SAND2016-1284PE

Sandia National Laboratories

SECANT QKD Grand Challenge LDRD

Sandia Communications and Authentication Network using Quantum Key Distribution

Sandia National Laboratories

LDRD

- **AlGaAs Quantum Photon Sources**

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

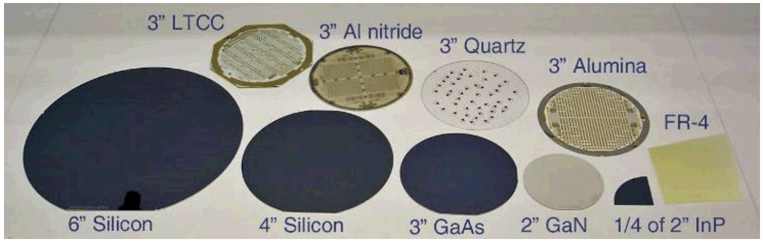
- Introduction to Sandia
- Review of quantum sources
- AlGaAs photon pair source
  - Theory of operation
  - Design
  - Results
- Future work

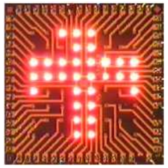
Sandia National Labs MESA Complex

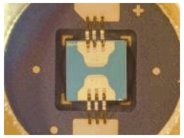
Sandia National Laboratories

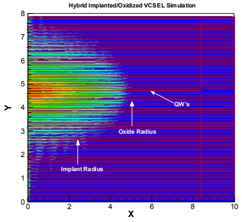
- Prove, Advance Technology Readiness Level, Productize
  - TRL1-6+: create, develop, prototype
  - Trusted
- Trusted, custom, low-volume, high-reliability products for harsh environments when industry is unwilling or unable to deliver
- Foundational Capabilities
  - III-V compound semiconductor epitaxy, microfabrication, integration
  - Si microfabrication, integration
  - Device physics, modeling, simulation
  - Microelectronics/optoelectronics, and complex mono/hetero-circuits

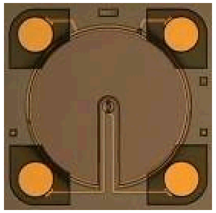
SiFab: 11,900 ft^2 Class 1
MicroFab: 14,230 ft^2 Class 10/100

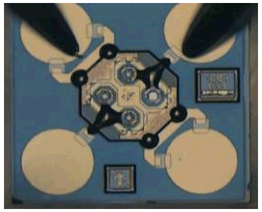


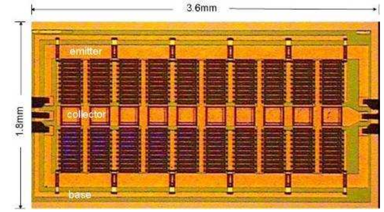


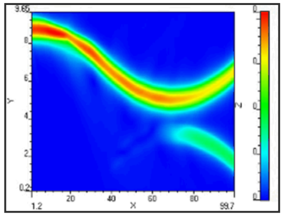


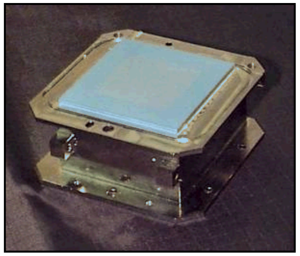


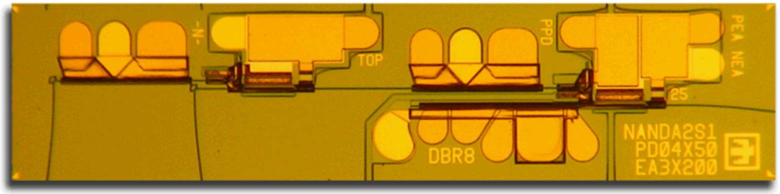


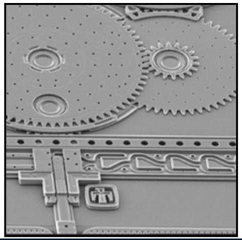


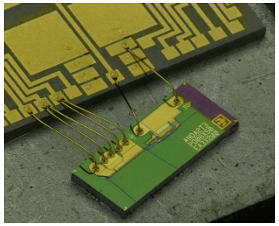












Single photon source applications:

1.) Quantum key distribution (SECANT GC)

- Attenuated laser can be used
- SPS is the gold standard for QKD
- Future QKD involving quantum repeaters

