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:

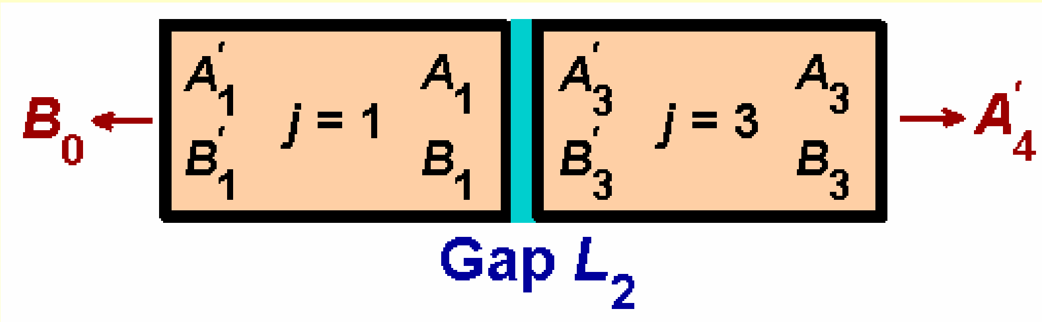
2. *Lengths* of the two subcavities
   and analyzed within a transfer-matrix approach

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, $L_2 \approx \lambda \approx 9\ \mu m$

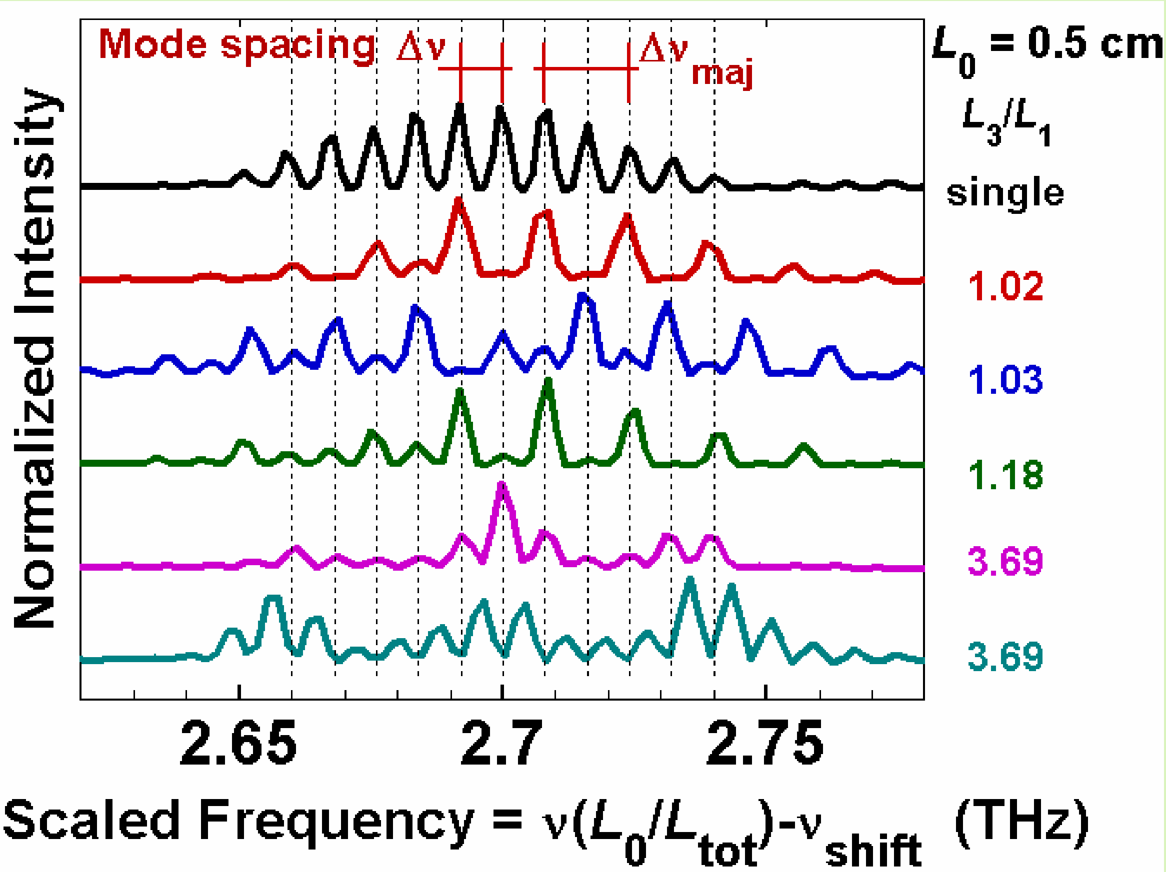
We investigate longitudinal modes of MIR/THz TSCC QCLs,

