Intersubband antipolariton: a new quasiparticle

Mauro F. Pereira

Materials and Engineering Research Institute
Sheffield Hallam University
M.Pereira@shu.ac.uk

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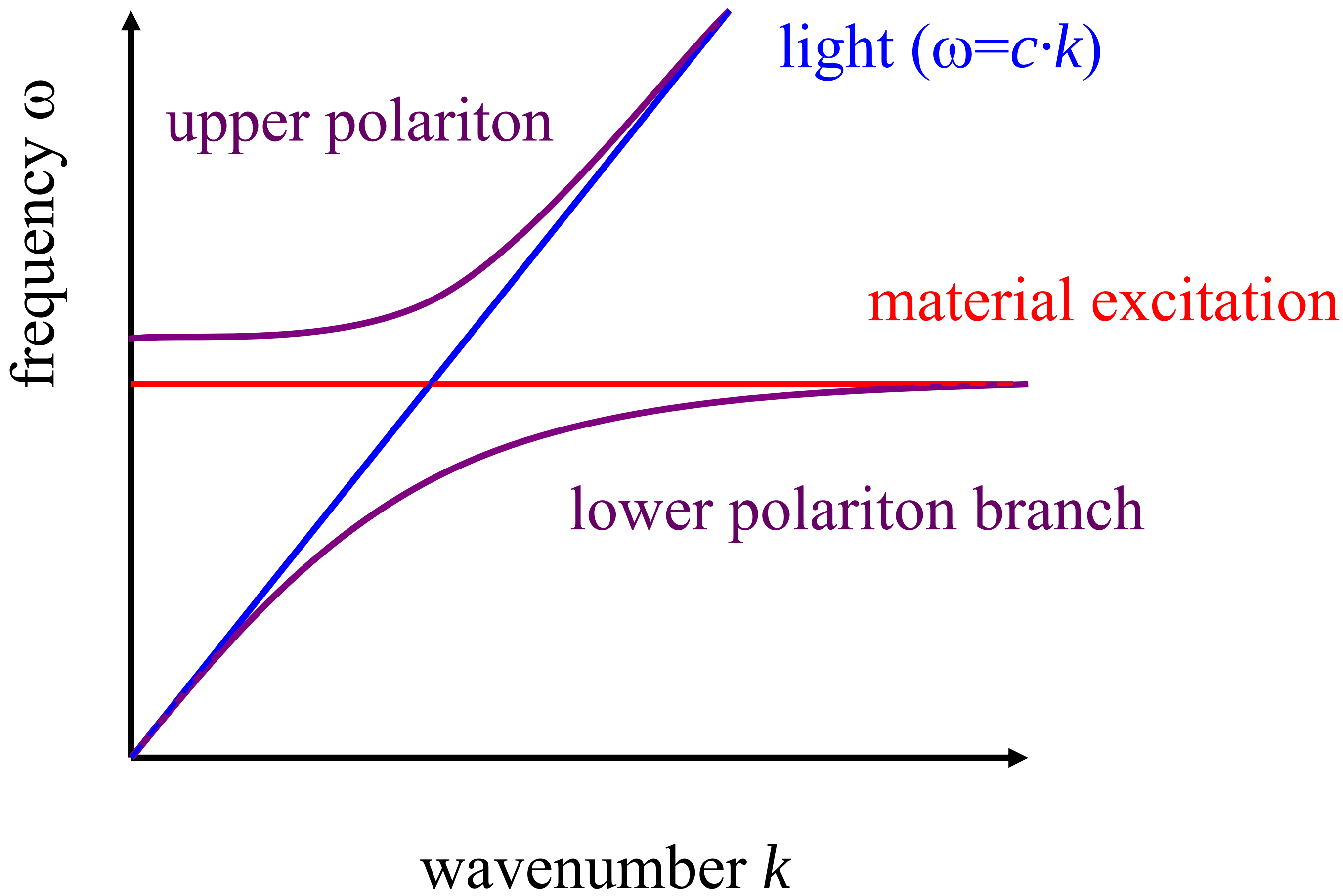
Outline

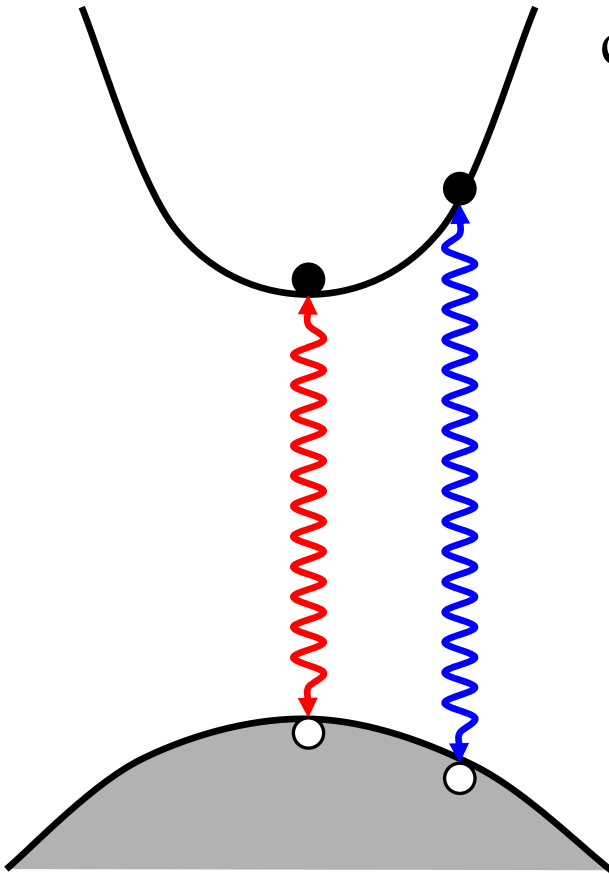
- Introduction
- Analytical approximations for the optical response and quasi-particle dispersions
- Interband vs intersubband coupling
- Summary

Polaritons



light (ω=c·k)
upper polariton
frequency ω
material excitation
lower polariton branch
wavenumber k

