Project Report
LSP-275

Compact Solid Etalon Computational Spectrometer: FY19 Optical Systems Technology Line-Supported Program

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17 December 2019

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This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001.

This report is the result of studies performed at Lincoln Laboratory, a federally funded research and development center operated by Massachusetts Institute of Technology. This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Under Secretary of Defense for Research and Engineering.

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ABSTRACT

The Compact Solid Etalon Computational Spectrometer line program is developing fabrication techniques for wedged low reflectivity etalons and algorithms enabling a novel hyperspectral imaging architecture based on a solid low finesse etalon paired with a traditional imager. The hyperspectral imager can be designed to operate for any spectral band with the selection of an appropriate imager and etalon substrate material. The architecture is a high throughput design for use in low light applications and can operation in single shot or scanning modes. The spectral performance can be both high spectral resolution and large spectral bandwidth in volumes no larger than the imager themselves. This offers significant volume reduction, up to 1 to 2 orders of magnitude, over traditional high resolution spectral devices. This is achieved by utilizing the advances and cost reduction of large high pixel count imagers essentially sacrificing spatial resolution in one axis and/or collection time for increases in spectral performance.

In order to offer the highest performance spectral imager, solid etalons are necessary compared to alternative air-gap wedged etalons which have been previously investigated. From the program onset, it was decided that pursuit of solid etalons is the key enabling component of this architecture and therefore prioritized. Initial modeling efforts determined the design requirements of wedged etalons targeting two important spectral bands. The first was a hybrid two material etalon for use in the visible to short wavelength infrared (VNIR/SWIR), 0.4–2.4 micrometer, spectral band. The second was a single material etalon for use in the long wavelength infrared (LWIR), 7.5–12 micrometer, spectral band. The etalon design requirements for these spectral bands will be discussed. Finally, an overview of the etalon fabrication development will be provided. It was the goal of this effort to develop a process that is volume scalable to provide a path to future low cost etalons specifically excluding custom hand-crafted techniques. The status of these efforts will be discussed with two viable paths determined for the hybrid VNIR/SWIR wedge and work still in progress for the LWIR single substrate etalon.

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1. INTRODUCTION

Spectrometers are instruments that measure the amount of light present in different spectral bands (i.e., wavelengths or colors). They are characterized by the detectable spectral band, spectral resolution, minimum detectable light level, and SWaP. Often achieving high performance for one metric comes at the expense of others. For example, achieving high spectral resolution typically requires large spectrometers whereas compact spectrometers with high spectral resolution require large input brightness. This program is pursuing a novel concept that overcomes several of these compromises. A specially designed low reflectivity wedged etalon is located in close proximity to the front of a focal plane array with negligible change in size. The wedged etalon functions to provide a wavelength-dependent encoding that can be used to determine the incident spectral distribution without actually dispersing the incident light. The large number of available pixels in modern cameras combined with the wavelength-dependent encoding provides high spectral resolution, all wavelengths transmitted to each pixel for high throughput, and it is compatible with all spectral bands when an appropriate detector and etalon material is selected. For the highest sensitivity hyperspectral configuration, the sensor linearly traverses across the scene collecting two dimensional spatial information each frame acquiring the necessary spectrally-encoded information with subsequent frames at different times. By trading between a reduced update rate to acquire an entire hyperspectral data cube, this mode of operation allows for longer ranges, or smaller collection apertures. The end result is the ability to transform any camera into a compact low cost spectrometer or hyperspectral imager replacing the current large and expensive spectrometers.

The main two efforts for this program are: 1) To develop fabrication techniques for wedged low reflectivity etalons and 2) Develop algorithms to appropriately filter and reconstruct the input spectrum based on the sampled scene. In order to offer the highest performance spectral imager, solid etalons are necessary compared to alternative air-gap wedged etalons which have been previously investigated. From the program onset, it was decided that pursuit of solid etalons is the key enabling component of this architecture and therefore prioritized. It was the goal of this effort to develop a fabrication process that is volume scalable to provide a path to future low cost etalons specifically excluding custom hand-crafted techniques.

This report is divided into three main sections. First, initial modeling efforts will be described which have determined the design requirements of wedged etalons targeting two important spectral bands. The first was a hybrid two material etalon for use in the visible to short wavelength infrared (VNIR/SWIR), 0.4–2.4 micrometer, spectral band. The second was a single material etalon for use in the long wavelength infrared (LWIR), 7.5–12 micrometer, spectral band. Second, an overview of the VNIR/SWIR etalon fabrication development will be provided from which two viable paths have been determined. Finally, the work still in progress for the LWIR single substrate etalon will be described outlining the process development to date and work still remaining.

