Nanowire light-emitters*

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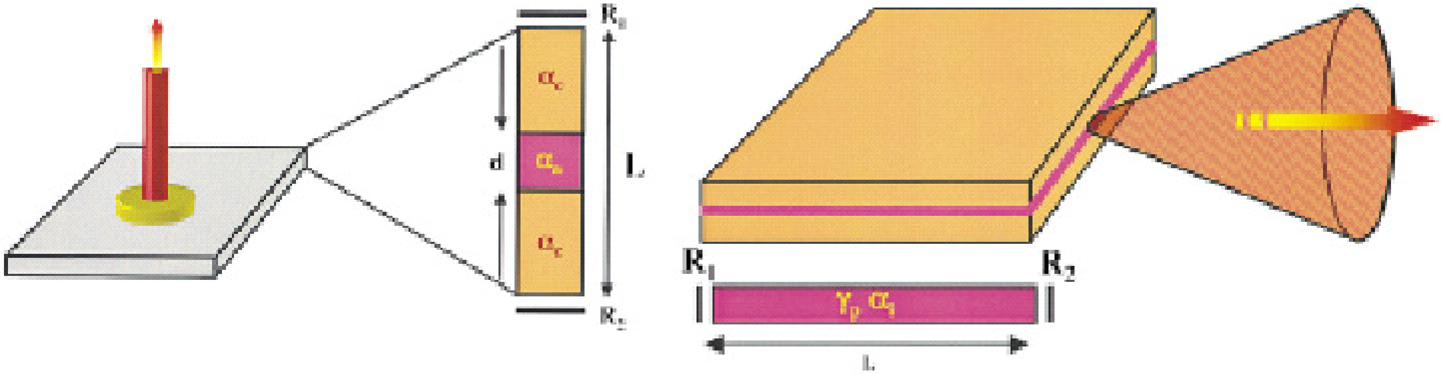
*Now with NanoPhotonics, Inc

Outline

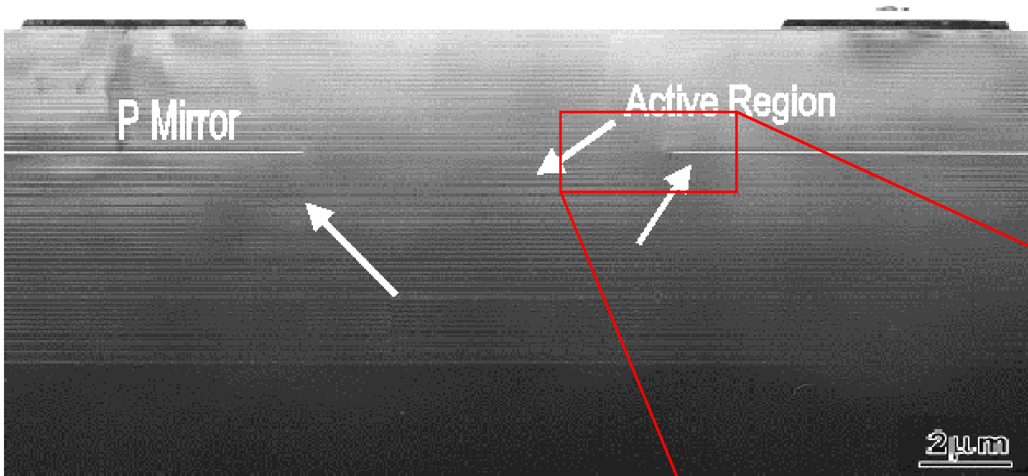
- Some background on light-emitters;
- Nanowire light-emitters;
- Proposed improvements on nanowire light-emitters;
- Summary

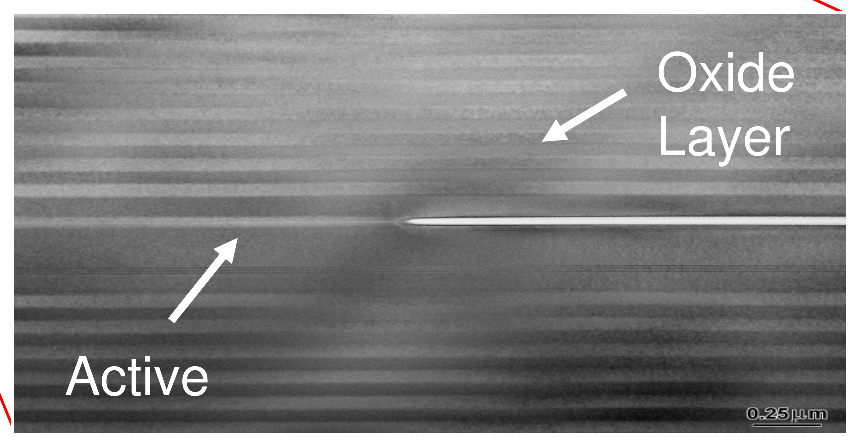
One of the problems with photonics



Most important component is hard to integrate and scale

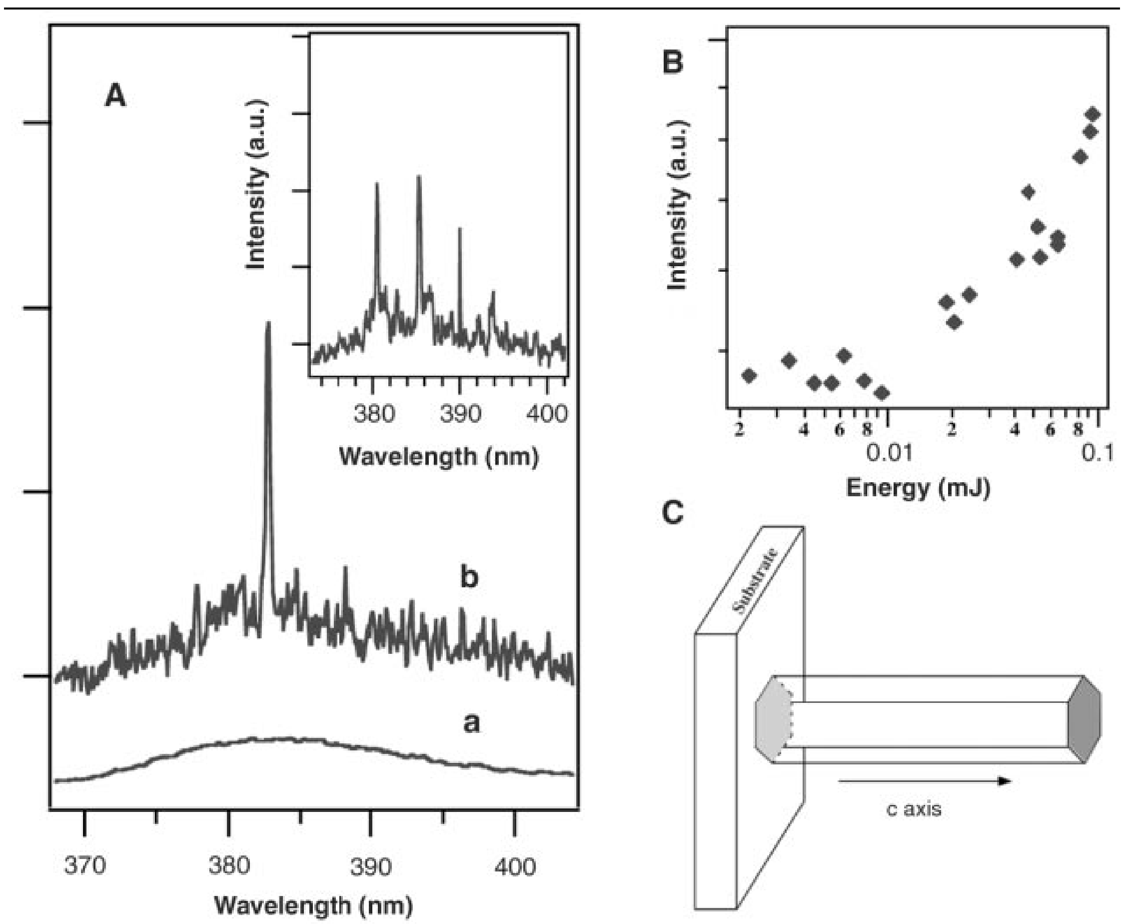
Some progress with the vertical-cavity laser