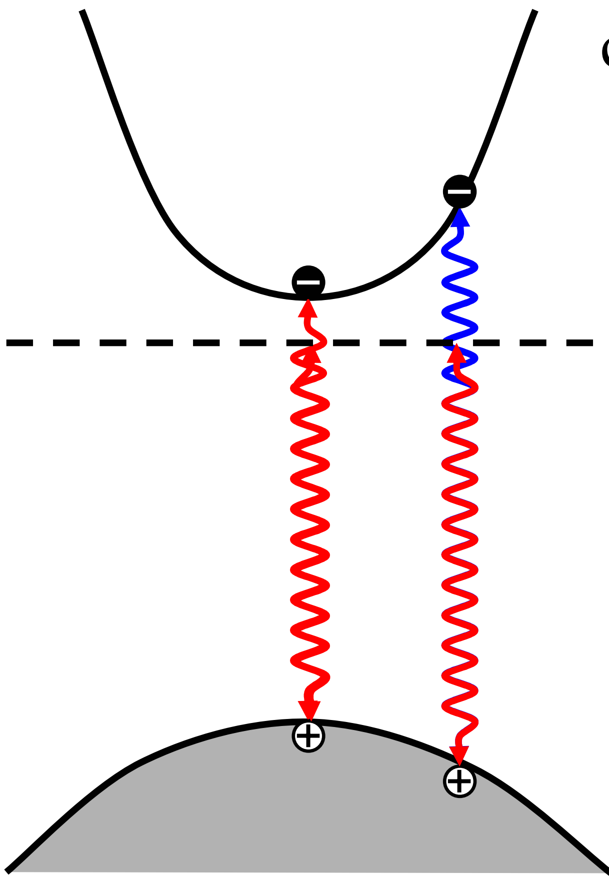
Interband polariton (??)



no sharply defined excitation energy

→ no polariton!

Exciton polariton



no sharply defined excitation energy

sharply defined excitation energy

→ polariton!

Excitons

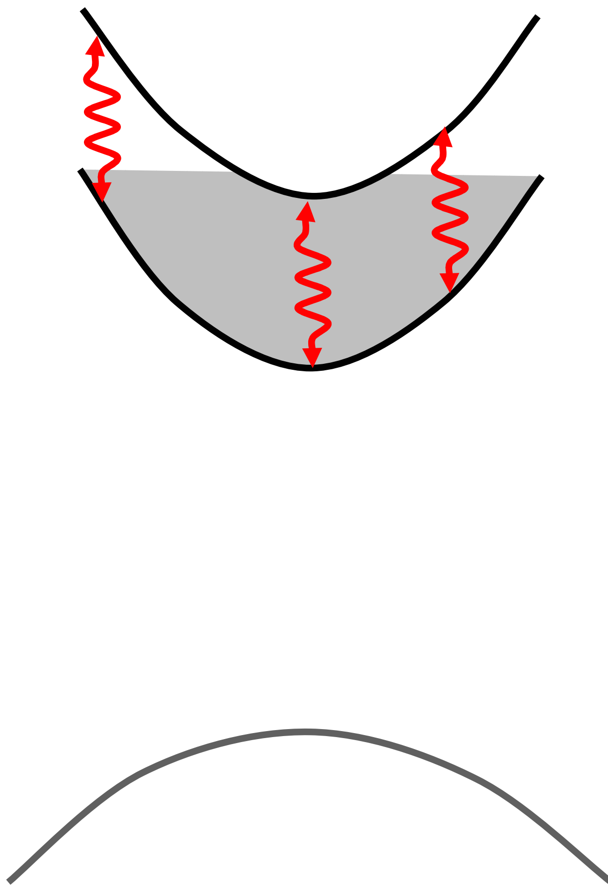
Wannier equation:

$$\left(\frac{\hbar^2 k_\mathrm{e}^2}{2m_\mathrm{e}} + \frac{\hbar^2 k_\mathrm{h}^2}{2m_\mathrm{h}}\right) \cdot \Psi(k_\mathrm{e}, k_\mathrm{h}) + \sum_q [1 - f_\mathrm{e} - f_\mathrm{h}] \cdot V(q) \cdot \Psi(k_\mathrm{e} + q, k_\mathrm{h} - q) = E \cdot \Psi(k_\mathrm{e}, k_\mathrm{h})$$

Pauli-blocking limits excitation. no inversion!

$$\left(\frac{\hbar^2 k_\mathrm{c}^2}{2m_\mathrm{c}} + \frac{\hbar^2 k_\mathrm{v}^2}{2m_\mathrm{v}}\right) \cdot \Psi(k_\mathrm{c}, k_\mathrm{v}) + \sum_q [f_\mathrm{v} - f_\mathrm{c}] \cdot V(q) \cdot \Psi(k_\mathrm{c} + q, k_\mathrm{v} - q) = E \cdot \Psi(k_\mathrm{c}, k_\mathrm{v})$$

Intersubband polariton



subbands:

