PRINCETON UNIVERSITY

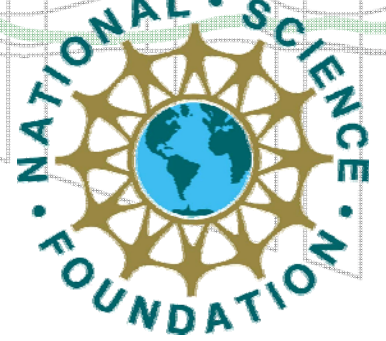
University of Sheffield

# High *k*-Space Lasing in Excited State Quantum Cascade Lasers

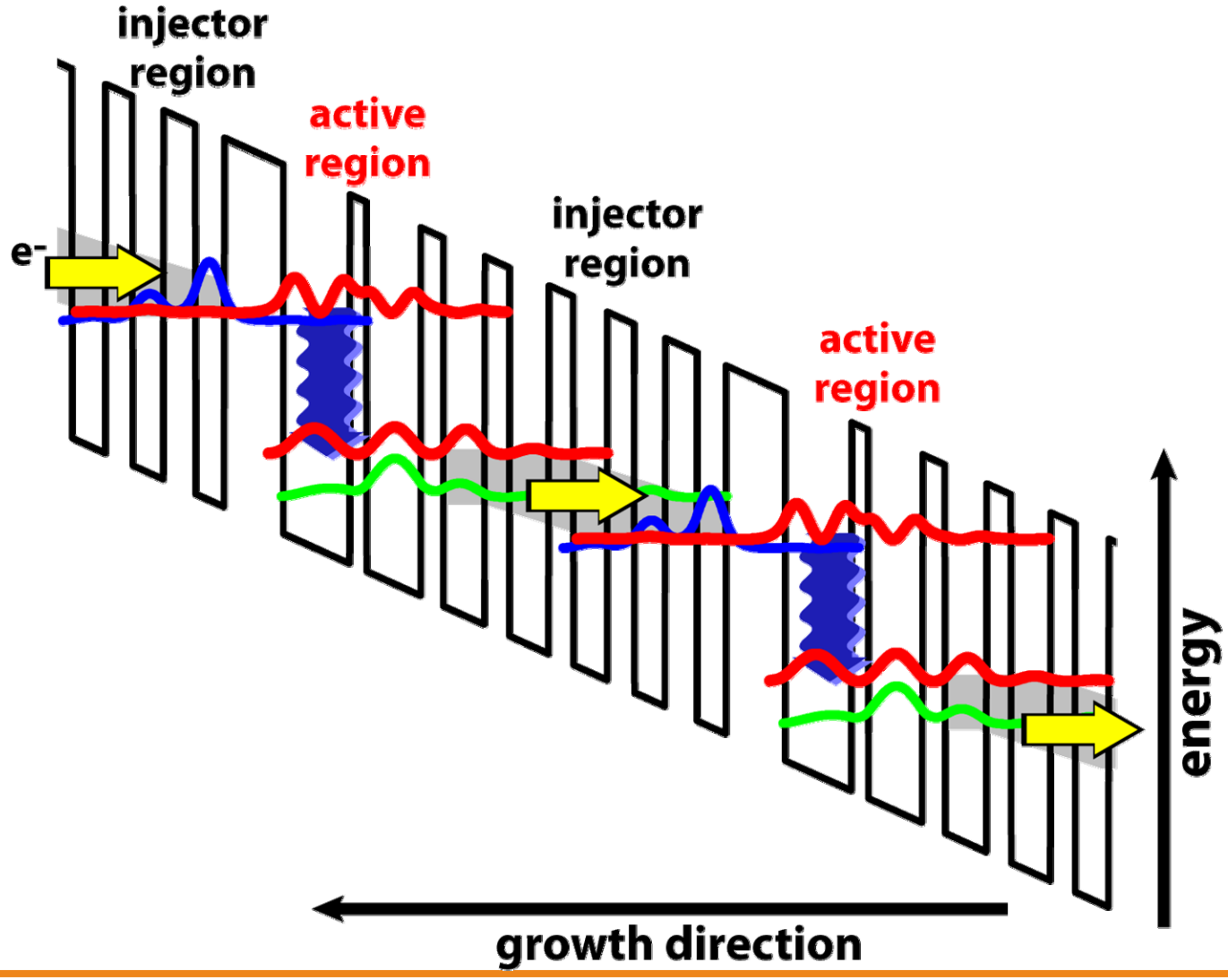

Kale J. Franz,[1] Stefan Menzel,[1,2] Anthony J. Hoffman,[1]
Dan Wasserman,[1,3] John W. Cockburn,[2] and Claire Gmachl[1]

*[1] Department of Electrical Engineering, Princeton University*
*[2] Department of Physics & Astronomy, University of Sheffield*
*[3] Currently: Department of Physics, University of Massachusetts, Lowell*