2.) Quantum metrology

- Low noise light source → better optical measurements

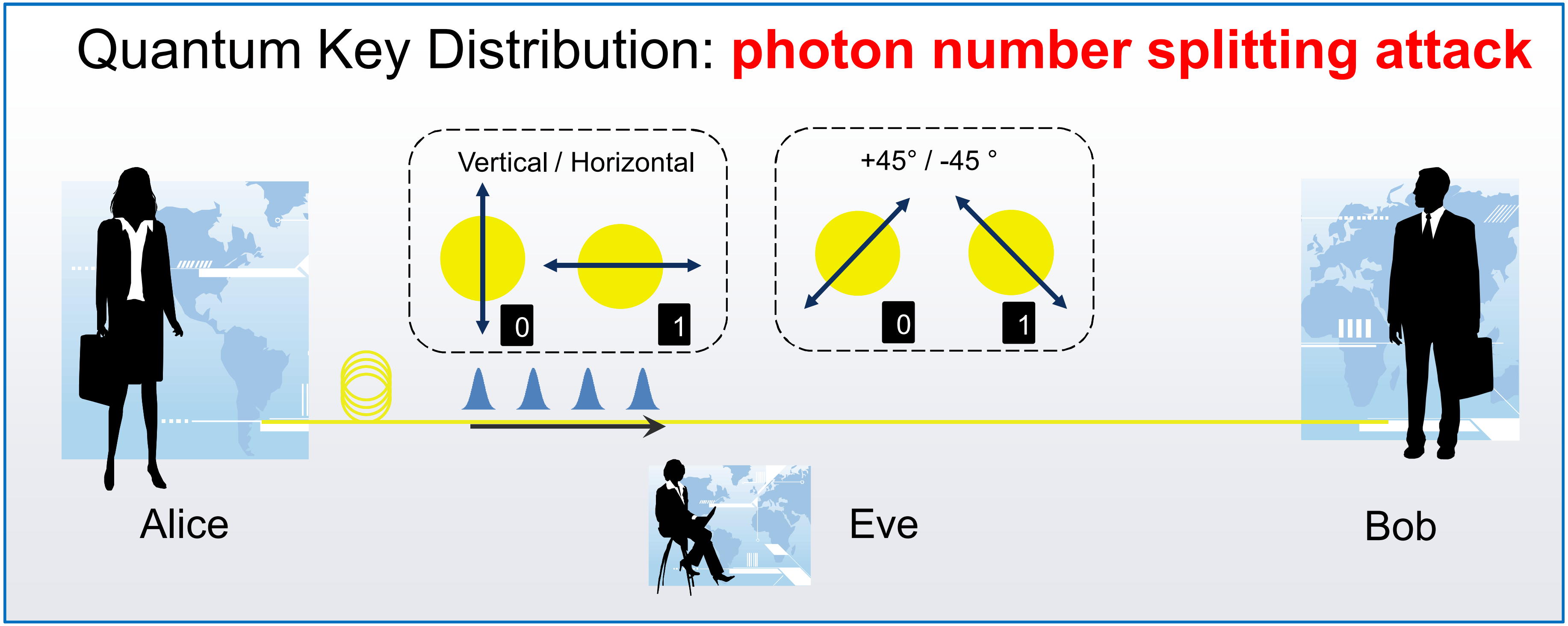
3.) Quantum computing with photons

- Use photons as qubits

4.) True random number generation

- Generate encryption keys, gambling, modeling complex systems

Single photons sources for QKD



If a pulse contains more than one photon:

- Eve can split off the extra photons and learn information about encryption key
- Security for DV relies on having only single photons (or doing error correction)
- multiple photons in a pulse is not desirable for QKD

Optical quantum sources

- Important attributes
  - Anti-bunching
  - Wavelength
  - Efficiency/brightness
  - Operating temperature
  - Compatibility with integration
  - Entangled sources

Sources used in quantum systems

- Attenuated laser sources
  - Uses classical laser with attenuation
  - Can be used in some quantum systems, but requires additional statistics and error correction
- Entangled photon pair sources
  - Produces entangled photon pairs, usually entangled through polarization
  - Spontaneous parametric down-conversion
  - Enables heralded photon generation
- Single photon sources
  - Produces a single photon at a time
  - Deterministic so photons are produced on demand

AlGaAs Introduction

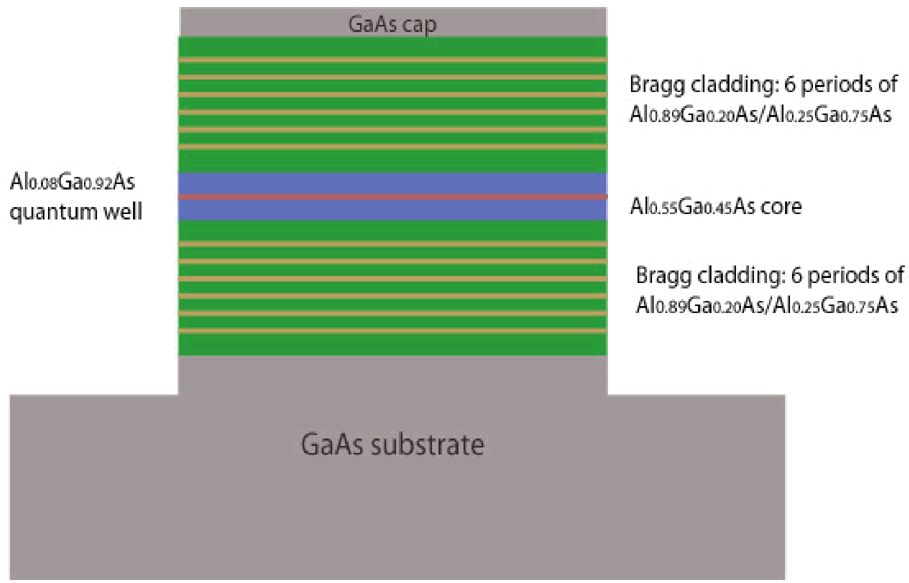
- Recent reports of using spontaneous parametric down conversion in AlGaAs-based waveguides to produce photon pairs
  - 785 nm photon produces a TE and TM 1550 nm photon pairs
  - F. Boitier, et. al., "Electrically Injected Photon-Pair Source at Room Temperature", *Phys. Rev. Lett.* 112, 183901, May 2014
- This work is well aligned with Sandia's historical expertise in:
  - III-V semiconductor growth
  - VCSEL DBR mirrors
  - Photonic integrated circuits

