

Investigation on Soliton Related Effects in Mid-Infrared Quantum-Cascade Lasers

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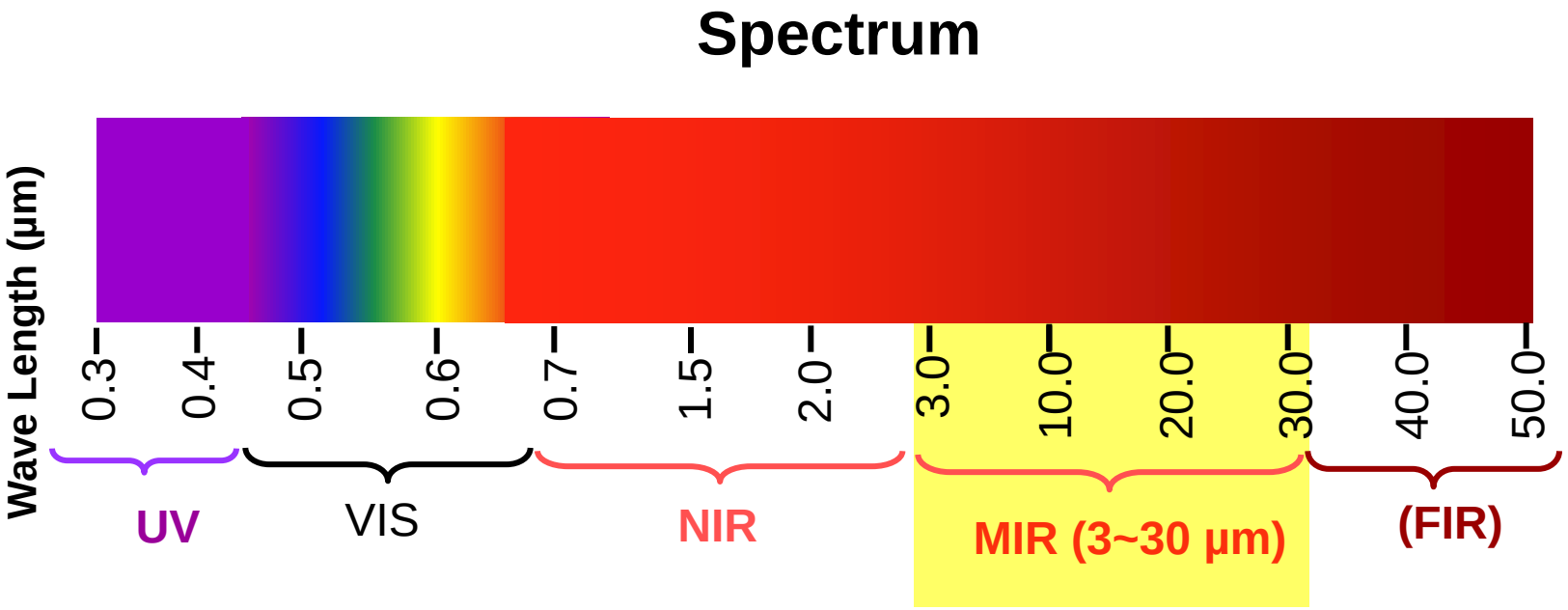
Debao Zhou, University of Minnesota Duluth, USA

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Outline

- Introduction to quantum-cascade lasers (QCL's)
- Overview on the dynamic study in QCLs
- Soliton related effects
- Motivation of current research
- Theoretical model and numerical procedure
- Results and conclusions

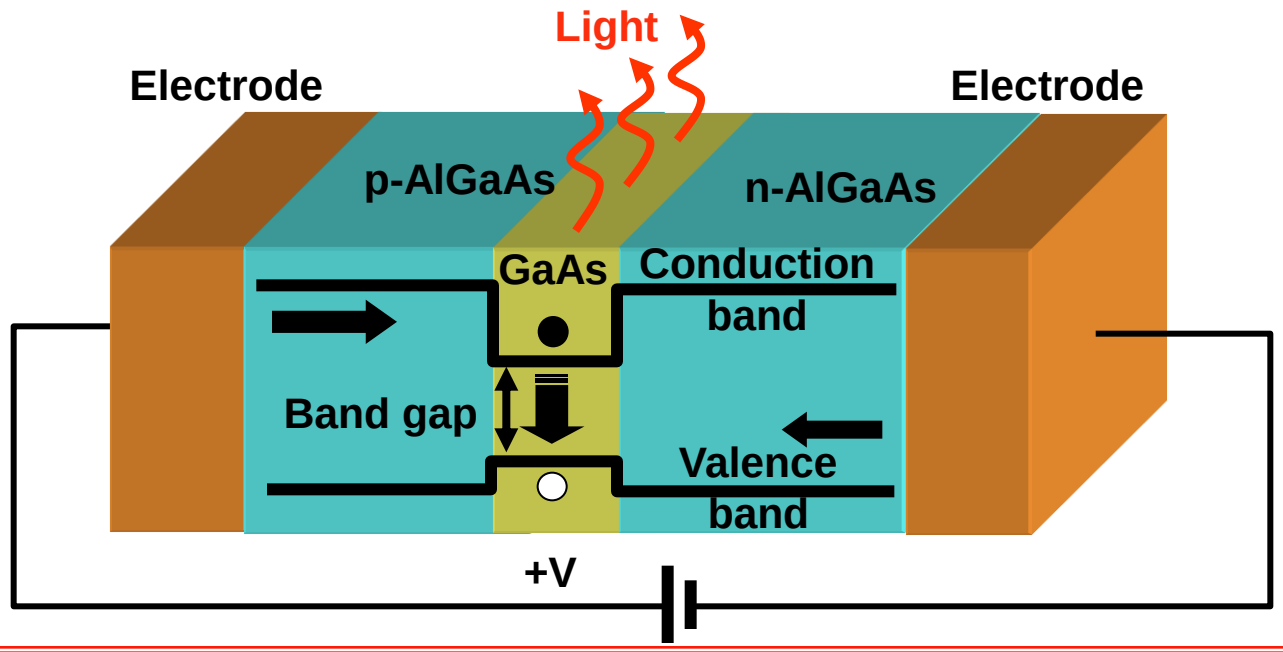
Quantum Cascade Lasers — MIR Light Emission



Most QCL's emit in the the mid-infrared (MIR) region (3~30 μm)

Many chemical gases have strong absorption in mid-infrared region, such as CO,NH_3, NO, SO_2, *etc*.

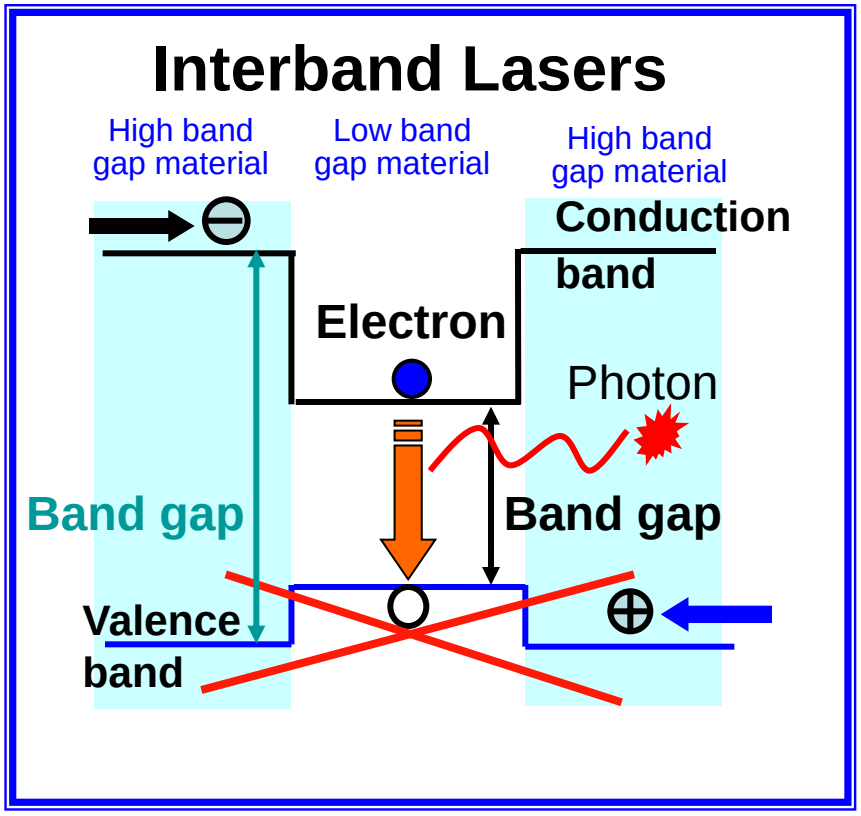
Conventional Semiconductor Lasers-Interband Lasers

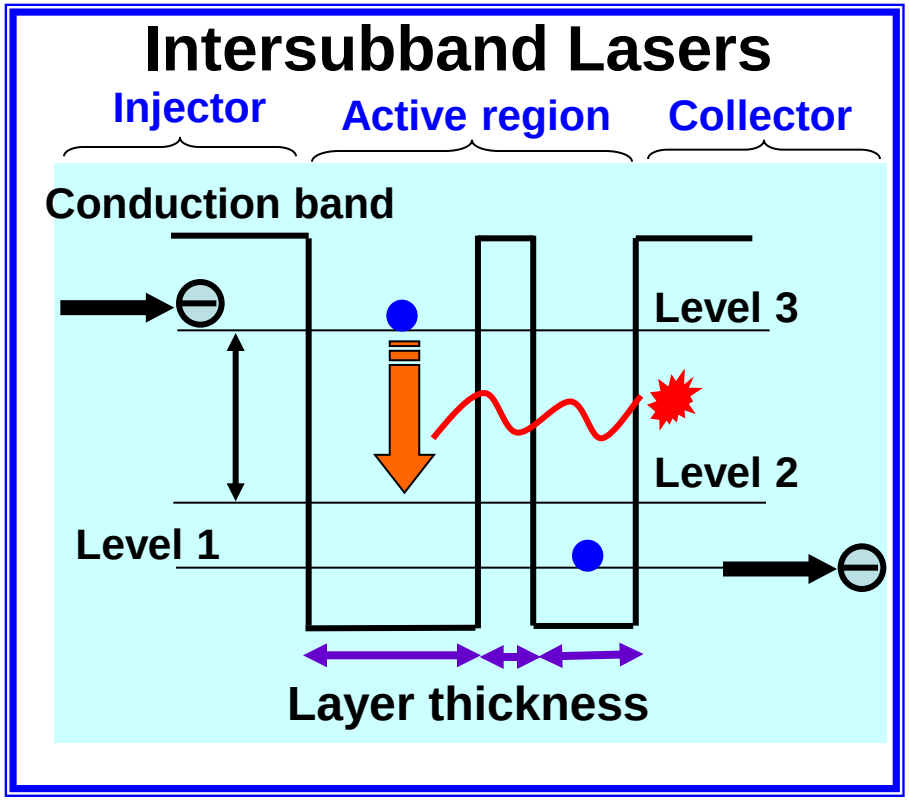


Disadvantages:

- **Emission wavelength depends on material**
- **Difficult to generate long wavelength, i.e., colors in the MIR to FIR region, no good (robust, cost-effective) materials available**
- **Very difficult to generate more than one color per laser**

Quantum-Cascade Lasers– Intersubband Lasers

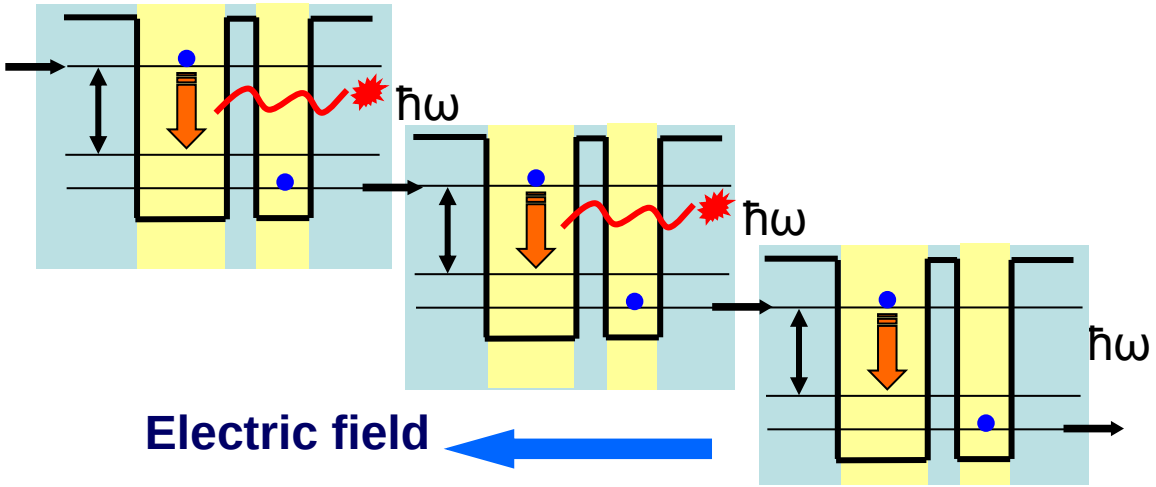




Advantages:

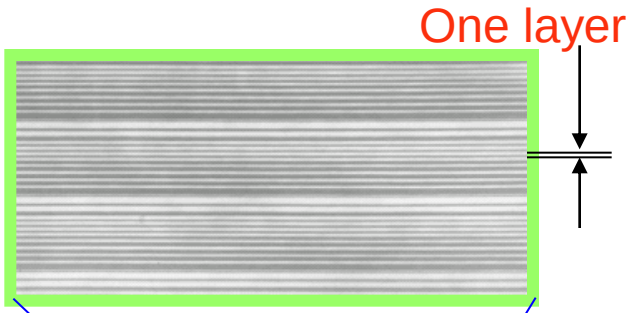
- Wavelength depends on layer thickness (flexible design)
- Well-understood materials can be used for long wavelength
- Multiple colors can be generated in same laser

Cascade Effect



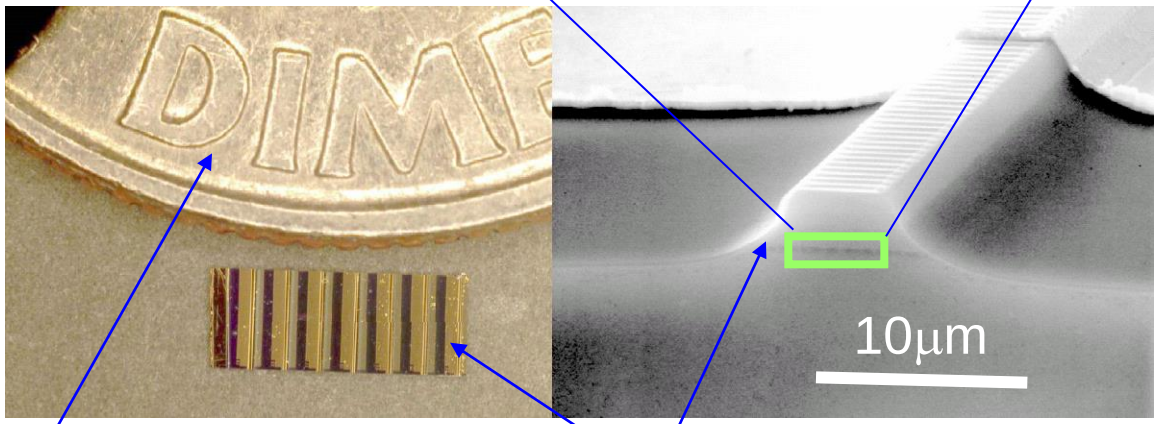
Cascade effects

Cross section of a QCL: Note that each layer thickness is a few nanometers



One electron emits *N* photons to generate high output power

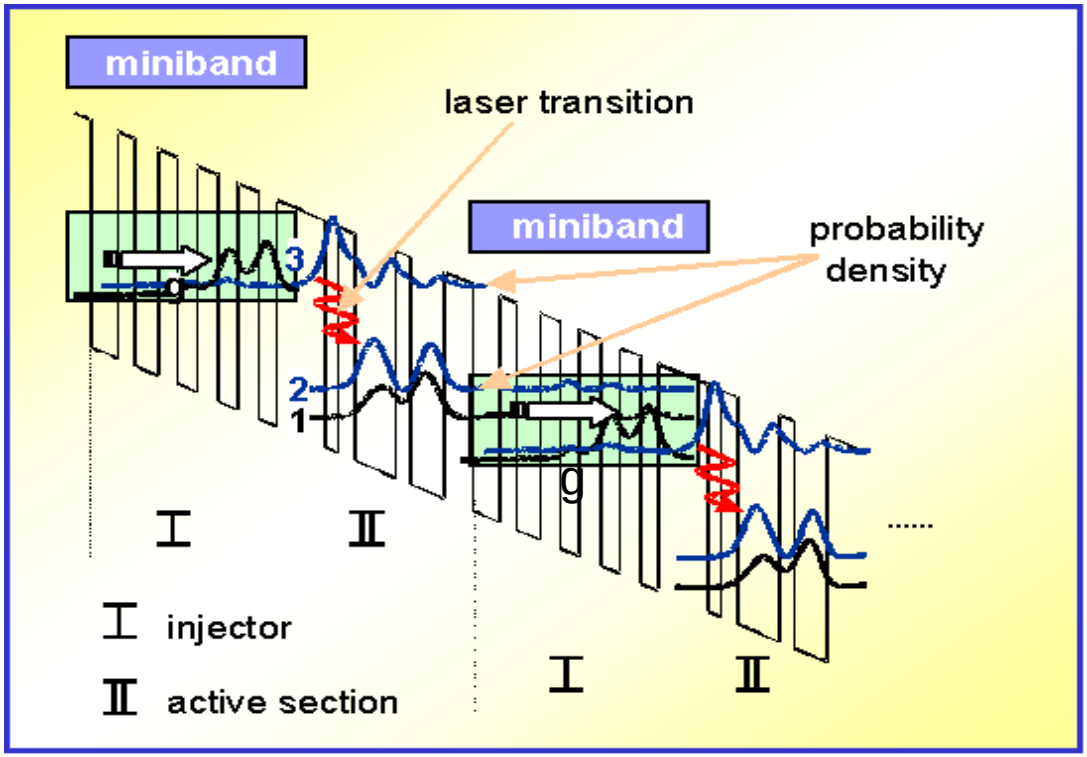
Typically *N*=20-50 stages make up a single quantum cascade laser



Dime coin

Quantum cascade laser

Carrier Transition Mechanism in QCL's



Band Structure of two periods of an InGaAs/AlInAs QCL

- E_{32} defines $\hbar\omega$ for lasing
- $\tau_{32} > \tau_2$ is necessary for population inversion
- $\Delta E_{21} \approx E_{LO}$ to maximize the population inversion

Characteristics of Quantum-Cascade Lasers

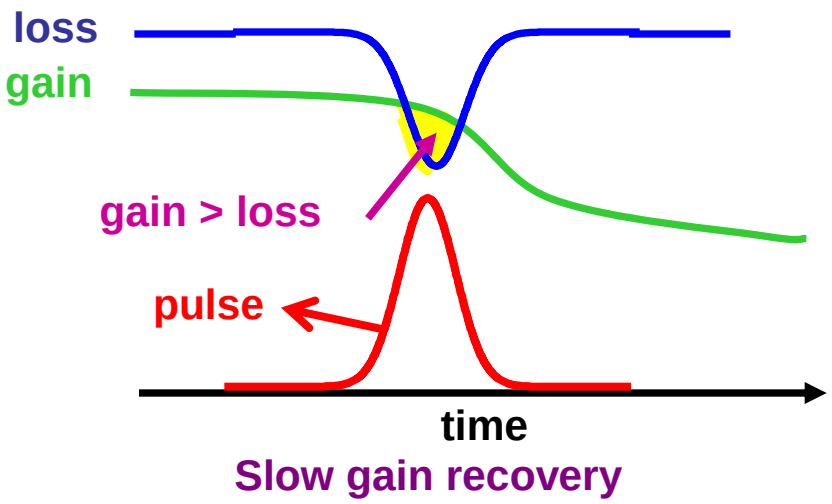
Intrinsic properties

- Wavelength agility
  - layer thickness determines emission wavelength
  - InGaAs/AlInAs 3.5 -24 um
- High optical power (up to a few Watts)
  - Cascading effect recycles electrons
- Ultrafast carrier relaxation dynamics, fast gain recover time
  - Longitudinal (LO) phonon scattering (on picosecond)
- Large optical nonlinearity
  - Giant dipole matrix elements leading to large nonlinear susceptibilities

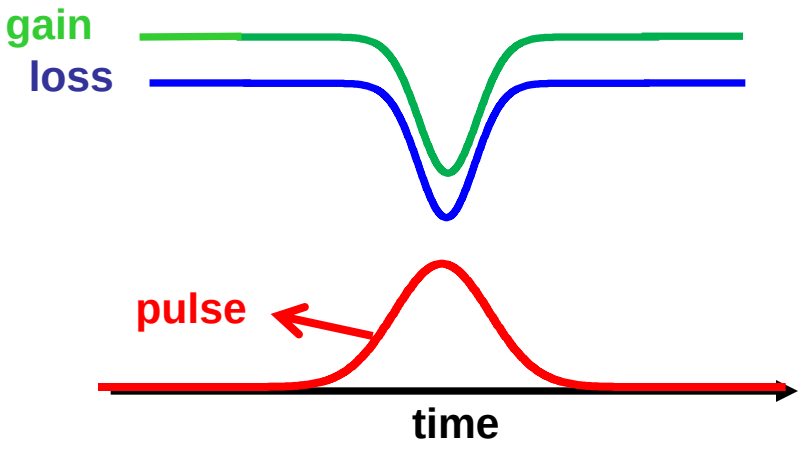
Gain Recovery Time of QCLs and Traditional Semiconductor Lasers

