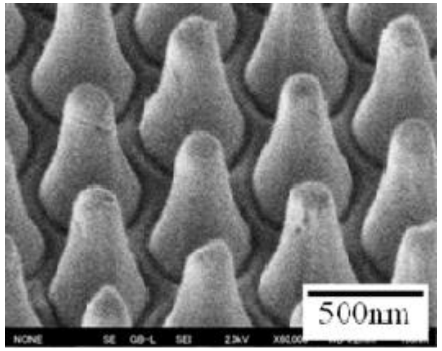
Optimization of a nanostructured moth-eye anti-reflective coating in RSoft

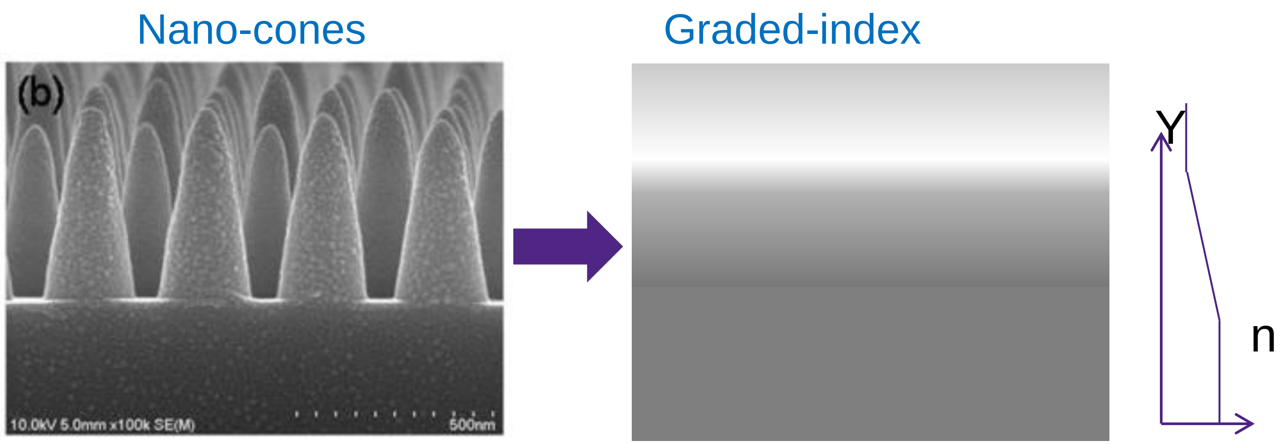
Moth-eye anti-reflective structures

- 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



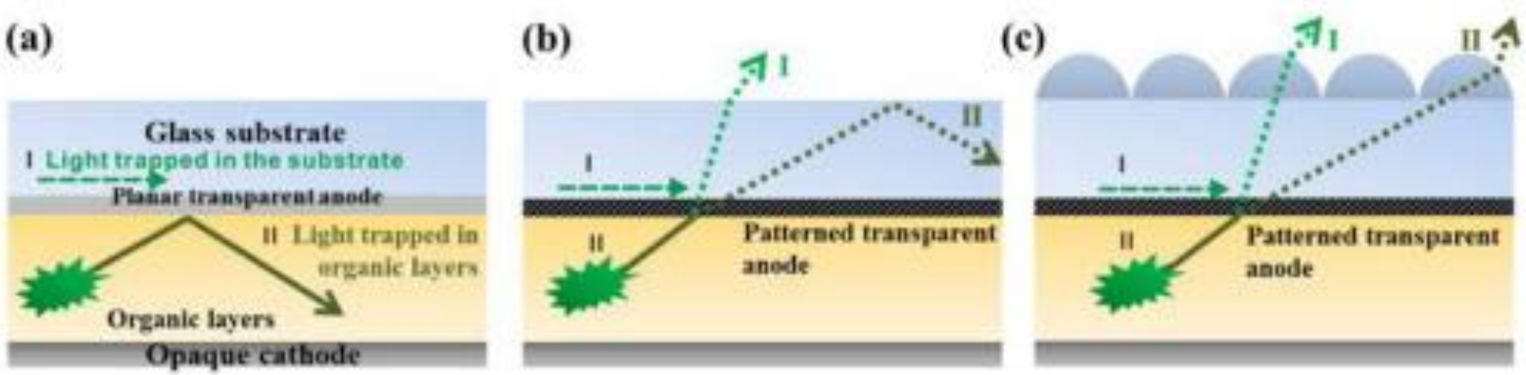
T. Kondo, *et al,* Proc. of SPIE Vol. 7602 (2010) 76021M-1