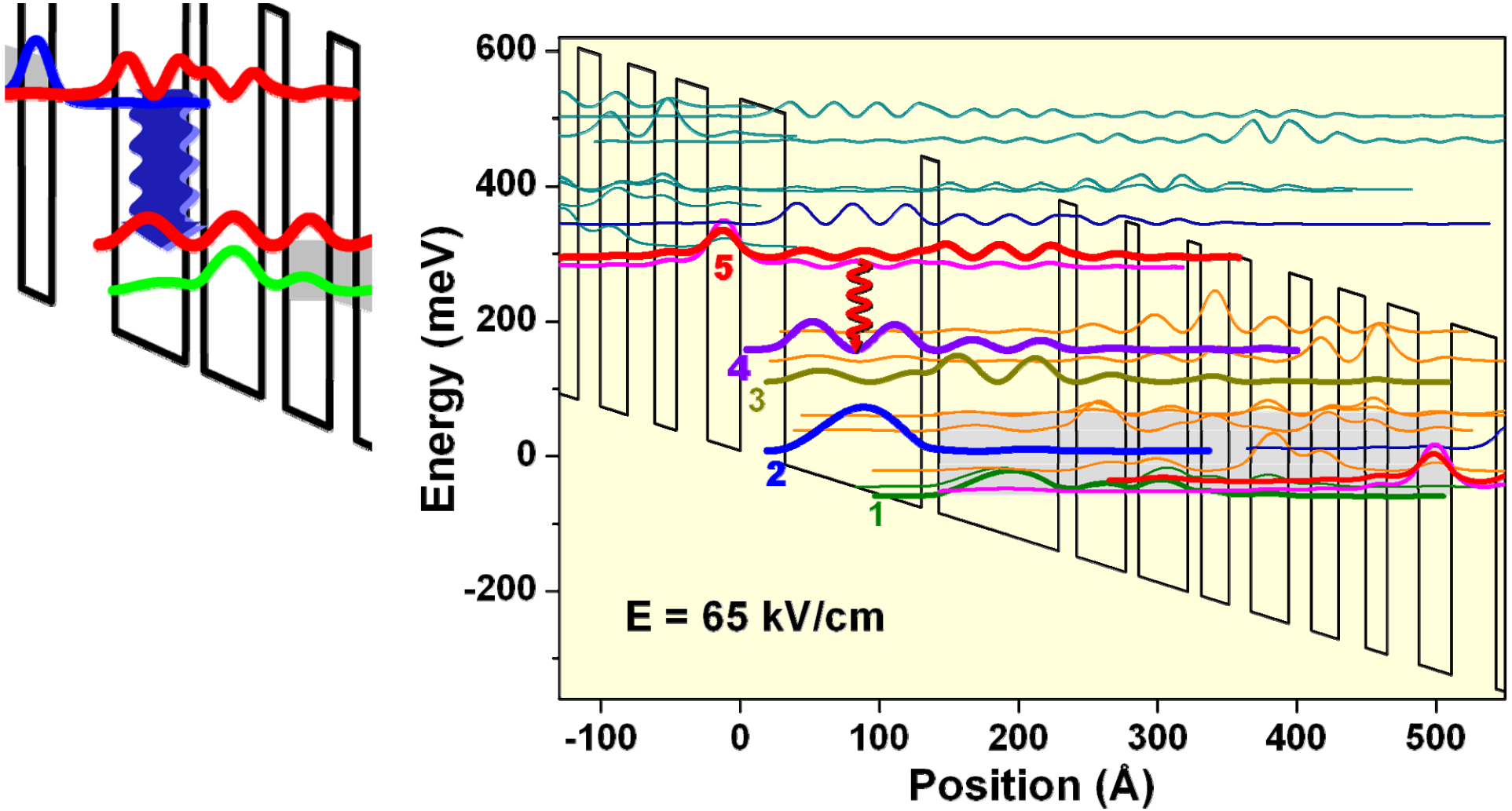




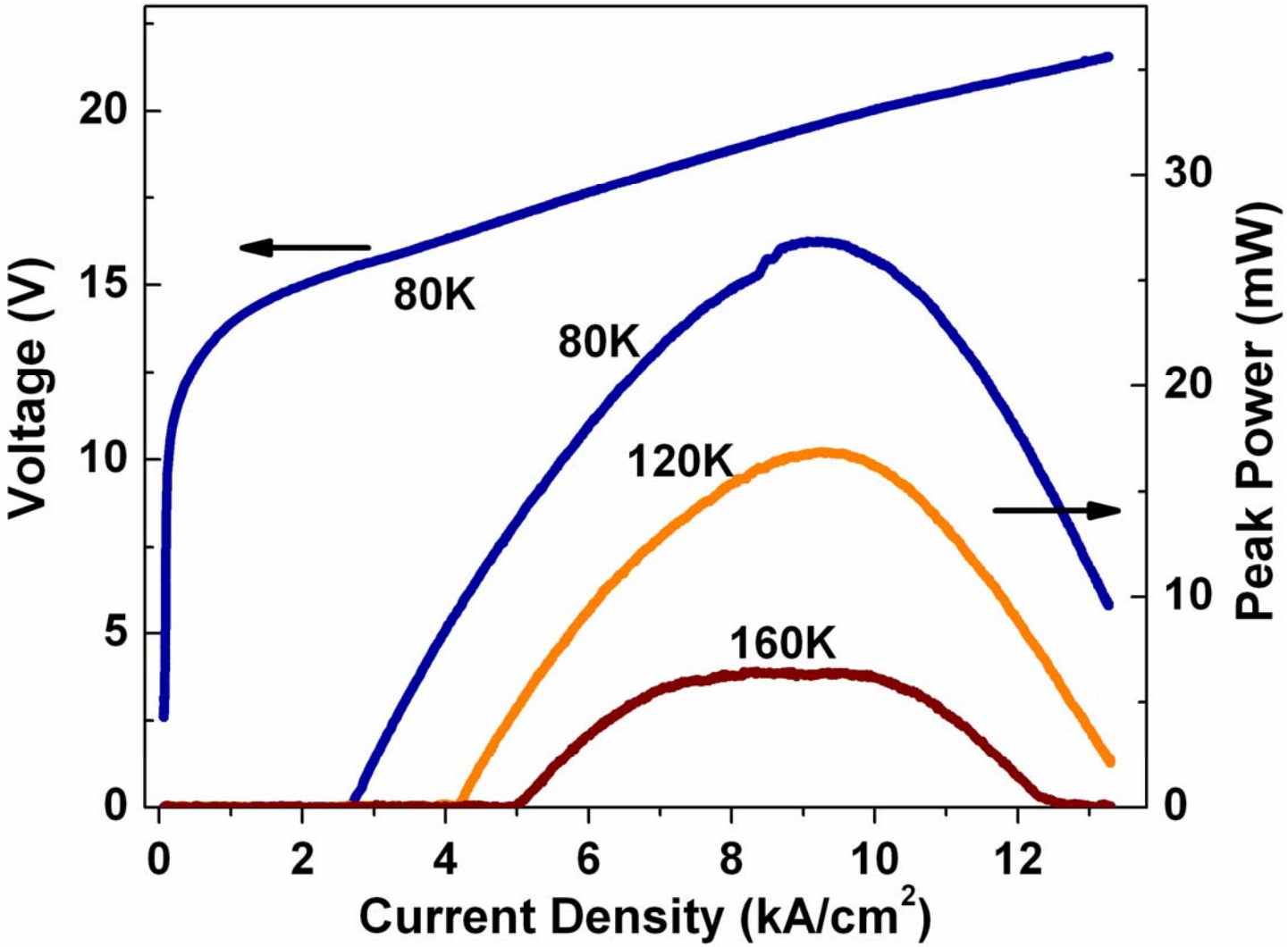
# Quantum Cascade Lasers



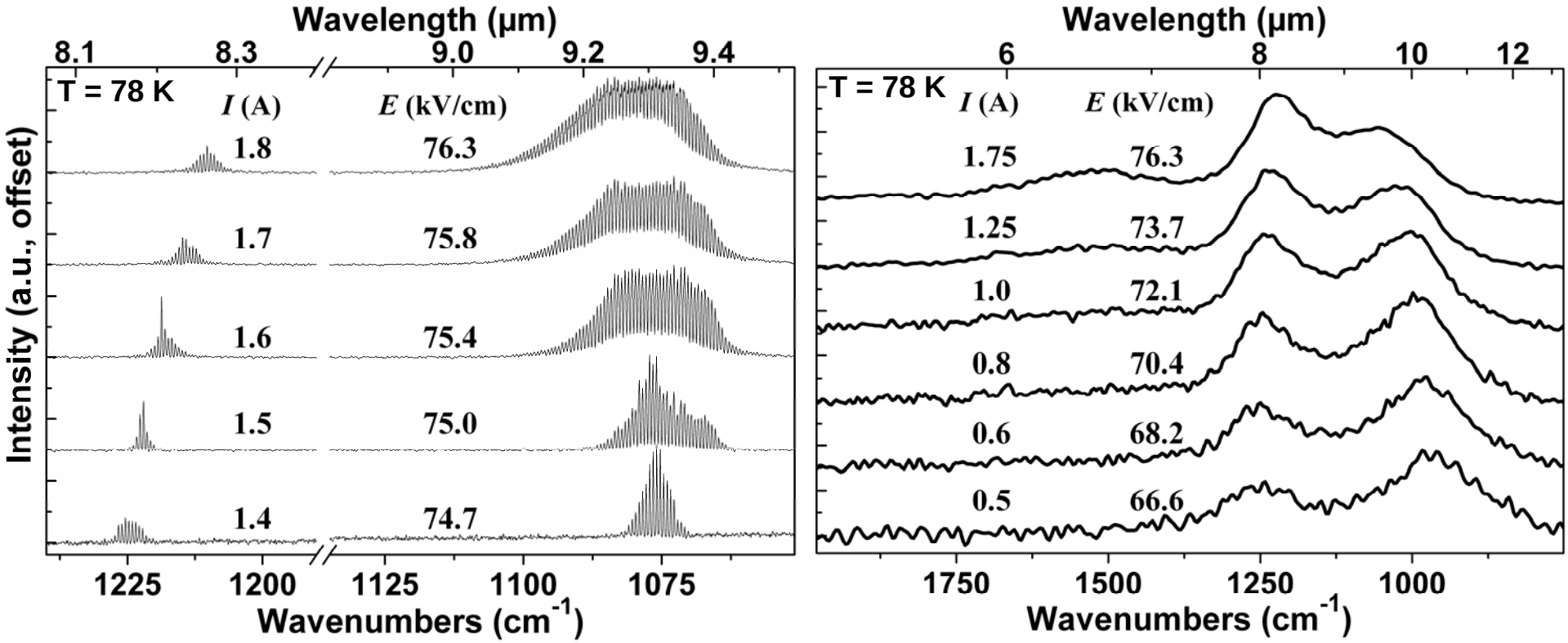
# 9.5 μm Excited State Laser



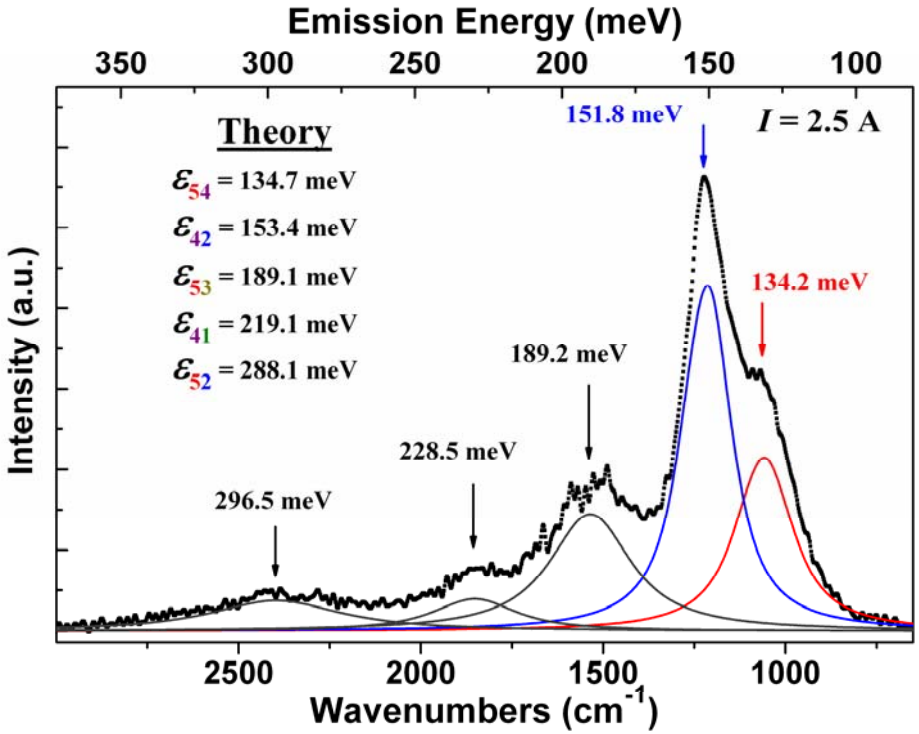
# Excited State QC Laser
# Current – Voltage Curves

