Metalens Metrology Methods

Technical Note

Introduction

Metalenses have significant differences from conventional lenses that require extra consideration for lens metrology.

1. Chromatic aberrations: Chromatic aberrations are much larger in metalenses and other diffractive optics compared to conventional lenses. For the most common metalens designs, the chromatic focal shift (the change the focal length due to a change in wavelength) follows a simple equation.

$$f(\lambda) = f_0 \frac{\lambda_0}{\lambda} \quad \textit{(equation 1)}$$

   Where $f(\lambda)$is the focal length at the measured wavelength, λ_0 is the design wavelength, and $f_0$is the design focal length.

2. Diffraction efficiency: Unlike refractive lenses, diffractive lenses like metalenses do not direct 100% in one direction. For any non-ideal metalens, some portion of the light is directed toward the zero-order mode (specularly transmitted) and into higher order modes and negative order modes. The higher order modes will focus light at a shorter focal length. For example, the 2^{nd} order mode has a focal length that is half of the first order mode.

Metalenses are generally fabricated on wafer, which presents an advantage in terms of metrology at large scales. A metalens metrology tool can be designed to work with arrays of lenses on wafers, rather than just individual lenses. A single wafer designed for mass-production of metalenses can contain thousands of lenses and an appropriate metrology tool can measure them in quick succession. Properly set up, the metrology processes for metalenses can have greatly enhanced throughput by reduction of loading and alignment.

The metalens fabrication process can be used to fabricate elements with a wide variety of optical functions. In addition to lenses, one optical function is that of a linear diffraction grating, commonly referred to as a “beam bender”. Another function is that of a “beam generator” or “structured light generator”. However, for this article only the characterization of metalenses will be discussed.

Moxtek’s Metalens Characterization Setup

Moxtek uses an ImageMaster HR Wafer built by Trioptics Gmbh. This tool uses an infinite-finite setup for lens characterization. It has been set up with a tray for measuring 8in wafers as well as trays for individual parts. A large NA objective is installed so that large NA metalenses can be measured.

MTF

The infinite-finite setup functions is shown in figure 1. For MTF measurements, the setup begins with an illuminated cross reticle. A collimating lens projects this image to infinite. The metalens focuses the light to the image plane. The image plan is collected by a microscope objective and relayed to a camera. The camera image is analyzed to determine the MTF.

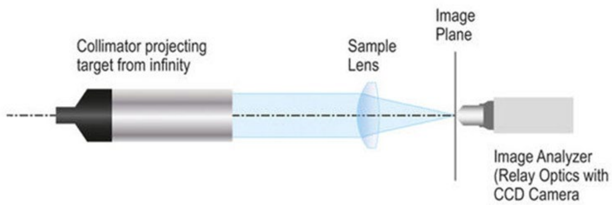


Figure 1. Diagram of infinite-finite setup. Image made by Trioptics Gmbh.

The measured MTF of any lens illuminated by a finite bandwidth source will be reduced by chromatic aberrations. For any lens, axial chromatic aberration is proportional to the product of the bandwidth and the diameter of the lens (assuming other parameters like focal length or lens material are held constant). Metalenses have intrinsically large dispersion, so for large metalenses, care must be taken to select a source with a narrow enough bandwidth so that MTF is accurately characterized.

Metalens Efficiency

We define the metalens efficiency as the average brightness of a diffuser image formed by the metalens, divided by that of an ideal lens. In academia, the efficiency is often calculated from the integration the signal within several multiples of the FWHM of the focus. We believe that the average brightness of a diffuser is less convoluted with resolution than the integration of light inside of a circle with the radius equal to a multiple of the full-width half-maximum of the focal point, which is more commonly used in academia.

We measure the brightness using an infinite-finite setup. An illuminated diffuser reticle is collimated by a tube lens and directed toward the metalens which recreates the image below it. A microscope setup collects the light in the recreated image, which is measured by a camera.

