Modeling Optical Instruments with FRED®

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The capability to model optical instrument prior to detailed design and analysis is very powerful tool that can save schedule time, development dollars, and gives great insight into many facets of a product development effort. FRED® optical engineering software from Photon Engineering has the capability to model optical instruments from the light source through the instrument and sample measurement area and finally to the detector. Each optical instrument has its unique modeling challenges such as complex light source radiance, scanning wavelengths, unique scattering pattern BRDF, dynamic scanning mechanism, multiple paths, polarization, electro-optically active medium, and so forth. I have found FRED® to be capable of modeling just about any instrument I have wanted to model.

Instrument Modeling Benefits

The return on investment of one's time used in developing an instrument model prior to launching a full on development project is astronomical. One of the reasons the return on investment of time is because of the power of FRED® in a trained optical modeling engineers hands. The time to model an optical instrument is very minimal and can be approached in a step wise fashion from basic optical system to increasing levels of complexity and analysis. This step wise method of instrument modeling is an excellent use of the tool in an instrument analysis and development effort. The step wise method of complexity models the critical optical components first and then builds the complexity of the actual hardware shape and size in successive steps. We can see an example of an ellipsometer in model in Figure 1 below.

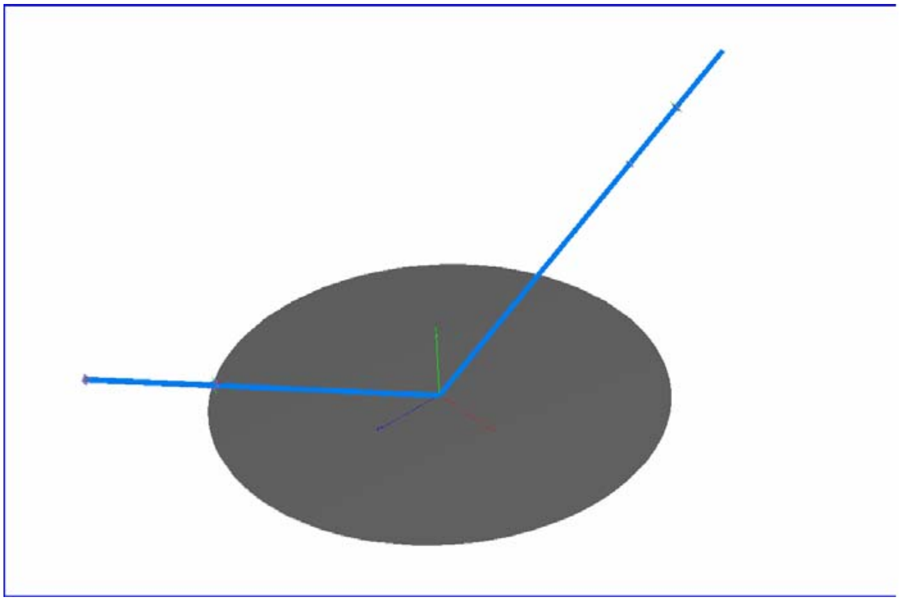


Figure 1. A simple model of an ellipsometer

In this simplified starting model we have a simple collimated monochromatic source of polarized light oriented at a specific angle to the direction of propagation. Between the source and sample wafer we have an compensator which is a simplified model of this component. We put a sampled polarizer on the surface of a window. A real compensator often consists of a Soleil-Babinet Compensator which is two sliding wedges of birefringent optical materials with a wave plate. A Berek Compensator is another type of compensator which is a wave plate with a tilting plate of birefringent optical material. While these two types of dynamic polarization components are easy to model in FRED® their complexity is unnecessary at this point in the modeling of the optical instrument. As the complexity of the optical instrument model needs to increase, the complexity of the optical components can increase in proportion.

Having an instrument model enables one to investigate system design tradeoffs and system design “what if’s” prior to making a hard design specification and spending development funds on drawings, building prototypes, final designs, or final design hardware. Developing an optical instrument software model also enables one to investigate instrument footprints and different packaging ideas and concepts. This is very important when working with industrial designers on your team who often want to shape the outer case of an instrument. The outer case and it shape often interferes with the static or dynamic optical path of an instrument.

