

Simulation of laser diode to fiber coupling

INTRODUCTION

This knowledge base article discusses how to use FRED to accurately model the coupling from a ball-lens capped semiconductor laser diode to a single mode fiber - an optical system common in optical fiber communication applications. This model demonstrates FRED's capability to propagate coherent fields, its accurate Laser Diode Beam source type and its ability to calculate fiber coupling efficiency.

Longitudinal, horizontal and angular alignment sensitivity of the fiber position is studied via embedded scripts.

THE MODEL

The semiconductor laser diode used in this FRED model is the Mitsubishi ML725C8F. This is an InGaAsP / InP multiple quantum well (MQW) laser that operates at 1310nm wavelength. The Mitsubishi source specifications define the output beam divergence angles in x and y to be 25 and 30 degrees respectively (full 1/e width of the power far field profile). No mention is made of any offsets in the focal positions in x and y so they are assumed to be coincident and at the source.

This laser diode source is modeled in FRED using the *Laser Diode Beam* source type and is set to produce coherent input.

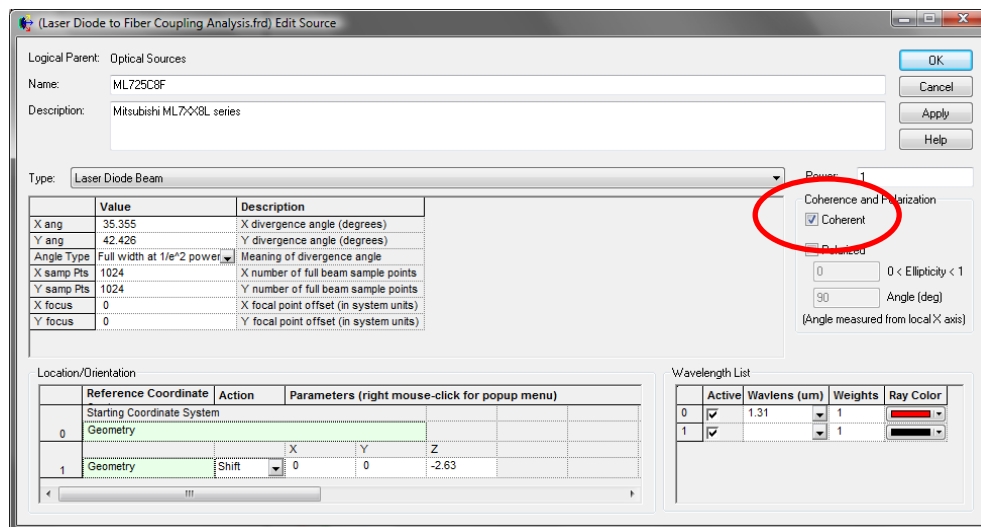


Fig 1. Edit Source panel of the laser diode source.

Note that in the settings for the *Laser Diode Beam* source, the divergence angles are defined by the $1/e^2$ level of the power. This requires that the angles provided by the manufacturer are multiplied by a factor of $\sqrt{2}$.

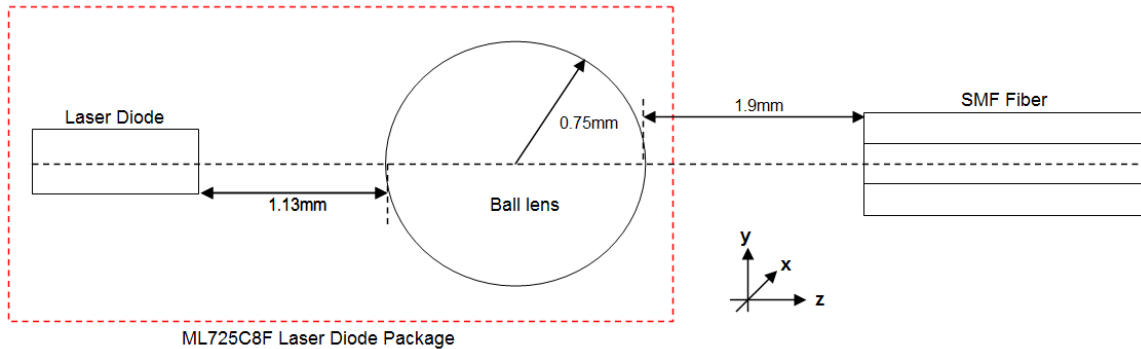


Fig 2. Schematic (Side View) of the ball-lens capped laser diode to fiber system

The 1.5mm diameter ball lens is part of the Mitsubishi laser diode package and is positioned 1.88mm from the emitting surface of the laser diode.

