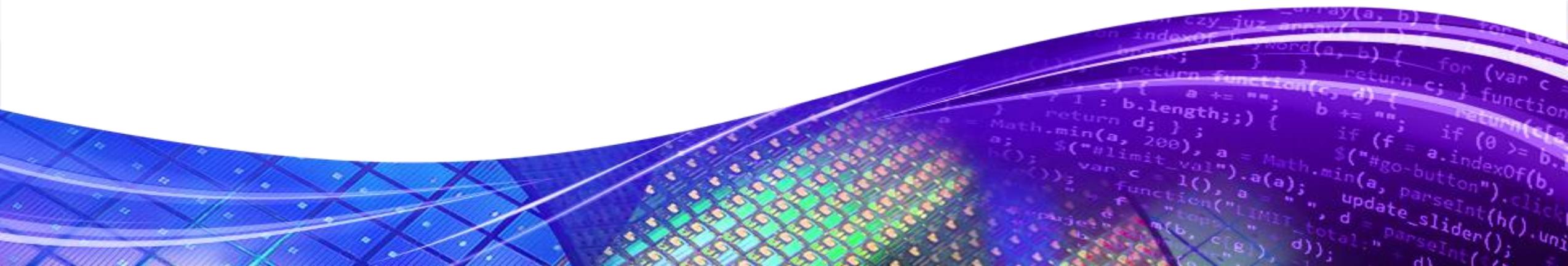
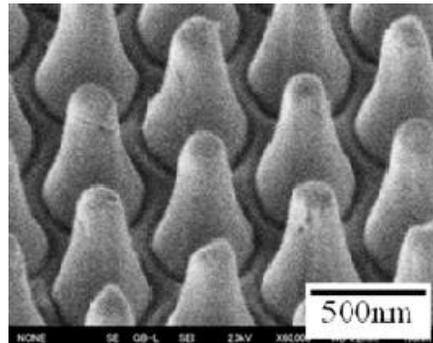


Optimization of a nanostructured moth-eye anti-reflective coating in RSoft



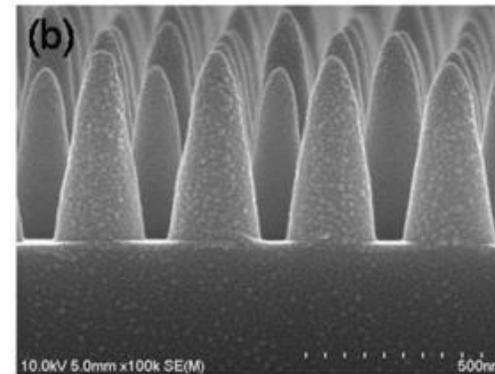
Moth-eye anti-reflective structures

- Microscale structures on the surface of optical interfaces have been known for over a century as an effective method of reducing Fresnel reflections.
- The eyes of a moth are covered with a natural anti-reflective nanostructured film
 - The moth-eye pattern is a pattern of subwavelength “bumps”; reduces reflection by creating an effective refractive index gradient between the air and the medium.
 - The moth-eye structure is one of the most effective nanostructures to reduce reflection