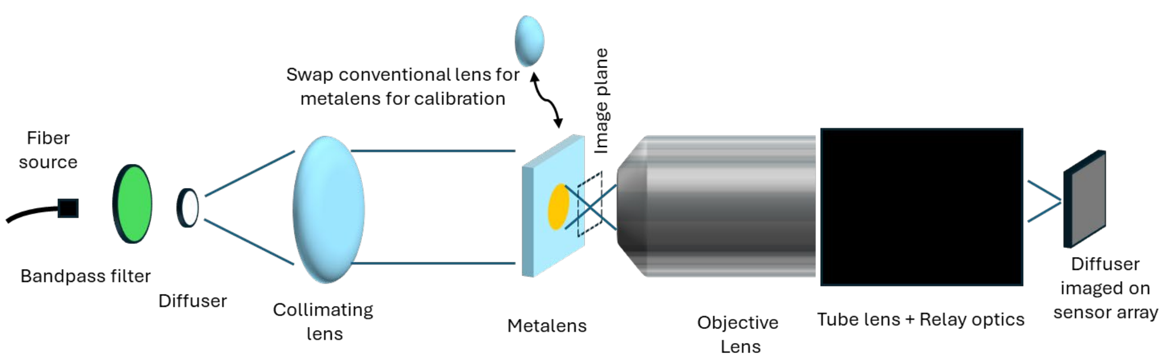


Figure 2. Diagram of setup for efficiency measurement. It is the same as in MTF measurements except the cross-reticle is replaced with a diffuser reticle.

We calculate the brightness for an ideal lens by placing a conventional lens in the above setup and then correcting for the transmission losses (as provided by the vendor). When measuring a metalens that has a different diameter and focal length compared to the conventional lens, we can normalize the signal for each by multiplying by the square of the focal length to account for magnification and divide by the area of the lens aperture to account for the input power.

A baseline measurement is performed alongside each run of lens measurements. The baseline measurement collects the raw signal when no sample lens is in place, so that the signal is only a function of the source power. In the efficiency calculation, the signal of both the metalens and conventional lens are divided by their corresponding baseline values, which accounts for fluctuations in source power over time.

The absolute efficiency of the metalens is calculated using equation 2.

$$E = \frac{S_1\, f_1^2\, t_2\, A_2\, B_2}{S_2\, f_2^2\, t_1\, A_1\, B_2\, T_2} \qquad (equation\ 2)$$

where E is the absolute efficiency, subscript 1 refers to the values of the metalens measurement and subscript 2 refers to the values of the calibration lens. S_1, S_2 are the raw integrated signals. f_1, f_2 are the focal lengths. t_1, t_2 are the shutter times of the measurement. A_1, A_2 are the areas of the lenses. B_1, B_2 are the raw signals of the baseline measurements. T_2 is the transmission of the conventional lens.

Zero-order efficiency

For measuring the zero-order efficiency, we first put the tool in a position where the objective lens is focused and centered on the lens image plane. Then we translate the lens laterally so that the objective lens is focused away from the focused image. This limits the collected light to only the specularly transmitted mode. The zero-order efficiency is the specularly transmitted signal is divided by the baseline signal (the specularly transmitted signal performed without a sample lens).

Effective Focal Length

The effective focal length (EFL) is measured using the built-in double-slit EFL measurement. Instead of a cross-reticle, a double-slit reticle is used. The spacing between the slits is measured on the camera, and this distance is used to calculate the magnification and thus the EFL of the lens. In general, it is not necessary to measure EFL each manufactured lens as typical manufacturing variations of metalenses have little effect on EFL.

Distortion

The distortion of a lens can be measured by performing a sweep of angles of incidence (AOI). The angle of incidence can be adjusted over a 105° field of view (FOV). The coordinate of the focal point is measured at a sweep of AOI to determine the distortion. The distance of the focal plane can also be measured to determine the Petzvald curvature of the lens.

