The Linewidth of MIR Intersubband Light Sources

M.F. Pereira

Theory of Semiconductor Materials and Optics

Materials and Engineering Research Institute
Sheffield Hallam University
S1 1WB Sheffield, United Kingdom
M.Pereira@shu.ac.uk   M.Pereira@tera-mir.org

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Outline

- Origin of the α-factor
- Fundamental reason for nonzero ISB α
- The gain without inversion case
- Summary

Origin of the α factor

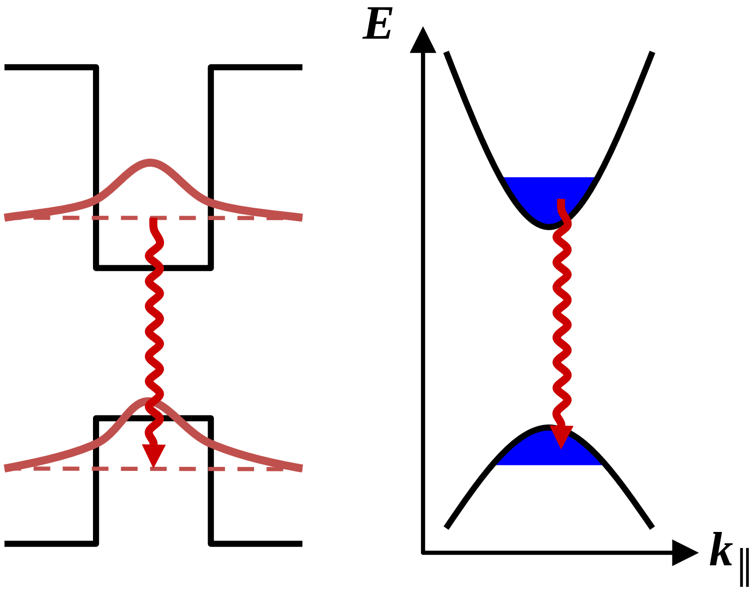
- Conventional laser – Schalow-Townes

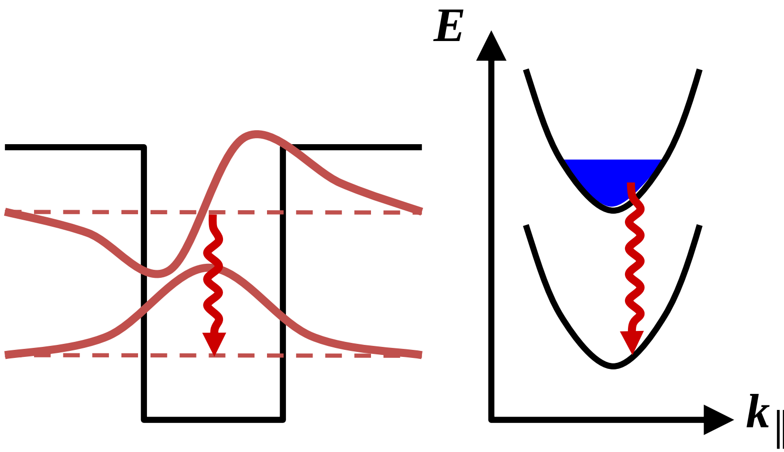
$$\Delta\nu_{ST} = {}^{A}/_{n_{ss}}$$

- A is the spontaneous emission coefficient and n_{ss} is the number of photons in the lasing mode at steady state.
- Semicondutor laser – Henry's α factor or linewidth enhancement factor

$$\Delta\nu = (1+\alpha^2)\,\Delta\nu_{ST}$$

Interband vs. Intersubband Optics:





interband transition

- bipolar
- photon energy determined by bandgap energy E_{gap} of material

intersubband transition

- unipolar
- photon energy determined by well thickness, adjustable

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The intersubband case

- In usual GaAg-AlGaAs the effective masses are almost the same on both upper and lower lasing subbands – leading to an almost exactly Lorentzian linesahpe and *expected zero α factor at peak gain*.

- However, experimental results show values from -0.5 to 0.5 (subthreshold) and from 0.2 to 3 above threshold. (MIR). See L. Jumpertz et al AIP Advances 6, 015212 (2016).
- THz case: 0.2 to 0.5.