In the hands of a capable optical instrument modeler FRED® and quickly and easily perform these optical path gymnastics to analyze different outer case shapes and interactively show the industrial designer the impact of the case shape on the optical design path. This knowledge of optical path impact along with visually seeing the components and ray paths in three dimensions, will almost always enable a more effective and more creative solution for the instrument overall design.

Another benefit of optical instrument modeling is in the signal detection and processing area. Electrical engineers and process engineers can look at signal levels from the instrument measurements based upon how much power reaches the detectors. Based upon the power, irradiance, or other radiometric or photometric based measurement an instrument model can provide signal level information. This information can be used to determine amplifier designs, signal to noise ratios, optical source strength and power supply design or selection. In addition signal level information will also be used by process engineers to understand measurement speed, fabrication throughput, process time, or other production parameters that the optical instrument may affect.

Once a system model exists it is useful to application engineers, production engineers, and marketing engineers to perform “what if” analysis on the use of the optical instrument to measure or characterize “other” materials. Some of these “other” materials will be to understand how the instrument will behave on materials with different refractive index, reflectivity, transmission, BRDF, absorption, colors, spectral bands, measurement speeds, edge slopes and so forth. These “other” measurement requests often lead to instrument accessory development or instrument model enhancement for the next model with larger or different capability for measurement or characterization. With FRED® it is easy to investigate the optical instrument performance to the “other” conditions with the electronic instrument model.

Modeling Optical Sources In FRED®

Following our method of developing an optical instrument moving from simple to complex we can start with a simple optical source and move to more complex models. Initially we typically want to make sure that our source will propagate from the source section through the collection and shaping system, through the measurement or sample section, and finally into the detector and analysis section. Along this path may be apertures, polarization components, static or dynamic mirrors, shutters, irises, lenses, and detectors. It is best to start the simple model with a collimated beam of a single color of unpolarized light.

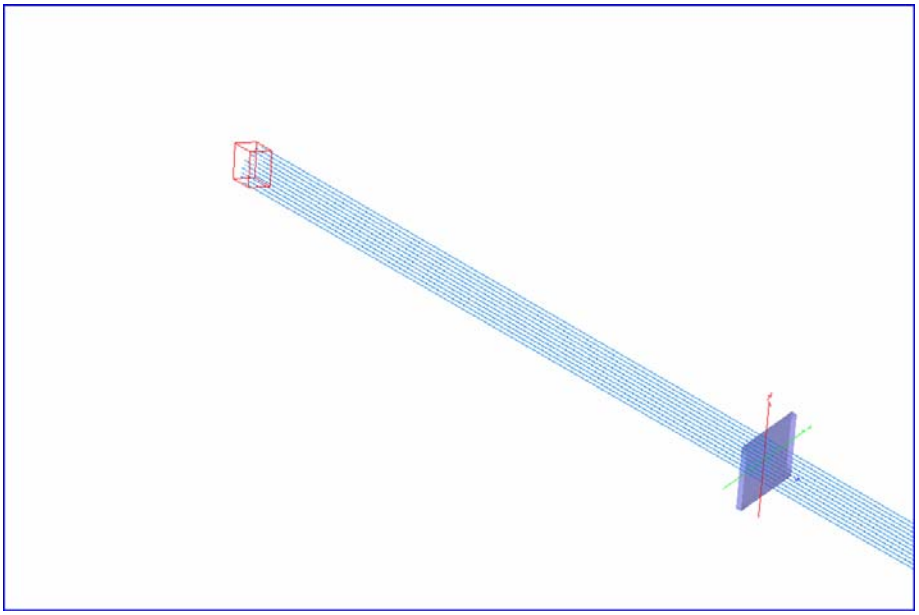


Figure 2. 3mm diameter beam of unpolarized 750nm light

In Figure 2 here we have a 3 mm diameter elliptical cross section (circular) beam of collimated light with 121 rays and a total power of 1 watt which is unpolarized and has a wavelength of 750nm. FRED® has the capability to model point sources, Gaussian and astigmatic Gaussian beams, volume sources, rays into certain angular ranges or shapes with various kinds of apodization. FRED® can also read in ray distribution files from measured lamps.

For our simple model case here we have a broad band tungsten source and we want to perform measurements through the spectrum with our ellipsometer so we will need to scan the wavelength in our model. To scan the wavelength in our model we need to write a script using the FRED® scripting language.