This is created in FRED using a spherical *Element Primitive*, and for convenience, the global origin is chosen to be where the output surface of the ball lens intercepts the optical axis.

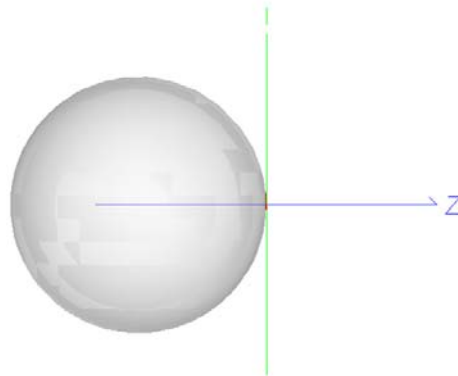


Fig 3. The definition of the global origin

It should be noted that FRED's N-BK7 model is used to define the material of the ball lens. The refractive index used at 1310nm wavelength is 1.5036.

The single mode fiber (SMF) used in the model is located 1.9mm from the global origin and its structure (defined in the figure below) is based on values that are typical for a SMF. The fiber core has radius 5 microns and is surrounded by a cladding that is 125 microns across. The refractive index values for the core and the cladding are 1.465 and 1.47 respectively giving a refractive index difference of 0.36%.

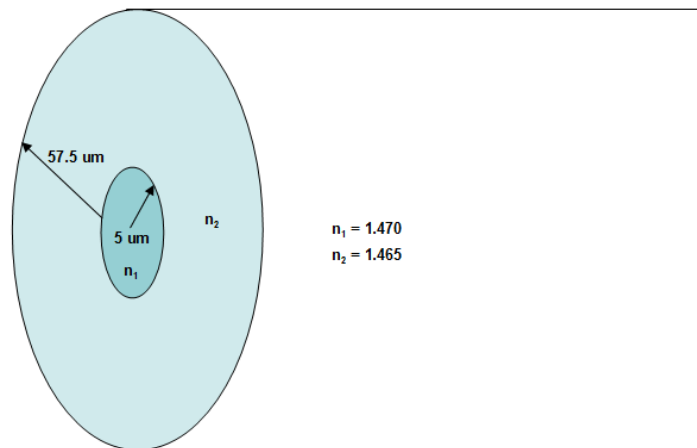
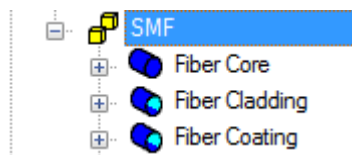


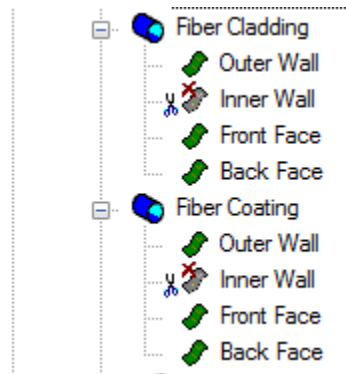
Fig 4. Schematic of the single mode fiber

An absorbing coating, or jacket, that surrounds the fiber is also included in the model.

The fiber is defined in FRED as a *Subassembly* consisting of multiple *Element Primitives* – a cylinder for the core, and pipes for both of the cladding and coating:



Note that inside wall of the “Fiber Cladding” pipe exactly coincides with the outer wall of the “Fiber Core” cylinder. To model this correctly the user needs to manually set the *Inner Wall* of the cladding pipe to be *Never Traceable*. Failure to do this will lead to raytrace errors as we have two surfaces located at exactly the same position in space and with two different sets of materials. The same needs to be done for the *Inner Wall* of “Fiber Coating.”



In this model the fiber coating is considered to be absorbing and has *Halt All* raytrace control. All other surfaces are uncoated.

SIMULATION

FRED calculates the fiber coupling efficiency (CE) using the following equation:

$$CE = \frac{\iint E_{inc} E_{fiber}}{\iint E_{inc} E_{inc}^*}$$

where E_{inc} is the incident field, and E_{fiber} is the field profile of the fundamental mode of the fiber (calculated automatically by FRED given the fiber specifications).