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Origin of the nonzero α-factor

- A nonzero α at peak gain has been attributed to a combination of nonparabolicity and many-body effects. See Liu et al, Optics Express 21, 27804-27815 (2013).

- ***However I show here that the most fundamental reason stems from considering counter-rotating terms in the optical susceptibility.***

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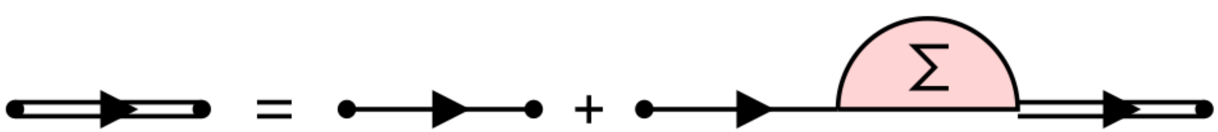
Connection between Macroscopic Measurables and Microscopic Theory

$$\alpha(\omega) = -\frac{\delta\Re\{\chi(\omega)\}}{\delta\Im\{\chi(\omega)\}}$$

- The susceptibility is derived from the solutions of a NGFE approach.

$$\chi(\omega) = \sum_{i,j,k} \wp_{ij}(k) G^{<}_{ji}(\omega,k) / E(\omega) + \wp_{ji}(k) G^{<}_{ij}(\omega,k) / E(\omega)$$



Origin of the nonzero α-factor

- For parabolic bands and without manybody effects

$$\delta\chi(E) = \frac{\wp^2 \delta N}{V}\left[\frac{1}{E - \Delta + i\Gamma} - \frac{1}{E + \Delta + i\Gamma}\right]$$

$$\alpha = \frac{\Delta^2 + \Gamma^2 - E^2}{2\Gamma E}$$

- The peak again is still almost exactly at the RWA resonance but the real part is nonzero due to the CRWA term. *However nonparabolicity and manybody effects are required to explain negative values.*

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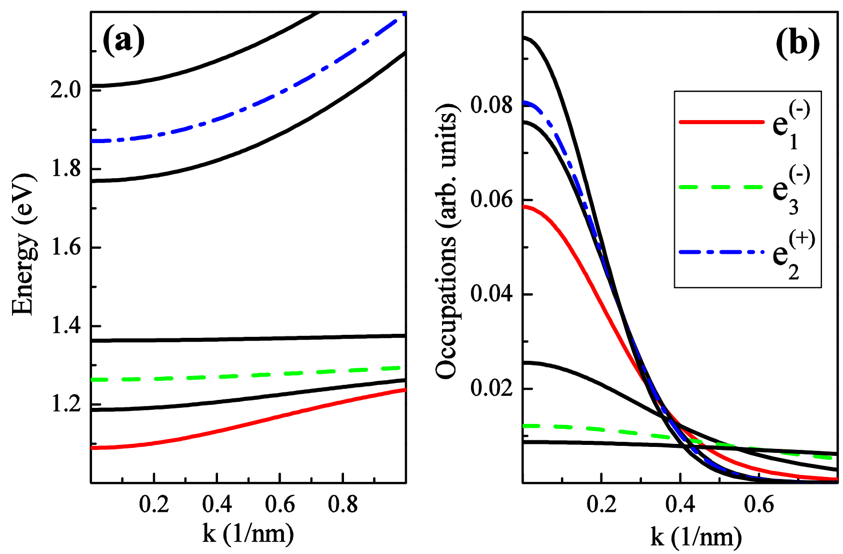
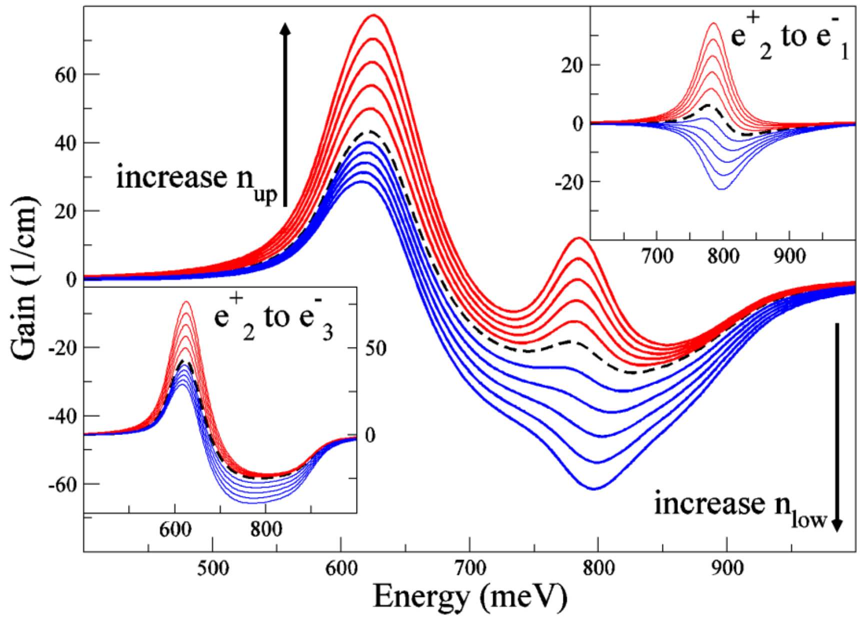
ISB Dilute Nitride Band Engineering

