Rethinking and Redesigning the Semiconductor Laser for Quantum Noise Control

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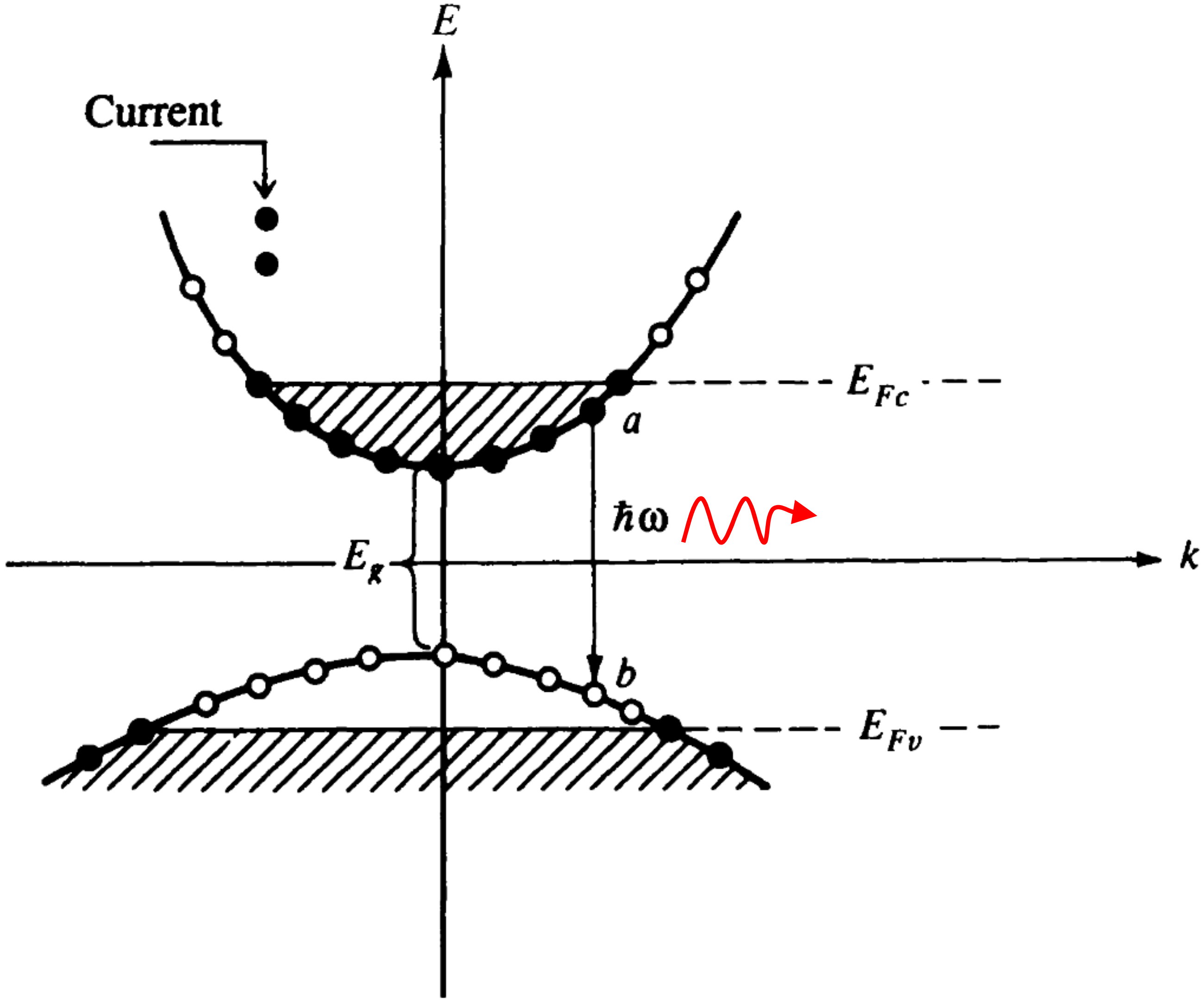
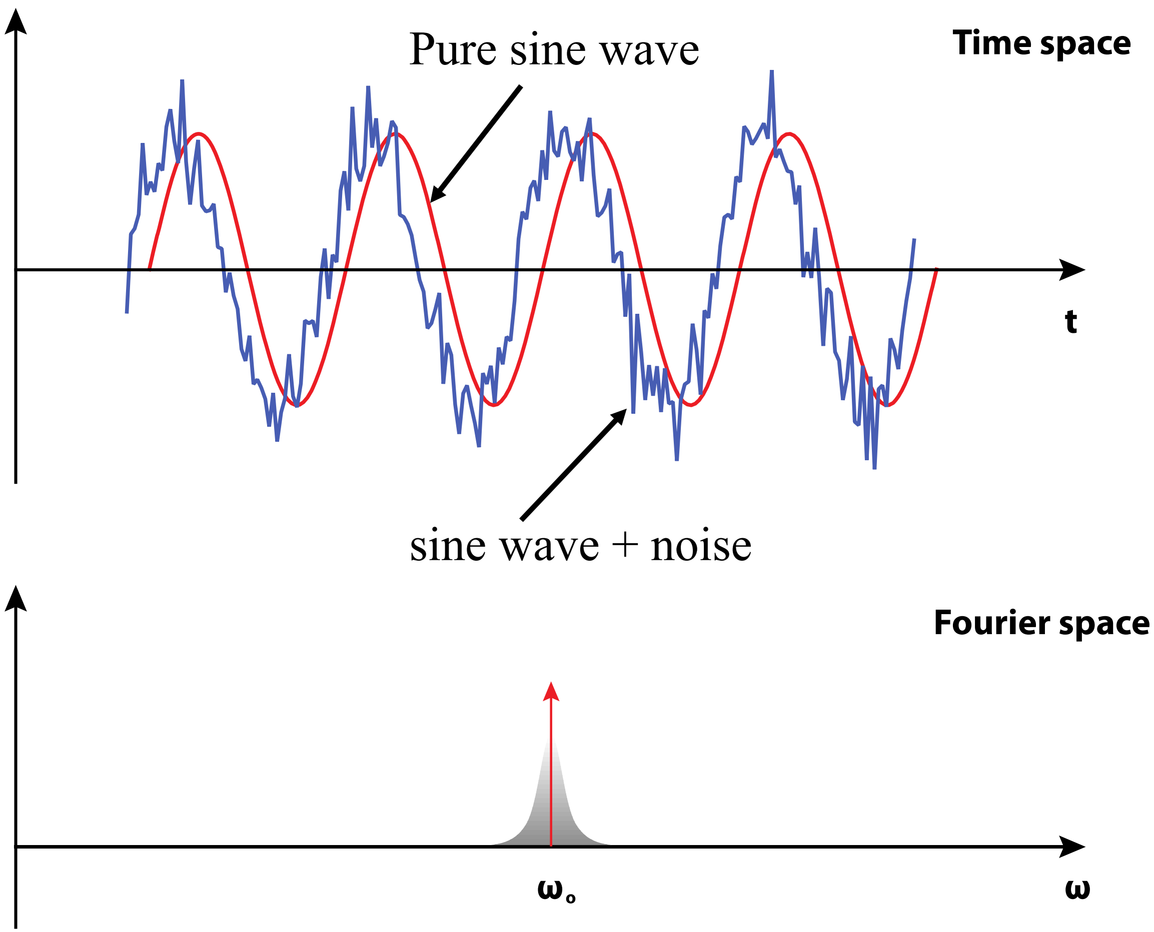
Non-thermal quasi equilibruim



A. Yariv and P. Yeh, Photonics 6th Ed., 2007, Fig 15.4

Harmonic waves, the basic waves of nature – Real waves



Deviation from ideality due to:

- Quantum mechanics (God's noise).
- Noisy environment.
- Information (modulation).

Early work

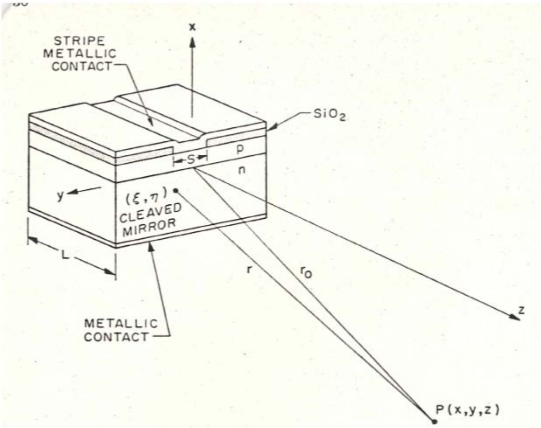


Fig. 1. Definition of Cartesian coordinate system (x, y, z) relative to a stripe-geometry laser. The xy plane $z = 0$ coincides with the front laser mirror, which radiates in the half-space $z > 0$. $P(x, y, z)$ represents a far-field observation point, which is a distance r from a point (ξ, η) on the laser mirror.

