**Sunday, August 10th, 2019**

# Silicon-on-insulator holey photonic crystal waveguides for mid-IR gas sensing

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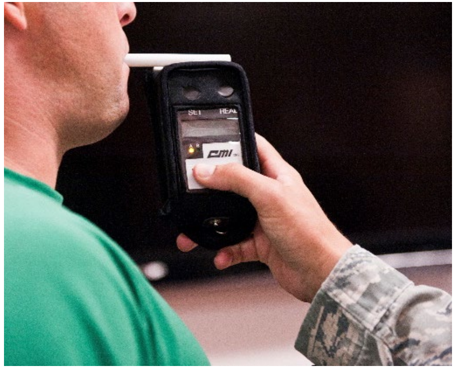
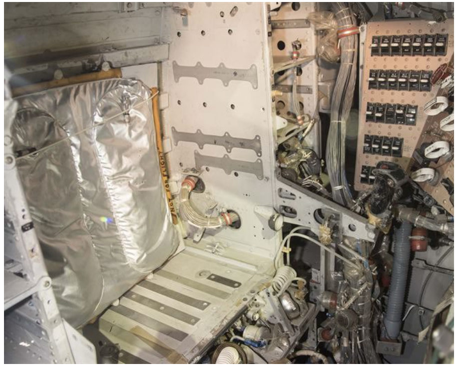
**Principal Investigator:** Professor Ray Chen

NSF
National
Nanotechnology
Coordinated
Infrastructure
TEXAS
The University of Texas at Austin

# Portable gas sensors are widely used

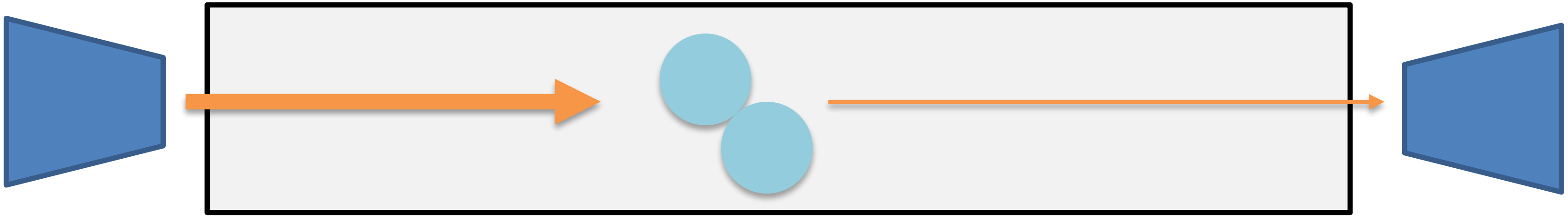
- Breathalyzers
- Leak detection
- Chemical agent sensing
- Gas monitoring in space





# Background

- Sensors often use absorption spectroscopy
- Mid-IR sensing over current near-IR tech



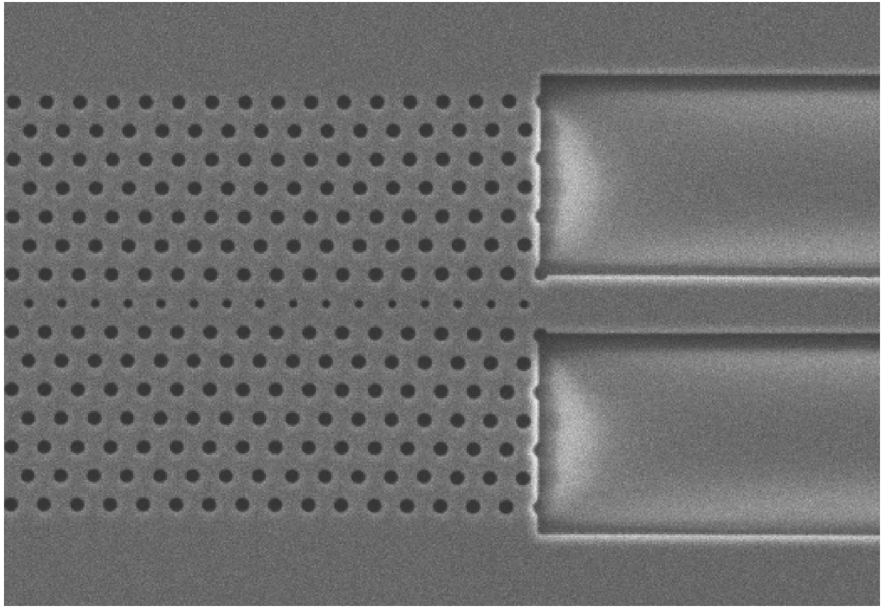
**Laser**
Emission
λ = 3.43 µm

**Gas molecule**
Absorption of energy

**Detector**
Detection

# REU Project

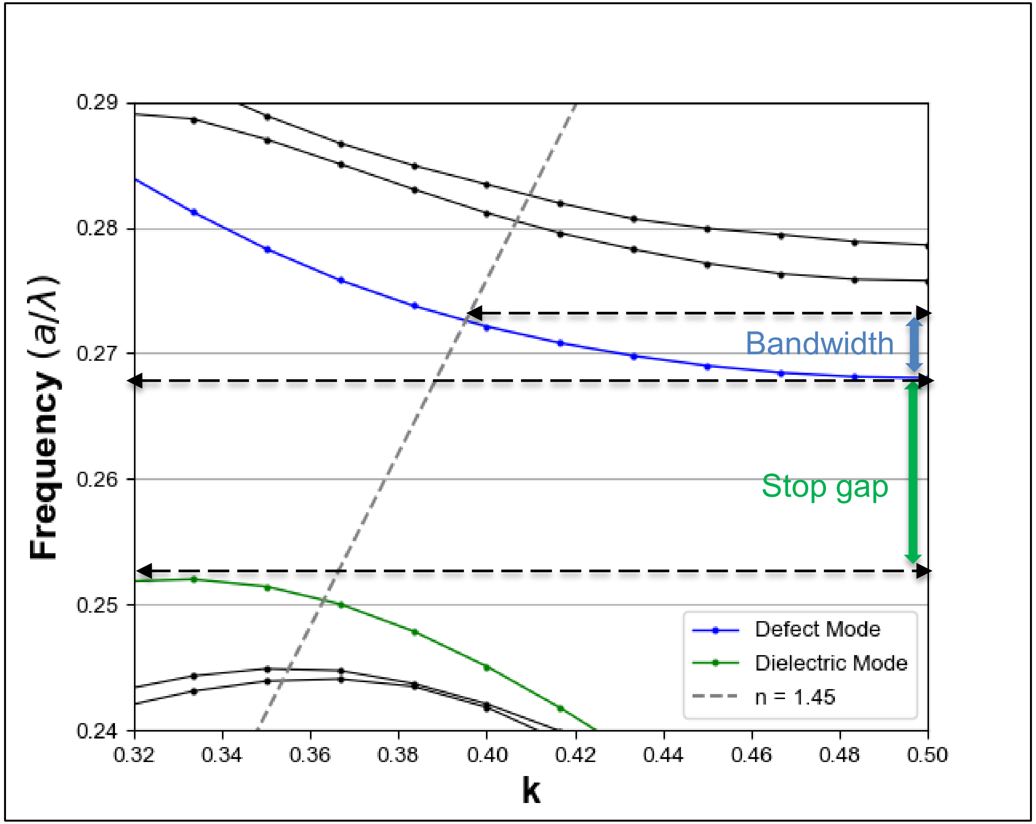
- Silicon-on-insulator holey photonic crystal waveguides
  - Layered silicon substrate
  - Repeated patterns
  - Light propagates along hole defects