In general, CE is a complex quantity, and therefore the coupled power is actually

$$CE_{power} = Re[CE]^2 + Im[CE]^2$$

Therefore to calculate the fiber coupling accurately an *Analysis Surface* needs to be located just behind the fiber entrance to ensure that the reflection coefficient at this interface is correctly taken into account.

It is important that the *Analysis Surface* is larger than the expected mode field diameter (MFD) of the fundamental mode so as to perform an accurate overlap integral. It is also important to be aware that the accuracy of this numerical integration is dependant on the number of divisions in the *Analysis Surface*. In this case 251 x 251 on a 50um wide *Analysis Surface* is deemed sufficient.

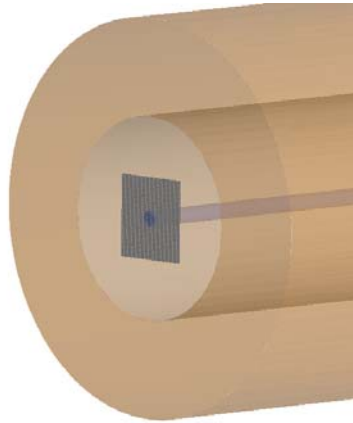


Fig 5. Showing the Analysis Surface just behind the fiber interface

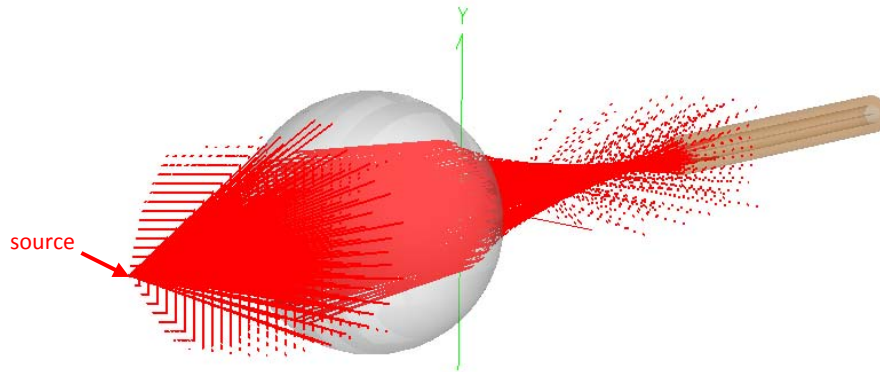


Fig 6. Source with 128 x 128 sample points traced and rendered through the system

The value returned by FRED's fiber coupling efficiency calculation is the overlap fraction between the two field profiles. It does not take into account the power of the incident field. Therefore understanding how much power is coupled to the mode must be done in two steps:

1. Determine the amount of power (P) at the *Analysis Surface* by performing an Irradiance calculation
2. Determine the CE fraction from the fiber coupling efficiency analysis

The amount of power that is coupled to the fiber mode is given simply by $P * CE_{power}$.

After tracing the rays from the source with 2048 x 2048 sample points, the fraction of source power that reaches the *Analysis Surface* behind the fiber interface is displayed in the *Output Window* when we calculate the Irradiance.