Large numbers of VCSELs can be manufactured using batch techniques; but integration with other devices is still not a routine process.

Active photonic device scaling: the nanowire emitter



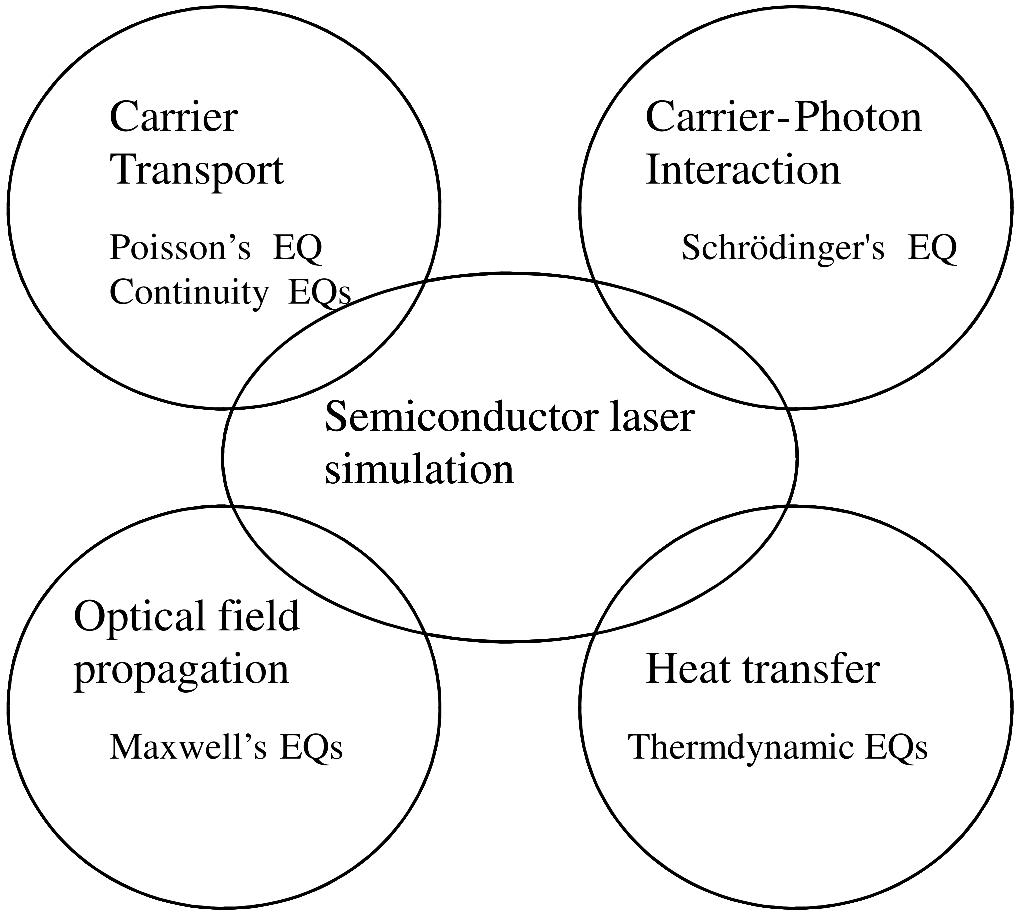
Optically pumped ZnO nanowire emiters with diameters from 20 – 150 nm, and lengths ~10 um.

Huang, Mao, Feick, Yan, Wu, Kind, Weber, Russo, Yang, *Science* 292 1897 (2001).

A computational model for understanding nano-emitters

- Coupled carrier-transport and photon-generation rate equations;
- FDTD method for allowed modal solutions and field profiles;
- Include coupling of spontaneous emission into the lasing modes (size effect);
- Model should be self-consistent.

The parameter space for a laser



Device equations governing semiconductor lasers

Coupled opto-electronic qquations

Carrier Transport Equations (Local)

$$\nabla \cdot \left(-\varepsilon_0 \varepsilon_{static} \nabla \psi\right) = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\nabla \cdot \vec{J}_n = -q\left(G - R_{au} - R_{SRH} - \mathbf{R}_{\mathbf{sp}} - \mathbf{R}_{\mathbf{st}}\right)$$

$$\nabla \cdot \vec{J}_p = q\left(G - R_{au} - R_{SRH} - \mathbf{R}_{\mathbf{sp}} - \mathbf{R}_{\mathbf{st}}\right)$$

$$\vec{J}_n = qD_n \nabla n - q\mu_n n \nabla \psi$$

$$\vec{J}_p = -qD_p \nabla p - q\mu_p p \nabla \psi$$

ψ -- electrostatic potential
n, p – electron, hole concentrations
J_n, J_p -- current densities
S_m -- Photon density of mth mode

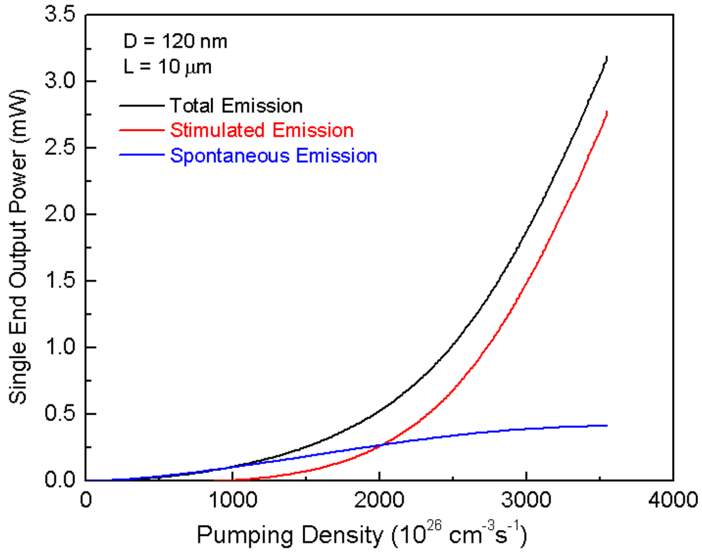
G -- carrier generation rate
R -- carrier recombination rates
D -- diffusion coefficient
μ-- mobility