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

Moth-eye anti-reflective structure applications

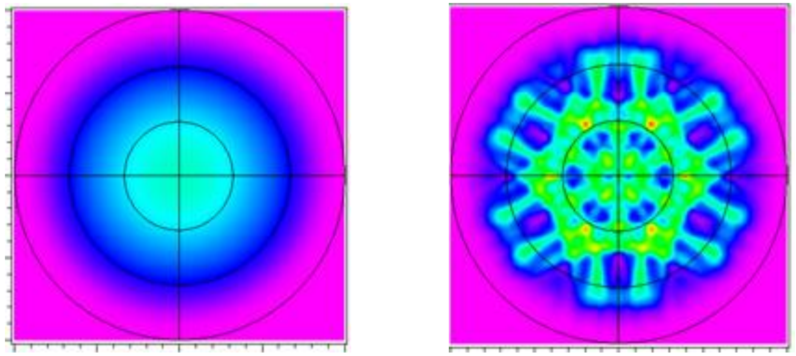
- Moth-eye nanostructures can be patterned on surfaces to give them antireflection properties
- Moth-eye structures have several advantages over traditional thin-film AR coatings
  - Environmental tolerance
  - Surface adhesion
  - Single-material fabrication
  - Minimal surface preparation
  - Higher 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

Far-field patterns

Flat Textured



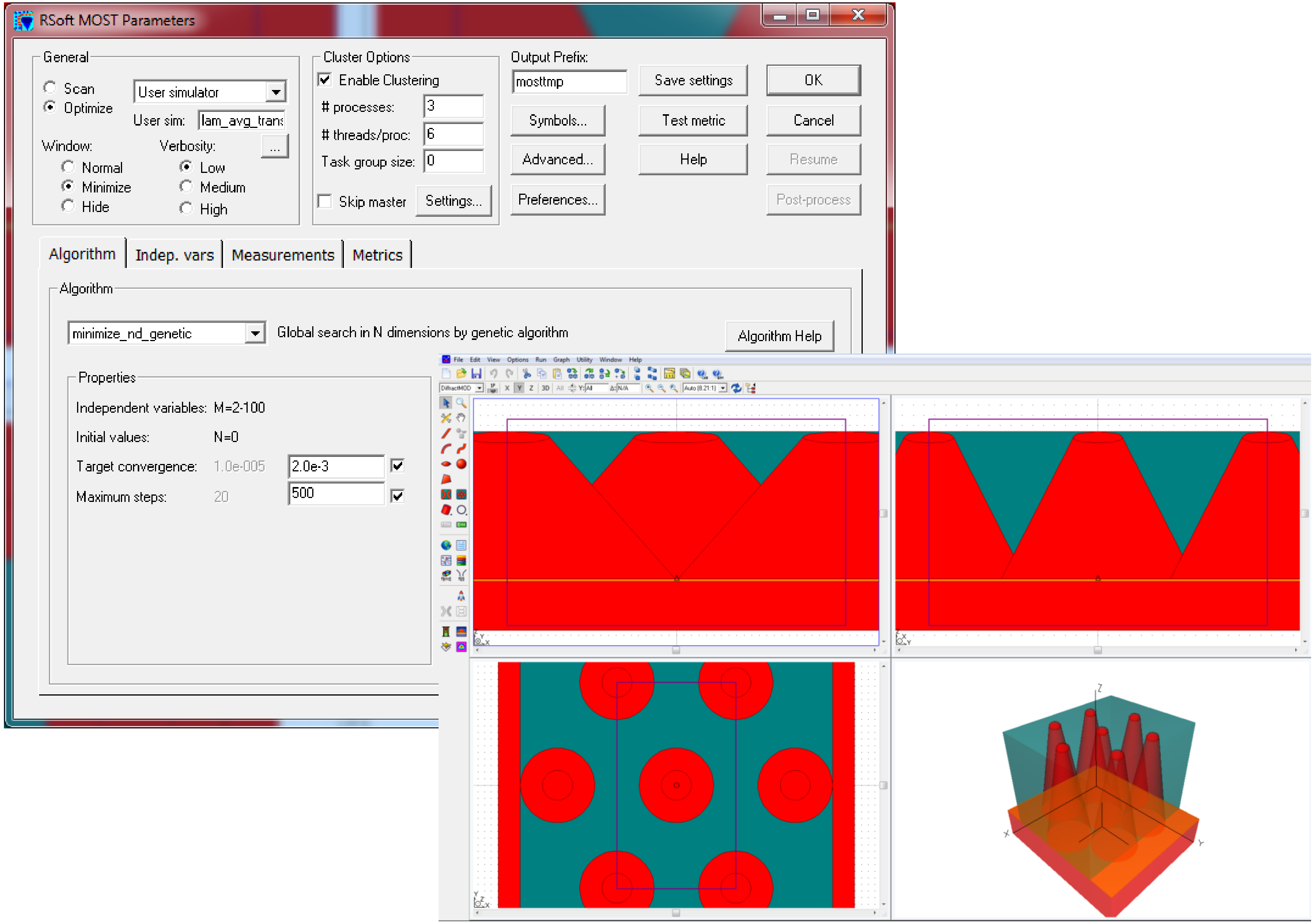
Ou, Qing-Dong, et al., *Advanced Optical Materials* 3.1 (2015): 87-94.

