# Mode behavior, waveguide losses, and gain of two-sectioned, coupled-cavity GaAs/(Al,Ga)As THz and MIR QCLs

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# Outline

1. **Two-sectioned, coupled-cavity QCLs**

   ***Longitudinal modes observed for different*:**

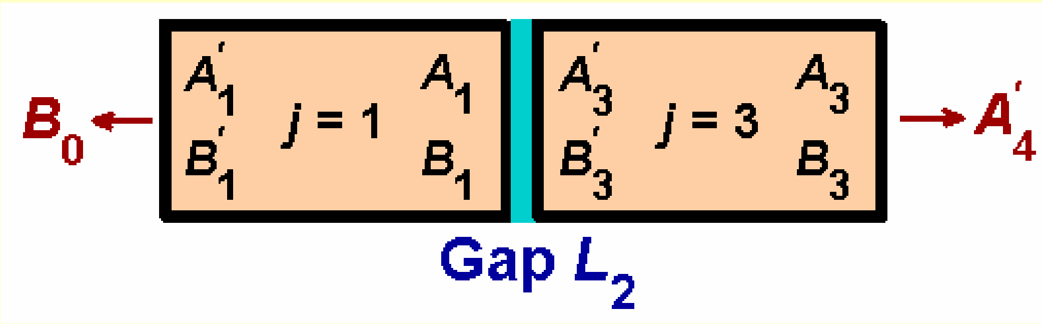
2. ***Lengths* of the two subcavities**
   **and analyzed within a transfer-matrix approach**

3. ***Current values* through the two subcavities**

4. ***Time delays* between both current pulses**

5. **Summary, outlook**

# T-sectioned, coupled-cavities (TSCC) lasers




***Parameters to control TSCC lasers*:**

- **total cavity length $L_{tot} = L_1 + L_3$**
- **ratio between lengths $L_3/L_1$**
- **currents $I_1$ and $I_3$**

**MIR: $L_2 \leq$ laser wavelength**
**THz: $L_2 <$ laser wavelength**

**Optical coupling between cavities $j = 1$ and 3 modifies longitudinal modes, indicated 1983 for interband lasers.**

# TSCC QCLs

**One mode behavior of MIR TSCC QCLs:**

**Hvozdara *et al*. 2000,** $L_2 \approx \lambda \approx 9\ \mu m$

**Höfling *et al*. 2006,** $L_2 \approx \lambda \approx 9\ \mu m$

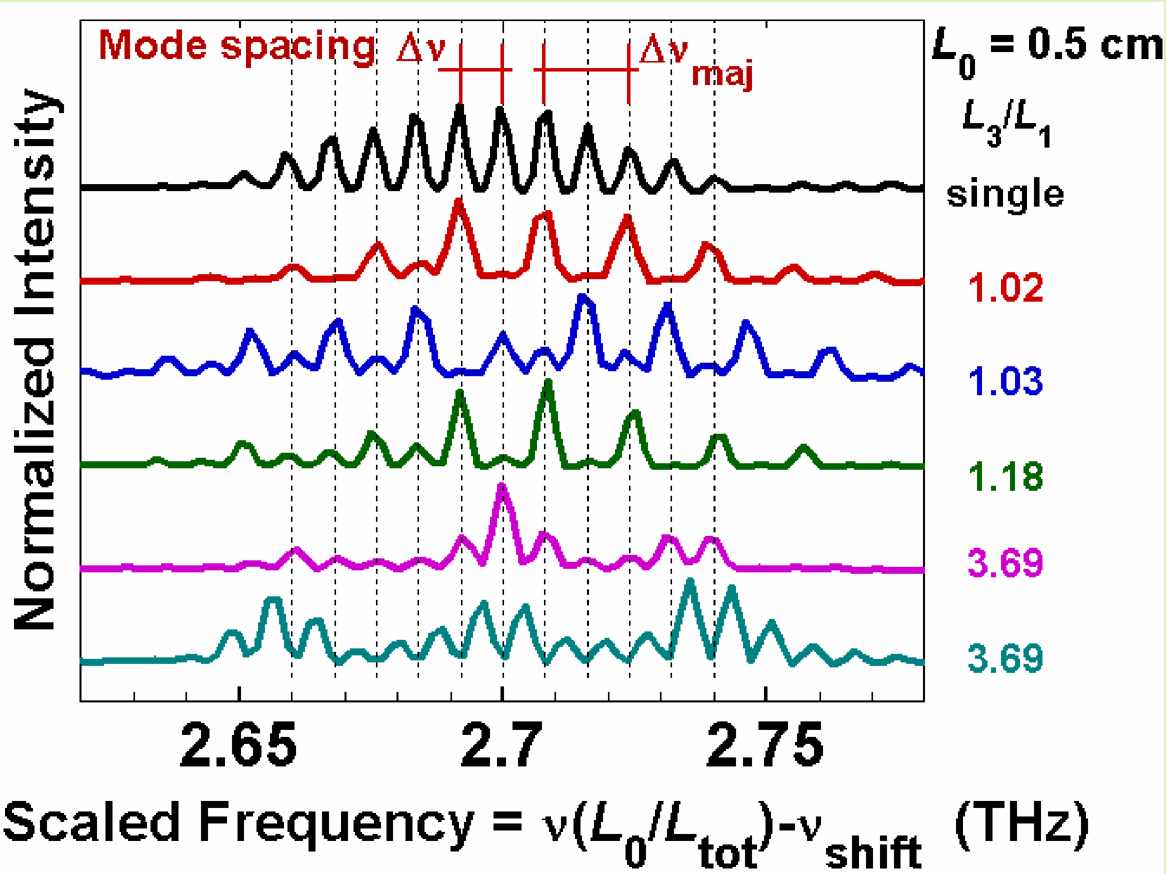
**We investigate longitudinal modes of MIR/THz TSCC QCLs,**