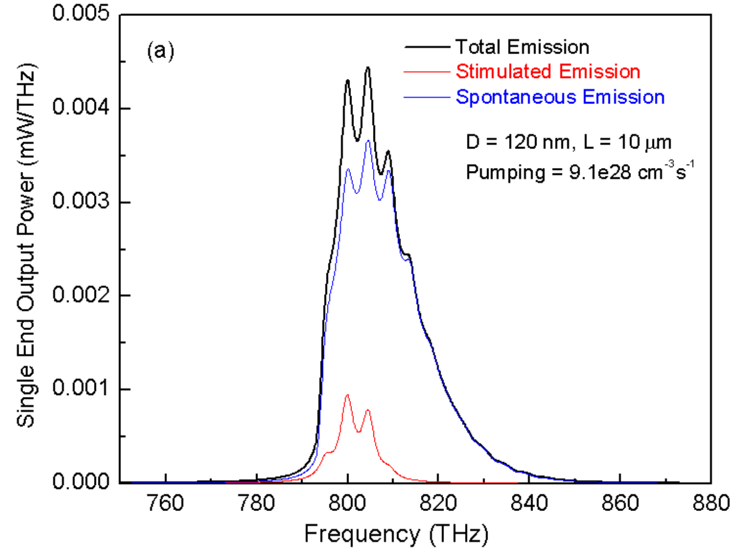
Photon Rate Equation (Global)

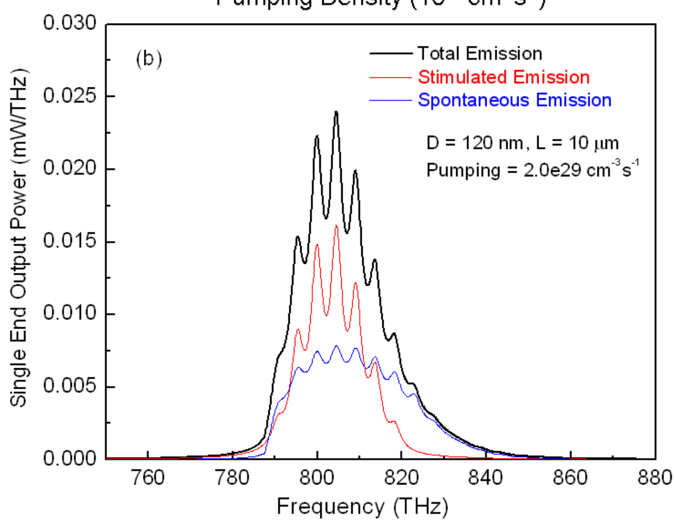
$$\mathbf{G}_{\mathbf{m}} S_m - \frac{S_m}{\boldsymbol{\tau}_{\mathbf{opt}}} + \beta \mathbf{R}_{\mathbf{sp,total}} = 0$$

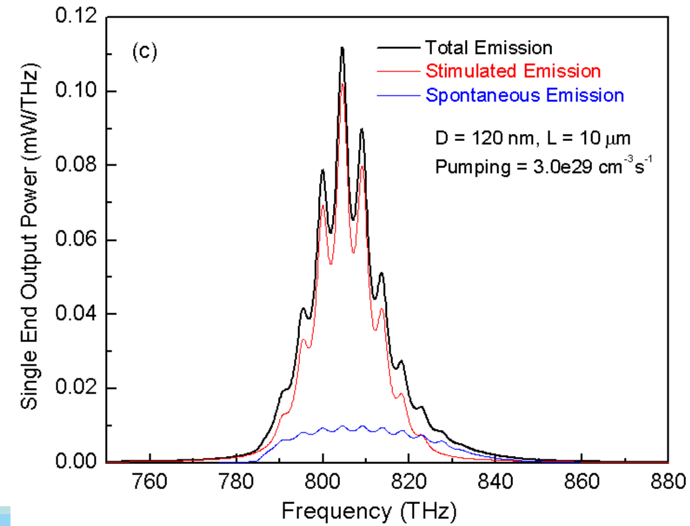
G_m -- modal gain calculated from local gain
τ_{opt} -- photon life time
β -- spontaneous emission factor
$R_{sp,total}$ -- total spontaneous emission rate

