17th Asian Physics Olympiad

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Experimental Problem– E2

Reflection Phase Shift of Metal

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E2: Reflection Phase Shift of Metal

- Introduction
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- Supporting Experiment
- Experimental Setup
- Results
- Acknowledgements

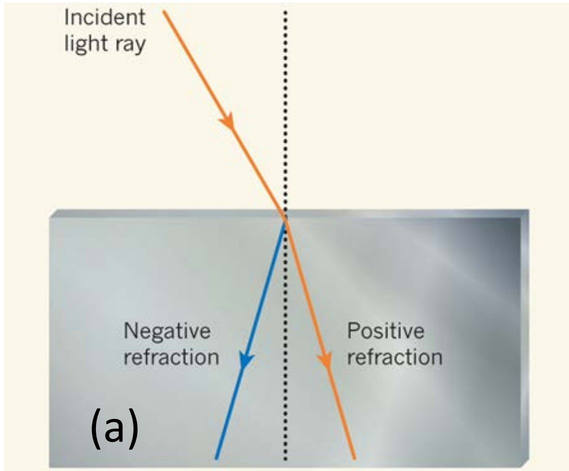
Introduction

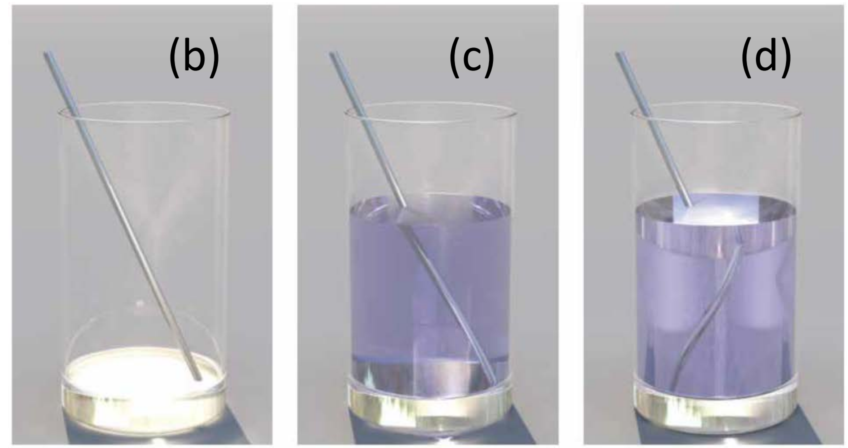
- Natural materials have refractive indexes (*n*) larger than that of vacuum, i.e. $n > 1$
- Maxwell's Equations do not exclude *n* to be other values, e.g. negative or zero
- Meta-materials, fabricated in the nano-scales, can have exotic refractive indexes,

  e. g. negative or complex values

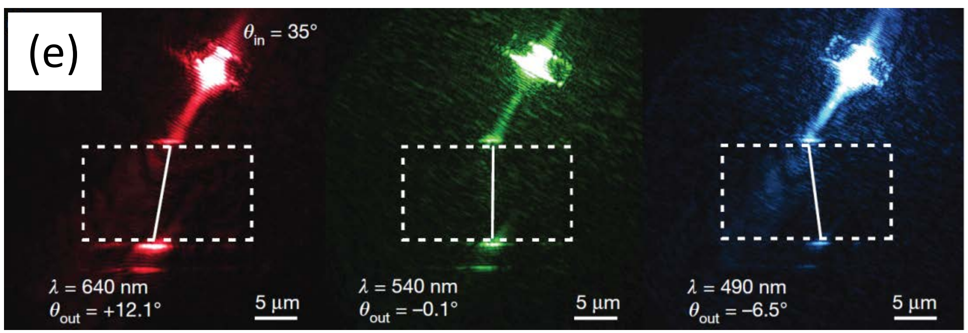
- Phenomena such as negative refraction or cloaking (invisibility) are possible

Negative Refraction





rod in air | rod in water n=1.3 | rod in NR water n = -1.3



(a) Positive vs. negative refraction. Photo taken from T. Tac and X. Zhang, Nature **480**, 42-43, (2011).

(b-d) Taken from "Photorealistic images of objects in effective negative-index materials", Optics Express **14**, 1842-1849 (2006).

(e) Taken from "Visible-frequency hyperbolic meta-surface", Nature 522, 192-196 (2015).

Introduction

- Measuring the refractive indexes of meta-materials is important for possible applications of the materials[1]

- Metals have complex refractive indexes due to absorptions

$$\hat{n} = n + ik$$

- Measurement of reflection phase shift (ϕ) can give information of the refractive index, i.e. at normal incidence[2]

$$\phi = \arctan\left(\frac{2k}{1-(n^2+k^2)}\right)$$

- For glass, reflection phase shift ϕ is 180º (or π radians) at normal incidence

- For metals, the reflection phase shift can take different values, depending on the absorptions

References:

*1) V. M. Shalaev, "PHYSICS: Transforming Light", Science **322** (5900): 384–386 (2008).*

*2) A. Dubois, "Effects of phase change on reflection in phase-measuring interference microscopy", App. Opt. **43**, 1503-1507 (2004).*

Introduction

- Phase measurement in the optical wavelengths is challenging

- Needs high precision

  e. g. a 10% measurement requires accurate optical path of 0.1 x wavelength ~ 65 nm for visible light!

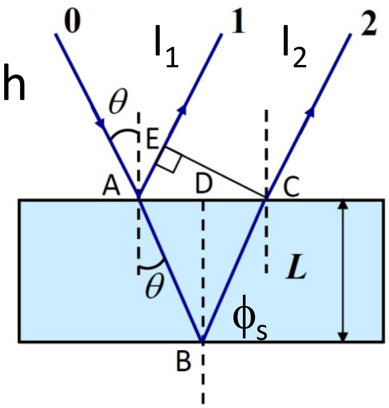
- Interference is a good method

  e.g. Fabry-Perot laser interferometry

Theory

Consider an ideal air-gap Fabry-Perot etalon as shown in the figure below:

Incident wavelength λ



Path difference of beams 1 and 2 for reflection interference

= AB+BC-AE

= $L/\cos(\theta) + L/\cos(\theta) - AC\sin(\theta)$

= $2L/\cos(\theta) - 2L\tan(\theta)\sin(\theta)$

= $2L[1-\sin^2(\theta)]/\cos(\theta)$

= $2L\cos(\theta)$

(Distances from E and C to the detector are assumed to be the same.)