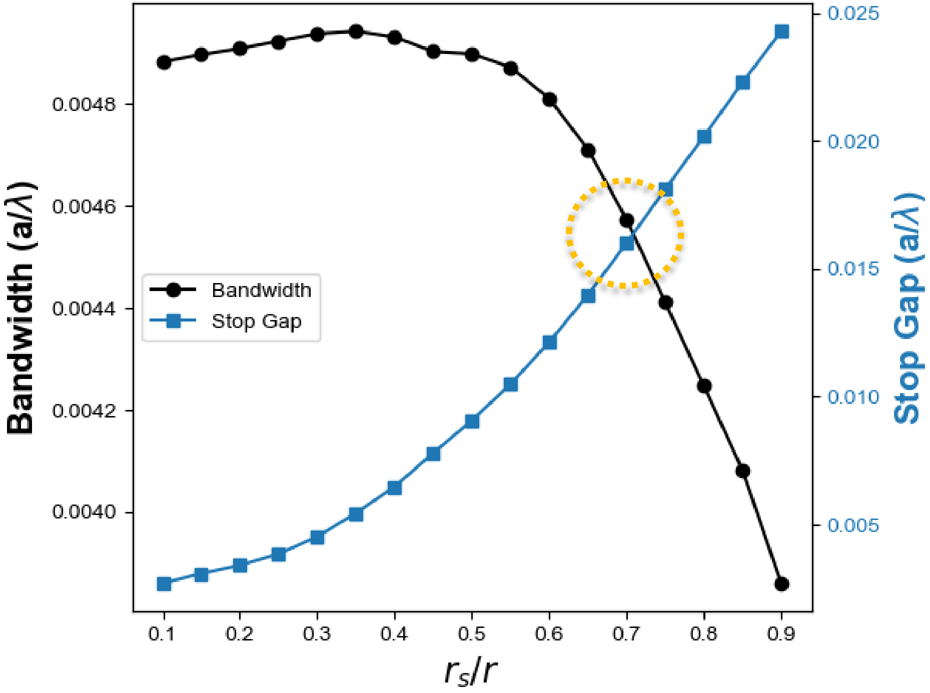
- **Goal:** Improve design & parameterize waveguide

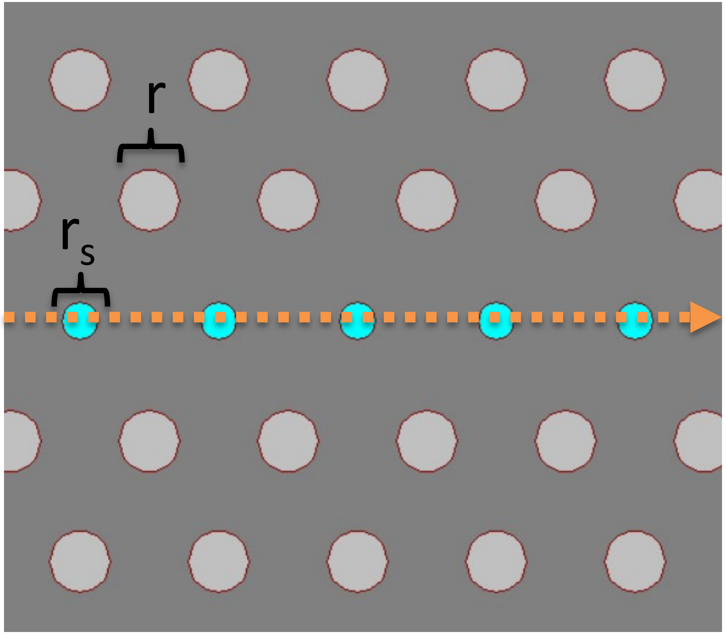
# Simulations

- Design parameters:
  - Defect hole radius
  - Waveguide width
  - Device thickness
- Metrics:
  - Bandwidth
  - Stop gap
  - Electric field profile

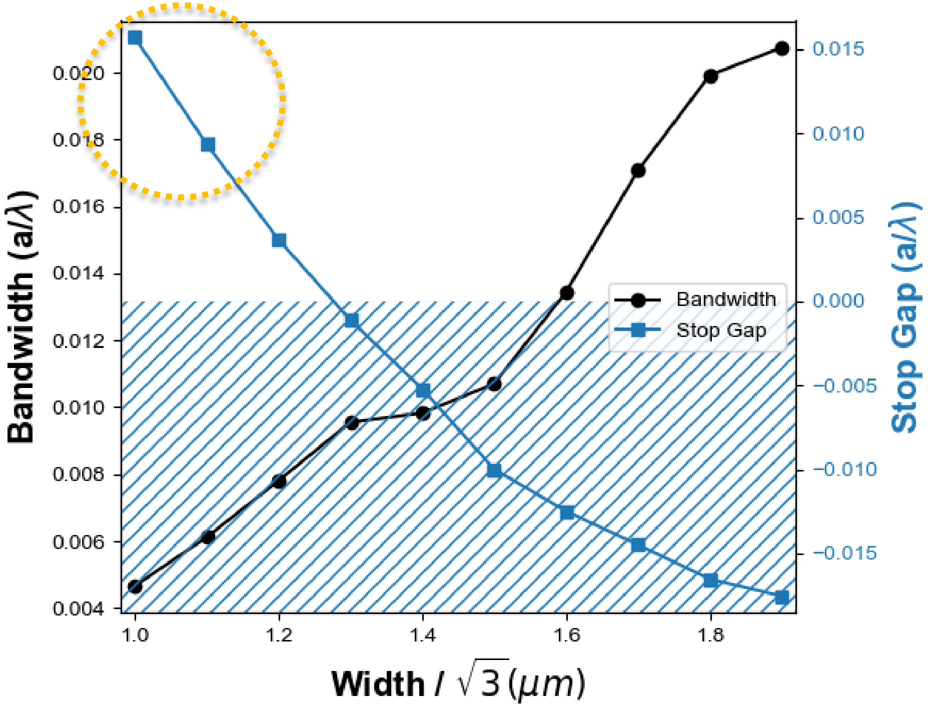


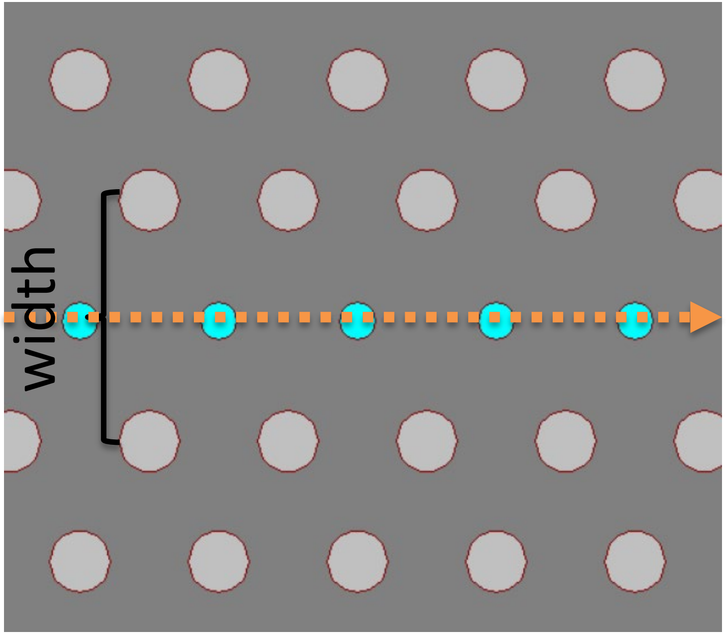
# Results: Optimal small hole radius simulation



