Diffusion of Photons in Scattering Media

- Light entering scattering medium breaks into different types
  - 1 Photons may be absorbed
  - 2 Photons may be highly scattered (many paths) until nearly uniform
    - Scattered photons lose almost all information of internal structure
  - 3 Photons may travel without scattering: called Ballistic photon
    - If photon scattered: but nearly ballistic path called quasi-ballistic
  - 4 Photons may be reflected back from the medium
Optical Tomography (OT)

- OT technique for highly scattering media
- Assume the Beer-Lambert Law
  - Light scattering grows exponentially
    - Tissue is forward scattering ($g \sim 0.9$)
    \[ I_{out} = I_{in} \exp[-(\mu_a + \mu_s)d] \quad \mu_{seff} = \mu_s(1 - g) \]
- Scattering Ratio (SR) for the test samples
  - Scattered to ballistic/quasi-ballistic photon ratio
    - Reduced scattering ratio is measured
  \[ SR = \frac{I_0}{I_{bq}} - 1 \]
- This work presents diode sources for optical imaging
  - Experimented with 670 nm (red) diode
    - Will implement 808 nm and 975 nm diode lasers
- Applied to scattering fluids and animal tissue
Existing OT Methods

• Three OT methods:
  - Time of flight (Time Domain)
  - Phase Coherence Domain
  - Angular Domain Imaging

• Time Domain
  - Based on path length
  - Shortest path photons arrive first

• Launch very short pulse
  - Few Femtosec
  - Ballistic arrive first
  - Quasi ballistic next
  - Scattered last

• Use high speed shutter to select
Existing OT Methods

- This work uses Angular Domain Imaging (ADI)
  - Laser source aligned to small acceptance angle angular filters
  - Ballistic/quasi-ballistic light deviates only small angles
    - Most scattered light outside acceptance angle
ADI and Angular Filters

- Use high aspect ratio micromachined tunnels
  - 51 µm diameter x 1 cm length
  - Tunnels spaced on 102 µm centers
  - Aspect ratio ~200:1
  - Acceptance angle ~0.29º
- Use test phantoms in 5 cm scattering fluid
  - Use lines/spaces (204, 153, 102, 51 µm)
- Experimentally calibrate scattering solution
  - Water with partially skimmed milk
    - SR increases with milk concentration
- Angular filter images one line
  - Sample is vertically stepped (52 µm)
  - Lines assembled into 2-D image
670 nm Laser Diode system

• New work with 670 nm diode laser
  ▪ Low cost, low power, highly portable
  ▪ Many diode wavelengths available

• Problem: asymmetric beam divergence
  ▪ Typical: 23° (V) and 8° (H)
  ▪ High-power aspheric lens (f = 4.5 mm)
    o Collimates vertical, overcorrects horizontal

• Corrected by cylindrical lens system
  o Beam expander collimates horizontally
ADI setup with 670nm Laser Diode

- Diode laser with aspheric and cylindrical lens system
- Produces 5 cm wide beam x 3.5 mm high line
- Test phantoms and scattering sample as before
  - Vertical stage raises scattering sample
- Angular filter aligned to laser and CMOS camera
Argon vs. 670 nm @ SR = 10^6:1

- Comparable performance for SR = 10^6:1 (\(\mu_{\text{seff}} = 2.76 \text{ cm}^{-1}\))
  - Contrast decreased for both
  - Results at 670 nm are on par or better
    - Improvement due to narrower line of illumination (3.5 mm vs. 25 mm)
    - Lines and gaps of 204 µm and 153 µm individually resolvable
    - Detectable 102 µm and 51 µm test phantoms
• Successful results at SR = $10^7$:1 ($\mu_{\text{seff}} = 3.22 \text{ cm}^{-1}$) @ 670 nm
  - More background scattered light than $10^6$:1
  - Digital image processing can improve contrast
  - Further improvement requires new optics for narrower 670 nm line
Introduce angular deviation of the light source

- ADI is filtering by acceptance angle
- Deviate light source by wedge prism
- Everything maintain in two measurements
  - Angular deviation of wedge prism:
    ~ 2-3x acceptance angle (e.g. 0.5°)
- Deviated system sees only scattered photons
- Get pixel by pixel measure by scatter light
  - More accurate background estimation

![Diagram of light source and measurement setup]

- Original scan
- 200 μm
- Scan with deviated light source
• Maximum SR = 4.5x10^8:1 for current setup
  • Original image not detectable
  • DSP is not enhancing enough
• Wedge subtraction with higher contrast