Wavelength Scanning Script Example

```
Steps = 152

For lambdact =  0.290 To Steps-1

        lambda = lambda + 0.01

        SetSourceIthWavelengthSpec 6,0,lambda
        theta = 0 'reset theta value for next loop

        ‘Rotate Polarization Compensator Loop Here

Next 'lambdact
```

Figure 3. Wavelength Scanning Script

This script scans the light source which is object number 6 from 0.3 microns (0.290 + 0.01) to 1.70 microns or 151 steps of 0.01 microns. In the middle of this For Next loop we rotate the polarization compensator. So with some fairly simple scripting and a simple optical source model we have a method to scan the wavelength of the source to develop a more sophisticated optical instrument model that covers from 0.3 to 1.7 microns.

In a typical optical instrument the next section would be the light collection or condenser system who’s job is to collect as much light as possible from the source and get it collimated and pointing down the optical axis towards the measurement chamber. Because we are using a simplified optical source that is collimated we will skip this section in our discussion here.

Optical System and Measurement Chamber

In a spectroscopic ellipsometer the optical measurement configuration is fairly simple. The wafer under test is oriented in a horizontal plane or a vertical plane. The measurement beam is typically incident at a sixty degree angle of incidence with collimated light whose polarization is rotated around the optical axis. The angle of reflection is equal to the angle of incidence due to the law of reflection so if we know the angle of incidence we know where the light will be reflected to for analysis.

We can see this basic optical instrument model layout configuration in Figure 4 below. On the left we have the optical source and then a linear polarizer and then the compensator. This optical source arm is incident at a sixty degree angle of incidence onto the wafer and it also reflects at the same angle or reflection. In the detector arm is a linear analyzer and the detector.

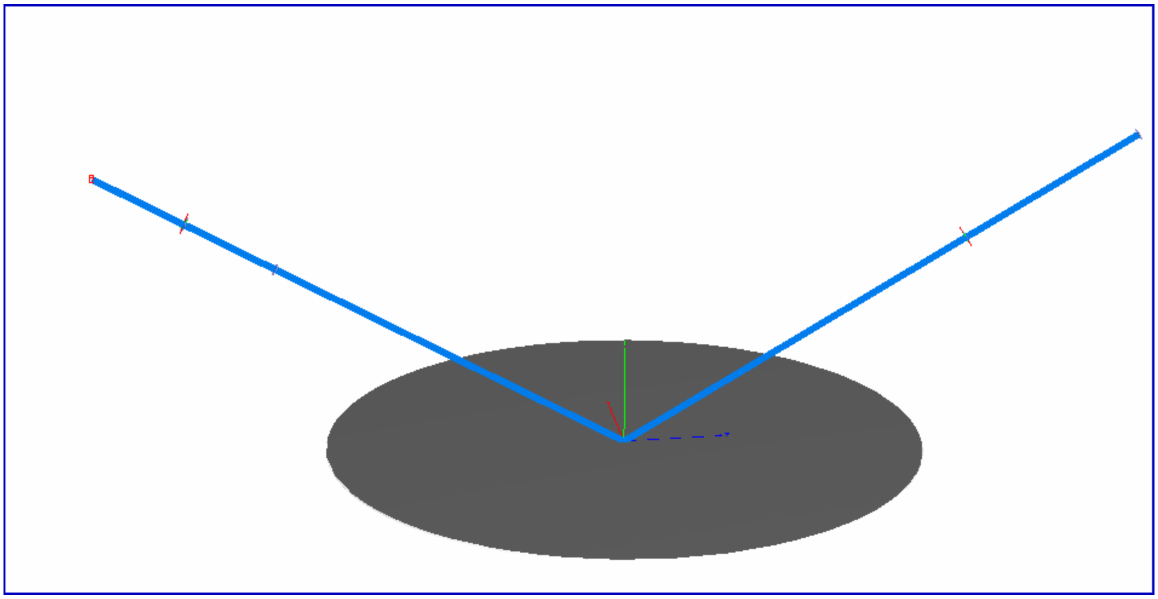


Figure 4. Optical Instrument Model of Ellipsometer Measuring Wafer

In Figure 5 we see a zoomed view of the source arm with the collimated light source the linear polarizer on a square glass window substrate and the compensator which is also on a round glass window substrate. To use a simple model of a linear polarization in FRED® we can put a polarizer wavefront coating or Jones Matrix type coating on the surface of the square glass window substrate. As shown in the Figure 6 below we have put a X type linear polarizer on the second surface of the square window.

