Final Project Report – September 22. 2000

LIGO-T010055-00-D

Conversion of LIGO Optical Metrology Data

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ABSTRACT

LIGO optics are currently measured at the wavelength and angle of intended use. For 45-degree optics such as Beamsplitters and Folding Mirrors this creates a problem in that the air path for the measurement is increased from 3 cm to roughly a meter. Local changes in index of refraction within the air path add significantly to the measurement error for these very high quality optics. The extension of the optical path results in a much greater significance of certain error generating factors such as air-turbulences and temperature fluctuations which introduce changes in refractive index within the air path. In addition to these random errors, when measuring at 0-degree incidence angle there is a strong factor of a systematic error which originates from the fact that the thin layer coating applied to the LIGO BeamSplitters has been designed for 45-degree incidence. Another systematic error occurs due to the fact that the coating is slightly thinner at the center of the optic and that the coating inflicts some stress on the substrate surface thus curving it a little. All this results in the radius of curvature being not exactly the same as the one measured before deposition of the coating.

Introduction to the objective of the project

The ultimate goal would be a creation of some numerical "black box" that would take the 0-degree data, stir it up a little and come up with a synthetic phase-map that would look better than the actual 45-degree measurement. This is only said easily, as due to the thin-layer coating on the BeamSplitter the phase-shift changes significantly as compared to the uncoated underlying surface. What is even more interesting, since this is a 50% reflectance coating, it has to be designed very carefully. There can be many layer configurations resulting in 50% reflectance at 45-degrees meanwhile having a completely different reflectance at 0-degrees. Hence it is crucial to have some information about the thickness of the coating. This is obtained by ellipsometric measurement. When we have the information on coating thickness and input 0-degree measurement data and the conversion factor, we can actually create a synthetic phase-map that looks like a 45-degree measurement, except that it shows no trace of thermal turbulence (typical for a 45-degree measurement) and repeats the 0-degree surface profile modifying it a little. Applying this method of conversion we can eliminate the "rough" errors characteristic for the 45-degree measurement, repeating only the much smaller errors included within the 0-degree measurement plus the error of the method itself (which is lower than the errors occurring due to the increase of the optical path).

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Materials and Methods

All the numerical simulations were performed with the use of Mathematica analysis package and the modified beam behavior simulator provided originally by Hiroaki Yamamoto who also works with the LIGO project. This gave a detailed view of how the light beam may behave when it reflects from a 6-layer coated optical surface designed to be a 50% BeamSplitter.

All the measurements were taken with the WYKO2000™ laser interferometer (Fizeau configuration) and the Veeco VISION32™ metrological software. The sets of real measurements of two BeamSplitters were extracted and processed to a format comparable with the simulation results.

Eventually, there was presented a final conclusion about how to perform the data conversion and how to modify the 0-degree data to make it look like a 45-degree measurement.

The conversion itself was performed with the use of VISION32™ software. A synthetically generated parabolic phase-map was added to the measured 0-degree phase-map to obtain a prediction of the 45-degree phase-map.

Chronological progress of the research

- Extraction of the coating thickness data from an ellipsometric measurement done by CSIRO, Australia.
- Modification of the Mathematica simulation program provided by Hiroaki Yamamoto to better suit the purpose of phase calculations.
- Input of the coating thickness data for each of the 10 measurement points and obtaining the reflectance/transmittance and phase-shift values for 0-degrees and 45-degrees incidence.
- Input of additional optical data:
  - Refractive indices of the coating layers and the substrate.
- Extracting data from the Mathematica simulation and creating a spreadsheet for data presentation (with the help of MSExcel™):
  - Point coordinates along the measured diameter → x,
  - Phase-shifts in degrees→nm→nm normalized to the central point phase-shift (by subtraction *from* the given point),
  - Reflectance/transmittance in %,
  - Layer thicknesses for each point thus creating a physical profile of the coating,
  - Calculating the cumulative thickness of the whole coating [by addition] and normalizing (by subtraction *from* the given point) these values to the central point thus obtaining a profile of the relative thickness deviation along the measured diameter,
  - Calculating the phase shift difference between 45- and 0- degrees incidence configurations [in *this* order: 45-0] thus obtaining a comparison characteristic that is *independent* of certain systematic errors that are repeated in both measurement configurations.
- Choosing and preparation of the real measurement phase-maps to make them compatible with the theoretical simulation output data:

- With the use of VISION™ software provided to backup WYKO™ interferometer measurements:
  - → Subtracting phase-maps of the reference flats from the measured phase-maps thus obtaining the actual phase-maps of the measured optics,
  - → Saving data in ASCII format.
- With the help of MSAccess™ database engine:
  - → Importing data to a database and running a query to eliminate datapoints without any phase-shift (since the CCD is rectangular and the optic is circular, there is a lot of surplus, "Bad" datapoints),
  - → Running a query to extract data only along two diameters corresponding to the x and y axes,
  - → Exporting data to MSExcel™ format.
- With the help of MSExcel™:
  - → For 0- and 45- degrees:
    - Input of the data,
    - Pixels→mm conversion for x, y coordinates,
    - *Relative-To-Center* normalization of the surface coordinates,
    - Degrees→nm conversion for phase-shifts,
    - RTC normalization of the phase-shifts.
  - → For 45-degrees only:
    - Elliptic→circular conversion for x coordinates (Since the optic is circular, viewed at 45-degrees angle it is seen as an ellipse by the CCD camera. Hence it has to be "stretched" numerically, multiplying the x value by a $\sqrt{2}$ factor).
    - Tilt phase-shift conversion [division by $\sqrt{2}$] (since in the 45-degree setup anything that protrudes perpendicularly from the surface is seen by the CCD camera as its diagonal cast and hence all the heights seem higher by a $\sqrt{2}$ factor).
- Decision to compare only the data measured along the x-axis, y-axis data being just x-axis 90-degrees rotation.

- Data comparison:
  - Generating 2^{nd} order polynomial fits for both 0- and 45-degree cases.
  - With the knowledge of the approximate equations generating synthetic, smooth parabolic profiles for both measurements.
  - Adjusting the synthetic datasets by means of RTC normalization.
  - Subtracting 0-degree phase-shifts *from* 45-degree phase-shifts thus obtaining a differential profile fully compatible with the simulated one.
- Estimation of errors and usability of the comparison.
- Transformation of the 0-degree measurement data into 45-degree synthetic data by adding the function described by the approximate equation of theoretical difference between 45- and 0-degree cases to the 0-degree measurement profile. This modifying function appears to agree very well with the parabolic function – this being an ideal representation of the power aberration.
- Obtaining a synthetic 45-degree dataset that has all local properties of the converted 0-degree measurement (it repeats the "microshape" of the phase-map) but its global properties resemble a 45-degree measurement.

Observations

During the course of my research I have made the following observations:

- The ellipsometric measurement done by CSIRO provides me with data from about 10 measurement points along one diameter which is way too little information for creating reliable opinion as for what the microshape of the surface really is. By the measurement taken in the central point after a 180-degrees rotation of the optic the dataset reveals the systematic error of the ellipsometric measurement. This thickness specification inaccuracy translates into our inability to specify the phase-shift difference any lower then 1nm. This is the absolute lower limit of the accuracy of the whole conversion.
- The fact that we have only so few measurement points, results in additional inaccuracy of any approximated profile comparing to the real profile that we do not know.
- Although with the provided refractive indices the value of reflectance is about 47% (which is way outside the (50±1)% accepted error range), after an optimization of the refractive indices I found out that, however the reflectance can very well reach the level of exactly 50%, the phase-shifts move up and down uniformly in both 0- and 45- degree cases, which means that the difference remains constant. Thanks to the differential approach to the whole problem we can ignore the fact that the provided refractive indices return a somewhat incorrect value of reflectance (which was measured to be around (50±0.1) %). I have double checked the situation with optimized refractive indices and it shows that the phase-shift difference *does* change a little but this change is in the order of 0.25nm which is 4 times smaller than the lowest limit of inaccuracy in this experiment. So even if there is a slight deviation due to the inaccurate definition of the refractive indices, both itself and its effects remain invisible to us.
- I have as well inspected the possibility of some error introduction due to the random error of the ellipsometric measurement. This error can be defined as an average of the random measurement errors for each coating layer and then multiplied by the number of layers. To make sure that I accounted for the worst possible case I examined two situations: with layers of one type having the maximum positive error while layers of the other type having the maximum negative error and then *vice versa*. Thanks to this approach I was sure to cover the widest range of potential errors. The error estimate obtained in such a way also did not go beyond the level of 1nm, thus being unnoticeable to us. (By this I mean here that even if we do notice this error we can never be sure where it *really* comes from since anything *below* 1nm is indefinite.)
- I suppose that the phase-shift error resulting from the inaccuracy of x and y setting during the ellipsometric measurement is also below the 1nm level.
- Thanks to the differential approach to the problem I was able to eliminate any influence inflicted by the fact that the simulation discusses only the coating, whereas the measurement is taken of both the coating and the underlying substrate surface. Subtracting the measured phase-shifts at 0-degrees from the processed (accounting for the 45-degree heights change and shape change) phase-shifts at 45-degrees I reduced the substrate thus obtaining a difference fully compatible with the one obtained from the simulation. Moreover, some of the systematic errors that are repeated with the same sign in both measurement configurations (i.e. errors of the setup, of some constant environmental feature, etc *but* not the errors originating from effects characteristic *only* to the 45-degree measurement) are also eliminated this way.

