

## OPTI 415 Overview

OPTI 415 is an engineering course that is designed to unite concepts from several geometrical and physical optics courses. The goal of the class is to provide understanding of the requirements for specifying optical elements, fabricating the parts and evaluating the performance of the delivered part.

### Instructor

Jim Schwiegerling

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### Course Web Site

<https://wp.optics.arizona.edu/visualopticslab/courses/opti-415r-optical-specifications-fabrication-and-testing/>

### Tests (Take Home/Open Notes)

Midterm                      TBD, end of March/Early April

No Final Exam

### Grading

Homeworks                33% (approximately 8 homeworks)

Midterm                    33%

Final Project             34% (Due last day of class)

Homework grades will be decreased by 10% for each day they are late.

### Teaching Assistants

Josh McDonald

[jpmcd@email.arizona.edu](mailto:jpmcd@email.arizona.edu)

Office Hours: No specific office hours. Coordinate with the TA and the instructor through email to arrange meeting times to answer questions regarding the course material.

### Required Texts

Schwiegerling J. *Optical Specification, Fabrication and Testing*. (SPIE, Bellingham, WA, 2014).

This text was written specifically for this class and contains a much more descriptive and neater overview of the course material than the lecture notes.

### Additional Suggested References

Fischer RE, Tadic-Galeb B, Yoder PR. *Optical System Design, 2<sup>nd</sup> ed.* (Mcgraw-Hill, New York, 2008).

Malacara D. *Optical Shop Testing, 3<sup>rd</sup> ed.* (Wiley, New Jersey, 2007).

Smith W. *Modern Optical Engineering, 4<sup>th</sup> ed.* (Mcgraw-Hill, New York, 2008).

## Draft Outline

1. Properties of Optical Systems
  - 1.1. Optical Properties of a Single Spherical Surface (Brief Review)
    - 1.1.1. Refractive Surface: Radius, Curvature, Focal Length and Power
    - 1.1.2. Reflective Surface: Focal Length and Power
    - 1.1.3. Gaussian Imaging Equation
    - 1.1.4. Newton's Equation
  - 1.2. Aperture and Field Stops (Brief Review)
    - 1.2.1. Aperture Stop Definition
    - 1.2.2. Marginal Ray
    - 1.2.3. Chief Ray
    - 1.2.4. Vignetting
    - 1.2.5. Field Stop Definition
      - 1.2.5.1. Image Sensor as Field Stop
        - 1.2.5.1.1. Standard CCD/CMOS sensor dimensions
  - 1.3. First Order Properties of an Optical System (Brief Review)
    - 1.3.1. Gaussian Reduction (Conceptually)
    - 1.3.2. ynu raytrace
    - 1.3.3. Cardinal Points
    - 1.3.4. Entrance and Exit Pupils
    - 1.3.5. Extension of Gaussian Imaging to Thick Systems
    - 1.3.6. Transverse and Longitudinal Magnification
    - 1.3.7. Lagrange invariant, Etendue, Throughput,  $A\Omega$  Product
    - 1.3.8. F-Number, Working F-Number and Numerical Aperture
    - 1.3.9. Depth of Field
    - 1.3.10. Field of View
    - 1.3.11. Front and Back Focal Distances
      - 1.3.11.1. Standard Flange distances for cameras
  - 1.4. Measurement of First Order Properties of Optical Systems
    - 1.4.1. Measurements based on Gaussian Imaging Equation
    - 1.4.2. Autocollimation Technique
    - 1.4.3. Neutralization Test
    - 1.4.4. Focimeter
    - 1.4.5. Focal Collimator
    - 1.4.6. Reciprocal Magnification
    - 1.4.7. Nodal-Slide Lens Bench
  - 1.5. Diffraction and Aberrations
    - 1.5.1. Black Box Optical System based on Cardinal Points and Pupils.
    - 1.5.2. Wavefront Picture of Optical Imaging
    - 1.5.3. Diffraction-Limited Systems and Connection to Fresnel Diffraction
    - 1.5.4. Point Spread Function (PSF) calculation and dimensions
    - 1.5.5. Sign and Coordinate System Conventions
    - 1.5.6. Optical Path Length (OPL), Optical Path Difference (OPD), Wavefront Error
    - 1.5.7. Transverse Ray Error and Spot Diagrams
    - 1.5.8. Aberrations of Rotationally Symmetric Optical Systems
      - 1.5.8.1. Piston and Tilt