For a two-beam approximation, the reflection interference intensity $I(\theta)$ can be written as below:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(2kL\cos\theta + \phi_s), \quad k = 2\pi/\lambda$$

For constructive interference (corresponding to reflection peak intensity):

$$2kL\cos\theta_m + \phi_s = 2m\pi \Rightarrow \quad m = \frac{2L\cos\theta_m}{\lambda} + \frac{\phi_s}{2\pi}$$

Theory

$$2kL\cos\theta_m + \phi_s = 2m\pi \Rightarrow \quad m = \frac{2L\cos\theta_m}{\lambda} + \frac{\phi_s}{2\pi}$$

- Choose the integer part of $\frac{2L\cos\theta_m}{\lambda}$ (Trunc($\frac{2L\cos\theta_m}{\lambda}$)) as the interference order *m*

- Thus a plot of

  m vs. *1/λ* for fixed incident angle

  or

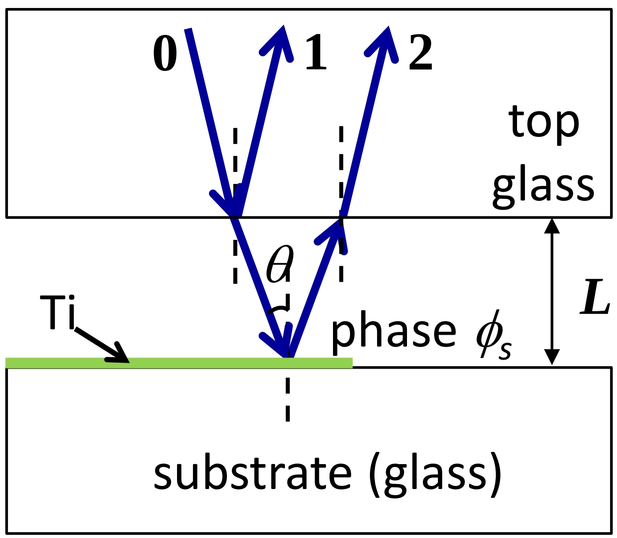
  m vs. cosθ_m for fixed wavelength

  will give a straight line.

  The slope of the line will give the air-gap spacing *L*, and the y-intercept will give the average phase $\phi_s/2\pi$.

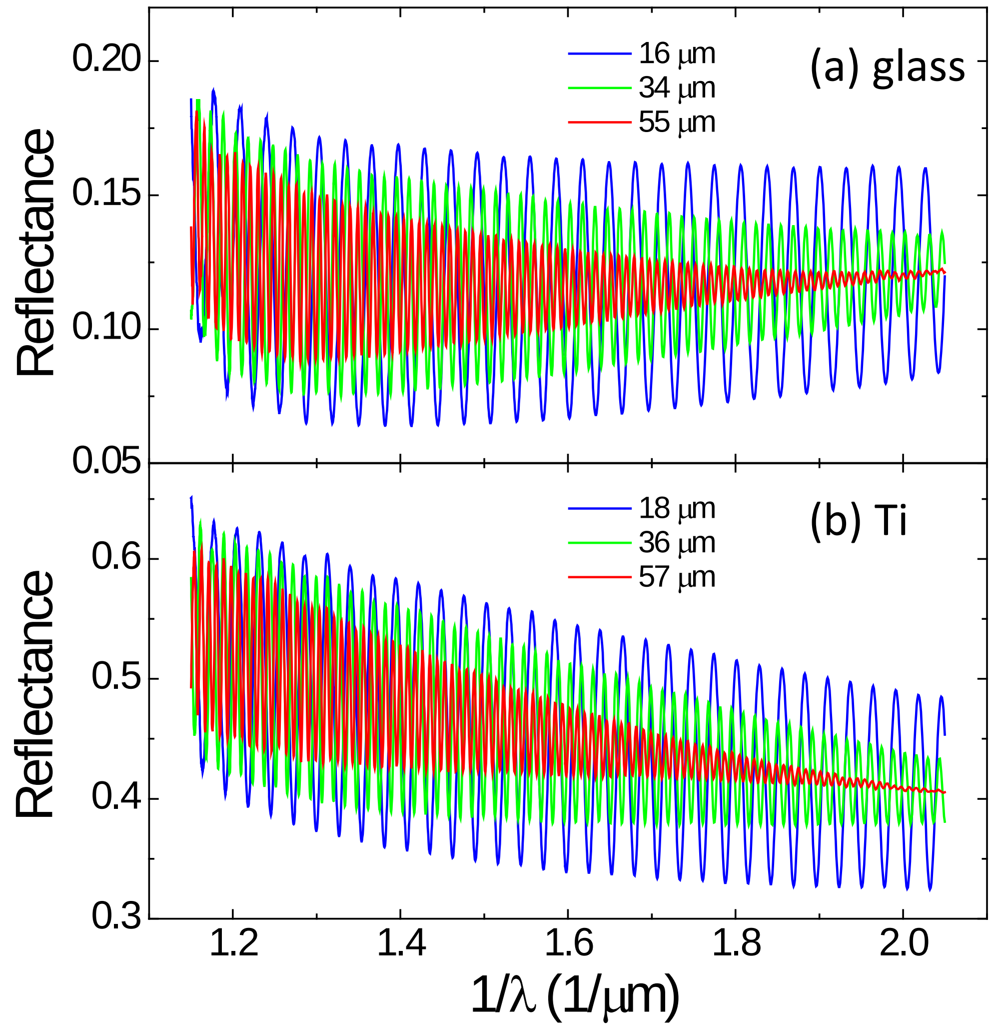
- The normalized reflection phase $\overline{\phi_s} = \phi_s/2\pi$ is thus defined within (-1, 0)