$L_2 \approx 0.4$ **to** $1\ \mu m$ **(Gap formed by cleaving the ridge.)**

**In the following we focus on results of THz devices**

# Length ratio of subcavities $L_3/L_1$ – mode suppression

**THz QCLs: design according to Barbieri *et al.*, APL 2004, single plasmon waveguides**




$I_{tot} = I_1 + I_3 \approx 1.5\ I_{thr} \approx 0.9\ I_{max}$

**Mode spacing:**

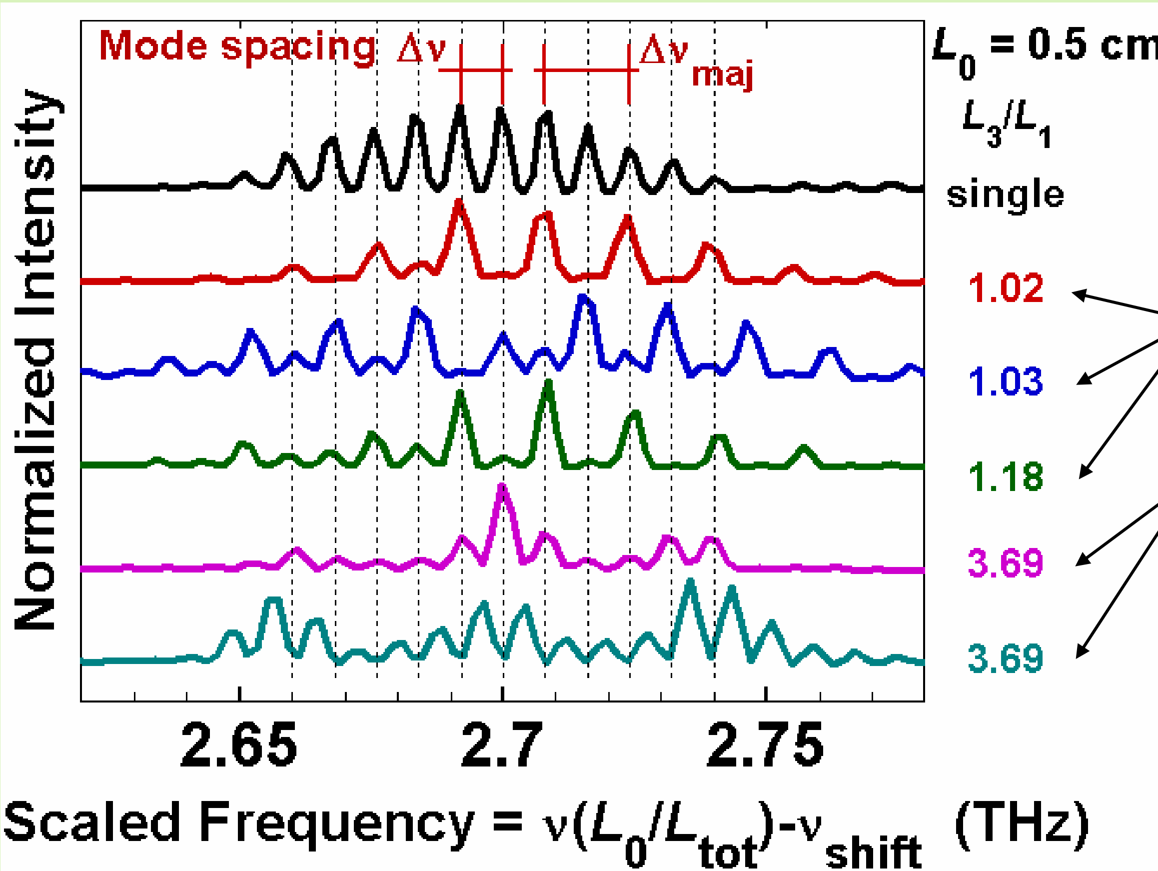
$\Delta\nu = 1/[2\ n_{eff}(L_1+L_3)]$

**Laser field penetrates into both subcavities**

**$\Delta\nu$ does not vary with $I_1$ and $I_3$**

**MIR: $\Delta\nu = f(I_1, I_3)$**

# Length ratio of subcavities $L_3/L_1$ – mode suppression




**Mode heights exhibit periodic modulation**

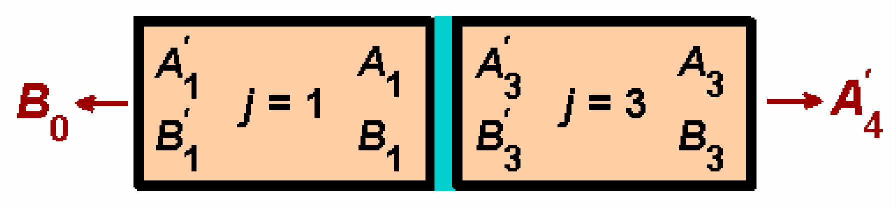
**one major/one minor mode**

**almost four minor modes**

**Number suppressed modes: $L_3/L_1$ ($L_3>L_1$)**

**Spacing major modes:**
$\Delta\nu_{maj} = (1+ L_3/L_1)\,\Delta\nu$

# Model for mode suppression – transfer-matrix approach




- Photon emission does not depend on laser field: optical constants are independent of intensity

- Interference partial waves: transfer matrix

$$\begin{pmatrix} A_0 = 0 \\ B_0 \end{pmatrix} = \mathrm{T} \begin{pmatrix} A'_4 \\ B'_4 = 0 \end{pmatrix}$$