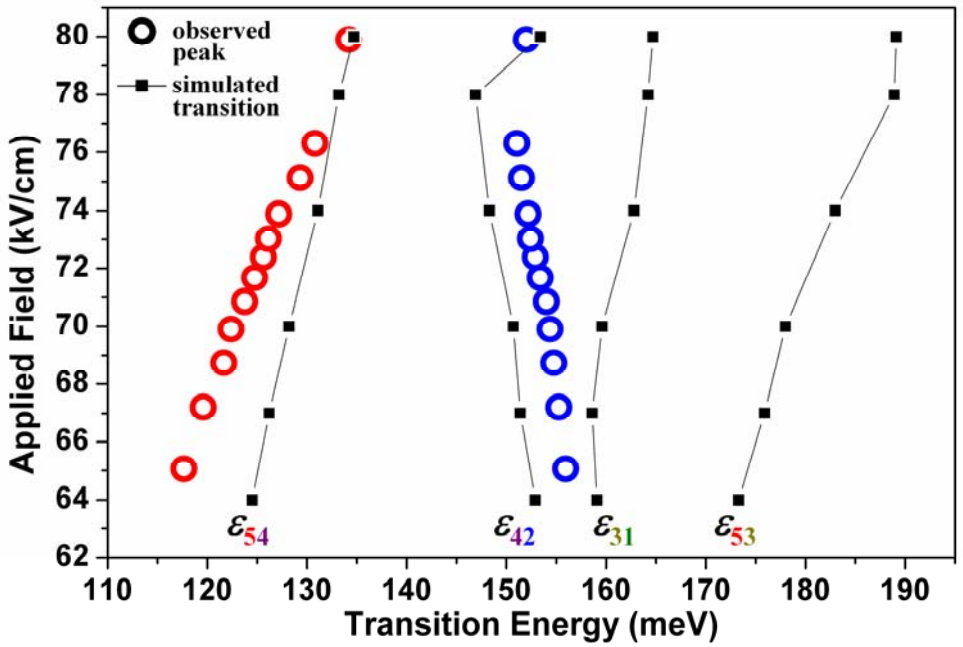


# Excited State Emission

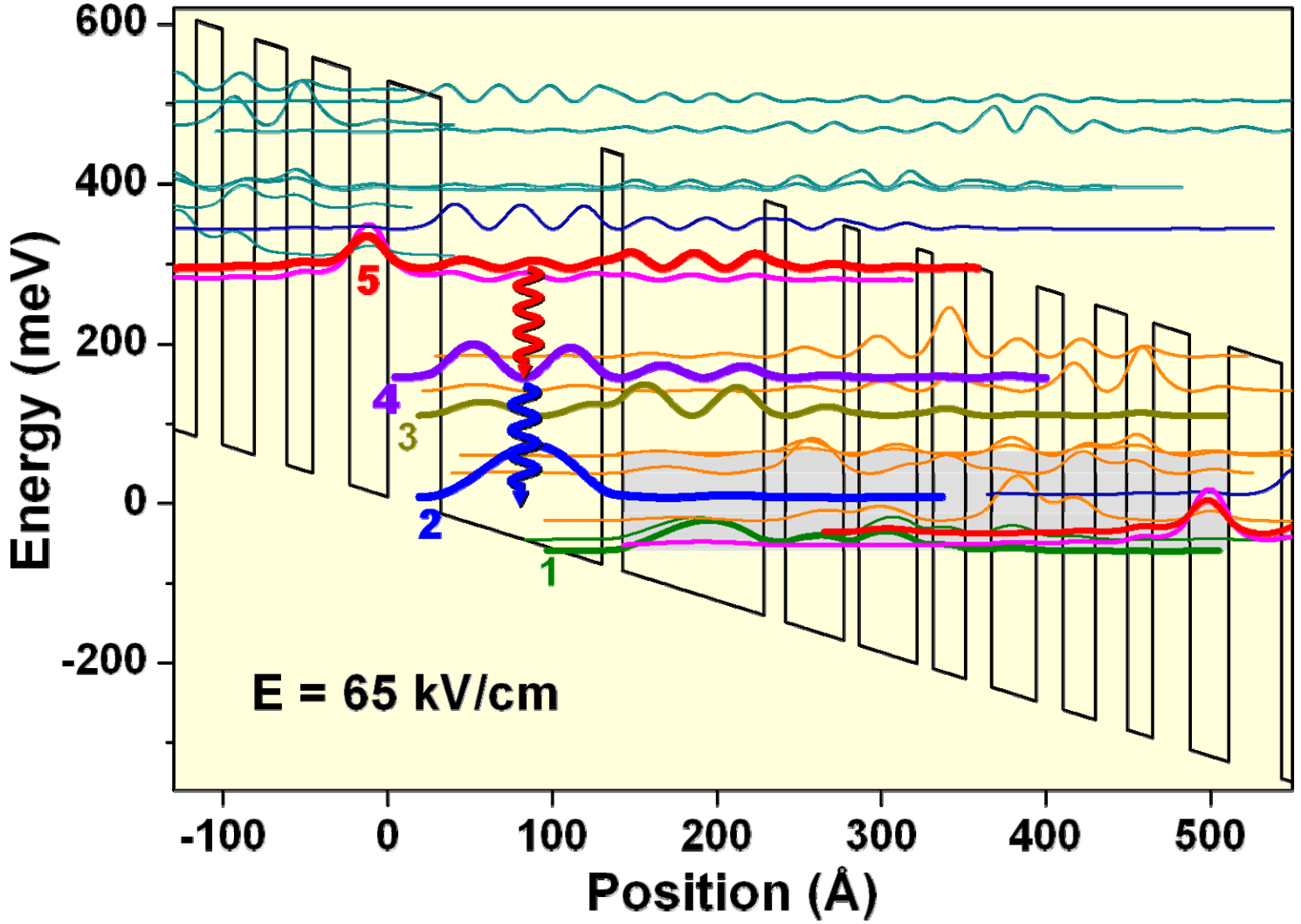


# Transition Identification

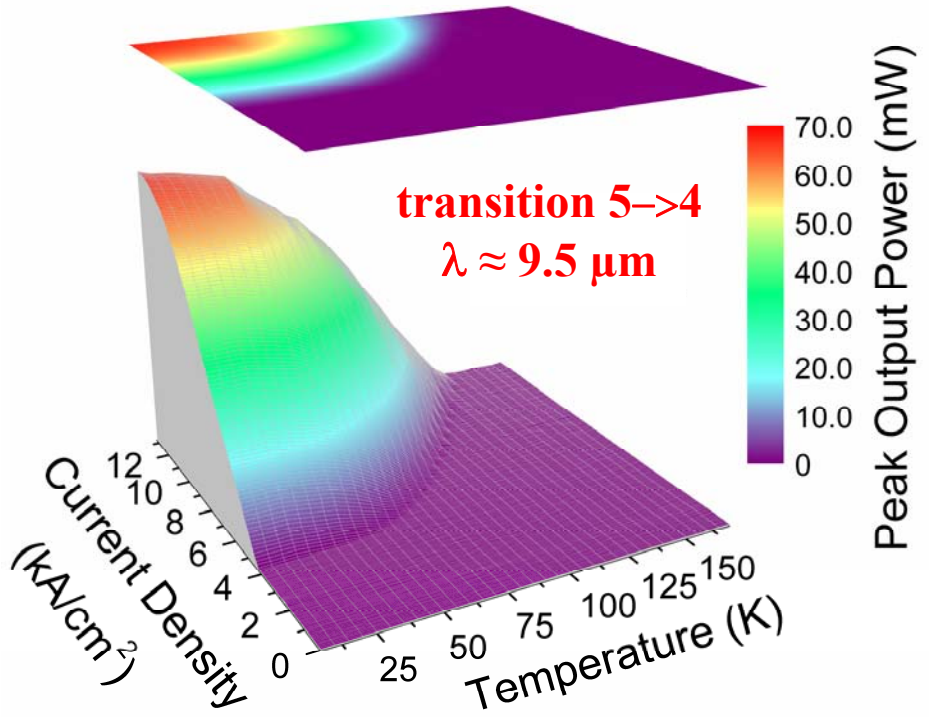


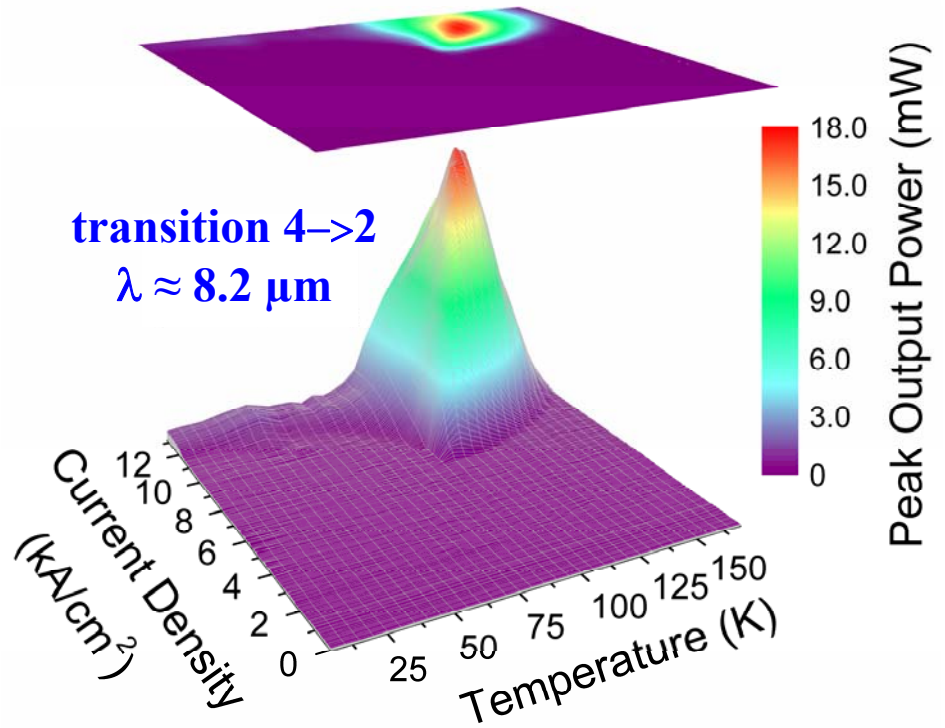



# Stacked Transitions

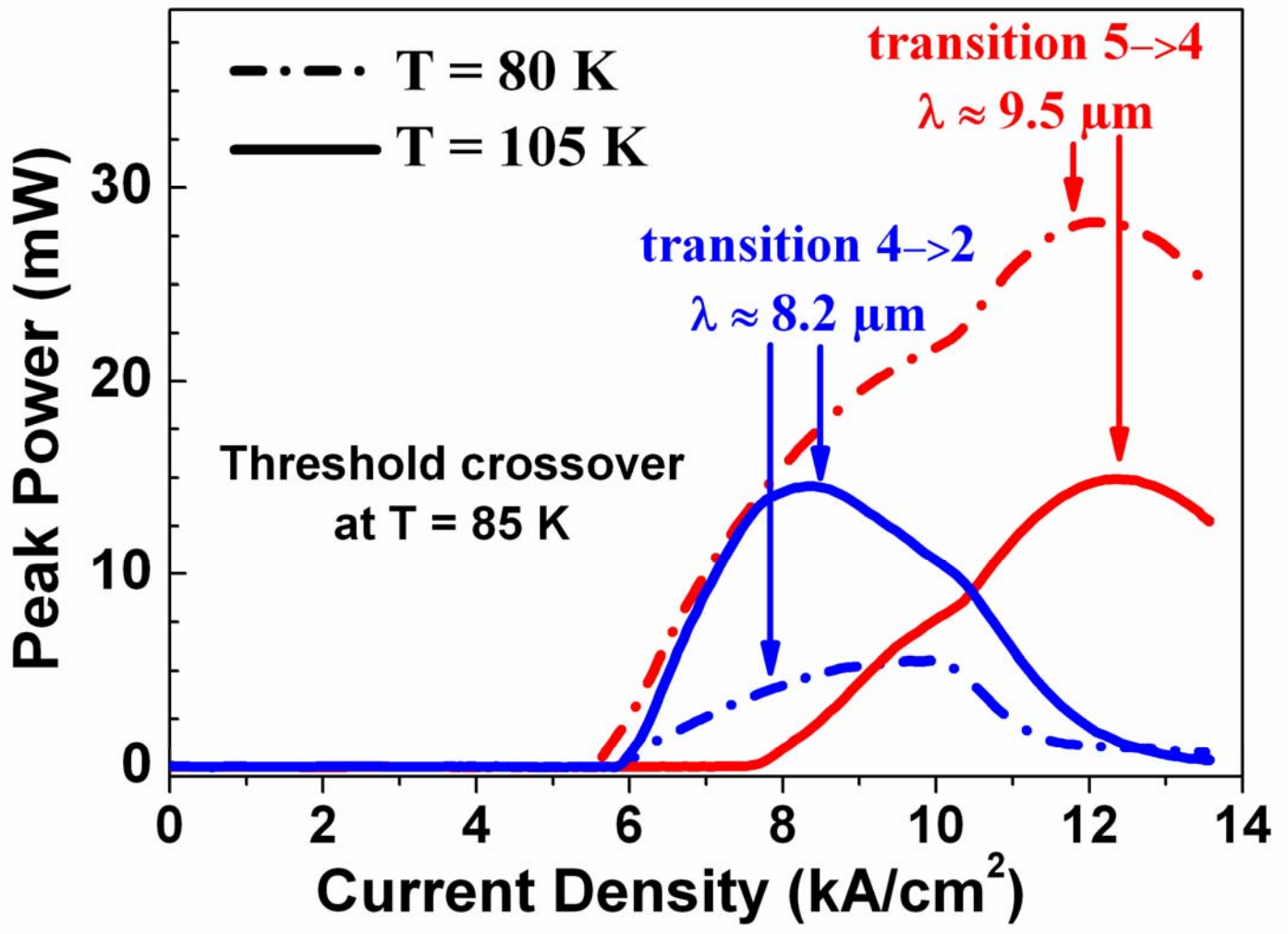


# Light – Current Data

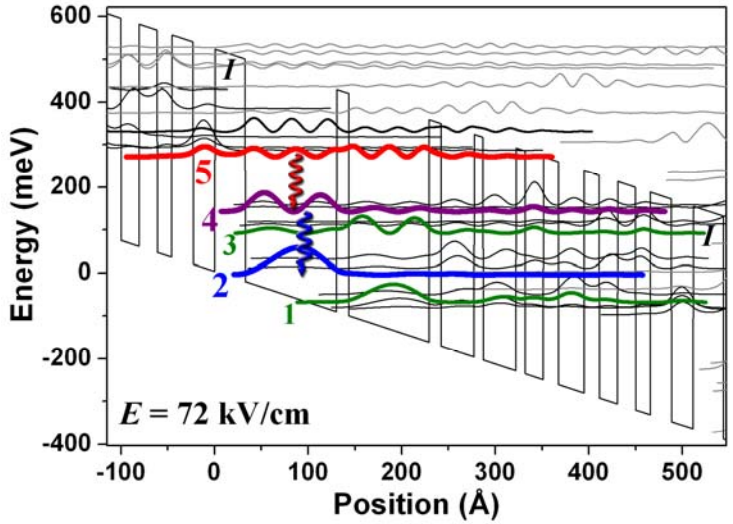