Technology advantages and challenges

- Advantages
  - Can operate in the 1550 nm telecommunications
  - Room temperature operation
  - Compatible with integration
  - AlGaAs is a well-known material system
- Challenges
  - Low efficiency
  - Momentum matching difficult due to wavelength dispersion in AlGaAs materials
  - Narrowband and requires tight growth tolerances

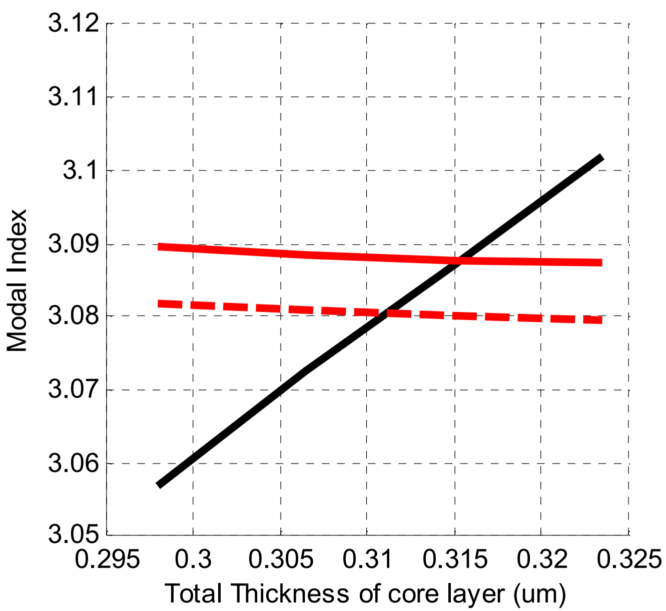
Approach

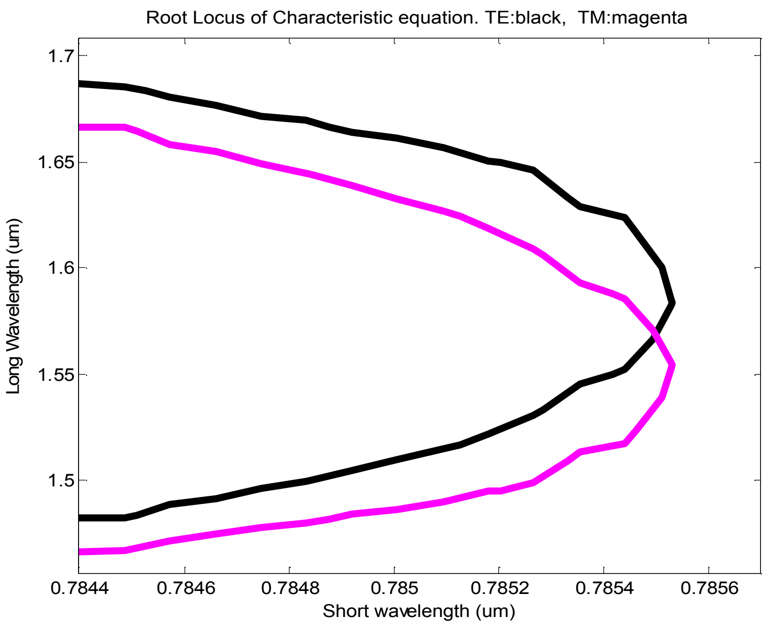
- Use a TE Bragg mode to allow for momentum matching
  - Short wavelength (~790 nm) guided by Bragg
  - Long wavelength (~1580 nm) index guided by difference in the cladding (DBR) and core of the waveguide
  - Electrically injected with p-contacts on GaAs cap and n-contact on GaAs substrate



Design

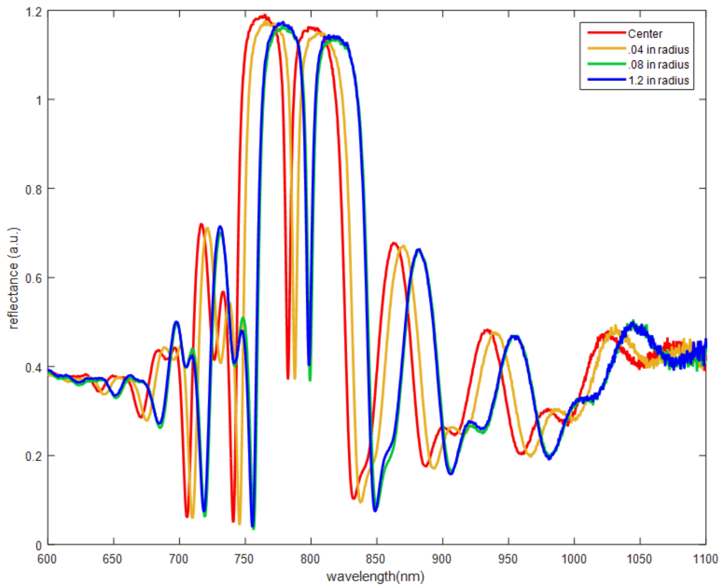
- Goal: Identify the conditions where momentum and energy would be conserved
  - Momentum matching is difficult in AlGaAs due to dispersion
  - Used index models to identify where momentum matching could be achieved