- No incoming light: *m* modes with complex eigenfrequencies $\hat{\nu}_m$

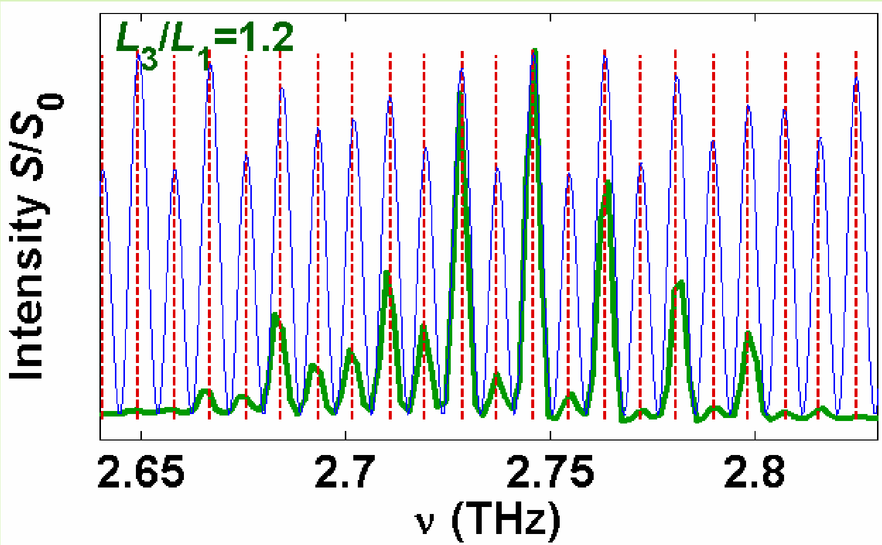
$$\mathrm{T}_{11}(\hat{\nu}_m) = 0$$

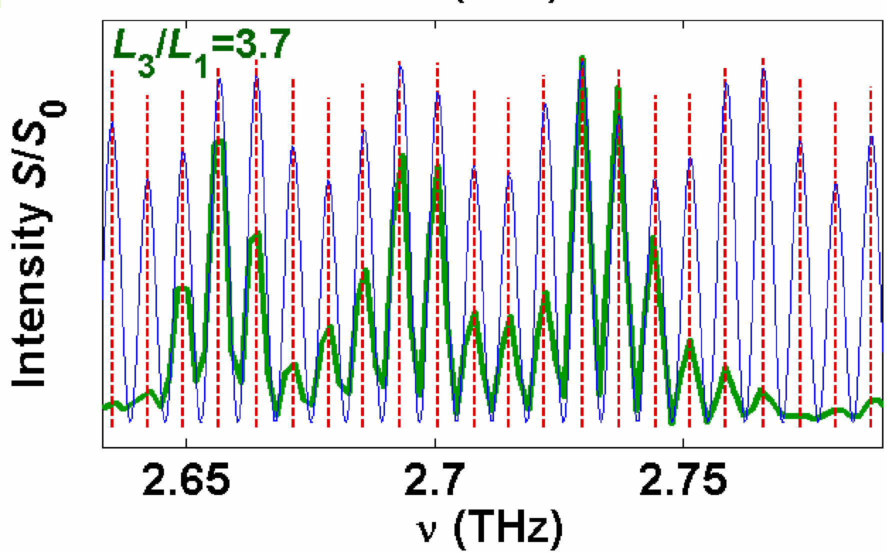
Mode frequencies $\nu_m = \mathrm{Re}\{\hat{\nu}_m\}$, mode heights $-1/\mathrm{Im}\{\hat{\nu}_m\}$