- The fundamental assumption of this project is that the phase-map of the optic, and hence its surface, is circularly symmetrical. Then, there is an even more general assumption that all different BeamSplitters have a more or less identical coating. This is obviously not true but judging from the inspection of another BeamSplitter than the initially measured one and having compared its 45-0 phase-shift difference to the simulated one, I can assess that the error of applying the approximate equation to convert 0-degree data into 45-degree data is still in the order of 1nm. What is more interesting here, that after examining the BeamSplitter y-axis data, that normally were always distorted by some constant thermal noise (possibly an air vent crossing the measurement field) and gave out a difference that deviated from the x-axis one by ±20nm. When we apply the conversion procedure, the error can very well remain close to the level of 1-2nm, so a quick comparison of numbers shows that some considerable success may be achieved in just eliminating the results of thermal noise.

Results

The result predicted for this project has been achieved – the 0-degree measurement phase-map has been converted into a 45-degree look-a-like phase-map that appears to be satisfactorily accurate. The method of conversion is easy to implement as an automatic procedure or may as well be applied manually with the use of existing software.

Problems remaining to be solved - discussion

- There is one essential problem unsolved yet but I think its origin is in the understanding of the physical phenomenon or rather the way it is measured.
  - It turns out that the definition of phase-shift in the simulation software is slightly different than the one used by VISION™ software. Namely, my simulation considers given phase-shift that is slower (i.e. it stays longer in the transmissive material of the BeamSplitter) than some other one as actually bigger (in a way one could perceive it as “longer”). The fundamental rule used by the simulation is using the incident beam phase-shift as a reference.
  - On the other hand, VISION™ software collects the data from the CCD facing the beam returning from the optic and calculates an average phase-shift level for the whole surface. Then it normalizes all data points referring to this average value and comes up with a phase-map of positive and negative phase-shifts. Thus, phase-shifts that are actually ahead of the others are considered positive and phase-shifts that are slower turn out as negative.
  - Presuming that my understanding is correct here, this results in the difference of phase-shift being opposite in both described situations (in the simulation, a bigger (slower) phase-shift minus a smaller (faster) phase-shift would result in a positive value, whereas *the same* situation in VISION™ would be a negative number minus a positive number thus resulting in a negative number). This idea has not been thoroughly discussed yet but if it proves to be true it should remove the last essential obstacle from the project.
- Another issue that may arise here is the fact that the optical surfaces are actually asymmetric. Since the whole idea of the project is based on repeating the 0-degree profile it may seem too rough to consider just the profile measured along one diameter. One might think that it would be good to be able to account for the asymmetry of the optic and

add some conversion value to the 0-degree measured phase-map that would vary depending on the radial and angular position on the surface. This would not cause the 0-degree phase-map to be repeated so uniformly. That is true, but we have to remember about the fundaments of the simulation being only 10 points from the ellipsometric measurement. This results in the simulated approximate plot of the thickness (and phase for that matter) being further from both the real surface (as measured ellipsometrically) and the real phase-shift (as measured with the interferometer). So among this festival of averaging, the undeniable deviations are lost within the 1nm (or probably somewhat bigger) error range. To really take these deviations into account one would have to come up with more detailed information about the surface itself (e.g. perform a more detailed ellipsometric measurement).

Directions of potential improvement and development

As mentioned in the section above, there are areas that would certainly appreciate some development but this would require more detailed fundamental resources. In addition, providing refractive indices that would assure 50% of reflectance could probably improve the simulation to an extent. The same refers to a more precise measurement of the coating thickness (i.e. going below the 1nm threshold). As for the circular variation of the measured surface, this improvement would require performing numerous measurements of the same optic being rotated by a small angle from measurement to measurement. Still, this would require a very strict stabilization of the measurement environment in order to minimize the random errors variation (so that what would be measured would actually be the variation of the surface and not a change of error distribution).

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