Calculated light output and spectra for a GaN nanowire light-emitter

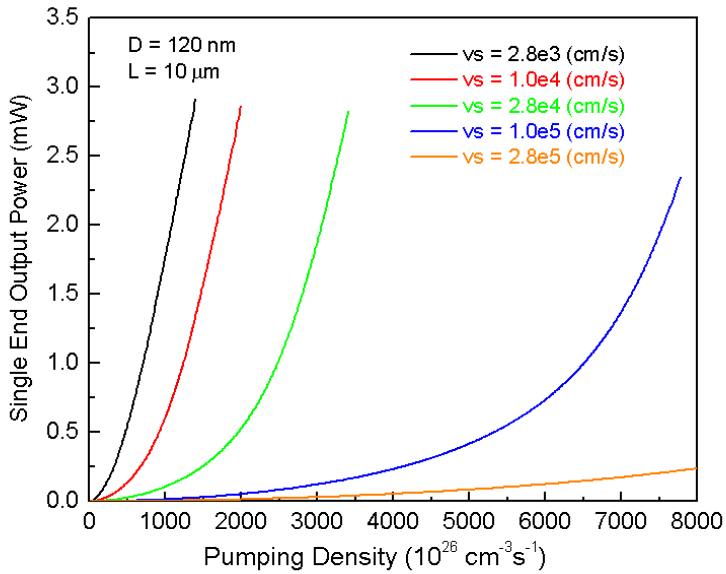


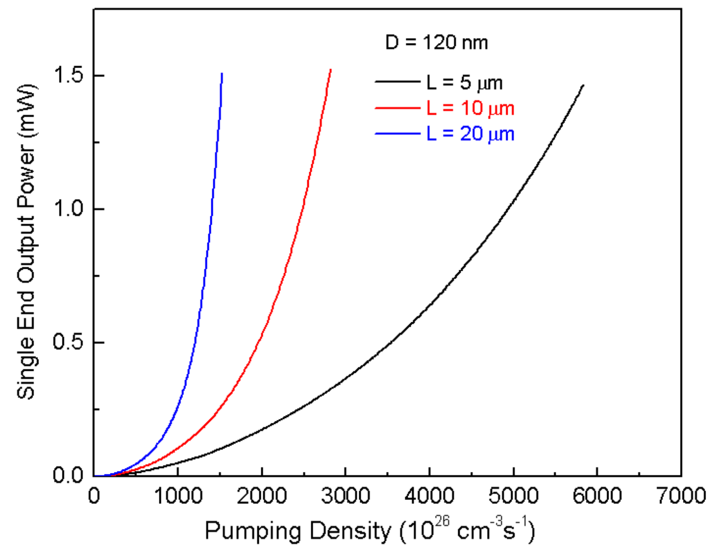


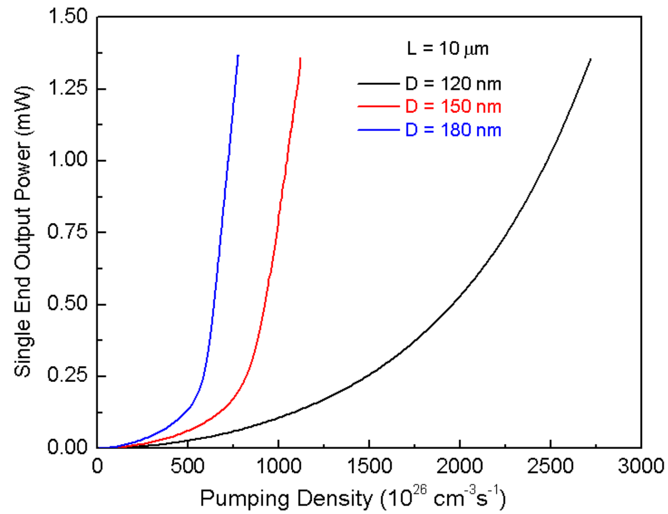




Calculated output-input characteristics for GaN nanowire emitters for various important parameters







Challenges of small emitters

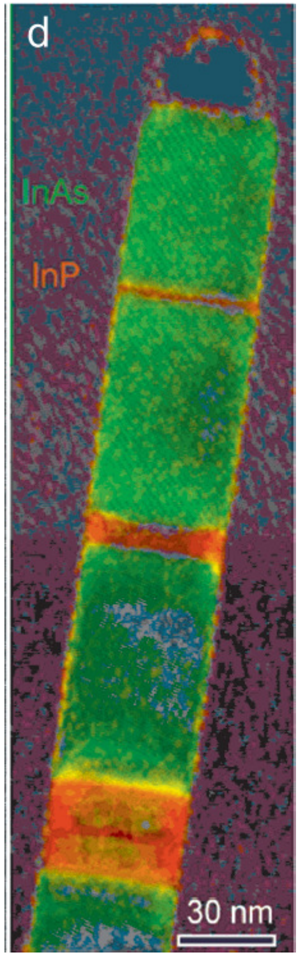
- Usually insufficient material gain;
- Very lossy (large mirror and diffractive losses);
- Severe mode competition for the little gain;
- Difficult to integrate with electrical pumping schemes;
- Large surface/volume rations => surface recombination problems.

Proposal: use distributed Bragg reflectors or 1-D photonic crystals in nanowires

- Distributed Bragg reflectors have been successfully used in lasers before;
- Growth of nanowire heterostructures has been demonstrated:
  - scale the heterostructures to DBR mirrror pairs;
  - calculate properties of DBR structures;
    - end mirror properties
    - photonic crystal properties