IEEE JOURNAL OF QUANTUM ELECTRONICS, JANUARY 1969

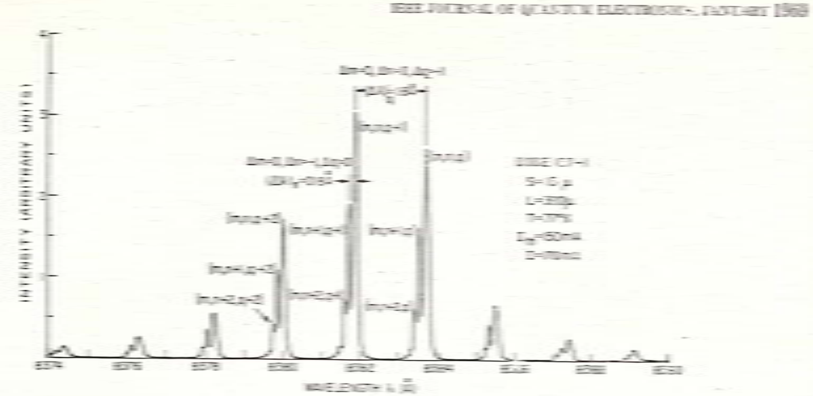


Fig. 2. Typical CW frequency spectrum of a GaAs laser showing several axial mode groups with their associated satellite resonances. Each peak in the spectrum represents the frequency of a resonant mode characterized by the mode numbers (m, n, q). In any one mode group, the transverse mode number m perpendicular to the junction plane and the longitudinal mode number q remain constant. The transverse mode number, n, parallel to the junction plane, increases by one from one consecutive satellite to another in the direction of decreasing wavelength.

Resonant Modes of GaAs Junction Lasers, Thomas H. Zachos , IEEE Journal of Quantum Electronics, Vol QE-5, No. 1, January **1969**

Caltech, 1975:
The first semiconductor DFB laser II

cw operation of distributed-feedback GaAs-GaAlAs diode lasers at temperatures up to 300 K

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(Received 17 June 1975; in final form 22 July 1975)

Caltech - Hitachi 1975

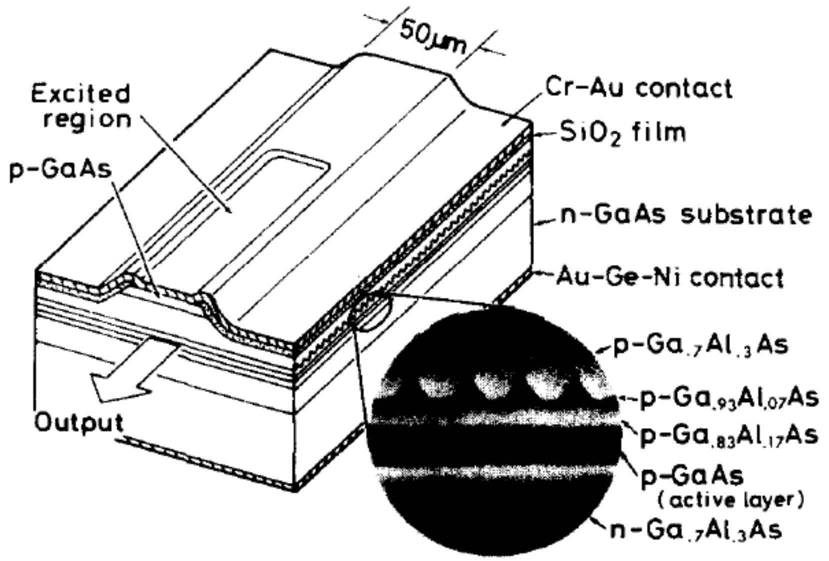
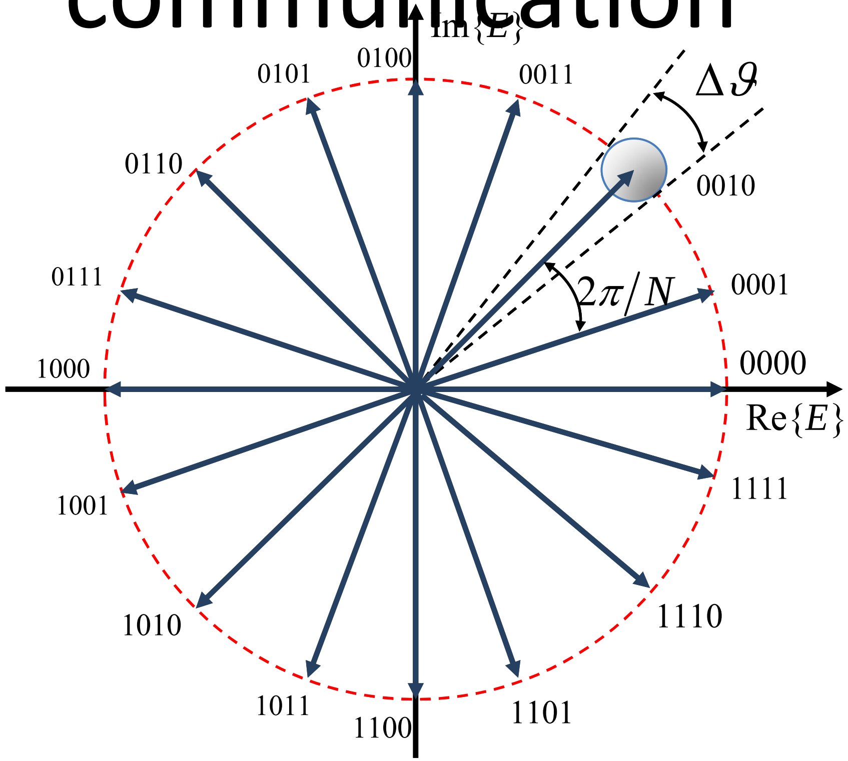


FIG. 1. Structure of the DFB laser with separate optical and carrier confinement.

Phase noise in coherent communication



To transmit N phases per pulse at rate $\frac{1}{t_p}$,

we would require $\Delta\vartheta(t_p) << \frac{2\pi}{N}$

Numerical example :

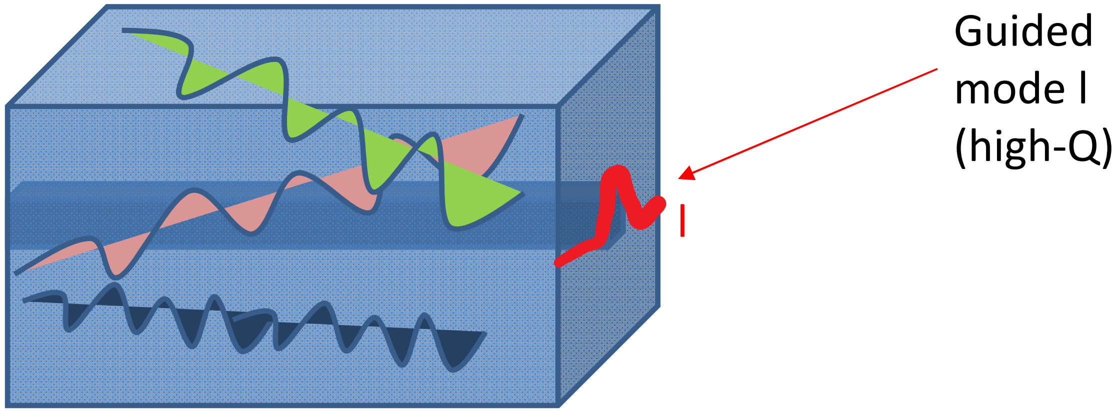
For $N = 256,\ \frac{1}{t_p} = 20GHz,\ P = 100mW$

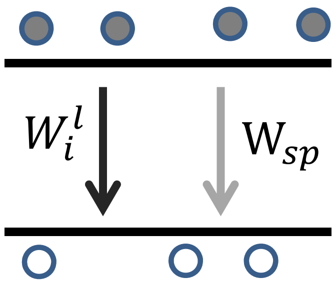
$\Rightarrow (\Delta\nu)_{laser} \leq 40kHz$