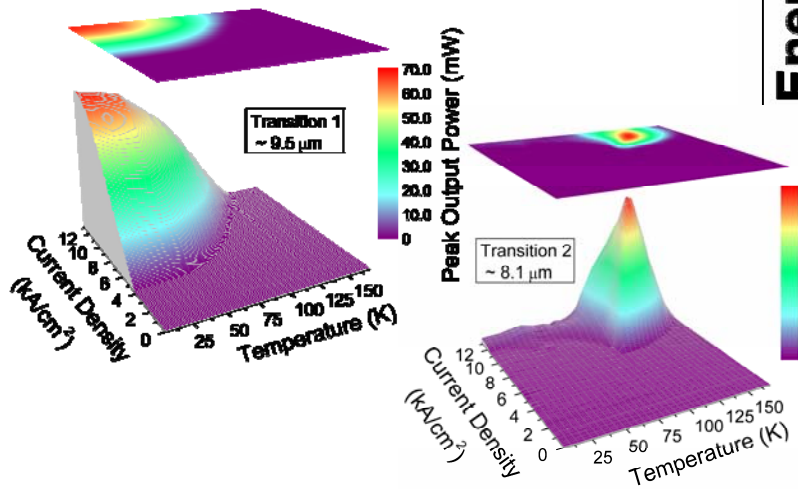



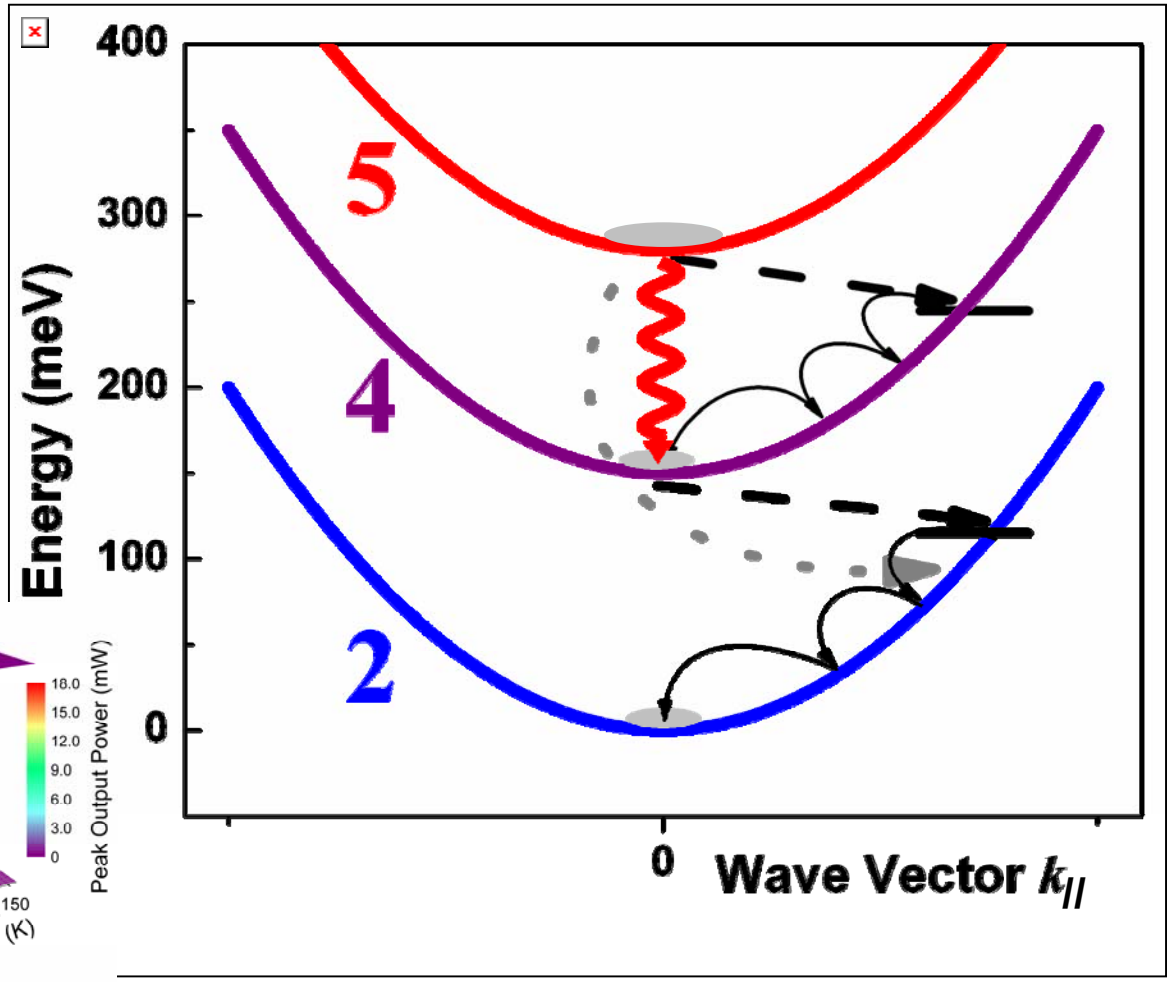
# Light – Current Cross Section



# High *k*-Space Model



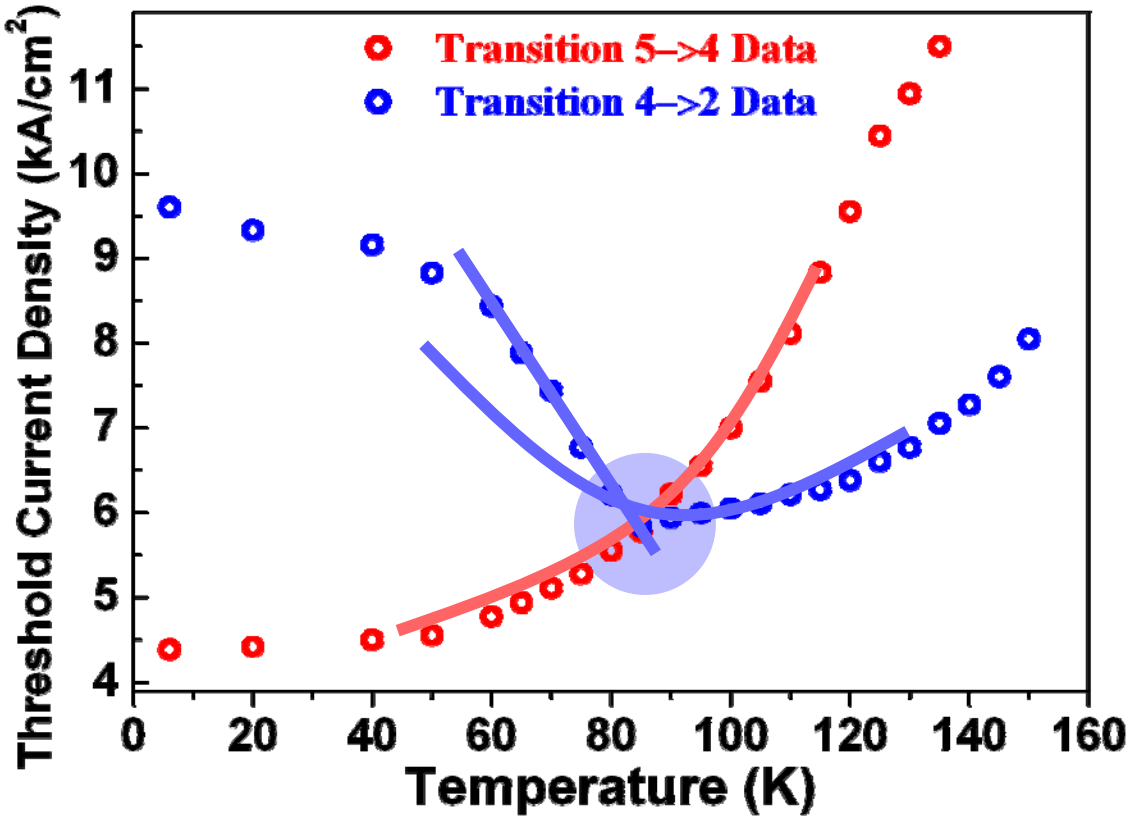



# Transition Thresholds

## Unique Features

1. Crossing of thresholds
2. Negative characteristic temperature
