

Benefits of angstrom absolute thickness and sub angstrom relative thickness measurements in optical applications

Date: September 2002

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This paper introduces a new generation of metrology which when coupled with critical applications or demanding manufacturing processes can bring significant improvement in the design and fabrication of optical components. It describes the use of broadband tunable lasers to optically and mechanically characterize solid Fabry-Perot etalons and explains how the technology can be transferred into a rugged, repeatable and reliable tool for the manufacturing floor.

Introduction

Measuring 0.5 nm absolute thickness ($\lambda_{\text{ref}} / 1,200$, $\lambda_{\text{ref}} = 632.8$ nm) or 0.05 nm ($\lambda_{\text{ref}} / 12,000$) thickness variation requires a strict control of all variables. Typically, when designing Fabry-Perot etalons, variables include wavelength, temperature, material and reflectivity of the mirrors. However, other variables such as surface roughness, angle of incidence, local wedge, coating loss, beam size and material dispersion also influence the final etalon output.

Fabry-Perot etalons are characterized through their peak transmission, Free Spectral Range (FSR) and finesse, where FSR means the frequency spacing of the transmission maxima and the finesse is the ratio of the FSR to the transmission width of an individual maximum. Then based on the refractive index value, the physical thickness of the solid etalon can be calculated. This is particularly useful when manufacturing parts at non-telecom wavelengths (semiconductor, aerospace...).

Design of a state of the art metrology solution

To achieve the specifications above, in particular the wafer Total Thickness Variation (TTV), a measurement station was designed to precisely control all parameters. Temperature is regulated to better than 0.1°C with thermo-electric coolers, normal incidence is checked by beam reflection to a maximum angle of 2 minutes, and indexes and dispersion are extracted from published literature (for instance fused silica or zerodur) or from in-house measurement and analysis. From an optical standpoint, the system relies on a NIST traceable sweeping laser that covers both C and L bands with sub-ppm accuracy.

The solution also offers flexibility to measure part thickness from a few tens of microns to several millimeters with 0.05 nm repeatability. For thicker substrates (up to 25mm) the accuracy and repeatability are reduced, primarily by temperature gradients, and a long temperature equilibration time is needed before acquiring data. The following graphs show the frequency response signal from a single wavelength scan of a silicon etalon wafer (Figure 1), conversion of a set of such measurements into a coarse grained thickness variation plot (Figure 2) and a partial 2D thickness map of another wafer (Figure 3).

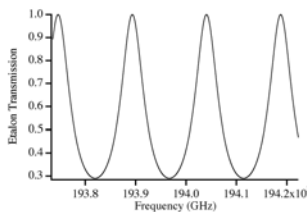
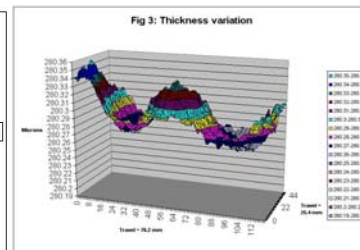
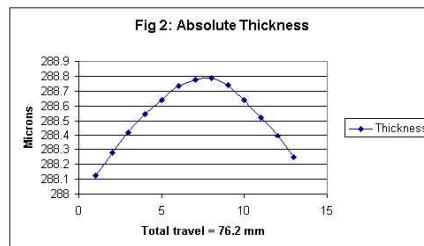


Fig. 1 Typical bare silicon etalon transmission signal.



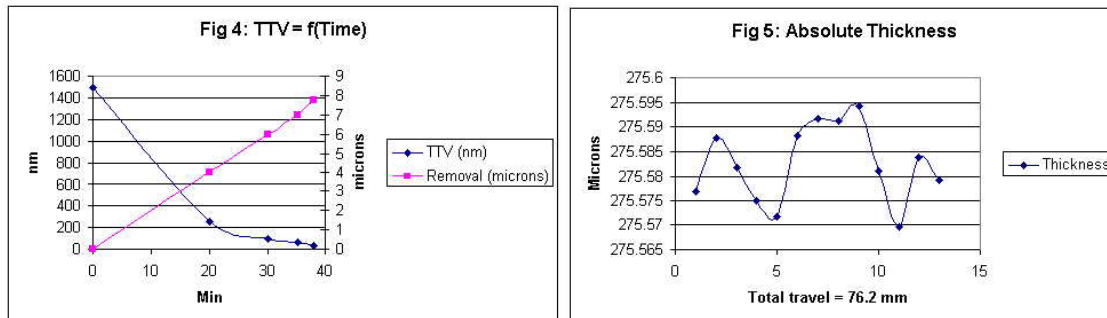
Productivity is a very important factor in expanding the system use to the manufacturing floor. To compete with existing systems, the data acquisition and instrument control have been optimized so that an area of 2000 mm² on a 100mm wafer (TTV < 50nm) can be mapped at a sub-millimeter point density to sub-nanometer thickness accuracy in less than 15 minutes.