T. Kondo, *et al*, Proc. of SPIE Vol. 7602 (2010) 76021M-1

Nano-cones



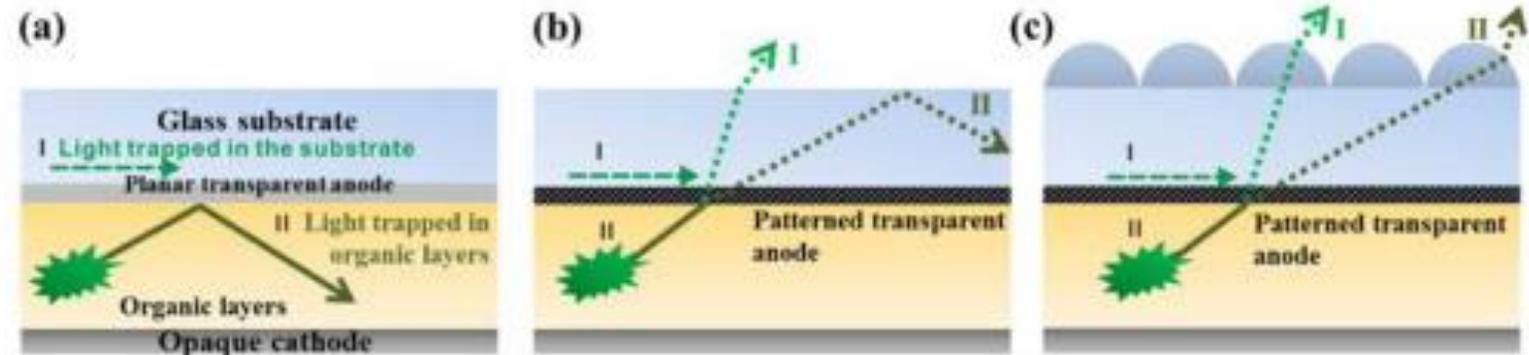
Graded-index



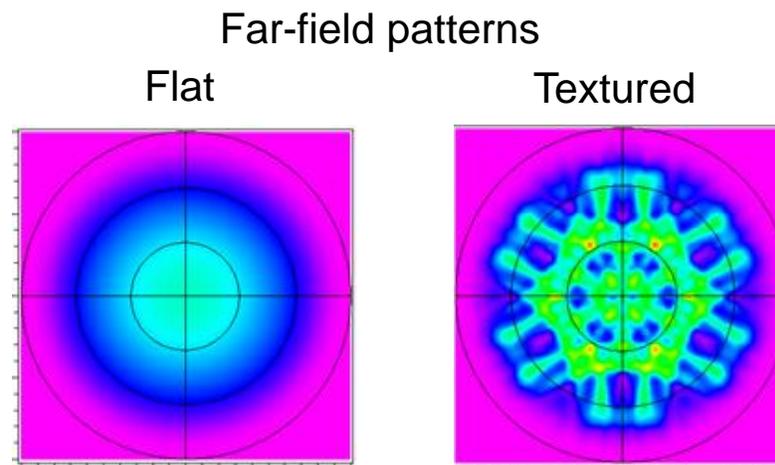
[1] Ou, Qing-Dong, et al., *Advanced Optical Materials* 3.1 (2015): 87-94.

Moth-eye anti-reflective structure applications

- Moth-eye nanostructures can be patterned on surfaces to give them antireflection properties
- Moth-eye structures have several advantages over traditional thin-film AR coatings
 - Environmental tolerance
 - Surface adhesion
 - Single-material fabrication
 - Minimal surface preparation
 - Higher laser-induced damage threshold
 - Self cleaning (lotus effect)
- Moth-eye structures are especially useful for reducing reflections from and increasing transmission between materials with a large refractive index contrast
 - Particularly important in high-power & low-loss applications
- Moth-eye AR structures have found uses in a number of applications, including laser systems, photovoltaics, LEDs, electronic displays, and fiber optics



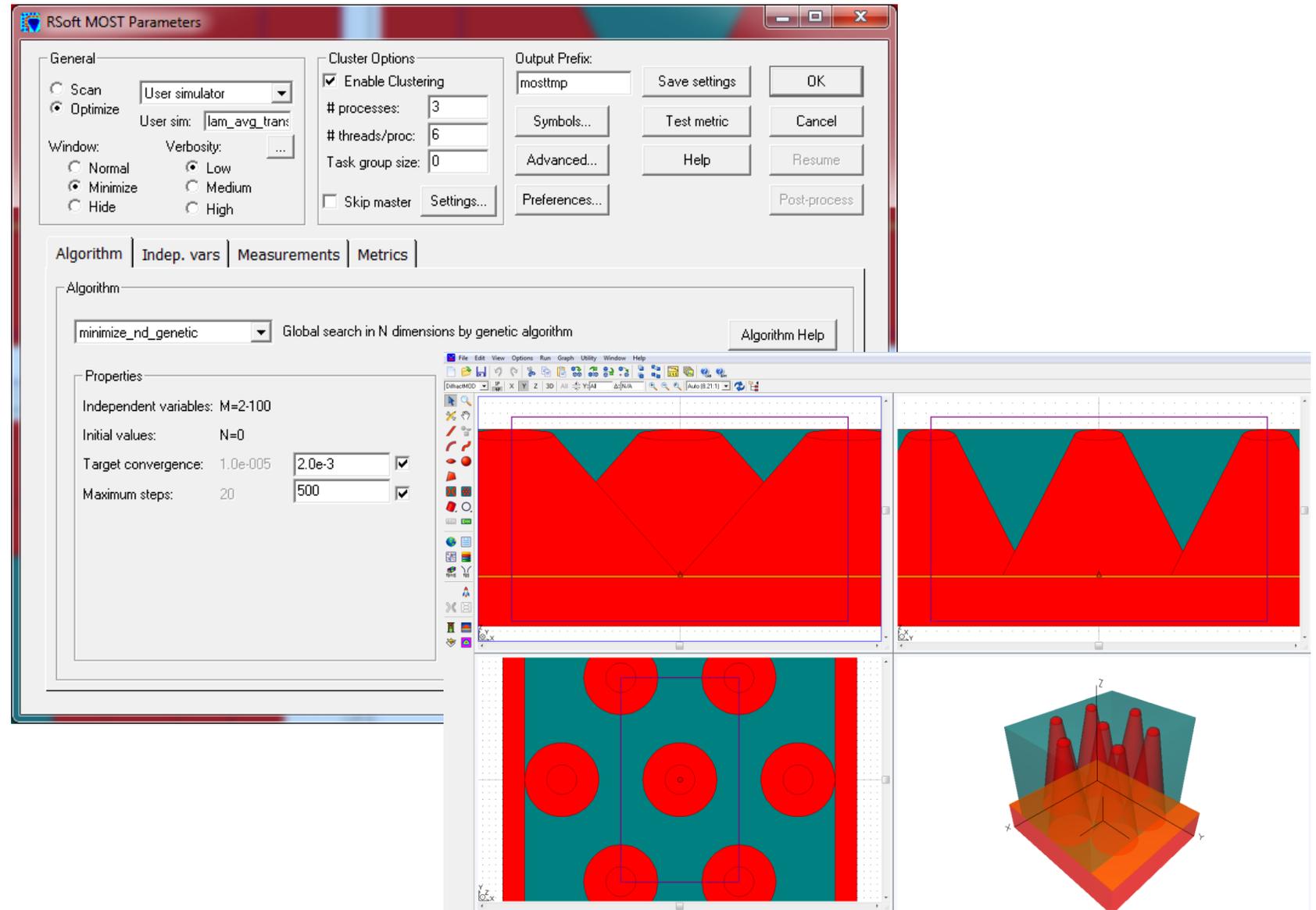
Moth-eye patterns can be used to increase the extraction efficiency from OLEDs by breaking up the total internal reflection