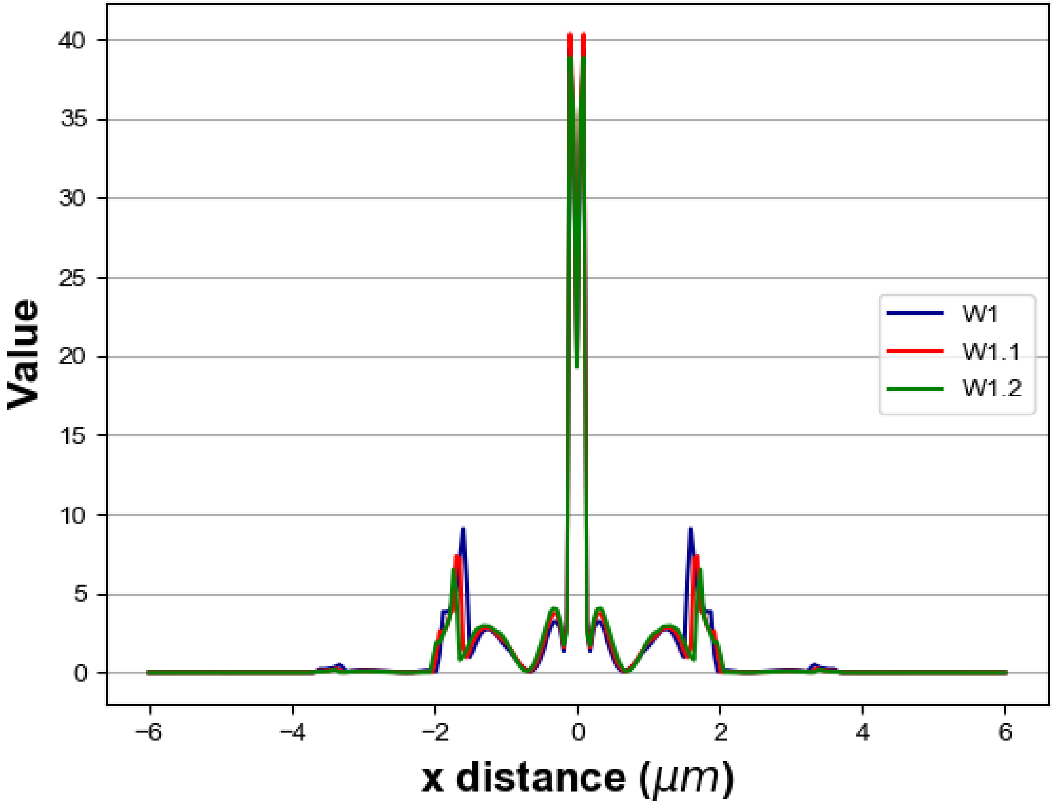


# Results: Guide width simulation

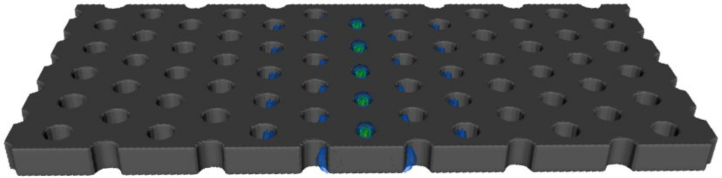




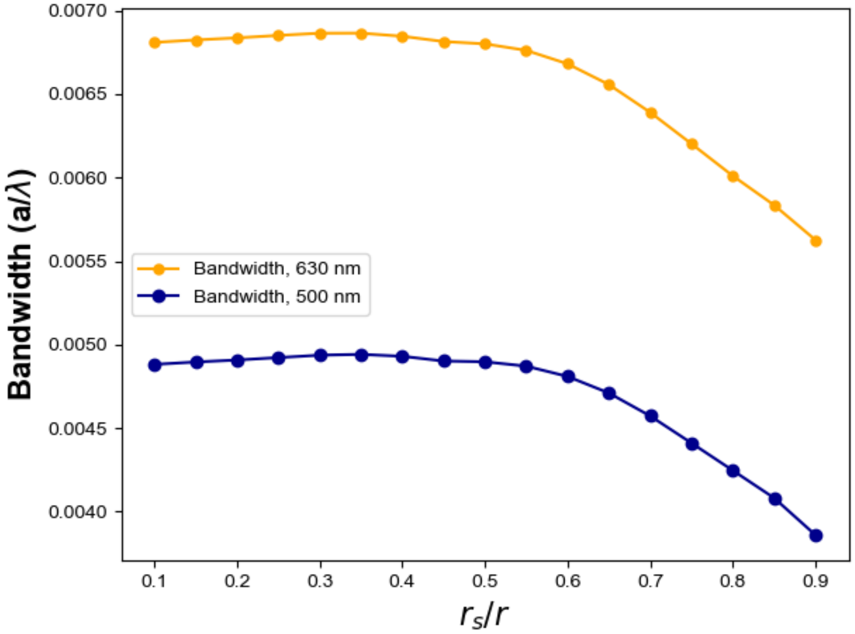
# Electric Field Intensity simulated profile