Quantum Noise Theory:

Modes in a box:

A box with many modes, but only one high-Q guided mode:





$$\frac{dN_2}{dt} = -W_i(N2 - N1) - W_{sp}N_2$$

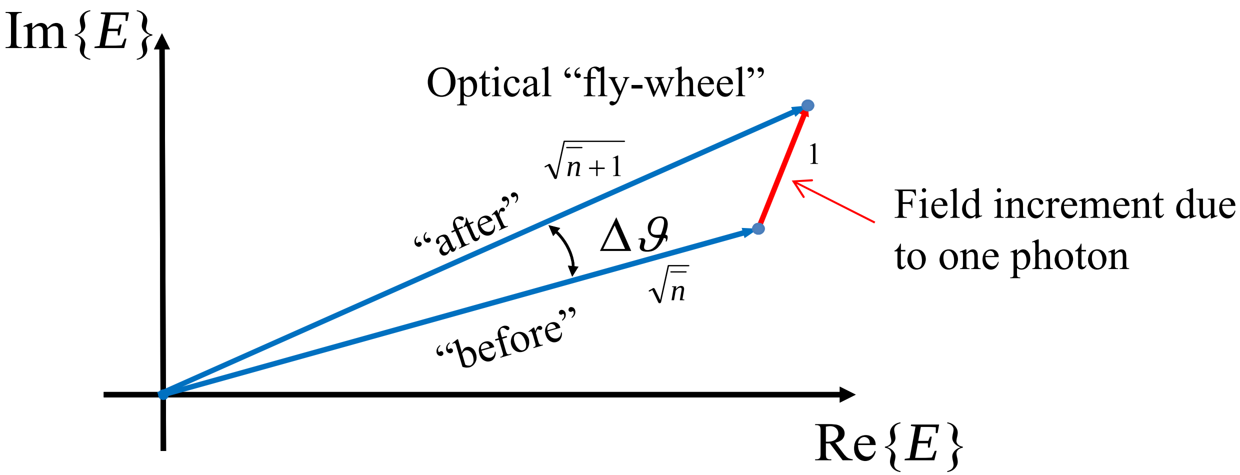
$$W_{sp} = \boldsymbol{W_{sp}^l} + \sum W_{sp}^i$$

Phase noise is only due to spontaneous emission into confined laser mode l

Laser Phase Noise

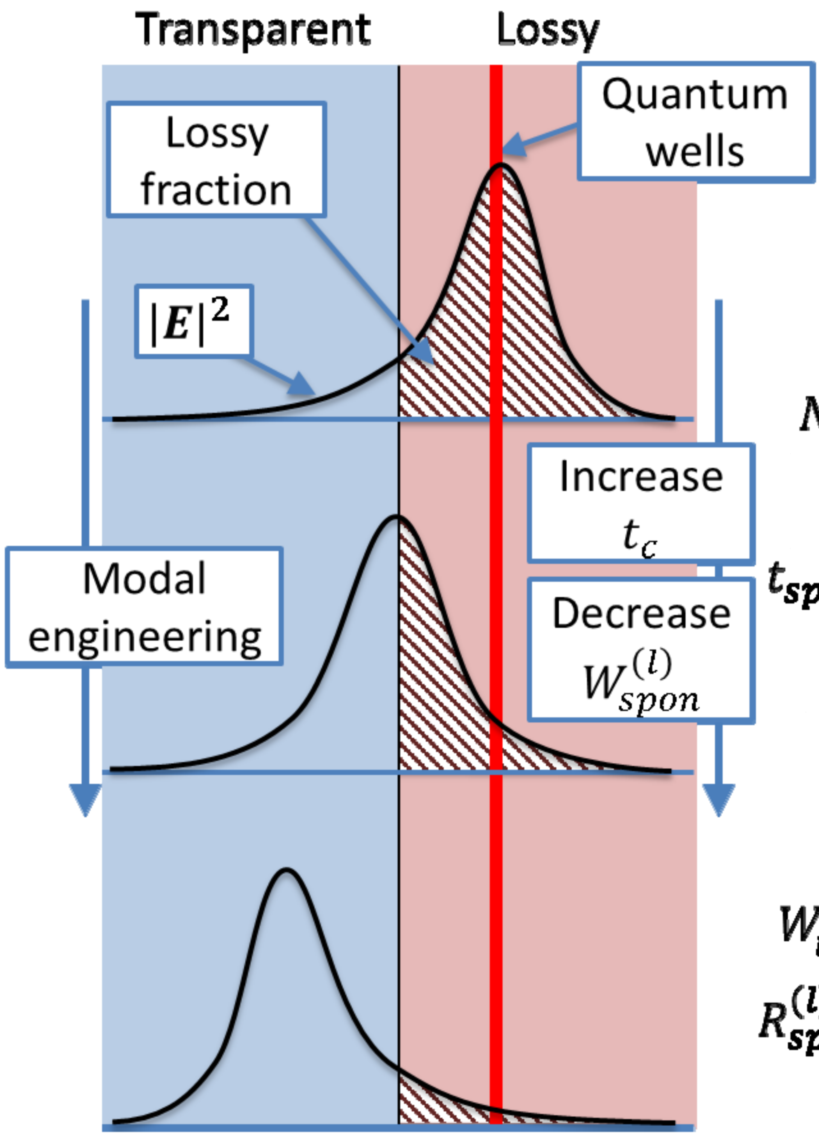
$$\langle [\Delta\phi(T)]^2 \rangle = \frac{R}{2n_l}T = \frac{N_{2,th}W_{sp}^l}{2n_l}T$$

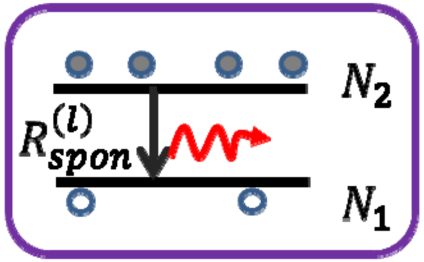
$N_{2,th}$ - total #electrons in conduction band, clamped at threshold
W_{sp}^l - spontaneous rate of transition into laser mode
n_l - number of photons in the mode
R - rate of transitions into lasing mode

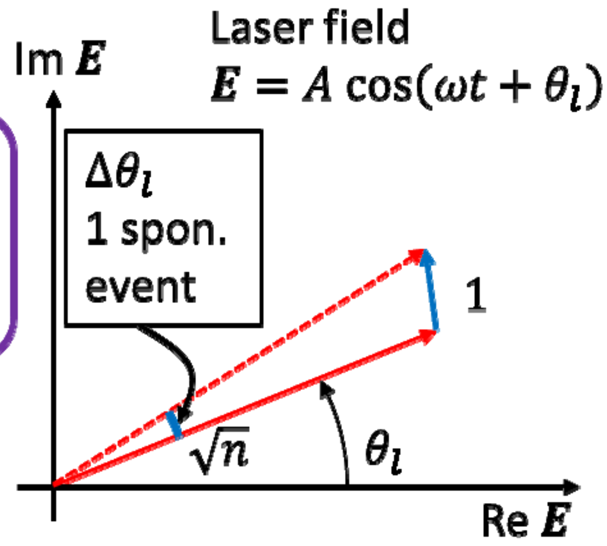


Effect of a single spontaneous emission event on the phase of the laser field

Quantum noise control







$$N_{2t} = \frac{1}{t_c W_{spon}^{(l)}} = \text{Ind. of modal eng.}$$

$$t_{spon} \neq W_{spon}^{(l)}$$

$$I_t = \frac{e}{t_{spon}} N_{2t} = \frac{e}{t_{spon}} \frac{1}{t_c W_{spon}^{(l)}} = \text{Ind. of modal eng.}$$