For non-rotationally symmetric lenses, the angle of incidence can be combined with a sample rotation to determine the footprint of the lens (i.e. the range of image plane coordinates for a given object).

Example lens performance

Here we select one lens and present an analysis of its performance. This lens has a 1mm diameter, and 2.5mm focal length. It's designed with a hyperbolic phase profile for 532nm wavelength.

MTF

MTF measurement at normal incidence at the target wavelength shows performance near the diffraction limit (figure 3). MTF is a standard measurement and Moxtek has the capability to perform this measurement on every sold lens.

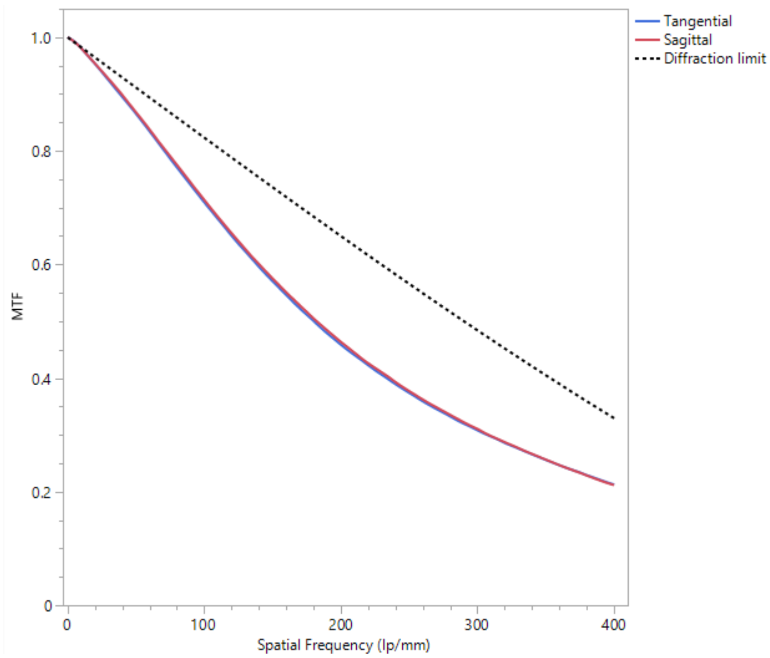


Figure 3. Measured tangential and sagittal MTF of selected lens at normal incidence, compared to the diffraction limit. The incident light was filtered by a bandpass filter centered at 532nm with 1nm FWHM.

Efficiency

The efficiency of the lens (defined above) was measured to be 90.5%. The zero-order efficiency was measured to be 1.6%. As with MTF, efficiency is a standard measurement and Moxtek has the capability to perform this measurement on every sold lens.

Chromatic aberrations

The example lens, designed for 532nm light, was measured with a set color filters with center wavelengths across the visible spectrum (figure 4). The efficiency is maintained for green (532nm center, 10nm FWHM) and red sources the designed wavelength but is significantly diminished for blue light. The MTF remains high across the spectrum. The focal length changes significantly with the filter wavelength, almost exactly matching the expected focal length according to diffraction calculations.