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

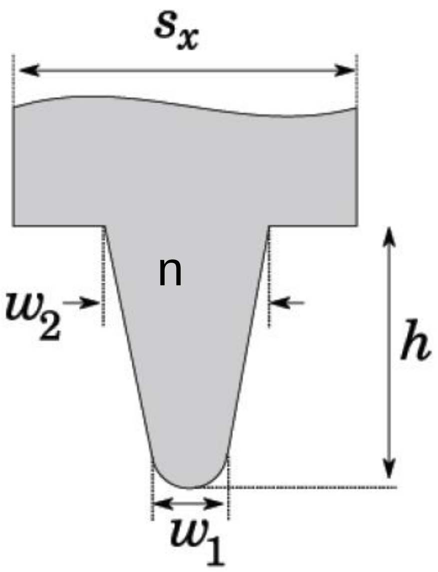
- Rigorous computational EM propagation methods, like FDTD and RCWA, can be used to accurately simulate the transmission/reflection from the moth-eye surface.
  - For this particular moth-eye structure, RSoft's DiffractMOD RCWA tool is utilized due to RCWA's speed advantages over FDTD

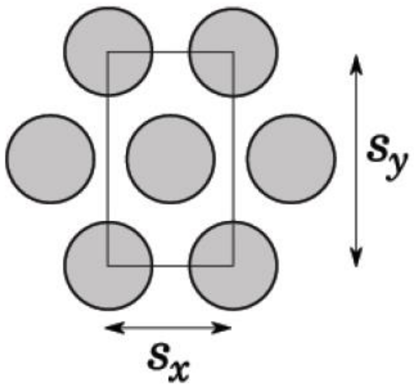
- RSoft's MOST Optimization and Scanning Utility is used in conjunction with DiffractMOD to optimize the reflection/transmission for the moth-eye AR pattern