approximately parallel bands

→ sharply defined excitation energy

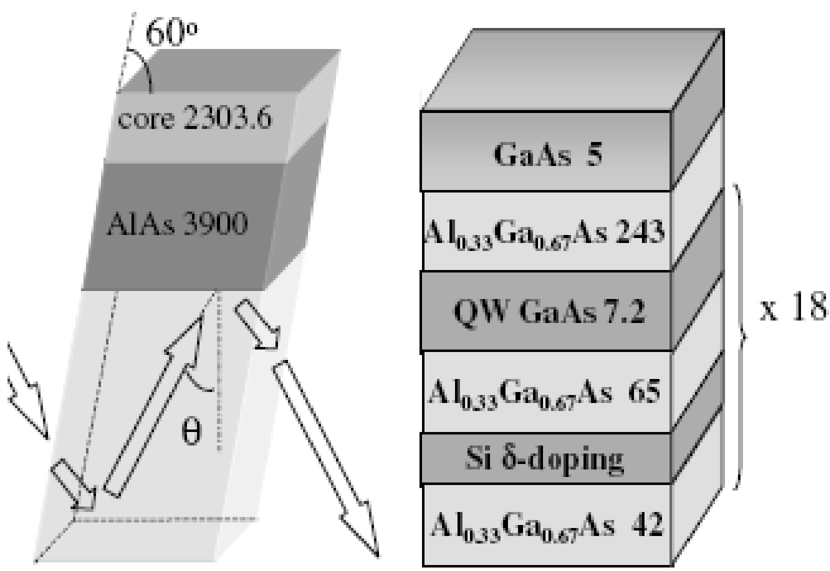
→ polariton

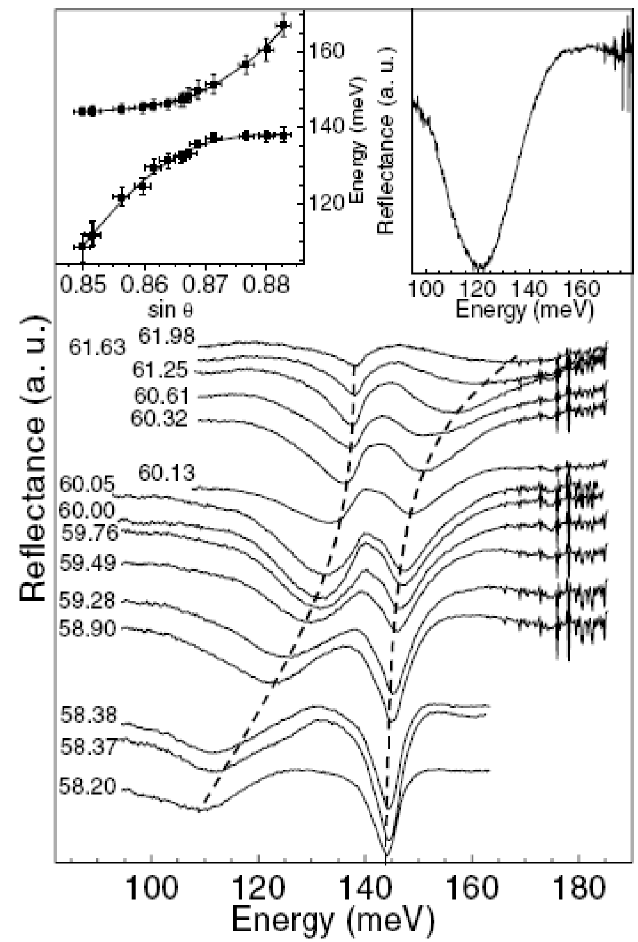
(even without coulomb interaction)

valence band

Polariton Coupling in Intersubband Transitions

Theoretical predictions by Ansheng Liu, PRB50, 8569 (1994); PRB55, 7101 (1997).





Measurement of microcavity polariton splitting of intersubband transitions by

Dini et al, PRL90, 116401 (2003).

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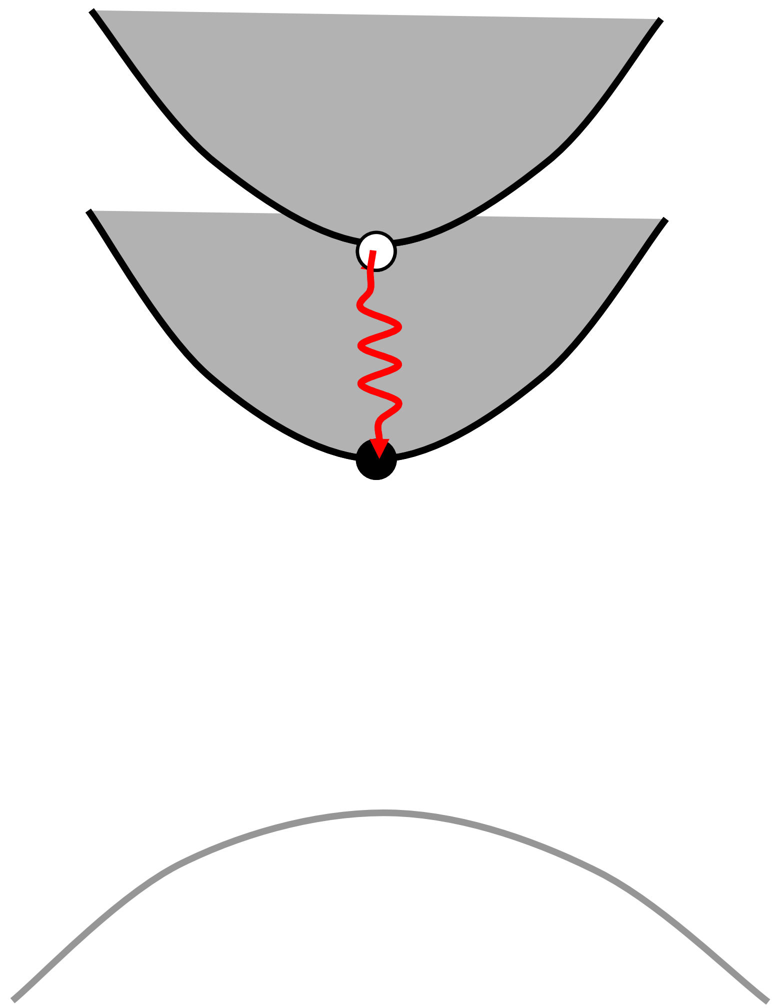
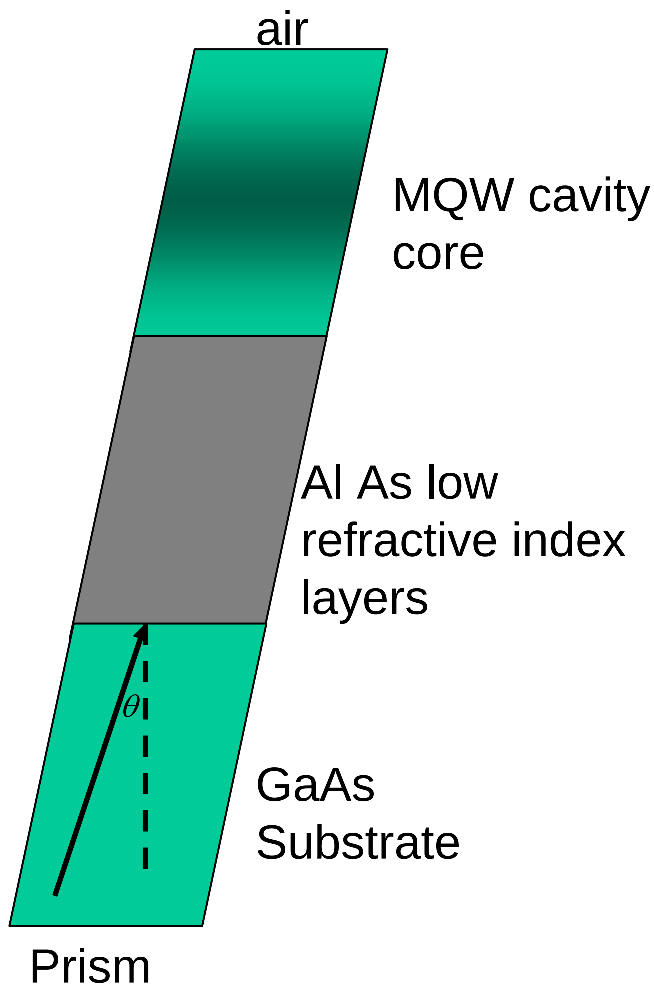
Intersubband antipolariton