$L_2 \approx 0.4$ **to 1** μm **(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:

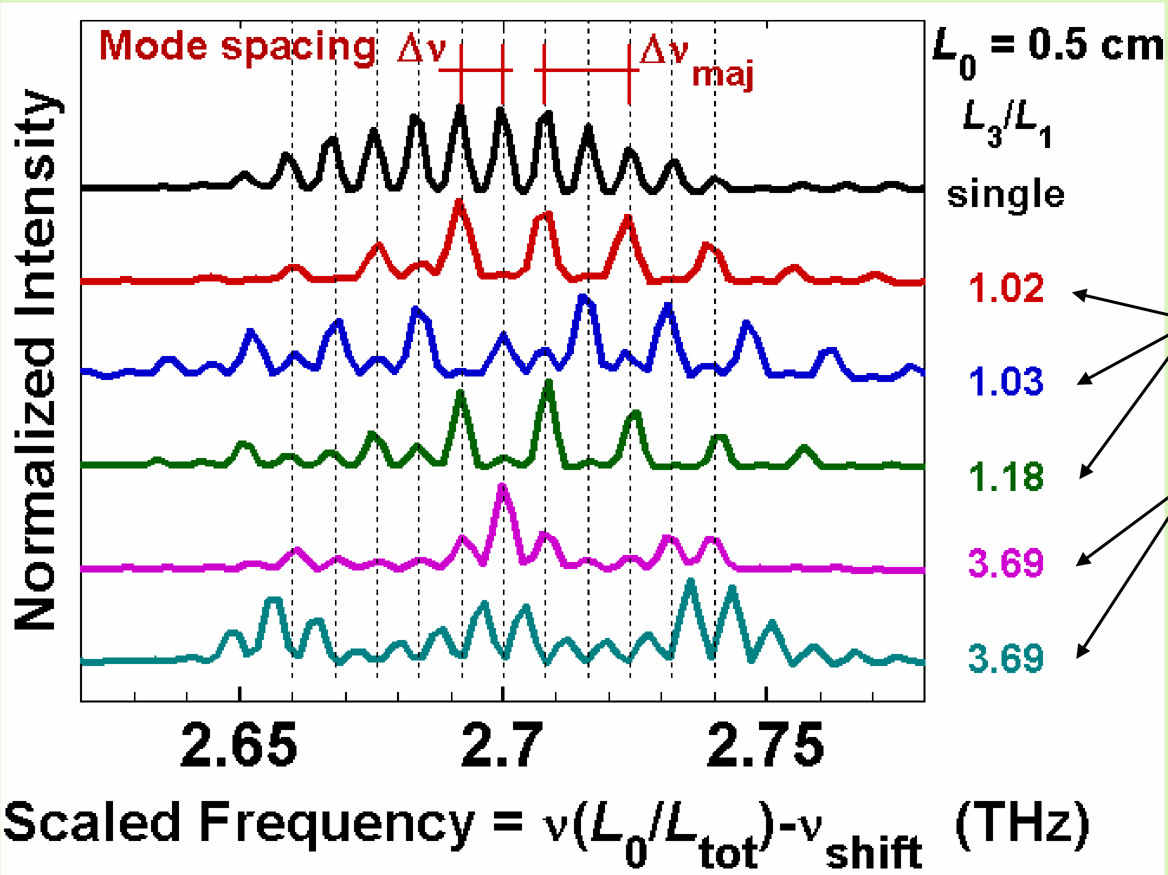
$\Delta\nu = 1/[2\ n_{eff}(L_1+L_3)]$

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



one major/one minor mode

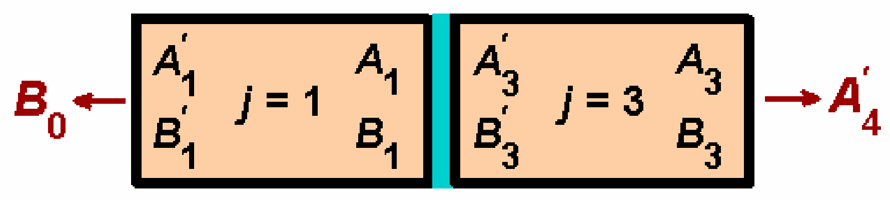
almost four minor modes

Mode heights exhibit periodic modulation

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

$$\begin{pmatrix} A_0 = 0 \\ B_0 \end{pmatrix} = \mathrm{T} \begin{pmatrix} A_4' \\ B_4' = 0 \end{pmatrix}$$