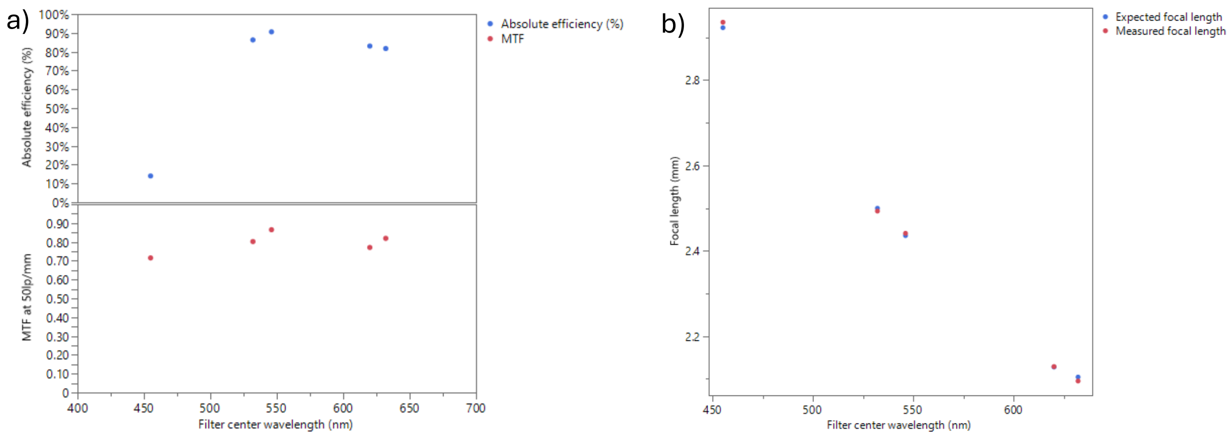
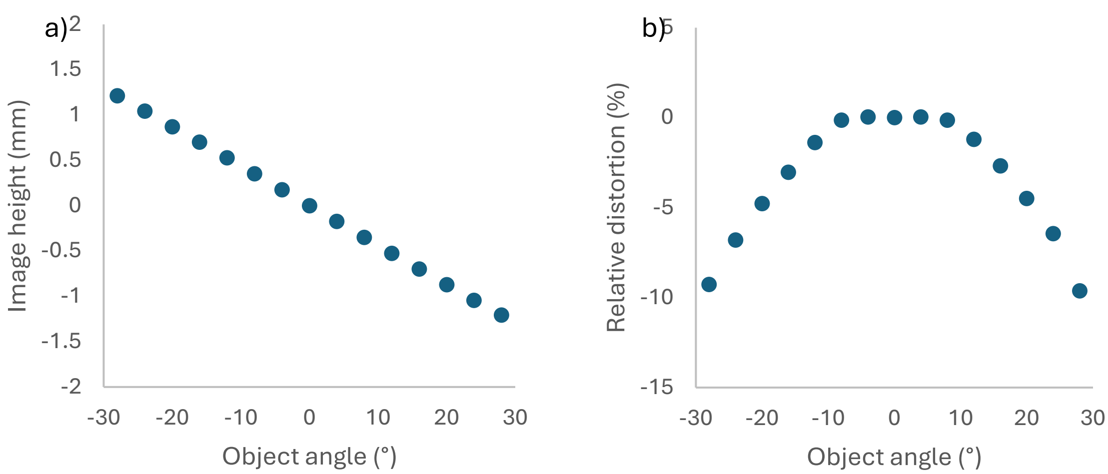


Figure 4. a) Plot of absolute efficiency and MTF of example lens using a sweep of different spectral bandpass filters. b) Plot of the measured and expected flange focal length (FFL) for the example lens.

Sweep of AOI

The measurement tool is capable of characterizing lens performance at a range of AOI (object angle). The distortion is low at small angles, but significant at angles above 15° (figure 5). The lens has a hyperbolic phase profile which gives a high MTF at normal incidence but the MTF is diminished significantly as the angle increases (figure 6). At angles 25° and below, the relative illumination is close to the theoretical maximum (figure 7).



5. a) Distortion plot for example lens at target wavelength. b) Relative distortion plot for example lens. Measured with 532nm center wavelength filter with 10nm FWHM.