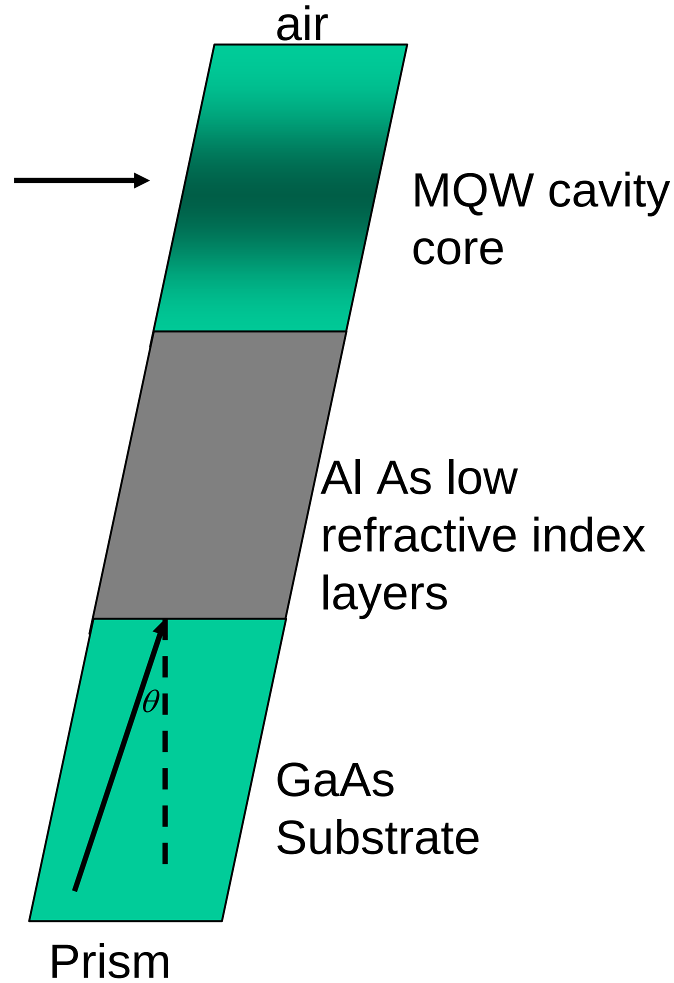


Microresonator Geometry



Microresonator Geometry

$$\varepsilon_b = \frac{1}{L_c} \sum_j \varepsilon_j L_j$$



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Microresonator Mode

- The microresonator mode is determined by the wave equation

$$\Delta E + \frac{\omega^2}{c^2}\varepsilon(\omega)E(\omega) = 0$$

- Neglecting the imaginary part of ε(ω) a simple solution can be used

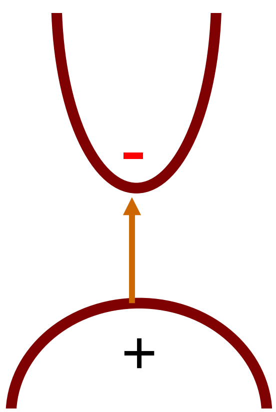
$$E(\omega) = E_0 e^{ik_x x}\sin(\frac{\pi z}{L_c})$$

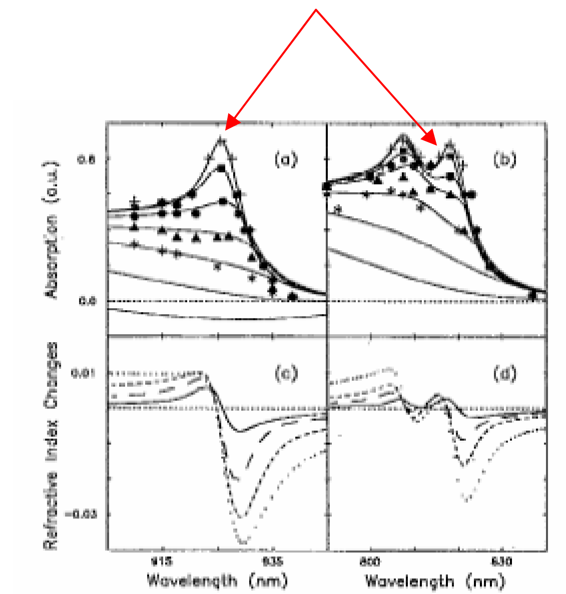
$$k_x = \frac{\omega}{c} n_s \sin\theta = \ldots = \frac{\omega}{c} n_b \sin\theta_b$$

Excitons

➢A linearly polarized electric field promotes and electron from the valence to the condcution band leaving a positive particle or hole behind.

➢The Coulomb interaction creates a hydrogen atom like resonance.





The Interband Polariton Case

- The dielectric constant is obtained from the numerical solution of Semiconductor Bloch Equations

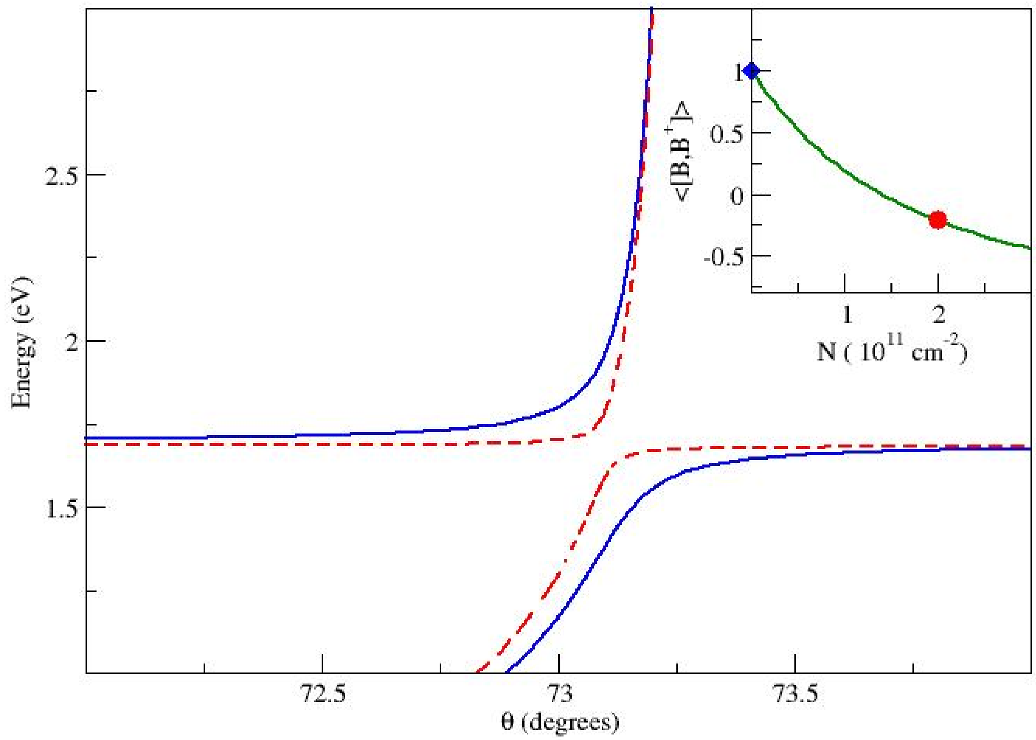
- The excitonic resonance at low temperature is adjusted to the simple formula