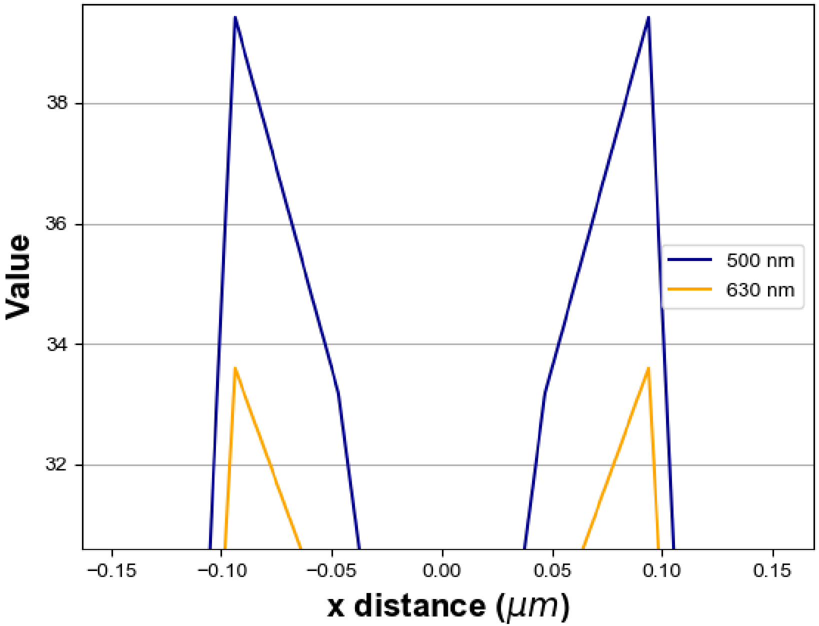


- Mode profile not strongly affected by guide width



# Results: Varying thickness simulation

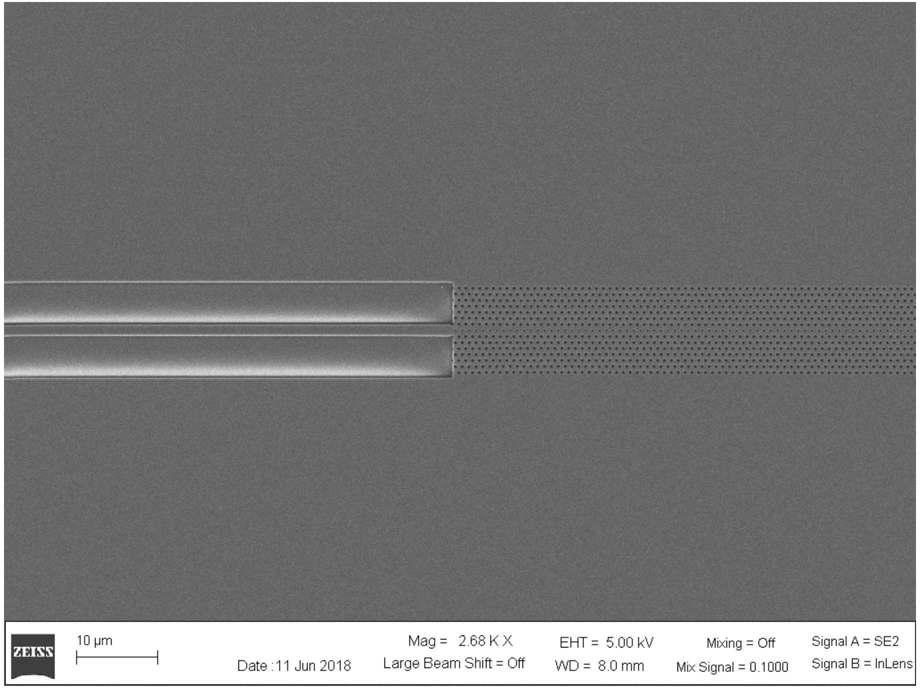


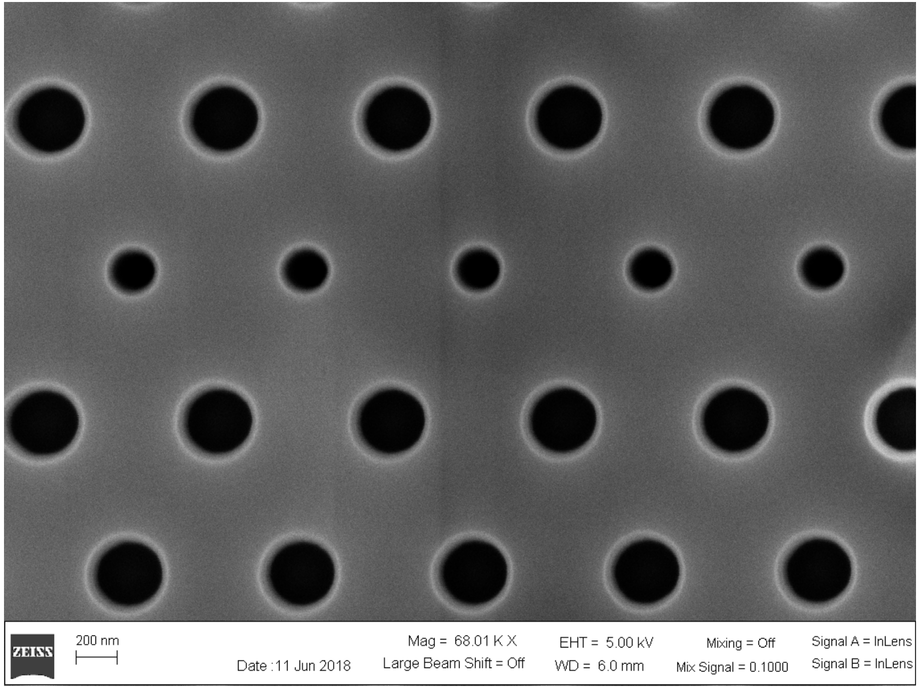


# Conclusions

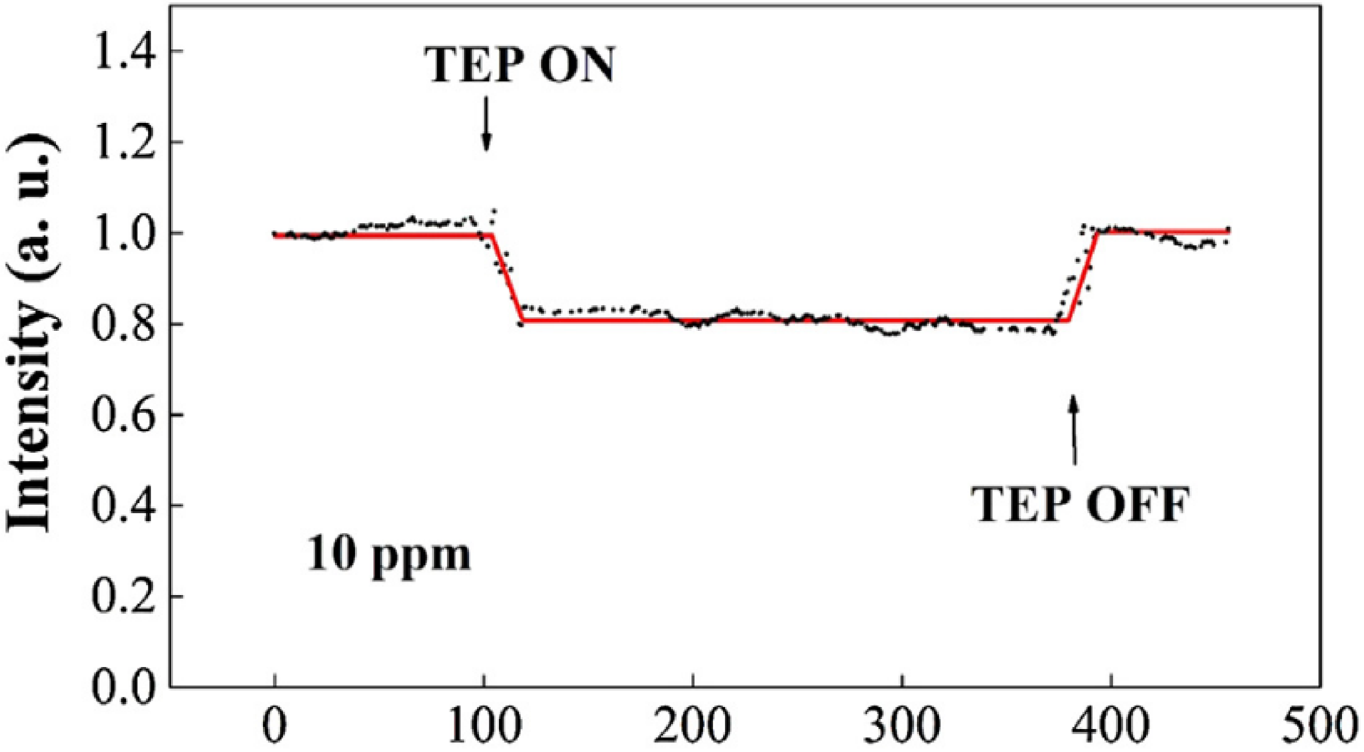
- We found optimal parameters:
  - $r_s/r$: 0.7
  - Width: W1
  - Thickness: tradeoff; thinner is more sensitive
- Waveguide fabricated according to design
- Future work: characterize light propagation and sensitivity to ethanol

# Backup


ZEISS
10 µm
Date :11 Jun 2018
Mag = 2.68 K X
Large Beam Shift = Off
EHT = 5.00 kV
WD = 8.0 mm
Mixing = Off
Mix Signal = 0.1000
Signal A = SE2
Signal B = InLens


ZEISS
200 nm
Date :11 Jun 2018
Mag = 68.01 K X
Large Beam Shift = Off
EHT = 5.00 kV
WD = 6.0 mm
Mixing = Off
Mix Signal = 0.1000
Signal A = InLens
Signal B = InLens

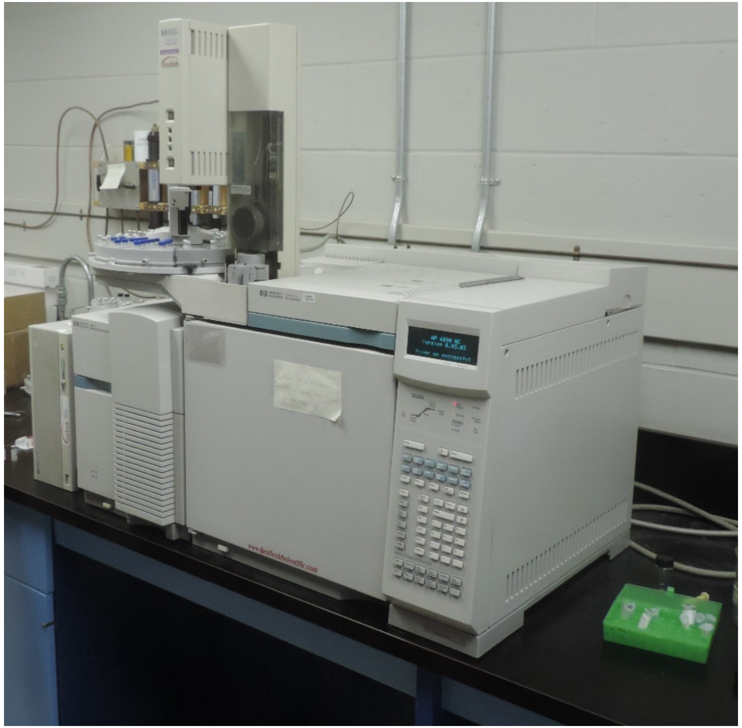
| **Design Parameters** | **Normalized E-Field Intensity** |
|---|---|
| **W1, 500 nm, rs/r = 0.7** | 1 |
| **W1.1**, 500 nm, rs/r = 0.7 | 1.0227 |
| **W1.2**, 500 nm, rs/r = 0.7 | 0.9855 |
| W1, **630 nm**, rs/r = 0.7 | 0.8523 |
| W1, 500 nm, **rs/r = 0.1** | 0.3950 |
| W1, 500 nm, **rs/r = 0.9** | 0.6753 |



[2] Zou, Y., Chakravarty, S., Wray, P., & Chen, R. T. (2015). Mid-infrared holey and slotted photonic crystal waveguides in silicon-on-sapphire for chemical warfare simulant detection. *Sensors and Actuators B: Chemical, 221*, 1094-1103.