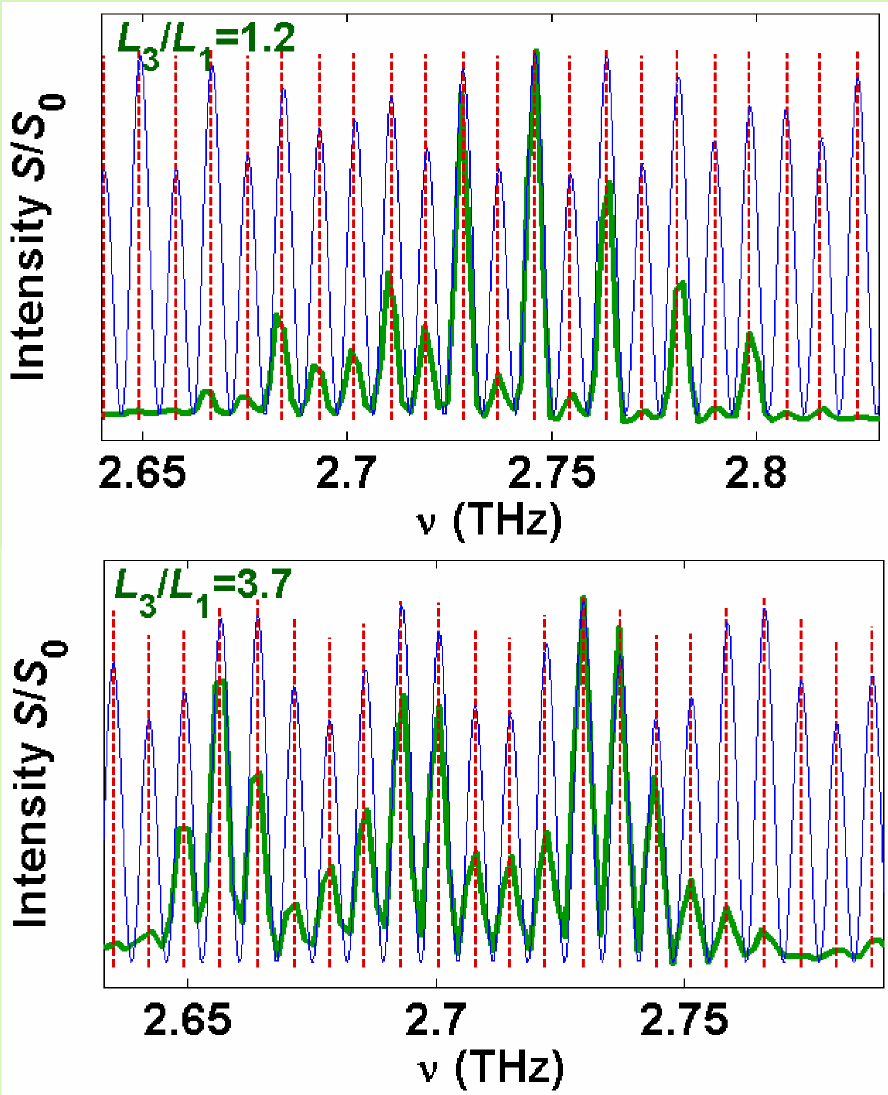
$$\mathrm{T}_{11}(\hat{\nu}_m) = 0$$

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

Spectral function TSCC resonator

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

Observed modes – calc. eigenfrequencies and spectral function



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

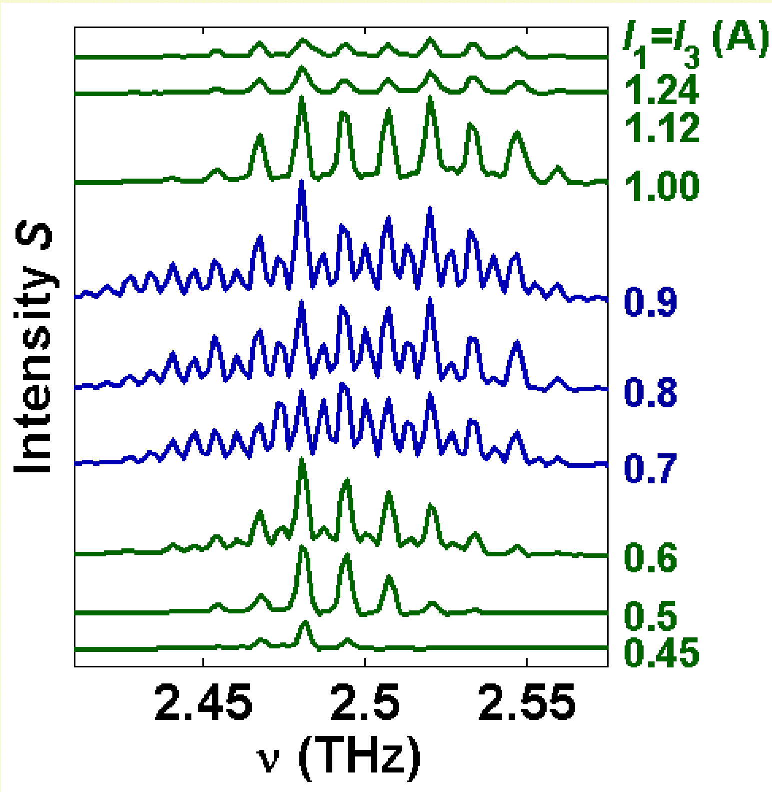