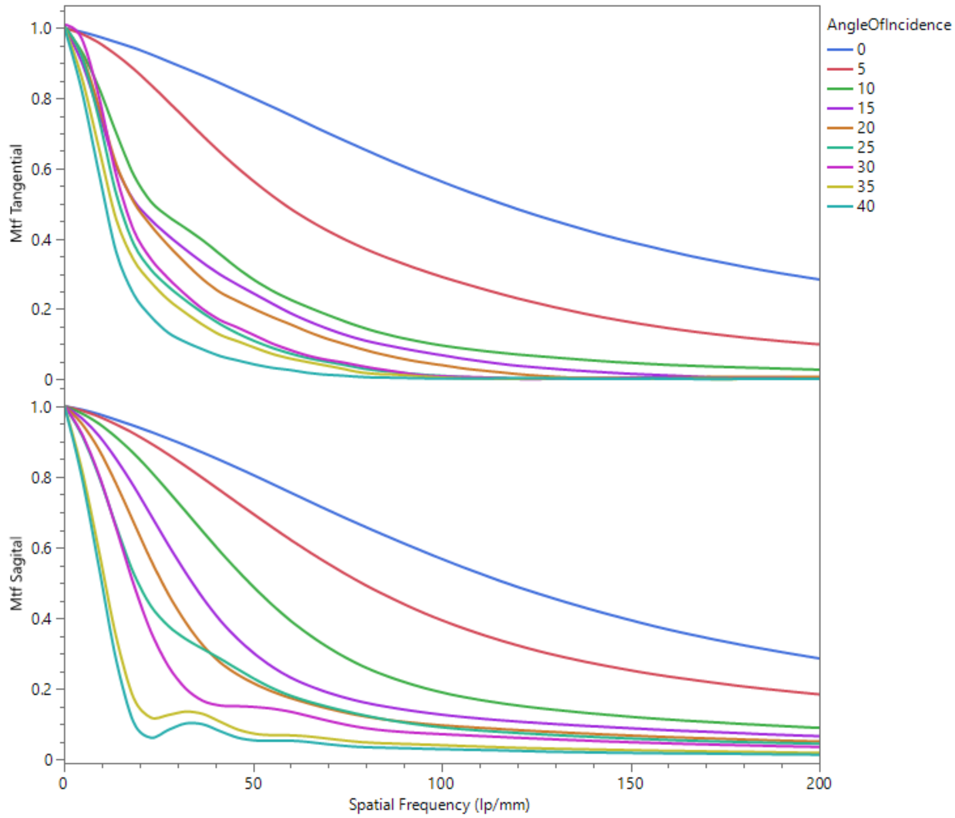


Figure 6. Plot of example lens MTF at different angles of incidence at target wavelength.

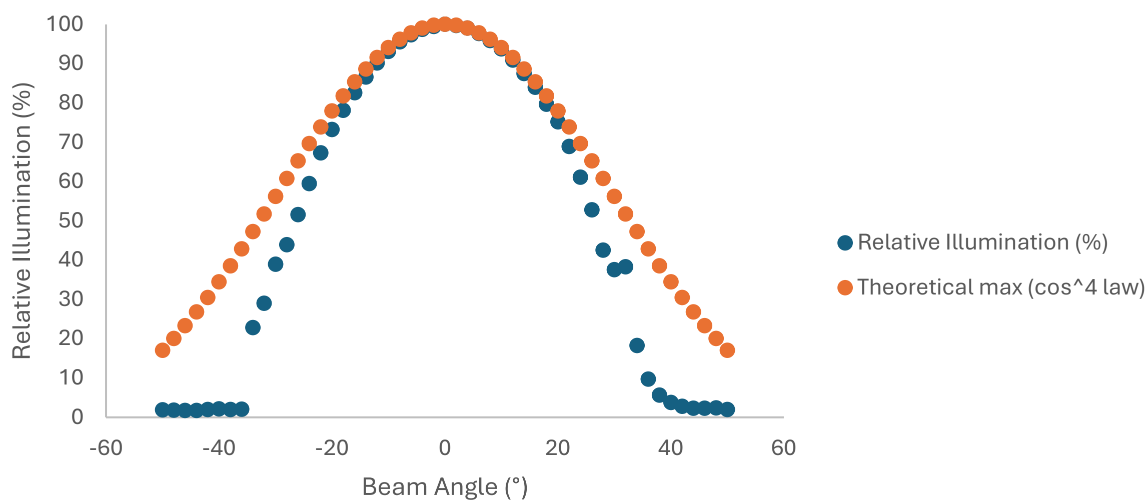


Figure 7. Plot of relative illumination of the example lens.