$$\langle \Delta\theta_l^2(T) \rangle = \frac{R_{spon}^{(l)}}{2n} T$$

$$W_i^{(l)} = W_{spon}^{(l)} n$$

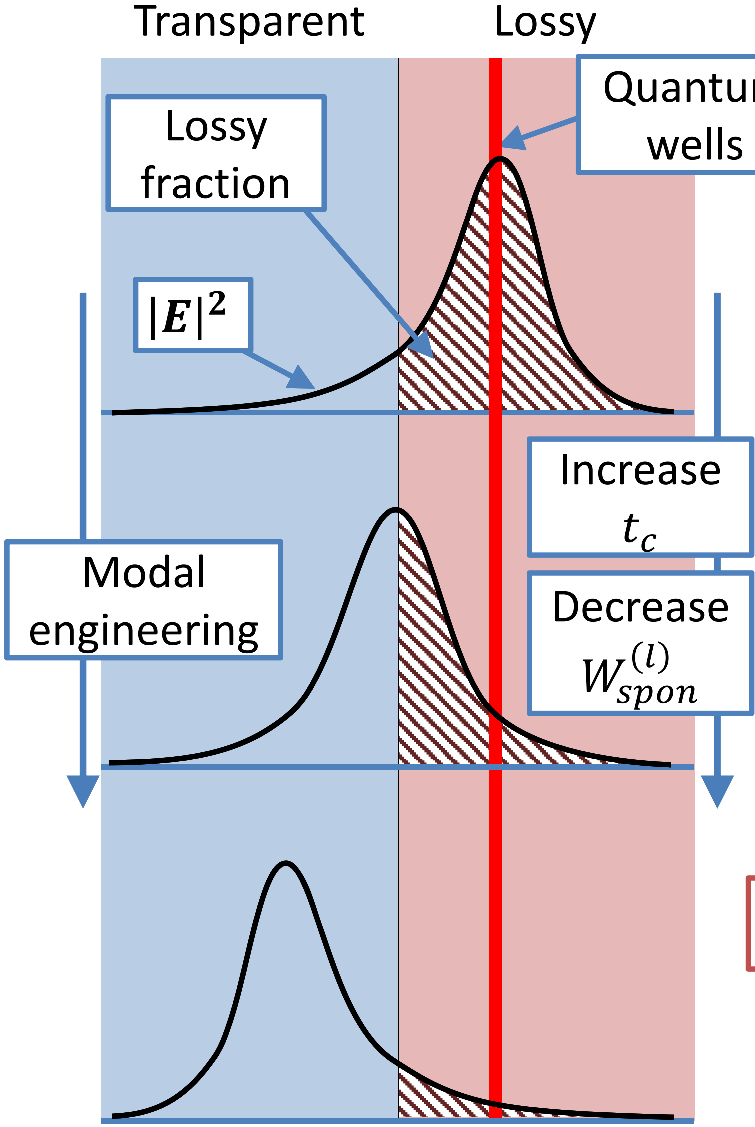
$$R_{spon}^{(l)} = N_{2t} W_{spon}^{(l)} = \frac{1}{t_c}$$

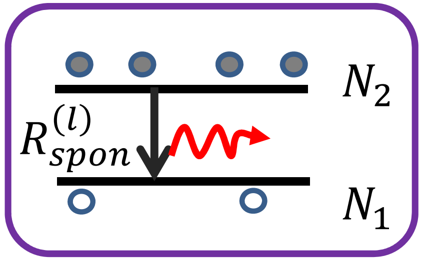
$$n = \frac{I - I_t}{e} t_c$$

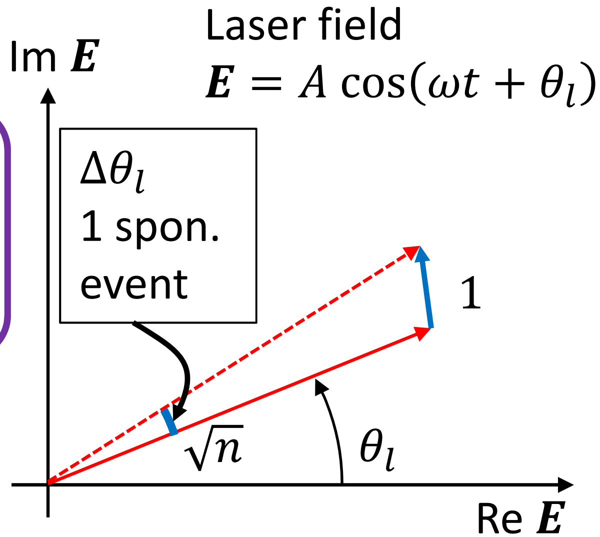
$$\langle \Delta\theta_l^2(T) \rangle \propto \frac{1}{t_c^2} \propto \frac{1}{Q^2}$$

$$t_c = \frac{Q}{\omega}$$

Quantum noise control







$$N_{2t} = \frac{1}{t_c W_{spon}^{(l)}}$$

$$t_c = \frac{Q}{\omega}$$

$$t_{spon} \neq W_{spon}^{(l)}$$

$$I_t = \frac{e}{t_{spon}} N_{2t} = \frac{e}{t_{spon}} \frac{1}{t_c W_{spon}^{(l)}}$$

$$W_i^{(l)} = W_{spon}^{(l)} n$$

$$R_{spon}^{(l)} = N_{2t} W_{spon}^{(l)} = \frac{1}{t_c}$$

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$$\langle \Delta\theta_l^2(T) \rangle \propto \frac{1}{t_c^2} \propto \frac{1}{Q^2}$$

The Schawlow-Townes Linewidth

From relation between induced and spontaneous emission

$$R = \frac{\eta}{t_c}$$

Photon number related to photon lifetime

$$n_l = \frac{(I - I_t)t_c}{e}$$

Recall:

$$Q = \omega t_c$$

$$\Delta\omega_{s-T} = \frac{R}{2n_l} = \frac{\eta\omega_l^2 e}{2(I - I_t)Q^2}$$

High-Q Hybrid

Conventional Hybrid

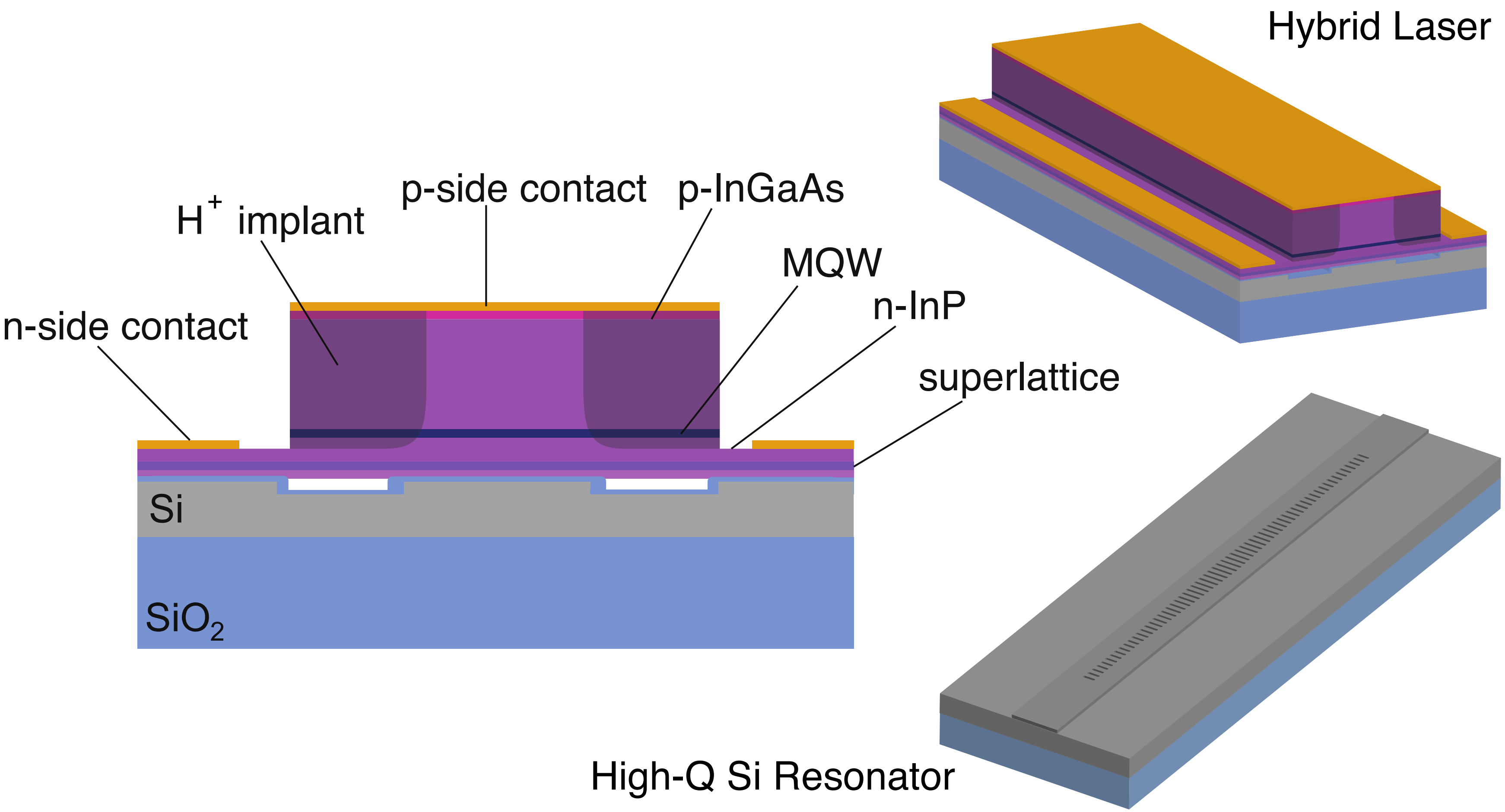
Technical Challenges

- New design paradigm for SC lasers

1. Minimizing mode energy in high loss III-V material. This reduces total rate of spontaneous emission

2. Increase total stored energy in the optical mode (High Q resonator) to reduce phase fluctuations at a given rate of spontaneous emission(optical flywheel effect)