Traditional semiconductor lasers: longer gain recovery time than cavity round-trip time, self-mode-locking (SML) is dominated by the saturable absorber (SA) effect

QCLs: gain recovery faster than cavity round-trip time, SML is not possible



Slow gain recovery



Fast gain recovery

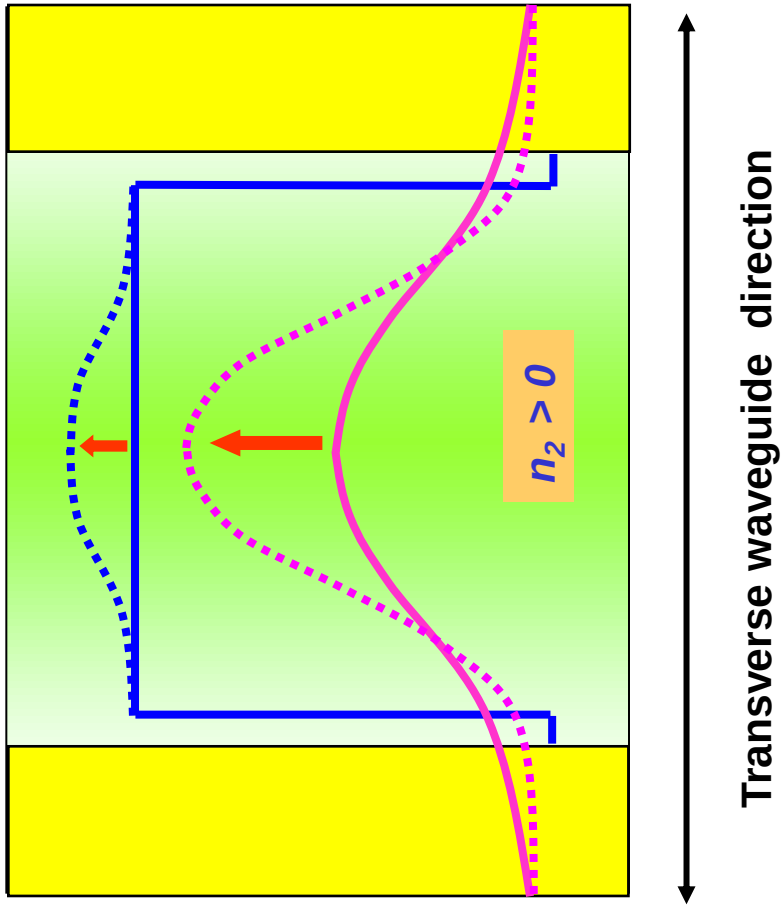
Optical Nonlinearities in QCLs

- **Optical Kerr nonlinearity due to large dipole matrix elements** $n_2 \propto \mathrm{Re}\left[\chi^{(3)}(\omega;\omega,\omega,-\omega)\right] \propto z_{mn}^4$
  - **Transverse Kerr effect, *i.e.*, saturable absorber (SA)**
  - **Longitudinal Kerr effect, *i.e.*, self-phase modulation (SPM)**

Saturable Absorber Effect

Intensity-dependent refractive index

$$n(t,\vec{r}) = n_0 + n_2 I(t,\vec{r}),$$



Transverse Kerr effect

$$\Delta n(x,y) = n_2 I(x,y)$$

Saturable absorber (SA) :

reduced waveguide loss at high optical intensity

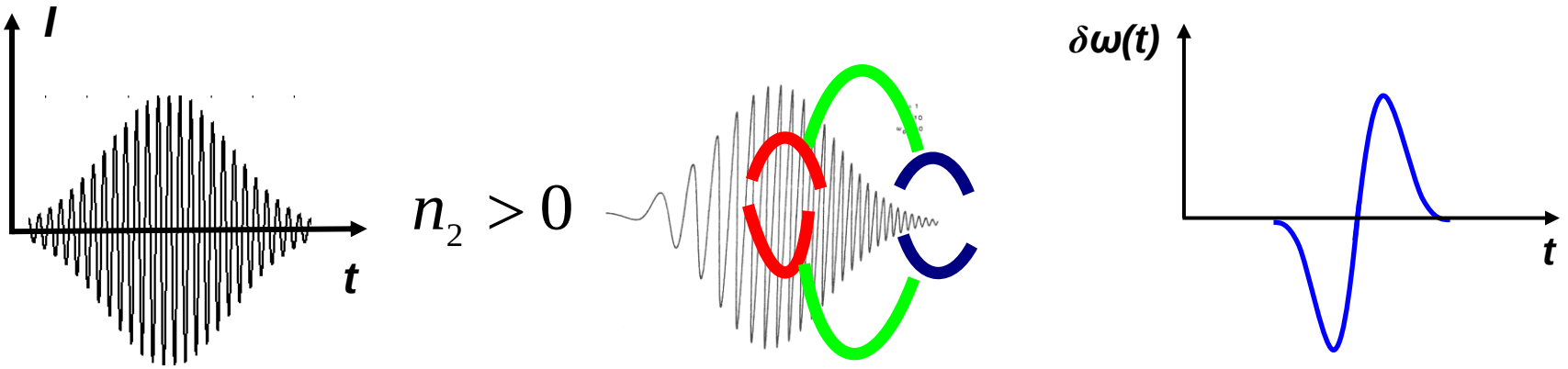
$$l = l_0 - \gamma |E|^2$$

Self-phase Modulation (SPM)

Intensity-dependent refractive index

$$n(t) = n_0 + n_2 I(t)$$

Longitudinal Kerr effect

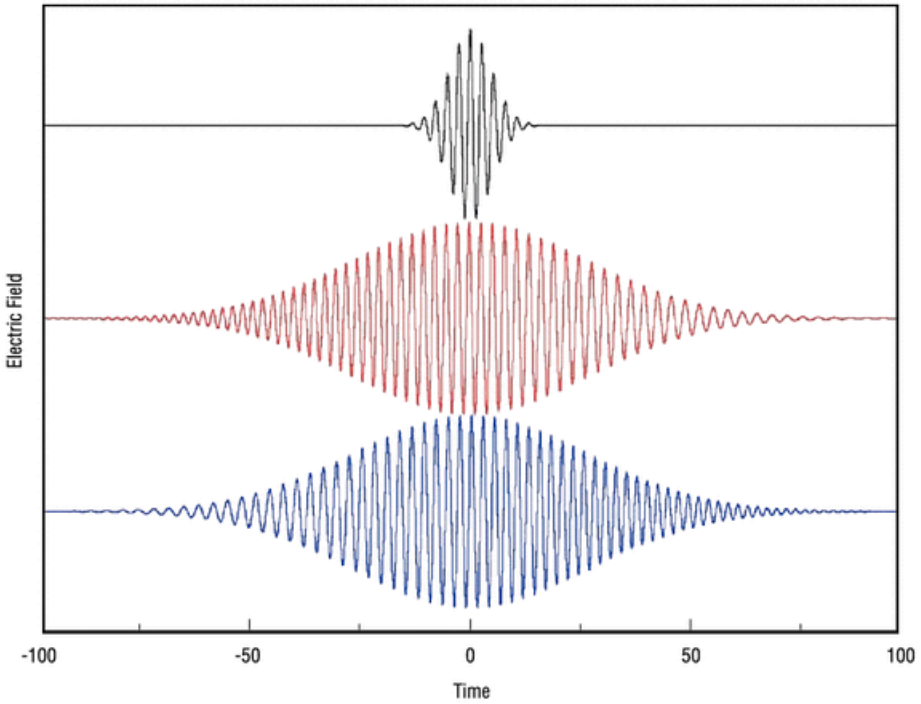


Self-phase modulation (SPM):

Additional phase shift: $\Delta\phi(t) = -\xi |E(t)|^2$ **and** $\xi \propto n_2$

Group-Velocity Dispersion (GVD)

Group-velocity dispersion (GVD): the frequency dependence of the group velocity in a medium, or (quantitatively) the derivative of the inverse group velocity with respect to angular frequency. The coefficient of GVD is represented by β_2.



No dispersion

Positive dispersion (normal dispersion): higher frequency components travel slower than the lower frequency components

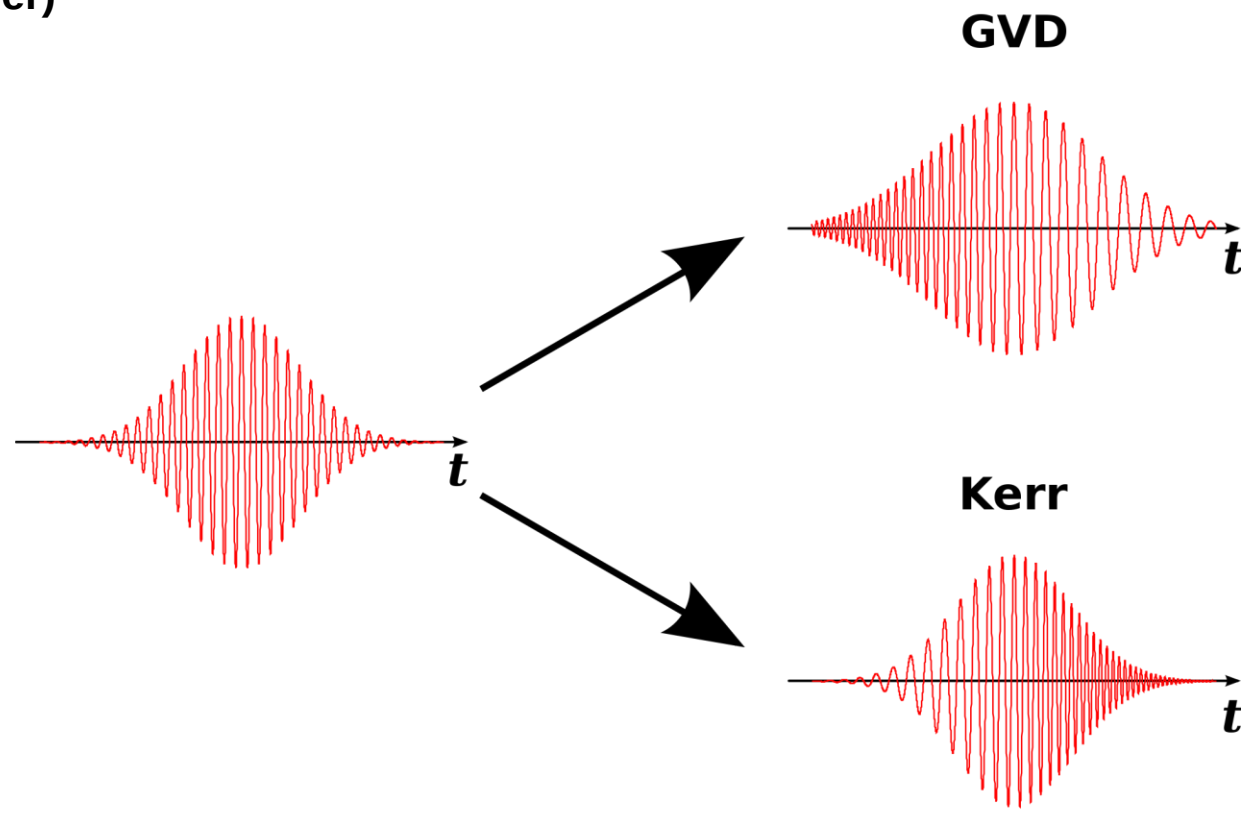
Negative dispersion (anomalous dispersion): higher frequency components travel faster than the lower frequency components

The presence of GVD in MIR QCLs has been experimentally substantiated by *H. Choi et al., Opt. Express 15, 15898-15907, 2007*.