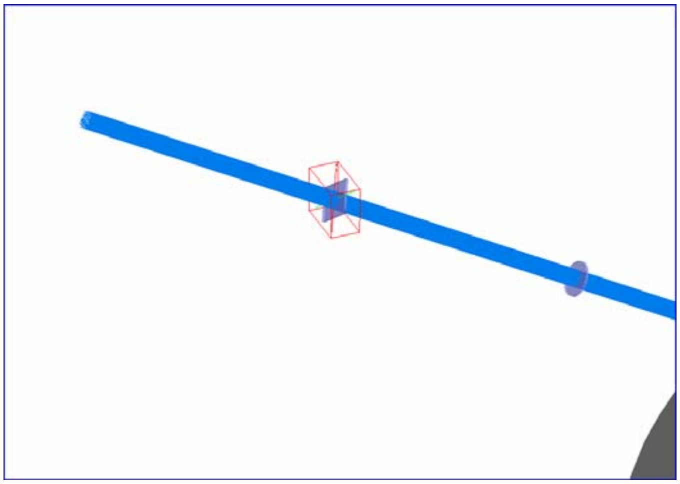
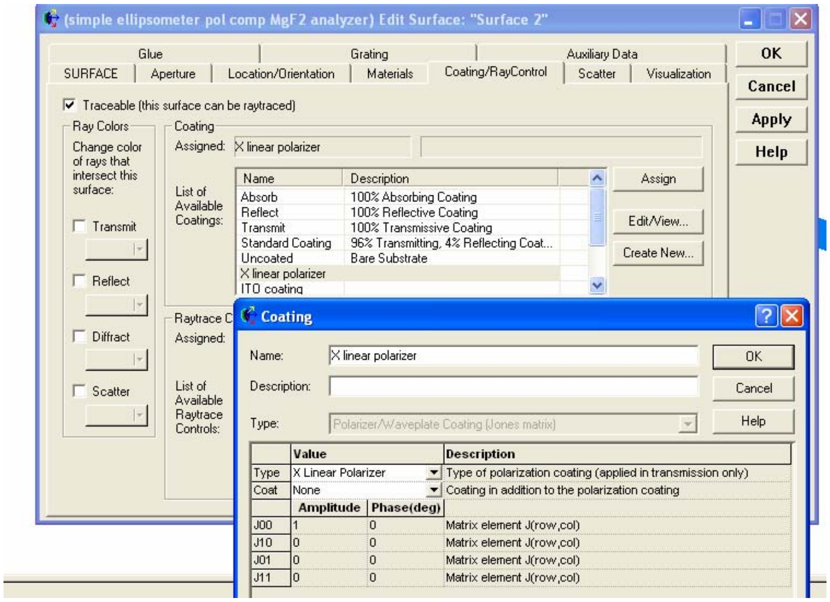


Figure 5. Source, Linear Polarizer, Compensator Substrate

On the second surface of the compensator we have put a polarizer wavefront coating which is a ¼ wave X fast axis type to simulate a quarter wave plate compensator in the most simple method for our initial optical instrument model. In the detector arm of the ellipsometer we have put another polarizer wavefront coating or Jones Matrix type coating on the surface of the second surface of the analyzer widown of the X type linear polarizer. With these three simple coatings and some scripting we have been able to create a simplified spectroscopic ellipsometer instrument model for further modeling and development analysis tasks.