band structure and occupations - local inversion - 7 nm $Ga_{0.98}N_{0.02}As/Al_{0.3}Ga_{0.7}As$



gain without inversion - dispersive shape only for similar effectibe masses



M. F. Pereira and S. Tomić, Appl. Phys. Lett. 98, 061101 (2011).

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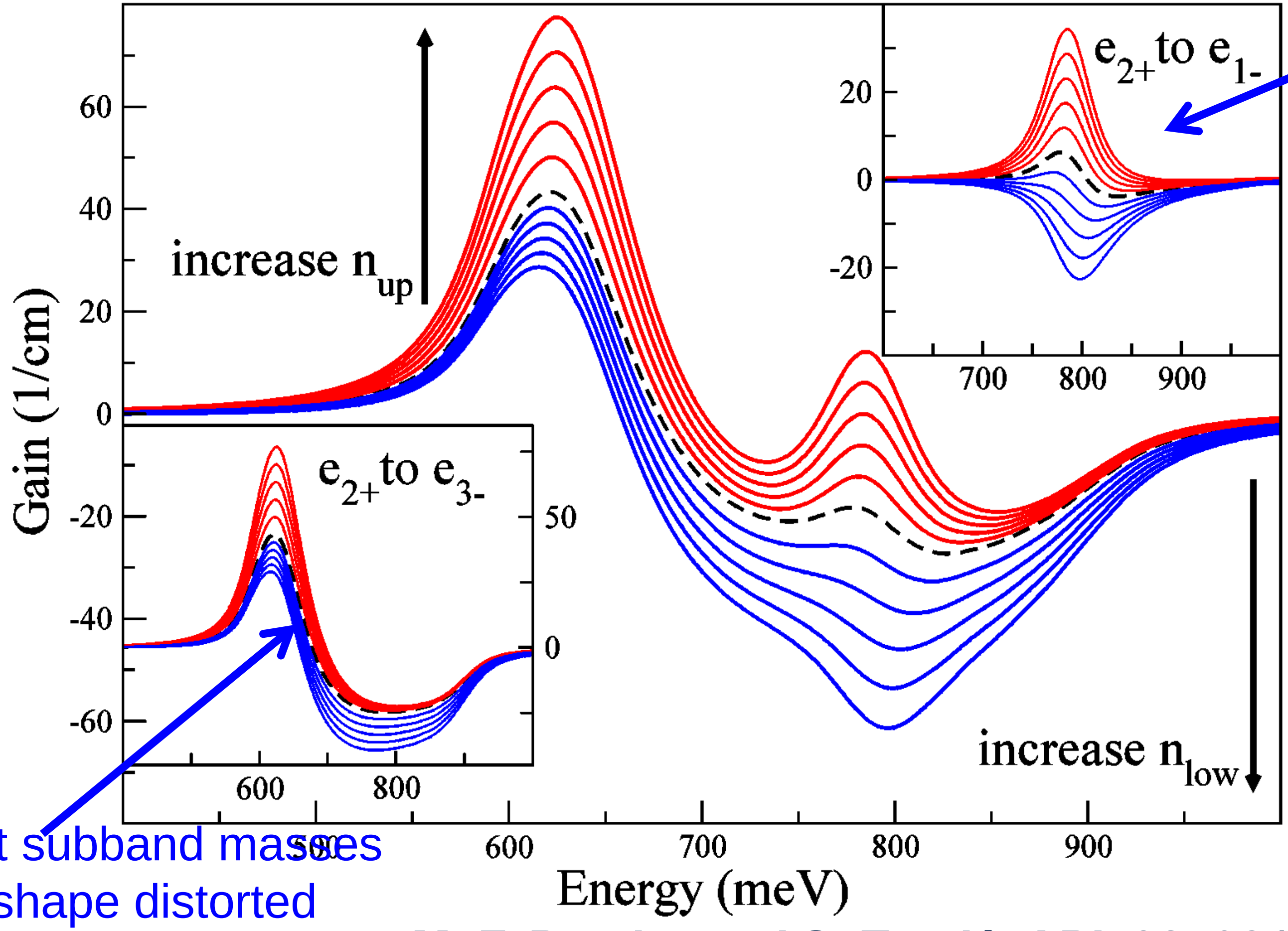
ISB Gain without Global Inversion