2. COMPUTATIONAL WEDGE ETALON SPECTROSCOPY AND DESIGN

In order for a device to function as an optical spectrometer it must measure the magnitude of all spectral components incident on the device. This incident light is typically collinear and overlapping so a method to separate the wavelengths is required. Traditionally this is accomplished by dispersing the wavelengths with a refractive or grating element combined with subsequent sensing elements. The wavelength range it operates over is referred to as the spectral bandwidth and the spectral binning, or sampling, is the spectral resolution. Ideally the larger both of these parameters are the better the spectrometer with the actual required parameters heavily dependent on the application. The computational wedge etalon spectrometer is a fundamentally different technique compared to dispersive techniques. Rather than separate the wavelengths, a unique wavelength-dependent encoding is applied due to the wedged etalon. All wavelengths remain overlapping and collinear. A schematic of the implementation is shown in Figure 1. A solid wedged etalon is placed in close proximity to a traditional imager's focal plane. The wedged etalon creates a wavelength-dependent encoding based on interference of the first two transmitted beams from the wedge. This interference is sampled by the imager to be used later to reconstruct the incident spectral distribution. The thickness of the wedge varies across the imager with notional transmission curves illustrated in Figure 1 for different sections of the wedge. The dimensions and index of refraction of the wedge determine the spectral bandwidth and spectral resolution of the spectrometer.

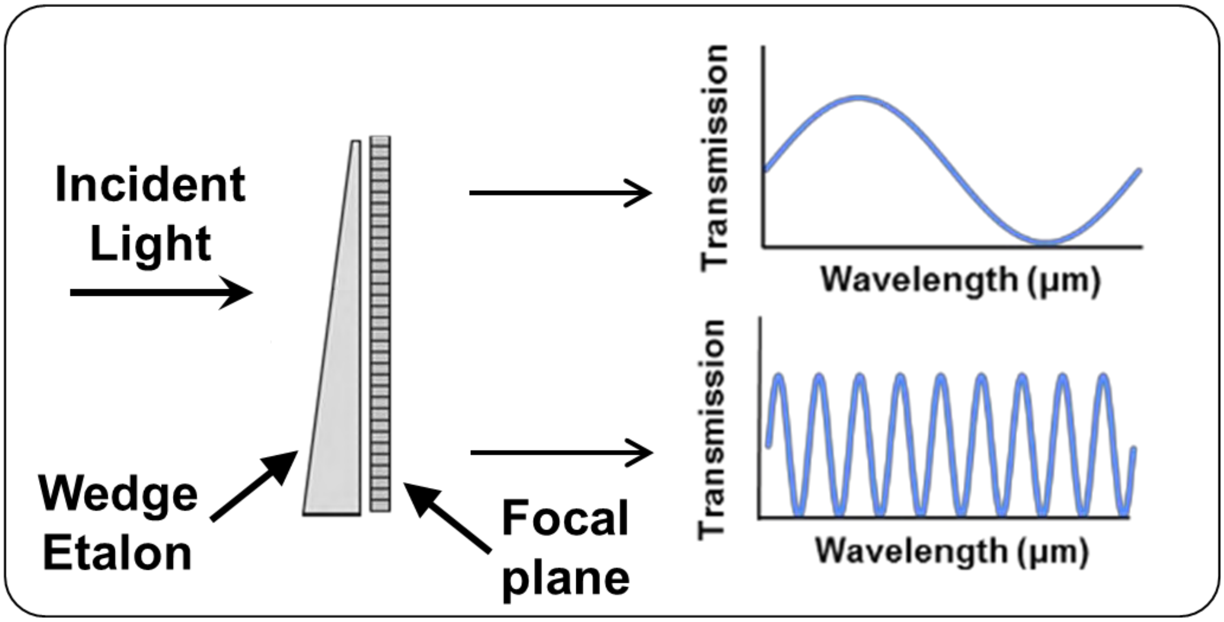


Figure 1. Schematic of wedged etalon spectrometer concept. Light is incident on the wedged etalon located in front of a traditional imager. The thickness of the etalon varies across the imager providing unique wavelength-dependent encoding illustrated on the right by the notional transmission curves representing the transmission for different sections of the wedged etalon.

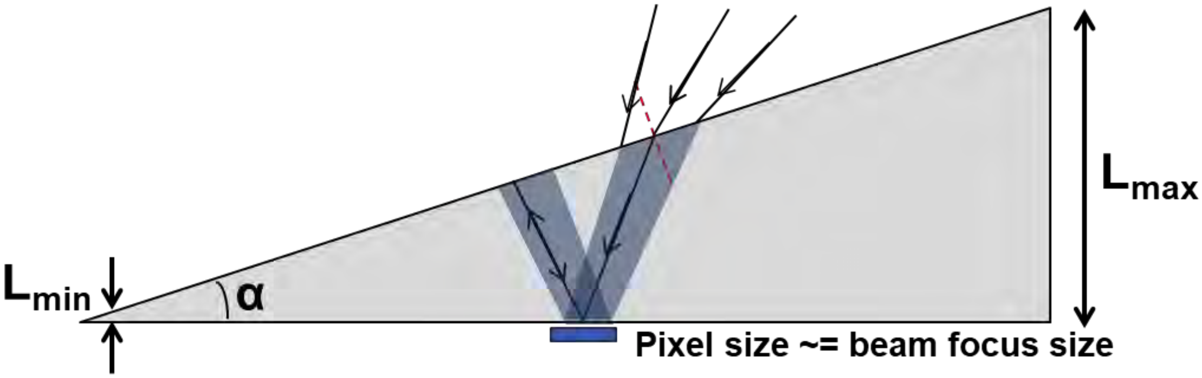


Figure 2. Schematic of wedge describing the important design parameters and beam paths for the two transmitted beams.

