Design of a Broad Wavelength Range Single Mode Fiber Coupling Optic

Design Description Document

OPT311 Senior Design Class

Customers	Tao Chen - ASML, Wilton, CT Teus Tukker - ASML, Veldhoven, NL
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Statement:

The Design of a Broad Wavelength Range Single Mode Fiber Coupling Optic project is a senior design driven fiber coupling lens system. As such its design inputs were derived from our collaborative efforts with our project customers and advisors, Tao Chen, Teus Tukker, Govind P. Agrawal, Julie Bentley, and Jacob Roccabruna.

This document has been approved by our customer (04/28/2023).

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1. Statement:

The Broad Wavelength Range Single Mode Fiber Coupling Optic project aims to investigate and model the coupling effects for discrete wavelengths in the broadband range of 400 to 2000 nm through an optical system. This project is conducted with the help of our project customers Teus Tukker and Tao Chen from ASML, and the design correction and additions are suggested by our faculty advisors Govind Agrawal, Julie Bentley, and Jacob Roccabruna.

We are not responsible for the production of the design and manufacturing of the design. We are not not responsible for the testing cost and potential damage due to the observation process.

2. Vision:

The prospective design product is a broad wavelength range single mode fiber coupling optical system intended for alignment in ASML lithography machines. Our goal is to investigate a design of a broadband fiber coupling optical system that couples a diffraction limited parallel beam of light into a single-mode fiber over a wavelength range from 400 to 2000 nanometers. We intend to accomplish our goal by modeling the design using OpticStudio with off-the-shelf parts from Optimax, and conduct performance analysis to determine parameter tolerances. We have freedom to design our own rotationally symmetric lenses and mirrors with the addition of an optional aspheric surface. Our design may include custom parts as long as these parts fulfill manufacturing tolerances of Optimax. We then aim to use this design to explore possible modes of manufacturing within volume, cost, and material specifications. In order to model the alignment properties of our setup, we will be demonstrating a single mode fiber and laser available for interactive alignment at the poster session.

3. Environment:

Our product is designed for use in an ASML SMASH (Smart Alignment Sensor Hybrid) Machine. The conditions within the machine are cleanroom grade ISO 5, defined by the following specifications:

- 21 ± 2 degrees Celsius
- Maximum particles/ft^3:
    - 3,500 $\geq$ 0.1 μm
    - 750 $\geq$ 0.2 μm
    - 300 $\geq$ 0.3 μm
    - 100 $\geq$ 0.4 μm
    - 0.7 $\geq$ 0.1 μm
- Relative Humidity: >0%

4. Regulatory Issues:

Given the scope of the project, regulatory requirements for this project will not be an immediate priority. The conceptual design is the main goal, however, with the possibility of completion before due time, manufacturing and tolerancing within the lithography machine system would require regulatory standards.

As standard for manufacturing facilities at ASML, the company follows ranges of ISO 7 through ISO 1 cleanroom standards. These range from basic shoe covers, safety glasses, hair nets, face covers, to full contamination suppression suits.

5. Fitness for Use:

The system will:

- Couple a 10 mm beam of a diffraction limited broadband source in free space into a fiber optic cable
- Perform optimally for 10 discrete wavelengths within the range of 400-2000 nm
- Maintain a numerical aperture of 0.15 for an object located at infinity
- Have a source mode matching the fiber input mode
- Be rotationally symmetric

It is desirable that:

- The design will incorporate spherical lenses, mirror surfaces, and an optional single aspheric surface
- Materials for lenses be chosen from the preferred glass list provided by customer
- The volume of the design does not exceed 300x100x100 mm^3
- Zernike aberrations are minimized
- Coupling efficiency of the optical power into the fiber is maximized
- The system does not exceed 6 surfaces
- The system optics are designed from a maximum of 3 materials

We are not responsible for:

- Producing a design that performs optimally for all wavelengths within the range 400 to 2000 nm outside of the 10 selected discrete wavelengths chosen for the design
- The coupling design at the fiber output

6. Timeline

Spring Semester:

January: Meet with customers to discuss final design constraints. Meet with advisors to discuss optimization.

- 1/11: Team meeting to discuss DDD plans and timeline
- 1/18: DDD 1 review in class with feedback
- 1/24: Customer meeting to discuss design and prototyping/demonstration
- 1/30: DDD 2 review in class with feedback, team meeting for logistics
- 1/31: Advisor meeting to discuss design progress and potential demonstration

February: Optimize model with faculty and customer feedback.

- 2/1: Team meeting to discuss design feedback and optimization
- 2/6: Team meeting to discuss logistics and responsibilities
- 2/7: Customer meeting to discuss design progress
- 2/8: Team meeting to discuss design feedback and optimization
- 2/13: DDD 3 review in class with feedback, team meeting for logistics
- 2/14: Advisor meeting to discuss design progress
- 2/15: Team meeting to discuss design feedback and optimization
- 2/20: Team meeting to discuss logistics and responsibilities
- 2/21: Customer meeting to discuss design progress
- 2/22: Team meeting to discuss design feedback and optimization
- 2/27: DDD Midterm review in class with feedback, team meeting for logistics
- 2/28: Advisor meeting to discuss design progress

March: Optimize model with faculty and customer feedback, submit design for custom optics components if necessary

- 3/1: Team meeting to discuss design feedback and optimization
- 3/4: DDD Midterm due
- 3/13: Team meeting to discuss logistics and responsibilities
- 3/14: Advisor meeting to discuss design progress
- 3/15: Team meeting to discuss design feedback and optimization
- 3/20: Team meeting to discuss logistics, Industrial Associate pitch rehearsal
- 3/21: Customer meeting to discuss design progress
- 3/22: Team meeting to discuss design feedback and optimization
- 3/27: Team meeting to discuss logistics and responsibilities
    - Final day for custom optic design prototype submission for manufacturing
- 3/28: Advisor meeting to discuss design progress
- 3/29: Team meeting to discuss design feedback and optimization
- 3/30: Industrial Associate’s Meeting

April: Develop prototype with customers. Test product in machine environmental conditions.