$$\varepsilon(\omega) = \varepsilon_b + 4\pi\lambda\chi(\omega),$$

$$\chi(\omega) \equiv -\frac{\varepsilon_b}{4\pi}\frac{\Lambda}{\omega - \omega_0 + i\delta}\sin^2\theta_b,$$

$$\lambda = N_w \frac{L_w}{L_c}$$

The Interband Polariton Case (TM)



Microcavity light-hole interband (exciton-polariton). The solid (blue) lines are for a pump-generated density N=0 and the dashed (red) curves are for N=2.51011 cm-2. The inset displays the commutator of the exciton operator as a function of injected carrier density.

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Intersubband Resonances in a Microcavity

$$k_x^2 + \frac{\pi^2}{L_c^2} = \frac{\omega^2}{c^2}\varepsilon(\omega)$$

$$\varepsilon(\omega) = \varepsilon_b + 4\pi\lambda\chi(\omega)$$

$$\lambda = N_w \frac{L_w}{L_c}$$

$$\chi(\omega) = 2\sum_{\mu\neq\nu,\vec{k}} \wp_{\mu\nu}\chi_{\nu\mu}(k,\omega)$$

$$\left[\hbar\omega - e_{\nu\mu}(k) + i\Gamma_{\nu\mu}(k,\omega)\right]\chi_{\nu\mu}(k,\omega) - \delta n_{\nu\mu}(k)\sum_{\vec{k}'\neq\vec{k}}\chi_{\nu\mu}(k',\omega)\tilde{V}^{\nu\mu}_{\vec{k}-\vec{k}'} = \wp_{\nu\mu}\delta n_{\nu\mu}(k)$$

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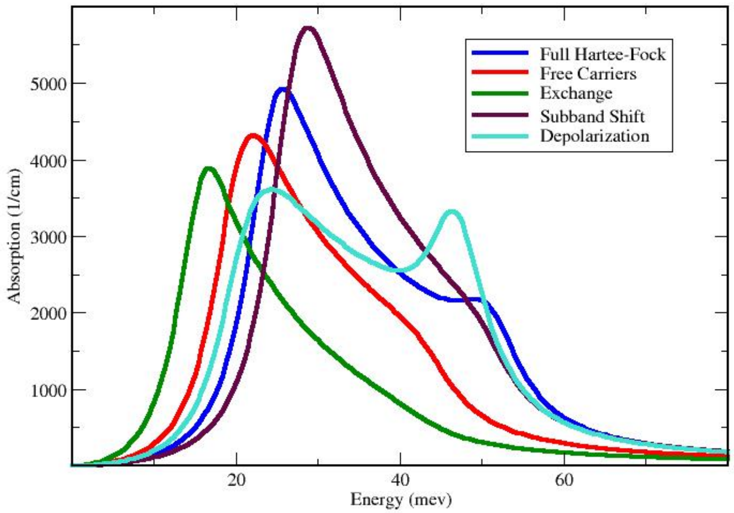
Intersubband Antipolaritons

- Analytical Expressions obtained considering:
  - Same effective mass in all subbands.
  - Neglect the exchange and subband shifts (that usually compensate each other to a large extent).
  - Keep only the depolarization correction.
  - Averaged k-independent dephasing (can be frequency dependent and the expression is still analytical).

Compensation of Many-Body Effects

$$\left[\hbar\omega - e_{\nu\mu}(k) + i\Gamma_{\nu\mu}(k,\omega)\right]\chi_{\nu\mu}(k,\omega) - \delta n_{\nu\mu}(k)\sum_{\vec{k}'}\chi_{\nu\mu}(k',\omega)\tilde{V}^{\nu\mu}_{\vec{k}-\vec{k}'} = \wp_{\nu\mu}\delta n_{\nu\mu}(k)$$



$$\left[\hbar\omega - \Delta E_{\nu\mu}(k) + i\Gamma_{\nu\mu}\right]\chi_{\nu\mu}(k,\omega) + 2\delta n_{\nu\mu}(k)V_0^{\nu\mu\mu\nu} = \wp_{\nu\mu}\delta n_{\nu\mu}$$

Analytical Approximation for the Effective Dielectric Constant (Effective Bulk)

- Analytical Expression for the dielectric constant

$$\varepsilon(\omega) = \varepsilon_b + \frac{2\pi}{\varepsilon_b V}\sum_{\mu<\nu}\left(\frac{\hbar\Delta_{\nu\mu}}{\hbar\omega - \Delta e_{\nu\mu} - \delta e_{\nu\mu} + i\Gamma_{\nu\mu}} + \frac{\hbar\Delta_{\nu\mu}}{\hbar\omega + \Delta e_{\nu\mu} + \delta e_{\nu\mu} + i\Gamma_{\nu\mu}}\right)$$

$$\delta e_{\nu\mu} = -\delta N_{\nu\mu} V_0^{\nu\mu\mu\nu}$$

$$\hbar\Delta_{\nu\mu} = \frac{2\pi}{\varepsilon_b} e^2 \frac{|d_{\nu\mu}|^2}{L_p} \delta n_{\nu\mu} \sin^2\theta_b$$