Figure 2 illustrates the wedge and highlights the three important design parameters. Namely the minimum thickness, Lmin, the maximum thickness, Lmax, and the wedge angle, alpha. The figure also illustrates the two transmitted beams which provide the wavelength-encoding. The first beam transmits directly thru both the front and back surfaces whereas the second beam reflects off of the back surface followed by another reflection from the front surface before finally transmitting thru the back surface interfering with the first beam. Due to the low front and back surface reflectivity, these are the only two beams that need to be considered. All other beams contain negligible power. This is a novel attribute to this approach and quite different from other etalon approaches which require multiple bounces/beams in order to complete the entire interference encoding. It also reduces the angle sensitivity thereby allowing operation at higher f-numbers of incident light. The design rules for the wedge etalon are as follows:

$$Spectrometer\ bandwidth = \lambda_{lower} = 4 * n * L_{min} \tag{1}$$

$$Spectral\ resolution = \Delta\upsilon\ (cm^{-1}) = \frac{1}{2 * n * L_{max}} \tag{2}$$

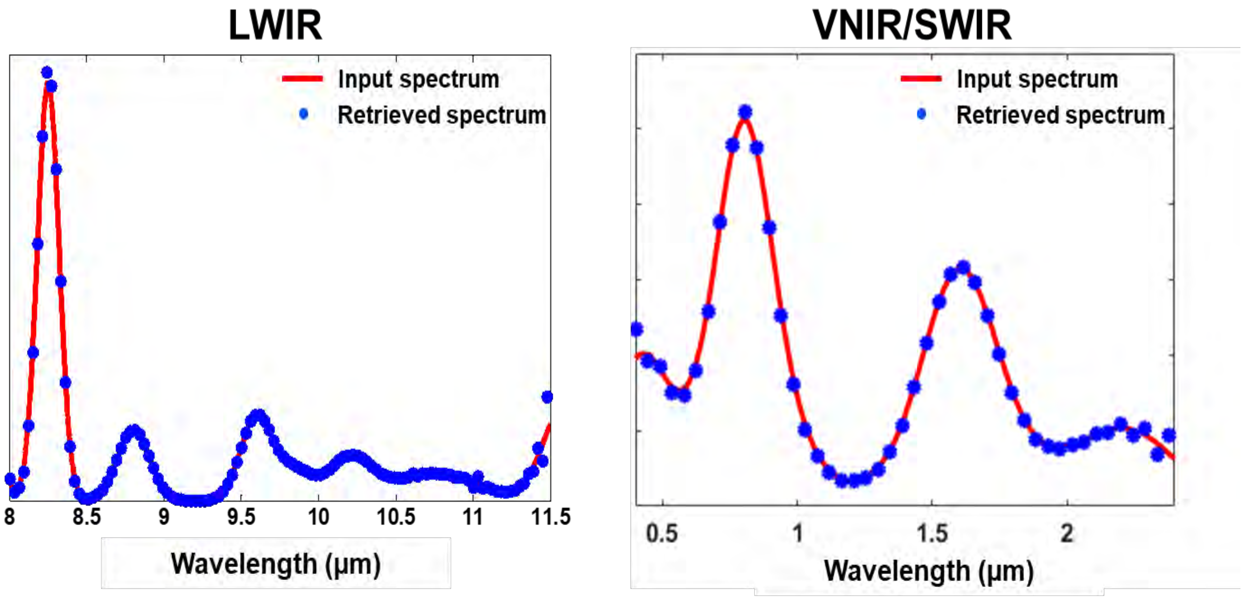
$$Wedge\ angle = \tan(\alpha) \sim \alpha = \frac{L_{max}}{N_{pixels} * pixel\ width} \tag{3}$$

The equations are all that are necessary to fully specify the wedge required based on the desired operational spectral bandwidth and spectral resolution. The number of pixels required to first order is Lmax divided by twice Lmin. However this can be reduced further depending on the exact spectral bandwidth and maximum and minimum wavelengths desired following similar principles found in Fourier sampling of time domain signals. Further analysis of these expressions finds that having a solid etalon with index of refraction, n, results in the following benefits.

- For a fixed spectral resolution, there is a factor of n improvement in f-number
- For a fixed f-number there is a factor of n^2 increase in spectral resolution

The typical index of refraction being considered have values of ~2.5–4 which translates into roughly an order of magnitude improvement in spectral resolution compared to prior air-gap etalons. This benefit applies to all imaging configurations that could be considered and is one of the key enabling aspects of this approach explaining why the program has chosen to only pursue solid etalons.

In order to determine the requirements for wedged etalons, a simulation model was developed incorporating the ability to specify etalon surface reflections, thicknesses, incident spectral distributions, number of pixels and detector noise. This model was exercised to understand the scaling and typical dimensions required for a variety of spectral bands. An example of two designs is shown in Figure 3. The first design case was for a LWIR spectrometer with a few wavenumbers of spectral resolution and the second case was for aVNIR/SWIR spectrometer with ~20 nm of spectral resolution. Upon inspection of the required etalon dimensions it becomes clear that a single substrate is highly unlikely for shorter wavelengths such as VNIR thus requiring a hybrid two material solution. However for the LWIR, the minimum dimension is ~1 µm making it quite possible to use a single substrate. Based on these cases the program elected to pursue two wedged etalon approaches. The first is a hybrid two material design targeting VNIR/SWIR, 0.4–2.4 µm, and the second is a single substrate approach targeting LWIR, 7.5–12 µm.