- 4/3: DDD 5 review in class with feedback, WordPress page development
- 4/4: Customer meeting to discuss design progress
- 4/5: Team meeting to discuss design feedback, WordPress page development
- 4/10: Team meeting to discuss logistics and responsibilities
- 4/11: Advisor meeting to discuss design progress
- 4/12: Team meeting to discuss design feedback and optimization
    - Final day to order non-custom parts for design prototype
- 4/17: Final DDD review in class, team meeting to discuss logistics
- 4/18: Final customer meeting
- 4/19: Team meeting to discuss poster design
- 4/24: Team meeting to discuss logistics and poster design
- 4/26: Team meeting to discuss poster design
    - Final day to print poster
- 4/28: Hajim School Design Day
- 4/30: Final project due

May: Graduation, Order of the Engineer Ceremony

- 5/12: Order of the Engineer Ceremony
- 5/13: Graduation

7. Risk Analysis:

Risk	Description	Impact	Probability	Mitigation
Laser (Leukos Rock 400 5)	High-power laser to gather sufficient signal, may hurt eyes (2-5W)	High	Low	Laser Safety Glasses and appropriate laser safety training from facility
CTE (optical and mechanical)	The lens selection needs to withstand and not be reshaped by laser thermal impact	High	Low	Filter preferred glass catalog to ensure selection accounts for high power laser
Signal	Unable to fit the beam into a single mode design with enough output	High	Low	Ensure that photon budget thoroughly considers the input beam

Time	Unable to thoroughly create and tolerance a final design in time	High	Low	Communicate with customer when specifications reach a breaking point in order to reframe the expectations
Transmission (weight wavelengths)	Developing a system that requires too many elements leading to transmission decay	Medium	High	Design with uncoated specification in mind limiting performance by access to elements
Packaging	Fiber couplers need to be used in very small circumstances	Medium	Low	Set strong constraints in the early design specifications to ensure proper packaging
Clean room environment inside machine	Cleanroom grade ISO 5	Medium	High	Design must aim to not contribute to particle contamination within the machine

8. Product Specifications:

The Optimax Catalog is the basis of lens material selection. Thus far, the most reliable material out of 50 search constraints appear to be N-BK7. Given our restrictions on coating materials. Our system should not surpass more than 5-6 surfaces, including cemented surfaces.

- NA = 0.15
- Fiber Core Size = 10 um
- Object at infinity
- Wavelength range 400 – 2000 nm
- High efficiency without AR coatings
- Spherical surfaces, optionally one asphere (no freeform)
- Glasses choice is restricted to the preferred glass list
- Volume goal is 300x100x100 mm^3

	Value	Where did you get your spec? e.g. product brochure/website, based on patent, from a paper, derivation (attach supporting docs/pics), or estimate/guess
Aperture	NA = 0.15	Customer Request
Field	0 degrees	Customer requests to design on-axis and provide tolerancing for certain amount of degrees of decenter of fiber
Wavelength	400-2000 nm	Customer Request
Focal Length	Undefined	System is defined through aperture rather than focal length
Magnification	1:1 unit	Beam 10mm diameter (object size) using 1" optics to reshape and clean the beam
Object distance variation	Does not apply	Volume constraint desired to be 300x100x100 mm^2
Sensor		Amount of light that the fiber is able to transport, photon budget of how much we have from free space
Sensor size	Unavailable	We have not signed an NDA
"Pixel" size	Unavailable	We have not signed an NDA
"Nyquist"	Unavailable	We have not signed an NDA
RMS wavefront	High phase match	Limited by mode matching at fiber
Spot size	High symmetry	Limited by amount of light incident
Telecentricity / Chief ray angle (CRA) on sensor	Unavailable	We have not signed an NDA
Relative Illumination and/or vignetting	No vignetting or vignetting apertures allowed	Customer Request
Diameter	Unconstrained	Volume constraint desired to be 300x100x100 mm^2
Length	Unconstrained	Volume constraint desired to be 300x100x100 mm^2
Working distance	Unconstrained	Volume constraint desired to be 300x100x100 mm^2
Filters/Windows	Does not apply	No need for filters or windows
Other packaging constraints (include sketch if needed)		Prefered glass list: https://www.optimaxsi.com/table/preferred-glass/

9. Theory and Background:

9.1 Fiber Coupling Literature:

The primary consideration for a broadband spectrum optic coupling device design is the propagation beam that is intended to be coupled into a fiber. The fiber coupler design is intended for use within an ASML lithography alignment system and is modeled with a well defined 10 mm broadband Gaussian beam in free space as a source. It is assumed that the intensity distribution of this source will not exhibit discontinuities or the butterfly effect. The mode diameter of this source is dependent on the desired numerical aperture of 0.15 and the wavelengths of interest as demonstrated in equation 1. This mode diameter calculation is integral to performance parameters of the design as inputted in OpticStudio in order to coordinate the desired mode field diameter range we expect from the input beam.

$$MFD = \frac{2 \cdot \lambda}{\pi \cdot \mathrm{NA}_{e^2}}$$

Equation 9.1: Mode field diameter as a function of wavelength and numerical aperture

The broadband source used for this project contains wavelengths that range from 400 to 2000 nanometers. Our goal is to incorporate a wide selection of at least 10 discrete wavelengths that perform optimally for our design within this range while maintaining mode matching of the source and the fiber input. In order to decide these wavelengths, a combination of two design techniques will be used. First, we will increase the design bandwidth by 50-60 nm at a time over a period of optimizations. In addition, we will select discrete spectral lines in the spectrum we have which are well researched by the literature.

The power distribution from the optical system that is received by the fiber can be defined as the effective numerical aperture, or NAe^2, for fiber, as per industry standards. This is due to the characterization of fibers by their $1/e^2$ diameter. Figure 1 demonstrates the various components of the beam waist translated into fiber space for a Gaussian beam focused onto a fiber optic input.

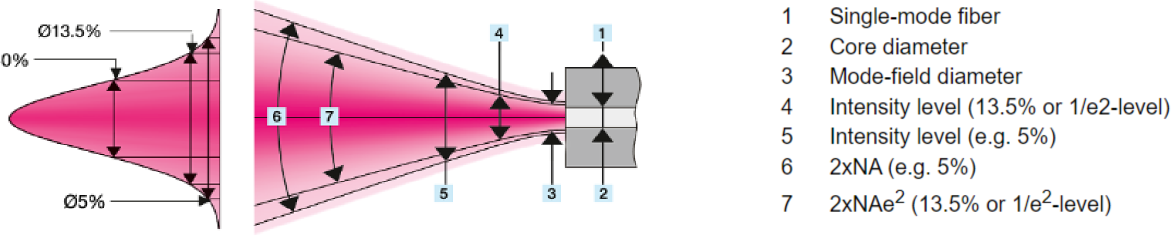


Figure 9.1: Gaussian Beam as defined for fiber input parameters in commercial level notation [5].

As a result of the broad range of wavelengths under consideration, it is imperative to examine the cases of a mismatched effective numerical aperture and the mode field diameter. This is especially important to consider when strategizing the design approach. Existing literature demonstrates the linear relationship between mode field diameter and effective numerical aperture indicating that no exponential contributions to coupling efficiency loss should be expected as either of them deviate from each other.

Another important consideration is how to determine the focal length of the system that provides optimal coupling efficiency. Maximum coupling efficacy comes from an ideal Gaussian beam with no presence of astigmatism that has a convergence of the circular beam equal to the effective numerical aperture. Moreover, the laser spot from the fiber end face needs to equal the mode field diameter (MFD) of the next single mode fiber. Keeping this in mind, the optimum focal length for a laser beam coupler with a particular beam diameter given at the effective numerical aperture ($\varnothing_{\text{beam}}$) can be defined following Equation 9.2. An alternate way to calculate the focal length with nominal NA is available, however, it requires a conversion factor for the difference in definition [6].

$$f' = \frac{0.5 \cdot \varnothing_{beam}}{\mathrm{NA}_{e^2}}$$

Equation 9.2: Focal Length as a function of numerical aperture

10. Fiber Coupling Optical System Analysis:

10.1 Micro Lens Fiber Coupling:

A monochromatic commercial microlens fiber coupler design of similar specifications can be used as an exemplar of our initial design considerations while working with OpticStudio. This setup demonstrates a single mode fiber to fiber coupling configuration, including two Corning SMF-28e Fibers coupled with a FC-Q-250 microlens array. This configuration, demonstrated in figure 2, is rotationally and laterally symmetric. The specifications of the fibers and the microlens array used in this system are detailed in Tables 1 and 2 respectively. By incorporating Physical Optics Propagation calculation on OpticStudio, we can expand this example to include complex modes as well as an accurate model of diffraction effects due to the beam propagation over long distances in free space relevant to our final design.