Supporting Experiment

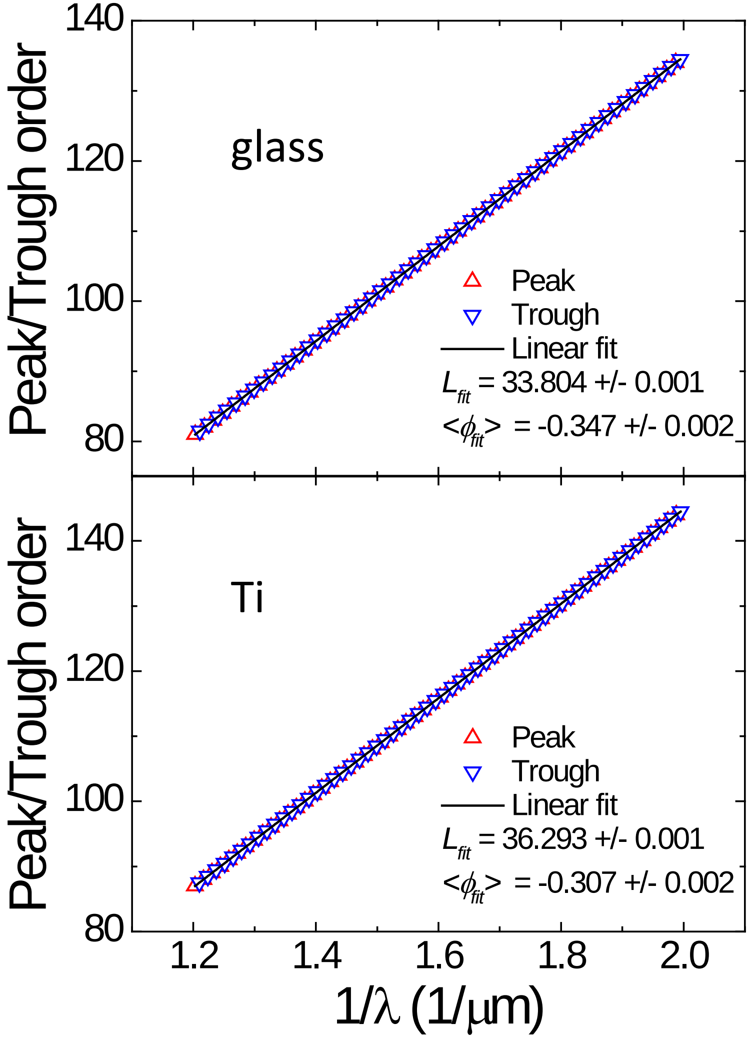


Schematic of Titanium- (Ti ~ 200 nm thick) coated air-gap etalon.

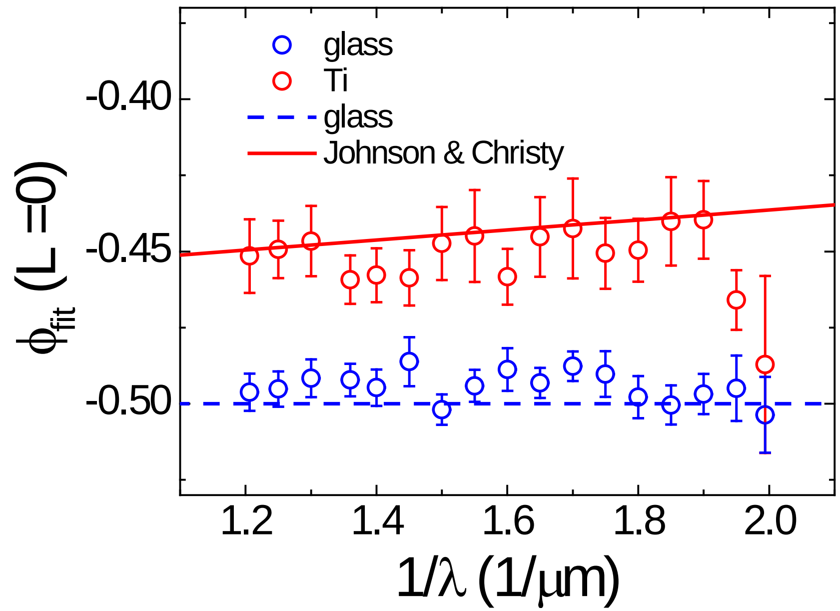
Normal incidence (θ = 0°) and measure reflectance for wavelengths between 450 to 850 nm.



Supporting Experiment



After corrections for numerical aperture effects



This technique is now published[1] and has been applied to the measurement of 1D Berry phase (Z-phase) in photonic crystals[2].