<u>Design: 116 Spectral Bands, 8 – 11.5 µm</u>

Uncoated Ge wedge index of refraction = 4

Thickness min = 1.5 µm, max = 418.5 µm

Front/Back surface reflection = 36%

FPA = 278 pixels in wedge dimension

<u>Design: 30 Spectral Bands, 0.4 – 2.4 µm</u>

Wedge index of refraction = 1.5

Thickness min = 67 nm, max = 11 µm

Front/Back surface reflection = 18%

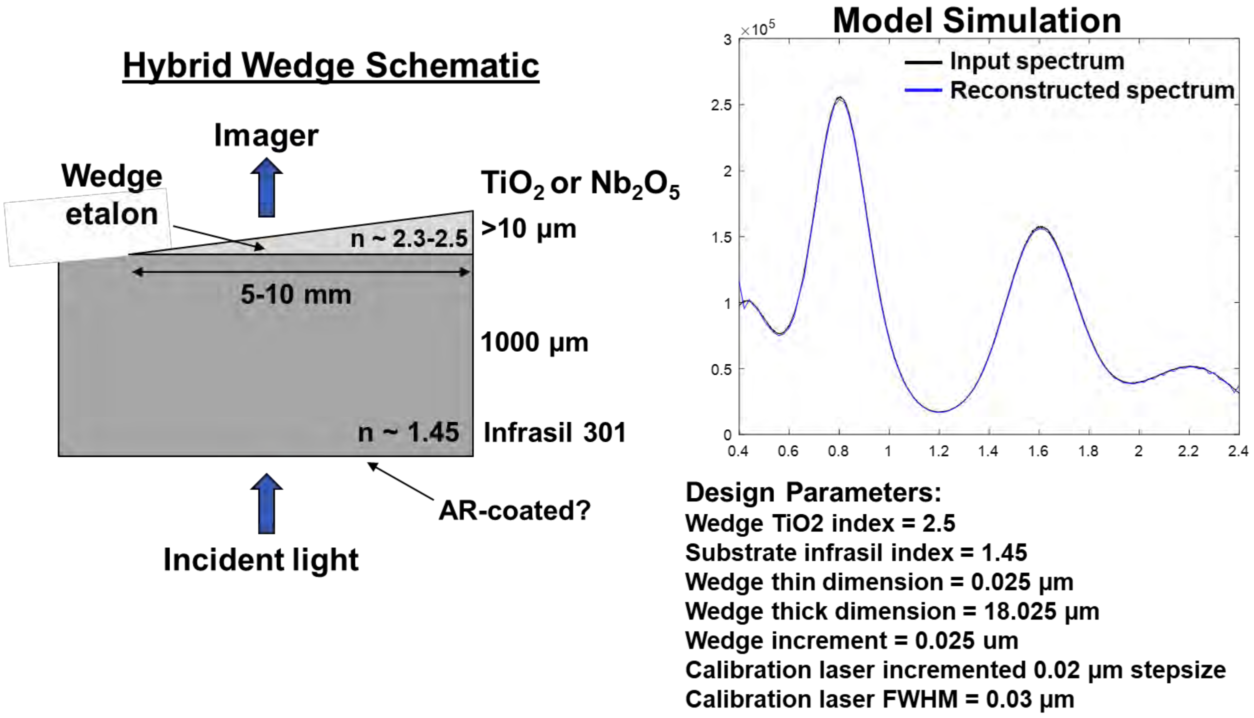
FPA = 128 pixels in wedge dimension

Figure 3. Simulation results for two wedged etalon spectrometer designs.

3. VNIR/SWIR HYBRID WEDGE ETALON DESIGN AND FABRICATION

Based on initial simulations it was determined that a hybrid two material design would be necessary for this spectral band due to the required minimum thickness of ~10s nm. A survey of potential optical materials was conducted targeting both high and low indices of refraction along with a requirement for transparency from 0.4–2.4 µm. Based on the findings of this survey a design was simulated and selected. The spectral bandwidth, 0.4–2.4 µm, and spectral resolution, 20 nm, were chosen as they cover several important applications. The combination of both spectral performance metrics would make this among the highest performing spectrometers for VNIR/SWIR in a footprint no larger than the imager itself. A schematic of the design and etalon requirements output from simulations are shown in Figure 4.

The process fabrication flow for the hybrid etalon design was to first deposit a high index layer with sufficient thickness for the maximum wedge dimension followed by a subsequent polishing step to create the wedge. The first deposition step was carried out by multiple coating vendors applying a variety of deposition techniques. All attempts at deposition of a TiO_2 layer ultimately failed after thicknesses of several microns due to the coefficient of thermal expansion mismatch between TiO_2 and Infrasil substrate. Photographs of typical results are shown in Figure 5.