Ou, Qing-Dong, et al.,
Advanced Optical Materials 3.1 (2015): 87-94.

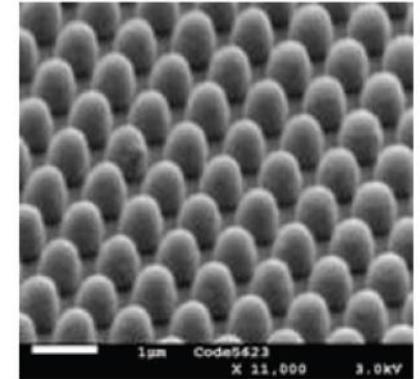
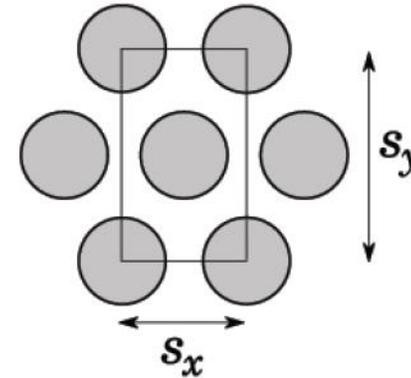
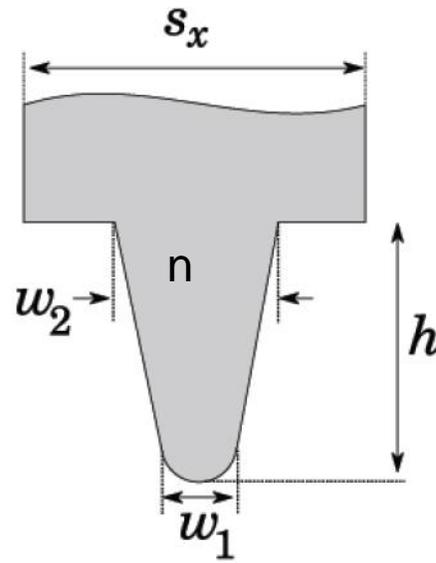
Moth-eye anti-reflective structure design for As_2S_3 optical fiber

- In this work, we optimize the shape and dimensions of moth-eye structures for maximum output coupling through the endfaces of As_2S_3 ($n=2.45$) chalcogenide optical fibers
- Rigorous computational EM propagation methods, like FDTD and RCWA, can be used to accurately simulate the transmission/reflection from the moth-eye surface.
 - For this particular moth-eye structure, RSoft's DiffractMOD RCWA tool is utilized due to RCWA's speed advantages over FDTD
- RSoft's MOST Optimization and Scanning Utility is used in conjunction with DiffractMOD to optimize the reflection/transmission for the moth-eye AR pattern