similar subband masses - dispersive shape



very different subband masses - dispersive shape distorted

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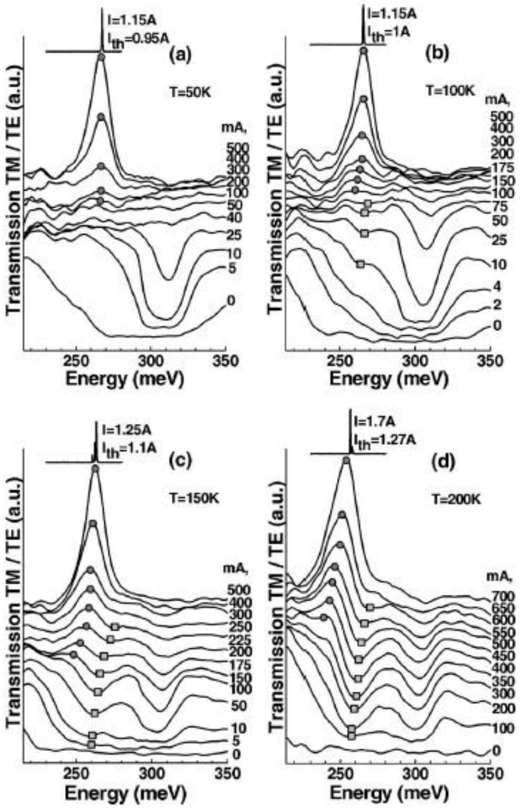
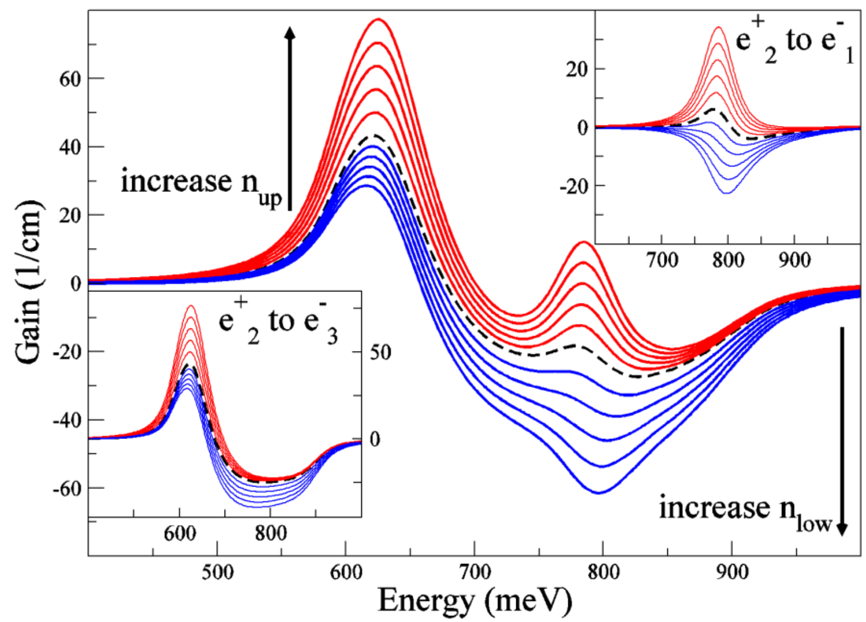
ISB Dispersive Gain Measured