Expanding the system capabilities

The most common manufacturing technique for obtaining wafers with low TTV is double sided polishing. Typically, wafers are placed in carriers that undergo planetary motion between two counter-rotating polishing plates. Pressure and speed can be controlled to influence removal rate, surface roughness and TTV. With this configuration, it is easy to generate parallel surfaces with a TTV in the range of $\lambda_{\text{ref}}/2$ for 50.8 or 76.2 mm wafers. With mapping times that improve with better TTV, a market interested in mass production of high quality etalons, and a manufacturing process that had not yet been challenged to the sub 100 nm level, researchers at Precision Photonics decided to perform a thorough investigation of the double-sided polishing process to determine the achievable TTV limit.

To thoroughly understand the process and measure the benefits of this state-of-the-art metrology, researchers utilized a system approach, an efficient methodology to get a full understanding of material removal processes. All operational factors were sorted, as well as input and output variables and metrology readings, and fed directly back into the process. The emphasis was put on measuring physical thickness.

Researchers chose silicon as the primary material for the tests as its high index of refraction enhances the effects of surface irregularities on the finished etalon. Wafers of 100mm diameter with thicknesses ranging from 300 micron to 1 millimeter were used throughout these tests. Absolute thickness was measured at 13 points on a linear 76.2 mm aperture on the wafer. This discrete measurement provided a fast, coarse grained characterization (less than a minute) of all wafers regardless of TTV, in a form suitable for manufacturing feedback. Figure 4 shows a wafer starting with a TTV of 1500 nm and improving to 25 nm ($\lambda_{\text{ref}}/25$) in only 40 minutes. Not only is the TTV controllable, but also the total material removal is well characterized, allowing manufacturing to hit specific etalon thickness targets with ease. Figure 5 shows a plot of the final thickness of the wafer with a 25 nm thickness variation across the wafer.



These experiments were repeated using various wafer batches and materials. Fused silica wafers with a diameter of 76mm were also tested and consistently measured at 60 nm TTV across the entire diameter.

Leveraging the benefits

Fabry-Perot etalons usually come with FSR, peak transmission and finesse specifications at a given temperature. To control peak transmission and finesse, reflective coatings are applied to both faces of the wafer. In addition to the reflective coatings, a thickness correction coating may be applied to one or both surfaces to compensate for manufacturing tolerances at the level of 100nm in absolute thickness. Both operations induce an optical phase shift in the etalon that affects the final FSR and transmission of the etalon. This is due to the mismatch of the refractive index of the correction layer from the bulk material and the added indexes of the reflective layers.

The high precision metrology also enables the absolute phase shifts and the wavelength dependent phase shifts of the optical coating to be measured. This is accomplished by comparing the wafers before and after the coating process. Experimental characterization of the phase shifts improves manufacturing reliability, by removing modeling dependencies that may exist in thin film calculations, and allows specific customer operating temperatures to be targeted at an early stage in the manufacturing process. This ensures higher yields by post processing only qualified wafer areas.

Although a plane parallel solid etalon is the most simple of etalons designs, manufacturing problems increase dramatically when designing a high finesse etalon. A high finesse for the plane parallel geometry starts at about 20 for the etalon dimensions considered in this paper. At these finesse levels the etalon becomes very sensitive to all parameters including alignment, local wedge (parallelism between both mirrors) and surface roughness. In the micro-optics of the telecom industry laser beam diffraction also plays a role in the finesse limit. In the case of these applications, the beam used is 0.8 mm in diameter, which sets the scales of surface roughness and local parallelism. Thickness variation across a 100 mm wafer can be erratic (Figure 5), but local parallelism dominates finesse and peak transmission. As a simple example, consider a nominal 50GHz Fused Silica telecom etalon (Figure 6) whose thickness varies by 10 nm in such a way that half the etalon is one thickness and the other half is 10 nm thicker. The FSR and peak transmission will be slightly different in both sections, and when a highly reflective coating is applied in an attempt to produce a high finesse etalon, the result will be a smearing of the transmission signal as seen in figure 7.

