**Slow Light via Resonant-tunneling Induced**

**Transparency in Quantum Well Heterostructures**

Petar Tzenov1\* and Christian Jirauschek1,

*1Institute for Nanoelectronics, Technical University of Munich, D-80333 Munich, Germany*

*\**[*petar.tzenov@tum.de*](mailto:petar.tzenov@tum.de)

**Introduction**

We present a theoretical and computational investigation of the possibility of achieving slow and superluminal terahertz light by exploiting the tunneling induced transparency effect in suitably engineered quantum well heterostructure devices [1]. Our calculations show that for optimal system parameters a slowdown factor larger than 10 could be possible and we also derive necessary conditions for achieving superluminal light.

**Model**

In our model, we consider a periodic structure consisting of two quantum wells per module, in which the lowest energy eigenstate of module I, couples via resonant tunneling to the excited state of the next period, i.e. II, and the resulting triplet and forms a type system (see Fig. 1a). At optimal bias, the electron levels, spanning an inter-module barrier, energetically align to form a strongly coupled pair of dressed states, which could result in a noticeable splitting in the absorption spectrum of the sample. Such an effect is familiar to the quantum cascade laser community [2, 3], however, to the extent of our knowledge, until this point it had not yet been considered in the context of producing slow light.

For our investigation we couple Schrödinger-Poisson, ensemble Monte-Carlo [4] and Maxwell-Bloch simulation codes, which enables us to self-consistently design and analyze various systems with the desired properties. Simulations with suitably chosen, but still realistic, parameters show the possibility of a group velocity delay by a factor of 11.6 with respect to the velocity of light in vacuum.

**Results**

Fig. 1b-e illustrates preliminary results from Maxwell-Bloch equation simulations for the propagation of a weak 30 picosecond pulse through a 2 mm long active region (shaded area), in the ideal case of vanishing dephasing. The propagation direction is along the *x*-axis, whereas the heterostructure growth direction along *z*. We have also neglected the dependence of the electric field on the transverse y-direction.

In the simulation snapshots of Fig. 1c-d we can observe a strong compression of the pulse upon its incidence on the active region, followed by reduction in its overall intensity due to dephasing. Upon leaving the interaction medium, the pulse is again broadened, Fig. 1e-f, as outside of the shaded area its group velocity is equal to the velocity of light in the host material. Our calculations reveal a group refractive index of , however we believe that better values can be achieved with a more careful parameter study.

z (nm)

0

10

20

30

40

50

x (mm)

0

1

2

3

4

5

**t = 96.0857 ps**

0

1

2

3

**t = 216.1928 ps**

0

1

2

3

x (mm)

0

1

2

3

4

5

**t = 264.2356 ps**

0

1

2

3

x (mm)

0

1

2

3

4

5

**t = 144.1285 ps**

0

1

2

3

0

1

2

3

4

5

0

1

2

3

**t = 48.0428 ps**

x (mm)

0

1

2

3

4

5

0

0.05

0.1

0.15

0.2

Energy (eV)

Intensity (a.u.)

Intensity (a.u.)

Intensity (a.u.)

Intensity (a.u.)

Intensity (a.u.)

**b**

**c**

**d**

**e**

**f**

**a**

**II**

**I**

x (mm)

Fig. 1. **a,** Schematic representation of two periods (module I and II) of the active region of the simulated structure together with the relevant wave functions, calculated in the tight-binding basis. **b**-**f,** Consecutivesnapshots from Maxwell-Bloch equation simulations of a 30 picosecond pulse propagating through 2mm of the active region in **a**. The interaction of the optical field with the active region is considered only in the shaded region, while outside it we model free propagation with constant group velocity equal to the bulk velocity in the medium.

**Conclusion**

In this submission we consider the usage of quantum well heterostructures for the creation of optical buffers for terahertz light. In contrast to the electromagnetically induced transparency effect (EIT) [5], such an approach offers the possibility to electrically control the coupling between the and states via simply varying the applied bias. Furthermore, the outlined technique seems as a promising approach, given the rapid advances in the growth and processing technologies for quantum well heterostructure devices and fine level of control achieved, especially by the quantum cascade laser research community [2,3].

**References** :

1. H. Borges, L. Sanz, J. Villas-Bôas, O. D. Neto, and A. Alcalde, “Tunneling induced transparency and slow light in quantum dot molecules,” Physical Review B, vol. 85, no. 11, p. 115425, 2012
2. J. Faist, F. Capasso, C. Sirtori, K. W. West, and L. Pfeiffer, “Controlling the sign of quantum interference by tunnelling from quantum wells,” Nature, vol. 390, no. 6660, pp. 589–591, 1997.
3. D. Burghoff, T.-Y. Kao, N. Han, C. W. I. Chan, X. Cai, Y. Yang, D. J. Hayton, J.-R. Gao, J. L. Reno, and Q. Hu, “Terahertz laser frequency combs,” Nat. Photonics, vol. 8, no. 6, pp. 462–467, 2014.
4. C. Jirauschek and T. Kubis, “Modeling techniques for quantum cascade lasers,” Applied Physics Reviews, vol. 1, no. 1, p. 011307, 2014.
5. K.-J. Boller, A. Imamoglu, and S. E. Harris, “Observation of electromagnetically induced transparency,” Physical Review Letters, vol. 66, no. 20, p. 2593,1991.