- 1.5.8.2. Seidel Aberrations
- 1.5.9. Aberrations of General Optical Systems
  - 1.5.9.1. Examples of non-rotationally symmetric systems
  - 1.5.9.2. Generalization of Seidel Aberrations to on-axis case
  - 1.5.9.3. Zernike polynomials
    - 1.5.9.3.1. Different variations found in literature
    - 1.5.9.3.2. Normalization, Radial Polynomials, Azimuthal components
    - 1.5.9.3.3. Examples of different orders of Zernike polynomials
    - 1.5.9.3.4. Representation of complex wavefront as linear combination
    - 1.5.9.3.5. Coordinate system conversions
    - 1.5.9.3.6. Pupil Size Conversion
    - 1.5.9.3.7. Fitting wavefront error to Zernike polynomials
- 1.5.10. Through-Focus PSF and Star Test
  - 1.5.10.1. Diffraction Limited Case (Defocus)
  - 1.5.10.2. Seidel Spherical Aberration
  - 1.5.10.3. Zernike Spherical Aberration
  - 1.5.10.4. Astigmatism
  - 1.5.10.5. Coma
- 1.5.11. Measurement of Distortion
  - 1.5.11.1. Conventional case
  - 1.5.11.2. Special Cases anamorphic,  $f\theta$  lens. Scheimpflug
- 1.6. Optical Quality Metrics
  - 1.6.1. Resolution Targets
    - 1.6.1.1. Rayleigh Criterion
  - 1.6.2. Strehl Ratio
  - 1.6.3. Peak-to-Valley and rms Wavefront Error
    - 1.6.3.1. Relationship to Zernike Coefficients
    - 1.6.3.2. Relationship to Strehl Ratio
  - 1.6.4. Encircled and Ensquared Energy
  - 1.6.5. Optical Transfer Function (OTF)
    - 1.6.5.1. Modulation Transfer Function (MTF)
    - 1.6.5.2. Phase Transfer Function (PTF)
    - 1.6.5.3. Fourier Transform relationship to PSF
    - 1.6.5.4. Autocorrelation of Pupil Function
    - 1.6.5.5. Line Spread Function
    - 1.6.5.6. Siemens Star
- 1.7. Aspheric Surfaces
  - 1.7.1. Conics
  - 1.7.2. Quadrics
  - 1.7.3. Higher Order Aspheres
  - 1.7.4. Torics
  - 1.7.5. Cylinders
- 2. Fabrication of Optical Surfaces
  - 2.1. Optical Materials
    - 2.1.1. Glass and Plastics
    - 2.1.2. Cauchy and Sellmeier Equations

- 2.1.3. Infrared and Ultraviolet Materials
- 2.2. Grinding and Polishing Flats, Windows and Prisms
- 2.3. Grinding and Polishing Spherical Surfaces
- 2.4. Grinding and Polishing Aspheric Surfaces
- 2.5. Diamond Turning and Fast Tool Servo
- 2.6. Magnetorheological Finishing
- 3. Non-interferometric Testing
  - 3.1. Autocollimator Tests
  - 3.2. Surface Radius of Curvature
    - 3.2.1. Geneva Gauge
    - 3.2.2. Spherometer
    - 3.2.3. Autostigmatic measurements
  - 3.3. Wavefronts
    - 3.3.1. Foucault Knife Edge Test
    - 3.3.2. Wire Test
    - 3.3.3. Ronchi Test
    - 3.3.4. Hartmann Screen Test
    - 3.3.5. Shack-Hartmann Sensor
      - 3.3.5.1. Fitting Shack-Hartmann Data to Zernike polynomials
- 4. Basic Interferometry and Optical Testing
  - 4.1. Review of Two Beam Interference
    - 4.1.1. Plane waves
    - 4.1.2. Spherical waves
    - 4.1.3. General wavefront shapes
    - 4.1.4. Visibility
    - 4.1.5. Coherence and Polarization
  - 4.2. Newton's Rings
    - 4.2.1. Patterns
    - 4.2.2. Determining convexity
    - 4.2.3. Test Plates
  - 4.3. Fizeau Interferometer
    - 4.3.1. Classical Fizeau
    - 4.3.2. Configurations for Flats, Concave and Convex Surfaces
    - 4.3.3. Laser Fizeau
  - 4.4. Twyman-Green Interferometer
    - 4.4.1. Common Configurations
  - 4.5. Mach-Zehnder Interferometer
    - 4.5.1. Common Configurations
    - 4.5.2. Single Pass
  - 4.6. Lateral Shearing Interferometers
    - 4.6.1. Common Configurations
    - 4.6.2. Derivatives of wavefronts
  - 4.7. Interferograms
    - 4.7.1. Seidel Aberrations
  - 4.8. Phase-Shifting Interferometry
    - 4.8.1. Phase Shifters

- 4.8.2. Algorithms
- 4.8.3. Phase unwrapping
- 4.8.4. Calibration and errors
- 4.9. Testing Aspheric Surfaces
  - 4.9.1. Computer Generated Holograms
- 5. Optical Specification
  - 5.1. ISO 1101 Standard
  - 5.2. ISO 10110 Standard
    - 5.2.1. General
    - 5.2.2. Stress Birefringence
    - 5.2.3. Bubbles and Inclusions
    - 5.2.4. Homogeneity
    - 5.2.5. Surface Form Errors
    - 5.2.6. Centering
    - 5.2.7. Surface Imperfections
    - 5.2.8. Texture
    - 5.2.9. Surface Treatment and Coatings
    - 5.2.10. Tables for Elements and Assemblies
    - 5.2.11. Non-toleranced Data
    - 5.2.12. Aspheric Surfaces
    - 5.2.13. Wavefront Deformation
    - 5.2.14. Laser Damage Threshold