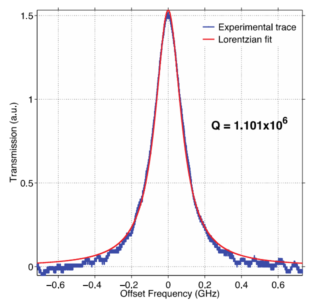
Basic Hybrid Si/III-V Structure

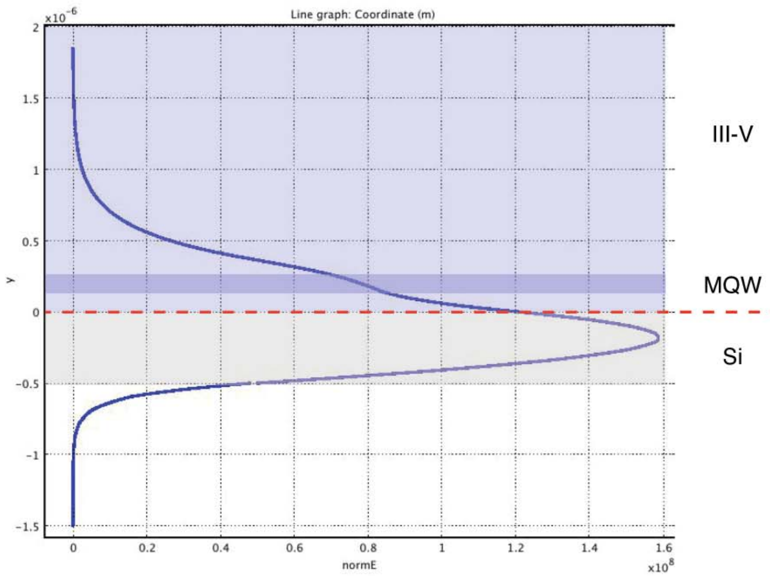


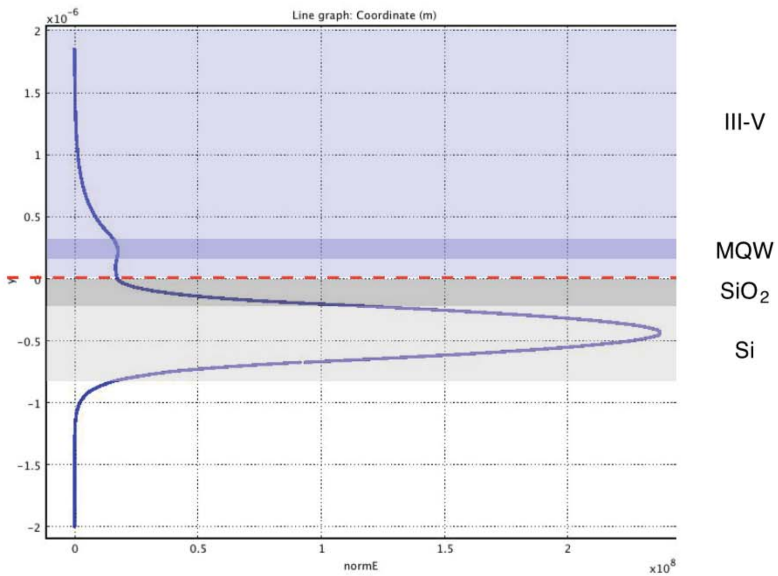
Ultra-coherent semiconductor lasers

<u>"Recipe" for Narrow-linewidth Hybrid Si/III-V laser:</u>

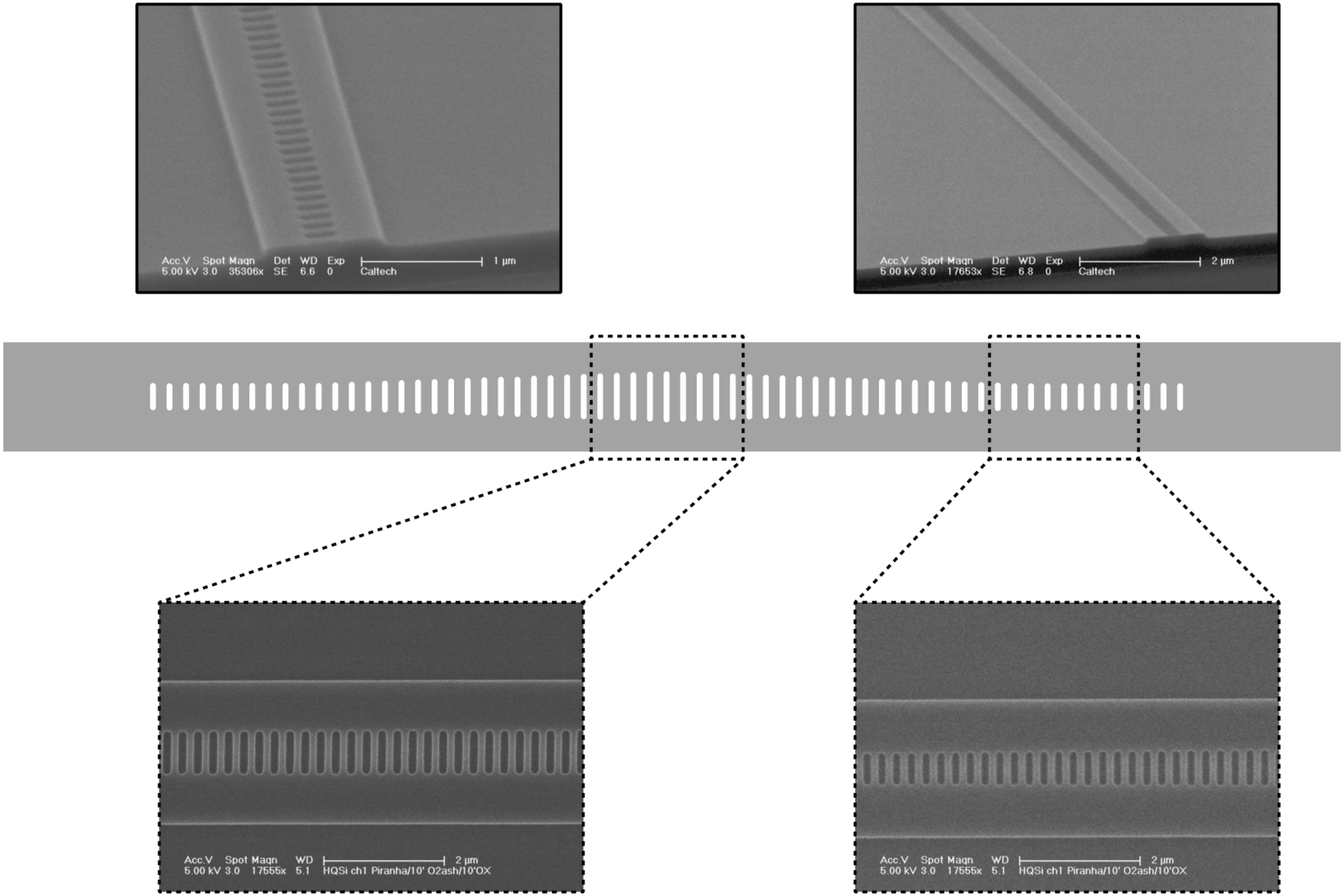
- High-Q resonator in Si
- Modal engineering



