Viewing the World Through Nanometer Eyes
or The Use of NSOM for Nanostructure Investigations

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Near Field Scanning Optical Microscopy (NSOM) has the ability to:

- Provide subwavelength spatial resolution (order of 100 nm)
- Investigate optical field strength within devices via evanescent coupling
- Analyze spectroscopic content of emitted or evanescent fields
Micro- and Nanometer Structures

Collection Mode NSOM

- Vertical Cavity Surface Emitting Lasers (VCSELs)
- Photonic Band Gap Materials
- Hybrid Structures
10µm Selectively Oxidized Vertical Cavity Surface Emitting Lasers

• Aditi Sharma, Howard Jackson, & Joseph Boyd

• An actively emitting element is probed with NSOM tip and Spectrometer in the Near Field
VCSEL Structure

- Square mesas etched past active layers via RIE
- Lateral oxidation of high Al content layer forms the aperture
- 10 µm square aperture leads to transverse multimode structure
Near Field Scanning Optical Spectroscopy

- Subwavelength tip aperture (80~100 nm) for spatially resolved information
- Near field collection (<20 nm from surface) for a spatial picture of modes at surface
- Spectral resolution for transverse mode differentiation

He-Ne Beam

Dither Piezo

Optical fiber to spectrometer
10 µm VCSEL

Threshold

Threshold found at \(~3.5\) mA via 3 different measurement techniques:

- Total output power of VCSEL vs. Current
- Peak Width of Modes vs. Current
- Peak Height to Fluorescence Ratio vs. Current

Output Power vs. Current for 10 µm VCSELs
Typical Spectra

Near-field spectra at x=10, y=10
T = 4s, ND = 0
02/02/01

Counts
Wavelength (nm)

1.5 mA Pumping Current

Near-field spectra at x=10, y=10
T = 4s, ND = 0
02/02/01

Counts
Wavelength (nm)

2.0 mA Pumping Current

Near-field spectra at x=10, y=10
T = 4s, ND = 2.5
02/02/01

Counts
Wavelength (nm)

3.3 mA Pumping Current

Near-field spectra at x=10, y=10
T = 4s, ND = 2.5
02/02/01

Counts
Wavelength (nm)

5 mA Pumping Current
Typical Spectra

- 3.3mA (~ threshold)
- 5mA
- 7.5mA
Typical Spectra

- 3.3 mA (~threshold)
- 5 mA
- 7.5 mA
Transverse Mode Spacing

- A nearly planar confocal resonator with \( d \ll R_1, R_2 \)

\[
\Delta \nu = \frac{c}{2\pi n z_0} = \frac{c \lambda_0}{2\pi^2 n^2 w_0^2}
\]

For 5 mA pumping current,

\[
\Delta \nu_5 = 2.23 \times 10^{11} \text{ Hz} = 0.537 \text{ nm}
\]

- Experimentally determined spacing for all currents:

\[
\Delta \nu = 0.2 \text{ nm} \pm 0.08 \text{ nm}
\]

- Yariv, Optical Electronics, 4th Ed.
• Modes show a red shift with increasing current
• The shift in peak position is linear with a slope of about 0.145 nm/mA
• Calculation indicates an increase in refractive index with temperature to be more likely cause
Temperature Related Effects

• Shift in Cavity Resonance

\[ d\lambda = L \, dn + n \, dL \]

– Due to Length Changes

\[ \Delta T = \frac{\Delta \lambda}{\partial L / \partial T} \, n \]

\[ \Delta T = 184 \, K \]

– Due to Index Changes

\[ \Delta T = \frac{\Delta \lambda}{\partial n / \partial T} \, L \]

\[ \Delta T = 9 \, K \]
Temperature Related Effects

• Shift in Cavity Gain Curve
  – Due to Band Gap Changes in GaAs

\[ E_g = 1.519 - \frac{5.405 \times 10^{-4} T^2}{T + 204} \]

– Varshni Semi-Emperical Formula

\[ \frac{dE_g}{dT} = -2 \frac{5.405 \times 10^{-4} T}{T + 204} + \frac{5.405 \times 10^{-4} T}{(T + 204)^2} \]

\[ \Delta T = 3.2 \text{ K for 0.892 nm shift} \]
\[ \Delta T = 10 \text{ K leads to 2.47 nm (4meV) shift} \]
Threshold (3.3 mA)

Near Field Total Integrated Intensity

Near Field 2D Scan at 3.3 mA
Total Integrated Intensity

log scale

Y (microns) Left to Right

X (microns) Front to Back

2400
2067
1780
1533
1321
1138
979.8
843.9
726.8
626.0
539.2
464.4
400.0
Near Field 2D Scans

Transverse mode structure (around threshold -- 3.3 mA)
Near Field 2D Scan at 3.3 mA, 0.25 μm step size

\[ \lambda = 849.58 \text{ nm} \]
Near Field 2D Scan at 3.3 mA, 0.25\( \mu \)m step size
\( \lambda = 849.46 \) nm
Near Field 2D Scan at 3.3 mA, 0.25\(\mu\) step size
\(\lambda = 848.29\) nm Line
10 micron VCSEL
5 mA  Near Field Scans