3. Sharp kink at threshold crossing



# Rate Equation Model

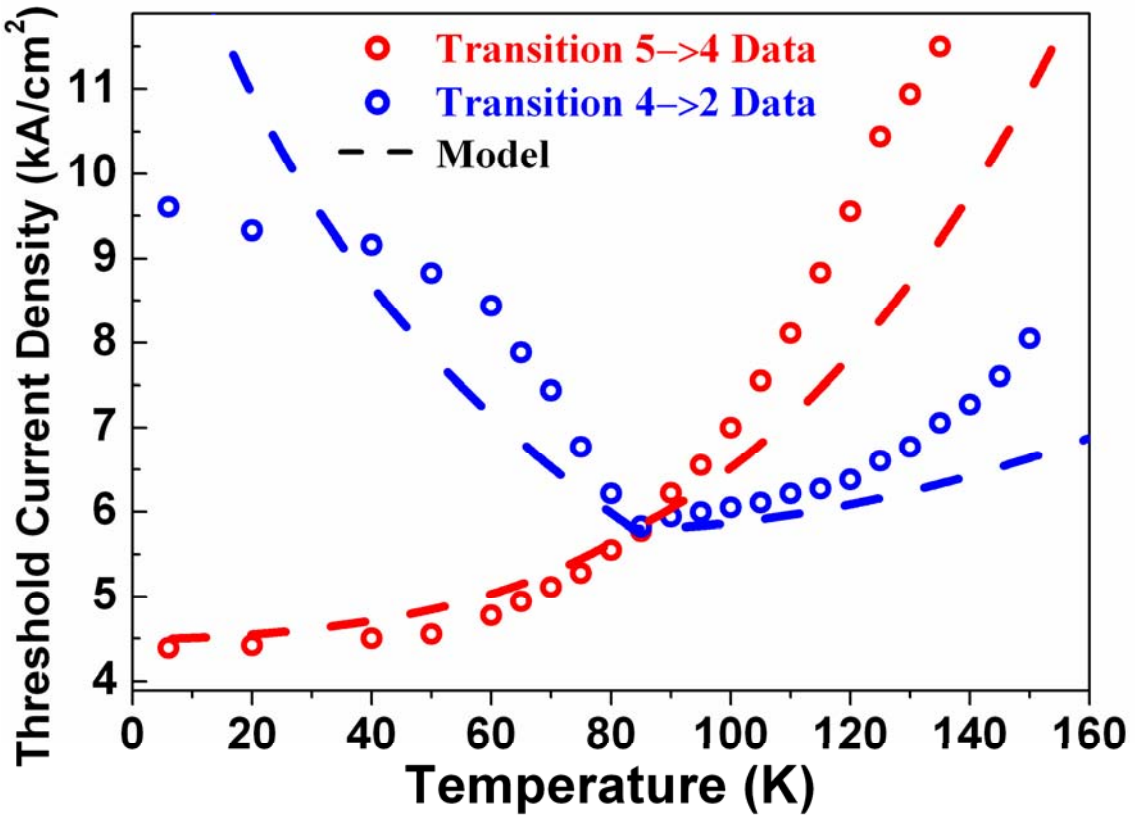
$$\frac{dN_5}{dt} = \eta\frac{J}{q} - \frac{N_5}{\tau_5(T)} - \frac{1}{N_p}\frac{c_0}{n_{eff}}g_c(N_5 - N_4)S_{54}$$

$$\frac{dN_{4k}}{dt} = (1-\eta)\frac{J}{q} + \frac{N_5}{\tau_{54}(T)} - \frac{N_{4k}}{\tau_{4k}(T)} - \frac{1}{N_p}\frac{c_0}{n_{eff}}g_c(N_{4k} - N_{2k})S_{42}$$