# Background

- Normal spectrometers are very large
- We want spectrometers on very small chips
  - Slow light effect
- Technology moving from near-IR to mid-IR



# Beer-Lambert

## Beer-Lambert Law:

$$I / I_0 = \exp[-\alpha L \gamma]$$

$\alpha$ = absorption coefficient

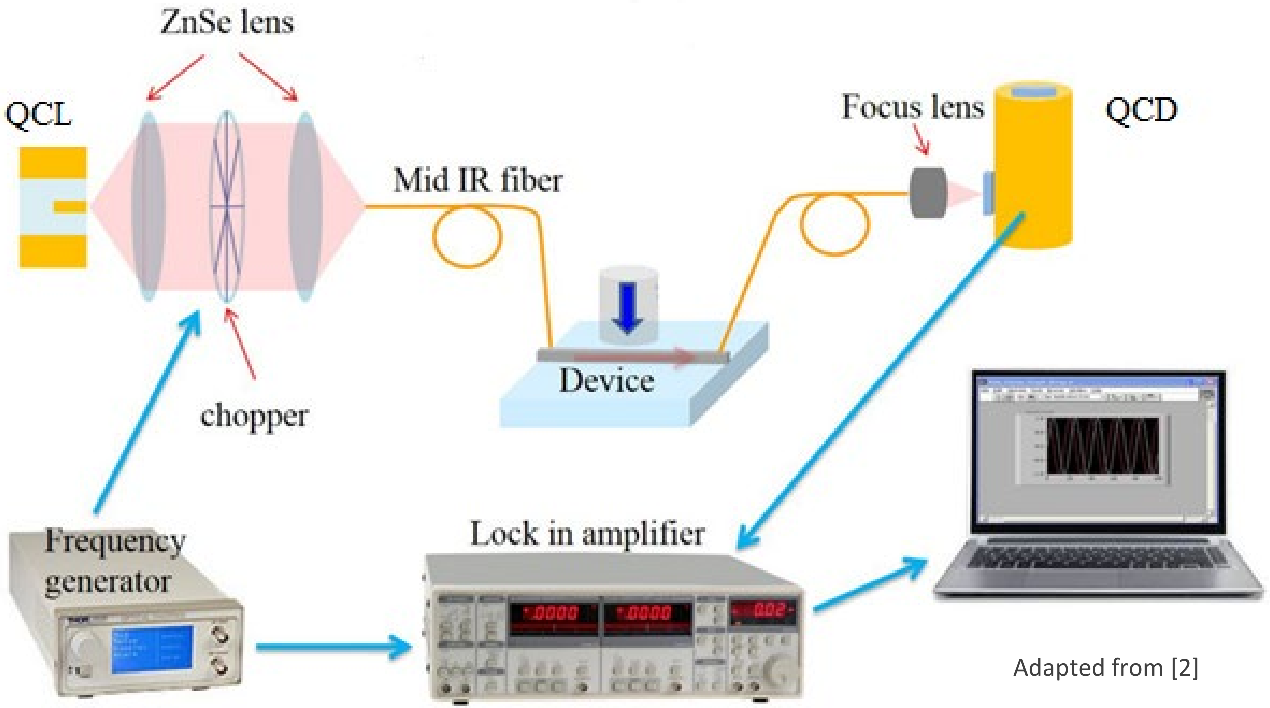
L = interaction length

$\gamma$ = absorption factor $\propto f\, v_g^{-1}$

f = filling factor

Holey photonic waveguides increase f and decrease $v_g$

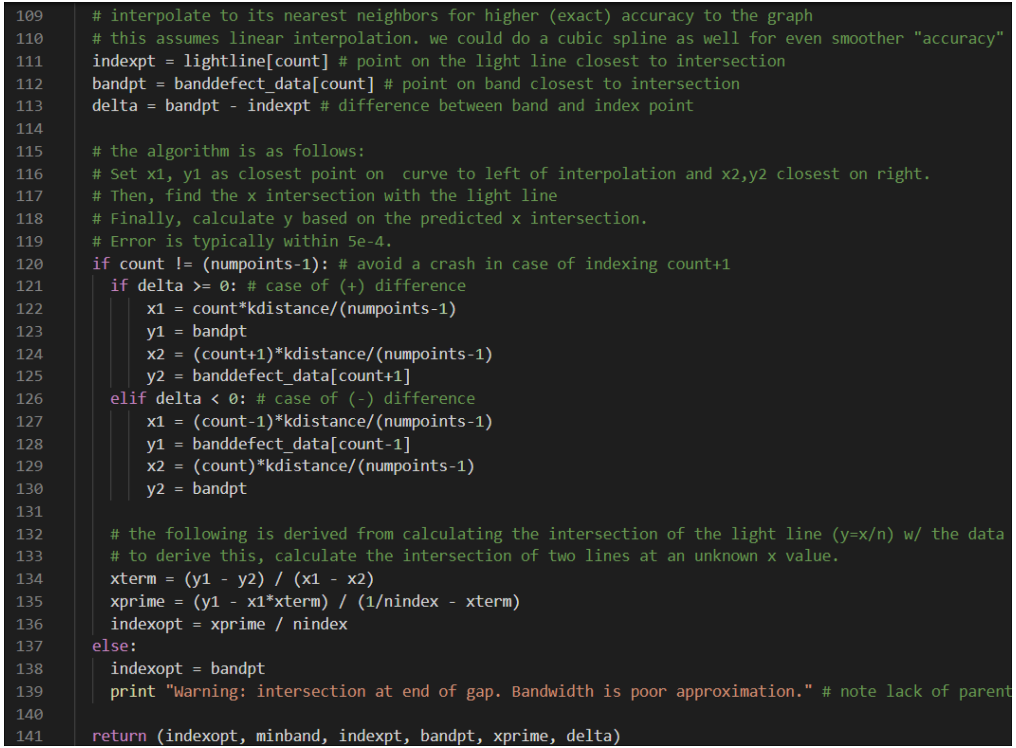
# Testing Setup



Adapted from [2]

# Python Script

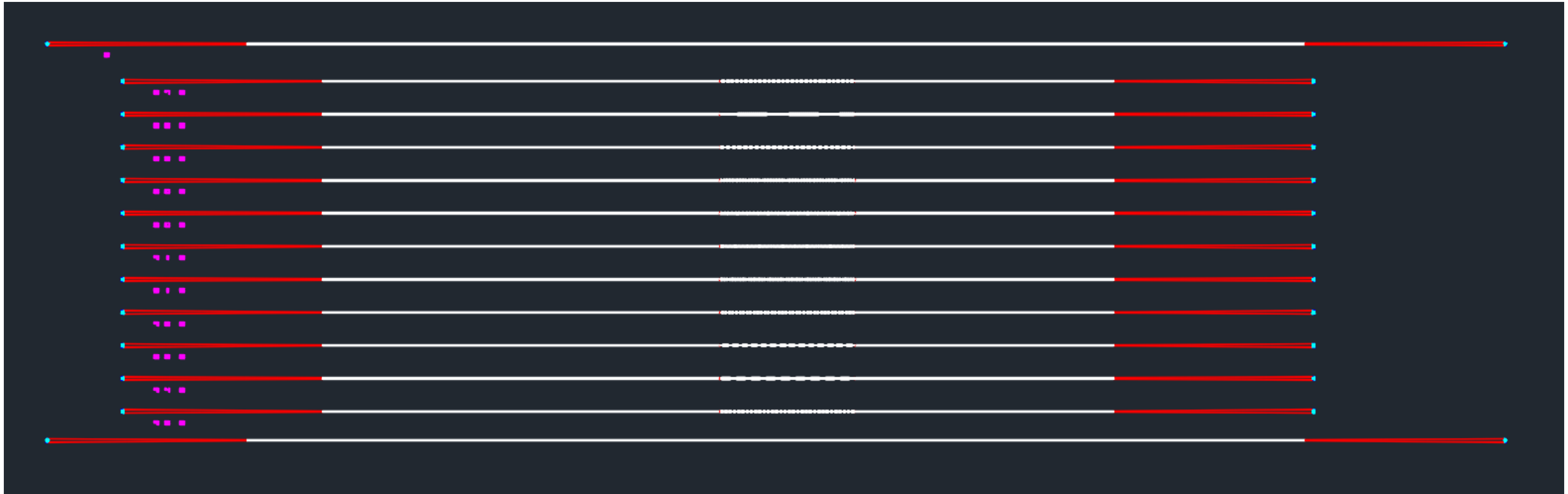
- Post-process data
- Integrates with simulation software
- Calculates bandwidth and stopgap and sweep parameters