Design Parameters:

Wedge TiO2 index = 2.5
Substrate infrasil index = 1.45
Wedge thin dimension = 0.025 µm
Wedge thick dimension = 18.025 µm
Wedge increment = 0.025 um
Calibration laser incremented 0.02 µm stepsize
Calibration laser FWHM = 0.03 µm

Figure 4. Schematic of VNIR/SWIR hybrid wedge etalon design along with etalon requirements determined from simulations for a 0.4–2.4 µm bandwidth and 20 nm spectral resolution.

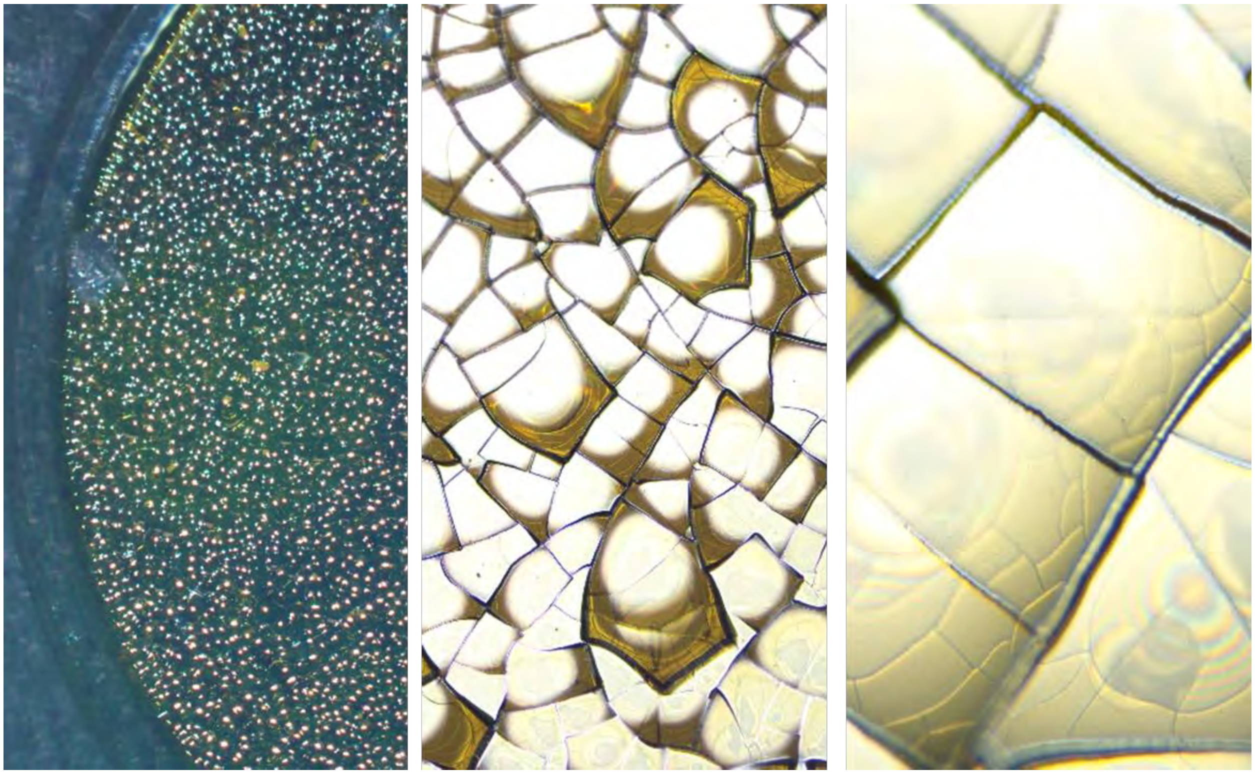


Figure 5. Photograph of cracked TiO_2 coated Infrasil under a variety of magnifications.

Although the coefficient of thermal expansion mismatch was not much smaller for Nb_2O_5 and the Infrasil substrate, a successful deposition occurred for layer thicknesses up to the 30 µm maximum thickness requested. This was additionally followed by successful polishing of the coated substrate leaving a wedged etalon on the Infrasil substrate. Photographs from white light illumination of a polished wedged etalon are shown in Figure 6. The rainbow colored lines indicate wavelength-dependent transmission expected of the wedged etalon which are spatially offset for different wavelength explaining the coloring of the images. The uniformity of the images also appear to indicate uniform etalon performance with no apparent degradation due to stresses from the coating and polishing process steps. These completed parts will be utilized in wedged etalon spectrometer configurations in Year two of the program.