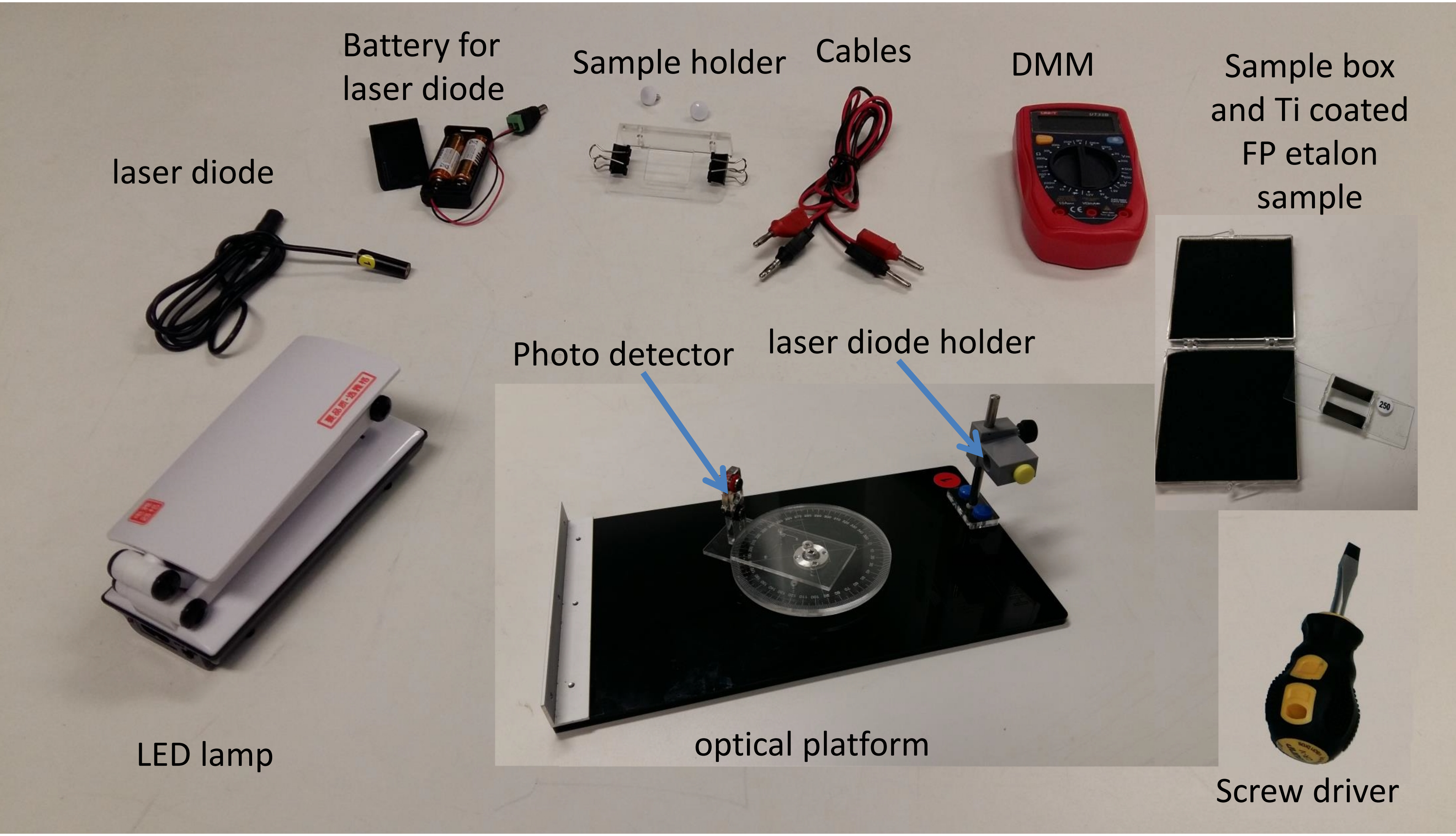
1) "Measurement of reflection phase using thick-gap Fabry–Perot etalon," T. K. Yung,. W. Gao, H. M. Leung, Q. Zhao, X. Wang, and W. Y. Tam, App. Opt. **55**, 7301-7306 (2016).

2) "Determination of Zak phase by reflection phase in 1D photonic crystals", Wensheng Gao, Ming Xiao, C. T. Chan and Wing Yim Tam*, Optics Letters **40**, 5259-5262 (2015).

Experimental Setup

- It would be difficult to require students to achieve the same precision as in our experiment using the simple setup for this reflection phase shift experiment
- Here we fix the wavelength and vary the incident angle
- Due to the difficulties in this experiment, e. g. mis-alignment, non-uniform air-gap, non-parallelism of the top and bottom plates, we only look for qualitative results