D.Revin et al. APL 92, 081110 (2008)





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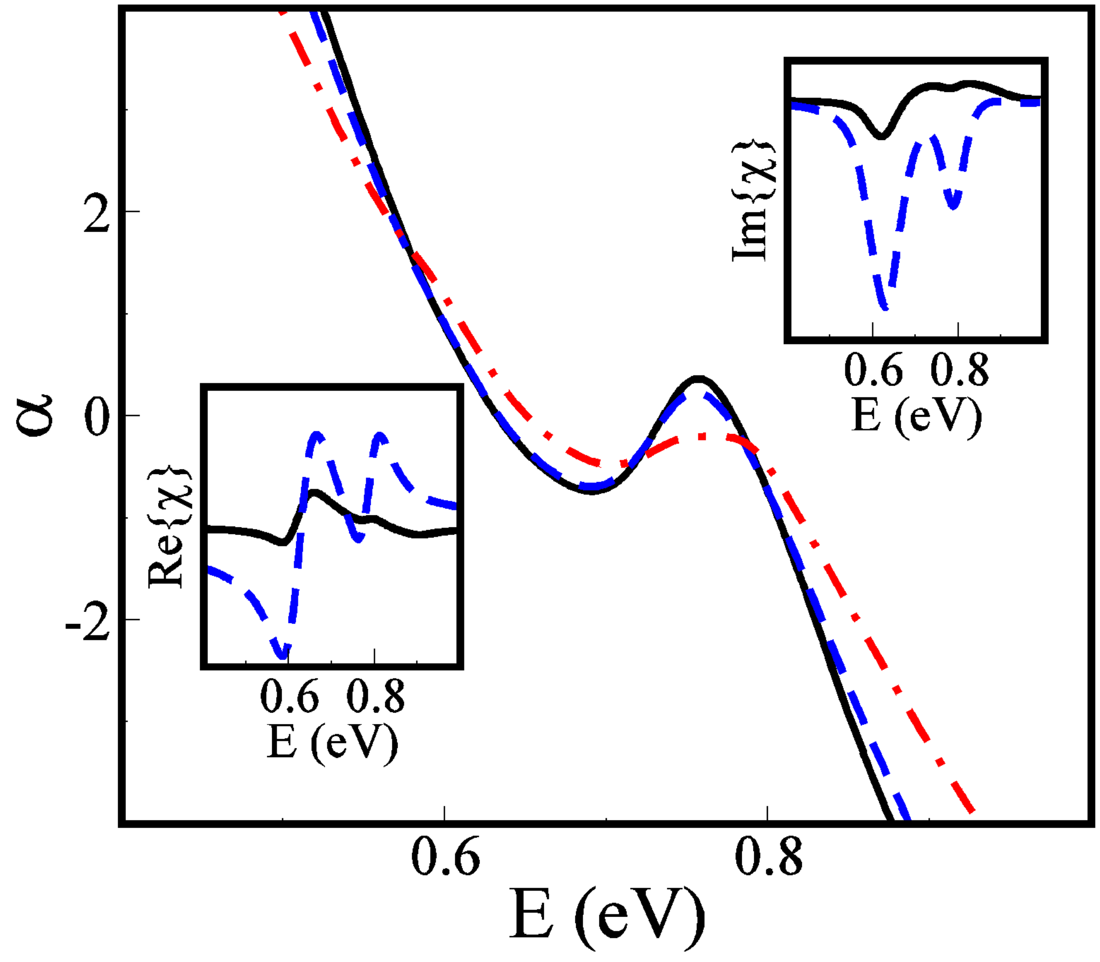
Evolution of α with increasing inversion