Soliton Related Effects

Soliton: a self-reinforcing solitary wave that maintains its shape while it propagates at a constant velocity. Solitons are caused by a cancellation of dispersion and Kerr nonlinearity in the medium.

Soliton related effects: GVD and Kerr nonlinearity (SPM and saturable absorber)



Research Motivation

- **Dynamic behavior of QCLs is very different from that of conventional lasers owing to the unique combination of ultra-fast carrier scatterings and gain recovery, significant nonlinearities, and dispersion effect in the lasing medium.**

- **The group-velocity dispersion (GVD), whose presence in a QCL cavity has been substantiated experimentally, has not been explicitly addressed in the study of dynamic behaviors in QCLs.**

- **In a nonlinear dispersive lasing medium, the combination of GVD and SPM could possibly lead to the soliton formation. However, the interplay between these two effects during the QCL coherent pulse progression has received less attention.**

Modeling Strategy

Maxwell-Bloch formulism (optical coherence is accounted):

E-field: $$\frac{\partial E}{\partial t}=\frac{c}{n}\left[-\frac{\partial E}{\partial z}-P-\frac{1}{2}\left(l_0-\hat{\gamma}\left|E\right|^2+i\hat{\xi}\left|E\right|^2\right)E-\frac{1}{2}i\beta_2\frac{\partial^2 E}{\partial t^2}\right]$$

Polarization: $$\frac{\partial P}{\partial t}=-\frac{1}{2}\sigma E-\frac{P}{T_2}$$

Population inversion: $$\frac{\partial \sigma}{\partial t}=\frac{l_0\left(p_r-1\right)}{T_1T_2}-\frac{\sigma}{T_1}+\left(E^*P+EP^*\right)$$

$\beta_{2:}$ GVD coefficient

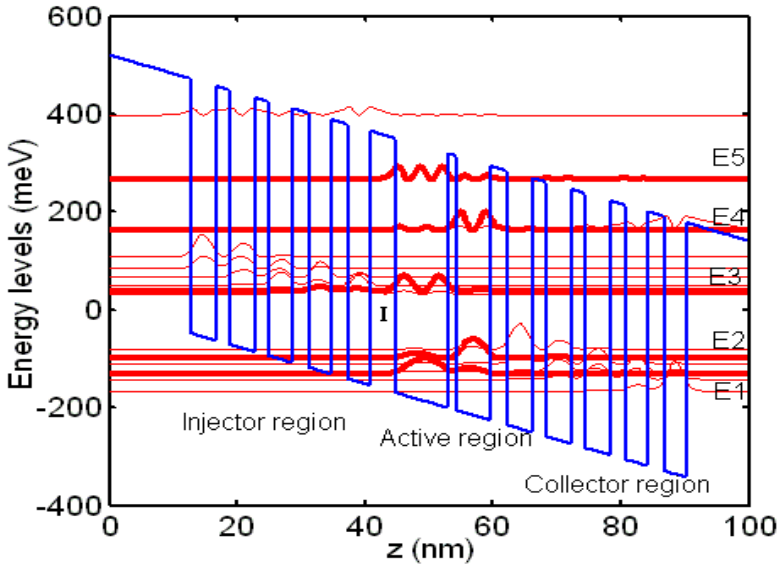
$\hat{\gamma}$: The normalized saturable absorber strength

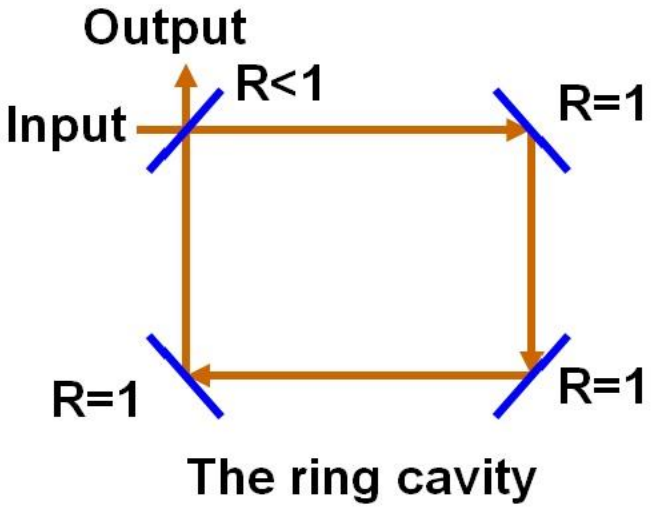
$\hat{\xi}$: The normalized SPM strength

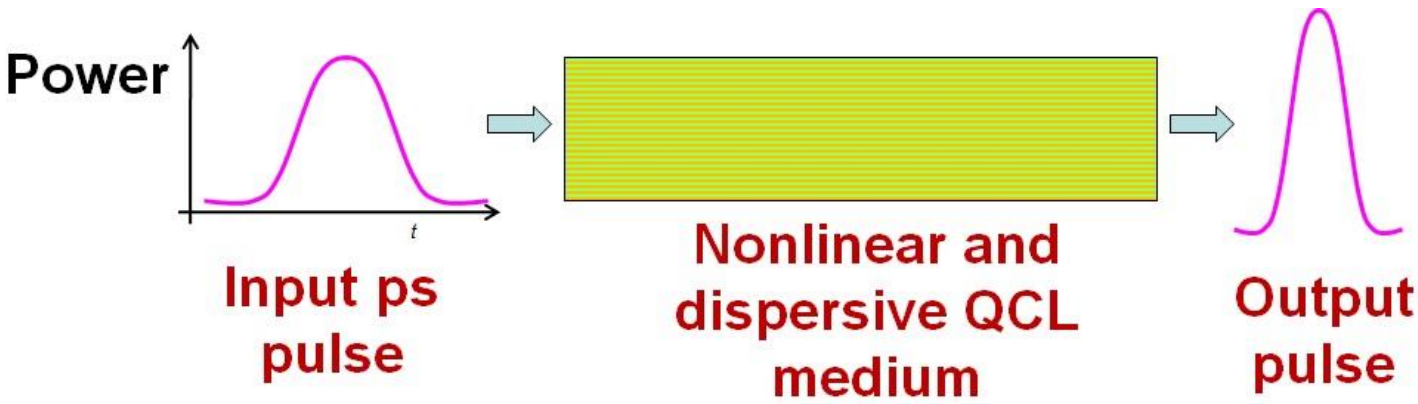
Numerical Procedure

- **The finite difference procedure in both spatial and time domains is needed.**
- **Due to the inclusion of GVD term, forthright applying FDM ends up with either a nonconvergence solution or a convergence solution after unreasonably long computation time.**
- **The nondimensionalization treatment prior to the FDM procedure is necessary for obtaining a convergent solution efficiently.**
- **The spectral domain analysis is carried out through the FFT transformation of the time-domain solution**

Features of QCL medium





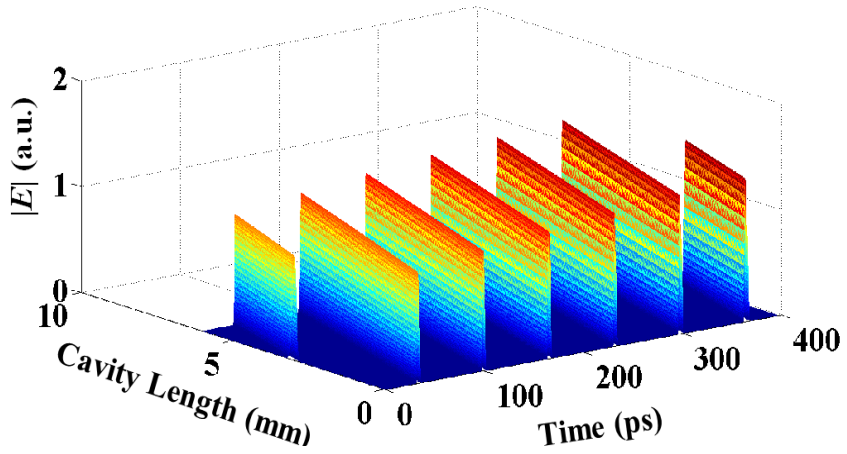


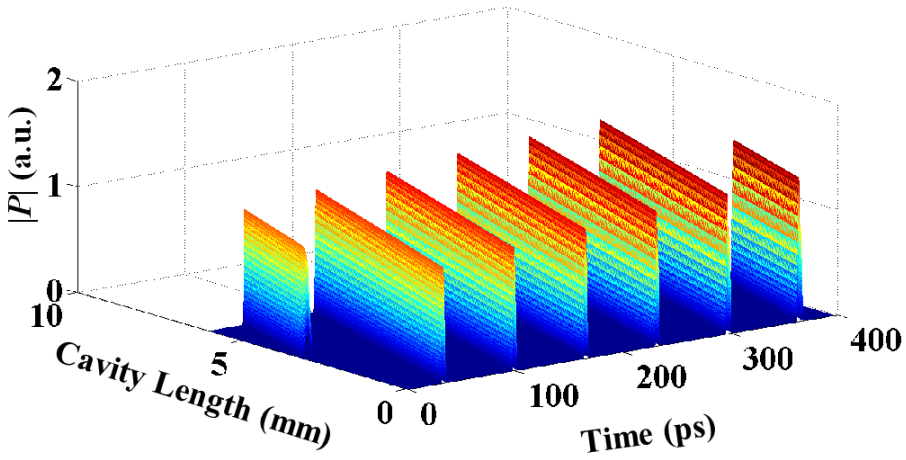
Parameters Adopted for the Laser Cavity

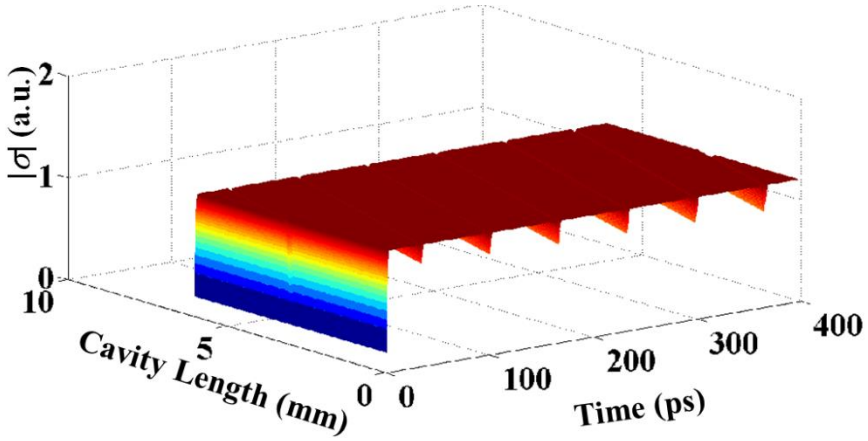
Symbol	QUANTITY	Value
n	Background refractive index	3.3
T_1	Longitudinal relaxation time	5×10^{-13} s
T_2	Transverse relaxation time	0.67×10^{-13} s
l_o	Linear cavity loss	700 m^{-1}
γ_0	SA strength	2.0×10^{-9} cm/V^2
ξ_0	SPM strength	1.2×10^{-6} cm/V^2
μ	Transition dipole matrix element	$e\times2.54$ nm
β_{20}	Coefficient of GVD	-4.6 ps^2/m
L	Cavity length	6.0 mm