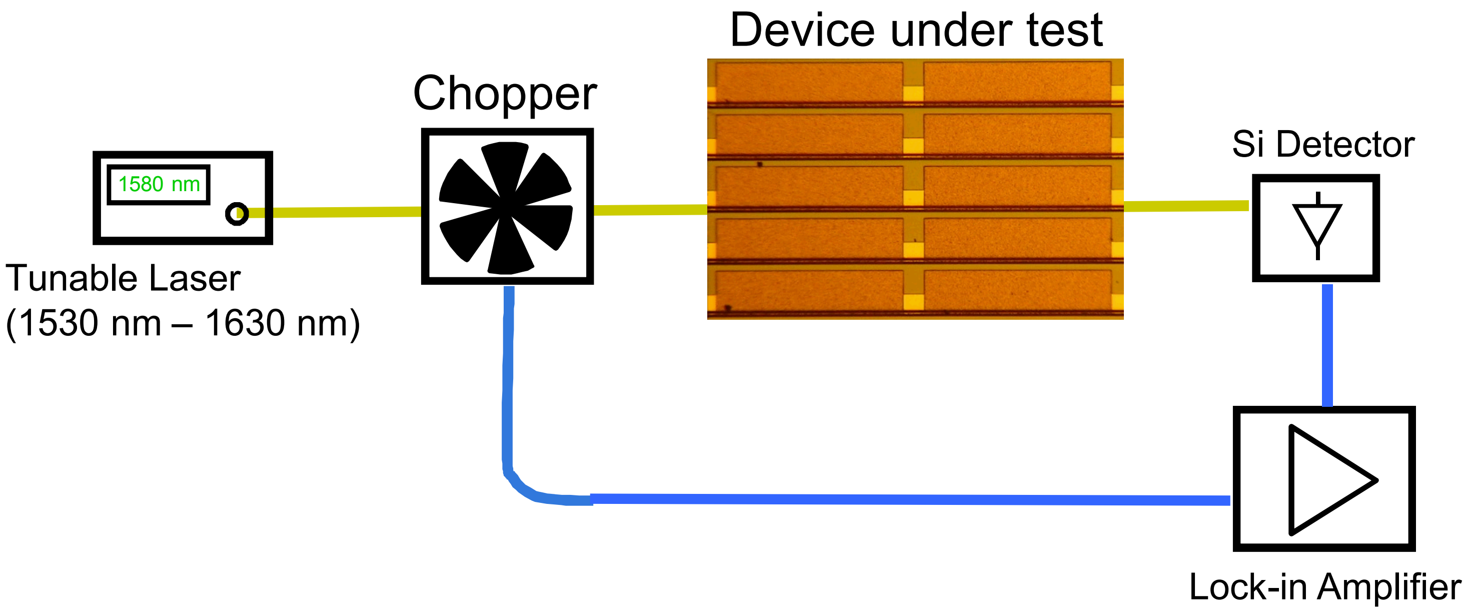


Calibration of Growth

- Goal: Characterize deviations in composition and index before growing full structure
  - This is important since the quantum well needs to be aligned to the nonlinear wavelength
- Cold cavity growth used to align experiment with theory
  - Intentional variation across wafer improves chance of QW and waveguide alignment