Footprint

A different, non-rotationally symmetric metalens was used to test the measurement of the lens footprint. The metalens was designed to focus a off-axis object plane to a sensor at the image plane at 633nm wavelength. The lens was measured at AOI and sample rotation corresponding to points at the corners and the center axes of the object plane. The measured positions were compared to the simulated positions (figure 8).

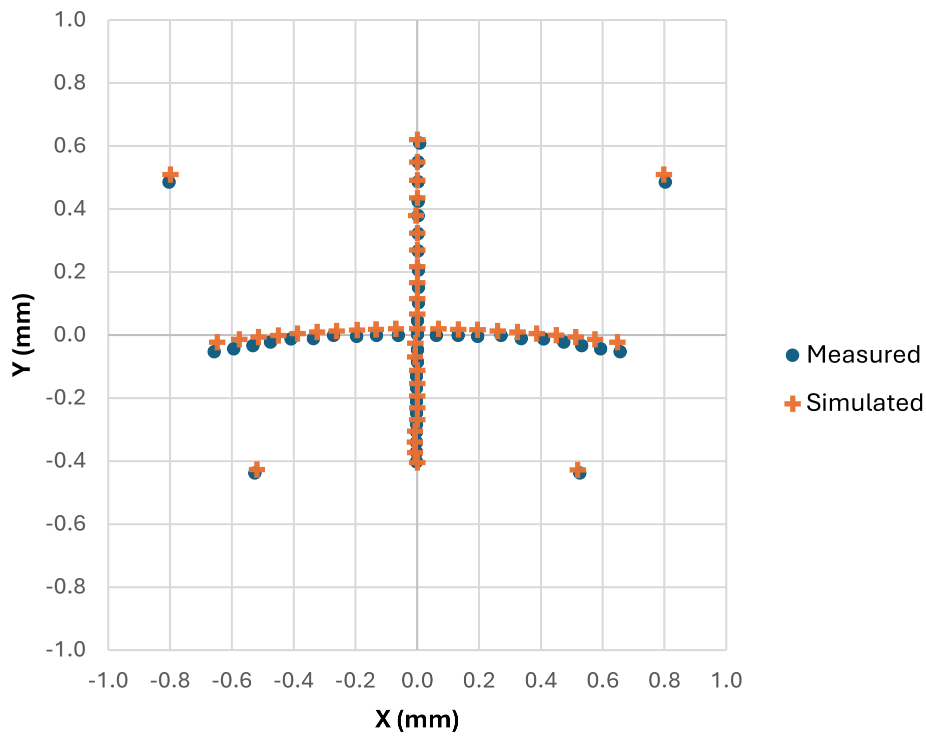


Figure 8. The measured and simulated footprint of a metalens designed for off-axis imaging.

Testing Metalens Uniformity

It is important that the fabricated metalenses have consistent performance. We look at 3 different kinds of uniformity: The uniformity of lenses within a single wafer, the uniformity of wafers within a lot, and the uniformity across many lots.

Uniformity within a wafer

To test the performance of production scale processes, Moxtek has made a wafer with optical elements written across the wafer. Each of 23 different elements were repeated 48 times across the wafer. For one of these elements, a lens designed for 532nm wavelength with 2mm diameter and 5mm focal length, the MTF curve of each replicated lens on a single wafer is plotted (figure 9). The MTF curve is nearly identical across the surface of the wafer.