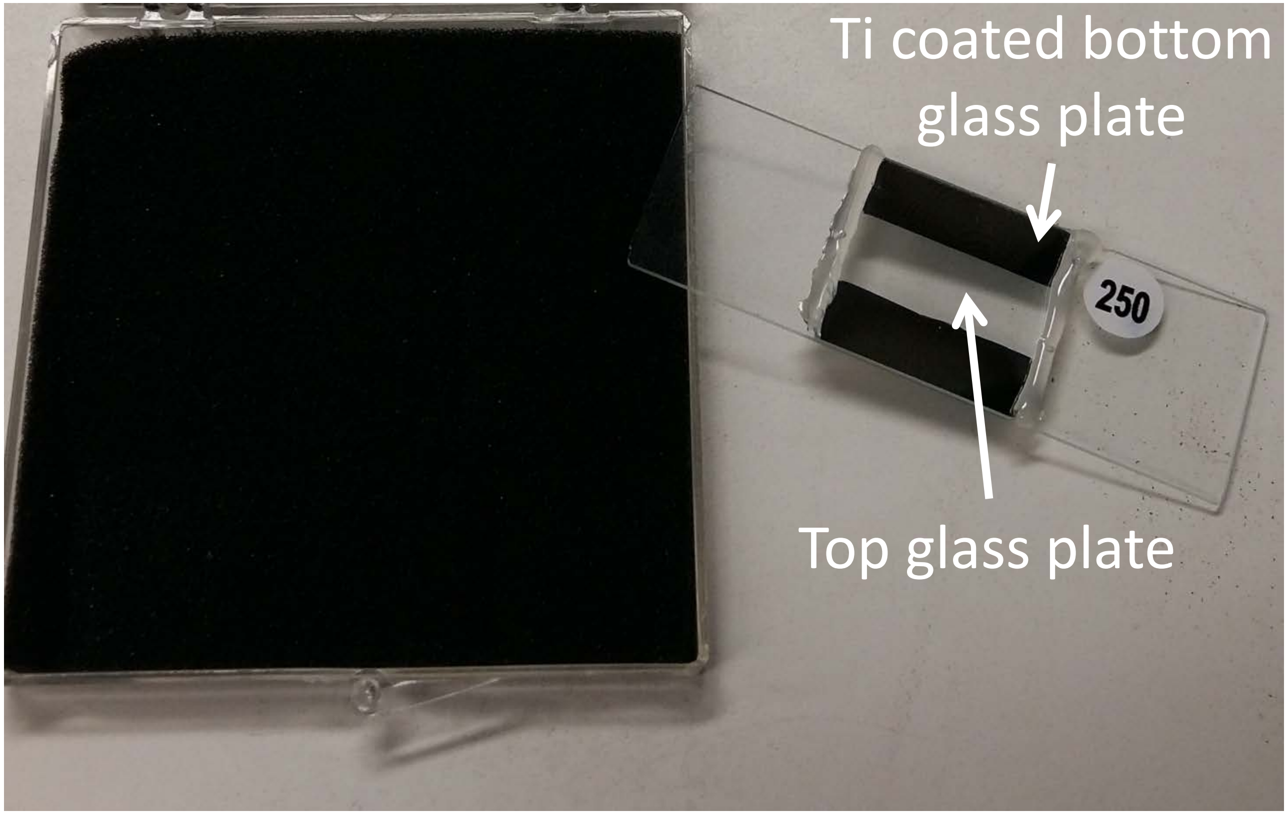
Experimental Setup



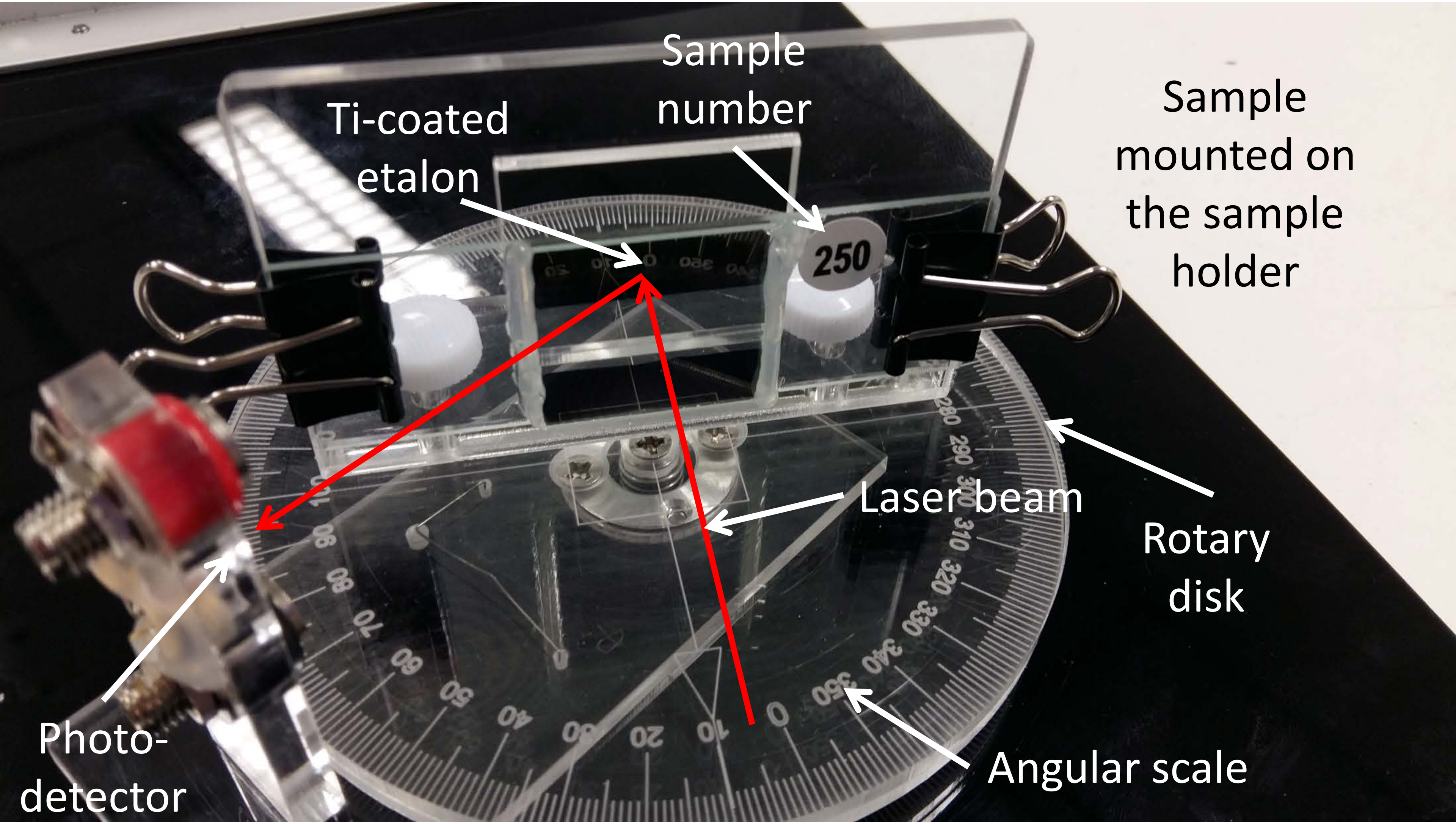
Experimental Setup

Ti-coated Fabry Perot etalon:

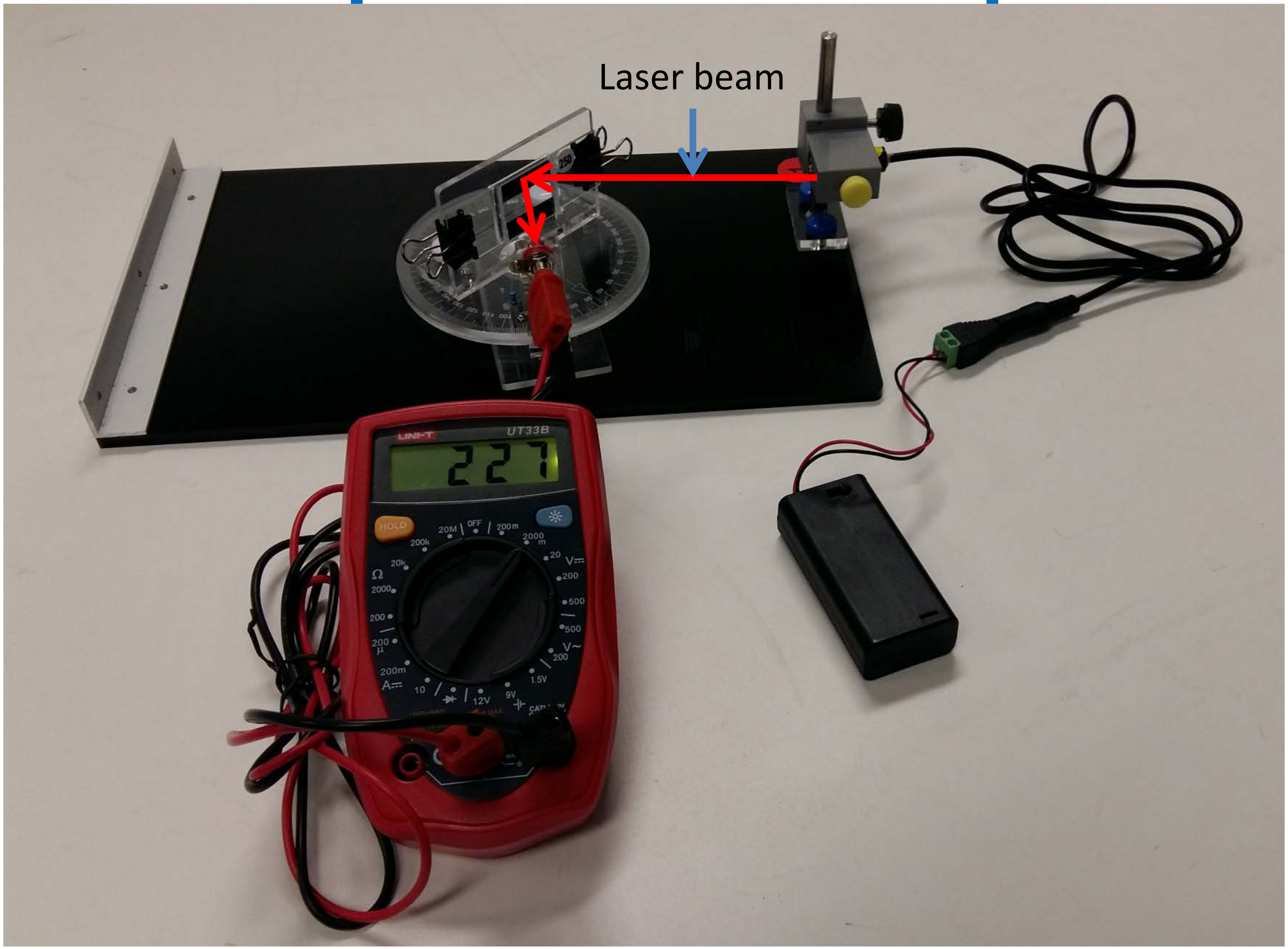
a Ti-coated bottom glass plate with on top a glass plate sandwiching an air-gap of ~ 5 micron in between



Experimental Setup



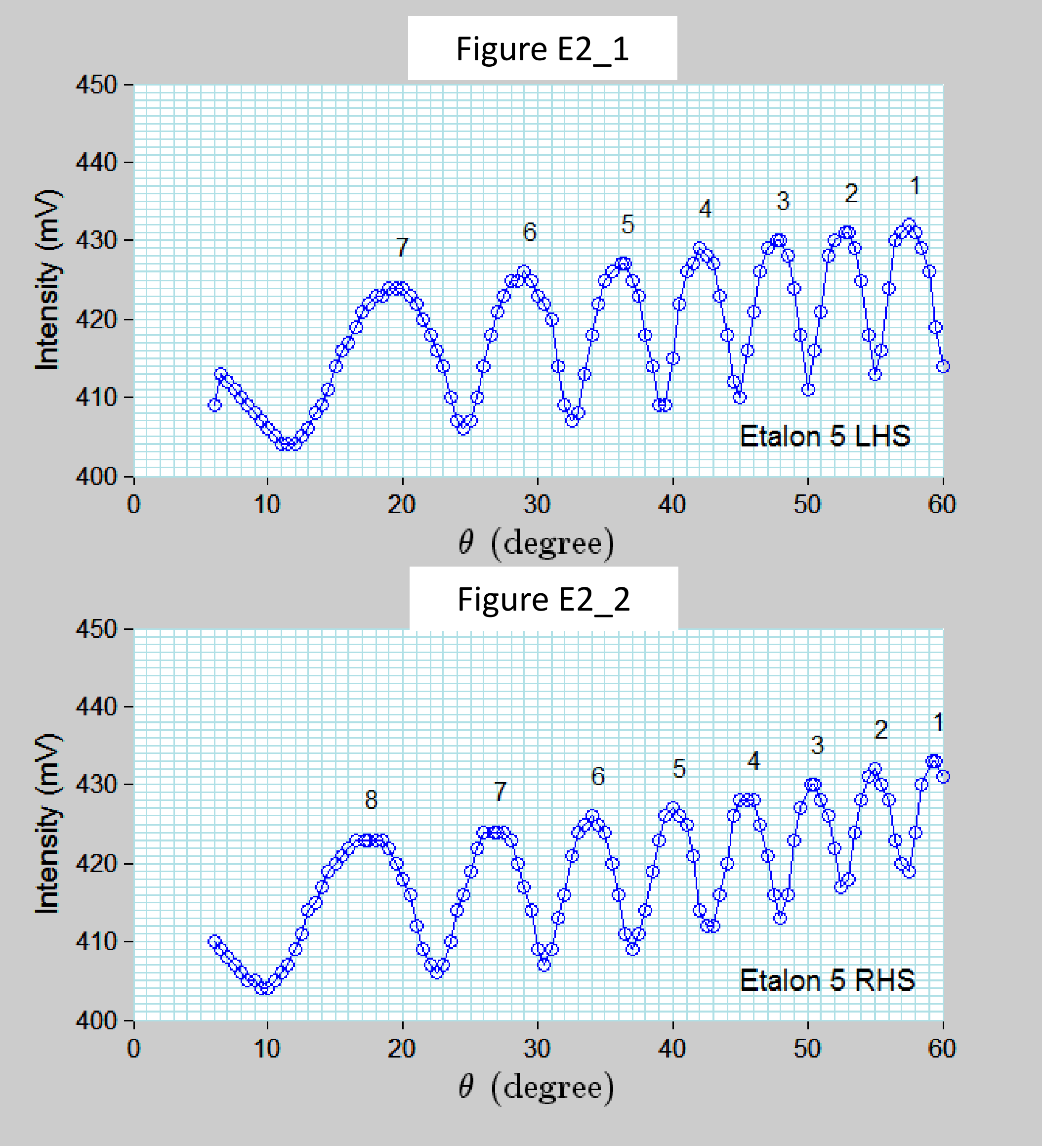
Experimental Setup



Measure the reflection interference intensity for both sides of the angular scale to reduce errors due to mis-alignment of the sample normal with respect to the angular scale and the laser beam.