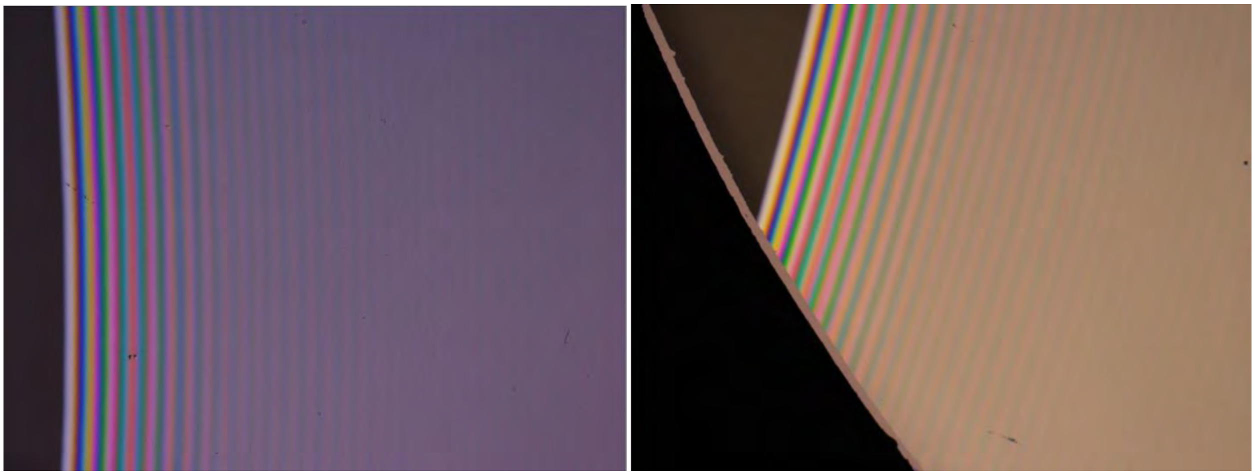


Figure 6. Photographs of white light illuminated wedge polished Nb_2O_5 coated Infrasil 301 substrates revealing the desired wedged etalon.

Due to the early repeated failures of TiO_2 coated Infrasil substrates, a second fabrication process was sought. Rather than depositing a high index of refraction material onto a low index of refraction substrate, a bonding approach would be attempted. Diffusion bonding, also known as adhesive-free bonding such as developed by Onyx optics, should also provide the required optical interface necessary for one of the wedged etalon faces. A second survey was conducted for high and low index of refractions pairs with similar coefficients of thermal expansion required for diffusion bonding. This was quite challenging and lead to a compromise on the optical transmission towards the SWIR end of the spectrum. The two materials eventually selected were BK_7 and Cleartran, which is a trademarked form of zinc sulfide. Cleartran has good transmission across the entire spectrum however BK_7 starts to absorb near 2.4 µm. However this loss may be negligible depending on the final required thickness of the BK_7 substrate. Onyx Optics was contracted to develop the bonding process for these two materials and successfully bonded the materials at the end of the first year. In year 2, the polishing of the wedge into the Cleartran substrate will be performed to determine if the mechanical integrity of the bond is sufficient to withstand the stresses during polishing. If successful then characterization of the final wedged Cleartran will be performed to determine if it performs optically as a thin wedge etalon.

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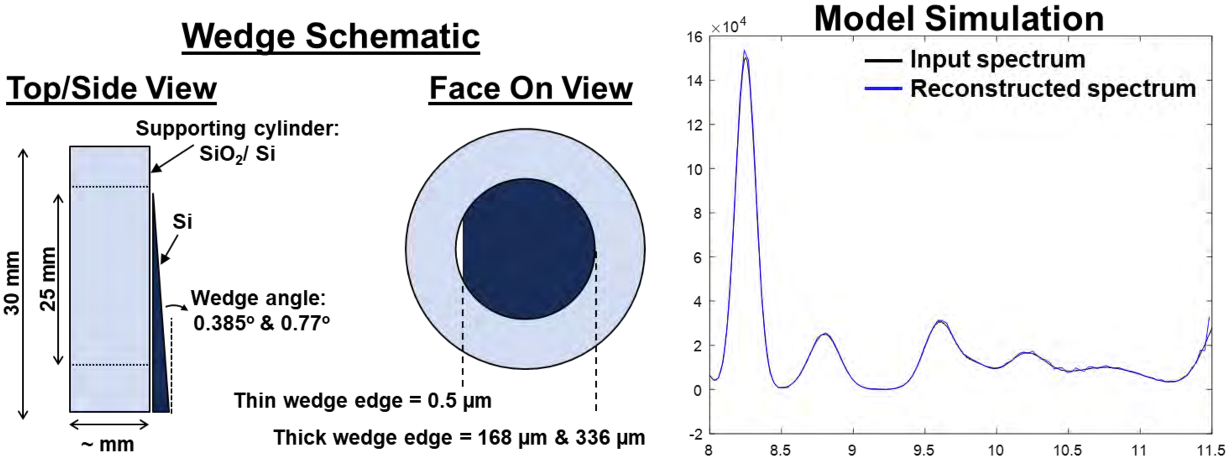
4. LWIR WEDGE ETALON DESIGN AND FABRICATION

Based on initial simulations it was determined that a minimum thickness of ~1 micron would be required for a LWIR wedged etalon making it challenging yet feasible to use a single substrate. Germanium is an ideal substrate material due to it high transmission, availability, and high index of refraction. However as will be discussed shortly, a viable path forward utilizing germanium was not found and silicon was selected. Although silicon isn't typically considered transmissive in LWIR due to the small thicknesses required for the wedged etalon the overall loss to absorption is quite small. Additionally, due to the small thickness of the thin dimension of the wedge an integrated supporting frame was considered as it will likely be required and became part of the overall design. A schematic of the design and etalon requirements output from simulations are shown in Figure 7.