Moth-eye anti-reflective structure parameters

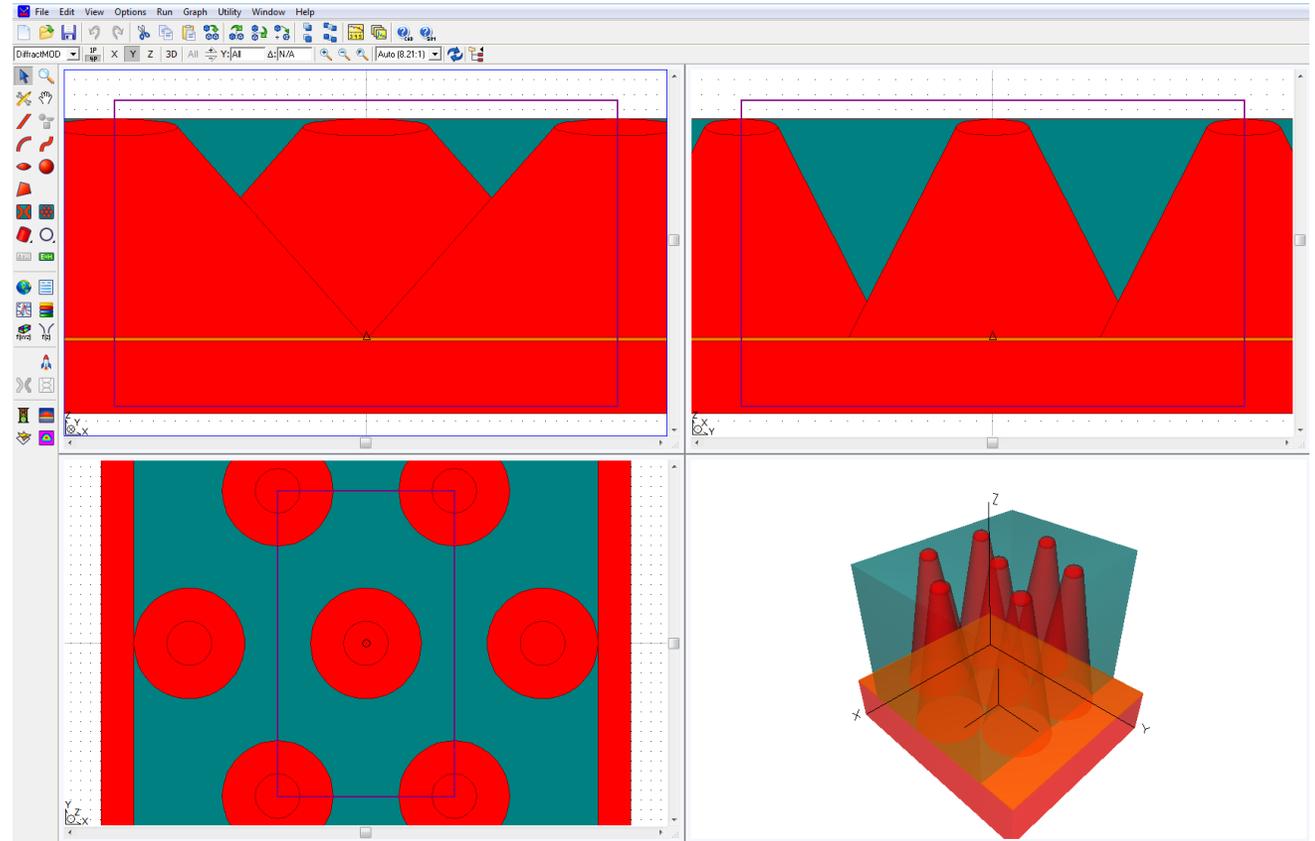
Parameter	Definition
H	Height of moth-eye cone
W1	Cone tip diameter
W2	Cone base diameter
Lattice	Hexagonal
Sx	Lattice packing constant
Sy	$\sqrt{(3Sx)}$
N	2.45 (As_2S_3)
Operating Wavelength	2-5um