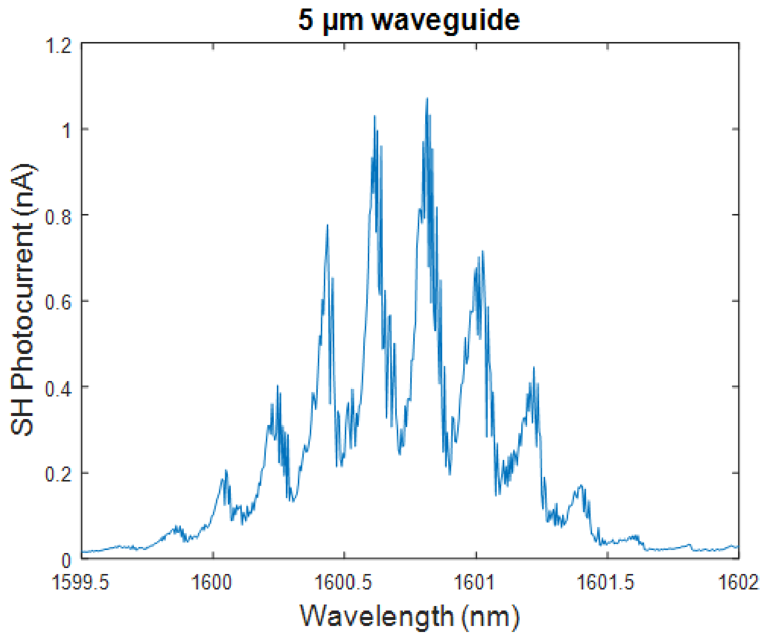


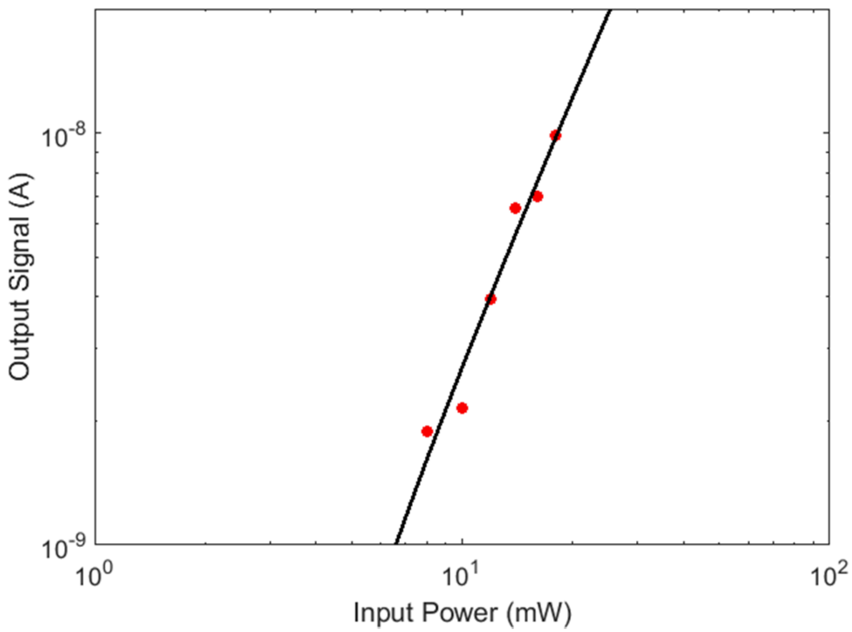
2^{nd} Harmonic Measurement



- First test is 2^{nd} harmonic generation
  - Creating a short wavelength from two long wavelength photons
- Waveguide is injected with long wavelength photons
  - Short wavelength (~800 nm) photons detected with Si detector
    - Si detector will not detect wavelengths >~1100 nm

Passive Waveguide Results





2nd harmonic generation at 1600 nm

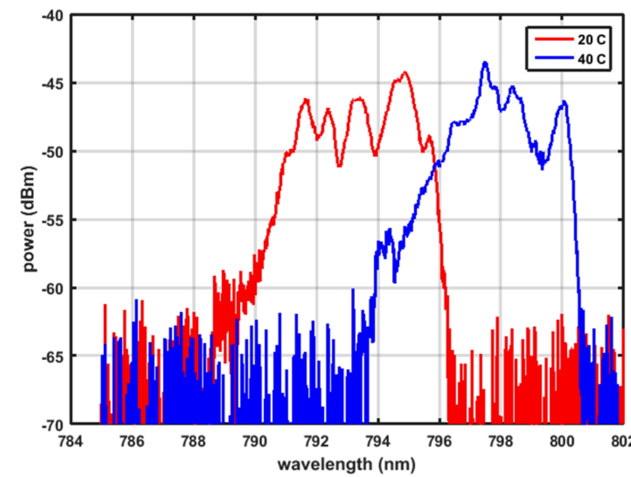
- Fringes due to Fabry-Perot cavity
- There is variation across the wafer due to DBR variation

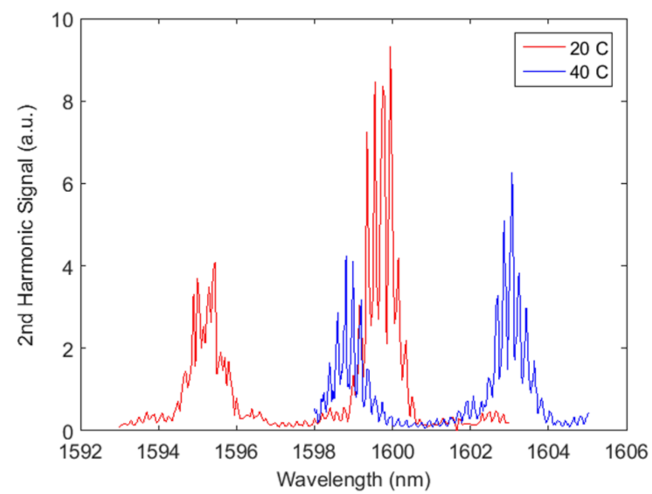
Pump power vs. generated 2nd harmonic generated power

- Expected quadratic dependence of nonlinearity shown

Active Device Characterize

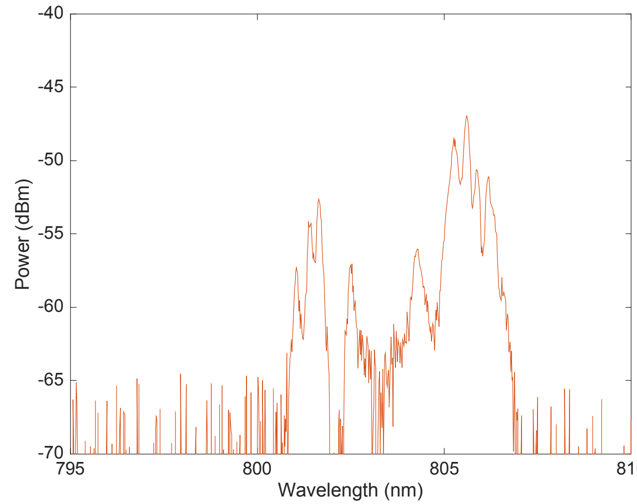
- Devices are mapped to understand the parameter space
  - Goal is to find the operating point where the lasing wavelength overlaps the waveguide nonlinearity
  - Tune using temperature and laser pump current