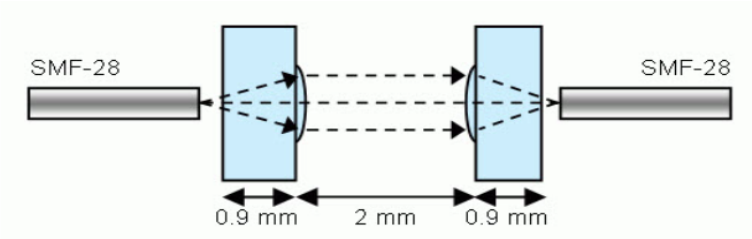


Figure 10.1.1: Single mode microlens fiber coupler configuration for a fiber to fiber design

Single Mode Fiber, Corning SMF-28e [1]	
Numerical Aperture	0.14
Core Diameter	8.2 µm
Mode Field Diameter @ 1.31 µ	9.2 ± 0.4 µm

Table 10.1.1: Specifications of single mode fibers, Corning SMF-28e, used for microlens fiber coupler configuration

Microlens Array, SUSS MicroOptics SMO399920 [2]	
Substrate material	Fused Silica
Substrate thickness	0.9 mm
Internal Transmission	>0.99
Lens Diameter	240 µm
Lens Pitch	250 µm
Radius of Curvature	330 µm
Conic Constant	0
Numerical Aperture	0.17

Table 10.1.2: Specifications of microlens array, SUSS MicroOptics SMO399920, used for fiber coupler configuration

In order to explore this example configuration, we modeled these specifications on OpticStudio, using fused silica as the substrate material and maintaining a numerical aperture of 0.14 for the single mode fibers surfaces. The lens separation was initially set to 2 mm, understanding that this distance was subject to vary during optimization. Our core diameter was determined by the standard corning fibers used in this example, which can be replaced with fibers capable of handling large bandwidths as our design develops. The OpticStudio inputs for the initial monochromatic design are detailed in table 10.1.3. Figure 10.1.3 demonstrates the optimized monochromatic single mode fiber to fiber coupling model as determined in OpticStudio.

Feature	Value
NA	0.164
Field	0° on-axis
Focal Length	-1.0433 mm
Diameter	240 um
Length	4.01 mm
Aspheric Surfaces	0
Transmission	100%

Table 10.1.3: Microlens array single mode fiber coupling configuration specifications

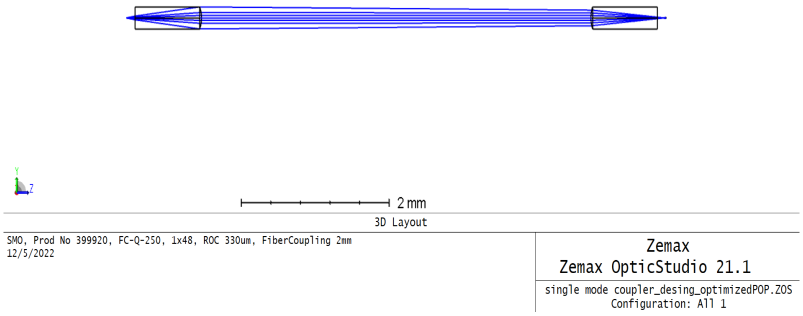
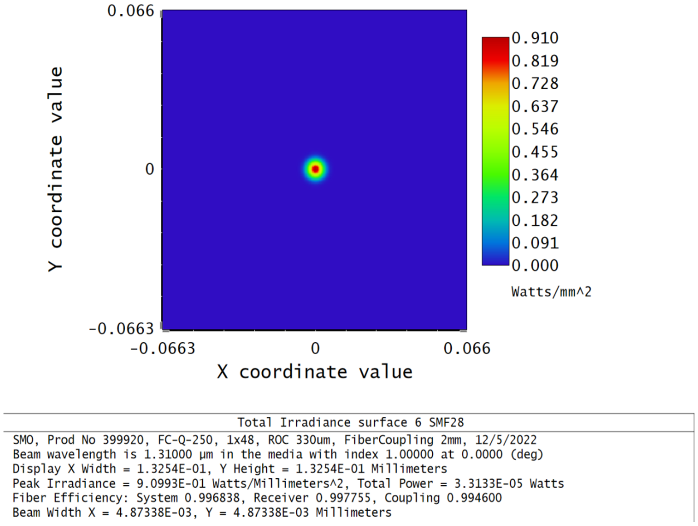


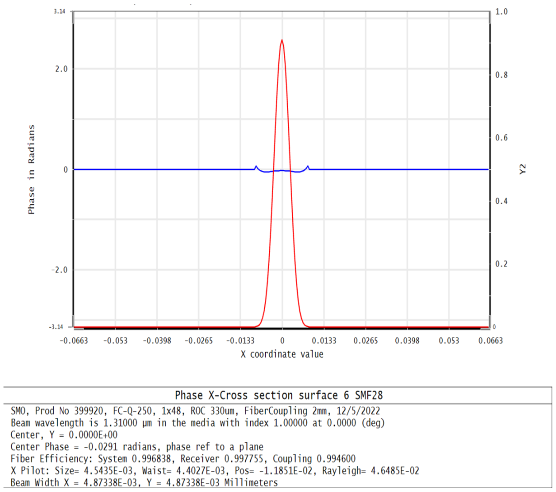
Figure 10.1.2: Monochromatic single mode microlens fiber coupler configuration modeled in OpticStudio

The irradiance plot for the monochromatic design at a wavelength of 1310 nanometers at the second fiber surface is demonstrated in figure 10.1.4. This plot reveals that the fiber efficiency of the coupler is 99.46% in this configuration.



```
Total Irradiance surface 6 SMF28
SMO, Prod No 399920, FC-Q-250, 1x48, ROC 330um, FiberCoupling 2mm, 12/5/2022
Beam wavelength is 1.31000 µm in the media with index 1.00000 at 0.0000 (deg)
Display X Width = 1.3254E-01, Y Height = 1.3254E-01 Millimeters
Peak Irradiance = 9.0993E-01 Watts/Millimeters^2, Total Power = 3.3133E-05 Watts
Fiber Efficiency: System 0.996838, Receiver 0.997755, Coupling 0.994600
Beam Width X = 4.87338E-03, Y = 4.87338E-03 Millimeters
```