A. Gordon et al., "Multimode regimes in quantum cascade lasers: from coherent instabilities to spatial hole burning," Phys. Rev. A, vo. 77, 053804, May 2008.

Time-domain Evolution

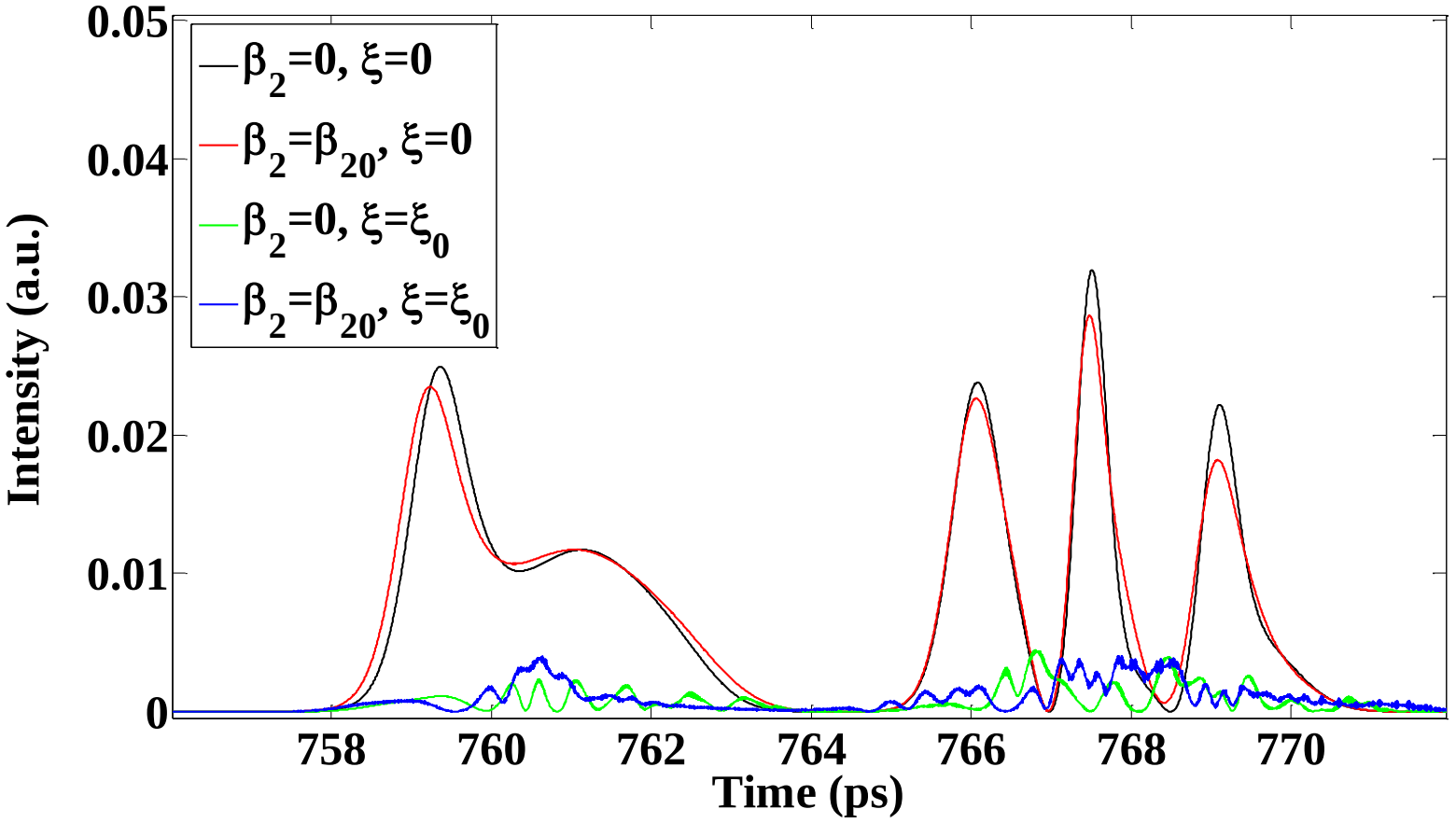




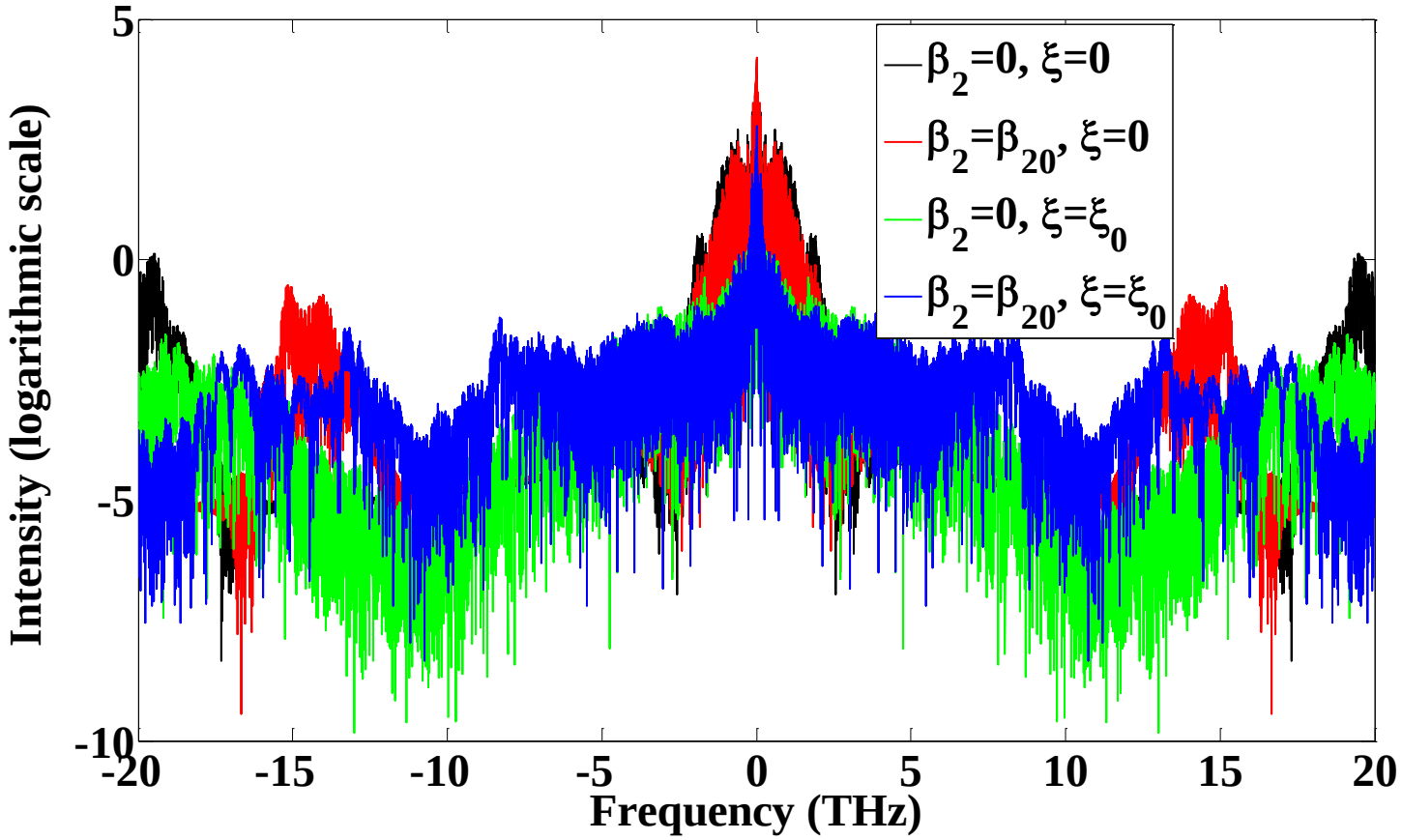


GVD, SPM and saturable absorber are all accounted.