Analytical Dispersion Relations

$$\hbar\omega_{\pm} = \hbar\omega_0\sqrt{\frac{1+\Omega_c^2 - x^2 \pm \sqrt{\left(1+\Omega_c^2 - x^2\right)^2 + 4\left(2\lambda\Delta x^2 - \Omega_c^2\right)\left(1-x^2\right)}}{2\left(1-x^2\right)}}$$

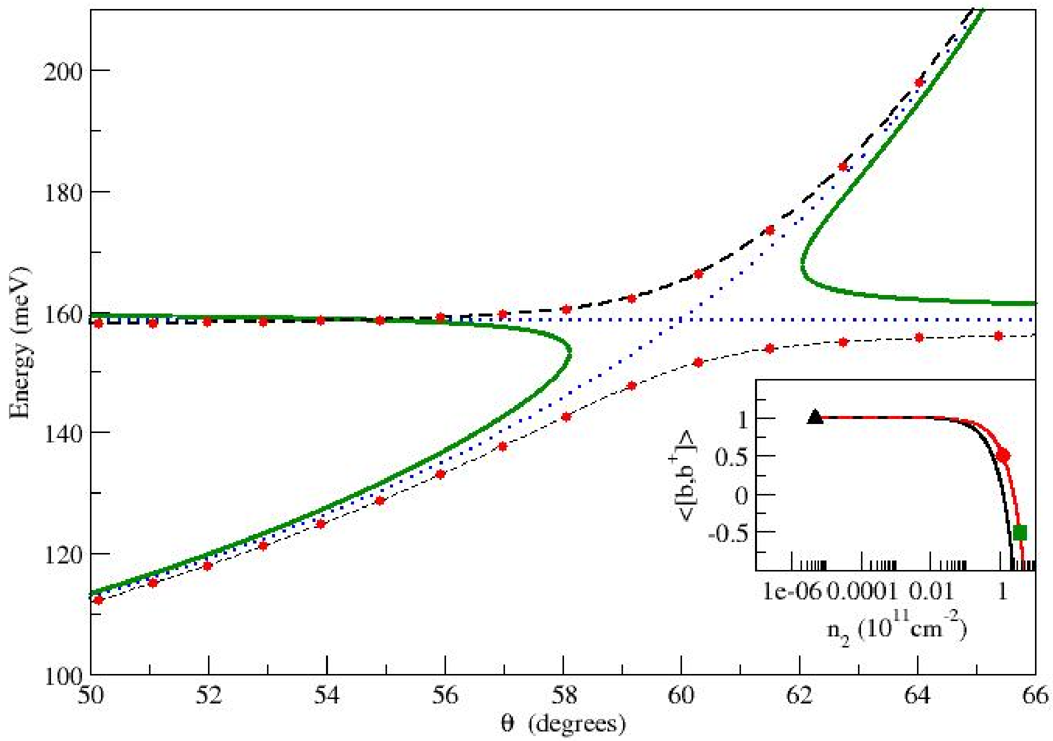
$$\hbar\omega_0 = \Delta E_{\nu\mu} + \delta e_{\nu\mu}$$

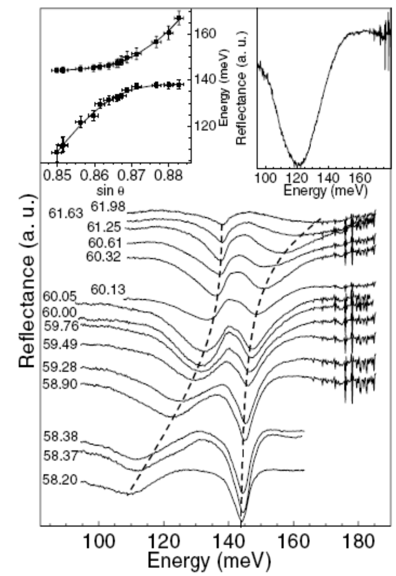
$$\Omega_c = \frac{\omega_c}{\omega_0}$$

$$x = \sin\theta\frac{n_s}{n_b}$$

$$\Delta = \frac{\Delta_{\nu\mu}}{\hbar\omega_0}b$$

Antipolaritons dispersion relation





M.F. Pereira, Phys Rev B 75, 195301 (2007).

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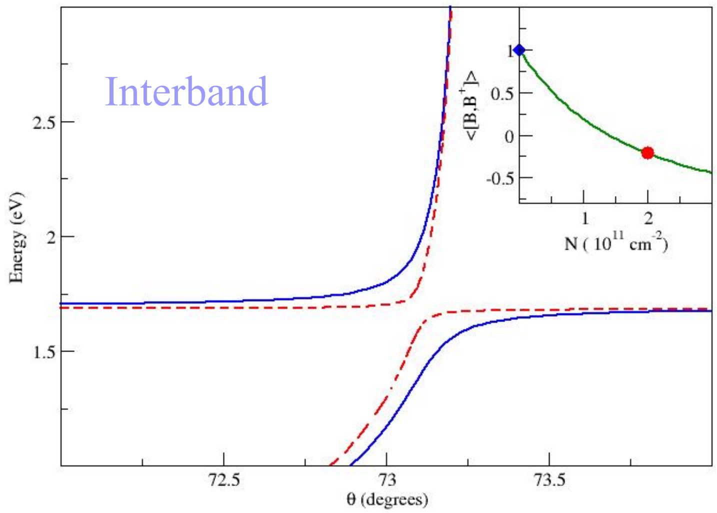
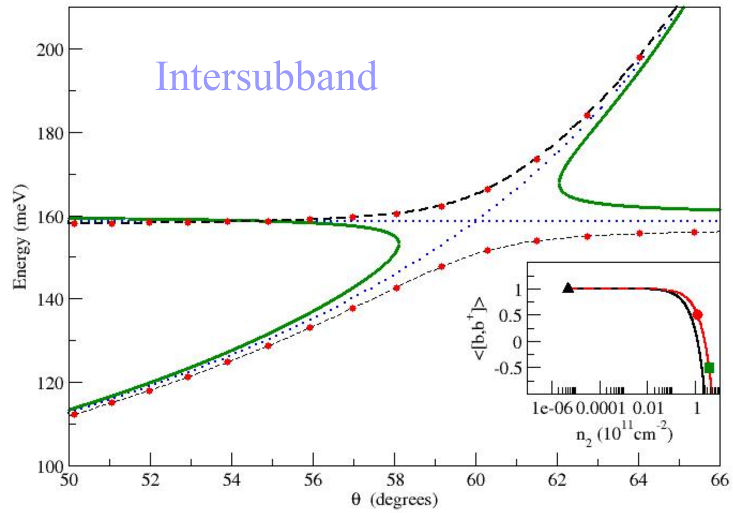
Interband vs. Intersubband