Figure 10.1.3. Total irradiance at the receiving fiber optic surface



```
Phase X-Cross section surface 6 SMF28
SMO, Prod No 399920, FC-Q-250, 1x48, ROC 330um, FiberCoupling 2mm, 12/5/2022
Beam wavelength is 1.31000 µm in the media with index 1.00000 at 0.0000 (deg)
Center, Y = 0.0000E+00
Center Phase = -0.0291 radians, phase ref to a plane
Fiber Efficiency: System 0.996838, Receiver 0.997755, Coupling 0.994600
X Pilot: Size= 4.5435E-03, Waist= 4.4027E-03, Pos= -1.1851E-02, Rayleigh= 4.6485E-02
Beam Width X = 4.87338E-03, Y = 4.87338E-03 Millimeters
```

Figure 10.1.4 : Phase X-Cross section for Surface in OpticStudio

Wavelength (um)	Coupling Efficiency (%)
1.31	95.55

Table 10.1.4: Coupling Efficiency at a wavelength of 1.31 um

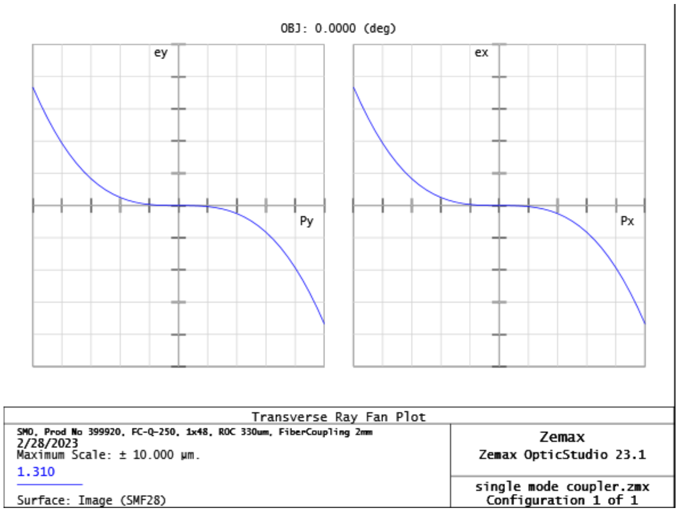


Figure 10.1.6: Transverse Ray fan plot for microlens fiber coupler

10.2 8 Wavelength Design:

We expand our design to a free-space broadband coupling device. In this design we explore an on-axis single mode coupling device that utilizes 3 lenses in order to produce an NA of 0.148. It is important to make a distinction between the first example and the one below illustrated in Figure 10.1.3; this system is not composed of microlenses as before. In addition, the entrance pupil diameter is determined by the system and is constrained to be greater than 10mm in order to fit the 10mm input collimated beam from the broadband laser.

Feature	**Value**
NA	0.148
Field	0° on-axis
Focal Length	124.4 mm
Diameter	39 mm
Length	151.4 mm
Aspheric Surfaces	2
Transmission	95.71%

Table 10.2.1: Broadband fiber coupler optic specifications

Wavelength (um)	Coupling Efficiency (%)
0.486	67.25
0.532	65.63
0.656	69.67
0.755	76.43
0.980	67.79
1.064	68.19
1.220	73.07
1.550	70.64

Table 10.2.2: Coupling efficiency for broadband fiber coupler optic for wavelengths from 486 to 1550 nm

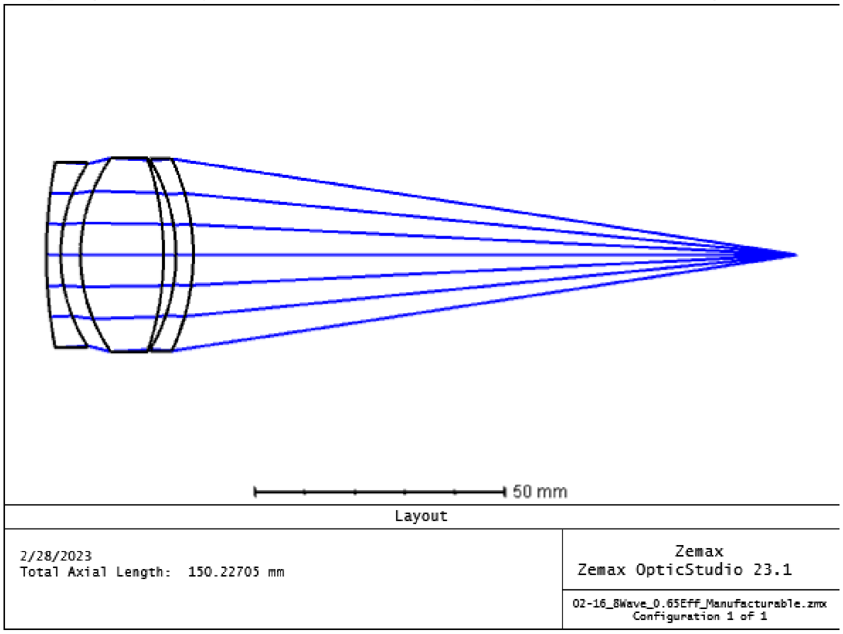


Figure 10.2.1: Broadband single mode fiber coupler configuration modeled in OpticStudio

The system is composed of three elements which utilize materials N-BK7, S-FPL53, F-2 for each element in the system respectively from left to right. Also, 2 aspheric surfaces are located on surface 3 and 4 in order to provide aid in the aberration correction of the system. As seen in Figure 10.2.2 the aspheric surfaces provide relatively flat curves, leaving color aberrations to dominate the performance of the system. The coupling efficiency of the system is almost completely dependent on how the color aberrations balance themselves. As seen in Table 10.2.2, the infrared portion of the spectrum provides for better coupling efficiency in comparison to the visible portion of the spectrum. The above should come as no surprise since the materials selected are very effective across the 450nm-2um wavelength range and start decreasing their color correcting performance when outside of this range.

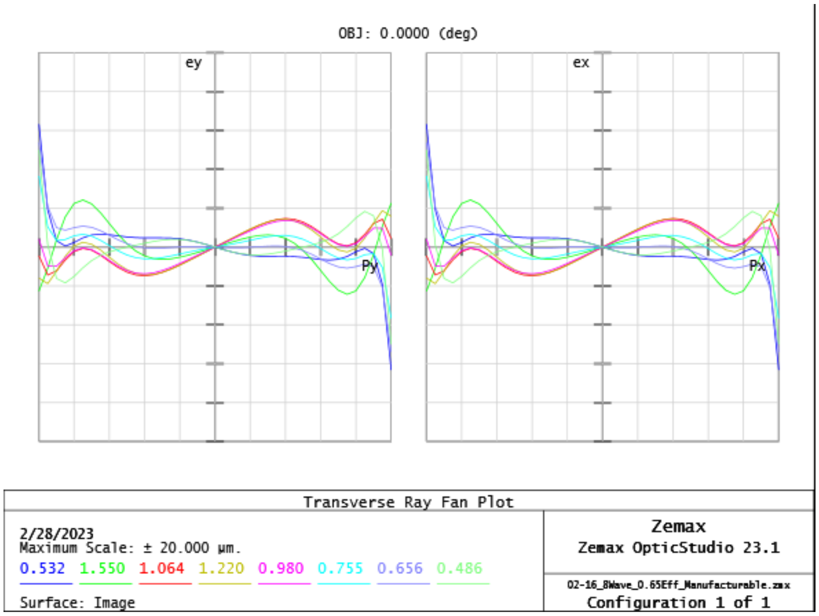


Figure 10.2.2: Transverse ray plot for broadband single mode fiber demonstrating 8 wavelengths

10.3 Diffractive Optic Design

For this design, we decided to conduct an experimentation on using a diffractive optic. Though this system is not entirely feasible from a monetary standpoint, we deem it a necessary exploratory design to demonstrate the benefits of using a diffractive optic rather than using strictly aspheres and regular lenses.