…

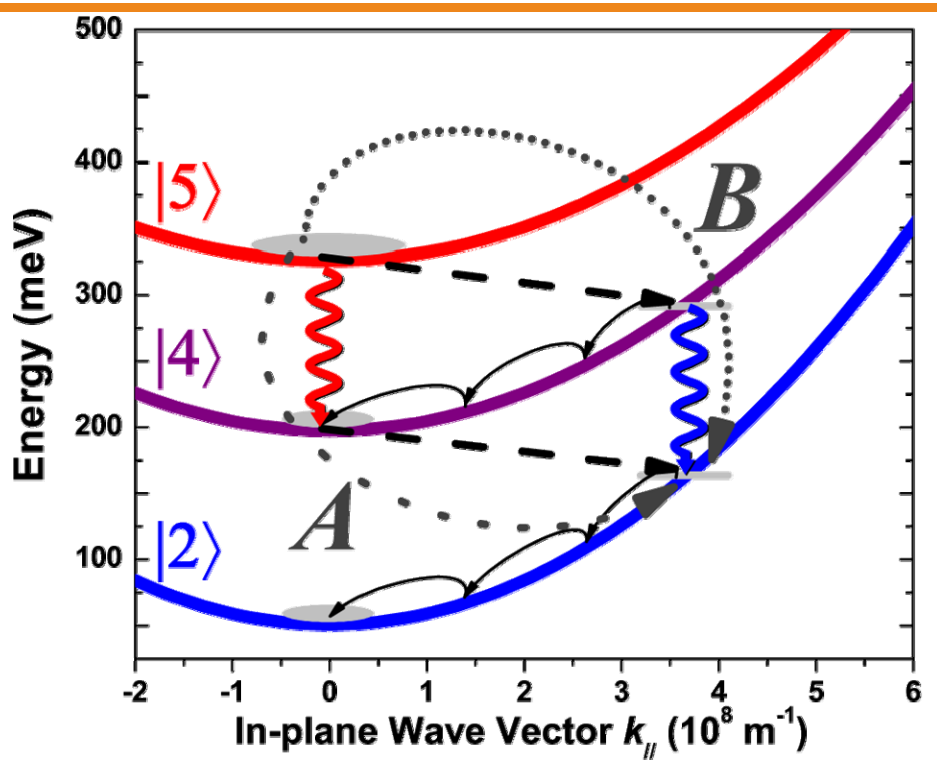
$$\frac{dS_{u\ell}}{dt} = \Gamma\frac{c_0}{n_{eff}}g_c(N_u - N_\ell)S_{u\ell} - \frac{S_{u\ell}}{\tau_{ph}}$$

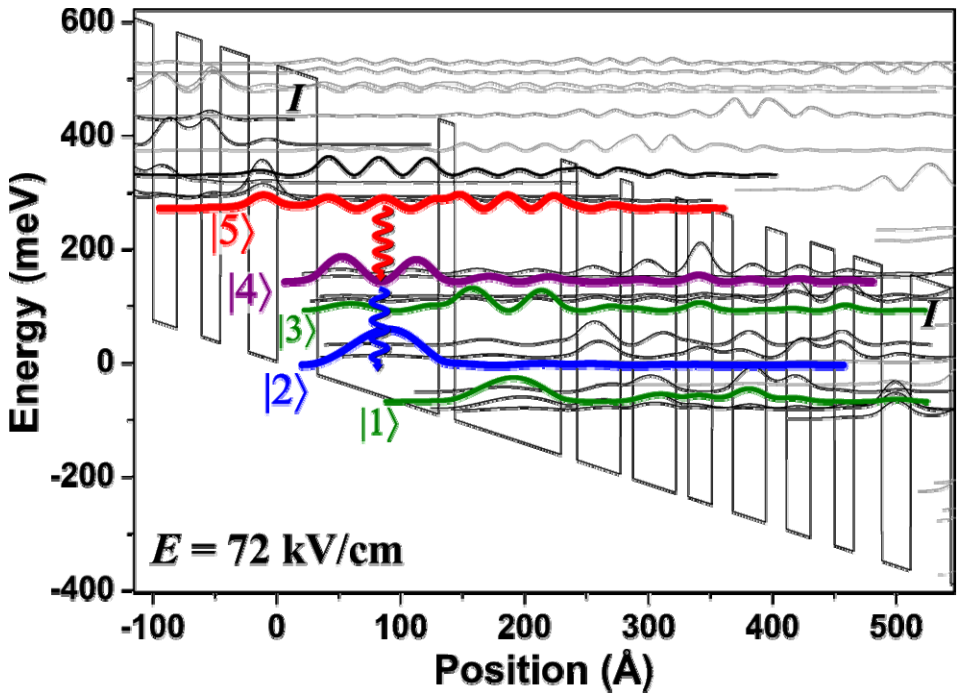
$$g_c = \frac{2q^2 E_{u\ell} z_{u\ell}^2}{\hbar c_0 \varepsilon_0 n_{eff} L_p \delta E_{u\ell}}$$