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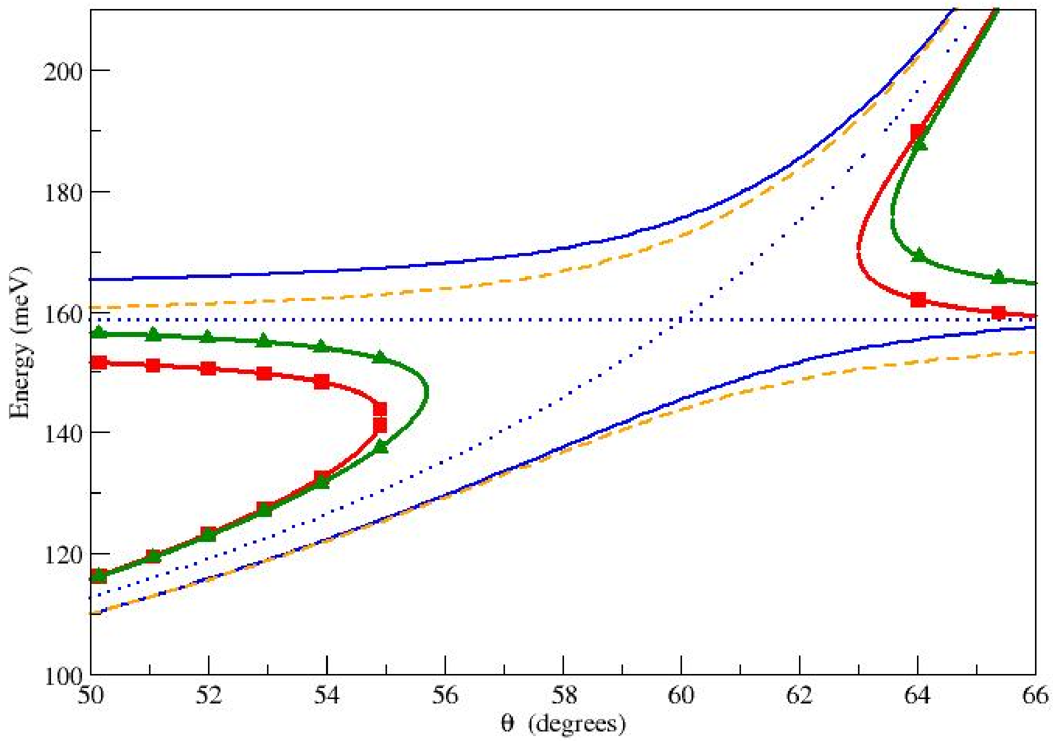
Influence of many body effects



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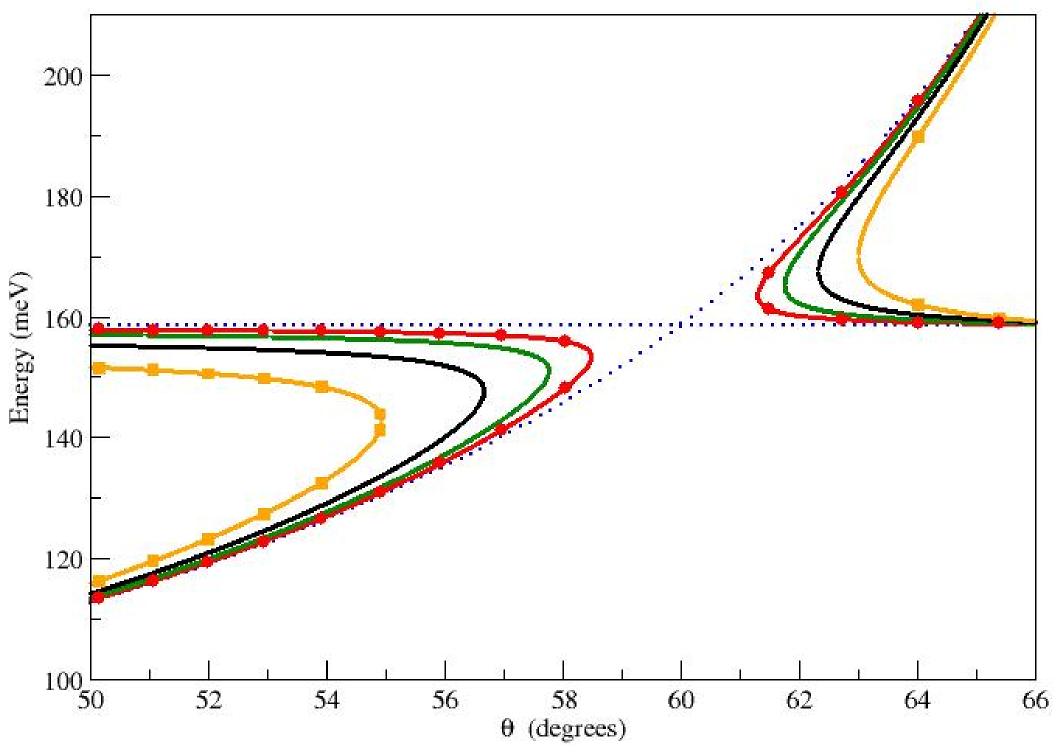
Anomalous dispersions as a function of inversion