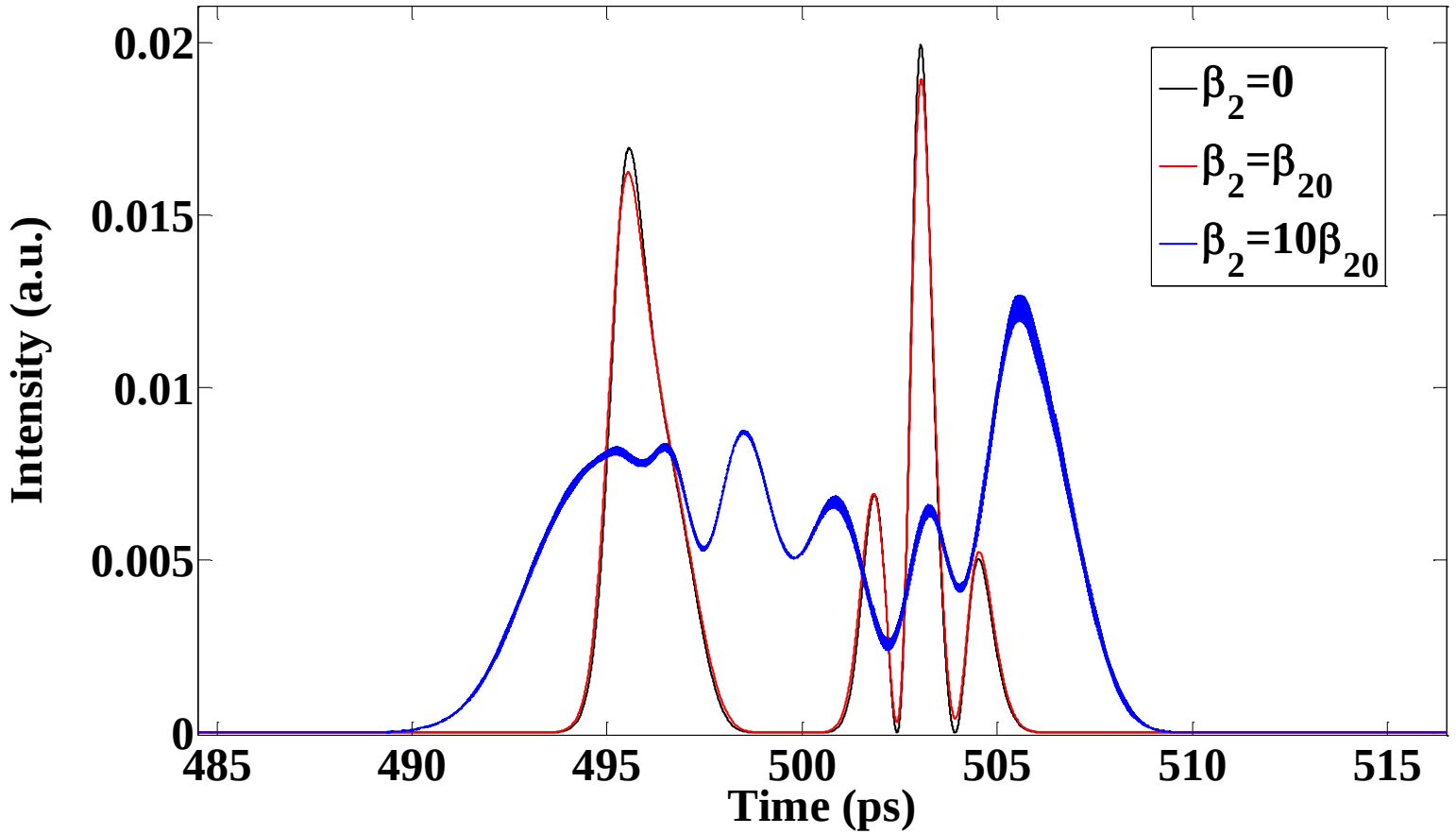
Time-domain Pulse Formation under Combined GVD and SPM Effects



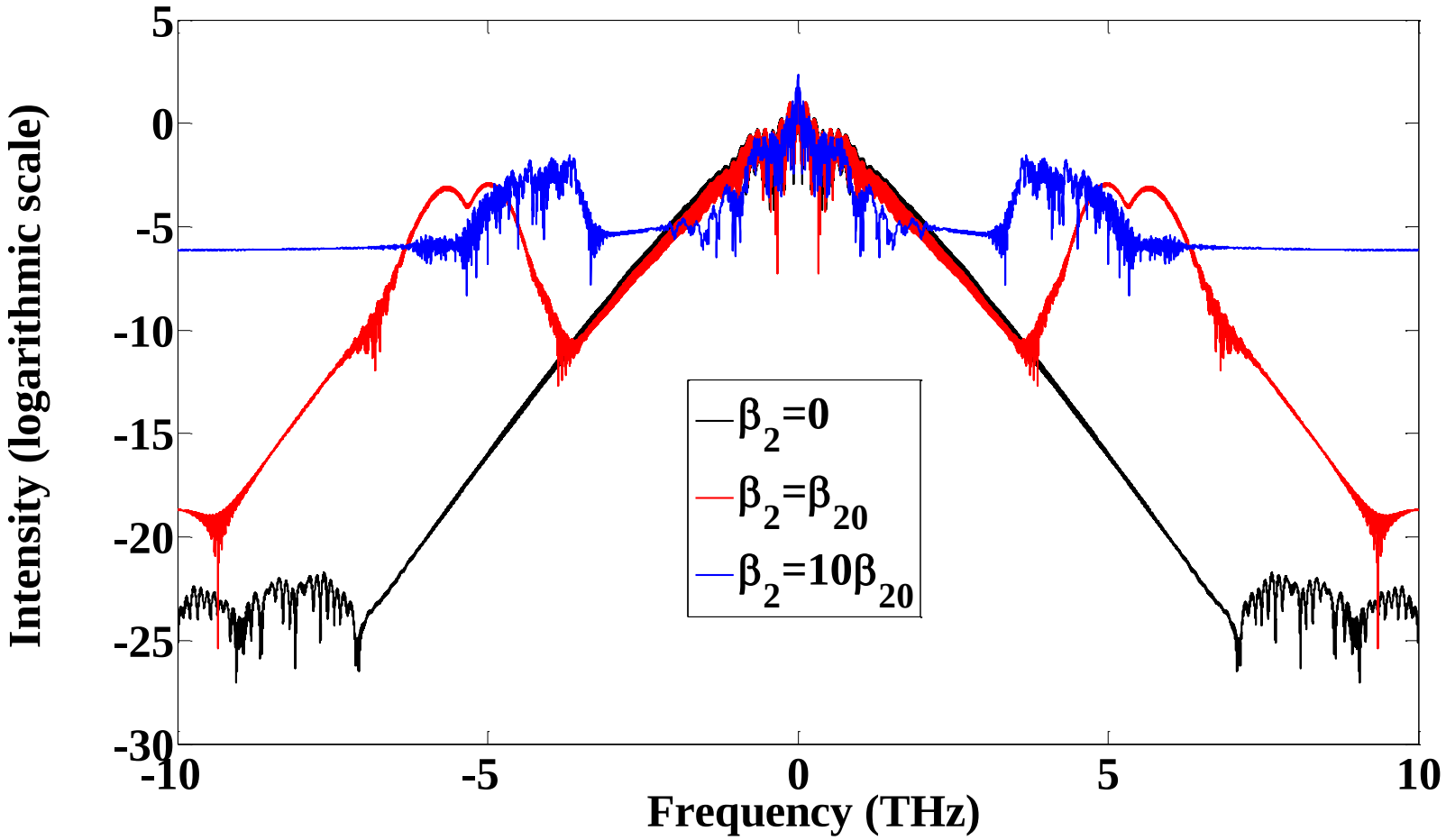
Optical Spectrum under Combined GVD and SPM Effects



Time-domain Pulse Formation Vs. GVD Strength

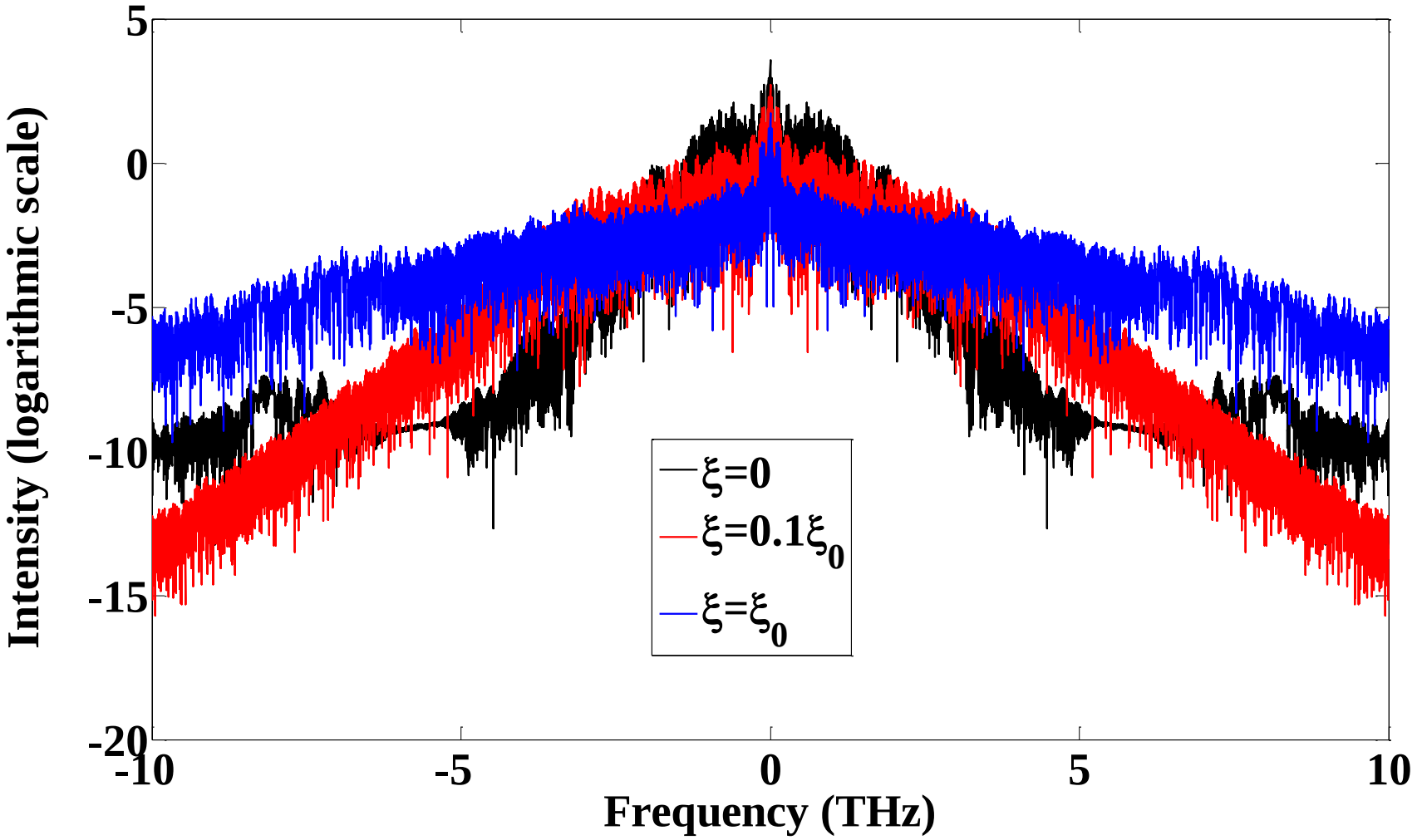


Optical Spectrum Vs. GVD Strength



- GVD needs to be strong enough to disturb the frequency spectrum.
- This agrees with the comments on the study of frequency combs (***G. Villares and J. Faist, Opt. Exp., Jan. 2015)***.