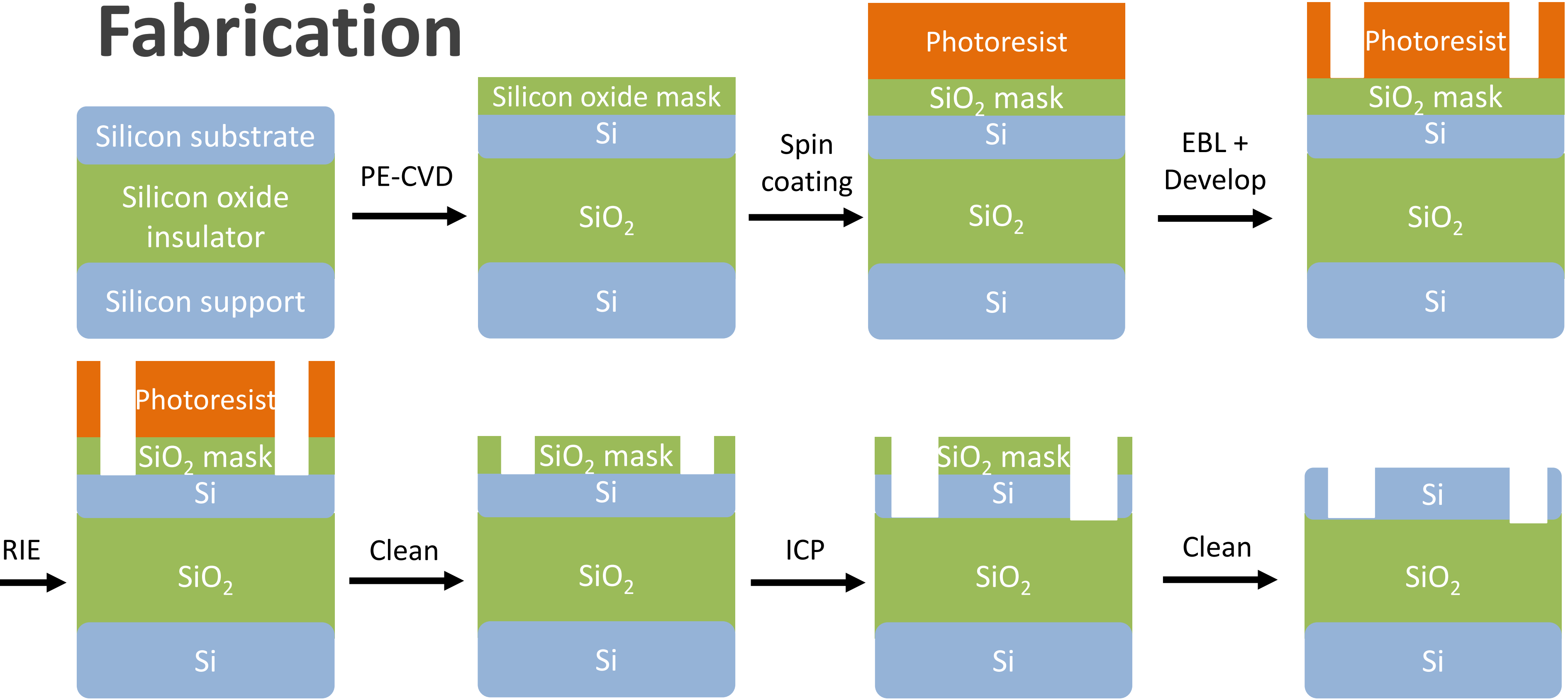
```python
# interpolate to its nearest neighbors for higher (exact) accuracy to the graph
# this assumes linear interpolation. we could do a cubic spline as well for even smoother "accuracy"
indexpt = lightline[count] # point on the light line closest to intersection
bandpt = banddefect_data[count] # point on band closest to intersection
delta = bandpt - indexpt # difference between band and index point

# the algorithm is as follows:
# Set x1, y1 as closest point on  curve to left of interpolation and x2,y2 closest on right.
# Then, find the x intersection with the light line
# Finally, calculate y based on the predicted x intersection.
# Error is typically within 5e-4.
if count != (numpoints-1): # avoid a crash in case of indexing count+1
  if delta >= 0: # case of (+) difference
      x1 = count*kdistance/(numpoints-1)
      y1 = bandpt
      x2 = (count+1)*kdistance/(numpoints-1)
      y2 = banddefect_data[count+1]
  elif delta < 0: # case of (-) difference
      x1 = (count-1)*kdistance/(numpoints-1)
      y1 = banddefect_data[count-1]
      x2 = (count)*kdistance/(numpoints-1)
      y2 = bandpt

  # the following is derived from calculating the intersection of the light line (y=x/n) w/ the data
  # to derive this, calculate the intersection of two lines at an unknown x value.
  xterm = (y1 - y2) / (x1 - x2)
  xprime = (y1 - x1*xterm) / (1/nindex - xterm)
  indexopt = xprime / nindex
else:
  indexopt = bandpt
  print "Warning: intersection at end of gap. Bandwidth is poor approximation." # note lack of parent

return (indexopt, minband, indexpt, bandpt, xprime, delta)
```