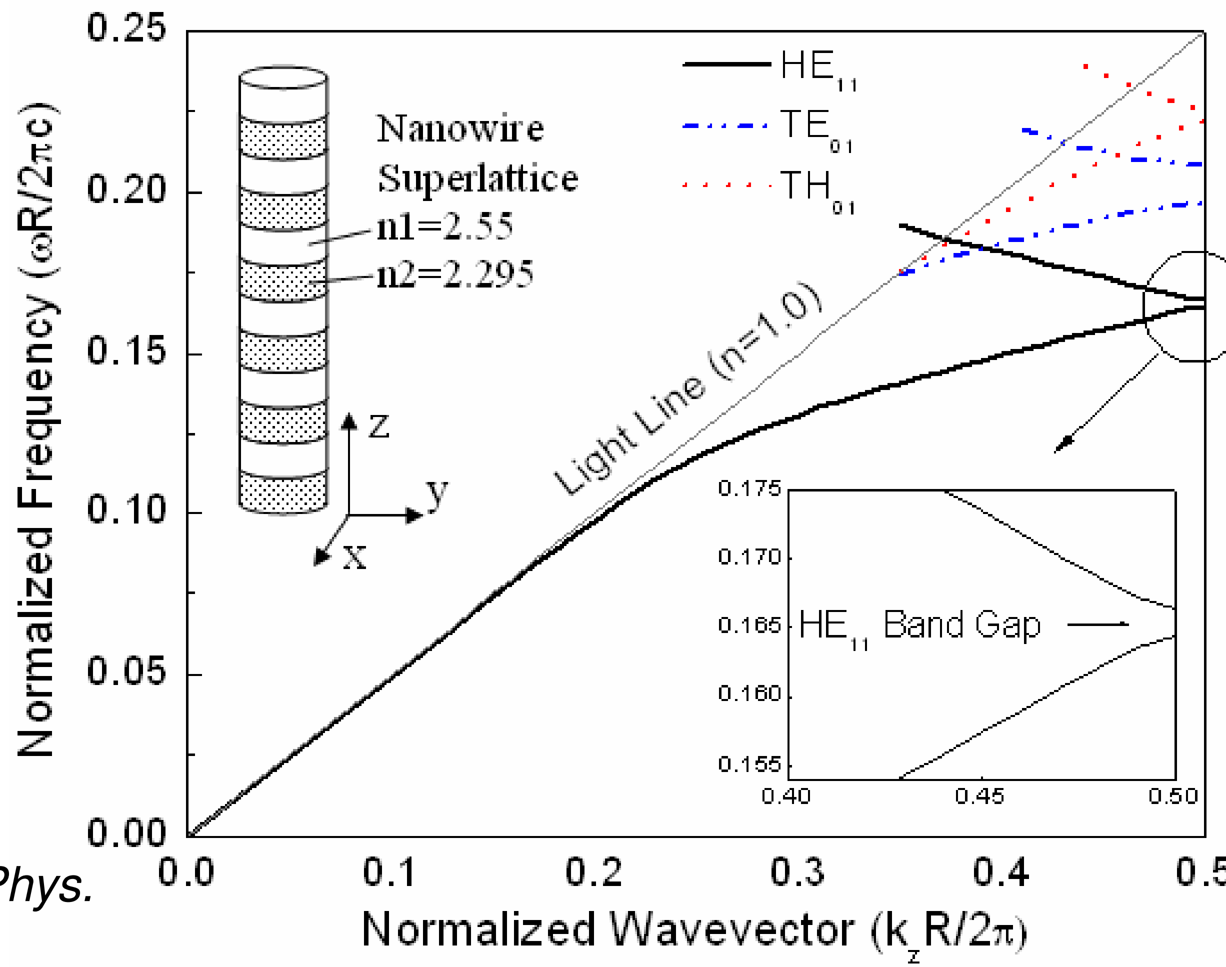
Nanowires and heterostructures

InAs/InP heterostructures



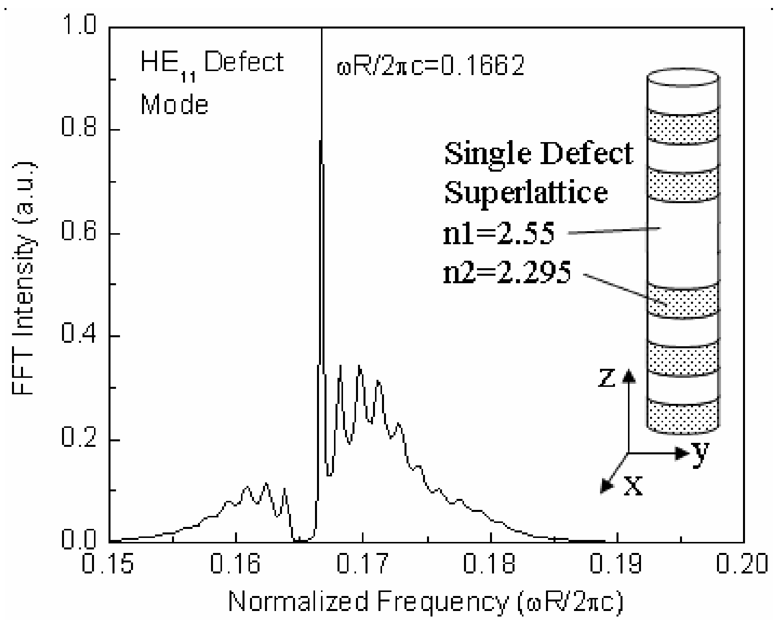
Bjork, Ohlsson, Sass, Persson, Samuelson
Nano Lett. 2 No. 2, 87-89 (2002).

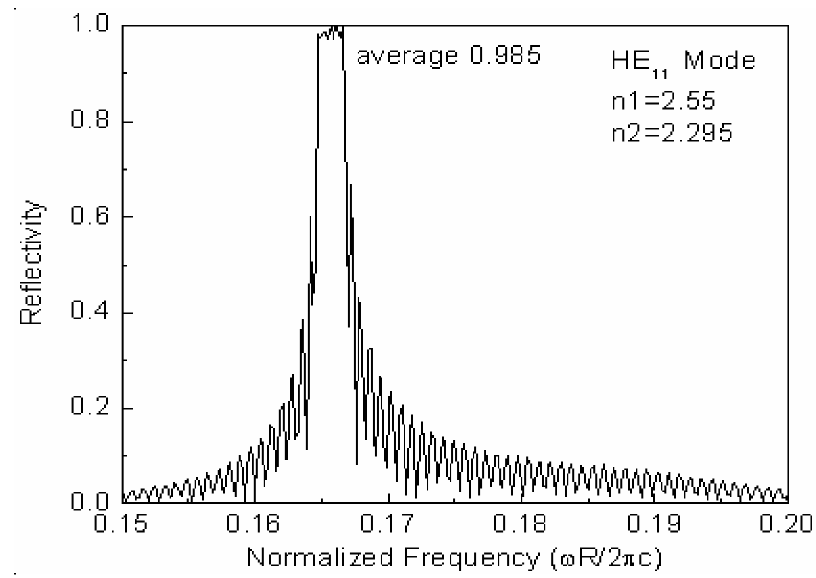
Proposal for a better nanowire laser: the superlattice photonic crystal structure



Chen and Towe, *Appl. Phys. Lett.*, 87 103111 (2005).

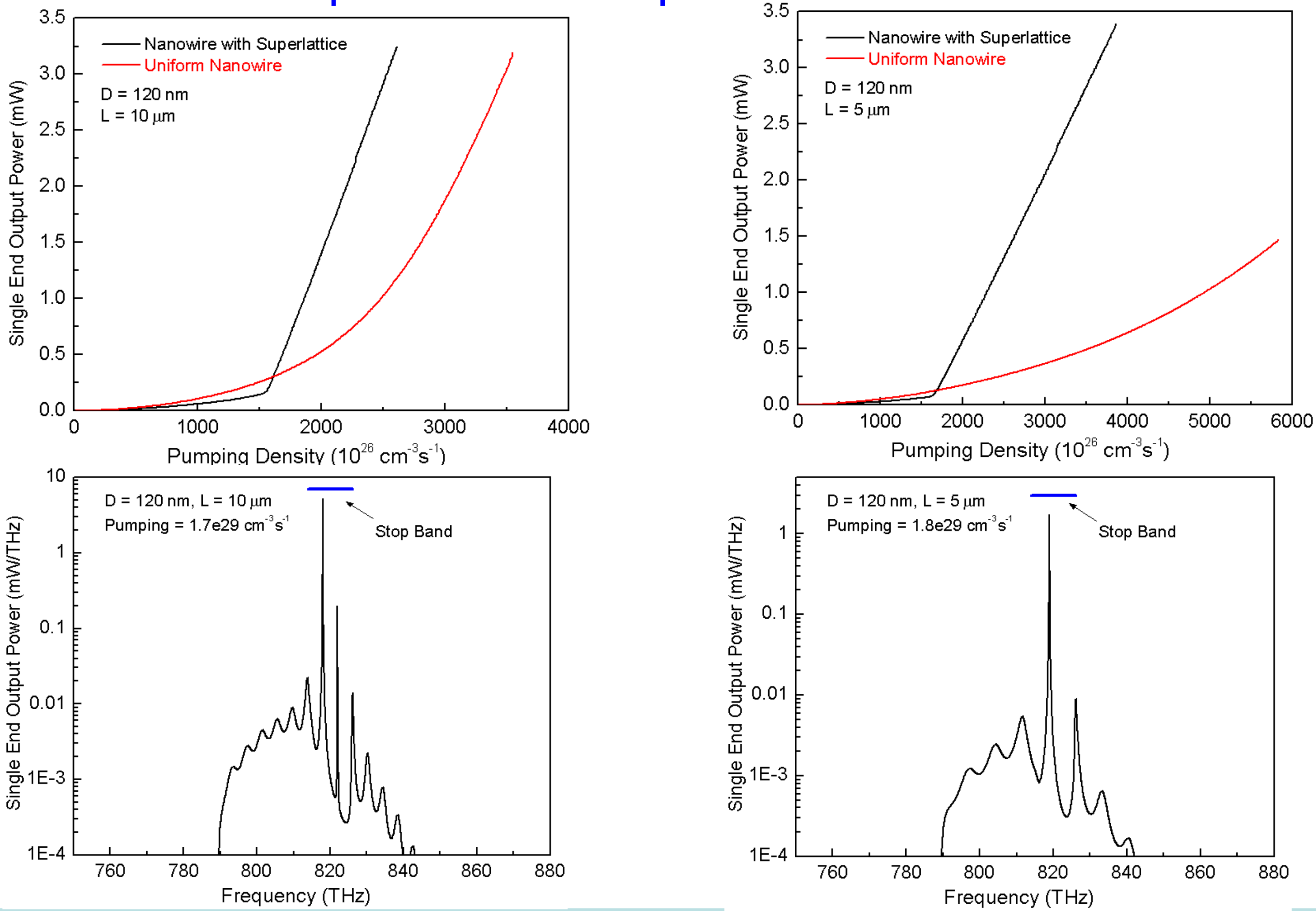
Defect mode spectral location and reflectivity of a nanowire superlattice laser cavity