Optical Spectrum Vs. SPM Strength



Conclusions

- **We present our theoretical analysis on coherent pulse progression in MIR QCLs under both GVD and SPM effects with background SA in the lasing medium.**

- **We found out from our simulation that the SPM and GVD have cancellation effects in the time domain. However, in the frequency domain, they affect the spectrum in different aspects.**

- **Our evaluation of GVD influence based on simulation results agrees with conclusions draw from the study of GVD effect on QCL frequency combs.**

- **The presented study lays the foundation for our further pursuit of the conditions for soliton propagation in the QCL medium by varying the parameters of the cavity and the properties of the medium.**

Related Publications

- J. Bai, H. Wang, Q. Wang, D. Zhou, K. Le and B. Wang, “Coherent pulse progression of mid-infrared quantum-cascade lasers under group-velocity dispersion and self-phase modulation,” *IEEE Journal of Quantum Electronics* (Accepted, in press), July 2016.
- J. Bai, H. Wang, Q. Wang, D. Zhou, K. Le, and Bo. Wang, "Coherent Pulse Propagation in Mid-infrared Quantum-Cascade Lasers with Nonlinear Dispersive Gain Medium", *OSA Conference on Mid-Infrared Coherent Sources (MICS)*, Hilton Long Beach, Long Beach, California, March 20-22, 2016.
- J. Bai and D. Zhou, “Stability Analysis of quantum-cascade lasers with intracavity nonlinearity and group-velocity dispersion*," Nonlinear Optics 2015,* Kauai, Hawaii, USA, July 26-31, 2015.
- J. Bai and D. Zhou, "Effect of group-velocity dispersion on the stability of quantum-cascade lasers," *Journal of Nanophotonics*, vol. 7, no. 1, 073079, October 2013.
- J. Bai, “Phase Instability and Amplitude Instability of Quantum-Cascade Lasers with Fabry-Perot Cavity”, *IEEE Transactions on Nanotechnology*, vol. 11, no. 2, pp. 292-297, March 2012.
- J. Bai, "Amplitude instability and phase instability of quantum-cascade lLasers under Kerr effect," *the 11th IEEE International Conference on Nanotechnology (IEEE NANO 2011)*, Portland, Oregon, Aug. 15-19, 2011.
- J. Bai, “Effect of self-phase modulation on the instabilities of quantum-cascade lasers”, *Journal of Nanophotonics,* vol. 4, 043519, 2010.
- J. Bai and D. Zhou, "Single-mode instability and multi-mode instability of quantum-cascade lasers", *IEEE Proceedings of 10th Conference on Nanotechnology (IEEE Nano 2010),* pp. 815-820, 2010. DOI: 10. 1109/NANO. 2010. 5697829, Seoul, Korea, Aug. 17-20, 2010.

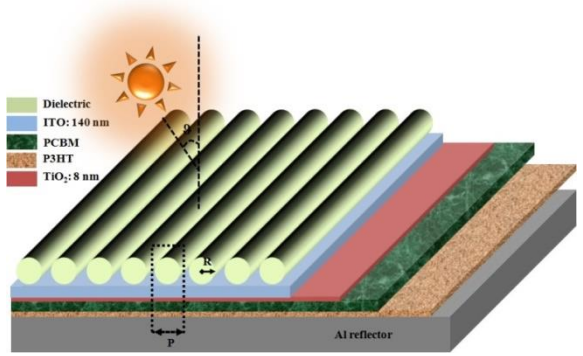
Other Ongoing Research Activities

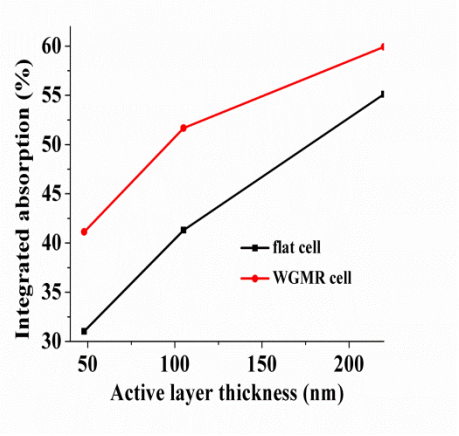
- **Nanoscale Solar cells**
  - Light trapping enhancement through nano-fibers as anti-reflection coating
  - Plasmonic solar cells
  - Quantum-dot intermediate band solar cells
- **Laser-based stethoscope for heartbeat detection**
- **E-skin pressure sensor array for colonoscopy**

What Can Nanotechnology Do to Improve PV Efficiency?

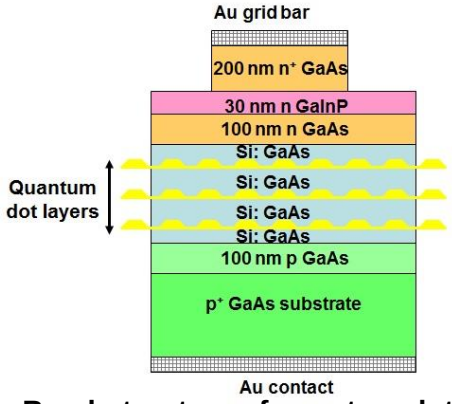
— Ongoing research projects

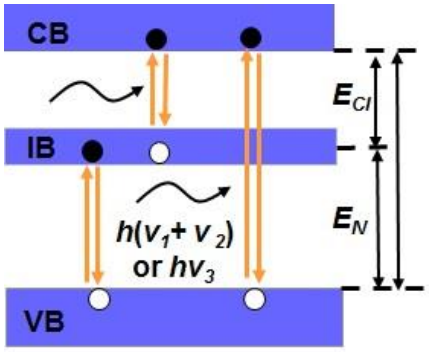
- **Incorporate the anti-reflection coating formed by nano-fibers to enhance the light trapping**





- **Engineer the semiconductor band-structure to optimize the absorption range in the solar spectrum**





Band-structure of quantum dot solar cells with additional intermediate band

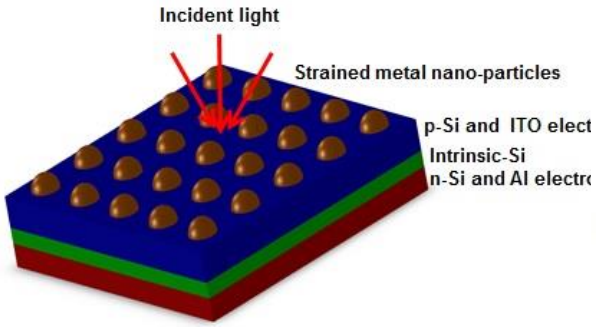
Khai Q. Le, M. Nixon & J. Bai, IEEE J. Photovoltaics 5, 1125-1129 (2015)

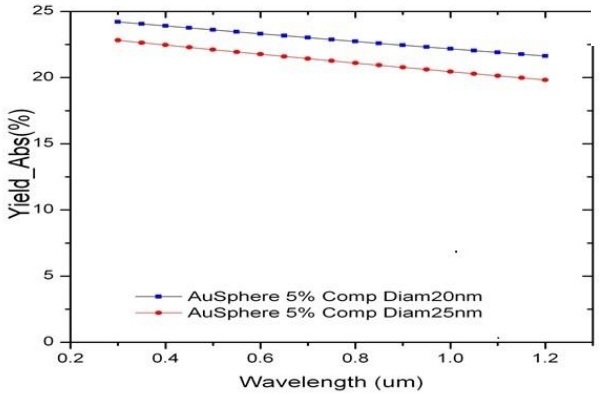
What Can Nanotechnology Do to Improve PV Efficiency?

— Ongoing research projects (Cont'd)

- **Utilize physics phenomena at nanoscale to enhance the absorption strength**

Strain-enhanced plasmonic solar cells

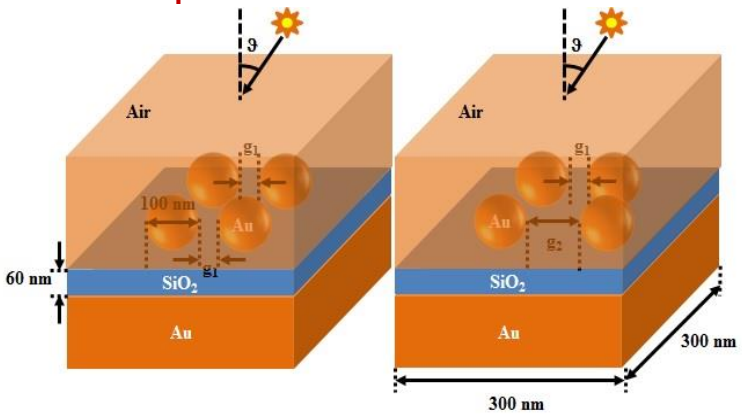


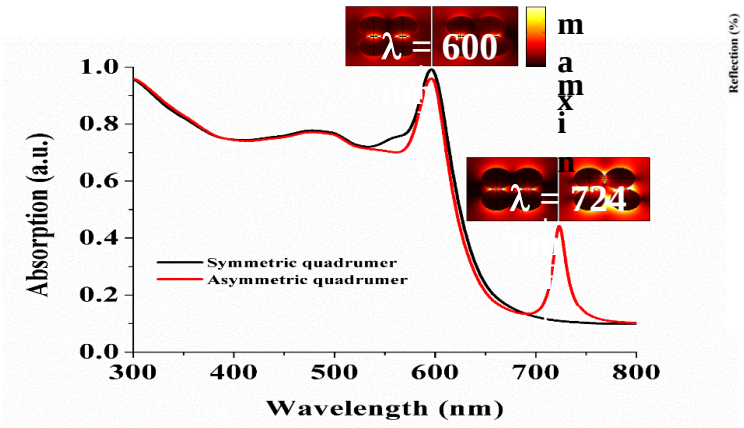


Strain effects on gold nanosphere array

X. Qian & J. Bai, J. Comput. Theor. , 10 (10), 2354-2360 (2013)

Efficient absorber design based on plasmonic Fano resonance

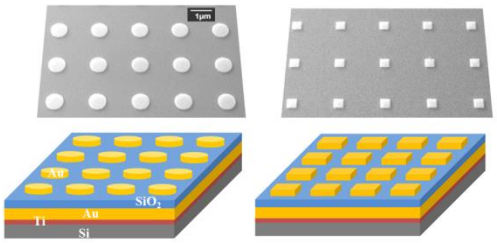




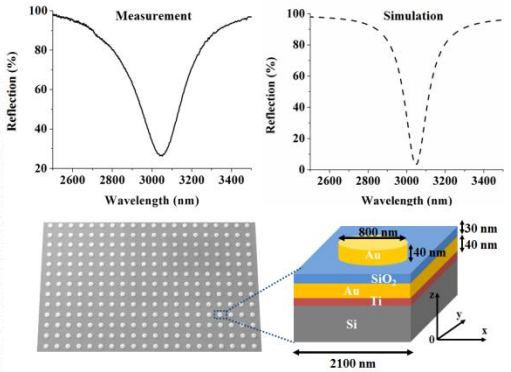
Absorption spectrum of a metamaterial absorber with array of nanospheres