Feature	Value
NA	0.1483419
Field	0° on-axis
Focal Length	123.459
Diameter	37.03806
Length	147.8196
Aspheric Surfaces	1
Transmission	76%

Table 10.3.1: Diffractive Optic fiber coupler specifications

Wavelength (um)	**Coupling Efficiency (%)**
0.486	64.91%
0.532	61.57%
0.655	65.96%
0.755	71.57%
0.980	60.94%
1.064	60.57%
1.220	64.73%
1.550	72.25%
1.645	68.43%
1.752	59.11%

Table 10.3.2: Coupling efficiency for diffractive fiber coupler for wavelengths from 486 to 1752 nm.

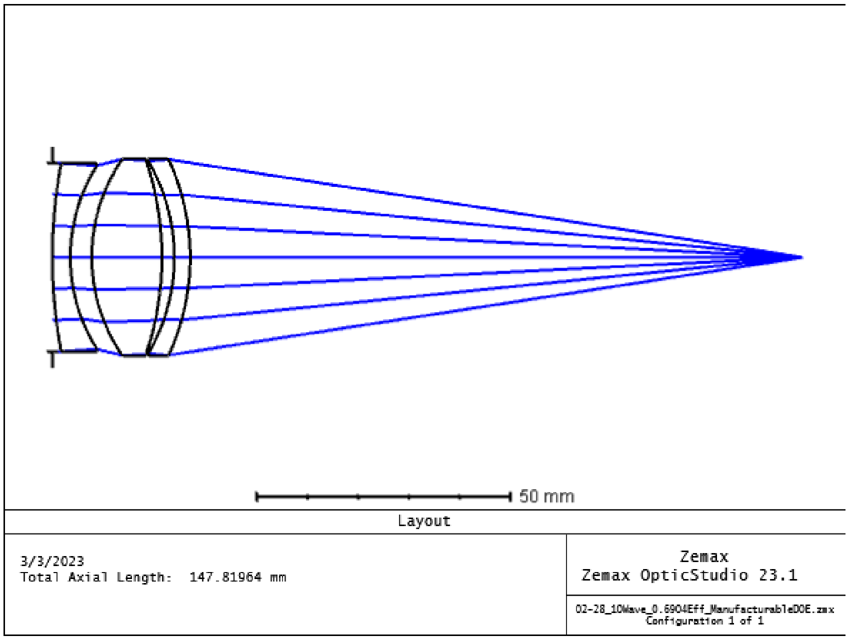
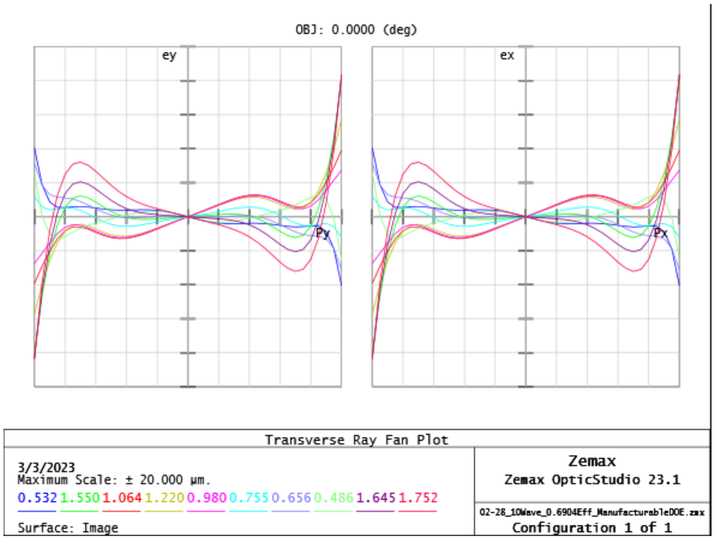


Figure 10.3.1: Diffractive optic fiber coupler configuration modeled in OpticStudio

The system is composed of three elements which utilize materials N-BK7, S-FPL53 , F-2 for each element in the system respectively from left to right meaning a very similar system to the one on section 10.2. Nonetheless this system has a major variation on the color spread as we can see in Figure 10.3.2 which is dominated by higher order spherical and color but of smaller order than the system in section 10.2. The tradeoff of this system is mostly manufacturability for performance since it has an average coupling efficiency of 69% but at the same time has 2nd order diffractive optics that would probably increase the cost of the system significantly for very little performance.



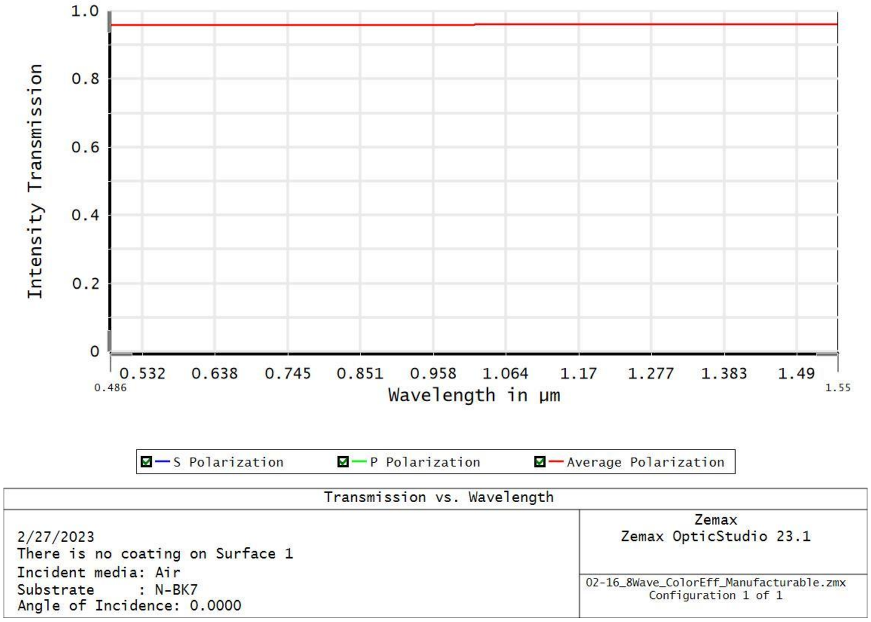
Transverse Ray Fan Plot

3/3/2023
Maximum Scale: ± 20.000 µm.
0.532 1.550 1.064 1.220 0.980 0.755 0.656 0.486 1.645 1.752
Surface: Image

Zemax
Zemax OpticStudio 23.1
02-28_10Wave_0.6904Eff_ManufacturableDOE.zmx
Configuration 1 of 1

Figure 10.3.2: Transverse ray plot of diffractive optic fiber coupler

After this experiment the team feels very confident to say that the desired wavelength band is a possible goal; it is just a matter of the accessibility to optical components that one can have to make the color correction happen. Moving forward we are optimizing systems for the current 10 wavelengths utilized in this experiment.