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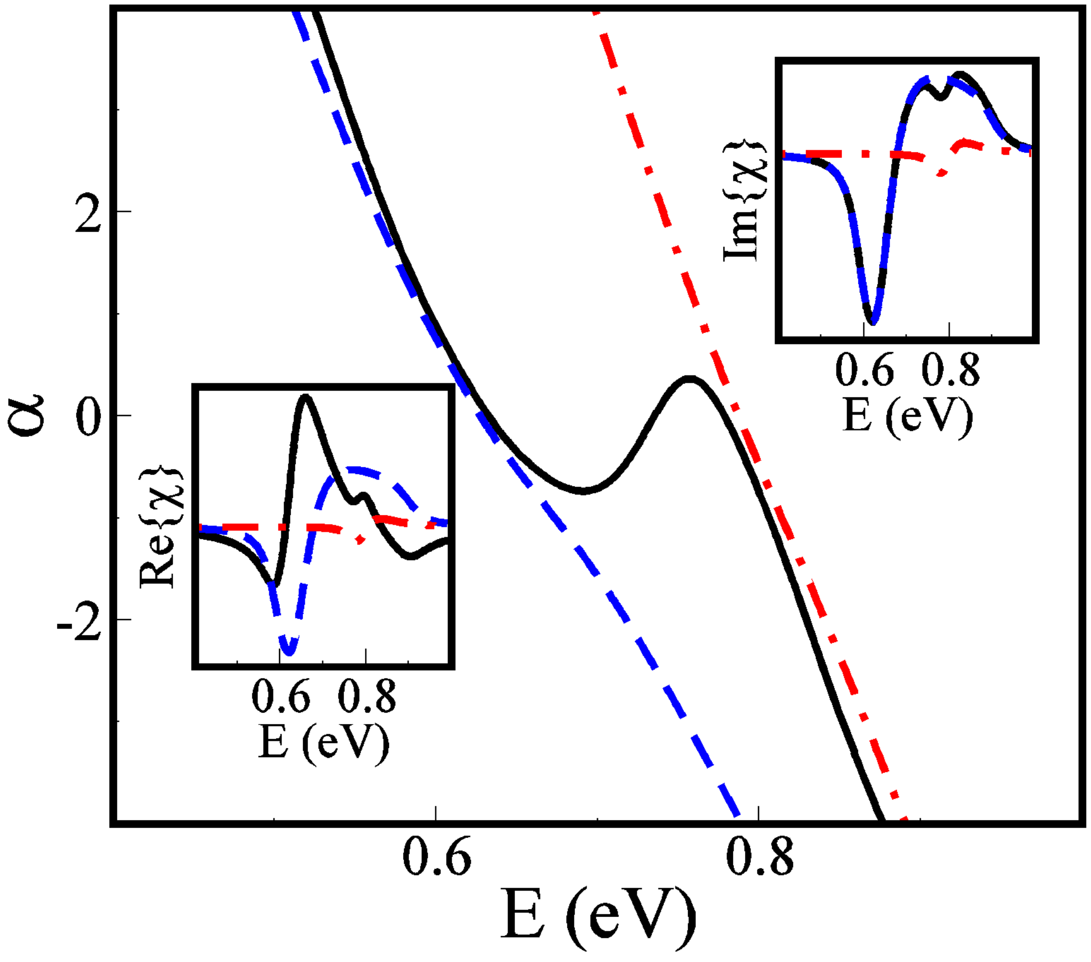
Combined effect of different transitions