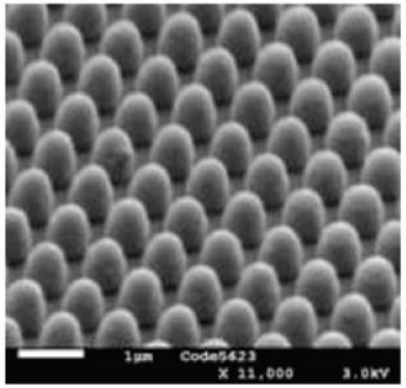


Moth-eye anti-reflective structure parameters

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



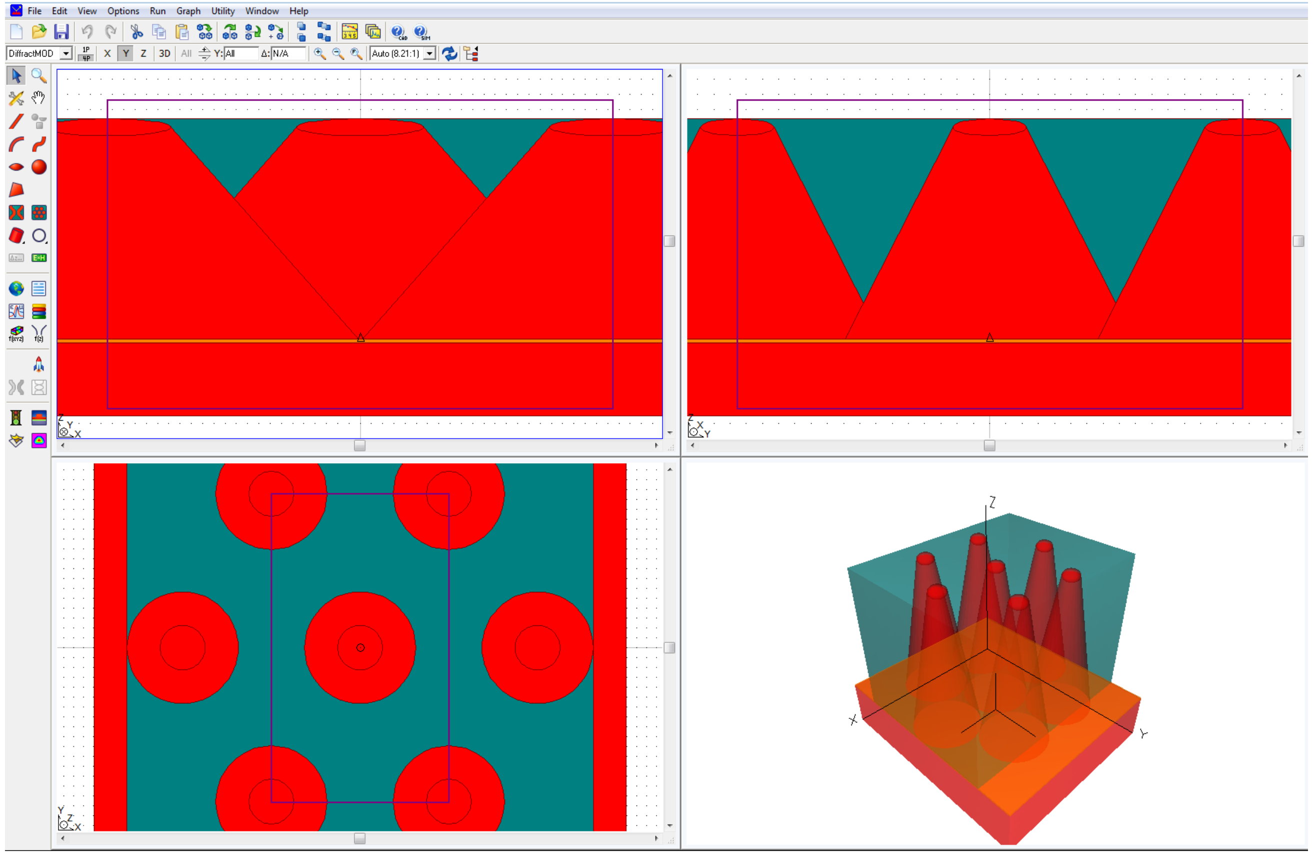




R. J. Weiblen et. al [1]

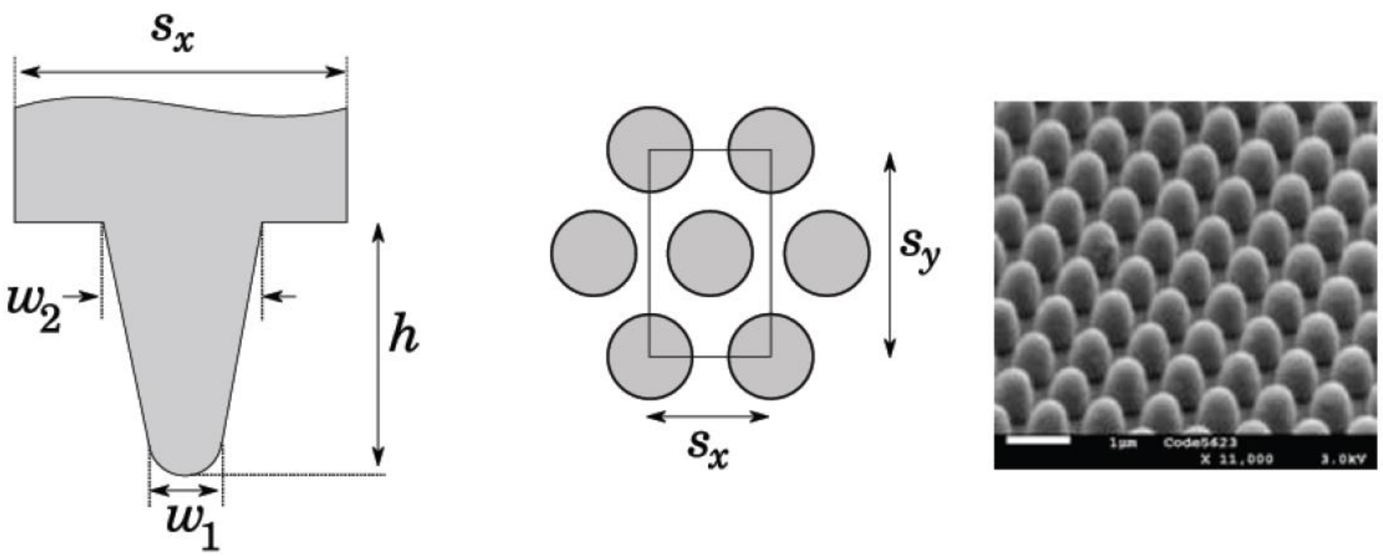
Simulation Parameters

- 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 (W1)
  - Base width (W2)
  - Height (H)
  - Lattice Period (Sx, Sy=$\sqrt{(3Sx)}$)