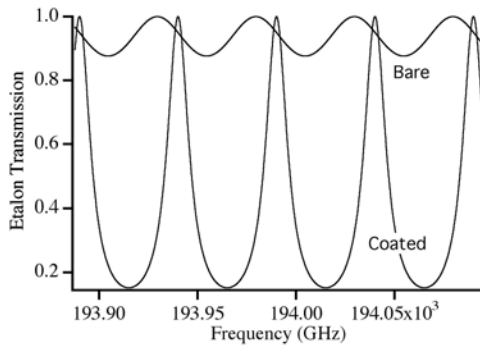


Fig. 6 Bare etalon FSR 50.03GHz, Coated 50.00GHz

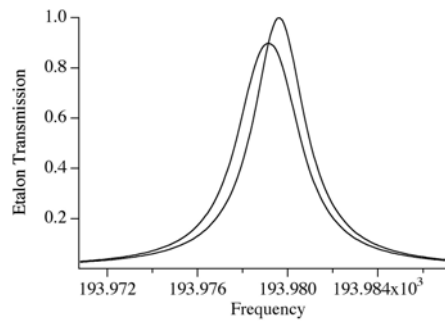
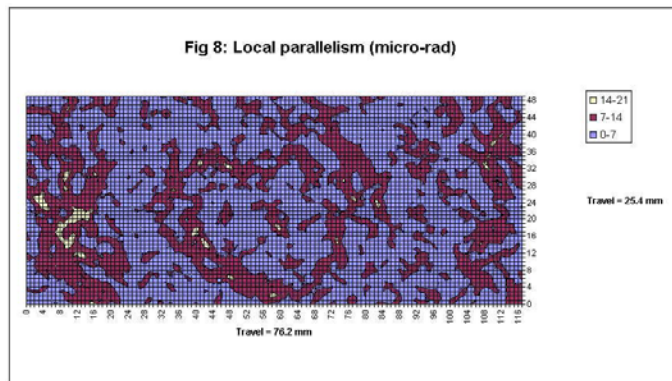


Fig. 7 Degradation of high finesse etalon by a 10nm wedge.

For the production and characterization of high finesse etalons it is essential to adopt a laser beam size that matches the one used in the final application. Since surface roughness and local wedge are averaged by the beam, the influence on the finesse and peak transmission can be dramatically different depending on the surface topography. The following graph (Figure 8) shows an example of local parallelism map (measured every 0.5 mm):

Thus, despite a TTV in the range of 60 nm on the range of the measured area, 50% of its total surface is within 7 μ -rad parallelism for a 0.5mm beam.



The high accuracy and wide wavelength range of telecom lasers used in this research allows the extension of the TTV analysis to multiple cavity etalons as well as single surfaces. For example, using a known optical flat as one side of an etalon, an air-gapped etalon can be formed with an unknown surface and the spacing (TTV) measured with sub-nanometer accuracy. The extension to multiple cavities is also straightforward and can be used as a means of directly measuring the refractive index and dispersion of a transparent material as well as physical deformations in large optical assemblies. The ability to measure optical wavelengths with better than ppm accuracy is the key to disentangling signals from multiple cavities while consistently providing nanometer scale accuracy for each subcomponent.

Conclusion

Sub nanometer or Angstrom resolution in thickness measurement brings significant improvements in optical applications by enabling the development of next generation applications. These can be found not only in the telecom industry but also in the semiconductor and aerospace industries. Other significant benefits of this technology are its reliability, self-calibration and insensitivity to the environment. As a result, manufactures have already begun successfully implementing this system and bring quality and productivity performances of conventional fabrication equipment to a new level with very limited machine upgrade and experiment. High accuracy etalon characterization technology has also led to the design of high precision opto-electronic components such as wavelength lockers used in tunable laser packages.