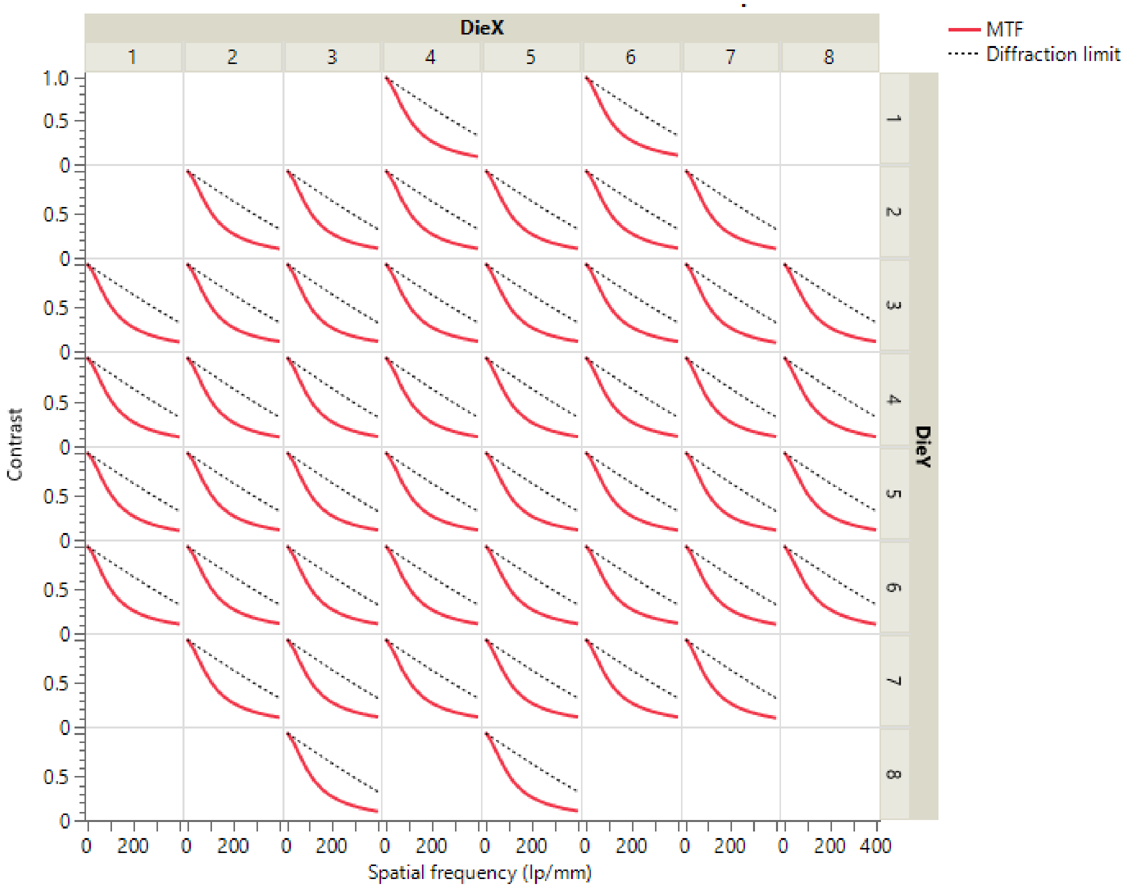


Figure 9. MTF curves for a single metalens repeated on 48 different dies times across the surface of the wafer. Light source was normally incident with the wavelength centered at 532nm. The lens was designed with 2mm diameter, 5mm focal length at 532nm and measured using a color filter with 532nm center wavelength and 10nm FWHM.

Uniformity between wafers and lots

To evaluate the consistency of the first metalens volume production tests, a single lens design was measured on each die of each wafer of a volume production lot. MTF, absolute efficiency, and zero-order efficiency were measured on each lens, with the results shown below in figure 10.

