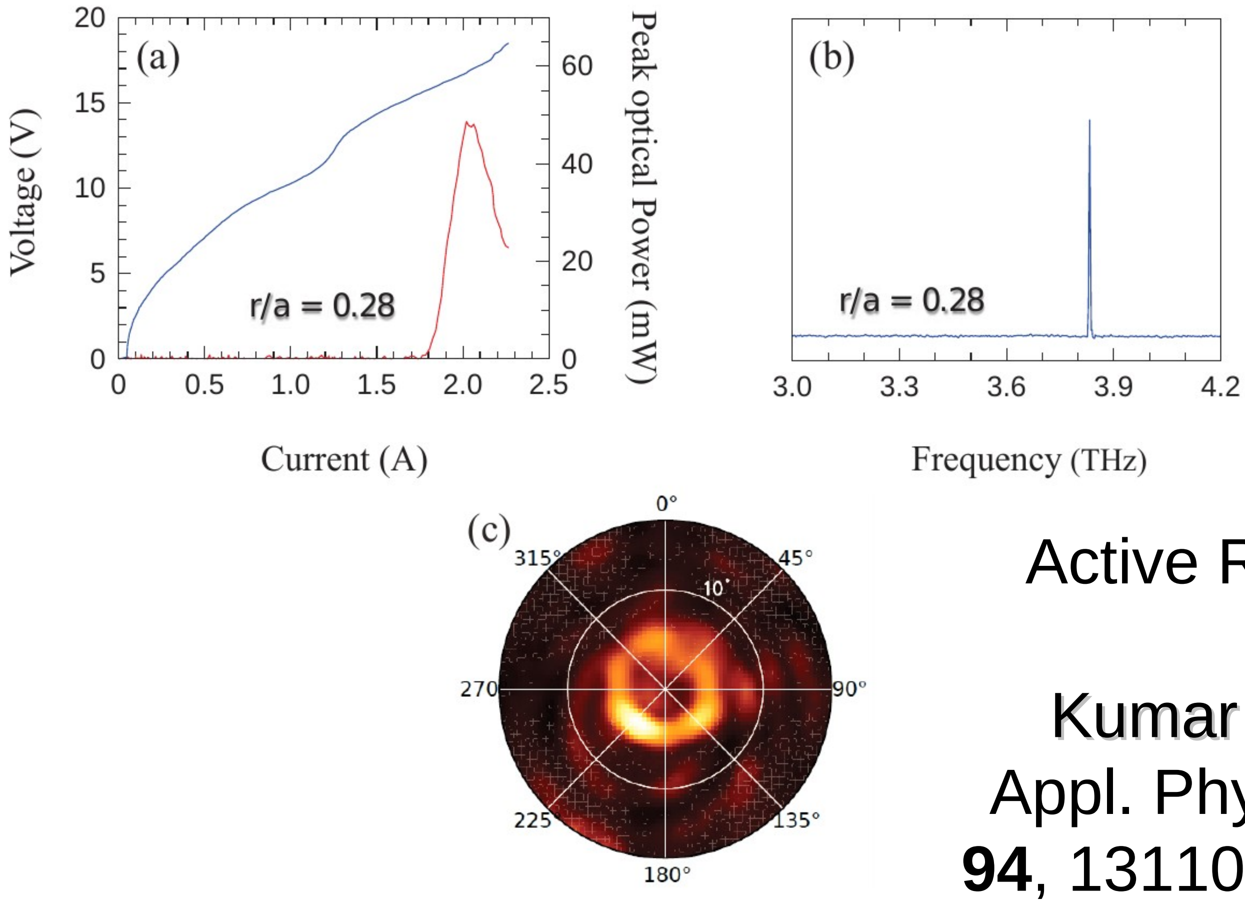
Double-metal waveguide ➔

- THz radiation confined in the direction of growth (vertical, z-axis)
- propagation in the *x-y* plane ➔ device is a nearly ideal 2D system

L341 active region



Prototype Device



Active Region

Kumar *et al.*
Appl. Phys. Lett.
94, 131105 (2009)