**Spectral function TSCC resonator**

$$P(\nu) = \mid T_{22} + r_{\mathrm{f}} T_{21} - r_{\mathrm{b}} T_{12} - r_{\mathrm{f}} r_{\mathrm{b}} T_{11} \mid^2$$

# Observed modes – calc. eigenfrequencies and spectral function




—— Exper., - - - $\hat{\nu}_m$ , —— $P(\nu)$

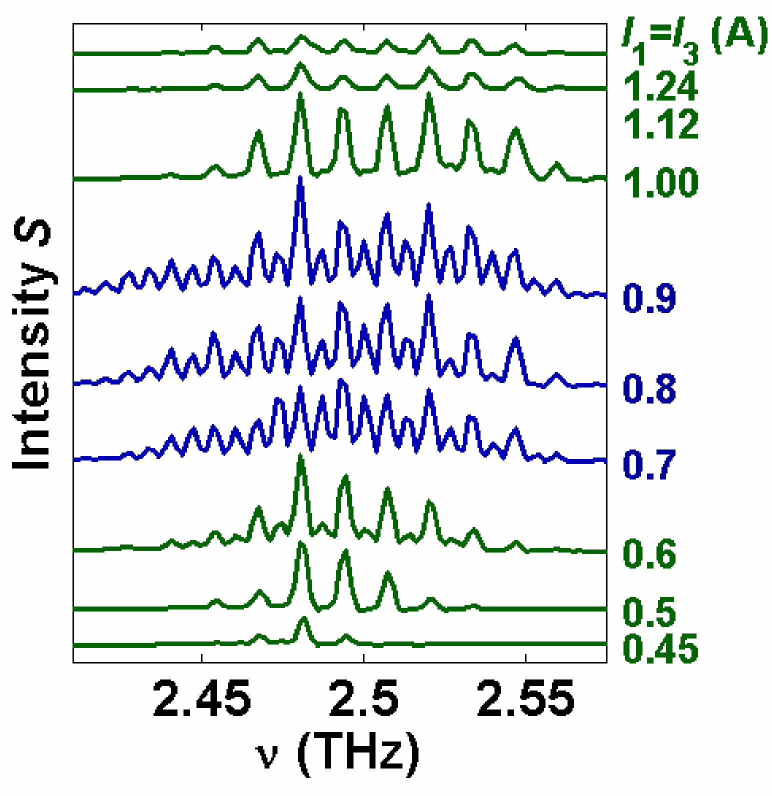
$I_{tot}$=1.5 $I_{thr} \approx$ 0.9 $I_{max}$