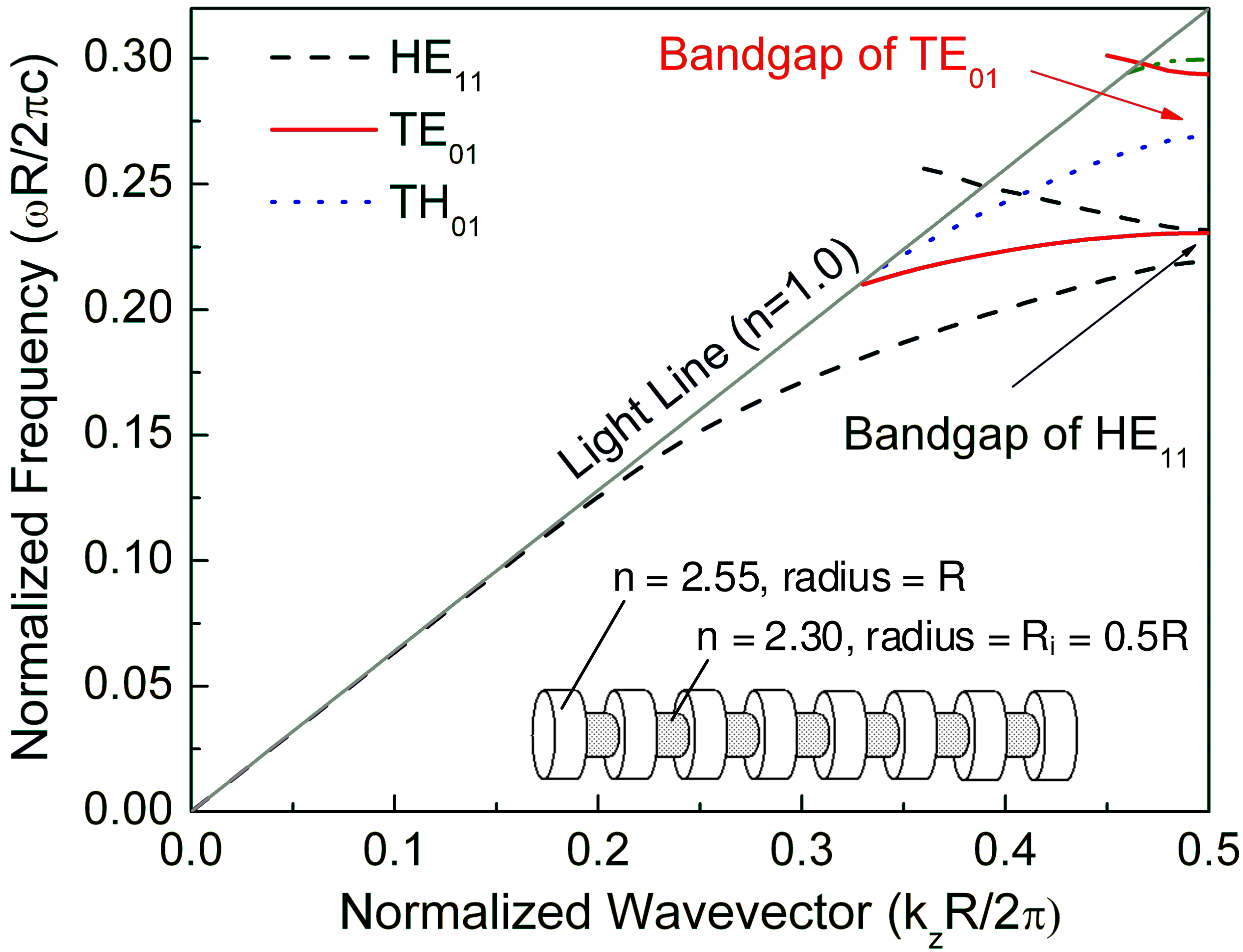




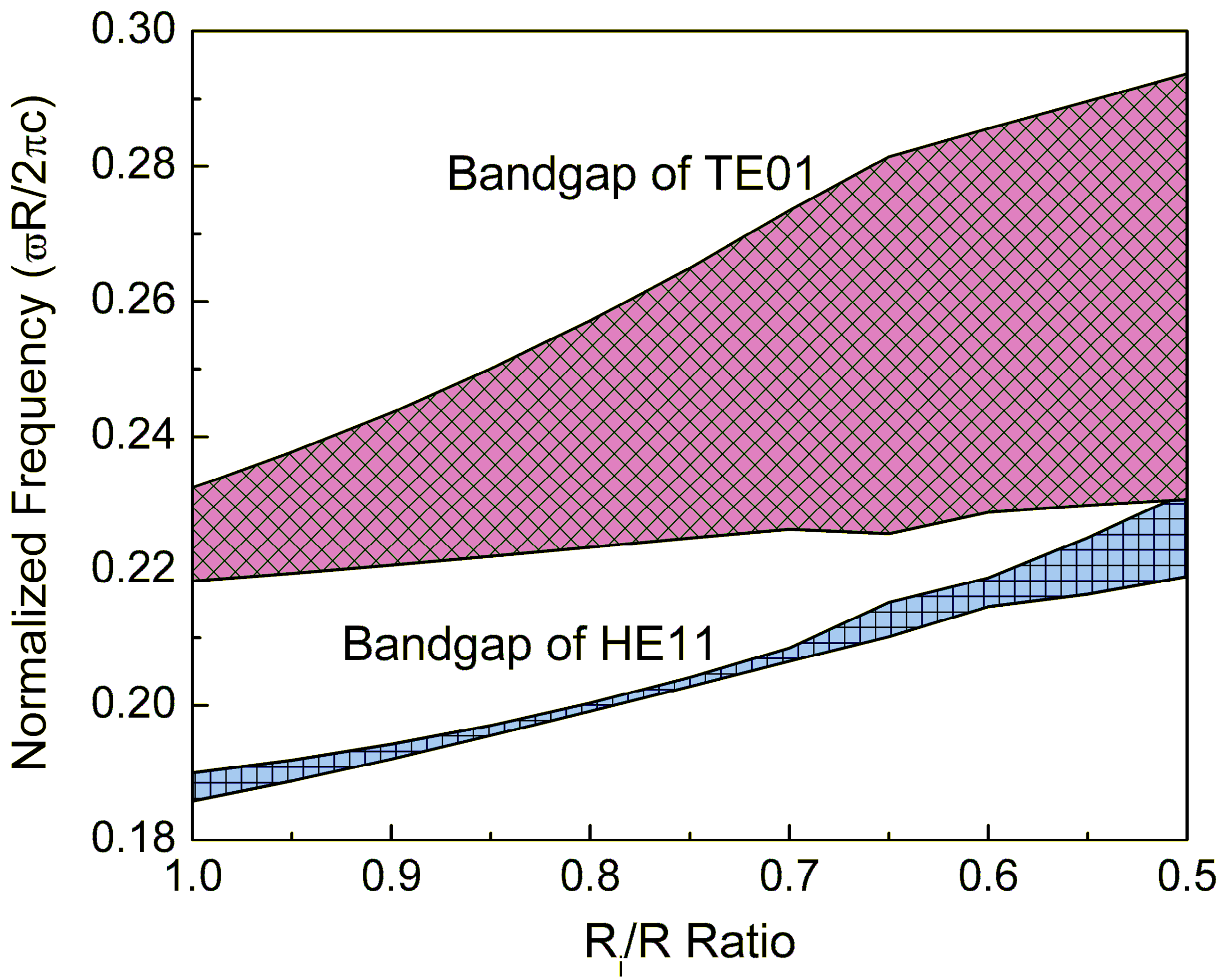
Chen and Towe, *Appl. Phys. Lett.*, 87 103111 (2005).