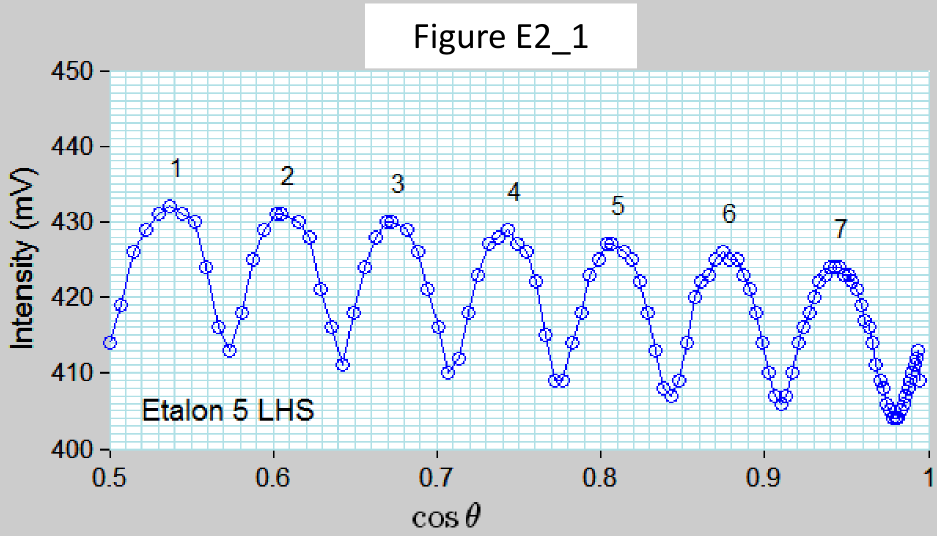
Experimental Result

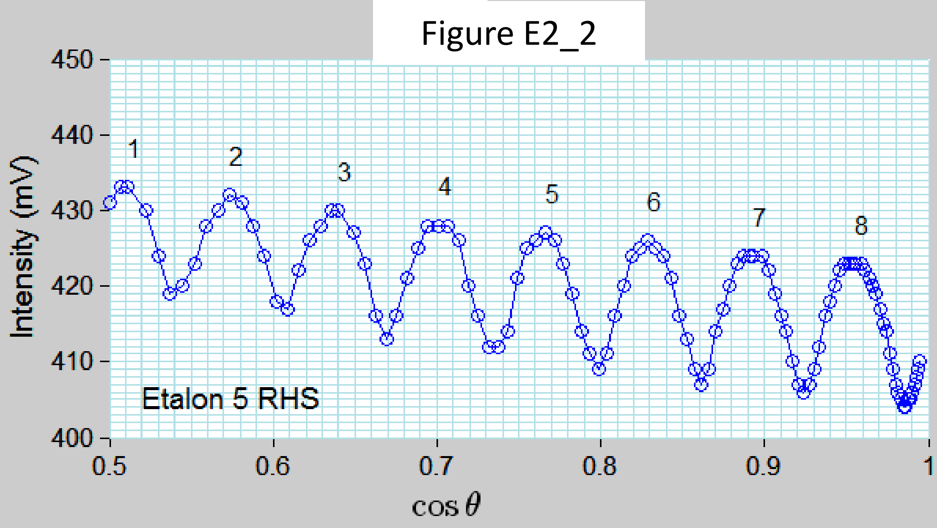
Ti etalon #5



Experimental Result

Ti etalon #5





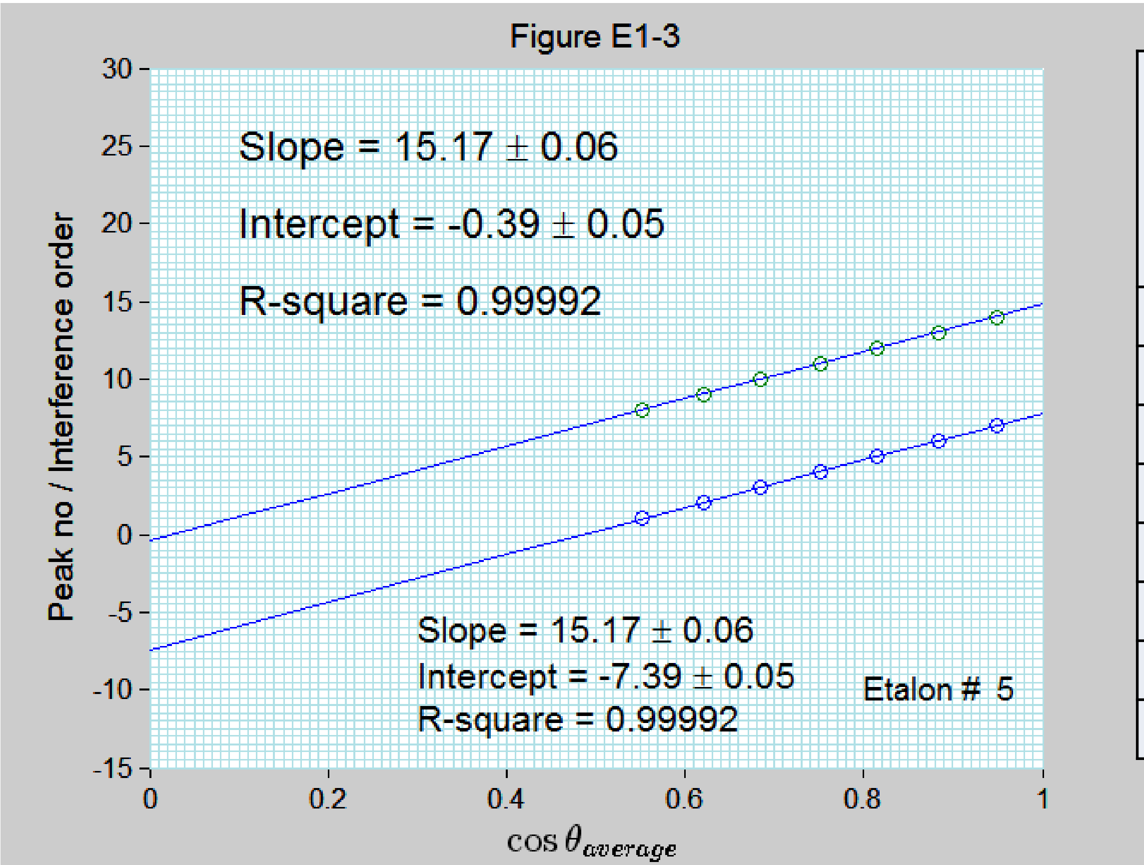
Experimental Result

Ti etalon #5

Peak # LHS	θ_{LHS} (degree)	Peak # RHS	θ_{RHS} (degree)	$\Theta_{average}$ (degree)	cos $\theta_{average}$	Interference Order m
7	19.5	8	17.25	18.5	0.948	14
6	29	7	26.75	28	0.883	13
5	36.25	6	34	35.38	0.815	12
4	42	5	40	41.25	0.752	11
3	47.75	4	45.5	46.88	0.684	10
2	52.75	3	50.25	51.63	0.621	9
1	57.5	2	55	56.5	0.552	8
		1	59.25			

Experimental Result

Ti etalon #5



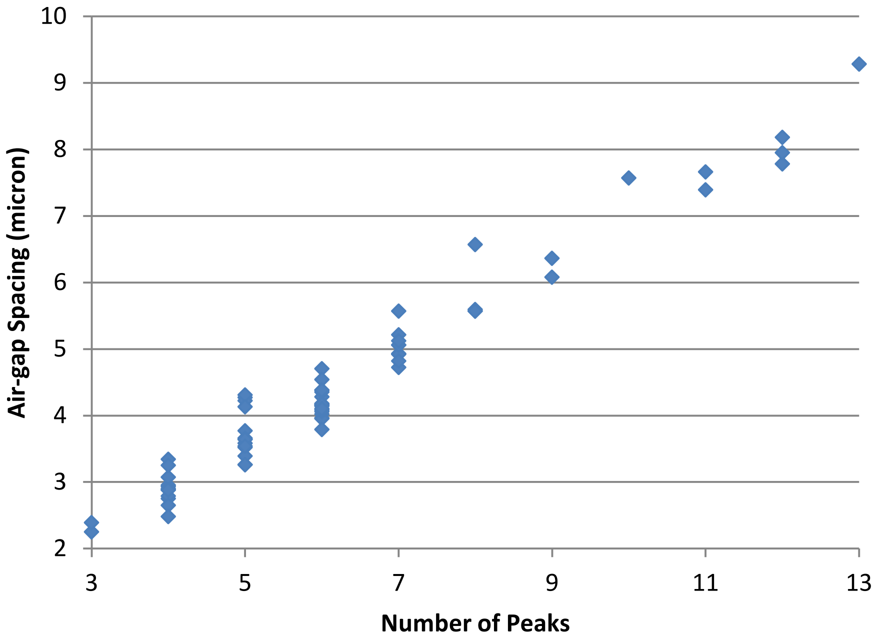
Peak # LHS	Peak # RHS	$\cos\theta_{average}$	Interference Order m
7	8	0.948	14