(simple ellipsometer pol comp MgF2 analyzer) Edit Surface: "Surface 2"

☑ Traceable (this surface can be raytraced)

Ray Colors

Change color of rays that intersect this surface:

☐ Transmit

☐ Reflect

☐ Diffract

☐ Scatter

Coating

Assigned: X linear polarizer

List of Available Coatings:

Name	Description
Absorb	100% Absorbing Coating
Reflect	100% Reflective Coating
Transmit	100% Transmissive Coating
Standard Coating	96% Transmitting, 4% Reflecting Coat...
Uncoated	Bare Substrate
X linear polarizer	
ITO coating	

Raytrace C

Assigned:

List of Available Raytrace Controls:

Coating

Name: X linear polarizer

Description:

Type: Polarizer/Waveplate Coating (Jones matrix)

	Value		Description
Type	X Linear Polarizer		Type of polarization coating (applied in transmission only)
Coat	None		Coating in addition to the polarization coating
	Amplitude	Phase(deg)	
J00	1	0	Matrix element J(row,col)
J10	0	0	Matrix element J(row,col)
J01	0	0	Matrix element J(row,col)
J11	0	0	Matrix element J(row,col)

Figure 6. Jones Matrix of Linear Polarizer Coating

Detectors and Signal Processing

In our spectroscopic ellipsometer model as we scan the wavelengths and trace the rays we are concerned with the total power from the source that makes it to the detector. In our FRED® script as you have seen before we scanned the wavelength of the source and we will now show the compensator polarization angle about the optical axis and the reading and recording of the detector total power. At each wavelength we rotate the compensator through 360 degrees of rotation about the optical axis and want to know the maximum and minimum total power levels as well as the compensator angles which correspond to these points.

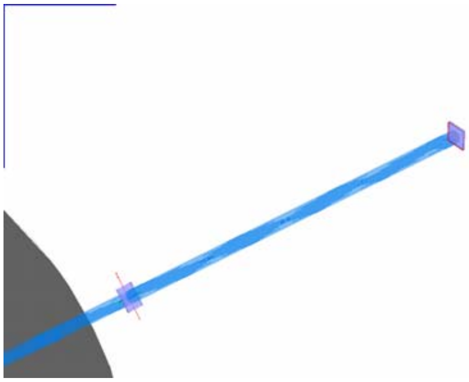


Figure 7. Detector Arm showing Analyzer and Detector

```
theta = 0 'reset theta value for next loop

                'add nested loop: compensator rotation
                For thetact = 0 To ASteps
                'change compensator angle

                SetOperation nSurf, 2, angle

                ' run the raytrace
                        DeleteRays
                        TraceCreateDraw

                'read detector
                Pwr = GetSurfIncidentPower (16)

                ‘find maximum and minimum power
                 If Pwr>maxpwr Then
                        maxpwr = Pwr
                        maxangle = theta
                 End If
                 If Pwr<minpwr Then
                        minpwr = Pwr
                        minangle = theta
                 End If

                'next angle
                theta = theta + 5

                Next
                'thetact

        'open file
        'Open filename For Output As #1
        Print #1, lambda, " ", maxpwr, " ", minpwr, " ", maxangle, " ", minangle
```

Figure 8. FRED® Script for compensator angle scan, ray tracing, and detector power

Within this inner part of the nested loop we first are setting the rotational angle of the compensator and then we perform a ray trace and then get the total power on the detector. Next we compare the current power on the detector to see if it is a maximum or minimum power. Finally we write out the data to a text file that lists the current wavelength, maximum and minimum powers and their corresponding angles, see Figure 9 below. With this measurement information from the simple file we can read this information from the text file into a MS Excel file and perform some additional calculations or plot the data.

Some calculations that we might want to perform would be to multiple the measured power in watts at each wavelength by the detector responsivity, in amps per watt, at the particular wavelength. This simple calculation will enable us to calculate a realistic signal in amps that our electrical engineer or process engineering designers will be interested in knowing.

```
Ellipsometer Data Table
2005-06-02
16:33:42
simple ellipsometer pol comp MgF2 analyzer

Measurement Data for ITO:
wavelength(um), max_power(W), min_power(W), max_angle(deg), min_angle(deg)
0.3 0.064521401873418 0.019028788622735 115 165
0.31 0.061612825804595 0.018317671219753 115 165
0.32 0.058906057897819 0.017788339273321 115 165
```

Figure 9. Sample Data from Text File written by Script

In MS Excel or other similar mathematical calculation programs the data can be used to perform the necessary calculations that the instrument will perform on the data from the detector and polarization information and generate graphs as shown below for modeled data.