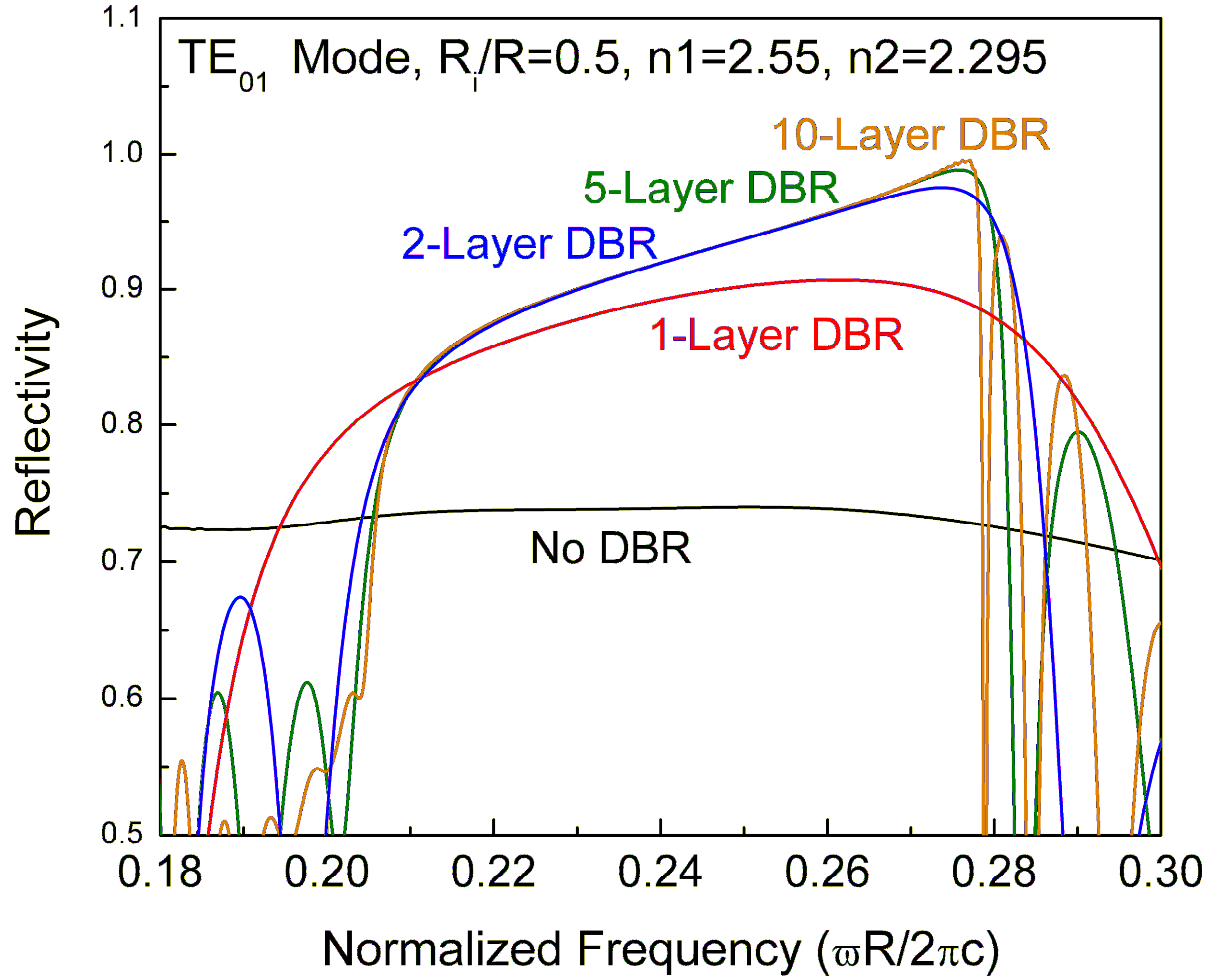
Calculated output-input characteristics and emitting spectra of a superlattice nanowire