R. J. Weiblen et. al [1]

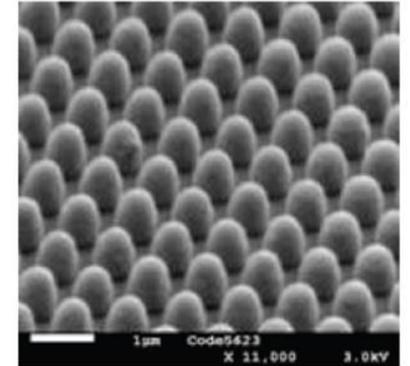
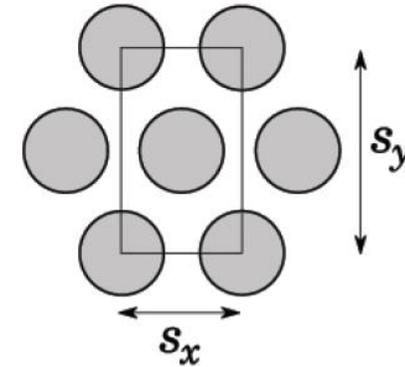
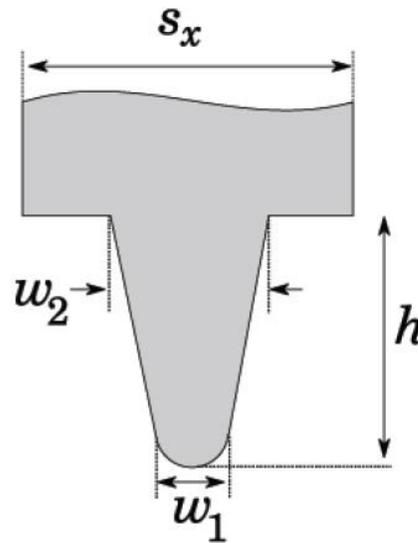
Simulation Parameters

- The source is a plane wave, incident on the moth-eye surface from below.
- The index resolution and # of harmonics used in the DiffractMOD simulation is chosen to ensure converged transmission/reflection results
- A single unit cell of the moth-eye structure, with periodic boundary conditions, is used to replicate the moth-eye array
- Note that for a circularly symmetric structures in a square or hexagonal packing scheme with normal incidence, it is sufficient to study a single polarization of incoming light [2,3]



Parameter Scanning

- It is always best to use MOST for parameter scanning before beginning a MOST optimization study
 - Provides quickest validation of the simulation
 - Prevents time-consuming mistakes when setting up optimization studies!
- For this structure, some parameters to investigate include
 - Tip width (w_1)
 - Base width (w_2)
 - Height (h)
 - Lattice Period ($S_x, S_y = \sqrt{3}S_x$)