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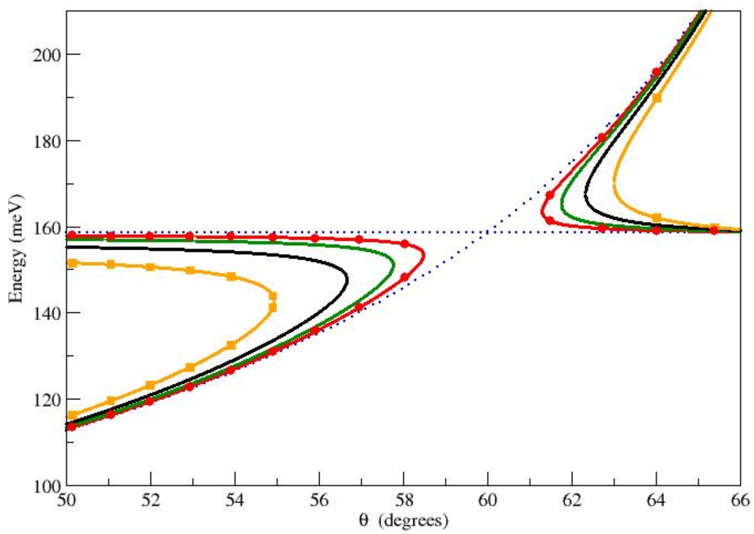
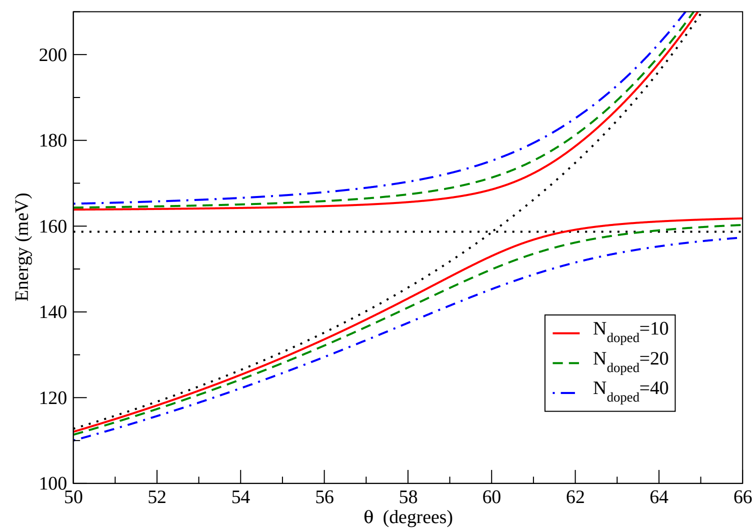
Anomalous dispersions as a function of inversion

In both absorption and gain cases, the branches are repelled from the cold cavity crossing as the excitation density increases.





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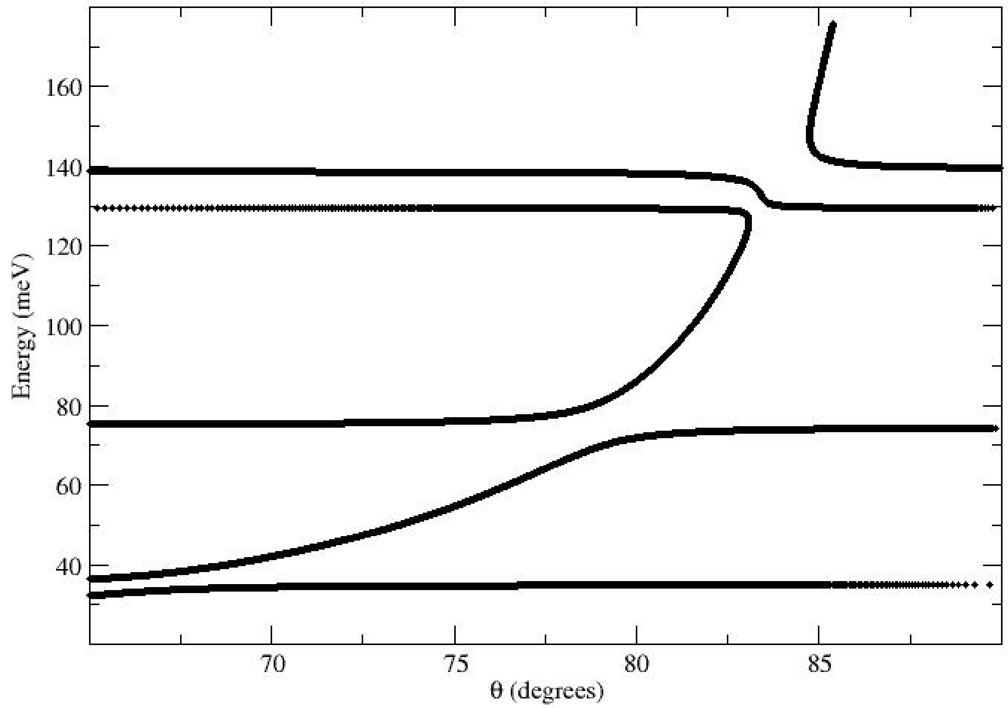
Microresonator with a Cascade Laser Core



Intersubband antipolariton dispersion relations for a 13.3 μm microresonator designed with 30 periods of the active region of the quantum cascade laser of C. Sirtori. et al, Appl. Phys. Lett. 73, 3486 (1998).

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Summary

In summary, this paper demonstrates that in the intersubband case, there is interesting physics beyond the polariton concept:

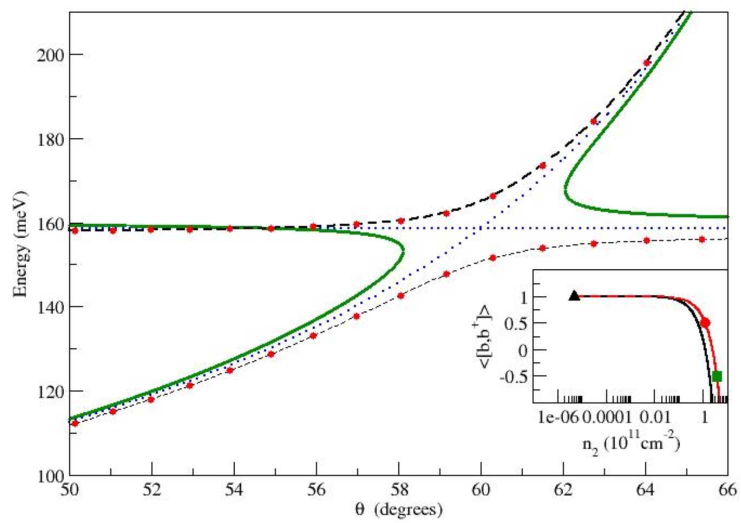
(i) Anomalous dispersions can be found for the optical gain region in which the medium is inverted

(ii) These dispersions are well described by an "intersubband antipolariton"

(iii) Bosonic Effects can be manipulated by selective injection.

Summary

Intersubband Antipolariton: a new quasi-particle concept.



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Forthcoming

(i) Full treatment of diagonal and nondiagonal dephasing.

(ii) Full reflection and transmission solution including many body effects beyond Hartree Fock. (Quantum Mechanical Input Output Relations).

(iii) Study multiple subband system with coexisting gain and absorption branches.

(iv) Further studies of strong correlation in intersubband optics beyond bosonic approximations.