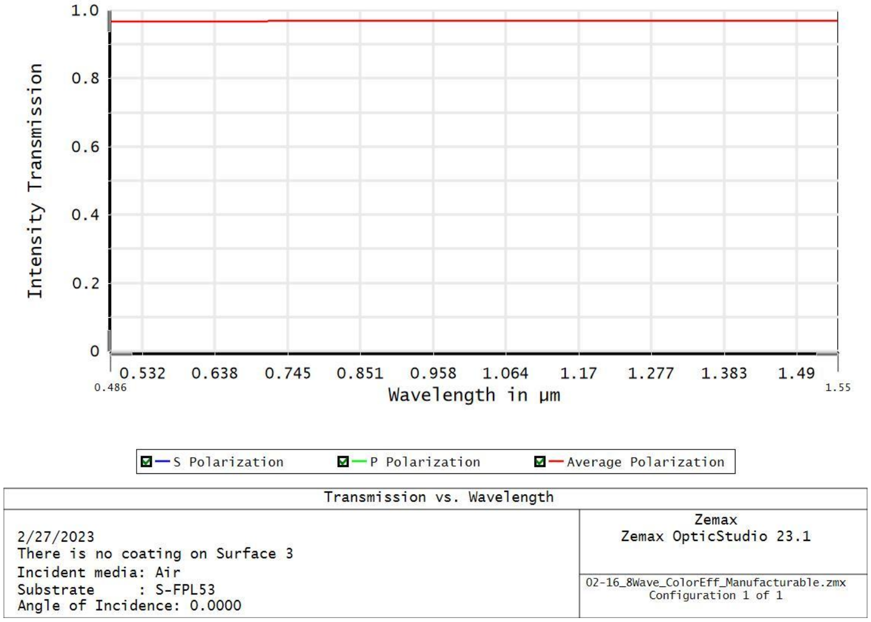


Transmission vs. Wavelength

2/27/2023
There is no coating on Surface 1
Incident media: Air
Substrate : N-BK7
Angle of Incidence: 0.0000

Zemax
Zemax OpticStudio 23.1
02-16_8Wave_ColorEff_Manufacturable.zmx
Configuration 1 of 1

Figure 11.1: Intensity transmission plot of a single N-BK7 surface vs wavelength



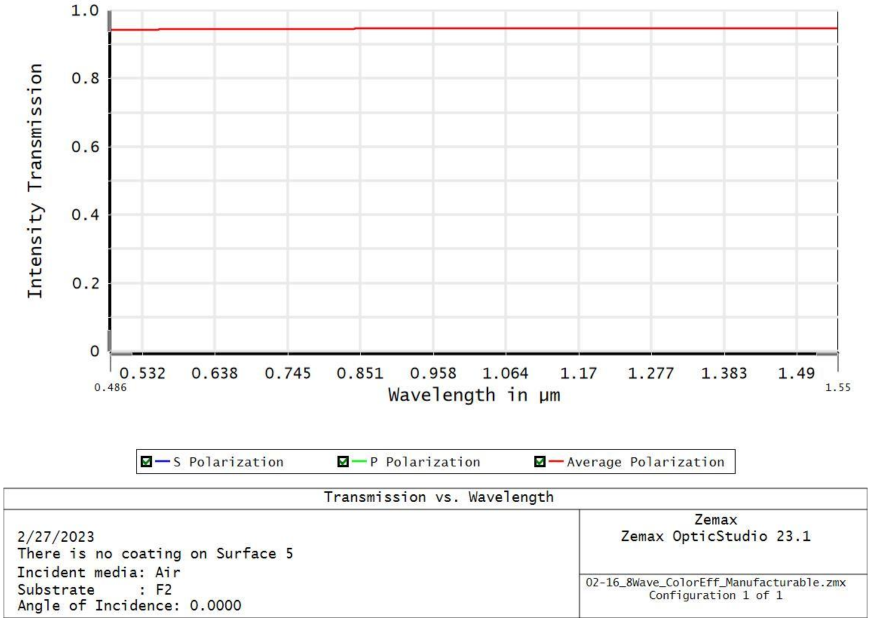
Transmission vs. Wavelength

2/27/2023
There is no coating on Surface 3
Incident media: Air
Substrate : S-FPL53
Angle of Incidence: 0.0000

Zemax
Zemax OpticStudio 23.1

02-16_8Wave_ColorEff_Manufacturable.zmx
Configuration 1 of 1

Figure 11.2: Intensity transmission plot of a single S-FPL53 surface vs wavelength



Transmission vs. Wavelength

2/27/2023
There is no coating on Surface 5
Incident media: Air
Substrate : F2
Angle of Incidence: 0.0000

Zemax
Zemax OpticStudio 23.1

02-16_8Wave_ColorEff_Manufacturable.zmx
Configuration 1 of 1

Figure 11.3: Intensity transmission plot of a single F2 surface vs wavelength

Wavelength (um)	Transmission			
	N-BK7	S-FPL53	F2	Total

0.486	95.71096%	96.72442%	94.23273%	73.33622%
0.532	95.74829%	96.74442%	94.32022%	73.62586%
0.656	95.81563%	96.78044%	94.46850%	74.12914%
0.755	95.84914%	96.82416%	94.53627%	74.41914%
0.980	95.90018%	96.82416%	94.62707 %	74.70282%
1.064	95.91472%	96.83126%	94.64939%	74.79074%
1.220	95.94011%	96.84326%	94.68452%	74.93578%
1.550	95.99165%	96.86634%	94.74446%	75.2049%

Table 11.1: Intensity transmission of a single surface of each material and the total transmission of the whole coupler