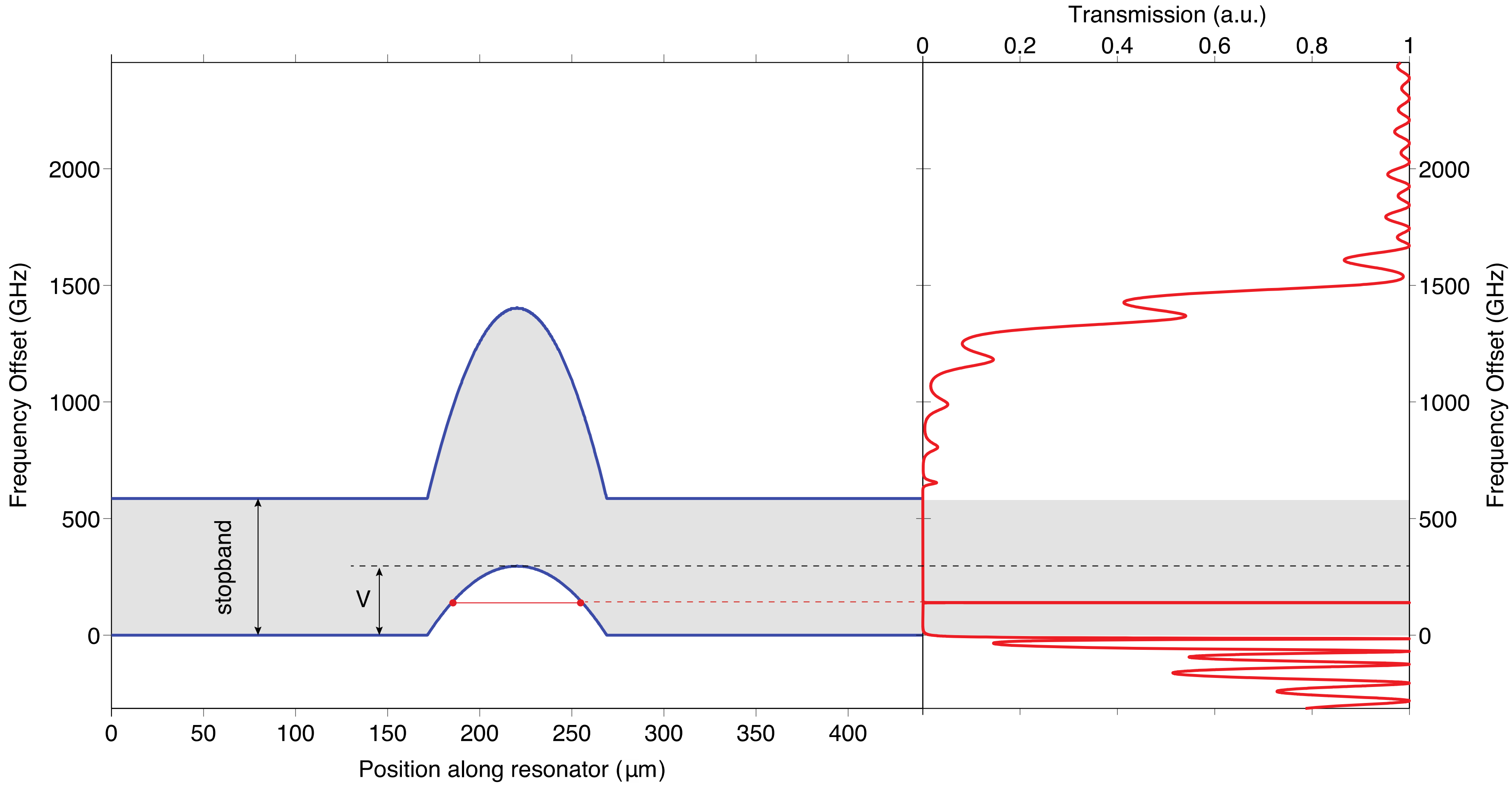




High-Q Si Resonator (SEM)