Design Parameters:
Wedge Silicon index = 3.4
Wedge Silicon absorption coefficient = 1 cm^{-1}
Wedge thin dimension = 0.5 µm
Wedge thick dimension = 335.5 µm
Wedge increment = 1.0 µm
Calibration laser incremented 0.03 µm stepsize
Calibration laser FWHM = 0.03 µm
Required pixels = 336

Figure 7. Schematic of LWIR wedge etalon design along with etalon requirements determined from simulations for an 8–11.5 µm bandwidth and 3 cm^{-1} spectral resolution.

Initially, a very similar design was considered using germanium however all vendors and specialists approached essentially no-bid or declined the effort. The common concern was always the thin dimension of the wedge and not having a process reliable enough to produce such a thin dimension or if produced not having a process to release such a fabricated part from the necessary fixturing without fracturing it. Based on this feedback, the substrate was switched to silicon looking to leverage the large infrastructure in silicon processing. Both greyscale lithography and wet etching processes are being considered.

The grand challenge of building a silicon etalon of this nature is the need to remove large amounts a material while maintaining submicron precision and resolution. The end-to-end process flow nearing the end of Year 1 for the silicon etalon is shown in Figure 8. This process integration approach aims to combine processes that can remove large amounts of material, while maintaining precision. However, with this process integration approach, notable fabrication challenges exist. The fabrication challenges are (1) a silicon etch is required to remove the thick handle it reasonable amount of time (less than 8 hours), (2) identification and implementation of masking materials that will withstand long etches, and (3) preservation of the thinnest portion of the etalon.

First, two silicon wafers are prepared as shown in Figure 8.

High Level Restrictions

- Mechanical polishing in optical polishing laboratory was chosen as the process to make etalon at a precise angle. This processes requires parts that are far smaller than 200 mm, therefore, all process steps after the mechanical polish will have to be completed in a laboratory can accommodate piece parts, such as E-lab.
- There are not deep silicon etchers available for this project at MIT LL, outside of the microelectronics laboratory. Therefore, bulk silicon removal will occur via an extended wet etch.

Step 1: Prepare Wafer

Starting wafers are SEMI precision 200 mm at 725 µm thick. The expected precision of selectivity removing 725 µm of the bulk with vary 10% or ±70 µm. This variation is far too large for the final etalon dimensions. Therefore, a platinum thin film is used as and etch stop. The optical fabrication laboratory will polish the wafer at an angle that will remove all of the 725 wafer one end, leaving the thin edge of the etalon unsupported and subject fracture. Therefore, two wafers will be bonded together to increase the overall thickness of the assembly for mechanical support. A thick PECVD deposited oxide is deposited and polished to enable oxide wafer bonding in the next step.

Step 2: Bond Wafer

Two wafers prepared in Step 1 are bonded with a standard oxide bonding approach that is process-of-record in the microelectronics laboratory. Prior to bonding both wafers were cleaned in a bath of H_2O_2 at 70°C for 10 min with ultrasonic excitation. The wafers were put into direct contact for bonding within an hour of cleaning. The wafers were bonded with a wafer bonder from SUSS microtect using recipe R-200_Strength_Imp-1_Triple-Stack. Finally the wafers were annealed for 3 hours at 175°C in furnace. Ultrasonic microscopy indicated complete bonding for all pairs.

Step 3: Dice and Polish

The bonded wafer pairs were sent for dicing into 36 mm x 36 mm squares. Some squares delaminated during dicing and the cause of this delamination was not found. The optical polishing laboratory was successfully able to polish a wedge into the bonded silicon wafer pair leaving an optical quality surface on the polished surface.

Step 4: Mount Sample

For the silicon etch, an acid etch containing nitric acid, hydrofluoric Acid, and acetic (HNA) acid was used to remove the bulk of the exposed silicon wafer. This particular wet etch can remove 725 µm of silicon in about 4 hours if heated appropriately. This acid is aggressive and careful selection masking materials were required to withstand a 4 hour etch. It was determined that a Teflon o-ring serving as the mask for the aperture and black wax (https://www.apiezon.com/index.php/products/applications/etch-resist) were viable as they don't dissolve in aqueous solutions and maintain structural integrity at low temperatures. Other thin film masks (polyimide, Al, Protek –B) were found to peel upon immersion in the HNA acid solution.

Step 5: Remove silicon

The sample holder containing the polished silicon wedge was submerged in HNA which was heated at 35°C, for at least 4 hours to remove the bulk of the silicon. The etch was not uniform and etching rates were found to depend heavily on sample orientation in the wet bath.

Step 6: Remove platinum and oxide

The platinum etch stop held up against the over etch necessary to clear silicon from the aperture. Aquaregia (a mixture of nitric acid and hydrochloric acid) was used to remove both platinum layers. Hydrofluoric acid was used to remove the oxide

Step 7: Remove sample from holder and black wax

The sample can be removed from the holder by deconstructing the holder. Black wax can then be dissolved in toluene or methyl isobutyl ketone (MIBK).

This development is still in process being continued into Year 2 of the program.