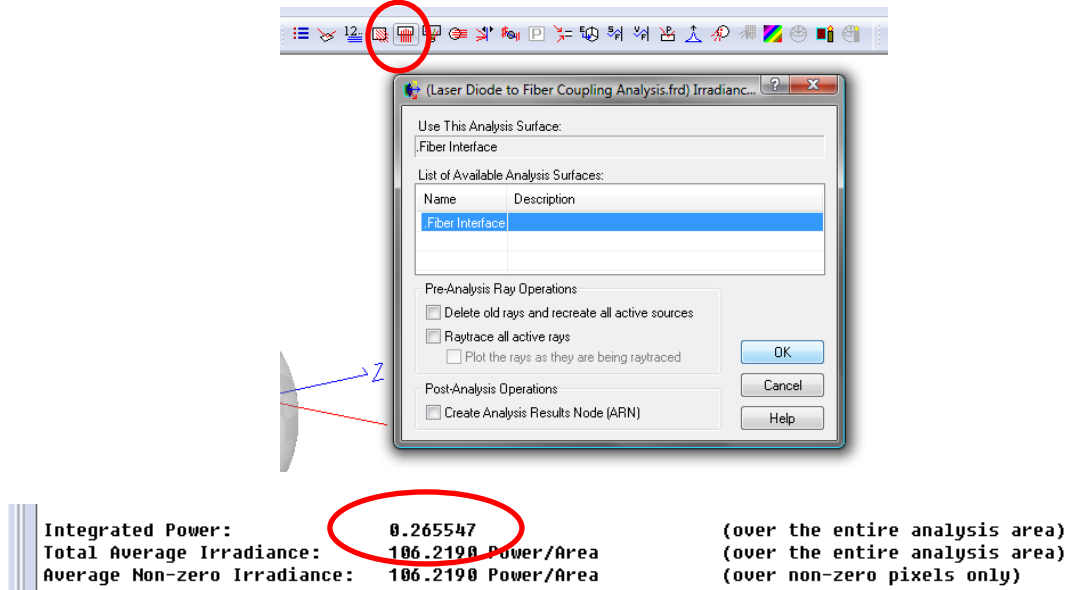


Fig 7. Integrated power at the Analysis Surface

26.55% of the source power reaches the *Analysis Surface*. To determine the coupling to the fiber mode FRED's *Fiber Coupling Efficiency* analysis is used. Note that the fiber core radius of 0.005mm has to be entered explicitly here.

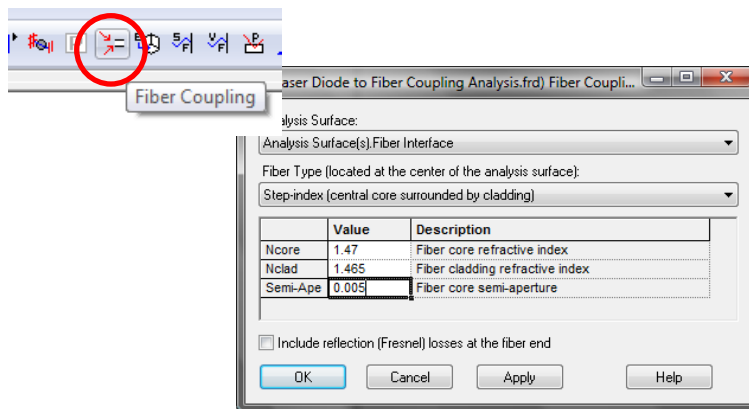
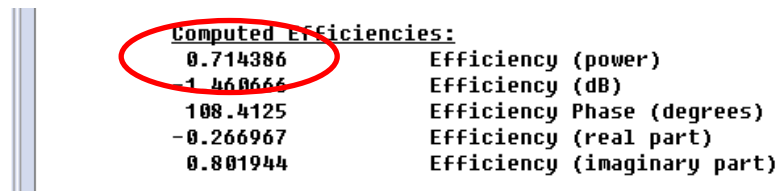


Fig 8. The Fiber Coupling Efficiency Analysis Dialog

After clicking OK, the results are displayed in the *Output Window*.



<u>Computed Efficiencies:</u>	
0.714386	Efficiency (power)
-1.460666	Efficiency (dB)
108.4125	Efficiency Phase (degrees)
-0.266967	Efficiency (real part)
0.801944	Efficiency (imaginary part)

Fig 9. The coupling efficiency as displayed in the *Output Window*

The coupling efficiency is 71.44%. Therefore in this system the total coupled power percentage is $71.44\% * 26.55\% = 19.0\%$.

The ML725C8F laser diode source operates at 5mW, therefore in this configuration, the fiber will be transmitting a signal of just under 1mW.

ALIGNMENT SENSITIVITIES

Understanding the fiber alignment sensitivity is critical for gauging the design tolerances and consequently the feasibility of a laser diode / fiber package. This can be done quite simply using FRED's scripting functionality.

There are three embedded scripts associated with this FRED document:

- Distance Scan
- Lateral Offset Scan
- Tilt Scan

The three scripts are similar to each other: each script adjusts the position of the fiber in user-controlled steps and calculates the coupling efficiency and prints the data to the Output Window and into a Microsoft Excel spreadsheet (if desired).

Longitudinal alignment sensitivity

At the top of the Distance Scan script the user inputs the start and end positions of the fiber and the resolution of the scan that they wish to run.