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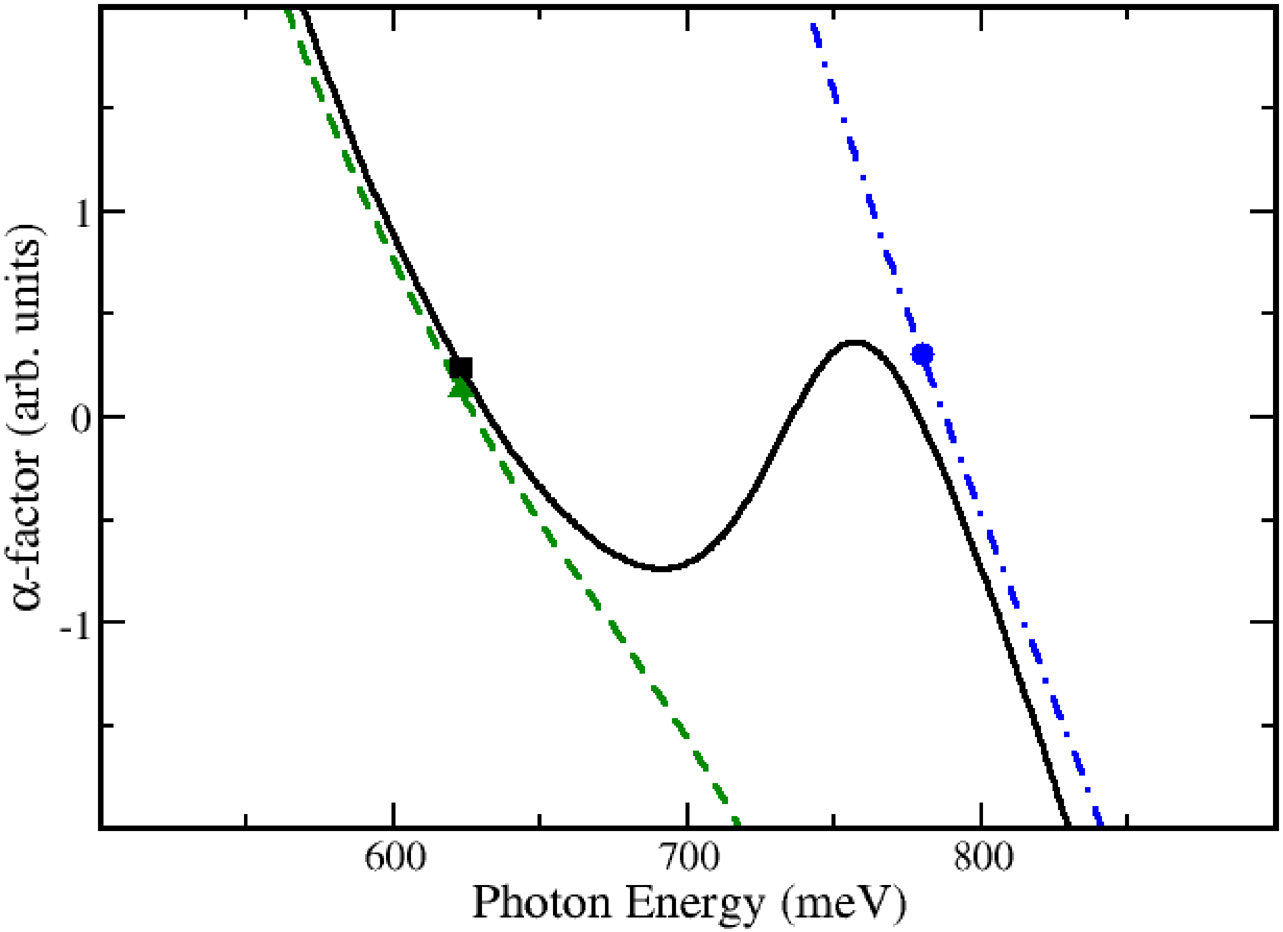
Combined effect of different transitions