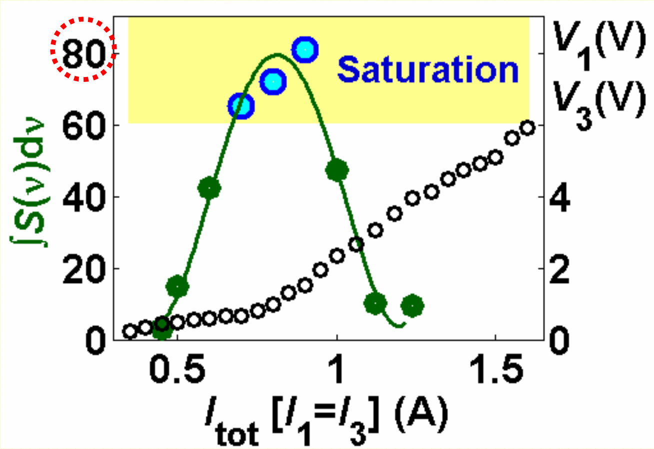
**Mode:**

- **suppression caused by multiplicative superposition of partial waves**
- **spacings $\Delta\nu$ described by T-matrix approach**
- **height modulation $\Delta S/S_0(\hat{\nu}) < \Delta S/S_0(P)$**
  **exp. $\Delta S/S_0$ > $\Delta S/S_0$ calc., stimulated emission not fully included in model**
- **$\Delta S$ related with $\Delta\nu$, Kramers-Kronig relation**

# Currents $I_1$ and $I_3$ – optical saturation and subband misalignment

**both cavities exhibit lasing; $I_{max} \approx 0.9$ A $\approx 2\, I_{thr}$; $L_3/L_1 \approx 1$**



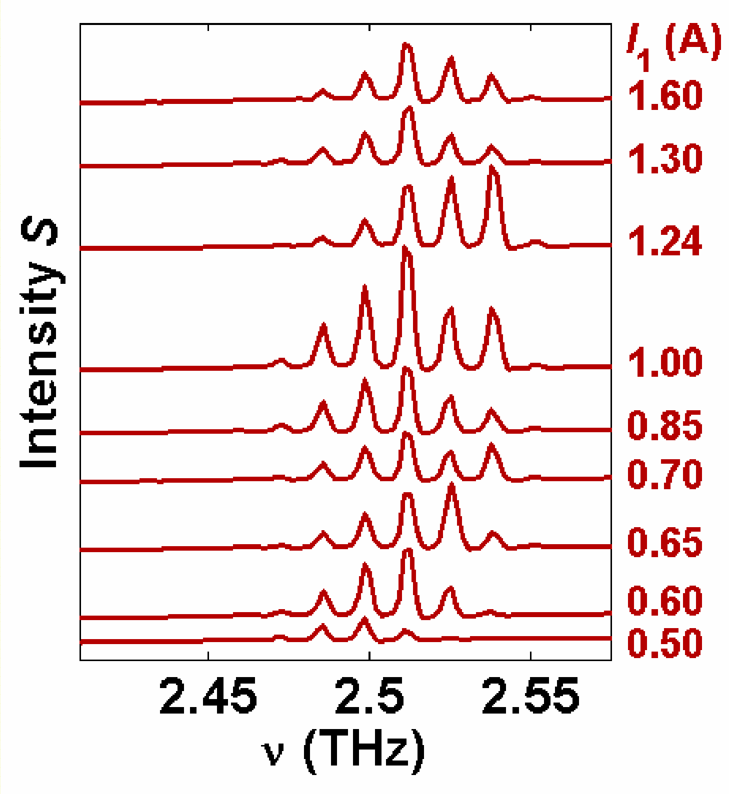

$I_{tot} < I_{max}$; $S < 60$; mode suppression

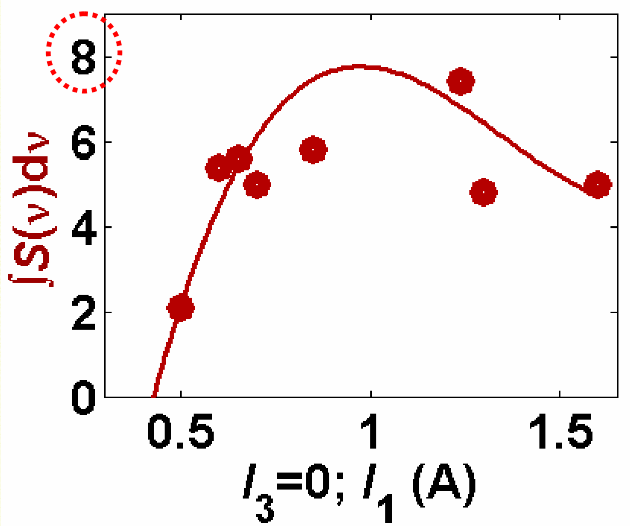
$I_{tot} \approx I_{max}$; $S_{max} \approx 80$
- saturation laser output
- suppression disappears
- subband misalignment