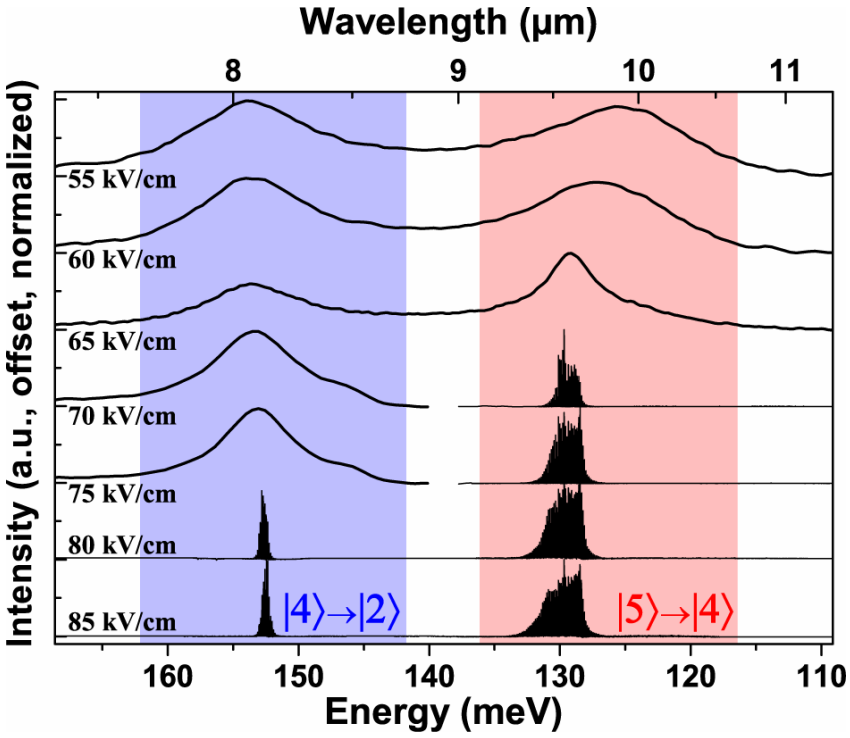


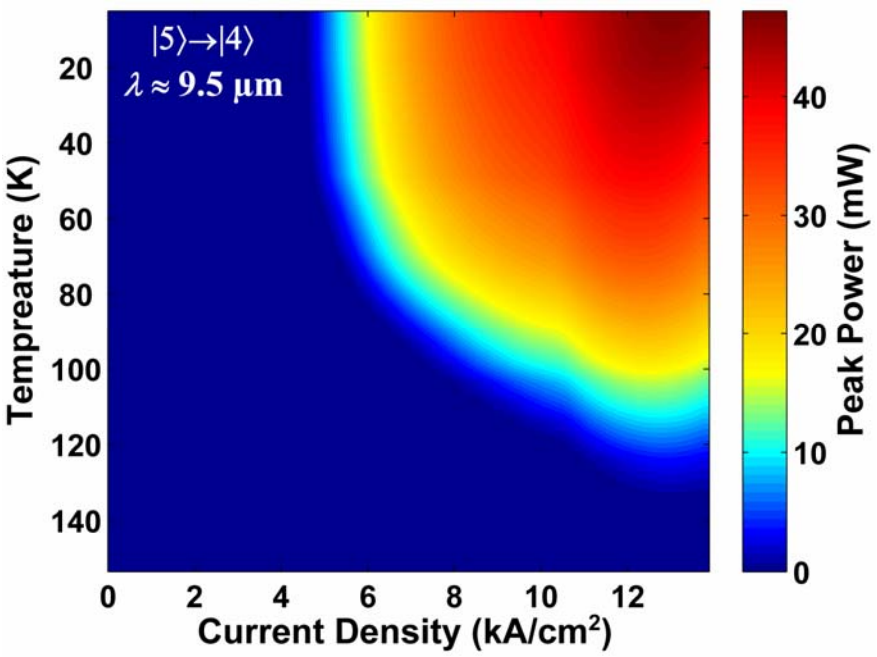
# Summary

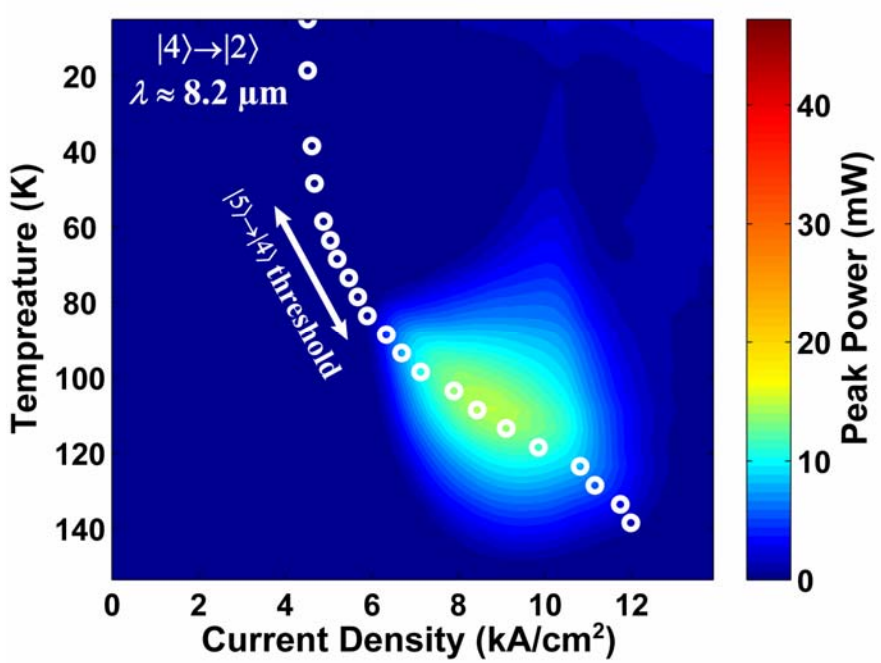
- Investigation of excited state QC lasers
- Dual wavelength emission
- Lasing high in *k*-space

