Dispersive Sweatt Model for Broadband Lens Design with Metasurfaces: supplemental document

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MS Singlet Layout

Figure S1

DSM Doublet Prescription

Figure S2 to S3

Table S1

1. MS Singlet Layout

We are addressing the lens' layout by MATLAB. Each of position the lens has a specific, desired phase delay at the design wavelength. This phase delay is used to select the associated radius of MA in MA libraries. We are using the phase delay as medium to mapping the MA in the correct position to generate the desired profile. Generally, the more Silicon in a MA the larger the phase delay; smaller nanoholes and larger nanopillars have large phase delay. Thus for NP MS singlet, the radius of MA at the center of the lens begins large and decreases toward the zone boundary to provide positive power. NH MS singlets follow the opposite trend. These layouts are shown in Figure S1. Note that the singlet has a large number of Fresnel zones which induce losses away from the design wavelength due to dispersion-driven phase mismatch at the zone boundary. A model is provided in the main text to quantify this loss.

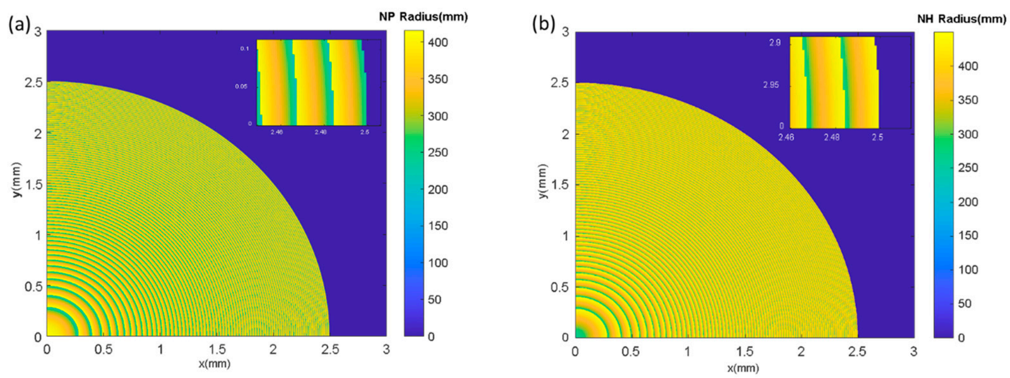

Figure. S1 Metasurface (MS) singlet layout for Si nanopillar (a) and Air nanohole (b) bases. Both singlets are 10mm focal length, F/2 and designed to operate in the midwave infrared band..

2. DSM Doublet Prescription

The main text summarized design results for a hybrid refractive/MS achromatic doublet designed using the DSM. Layout and MTFs were shown in Figure. 7. The MS is used to correct chromatic and monochromatic aberrations. A silicon refractive element was used to match the MS materials in order to highlight that chromatic correction was enabled by the MS dispersion; conventional color correction cannot be performed with a single material. The silicon nanopillar (NP) basis was used for the MS because it has larger dispersion than nanoholes and we need the dispersion for color correction. Here we report the complete prescription for the DSM design and provide additional geometric analysis.

As described the Section II(E), we represent metaatoms dispersion by equation 13. In Section IV(A) the NP dispersion factor was found to be $\alpha(\lambda)$ = 1.33 and 0.77 for 3.5 μm and 4.5 μm wavelengths, respectively. This yields an index of n = 11622.40 and 8716.03 for these wavelengths, respectively, using a design index of n_d = 10,000. We create an artificial glass material for the DSM and prescribe these index values in order to implement multiwavelength design in Zemax. A flat silicon substrate with a 500nm thickness is added between the Silicon lens and DSM material. The MS is represented as an Even asphere sag at the DSM/air interface.

We applied Zemax default merit function and AXCL operations to vary the C_{Si}, C_{DSW}, t_{BFD} and 6 terms of Even Asphere sag coefficients to optimize design for smallest RMS spot size. The complete lens prescription is provided below in table 1. The spot diagrams and MTFs for the hybrid refractive/DSM lens are shown in Figure. S2 after Zemax optimization.

Table S1. Hybrid Refractive/DSM Lens Prescription

Surface	Type	Radius (mm)	Thickness (mm)	Glass (mm)	Clear Diam (mm)
STO	Standard	Infinity	1.5	Air	4.99
2	Standard	24.09	2.5	Silicon	5.14
3	Standard	Infinity	0.5	Silicon	4.84
4	Standard	Infinity	0.003	DSM	4.78
5	Even Asphere	-855660.7	8.959285	Air	4.78

Surface	2nd Order (mm^2)	4nd Order (mm^4)	6th Order (mm^6)	8th Order (mm^8)	10th Order (mm^10)	12th Order (mm^12)
5	6.215E-07	-9.853E-08	6.449E-08	-1.832E-08	2.545E-09	-1.380E-10