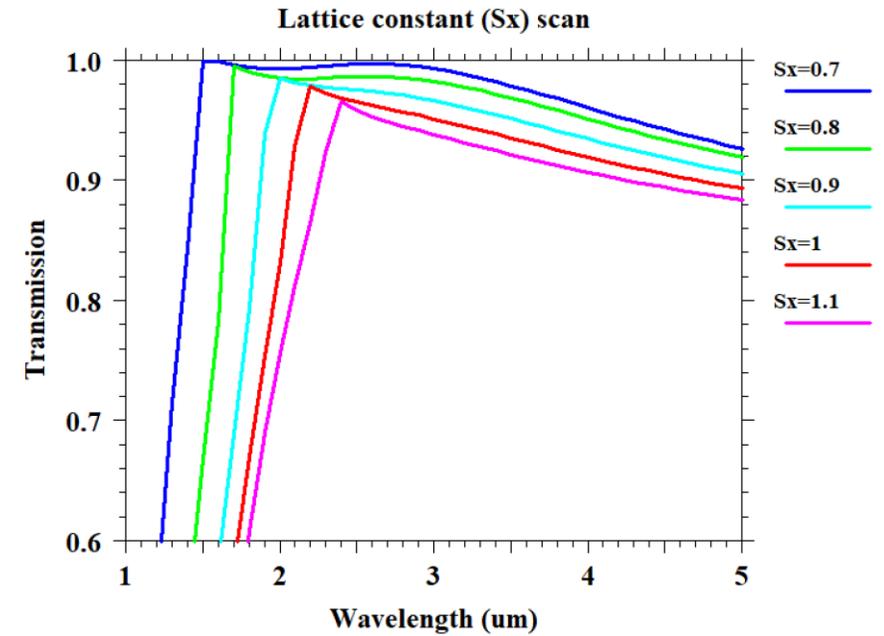
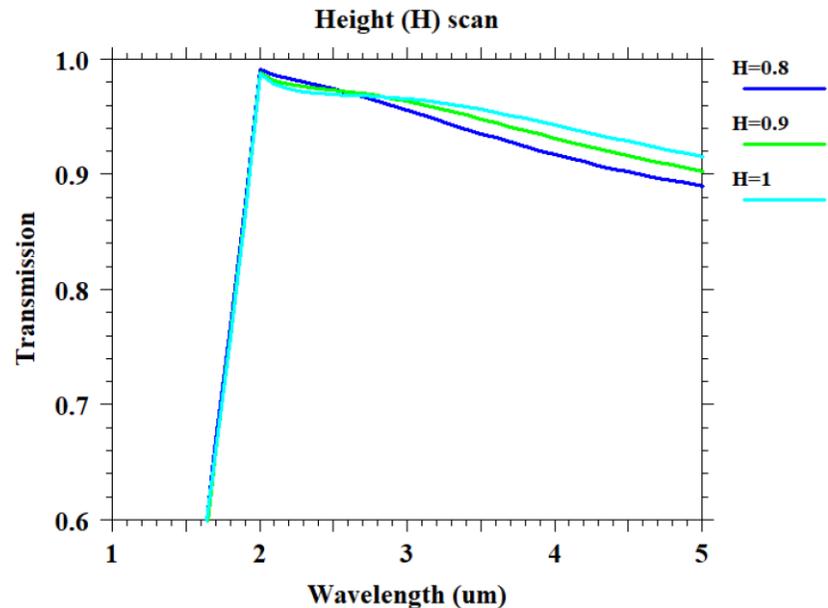
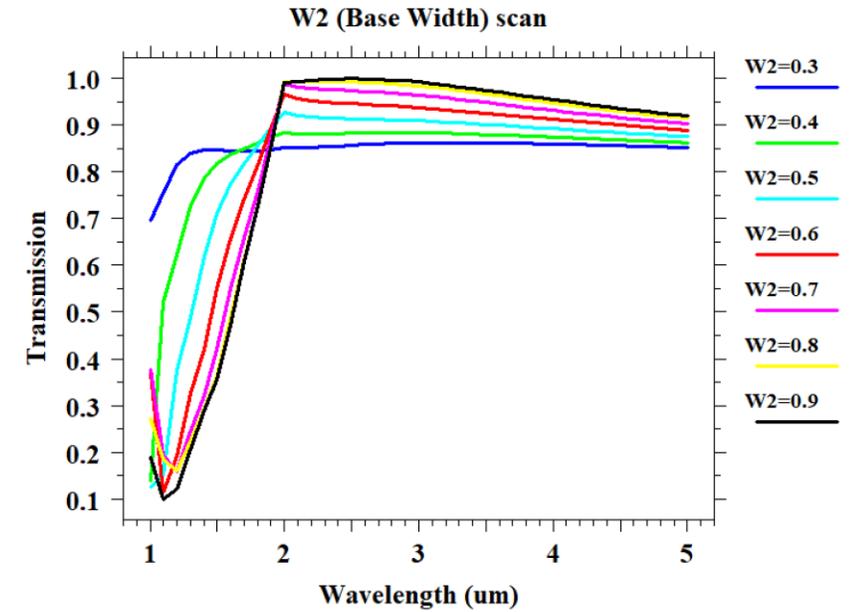
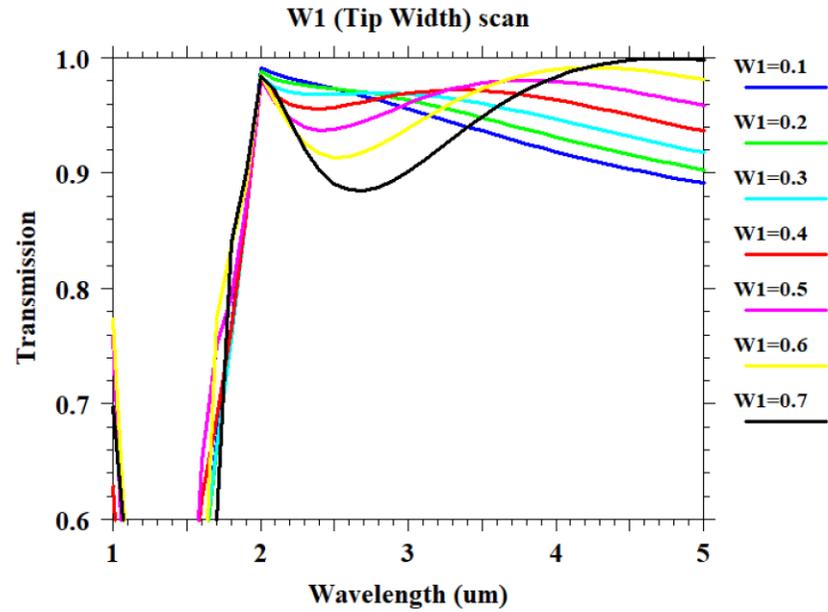
R. J. Weiblen et. al [1]

Parameter scanning

- DiffractMOD & MOST efficiently compute the moth-eye transmission vs. wavelength for a variety of individual simulation parameters.
- Parameter scans for W1, W2, H, Sx show good agreement with previous experimental and theoretical results [1]

- Simulation Parameters (unless scanned) are:

Parameter	Value
W1	0.2um
W2	0.7um
Sx	0.92um
Sy	1.59um
H	0.9um

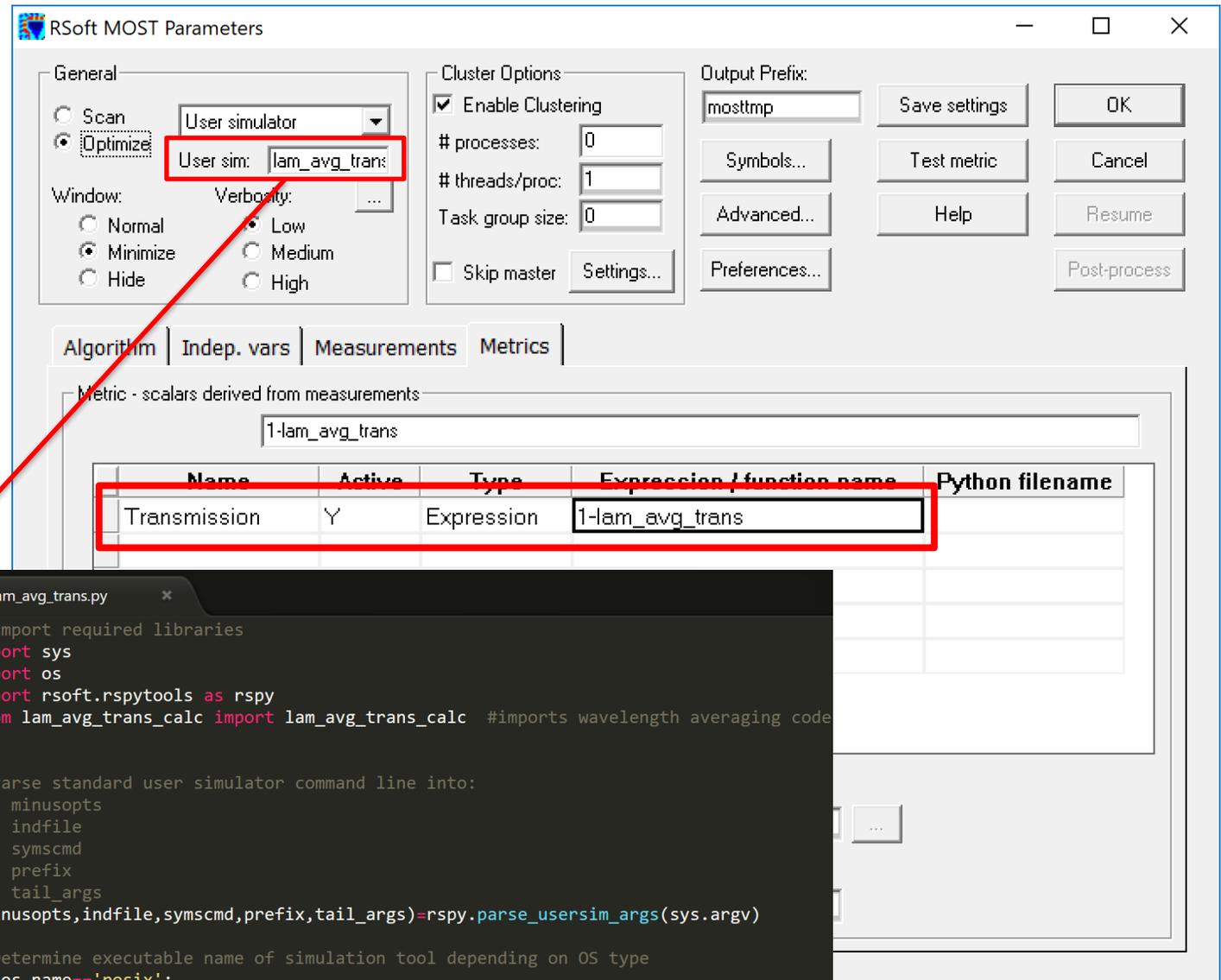


Parameter Optimization

- Here, we will optimize the design parameters of the moth-eye structure to achieve maximum averaged transmission from 2-5 μm .
- To achieve this, MOST's Optimization features will be used, with DiffractMOD as the simulation engine.
- A MOST "User Simulator" is written to control the optimization. The user simulator completes the following tasks
 - Runs the DiffractMOD simulations
 - Computes the averaged transmission (from 2-5 μm) from the DiffractMOD simulations
 - Using the averaged transmission as a target metric, the User Simulator uses MOST's genetic optimization algorithm to vary the structure parameters until maximum transmission (minimum reflection) is achieved