# CAD Design

- Design waveguides over range of lattice constants
- Used in E-beam lithography



# Fabrication



Silicon substrate
Silicon oxide insulator
Silicon support

PE-CVD

Silicon oxide mask
Si
$SiO_2$
Si

Spin coating

Photoresist
$SiO_2$ mask
Si
$SiO_2$
Si

EBL + Develop

Photoresist
$SiO_2$ mask
Si
$SiO_2$
Si

RIE

Photoresist
$SiO_2$ mask
Si
$SiO_2$
Si

Clean

$SiO_2$ mask
Si
$SiO_2$
Si

ICP

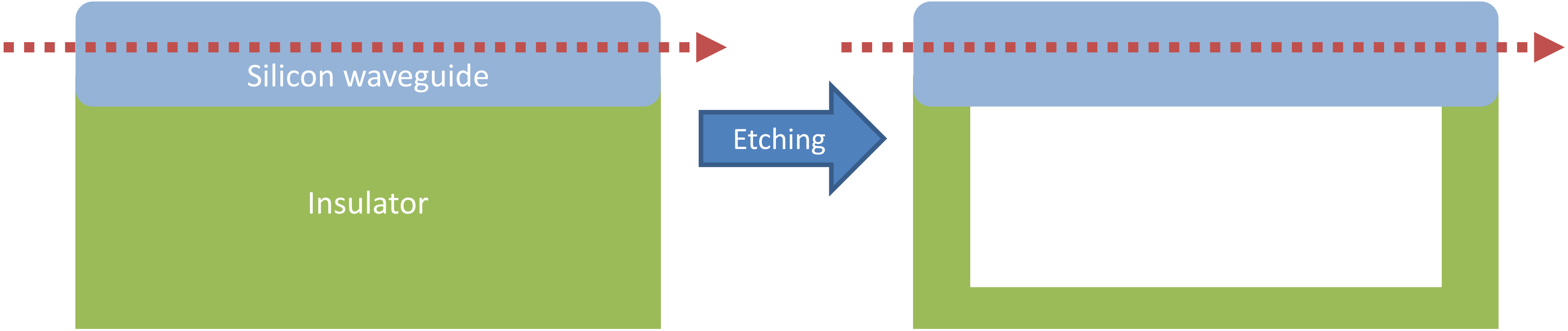
$SiO_2$ mask
Si
$SiO_2$
Si

Clean

Si
$SiO_2$
Si

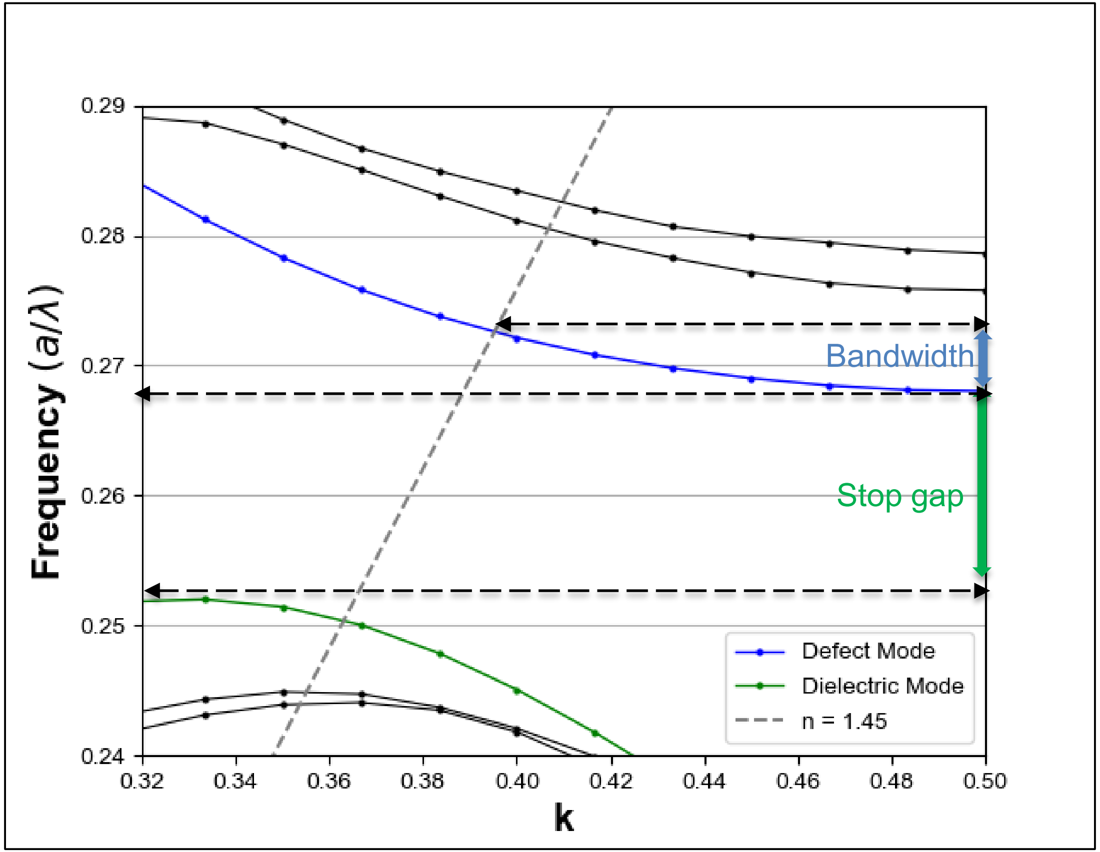
# Future work

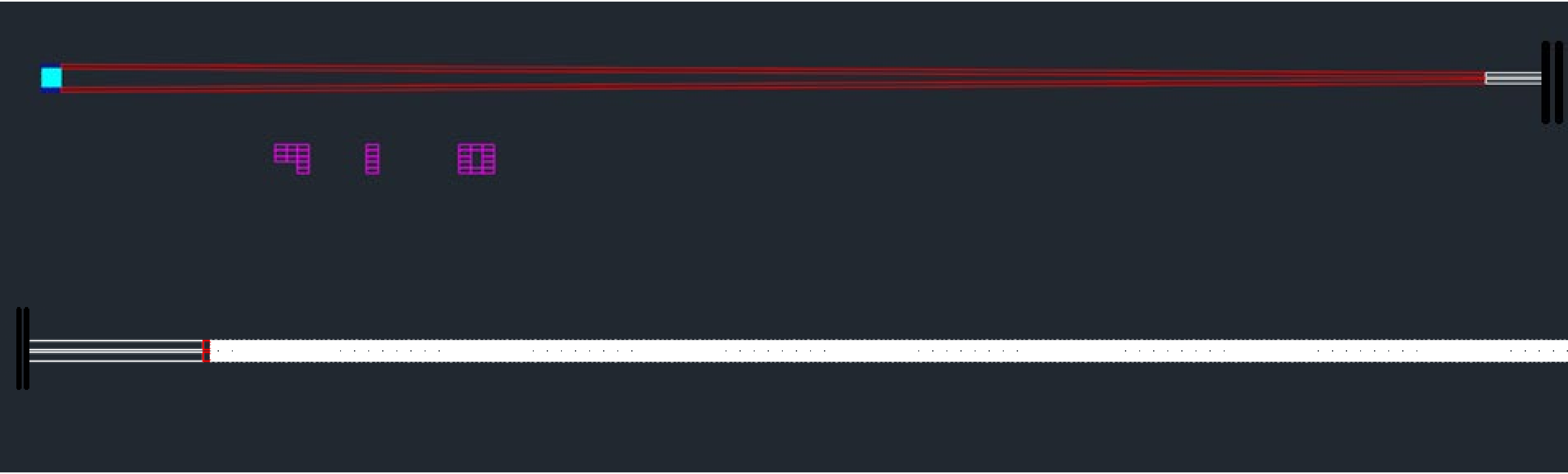
- Suspended membrane waveguides
  - – Minimize absorption losses with silicon oxide