K. Le & J. Bai, JOSA B, 32 (4), 595-600 (2015)

Experimental verification of absorption enhancement of nano-arrays

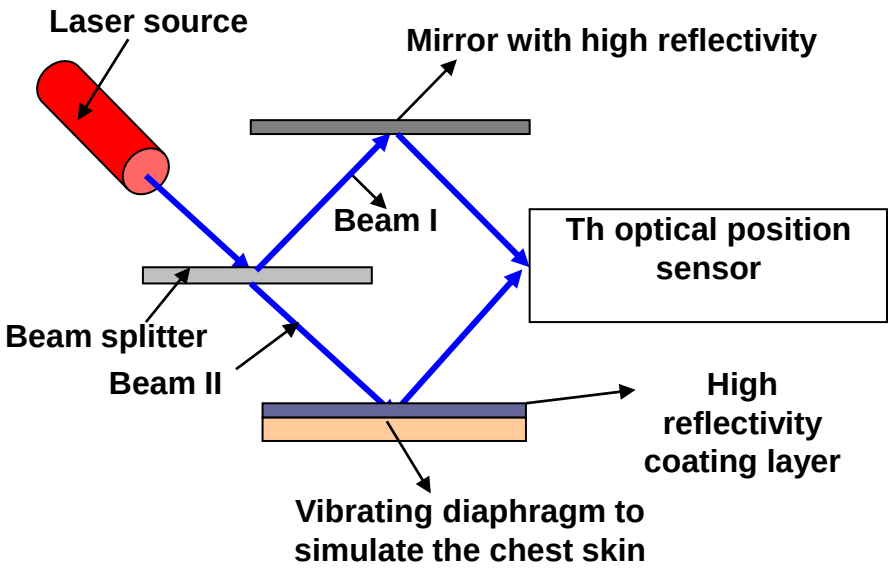


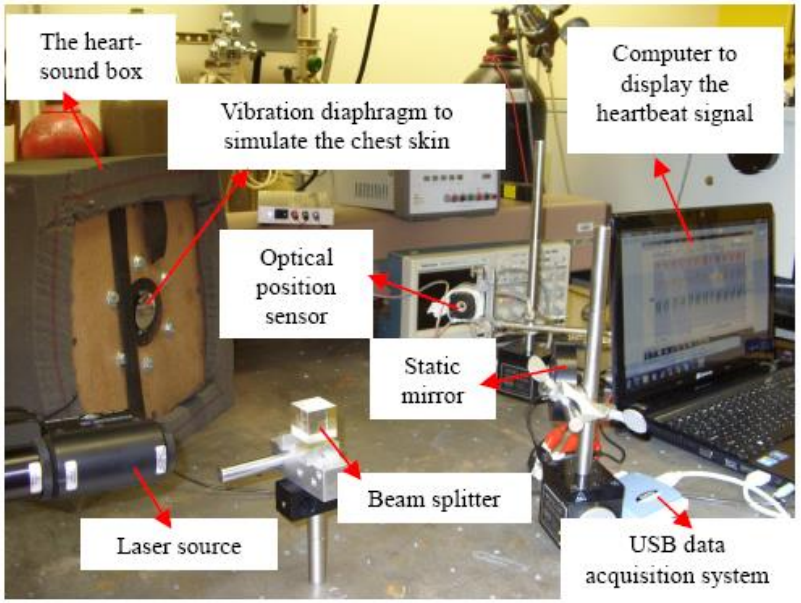
Two types of fabricated nanostructures



Comparison between experimental measurement and simulation results

Laser-based Stethoscope

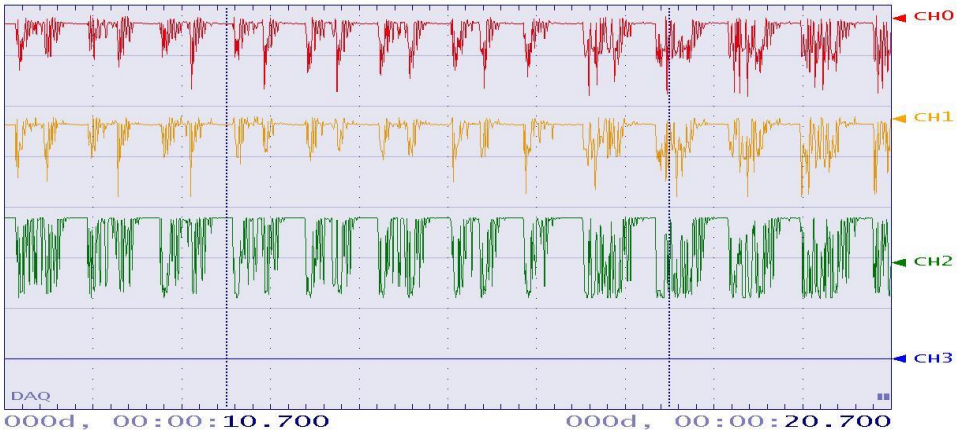




Applications:

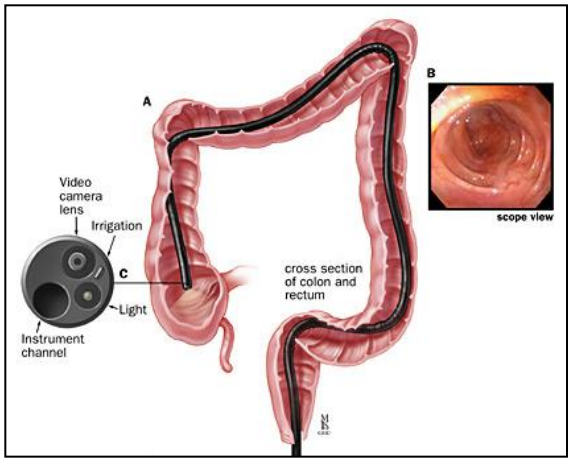
- Surmount the weaknesses of the conventional stethoscope caused by the limitation of human ear's ability to detect low frequency heart sound

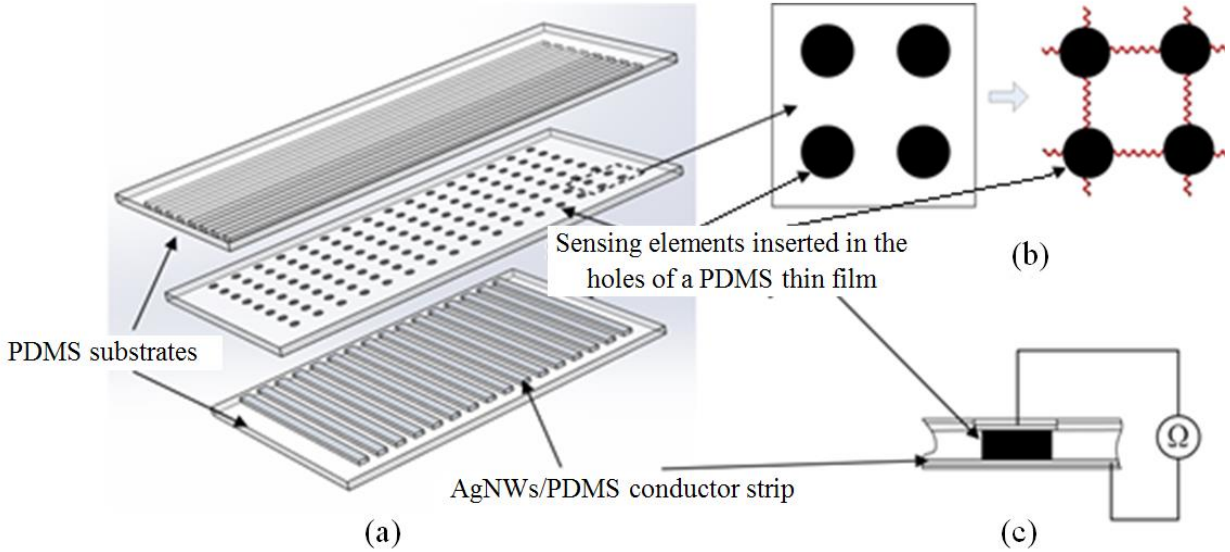
- Provide the practitioner visual representations of the sounds

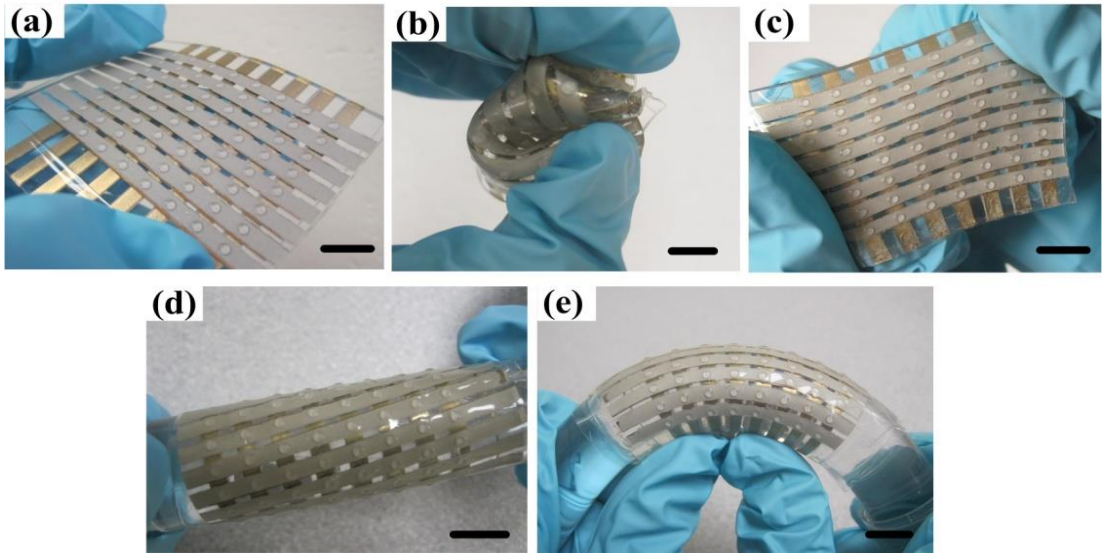


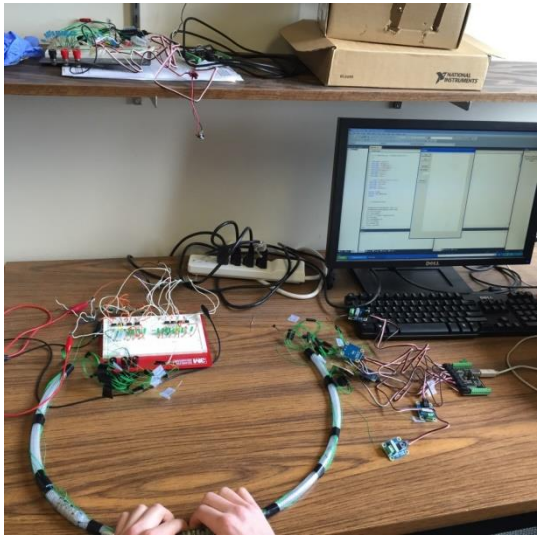
J. Bai et al., Journal of Biomedical Science and Technology, 2012

E-Skin Pressure Sensor Array for Colonoscopy









D. Zhou et al., IEEE Sensors Journal, 2016

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