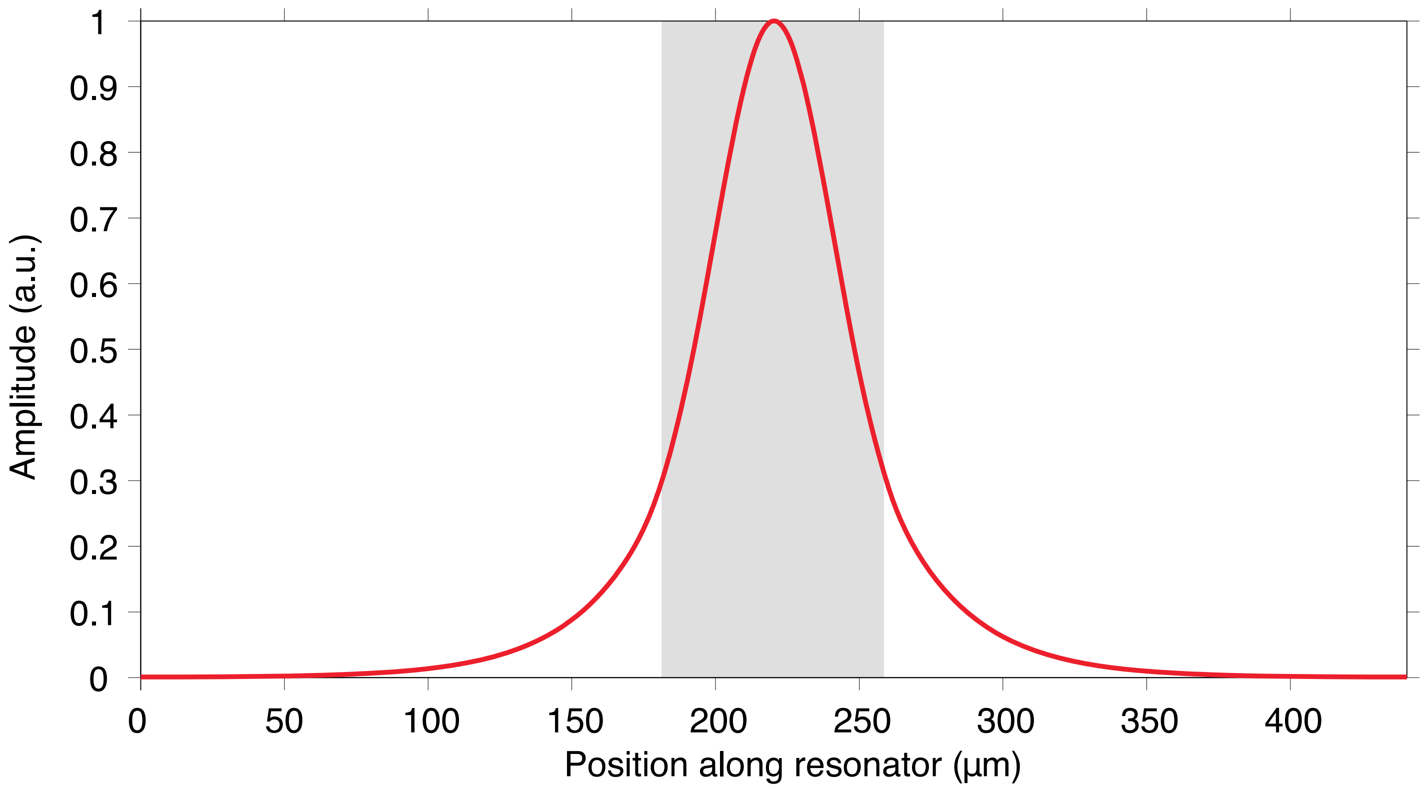
Transmission Spectrum vs Band Structure



Field Profile

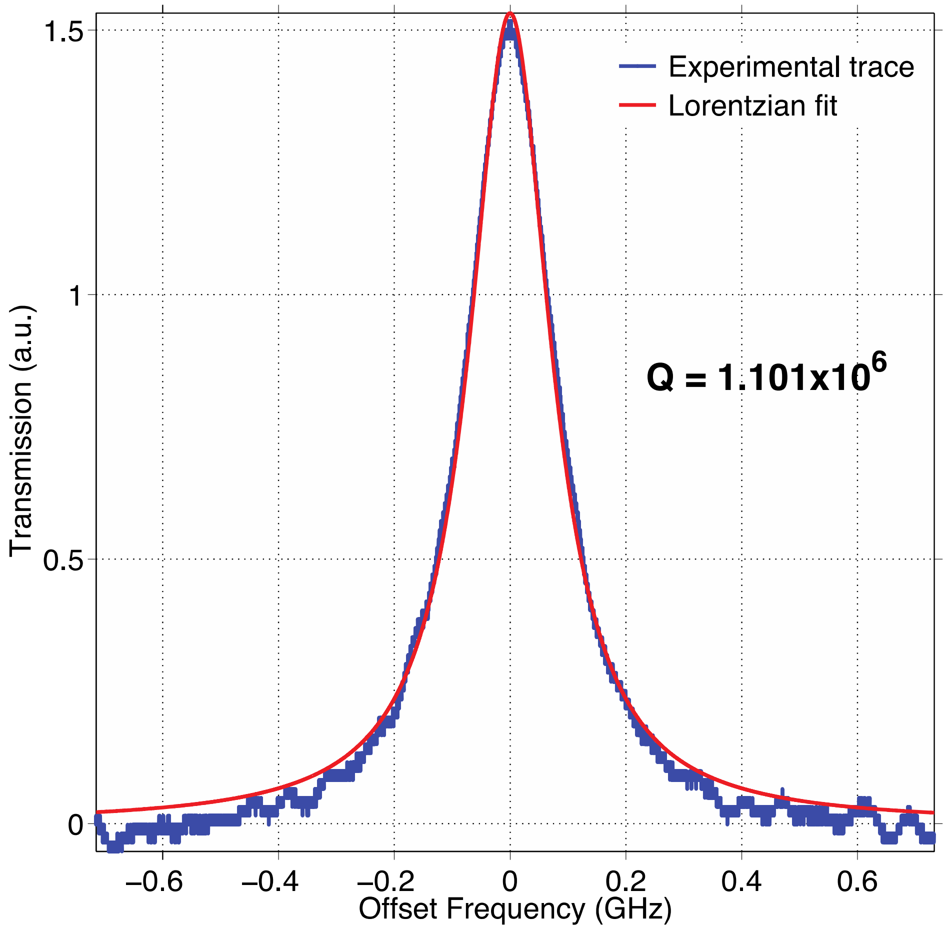
De-localized mode profile:

- Mitigates spatial hole-burning,
- Reduced scattering losses (narrow K-space profile)

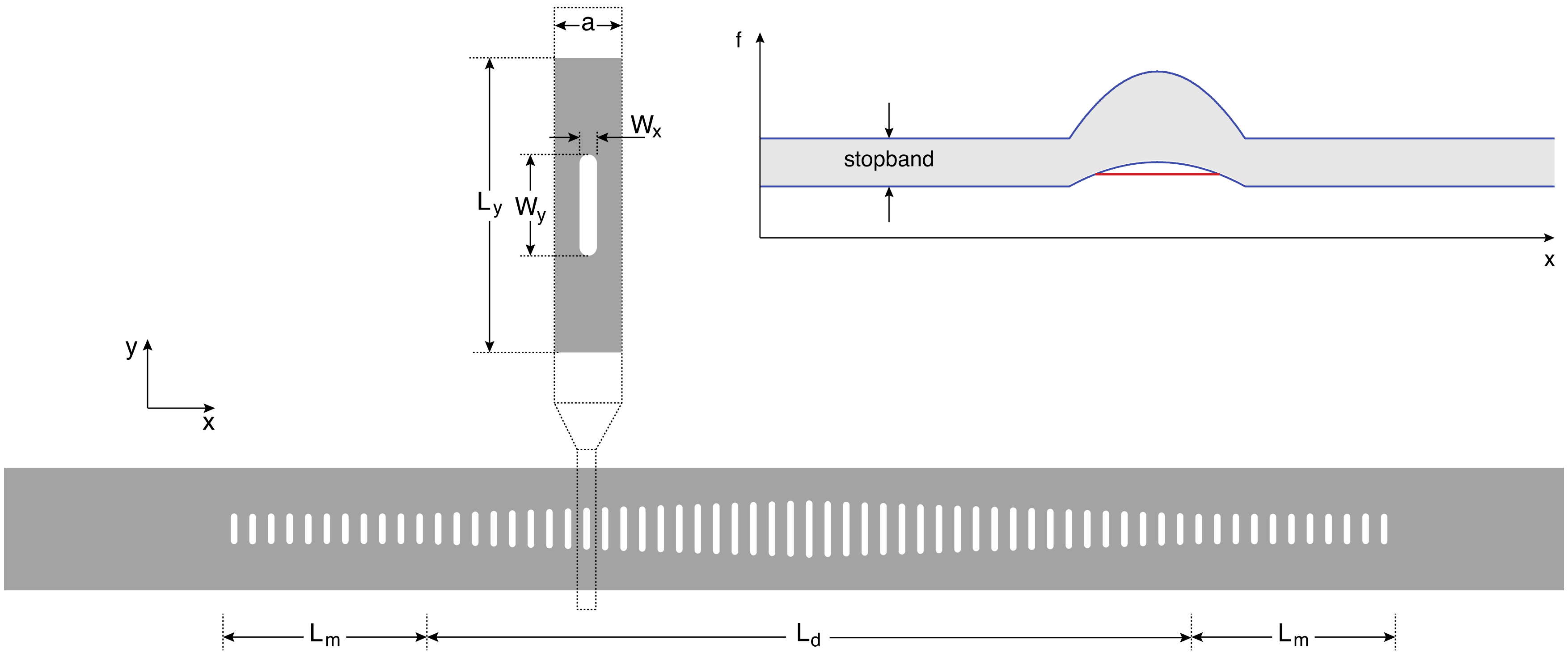


Si Resonator Quality Factor

Passive resonators results:

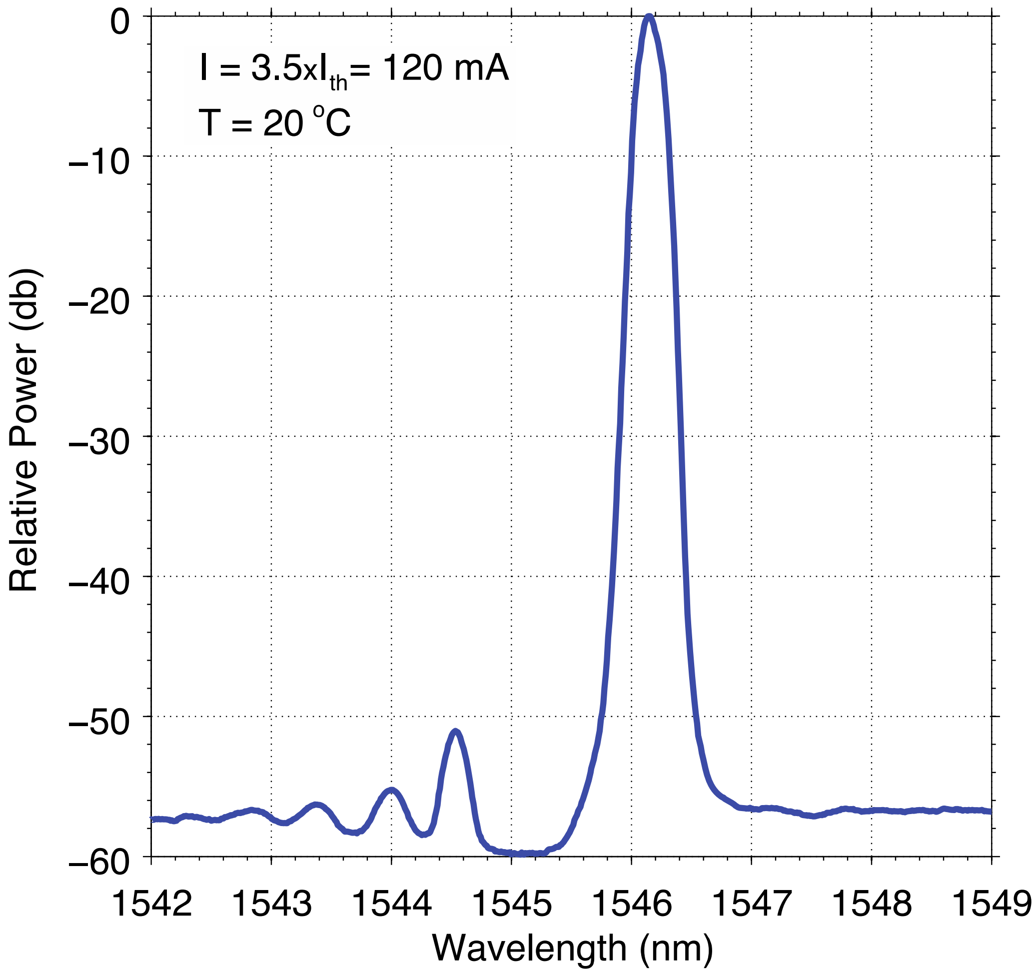


High-Q Grating Design



B. S. Song, S. Noda, T. Asano, and Y. Akahane, “Ultra-high-Q photonic crystal double-heterostructure nanocavity,” Nature Materials, vol. 4, no. 3, pp. 207-210, 2005.