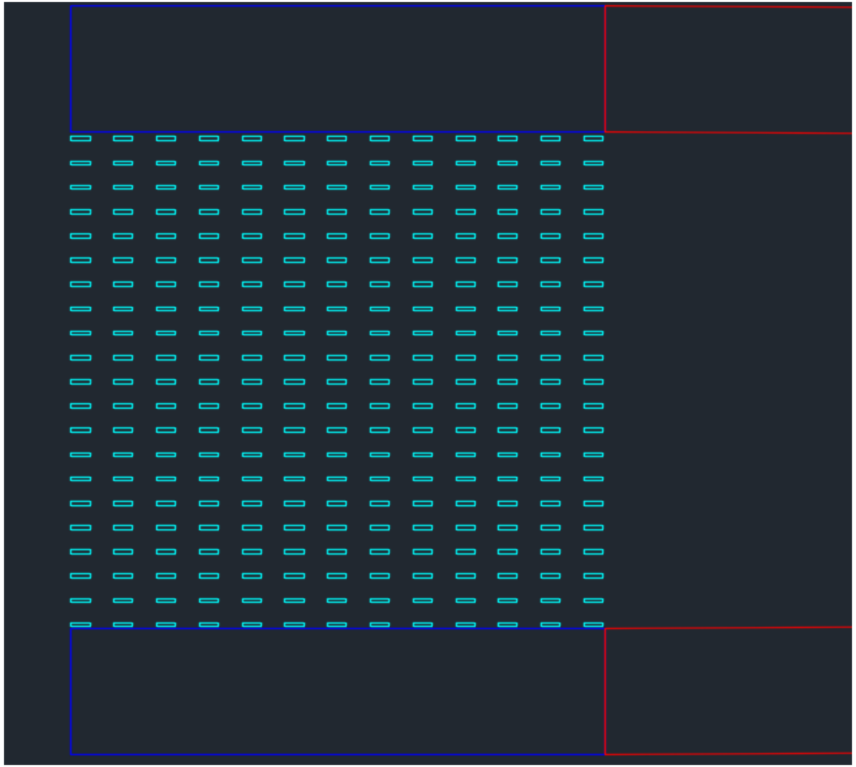


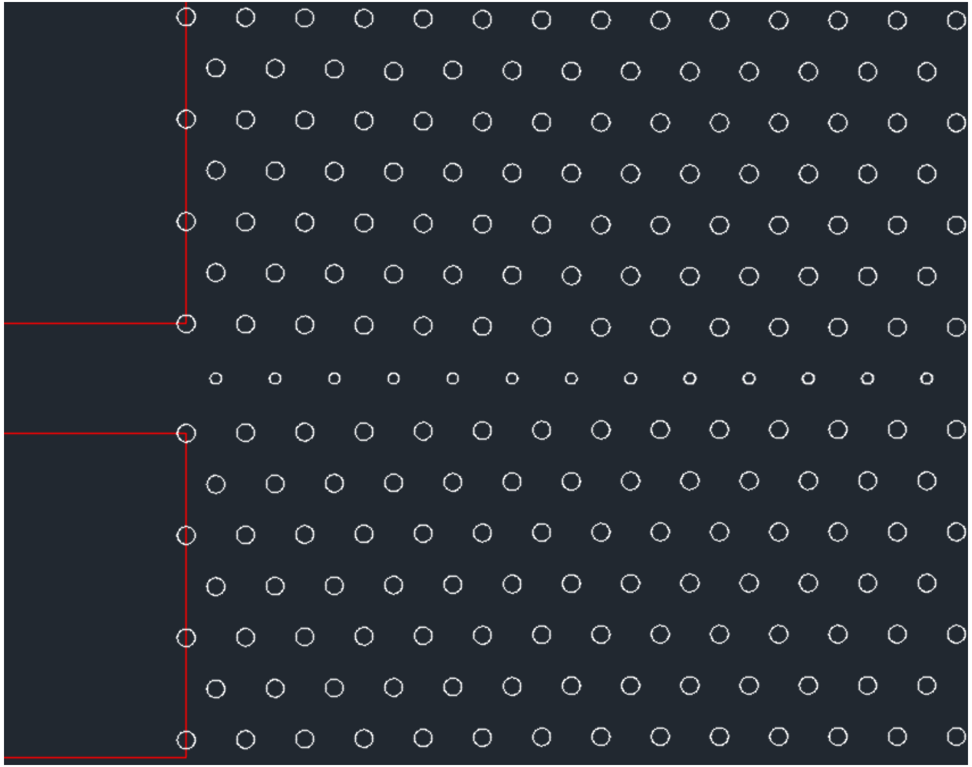
# Lattice Constant

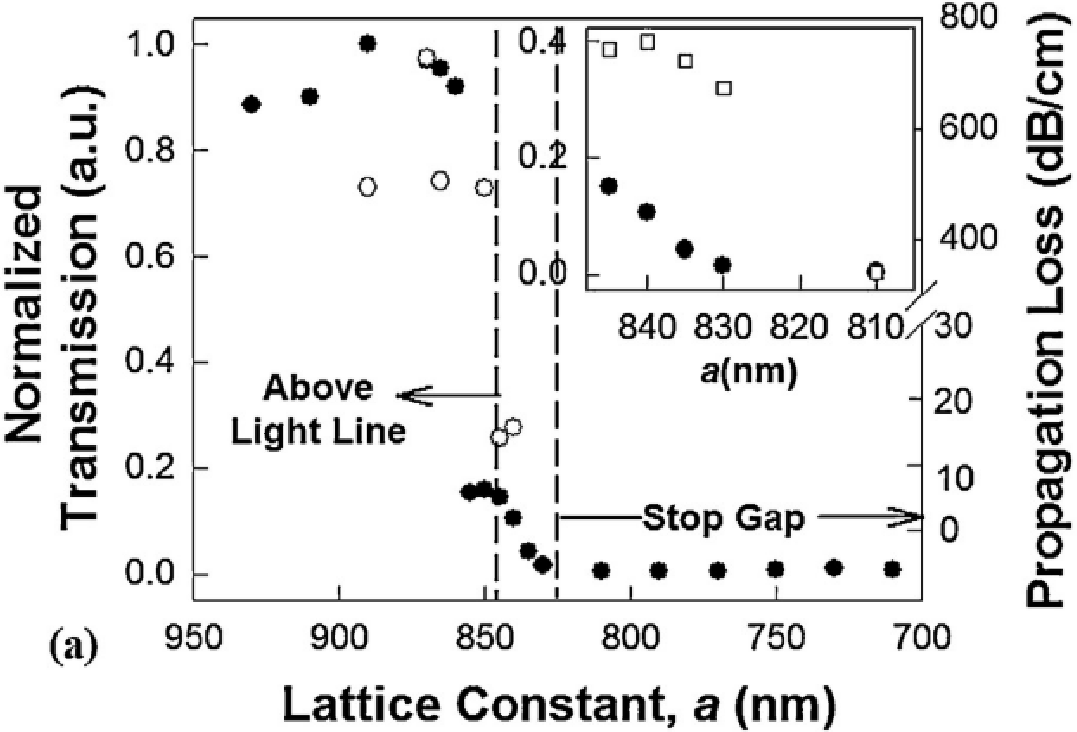
- Band edge: 0.268
- Laser wavelength: 3.4 nm
- 0.268 * 3.4 nm = **0.91 nm**



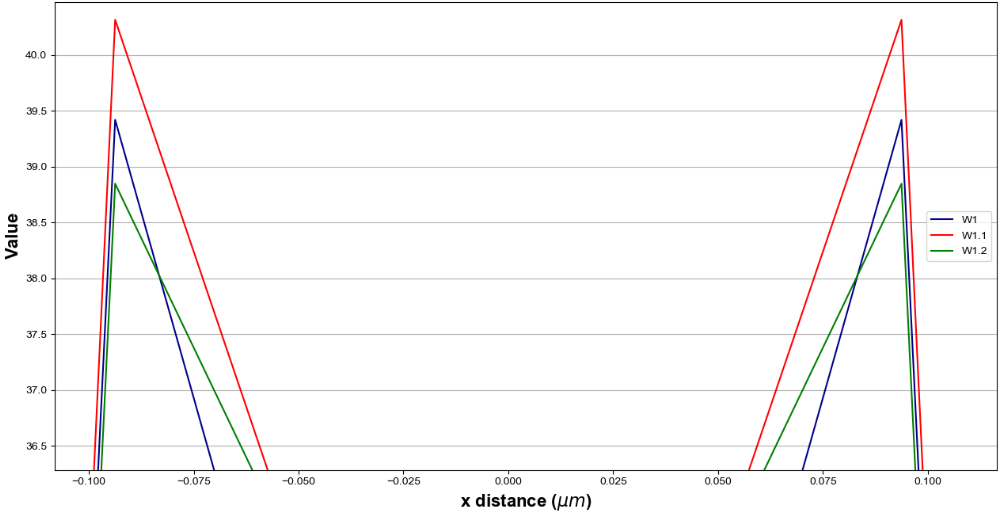




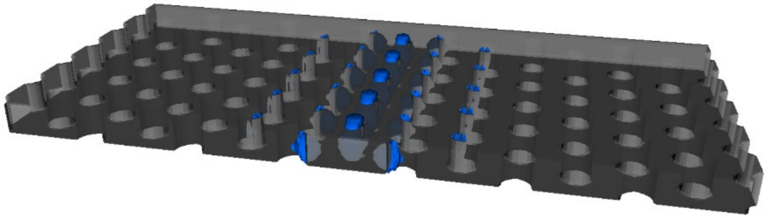



Normalized Transmission (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
Above Light Line
Stop Gap
0.4
0.2
0.0
840
830
820
810
a(nm)
800
600
400
30
20
10
0
Propagation Loss (dB/cm)
(a)
950
900
850
800
750
700
Lattice Constant, a (nm)

# Electric Field Intensity Profile

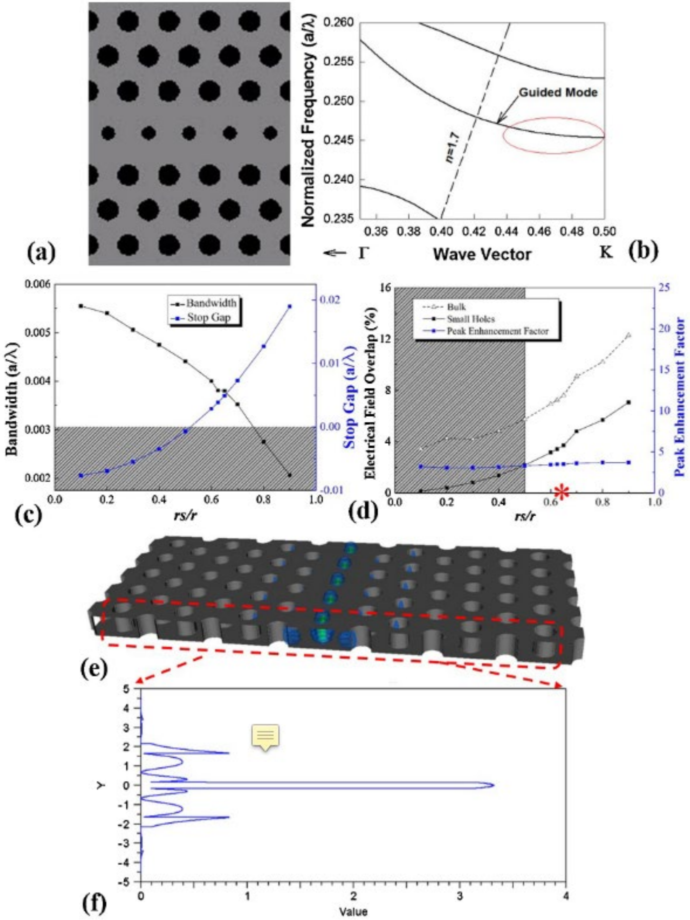


- Mode profile not strongly affected by guide width



# Methodology

- Slow wave effect
- Simulations
  - Rsoft CAD & Planewave Expansion
  - “A 2D simulation package from CAMFR is first utilized to get the optimized period and filling factor along waveguide propagation direction, as well as the effective subwavelength refractive index (nsub).” 2014
  - Mode profile
- Synthesis
  - CVD to deposit oxide on silicon
  - Electron beam lithography (EBL) to pattern components (e-beam resist)
  - Reactive ion etching to transfer e-beam pattern to silicon dioxide
  - Inductively coupled plasma (ICP) etching to transfer pattern to silicon
  - Chip cleaning with piranha / HF
- FWHM = 0.075 um


(a)
Normalized Frequency (a/λ)
0.260
0.255
0.250
0.245
0.240
0.235
Guided Mode
n=1.7
0.36 0.38 0.40 0.42 0.44 0.46 0.48 0.50
← Γ
Wave Vector
K
(b)
Bandwidth
Stop Gap
Bandwidth (a/λ)
Stop Gap (a/λ)
rs/r
(c)
Bulk
Small Holes
Peak Enhancement Factor
Electrical Field Overlap (%)
Peak Enhancement Factor
rs/r
(d)
(e)
Y
Value
(f)

[2]