$I_{tot}=1.5\ I_{thr} \approx 0.9\ I_{max}$

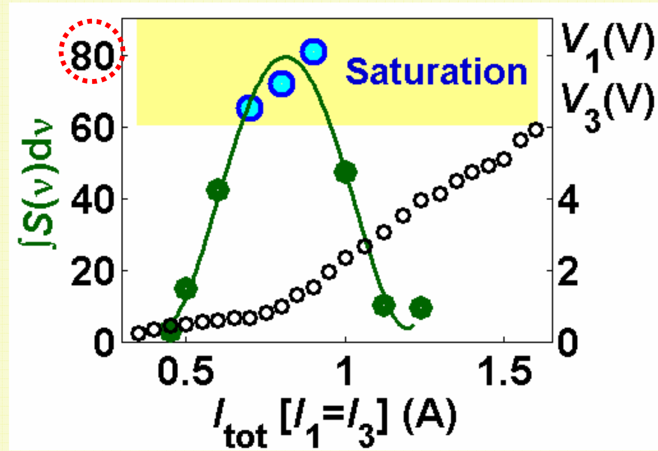
Mode:

- **suppression caused by multiplicative super-position 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
- **ΔS 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 $\approx 2\ I_{thr}$; $L_3/L_1 \approx 1$





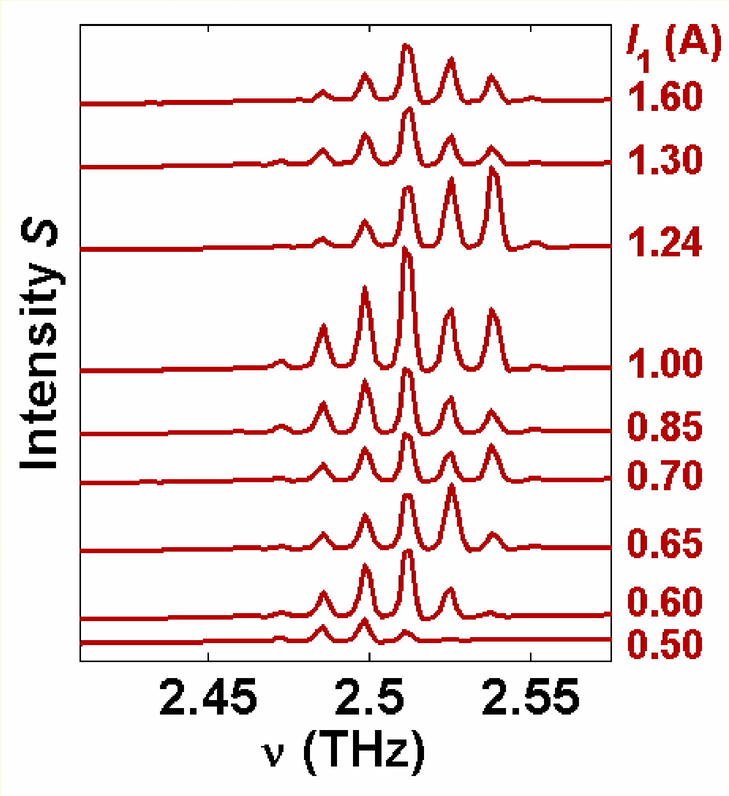
$I_{tot} < I_{max}$; $S < 60$; mode suppression