User simulator

- The user simulator for this optimization (lam_avg_trans.py) is written in Python, but any scripting language could be used
- This user simulator follows the standard RSoft user simulator calling conventions & syntax
- The user simulator computes the averaged transmission, from 2-5 μm , as lam_avg_trans
- 1-lam_avg_trans is then used as the MOST metric

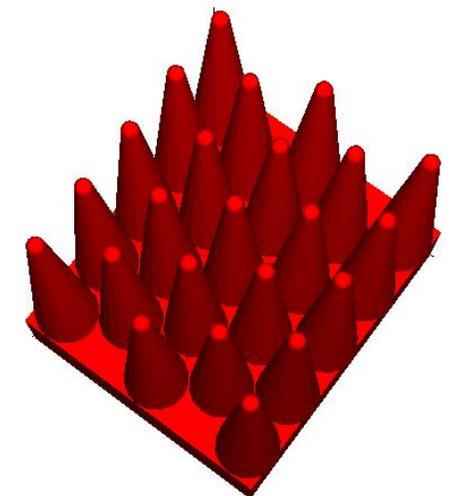
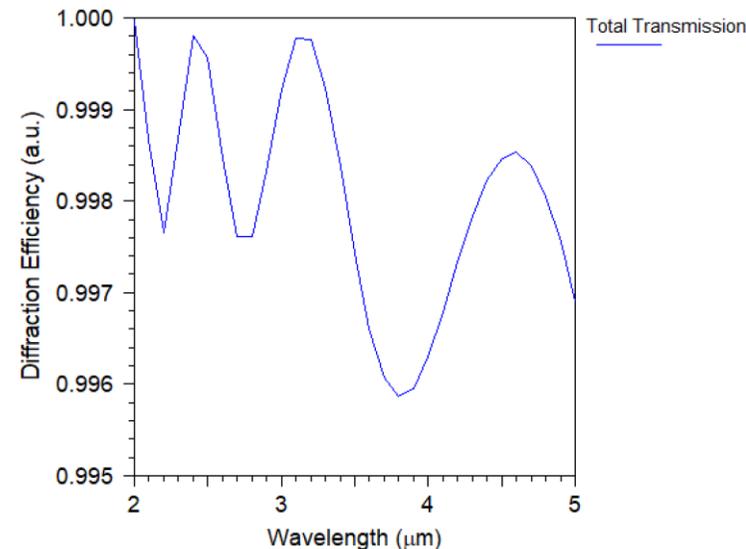


```
lam_avg_trans.py
1 # Import required libraries
2 import sys
3 import os
4 import rsoft.rspytools as rspy
5 from lam_avg_trans_calc import lam_avg_trans_calc #imports wavelength averaging code
6
7
8 # Parse standard user simulator command line into:
9 # minusopts
10 # indfile
11 # symscmd
12 # prefix
13 # tail_args
14 (minusopts,indfile,symscmd,prefix,tail_args)=rspy.parse_usersim_args(sys.argv)
15
16 # Determine executable name of simulation tool depending on OS type
17 if os.name=='posix':
18     sim_tool='xdfmod' #Linux
19 else:
20     sim_tool='dfmod.exe' #Windows
21
22 # Build the basic command, without the prefix so we can override it later:
23 # <sim_tool> <minusopts> <indfile> @<symsfile> <tail_args>
24 # All other commands will add additional arguments to the end of this command
```

Optimization Results

- For faster optimization speed, W2 was set to be equal to Sx
 - Fits in with theoretical expectation, from graded-index model, of what W2 should be for maximum transmission
- Optimized structure is shown to the right, averages 99.804% transmission from 2-5um.

Parameter	Optimized (Defined) Value	Optimization Range (if applicable)
H	2.973451636	$0.8 \leq H \leq 3\mu\text{m}$
W1	0.2263061559	$0 \leq W1 \leq 0.7\mu\text{m}$
W2	Sx	
Lattice	Hexagonal	
Sx	0.8980307418	$0.7 \leq Sx \leq 0.9 \mu\text{m}$
Sy	$\sqrt{3Sx}$	
N	2.45 (As_2S_3)	
Operating Wavelength	2-5um	



References

- [1] R. J. Weiblen, C. R. Menyuk, L. E. Busse, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Optimized moth-eye anti-reflective structures for As_2S_3 chalcogenide optical fibers," *Opt. Express* 24, 10172-10187 (2016)
- [2] Daniel H. Raguin and G. Michael Morris, "Antireflection structured surfaces for the infrared spectral region," *Appl. Opt.* 32, 1154-1167 (1993)
- [3] M. J. Steel, T. P. White, C. Martijn de Sterke, R. C. McPhedran, and L. C. Botten, "Symmetry and degeneracy in microstructured optical fibers," *Opt. Lett.* 26, 488-490 (2001)