The flag *exportToExcel* is set to True if the user wishes FRED to print the data to a Microsoft Excel spreadsheet and plot a graph.

```

*****SCAN SETTINGS*****
'Z-position of the fiber interface
      startVal    = 1.7
      endVal      = 2.0
      resolution  = 0.05
      exportToExcel = True
*****SCAN SETTINGS*****

```

Just under this the fiber parameters are defined. These are used for the fiber coupling efficiency calculation only.

```

*****FIBER SETTINGS*****
      wavelength = 1.31
      core_mat_id = FindMaterial( "Fiber Core" )
      clad_mat_id = FindMaterial( "Fiber Cladding" )
      n_core      = RefractiveIndex ( core_mat_id, wavelength )
      n_clad      = RefractiveIndex ( clad_mat_id, wavelength )
      r           = 0.005           'mm
*****FIBER SETTINGS*****

```

After the headers are printed, the main loop of the script starts. This is a “For” loop that will step by step alter the position of the fiber - [1], trace the rays - [2], calculate the Irradiance & determine the total power - [3], calculate the fiber coupling coefficient - [4], and finally calculate the mode power - [5].

```

Main Loop
For i = startVal To (endVal + resolution/2) Step resolution

  EnableTextPrinting(False)

  'set fiber position
  GetOperation fiberID, 1, op [1]
  op.val3 = i
  SetOperation fiberID, 1, op
  Update
  LoadAnalysis anaID, ana

  'trace rays
  DeleteRays [2]
  TraceCreate

  'create ARN of Irradiance at fiber and determine total power
  numRays = IrradianceToARN( anaID, "FiberPower " & i, arnNode ) [3]
  fiberPower = ARNComputeTotalPower( arnNode )

  [4] calculate fiber overlap coefficient
  :ount = FiberCoupleStepIndex( coupleReal, coupleImag, surfID, -1, ana, r, n_core, n_clad )

  [5] E = (coupleReal*coupleReal + coupleImag*coupleImag)

  'true coupling to fiber mode is total power multiplied by the overlap coefficient
  modePower = fiberPower * CE

```

Fig 10. The main loop of the “Distance Scan” script

Note that the function *FiberCoupleStepIndex* returns two values – “coupleReal” and “coupleImag” these variables are the real and imaginary coefficients.

The figure below shows the results for varying the distance from the ball lens to the fiber from 1.5mm to 2.5mm.

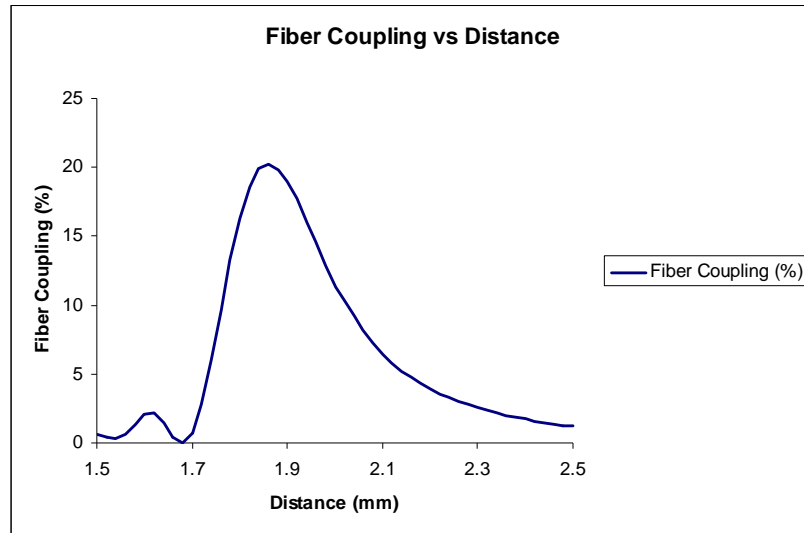


Fig 11. Fiber coupling vs Distance

The manufacturer of the laser diode, Mitsubishi, specifies that the maximum fiber coupled power is 0.8mW (16% efficiency) at a position of 1.9mm from the ball lens. FRED calculates a slightly larger value for the coupling. This difference can be explained by the fact that the coupling is very sensitive with respect to the fiber mode size and refractive index profile. Unfortunately the exact details of the fiber used by Mitsubishi are not given.