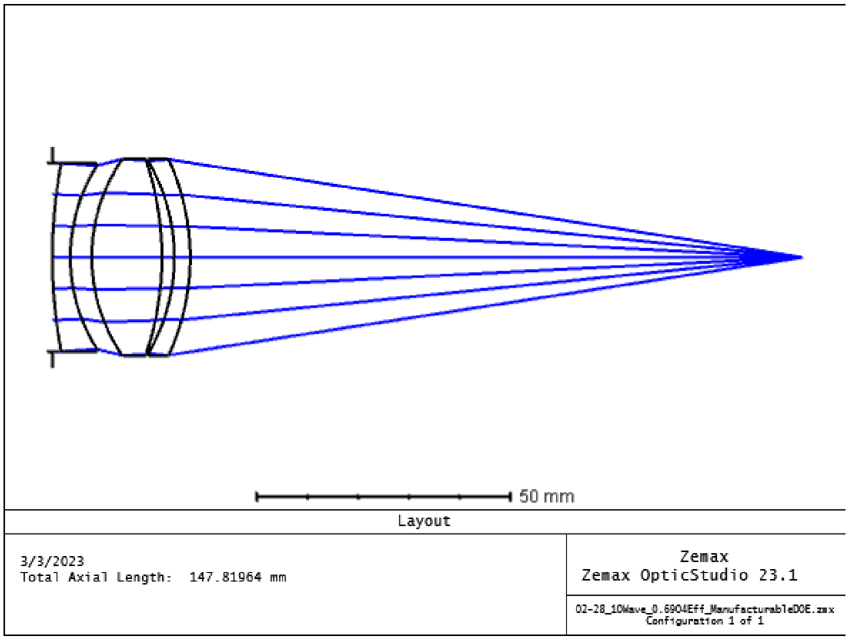
From the table above, the average transmission loss per surface is 4.26782%. The transmission loss on each surface depends on the material and the wavelength. Looking at the material, the transmission loss from least to greatest is S-FPL53, N-BK7, F2. When looking at the transmission loss by wavelength, the transmission loss decreases as the wavelength increases. Comparing these values and trends, the transmission loss increases as the refractive index increases.

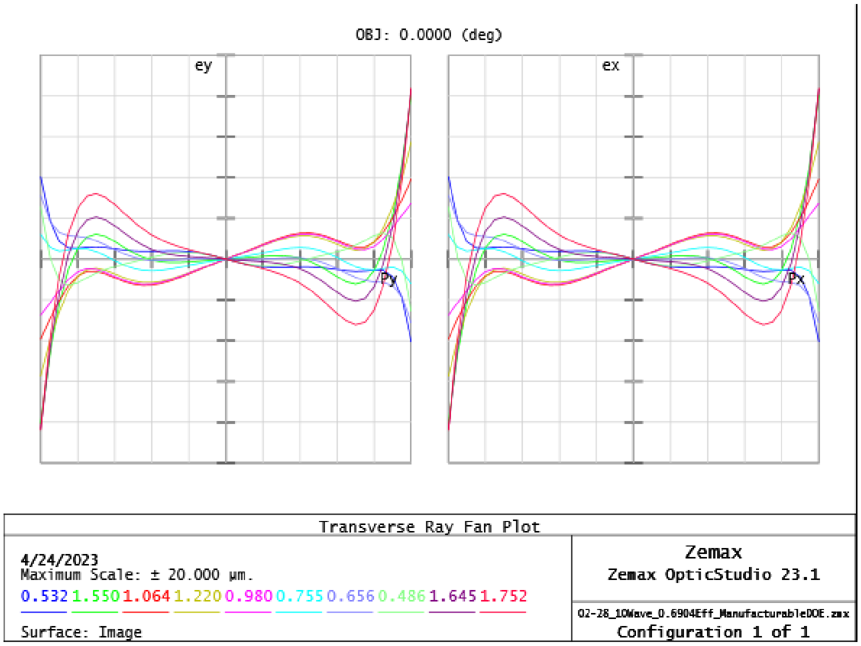
10.4 Full Spectrum Broadband Fiber Coupling Design

Feature	Value
NA	0.148
Field	0° on-axis
Focal Length	123.9
Diameter	38.79
Length	149.32
Aspheric Surfaces	2
Transmission	96.57%

Wavelength (um)	Coupling Efficiency (%)
486	69.76%

532	64.09%
655	70.58%
755	75.08%
980	59.65%
1064	58.97%
1220	64.12%
1550	76.94%
1645	73.95%
1752	64.49%

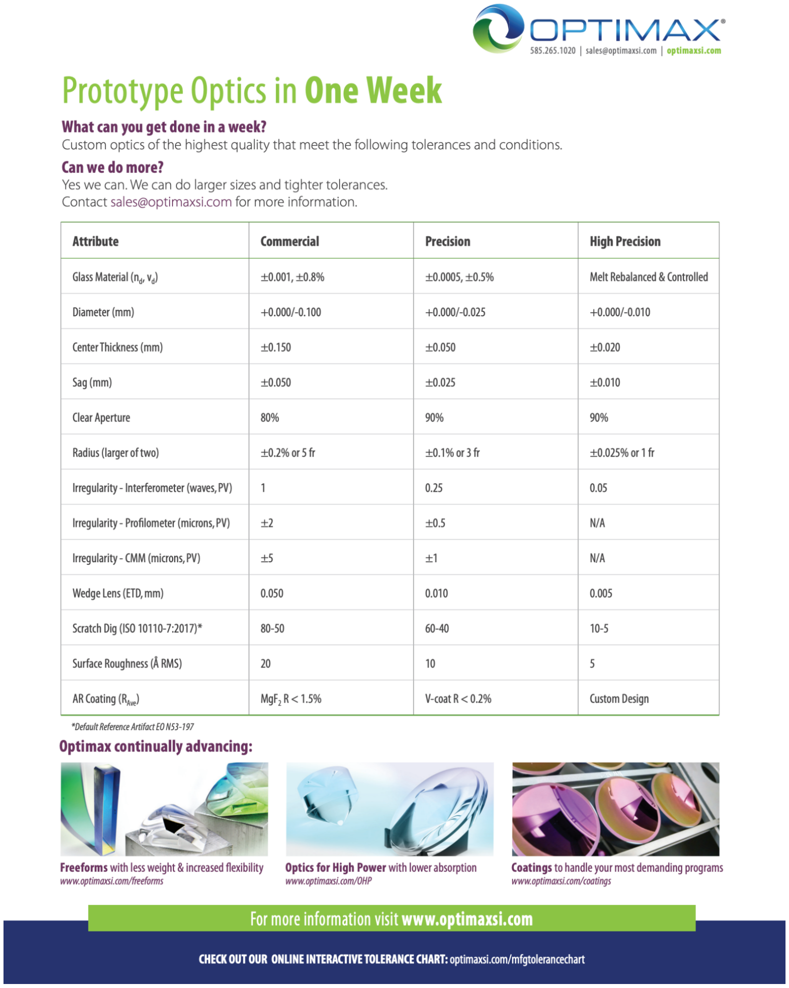




10.5 System Tolerancing for Aspheric Broadband Wavelength Design

All designs regardless of their nominal design performance need a fabrication and manufacturing analysis in order to ensure proper yield of the components and system arrangement. In this section we will be analyzing the 10 wavelength three element design that utilizes aspheric surfaces discussed in section –. The ideal manufacturer considered for this project is Optimax meaning that utilizing their tolerance chart for the analysis will be the first step of the tolerancing analysis process. All tolerances used to evaluate the design were derived and referenced from Figure 10.4.1. In terms of this design the majority of the tolerances used came from the precision column of the Optimax tolerance chart.