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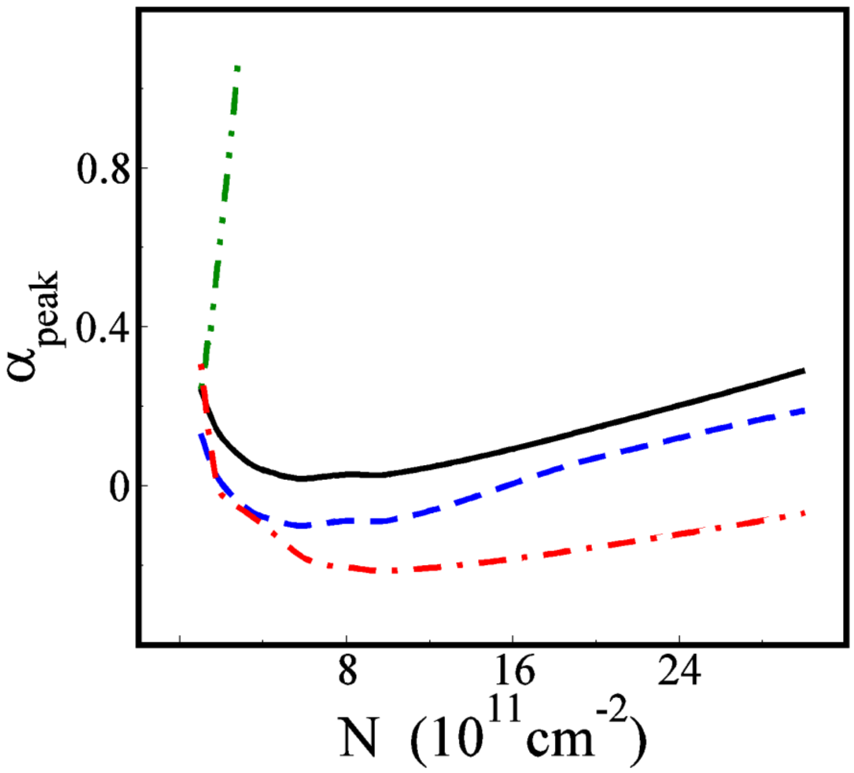
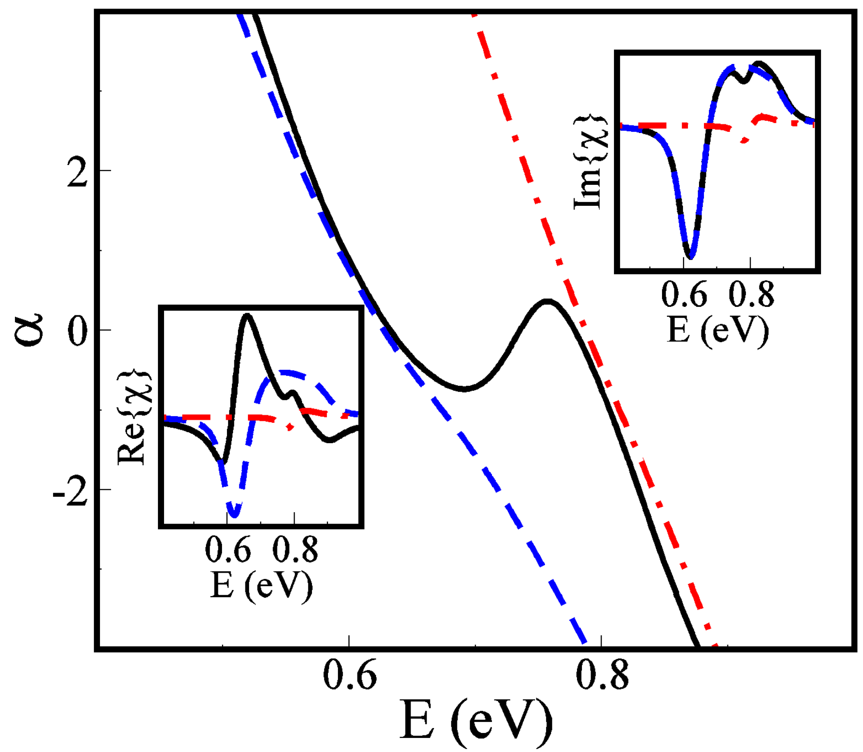
Combined effect of different transitions

M.F. Pereira, Applied Physics Letters 109, 222102 (2016)





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Summary

- This paper resolves the controversy created by intersubband α factors being measured with values ranging from -0.5 to 3 at peak gain , while they were expected to be zero.

- Counter rotating terms which are usually ignored because normally they do not affect the gain spectrum, are ultimately responsible for nonzero α factor at peak gain even without inclusion of nonparabolicity and manybody effects.

- For laser without inversion conditions, where the gain spectrum is typically dispersive instead of Lorentzian, the α factor at peak gain is a bit larger, but still within the range of values found for conventional intersubband lasers.

M.F. Pereira, Applied Physics Letters 109, 222102 (2016)

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