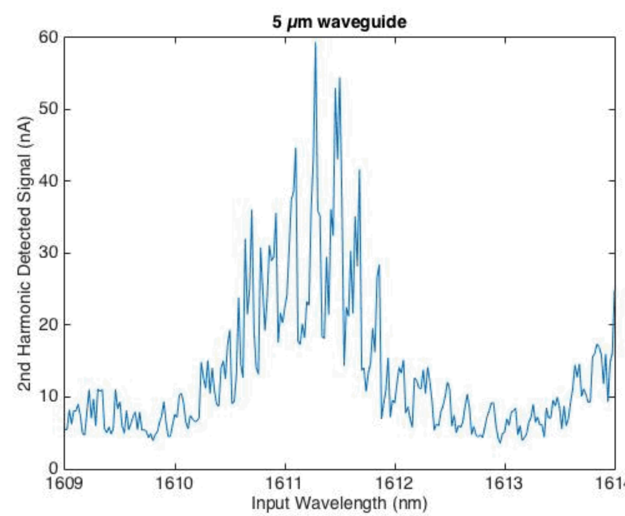




Active Device Characterize

- Devices are mapped to understand the parameter space
  - Goal is to find the operating point where the lasing wavelength overlaps the waveguide nonlinearity
  - Tune using temperature and laser pump current
  - Optimize overlap of nonlinearity and lasing wavelength at 50° C





Question: What can be extracted from experiment at the moment?

Answer: Some indication of phasing matching achieved.

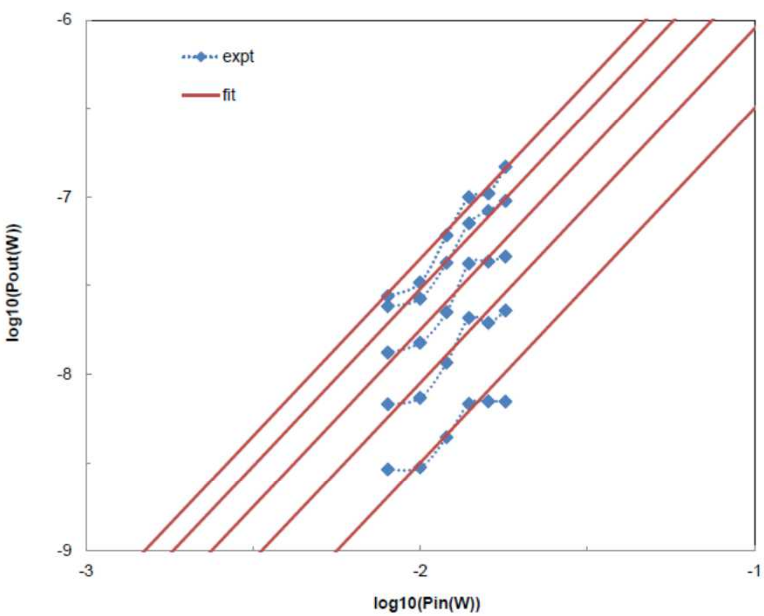
Approach:

(1) Get coefficent α from experiment

Fit:

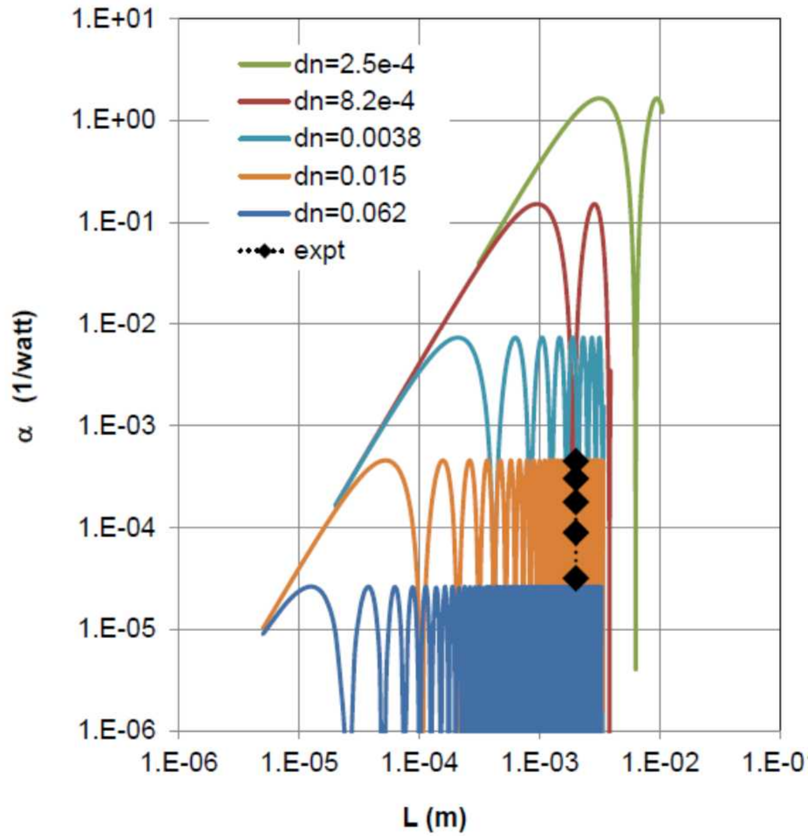
$$P_{out} = \alpha P_{in}^2$$

$$Log_{10}(P_{out}) = 2Log_{10}(P_{in}) + Log_{10}(\alpha)$$



(2) Fit it to theory:

$$\alpha = 2\left(\frac{\pi}{\lambda_{sh}}\right)^2 \frac{|\chi^{(2)}|^2}{n^3\varepsilon_0 c} \frac{1}{Area} L^2 \frac{sin^2(\Delta kL/2)}{(\Delta kL/2)^2}$$



Conservative estimate: 0.06<δn<0.0003

Less conservative: 0.02<δn<0.0008

Sum-frequency conversion – 2nd harmonic generation
Dependences on waveguide length and phase matching

$\lambda_{pump} = 1.57\mu m$

$\lambda_{sh} = 0.785\mu m$

$Waveguide = \lambda_{sh} \times \lambda_{sh} \times L$

$\chi^{(2)} = 3 \times 10^{-10} m/Volt$

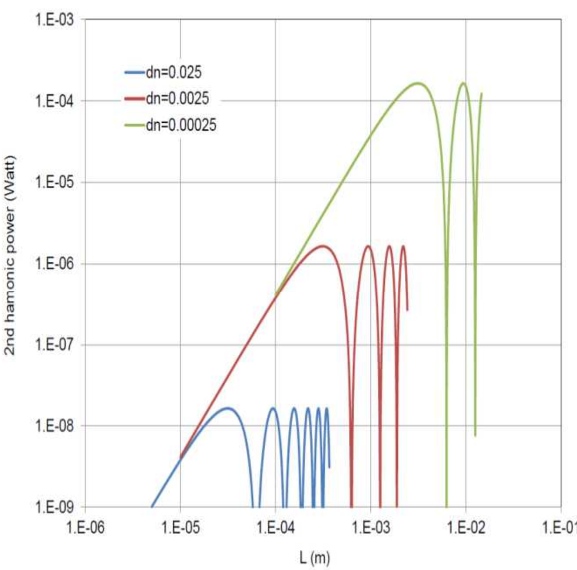
$$P_{sh} = 2\left(\frac{\pi}{\lambda_{sh}}\right)^2 \frac{\left|\chi^{(2)}\right|^2}{n^3 \varepsilon_0 c} \frac{1}{Area} L^2 \frac{sin^2(\Delta k L/2)}{(\Delta k L/2)^2} P_{pump}^2$$

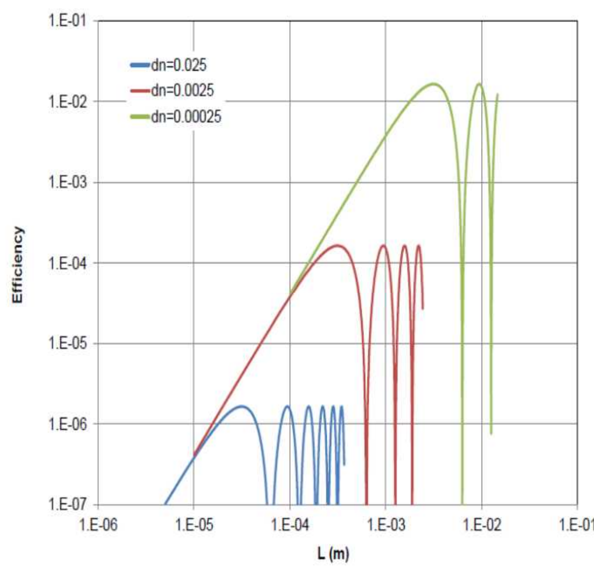
$$\Delta k = k_{sh} - 2k_{pump}$$

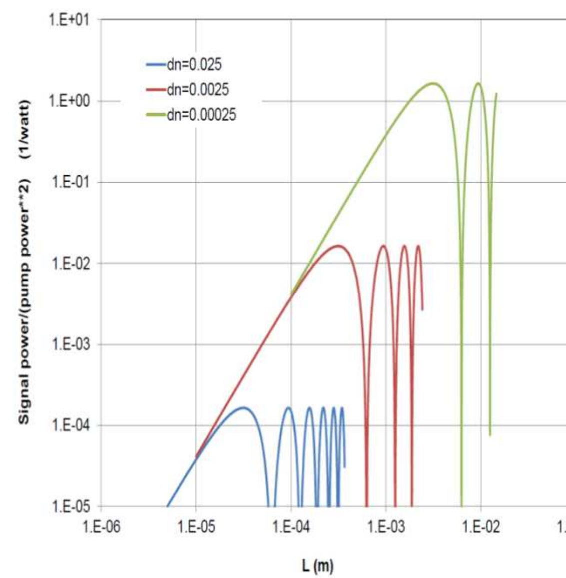
$$\delta n = \frac{\Delta k}{k_{pump}} \times n$$