The analysis for this design utilized 4,000 Monte Carlo simulations which evaluated the degradation of the RMS wavefront performance as a function of the precision manufacturing tolerances. It is important to note that all of the information that will be provided from these Monte Carlo's used Root-Sum-Squared to deliver findings. First, let's talk about the target that we set for this design. The nominal RMS wavefront of the design came to be 0.0647 and we decided that the as-built could withstand up to 10x of this nominal performance which means that the maximum RMS wavefront allowed is 1.6175. In order to analyze the system, compensators need to be put in place and for the scope of this project since this will be in a tight package inside the lithography machine the only viable compensator is defocus. On average the 4,000 Monte Carlo utilized only 3um of defocus to compensate which indicates that the system has a relatively stable back focal length across many configurations. The analysis also demonstrated that the mean RMS wavefront for all 4,000 systems was 1.3526 RMS with a standard deviation of 0.66 which means that the expected yield for the 4,000 systems is ≈ 71%.



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Glass Material (n_d, v_d)	±0.001, ±0.8%	±0.0005, ±0.5%	Melt Rebalanced & Controlled
Diameter (mm)	+0.000/-0.100	+0.000/-0.025	+0.000/-0.010
Center Thickness (mm)	±0.150	±0.050	±0.020
Sag (mm)	±0.050	±0.025	±0.010
Clear Aperture	80%	90%	90%
Radius (larger of two)	±0.2% or 5 fr	±0.1% or 3 fr	±0.025% or 1 fr
Irregularity - Interferometer (waves, PV)	1	0.25	0.05
Irregularity - Profilometer (microns, PV)	±2	±0.5	N/A
Irregularity - CMM (microns, PV)	±5	±1	N/A
Wedge Lens (ETD, mm)	0.050	0.010	0.005
Scratch Dig (ISO 10110-7:2017)*	80-50	60-40	10-5
Surface Roughness (Å RMS)	20	10	5
AR Coating (R_{Ave})	MgF_2 R < 1.5%	V-coat R < 0.2%	Custom Design

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Figure 10.4.1: Optimax Tolerance Chart

A very important question to ask once we see this percentage yield is, what parameters of the systems are the most contributing to the degradation of the RMS wavefront? In the particular design under analysis these are the decentrations and tilts of the aspheric element (element 2). The above should not surprise the reader since the air thicknesses of this short broadband coupler are on the micron scale and the design form cannot allow them to increase without creating back reflection issues.

11. Photon Budget:

For the photon budget, we will focus on the optical power transmitted from the fiber coupler (otherwise known as the output power), which would be the transmittance of the coupler multiplied by the input optical power and then integrated by the wavelength.

$$I_T(\lambda) = \int_{400\,nm}^{2000\,nm} I_0 T d\lambda$$

$$\text{where } I_0(\lambda) = \frac{cn\varepsilon_0}{2}|E|^2$$

After that, we would compare the input optical power with the fiber coupler's output power. Along with the transmitted power, we would measure and calculate the amount of optical power reflected and the amount absorbed by the optical fiber.

The most significant factor of the fiber coupler that would cause a high reflected power would be the absence of anti-reflective coatings throughout the system. In the absence of anti-reflection coatings, we can expect a 4% loss at each surface due to Fresnel Reflection. The above holds true for whatever surface has the lowest transmission, the lowest transmission value to the N power where N is the number of surfaces times 100 will give the transmission of the system.

12. System block diagram:

Listed below are two system block diagrams for visualization of the system at large, with our fiber coupler component setup.

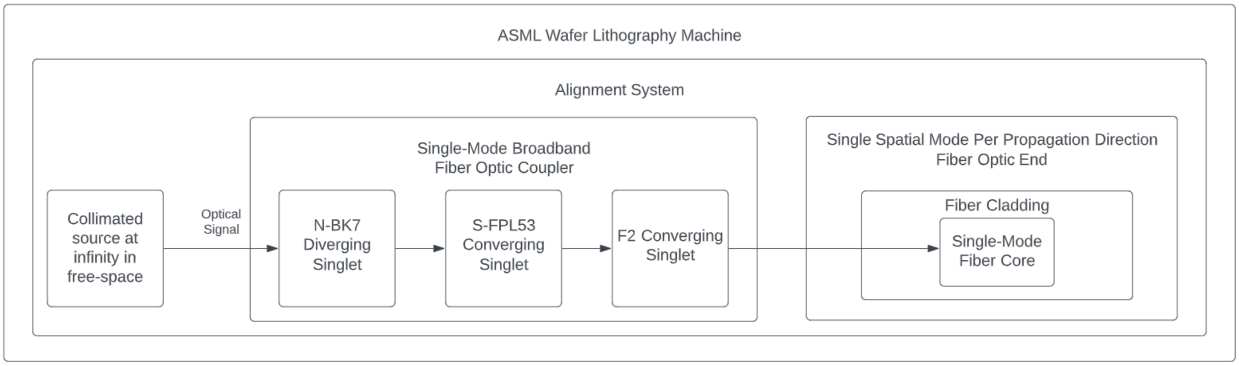

Figure 6. Block diagram of single mode broadband fiber optic coupler design within ASML SMASH, ORION System.

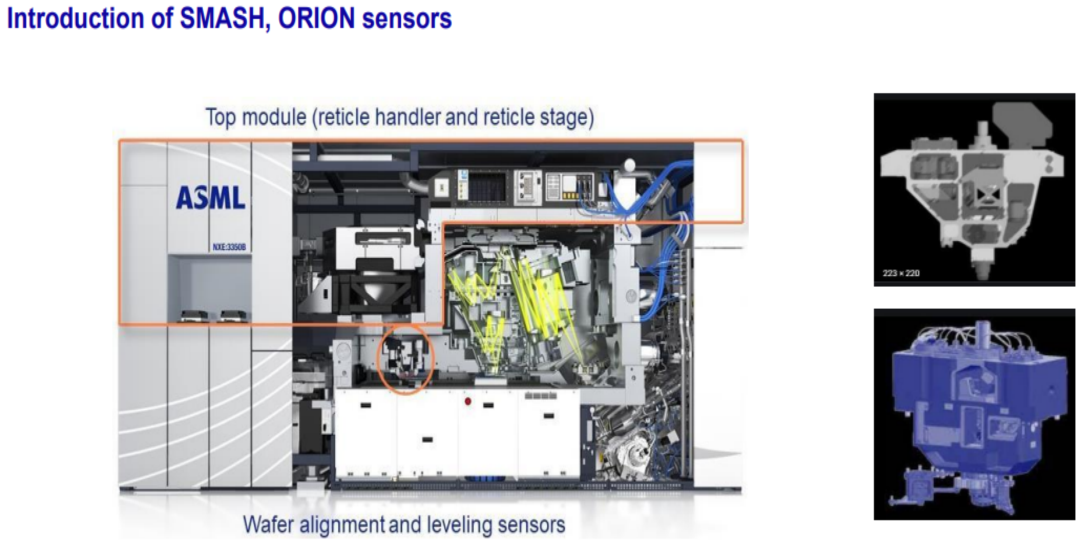

Figure 7. Diagram of ASML SMASH sensors located in the top module of the lithography machine.

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Patent#: 5018814 Broadband single-mode optical coupler
Patent#: 4842368 NxN single mode optical waveguide coupler