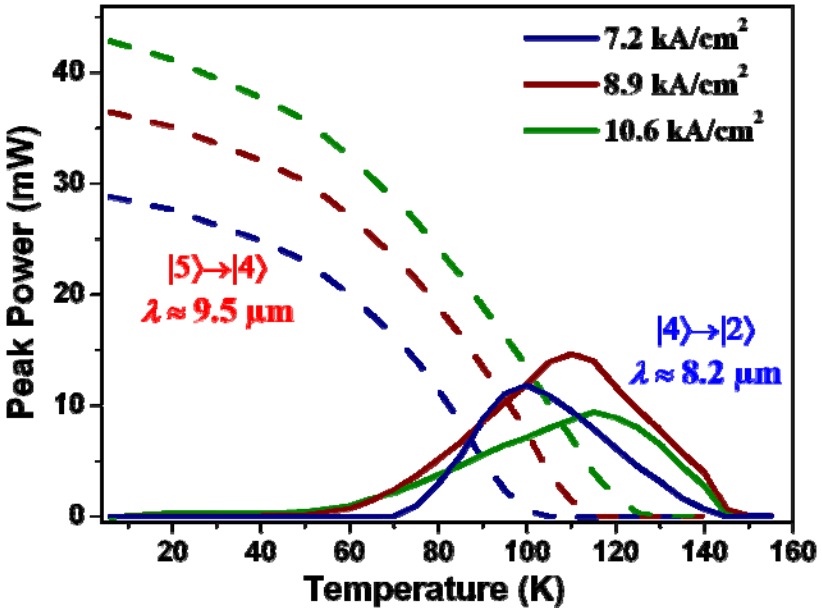


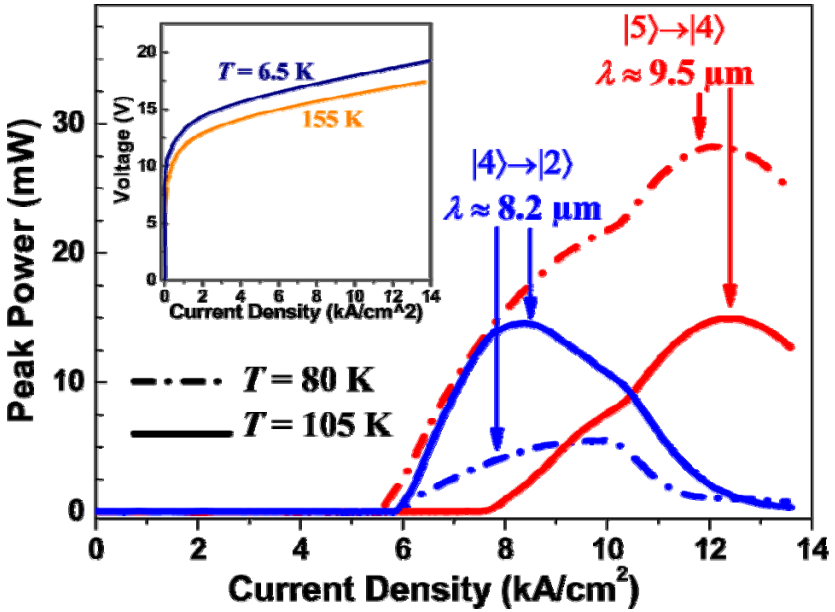

600
400
200
0
-200
-400
Energy (meV)
-100
0
100
200
300
400
500
Position (Å)
I
|5⟩
|4⟩
|3⟩
|2⟩
|1⟩
I
E = 72 kV/cm

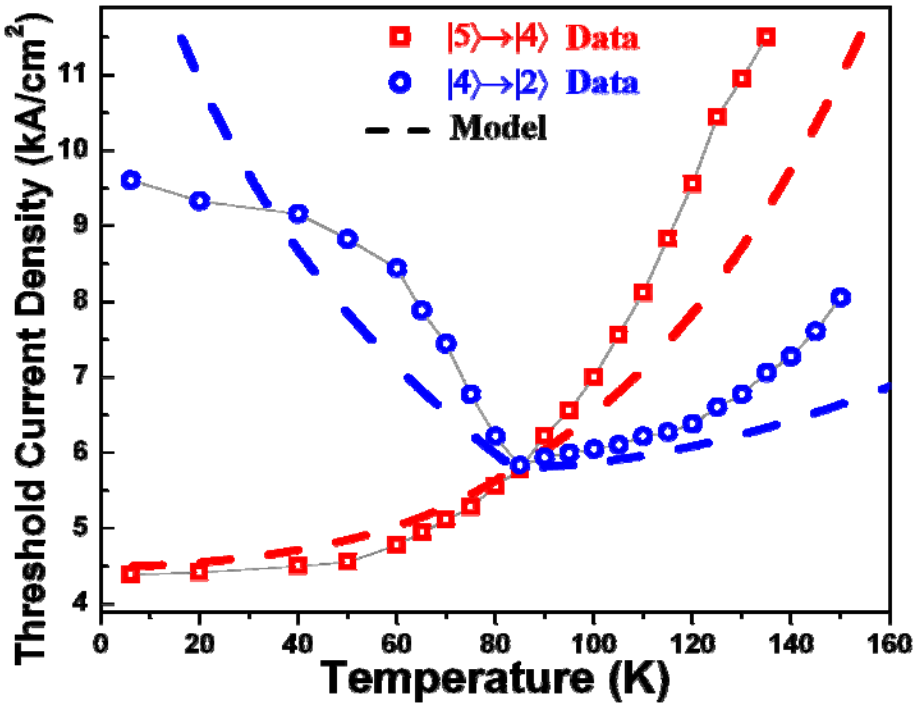

Wavelength (μm)
8
9
10
11
Intensity (a.u., offset, normalized)
55 kV/cm
60 kV/cm
65 kV/cm
70 kV/cm
75 kV/cm
80 kV/cm
85 kV/cm
|4⟩→|2⟩
|5⟩→|4⟩
160
150
140
130
120
110
Energy (meV)

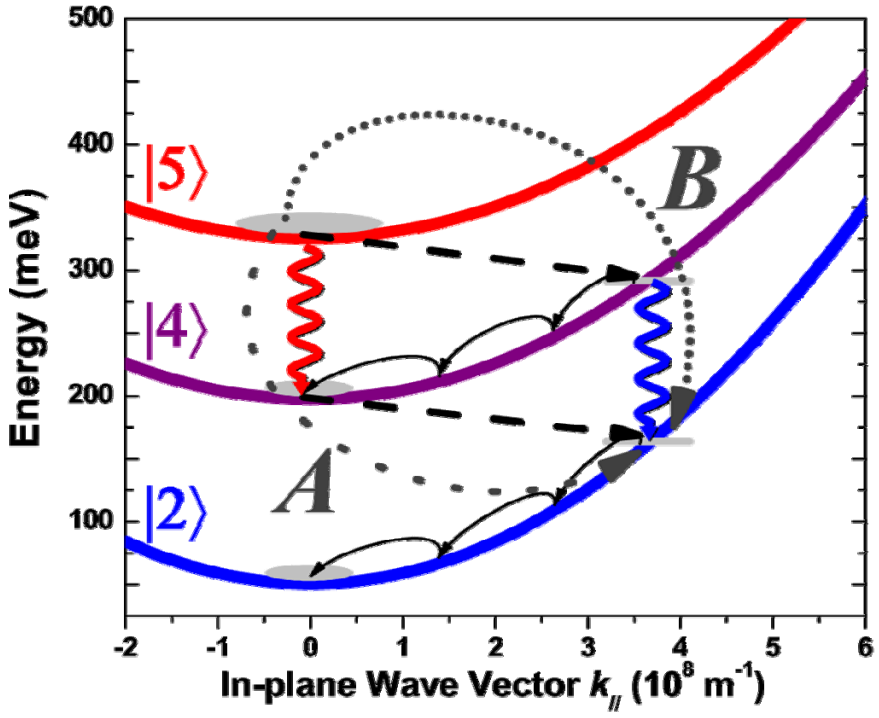

|5⟩→|4⟩
λ ≈ 9.5 μm
Tempreature (K)
20
40
60
80
100
120
140
0
2
4
6
8
10
12
Current Density (kA/cm²)
40
30
20
10
0
Peak Power (mW)


|4⟩→|2⟩
λ ≈ 8.2 μm
|5⟩→|4⟩ threshold
Tempreature (K)
20
40
60
80
100
120
140
0
2
4
6
8
10
12
Current Density (kA/cm²)
40
30
20
10
0
Peak Power (mW)


7.2 kA/cm²
8.9 kA/cm²
10.6 kA/cm²
|5⟩→|4⟩
λ ≈ 9.5 µm
|4⟩→|2⟩
λ ≈ 8.2 µm
Peak Power (mW)
Temperature (K)


T = 6.5 K
155 K
Voltage (V)
Current Density (kA/cm^2)
|5⟩→|4⟩
λ ≈ 9.5 µm
|4⟩→|2⟩
λ ≈ 8.2 µm
T = 80 K
T = 105 K
Peak Power (mW)
Current Density (kA/cm²)


|5⟩→|4⟩ Data
|4⟩→|2⟩ Data
Model
Threshold Current Density (kA/cm²)
Temperature (K)
4
5
6
7
8
9
10
11
0
20
40
60
80
100
120
140
160


|5⟩
|4⟩
|2⟩
B
A
Energy (meV)
In-plane Wave Vector $k_{//}$ ($10^8$ m$^{-1}$)
100
200
300
400
500
-2
-1
0
1
2
3
4
5
6