6	7	0.883	13
5	6	0.815	12
4	5	0.752	11
3	4	0.684	10
2	3	0.621	9
1	2	0.552	8
	1		

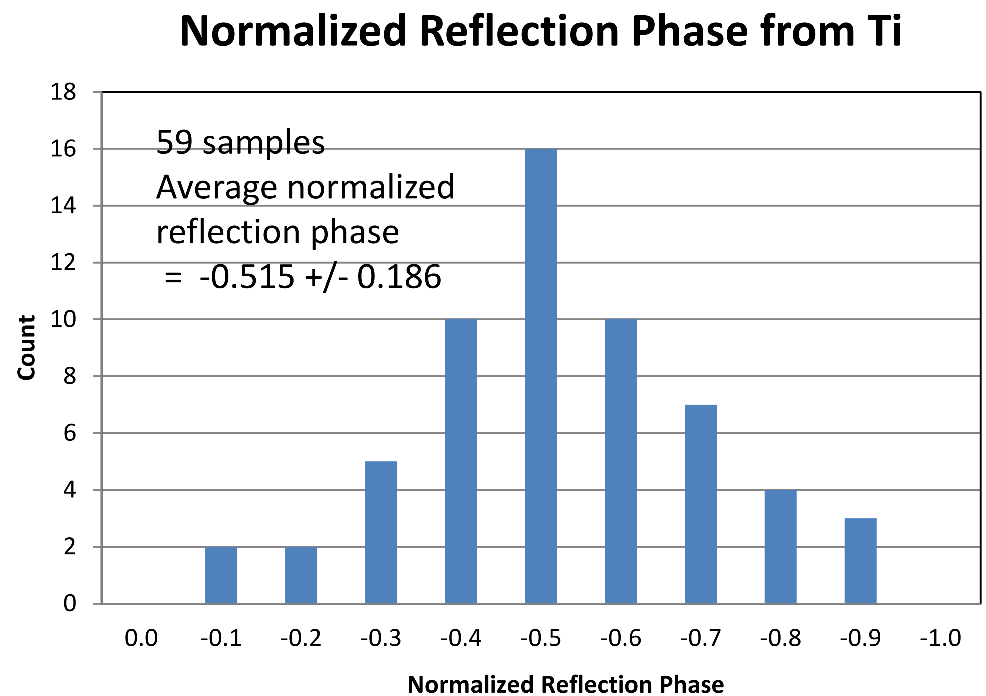
Air-gap spacing L = 0.65x15.17/2 = 4.93 +/- 0.06 μm

Normalized reflection phase $\overline{\phi_s}$ = -0.39 +/- 0.05

Error of reflection phase due to α = 1^o mis-alignment = $2L\sin\theta\sin\alpha/\lambda$ ~ 0.13

Experimental Result





Possible errors:

1. mis-alignment of the laser beam with respect to the angular scale
2. non-coaxial rotation of the Ti-coated surface of the etalon with the rotary disk
3. non-perfect parallelism between the two surfaces of the etalon
4. not the same spot is detected for different incident angles

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