2nd harmonic power and conversion efficiency versus propagation length for P_{pump} = 10mW

Perhaps for comparison with experiment – factor out quadratic pump power dependence







Down-conversion rate versus waveguide length for given wavevector mismatch

$\lambda_{pump} = 0.785\mu m$

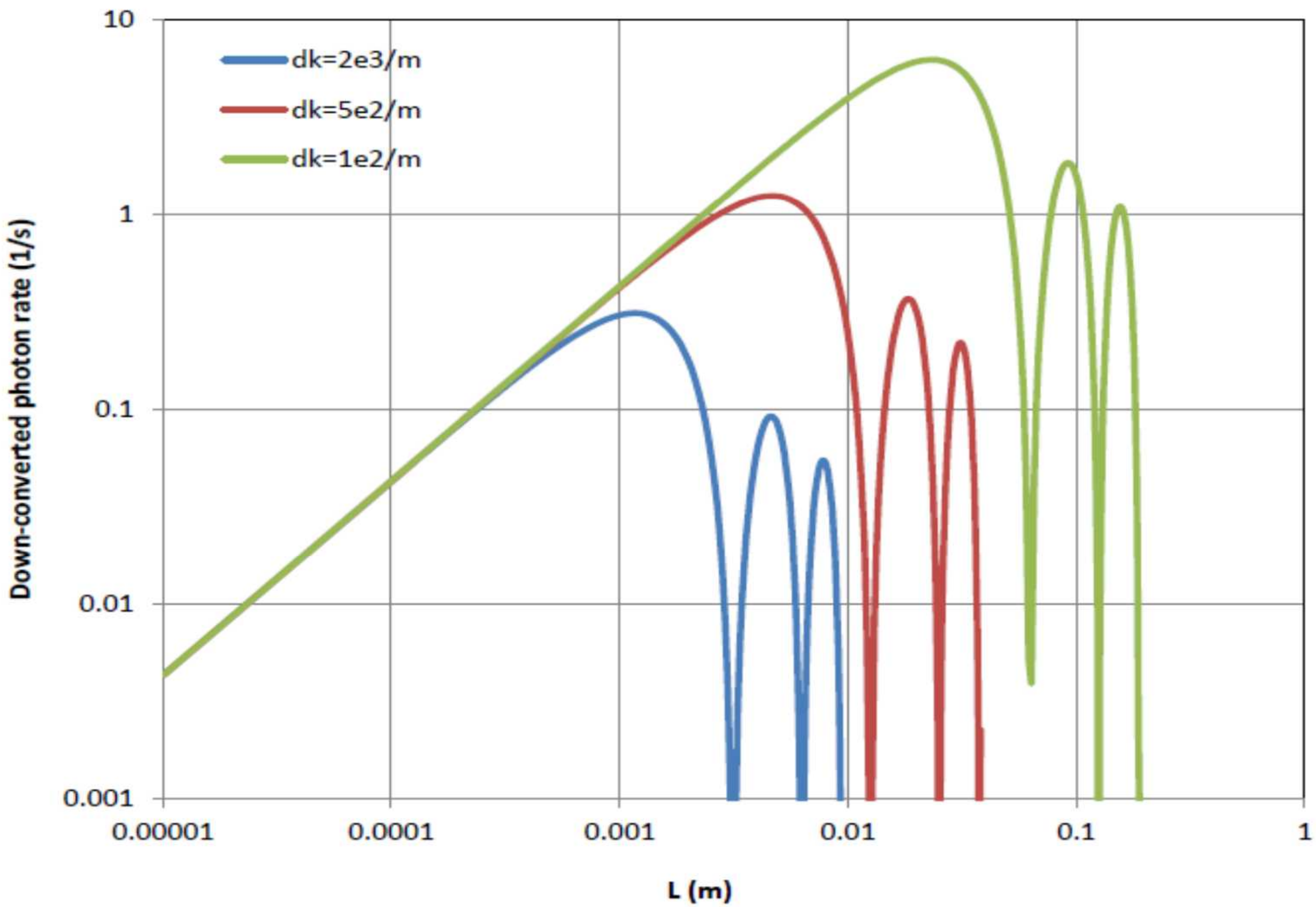
$\lambda_{idler} = \lambda_{signal} = 1.57\mu m$

$Waveguide = \lambda_{signal} \times \lambda_{signal} \times L$

$\chi^{(2)} = 3 \times 10^{-10} m/Volt$

$P_{pump} = 0.1\, mW$

$$\frac{dn_{signal}}{dt} = \frac{2\pi^2 \hbar c}{n^2 \varepsilon_0} \left|\chi^{(2)}\right|^2 \frac{1}{\lambda_{signal}^2} \frac{1}{\lambda_{pump}} \frac{1}{Area} L \frac{sin^2(\Delta kL/2)}{(\Delta kL/2)^2} \frac{P_{pump}}{\hbar\omega_{pump}}$$



Conclusions

- Exploring photon pair generation in AlGaAs based device structure
  - Compatible with chipscale integration
- Developing the theoretical models to understand the fundamental performance limits of the technology
- Future work will include implementing photonic integrated circuits to allow for greater control of the source

Exceptional service in the national interest

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Thank You

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