10 micron VCSEL#1  Near Field Plot
5 mA  850.0 nm Line  0.25 micron step

Y microns (left to right)
X microns (front to back)
Near Field 2D Scan, $\lambda = 849.72$ nm ([824] to [842])
5mA 10 micron VCSEL #1 0.25 micron step
4/24/01

Y microns (left to right)

Near Field 2D Scan 10 micron VCSEL#1 4/24/01 Data
5 mA 849.6 nm Line 0.25 micron step

X microns (front to back)
Near Field 2D Scan, $\lambda = 849.40$ nm ([866] to [888])
5mA 10 micron VCSEL #1 0.25 micron step
4/24/01

Near Field 2D Scan, $\lambda = 849.23$ nm ([891] to [908])
5mA 10 micron VCSEL #1 0.25 micron step
4/24/01
Near Field 2D Scan  10 micron VCSEL#1    4/24/01 Data
5 mA       848.73 nm Line       0.25 micron step
Y (microns)  Left to Right
X (microns)  Front to Back

Near Field 2D Scan  10 micron VCSEL#1    4/24/01 Data
5 mA       848.41 nm Line       0.25 micron step
Y (microns)  Left to Right
X (microns)  Front to Back

Near Field 2D Scan  10 micron VCSEL#1    4/24/01 Data
5 mA       848.11 nm Line       0.25 micron step
Y (microns)  Left to Right
X (microns)  Front to Back
10 micron VCSEL
7.5 mA Near Field Scans

Near Field 2D Scan  , $\lambda = 850.33$nm ([738] to [763])
7.5mA 10 micron VCSEL #1 0.25 micron step
4/25/01
Conclusions

• NSOM is a uniquely tool which allows probing with sub-wavelength spatial resolution.

• Near field experiments can
  – Provide spectral information eg VCSELs transverse mode structure

• NSOM makes A New World View Using Nanometer Eyes possible!
2D Triangular Photonic Lattice

• Amelia Carpenter & Cole Loomis
  Miami University, OH

• Aditi Sharma, Howard Jackson, Joe Boyd
  University of Cincinnati, OH

• Martin Charlton & G.J. Parker
  University of Southampton, UK
Photonic Band Gap Structures

Cole Loomis, Amelia Carpenter, Aditi Sharma, Howard Jackson, Dave Nagaski, Joseph Boyd, Martin Charlton, G.J. Parker

• Take a planar waveguide structure
• Etch air pores through waveguide core on order of wavelength

• Certain modes do NOT propagate
  – a photonic band gap is created
Experimental Setup

- Laser Diode $\lambda = 830$ nm
- HeNe Beam
- Channel Waveguide Sample (exaggerated)
- Split Piezo Tube
- Coupling Objective
- Fiber Tip
- Long Travel Vertical Positioner (submicron resolution)
Cross section of 2D sample with visible PBG

* 1.8 µm silicon dioxide substrate buffer layer (n=1.46), thermally grown
* 250 nm thick silicon nitride (n=2.02) waveguiding layer, vapor deposition
* 75 nm silicon dioxide cladding layer vapor deposition
The particular lattice structure in our sample consists of:

- Triangular lattice with 260 nm pitch
- Air pores 146 nm in diameter (fill factor is 0.286)
- 20 rows placed via electron beam lithography and plasma etching

**Note:** Pitch and Diameter of pores are less than visible wavelength
Schematic of 2D Lattice Embedded in Planar Waveguide
Calculated Photonic Band Gap

H (TE) Polarization
\( \varepsilon_a = 1.0 \)
\( \varepsilon_b = 4.0804 \)
f = 0.28597
199 G vectors
50 k/direction

Band Gap

0.428
0.391

\( \frac{a}{\lambda} \)
0.5
0.5
0.6
0.6
0.8
0.8
1
1

\( X \)
\( \Gamma \)
\( J \)
\( X \)
2D Scan of Beam Back-Reflected from PBG Lattice
2D Scan of PBG Lattice

Log Scale

HeNe Input

X Position (microns)
Back to Front

Y Position (microns)
Right to Left

#W9-20
Modeling of Photonic Waveguide Structure

• Triangular Lattice -- 1.7 µm guide
• 1.55 µm input to GaN structure
• 94% transmission
PBG Cavities

Contour Map of $H_y$

$Z (\mu m)$

$X (\mu m)$

$cT = 80$

Monitor Value

$cT (\mu m)$
New Hybrid Structures

• Combine VCSEL fabrication with 2-D photonic lattices
• Produce a planar active structure

Light Output

Cross-Section

Top View
Conclusions

• NSOM is a unique tool which allows probing with sub-wavelength spatial resolution.
  – Map EM fields via evanescent coupling eg waveguides
  – Image interference phenomena eg PBG lattices

• NSOM makes A New World View Using Nanometer Eyes possible!