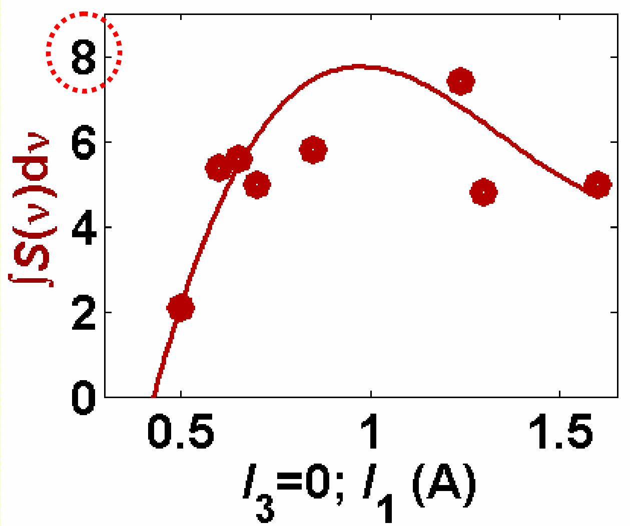
$I_{tot} \approx I_{max}$; $S_{max} \approx 80$
- saturation laser output
- suppression disappears
- subband misalignment

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

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

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

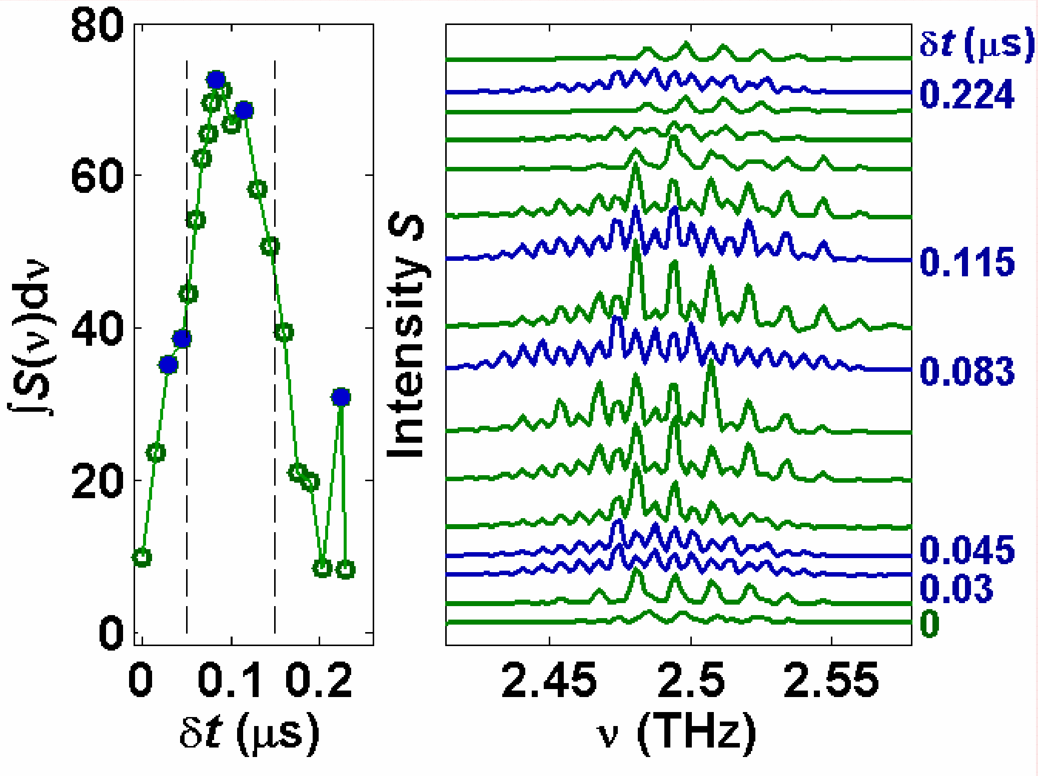




Low laser output, $S \approx 6 < S_{max} \approx 80$,
- no intensity saturation
- always mode suppression

Time delays δt 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 δt:
switching of mode structure

TSCC-like $\leftrightarrow$
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