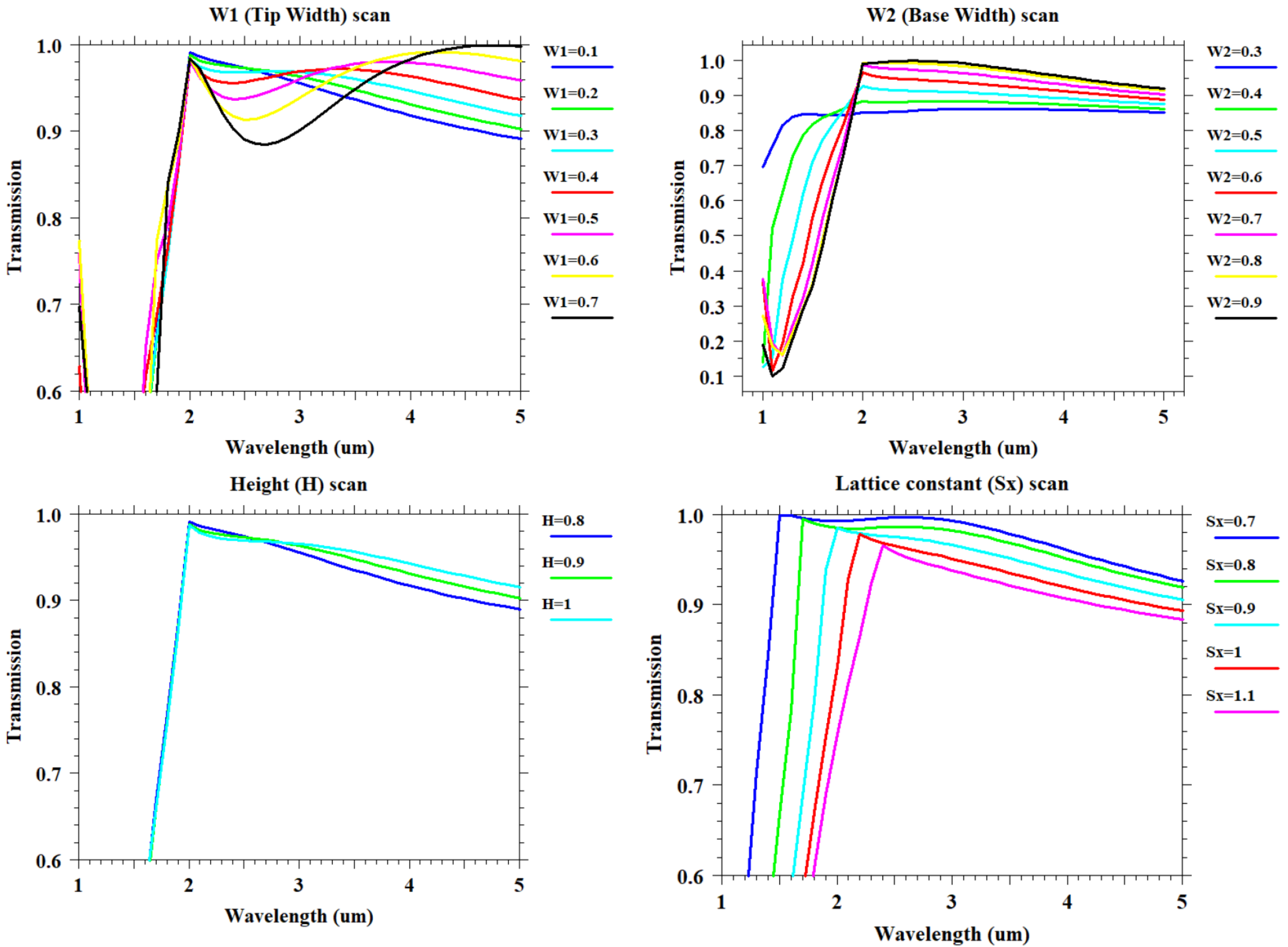


R. J. Weiblen et. al [1]

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

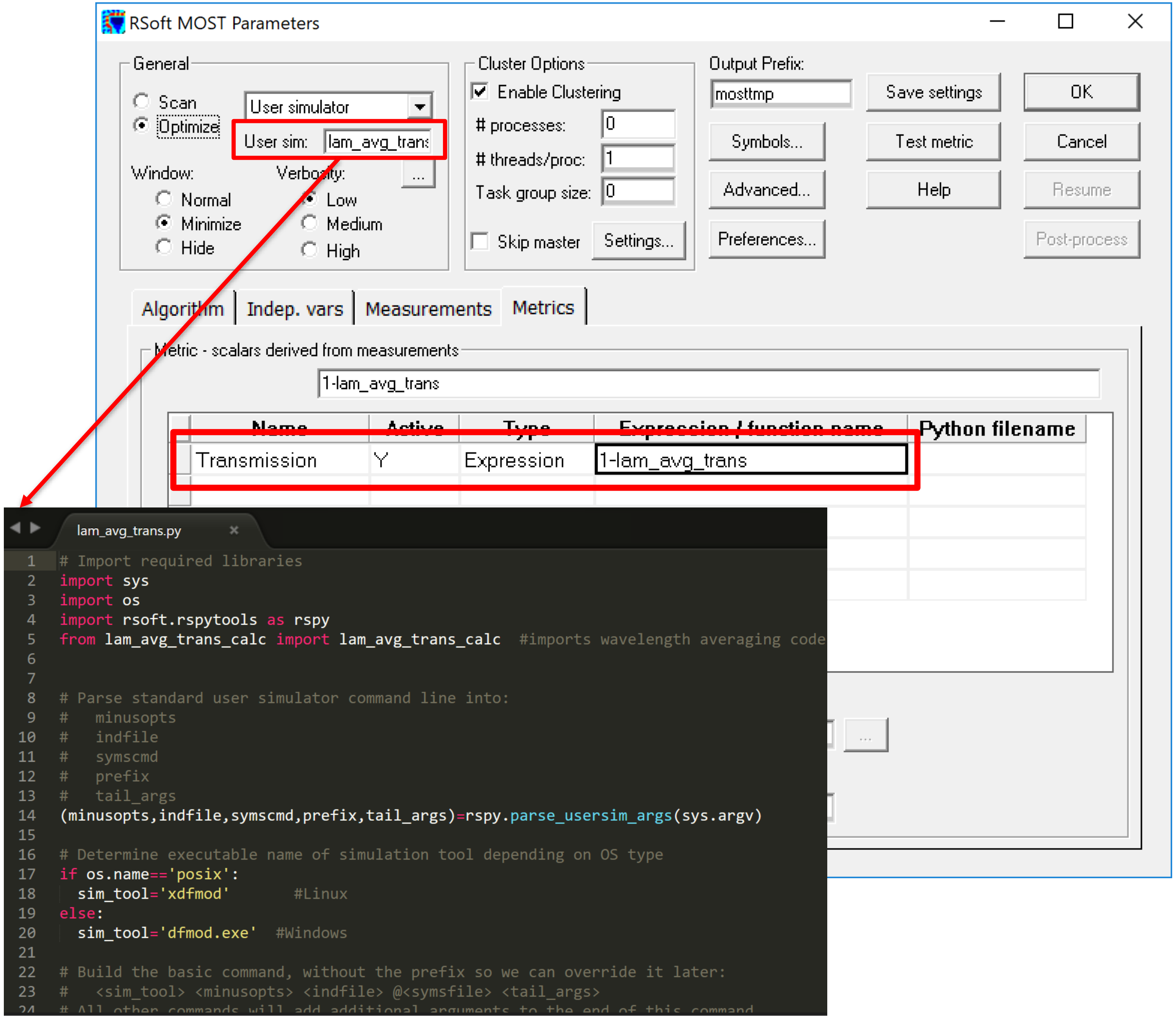
- Here, we will optimize the design parameters of the moth-eye structure to achieve maximum averaged transmission from 2-5μm.