Horizontal alignment sensitivity

The script “Lateral Offset Scan” is very similar to previous, except that the user defines the following parameters for the scan:

```

*****SCAN SETTINGS*****
'X or Y position of the fiber interface
startVal   = -0.010
endVal     = 0.010
resolution = 0.001
horizontal = True  'True = horizontal shift, False = vertical shift
zpos       = 1.86  'relative to (0,0,0)
exportToExcel = True
*****SCAN SETTINGS*****

```

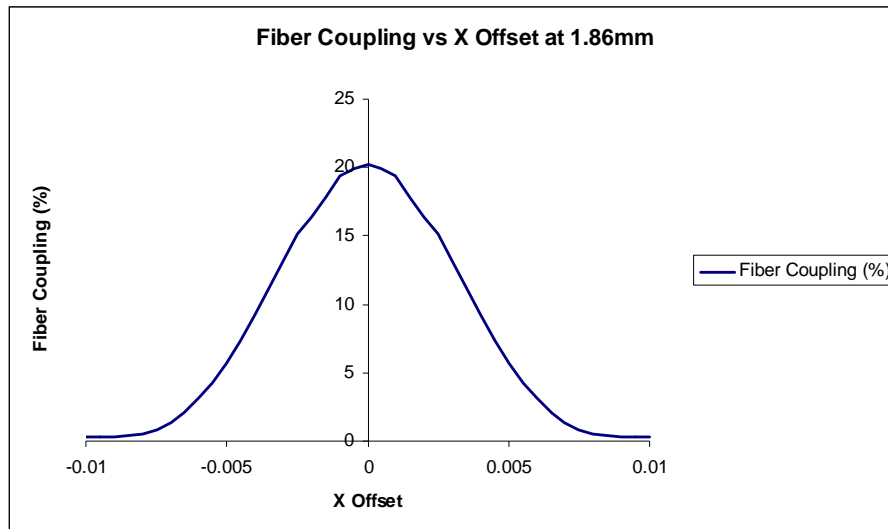


Fig 12. Fiber coupling vs horizontal offset at position $Z = 1.86$ mm

Orientation sensitivity

This script is also very similar to the previous scripts; here the user defines the angular range of the orientation. Note that this script tilts the fiber in the horizontal direction only, not at an arbitrary angle.

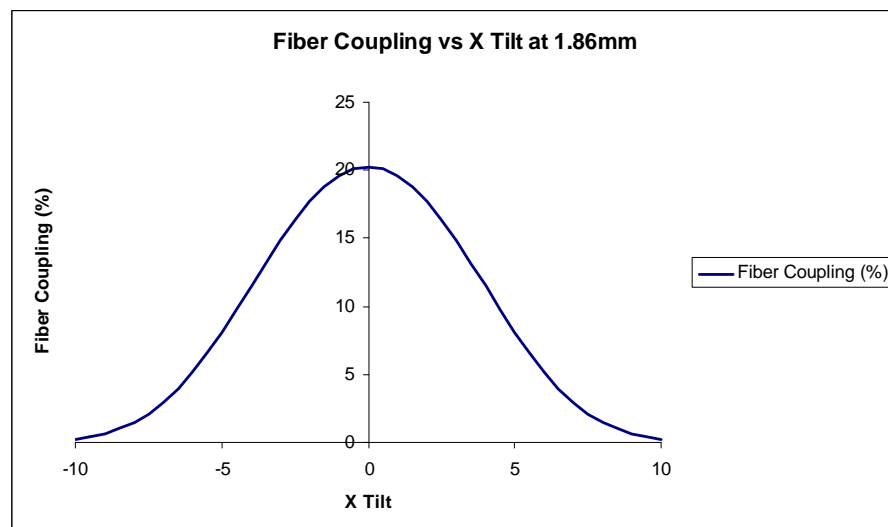


Fig 13. Fiber coupling vs horizontal tilt at position $Z = 1.86$ mm

CLOSING REMARKS

In this article FRED has shown to be capable of accurately calculating the coupling from a laser diode to a fiber. The result agrees well with the coupling information provided by the laser diode manufacturer. FRED's coherent propagation capability and accurate definition of a highly divergent coherent is critical for modeling this type of problem.