$I_{tot} > I_{max}$; $S < 60$; mode suppression

# Optical saturation and subband misalignment, $L_1/L_3 \approx 1$

one cavity is lasing; $I_{max} \approx 0.9$ A $\approx 2\, I_{thr}$

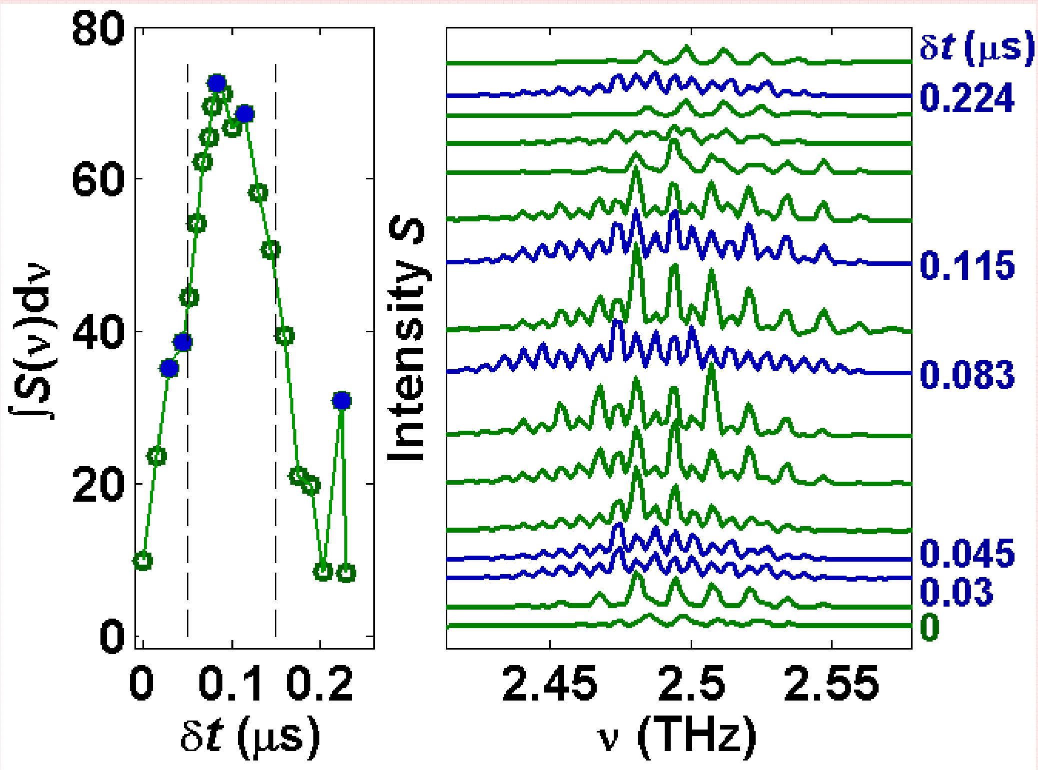



Low laser output, $S \approx 6 < S_{max} \approx 80$,
- no intensity saturation
- always mode suppression

# Time delays $\delta t$ between current pulses $I_1$ and $I_3$

$L_1/L_3 \approx 1$; $I_1=I_3=0.7$ A $\approx 1.6\ I_{thr} \approx 0.84\ I_{max}$




Particular values of
$I_1 + I_3 \approx I_{max}$ and $\delta t$:
switching of mode structure

TSCC-like ↔
single-cavity-like

Mode switching hints on dynamical effects in lasing?

# Summary, conclusions, and outlook

**Observed features longitudinal modes: described by T-matrix:**

- suppression of $N = L_3/L_1$ modes – interference effects ✓
- suppression disappears – optical saturation –
- switching mode features – dynamical effects? –

THz: laser field always in both subcavities ✓

MIR: light can be focussed in one cavity –

**Stimulated emission**

**Interplay between:**

**photon emission, photon density, and electron populations has to be fully included in T-matrix approach**