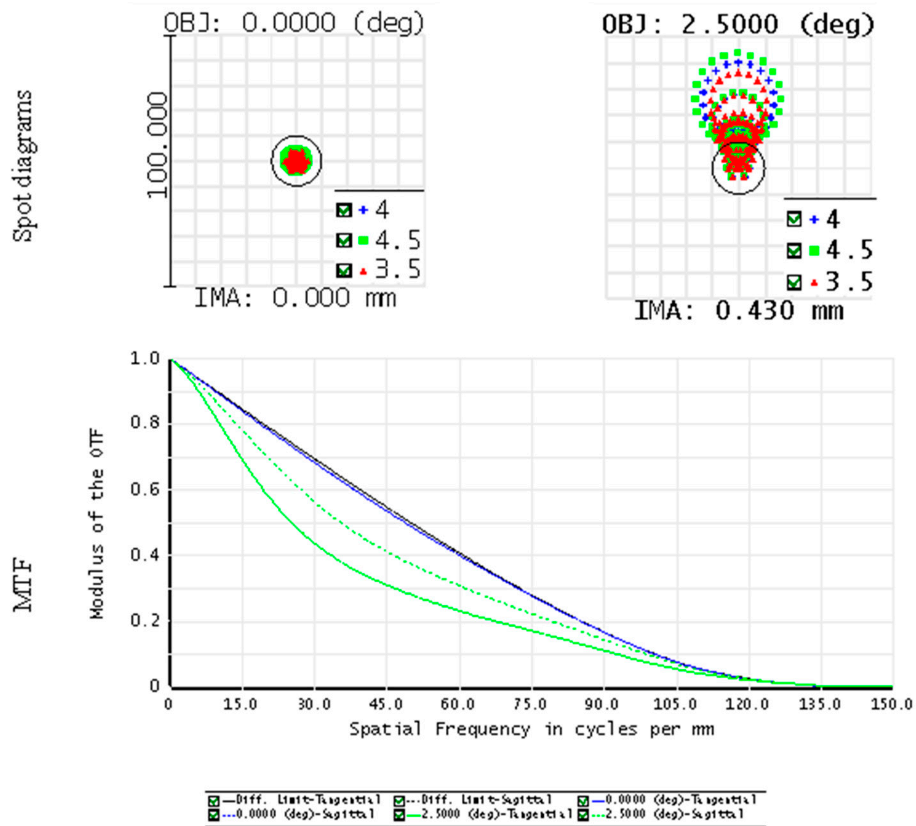

Figure S2. Geometric analyses for the 10 mm, f/#=2 hybrid achromatic doublet comprised of a refractive and metasurface element. The spot diagrams and the modulation transfer function (MTF) are shown for λ=3.5μm,4μm,4.5μm and field-of-view FOV=0°,2.5°.

With the Zemax design, we use Matlab to perform a layout to the 4 μm wavelength profile. The sag is converted to phase delay and then the NP library is used to assign metaatom radii across the aperture. After completing the layout we can compute the phase profiles (within the local uniformity approximation, LUA) for the off-design wavelengths. In Figure. S3 we plot the resulting real (i.e. LUA) phase and the design (i.e. DSM) phase. The two are in excellent agreement illustrating the efficacy of the DSM to represent the metaatom dispersion. This excellent agreement is also evident in the similarity of the MTFs provided in the main text. This shows that the DSM provides an effective tool to design broadband metalenses with spectrally correlated phase profiles that can be realized in a given meta-atom basis.

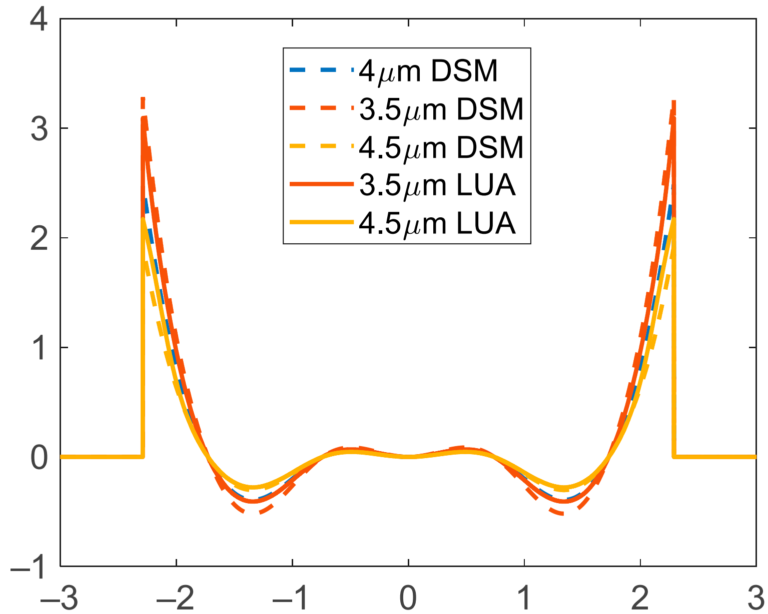

Figure S3. Metasurface phase profiles for the hybrid refractive/MS achromatic lens. DSM (dash) and real LUA phase (solid) are shown for the three wavelengths used for DSM optimization. The real LUA phase for the design wavelength 4 microns is not shown because it exactly follows DSM target.