- 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 2-5μm) 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

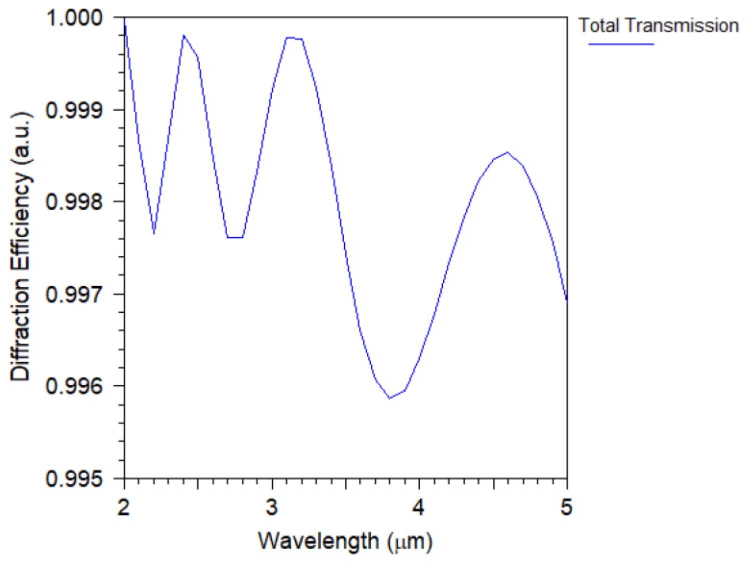


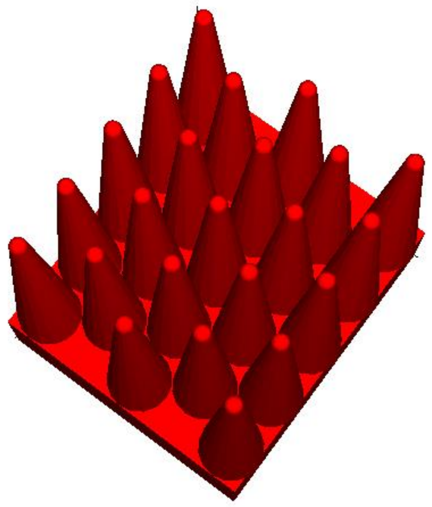
Optimization Results

- 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 ≤ H ≤ 3um
W1	0.2263061559	0 ≤ W1 ≤ 0.7um
W2	Sx	
Lattice	Hexagonal	
Sx	0.8980307418	0.7 ≤ Sx ≤ 0.9 um
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_3chalcogenide 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)