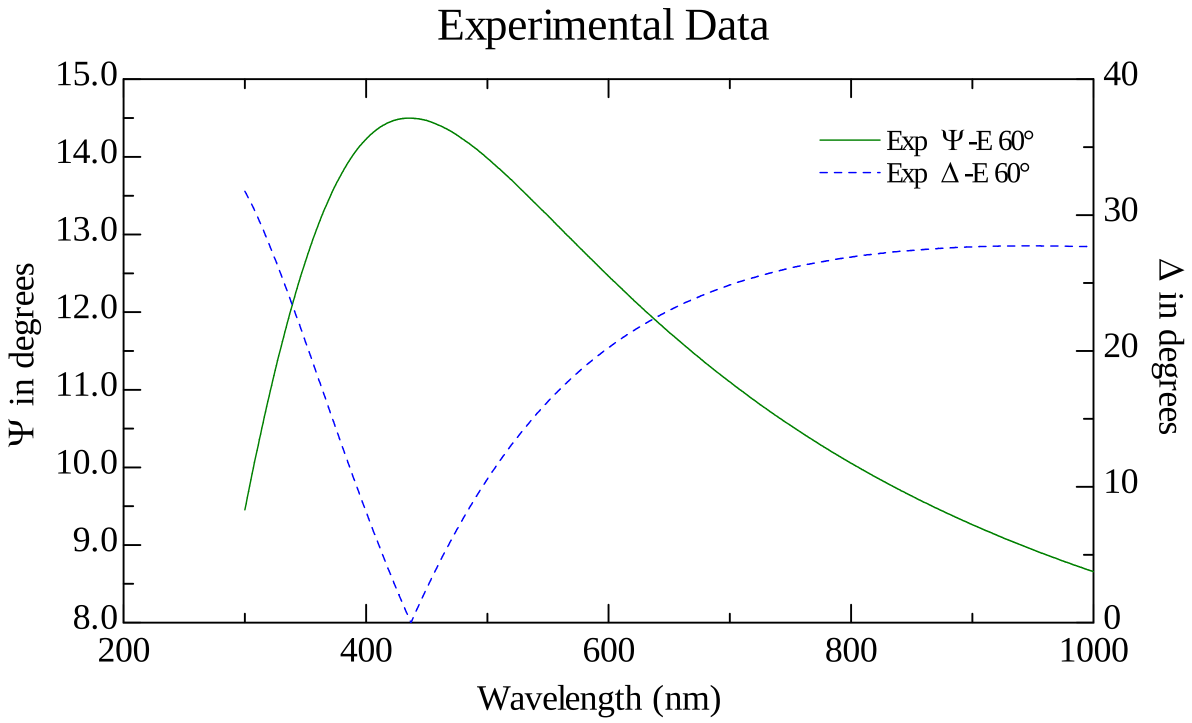


Figure 10. Spectroscopic Ellipsometer Model Data 100nm MgF2 on Glass

At this point with a simple optical instrument model build and debugged one can now start playing what if scenarios with the different optical components or the instrument or sample measurement parameters. The industrial designers can now start looking at playing gymnastics with the optical path of the instrument to perform their packaging miracles to make the instrument case design look wonderful and appealing. The optical instrument model at this point is also very useful as a visual communication tool for managers, marketers, other engineering disciplines, and advertising people. The ability to show an instrument model in 3D and also to spin it around and show different views of the whole system or details of zooming in on subsystem or components in invaluable early on in an instrument development project. For the price of about $5K worth of software and training and about one week it is fairly easy to have a basic model up and running. Of course this all depends upon having the necessary data and some level of proficiency with FRED®. One can always hire a consulting firm to develop the basic model for them quickly and then use the model themselves for modeling, extension, and further development.

Scripting Pseudo Code Basics

I wanted to give a brief outline of the pseudo code scripting that was used to develop this spectroscopic ellipsometer. This pseudo code was used in the development of the actual script.

```
Dimension Variables
Define Parameters
Open File
Write formatted data and headers to file
Initialize variables
Scan wavelength of source loop
Scan compensator angle loop
        Trace rays
        Analyze detector power
Loop compensator angle
Loop wavelength
```

This script scanned the wavelength of the source from 300 to 1000nm in 10nm increments and moved the compensator 360 degrees around the optical axis in 5 degree increments while tracing 81 rays at each position. This combination of 70 wavelength, at 72 rotational positions, and tracing 81 rays at each position accounts for over 400K rays being traced in a matter of minutes to perform a simulated optical instrument measurement sample. This automation by scripting in FRED® is quite powerful and an incredible time savings compared to manually performing these wavelength, compensator rotations, ray tracings, power readings, and max/min comparisons.