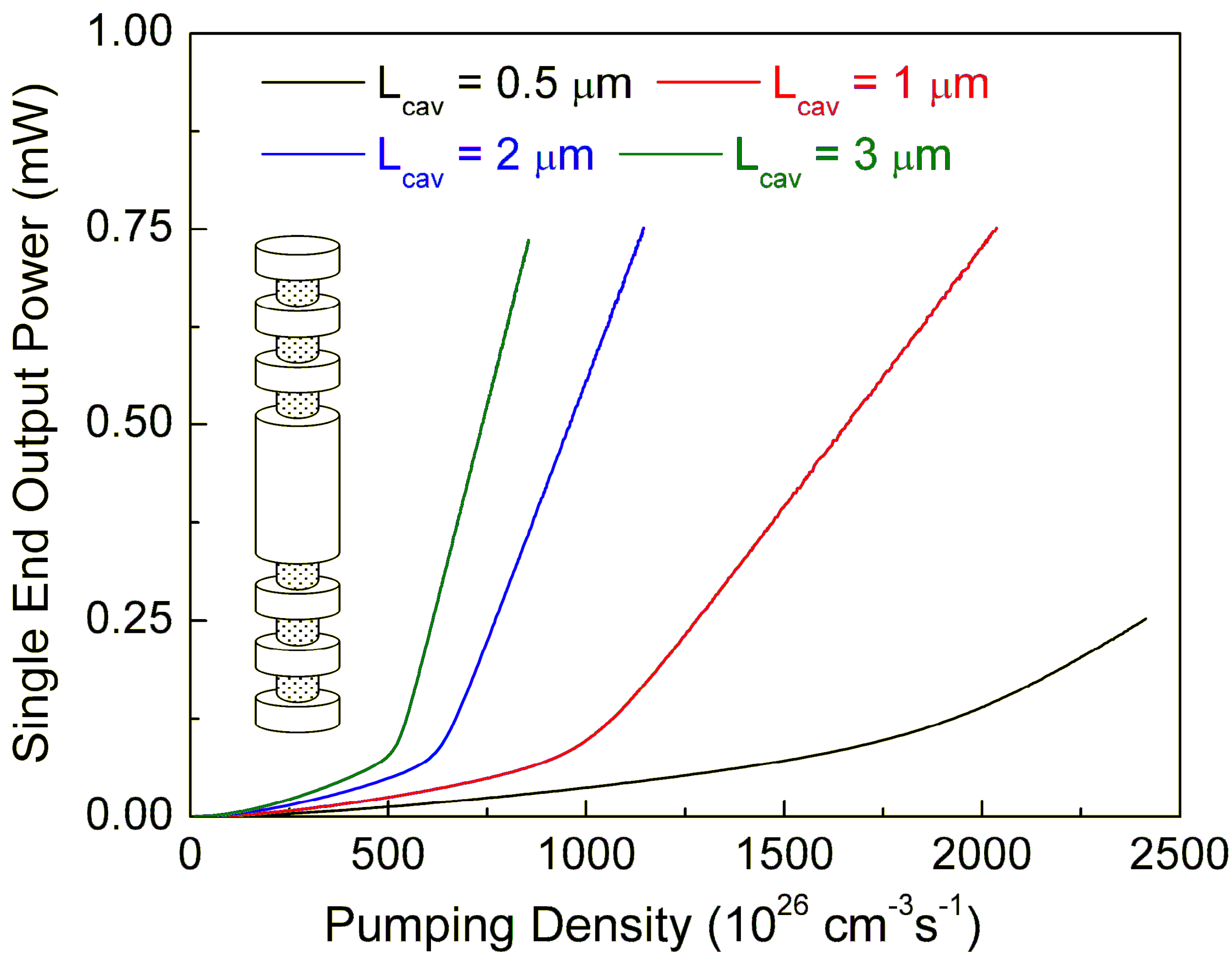


Normalized Frequency (ωR/2πc)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
Normalized Wavevector ($k_zR/2\pi$)
HE_{11}
TE_{01}
TH_{01}
Bandgap of TE_{01}
Light Line (n=1.0)
Bandgap of HE_{11}
n = 2.55, radius = R
n = 2.30, radius = R_i = 0.5R

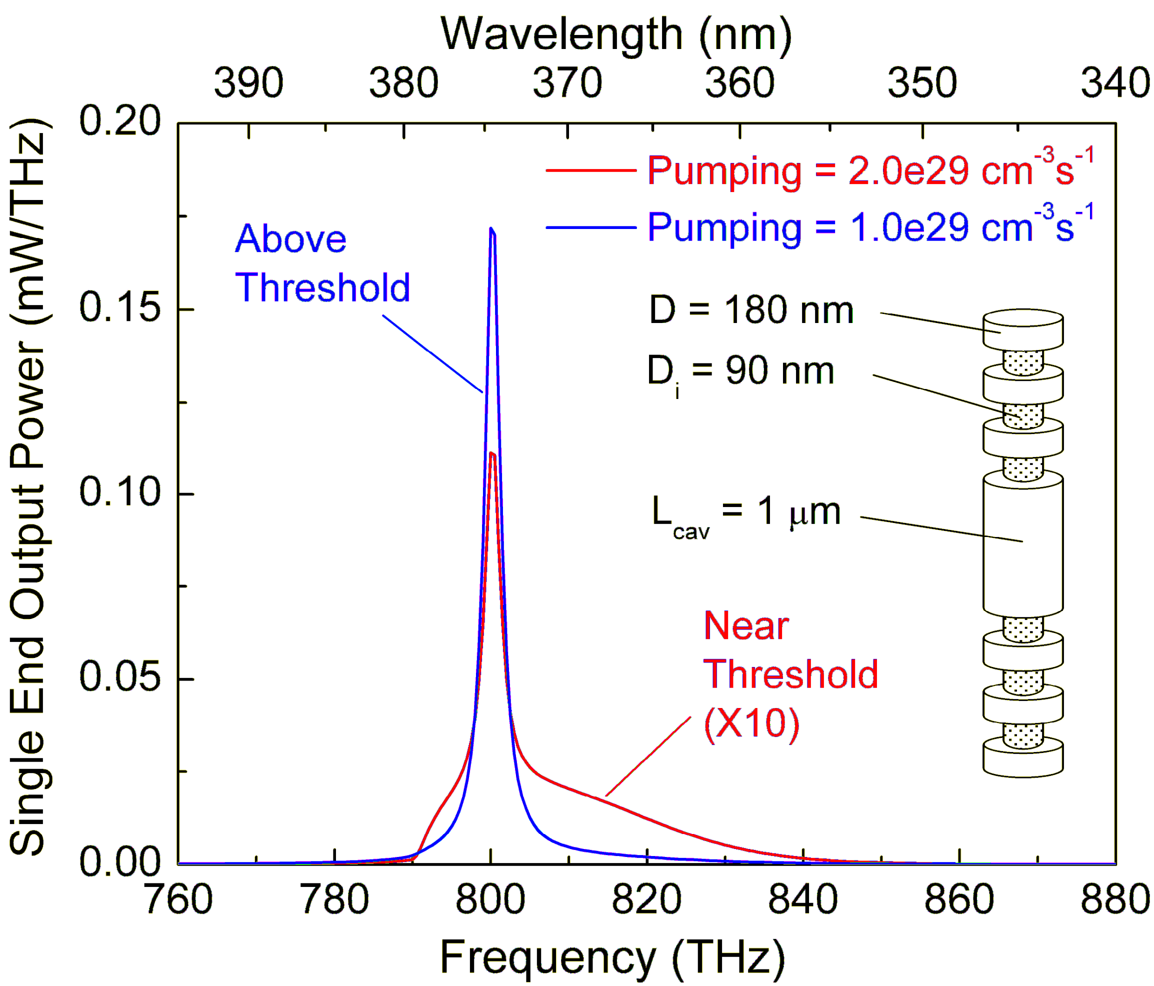

Bandgap of TE01
Bandgap of HE11
Normalized Frequency (ϖR/2πc)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
1.0
0.9
0.8
0.7
0.6
0.5
R_i/R Ratio



TE01 Mode, Ri/R=0.5, n1=2.55, n2=2.295
10-Layer DBR
5-Layer DBR
2-Layer DBR
1-Layer DBR
No DBR
Reflectivity
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.18
0.20
0.22
0.24
0.26
0.28
0.30
Normalized Frequency (ϖR/2πc)



1.00
0.75
0.50
0.25
0.00
Single End Output Power (mW)
0
500
1000
1500
2000
2500
Pumping Density (10^26 cm^-3s^-1)
L_cav = 0.5 μm
L_cav = 1 μm
L_cav = 2 μm
L_cav = 3 μm


Wavelength (nm)
390
380
370
360
350
340
0.20
0.15
0.10
0.05
0.00
Single End Output Power (mW/THz)
Pumping = 2.0e29 cm^{-3}s^{-1}
Pumping = 1.0e29 cm^{-3}s^{-1}
Above
Threshold
D = 180 nm
D_i = 90 nm
L_{cav} = 1 μm
Near
Threshold
(X10)
760
780
800
820
840
860
880
Frequency (THz)

Summary

- Interaction of light with size-dependent effects in nanostructures offer device design opportunities for next-generation optoelectronics devices;
- Most significant impact will likely be in components that offer ease of integration with other devices;
- Integration with electronics will probably mean having to deal with heterogeneous integration technologies.