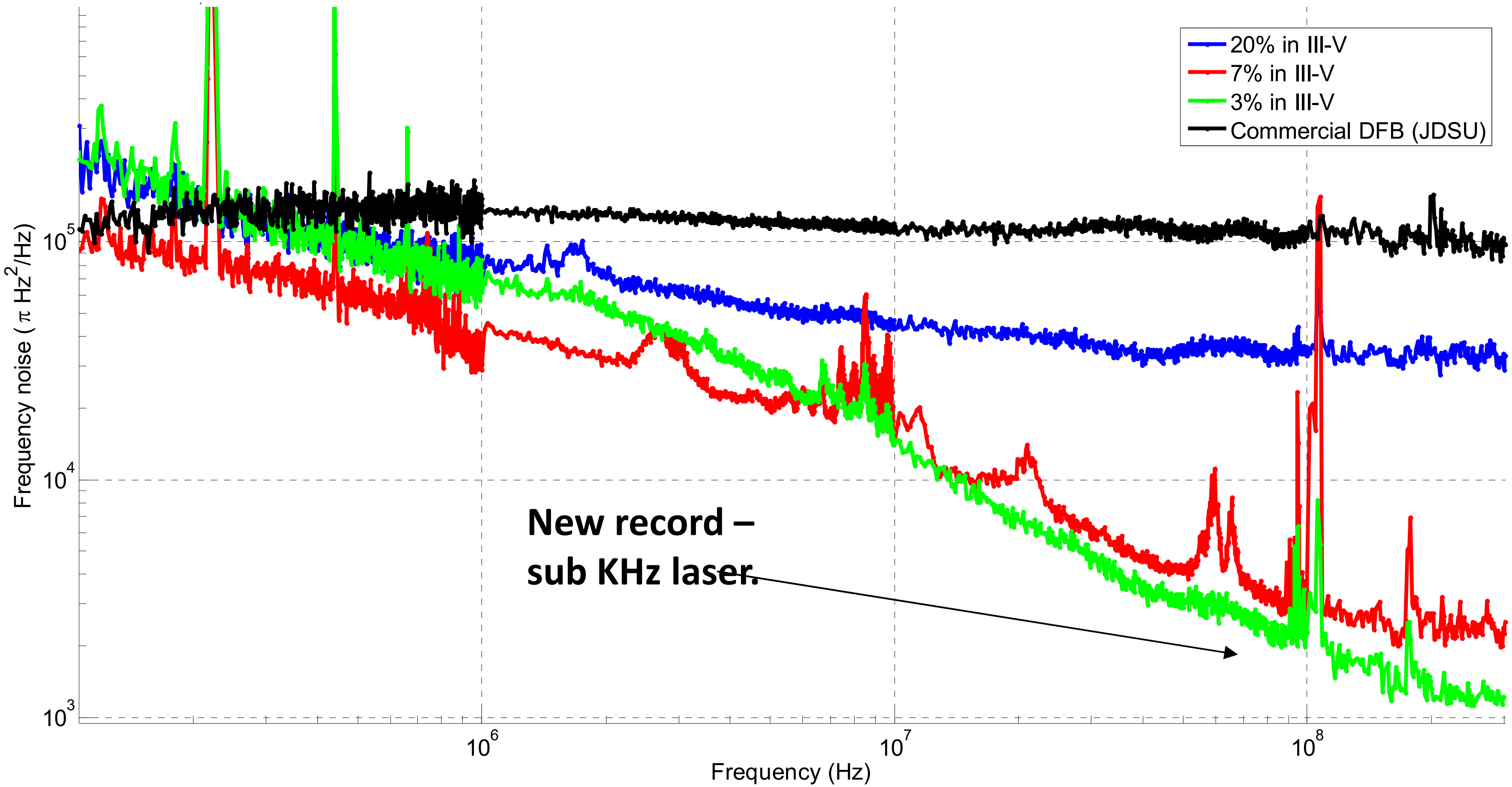
Optical Spectrum



- High SMSR of more than 50 db.

Frequency-Noise Spectra

Trend – lower noise with reduced III-V overlap



▪ summary

Quantum control of the spontaneous emission into the laser mode in the Semiconductor Laser plus the integral incorporation of a high Q resonator have resulted in 3 orders of magnitude reduction of the frequency noise. More should be possible

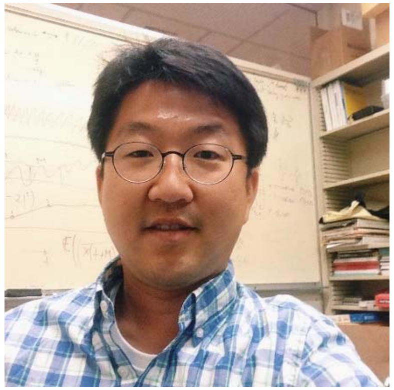
The same theory predicts and we are investigating a fundamental modification of the major laser performance parameters. These include:

orders of magnitude, lowering of the Resonance Relaxation Frequency.

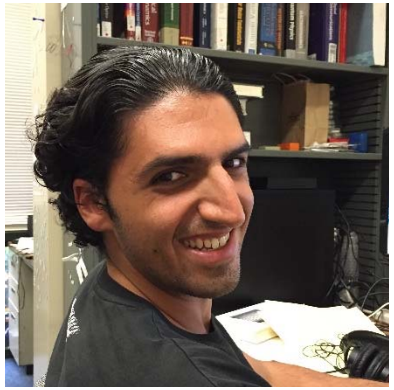
reduction to near zero of the Henry-Alpha parameter (amplitude –to-phase coupling)

Large insensitivity (30-40db) to feedback insensitivity and thus the hope of reducing, or even eliminating, the use of isolators.

The Team



Dongwan Kim



Mark Harfouche

Dr. Naresh Satyan

Dr. Yasha Vilenchik

Dr. Christos Santis

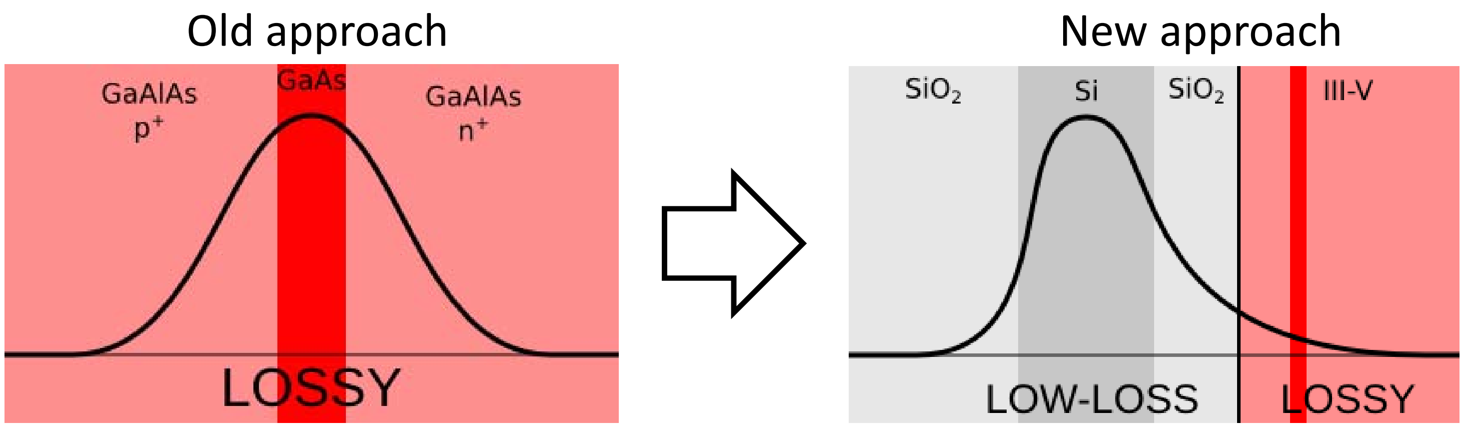
Dr. George Rakuljic

Sponsors: ARO, DARPA (MTO)

Innovative Claims

- Narrow-linewidth semiconductor lasers through a fundamentally new approach to laser design.

Example:



- Drastic SWAP-C reduction in the narrow-linewidth field - Key driver in coherent communication, consumer sensing, LIDAR and timing applications