I should also point out that with the FRED® scripting that any parameter or variable that one can change manually can be changed using scripting. These parameters might include positions such as the six degrees of freedom of every surface and component, wavelengths, polarizations, power, coherence, surface – radius, center thicknes, temperature, pressure, number of pixels, positions, raytrace properties such as transmission or reflection, scatter properties, visualization features, colors, and so on – your mind is the only limit.

Off the Shelf Breadboard Modeling – Catalog Components

The main emphasis of this white paper has been to model custom optical instruments. We also realize that more often engineers are called upon to setup experiements and breadboards of instruments using off the shelf catalog components. You are in luck here also. One can download opto-mechanical drawings of the various components that are planned to be used in the breadboard and arrange them and put in beam paths and ensure the model will work prior to purchasing the components.

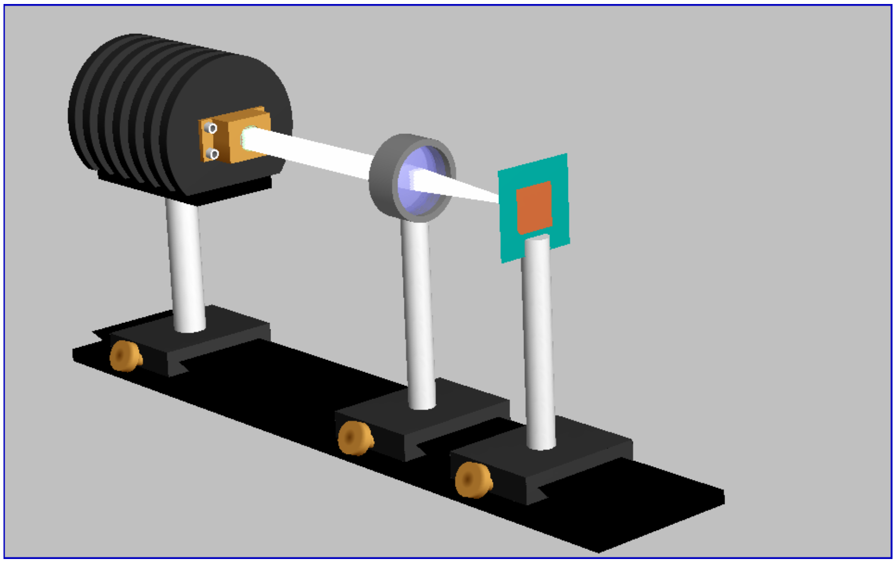


Figure 11. Laser Diode Off-the-shelf breadboard design

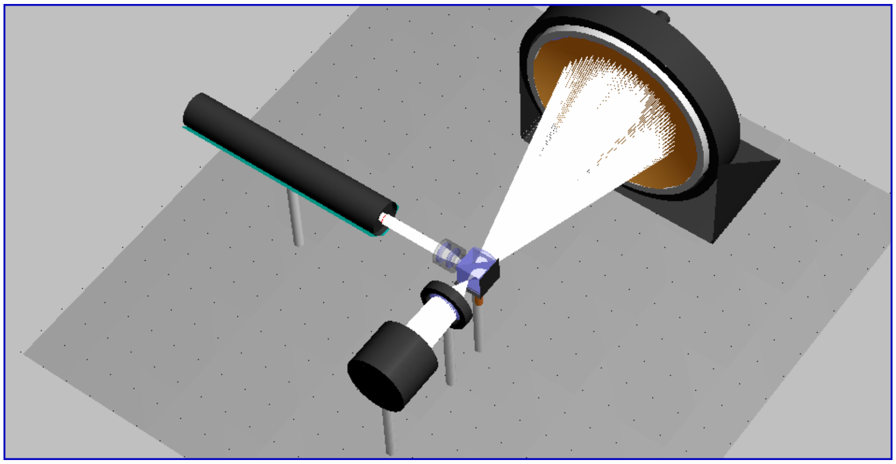


Figure 12. Shack Cube Interferometer Off-the-shelf breadboard