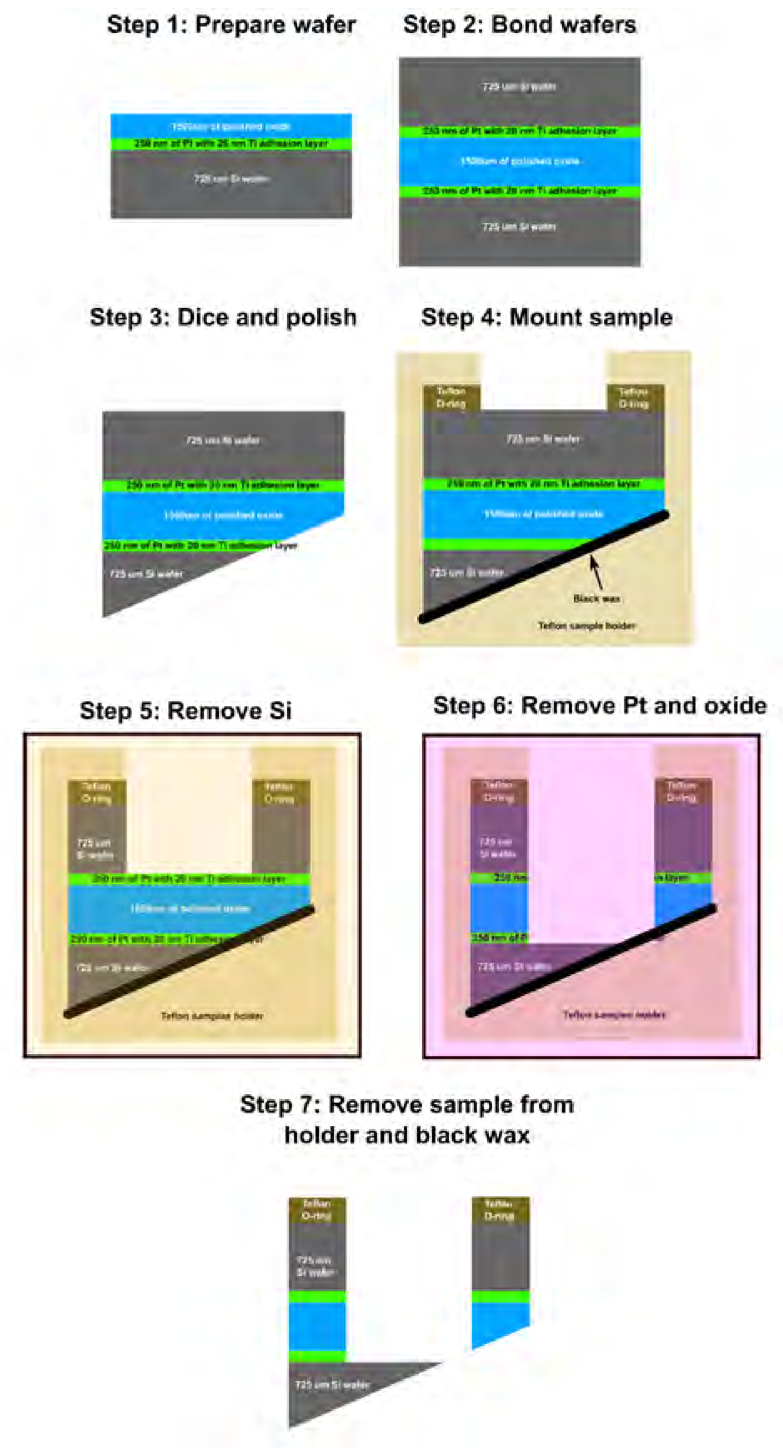


Figure 8. End-to-end process flow of silicon wedge etalon fabrication.

SUMMARY

The Compact Solid Etalon Computational Spectrometer line program is developing fabrication techniques for wedged low reflectivity etalons and algorithms enabling a novel hyperspectral imaging architecture based on a solid low finesse etalon paired with a traditional imager. In order to offer the highest performance spectral imager, solid etalons are necessary compared to alternative air-gap wedged etalons which have been previously investigated. From the program onset, it was decided that pursuit of solid etalons is the key enabling component of this architecture and therefore prioritized. Initial modeling efforts determined the design requirements of wedged etalons targeting two important spectral bands. For the first spectral band, a hybrid two material etalon for use in the visible to short wavelength infrared (VNIR/SWIR), 0.4–2.4 µm, spectral band was selected. Two fabrication approaches for the hybrid wedged etalon were developed during the first year. The first based on a deposition of a thick high index of refraction coating, Nb_2O_5, onto a low index of refraction substrate, Infrasil 301. The second a diffusion bonding based approach of Cleartran and BK_7 substrates. For the second spectral band, a single substrate etalon for use in the long wavelength infrared (LWIR), 7.5–12 µm, spectral band was selected. Initial efforts pursued germanium as the substrate material however no fabrication processes could be found and so the substrate material was switched to silicon to leverage the large silicon processing infrastructure. Although not traditionally considered transmissive in LWIR due to the small thicknesses necessary for the wedge etalon, the absorption losses in silicon are small. The etalon design requirements for both of these spectral bands were discussed along with a description of the overall wedged etalon spectrometer approach.