Experimental Problem– E2

Reflection Phase Shift of Metal

Wing Yim Tam (譚永炎)
E2: Reflection Phase Shift of Metal

- Introduction
- Theory
- 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

(b-d) Taken from “Photorealistic images of objects in effective negative-index materials”, Optics Express 14, 1842-1849 (2006).
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 (\(\phi\)) 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 \(\phi\) is 180° (or \(\pi\) radians) at normal incidence

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

References:
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:

Path difference of beams 1 and 2 for reflection interference:

\[ \text{Path difference} = AB + BC - AE = L/cos(\theta) + L/cos(\theta) - AC\sin(\theta) \]

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

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

\[ = 2L\cos(\theta) \]

(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:

\[ I = I_1 + I_2 + 2\sqrt{I_1I_2} \cos(2kL\cos(\theta) + \phi_s), \quad k = 2\pi / \lambda \]

For constructive interference (corresponding to reflection peak intensity):

\[ 2kL\cos(\theta_m) + \phi_s = 2m\pi \Rightarrow m = \frac{2L\cos(\theta_m)}{\lambda} + \frac{\phi_s}{2\pi} \]
Theory

\[2kL \cos \theta_m + \phi_s = 2m\pi \implies m = \frac{2L \cos \theta_m}{\lambda} + \frac{\phi_s}{2\pi}\]

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

• Thus a plot of

\[m \text{ vs. } \frac{1}{\lambda} \quad \text{for fixed incident angle}\]

or

\[m \text{ vs. } \cos \theta_m \quad \text{for fixed wavelength}\]

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 ($\theta = 0^\circ$) and measure reflectance for wavelengths between 450 to 850 nm.
This technique is now published\(^{(1)}\) and has been applied to the measurement of 1D Berry phase (Z-phase) in photonic crystals\(^{(2)}\).


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

- LED lamp
- Laser diode
- Battery for laser diode
- Sample holder
- Cables
- DMM
- Sample box and Ti coated FP etalon sample
- Photo detector
- Laser diode holder
- Optical platform
- Screwdriver
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

- Sample mounted on the sample holder
- Ti-coated etalon
- Laser beam
- Rotary disk
- Angular scale
- Photo-detector
- Sample number
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

Figure E2_1

Figure E2_2
Experimental Result

Ti etalon #5

Figure E2_1

Figure E2_2
## Experimental Result

Ti etalon #5

<table>
<thead>
<tr>
<th>Peak # LHS</th>
<th>$\theta_{\text{LHS}}$ (degree)</th>
<th>Peak # RHS</th>
<th>$\theta_{\text{RHS}}$ (degree)</th>
<th>$\Theta_{\text{average}}$ (degree)</th>
<th>$\cos \theta_{\text{average}}$</th>
<th>Interference Order $m$</th>
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**Experimental Result**

Ti etalon #5

Air-gap spacing \( L = 0.65 \times 15.17/2 = 4.93 \pm 0.06 \) µm

Normalized reflection phase \( \phi_s = -0.39 \pm 0.05 \)

Error of reflection phase due to \( \alpha = 1^\circ \) mis-alignment = \( 2L \sin \theta \sin \alpha/\lambda \sim 0.13 \)

### Figure E1-3

- Slope = 15.17 ± 0.06
- Intercept = -0.39 ± 0.05
- R-square = 0.99992

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<tr>
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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

Normalized Reflection Phase from Ti

59 samples
Average normalized reflection phase
= -0.515 +/- 0.186

Air-gap Spacing (micron)
Number of Peaks

Normalized Reflection Phase
Count

0.0 -0.1 -0.2 -0.3 -0.4 -0.5 -0.6 -0.7 -0.8 -0.9 -1.0
0 2 4 6 8 10 12 14 16 18
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