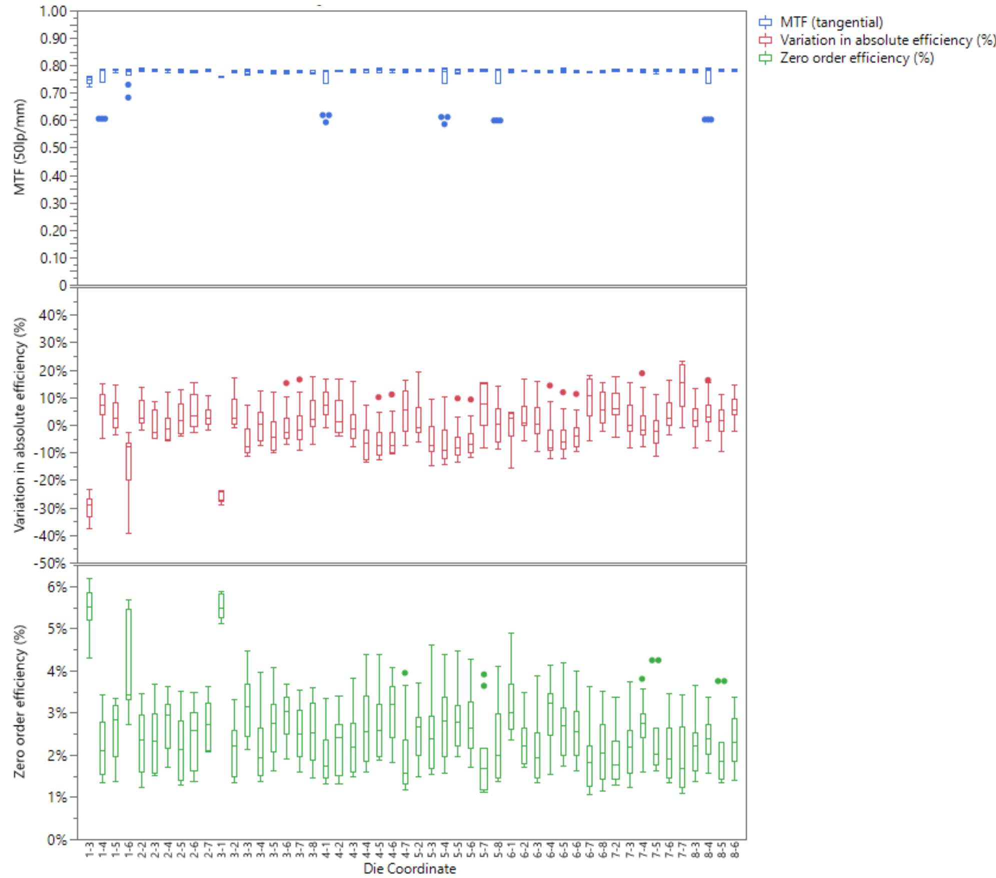


Figure 10. MTF, absolute efficiency, and zero-order efficiency wavength for every lens produced on a 12-wafer lot with 48 dies. The lens was designed with 2mm diameter, 5mm focal length at 532nm and measured using a color filter with 532nm center wavelength and 10nm FWHM.

Special considerations

Effect of Filter Bandwidth

Due to stronger chromatic focal shift, metalenses are more sensitive to filter bandwidth than conventional lenses are. The magnitude of chromatic aberrations of any lens is proportional to the product of the spectral bandwidth and the radius of the lens, assuming a constant numerical aperture. For large metalenses, the magnitude of the chromatic aberrations can be large and can be the predominant source of aberrations even when using a narrowband measurement.

The effects of the filter bandwidth in a real metalens was characterized by measuring the same lens with two bandpass filters with similar center wavelengths (632nm and 633nm) but different bandwidths (12nm and 3nm respectively). Two lenses with the same numerical aperture and meta-atom library were measured this way: a 1mm diameter lens with a 2.5mm focal length, and a 4mm diameter lens with a 10mm focal length. Results are shown in figure 11. The dramatic improvement in MTF when the bandwidth is decreased indicates that chromatic aberrations have a huge effect on measured performance, even when the measurement is narrowband and only the performance at a single wavelength is desired. When targeting a measurement to measure performance at a single wavelength, it is important to use an appropriate bandwidth.

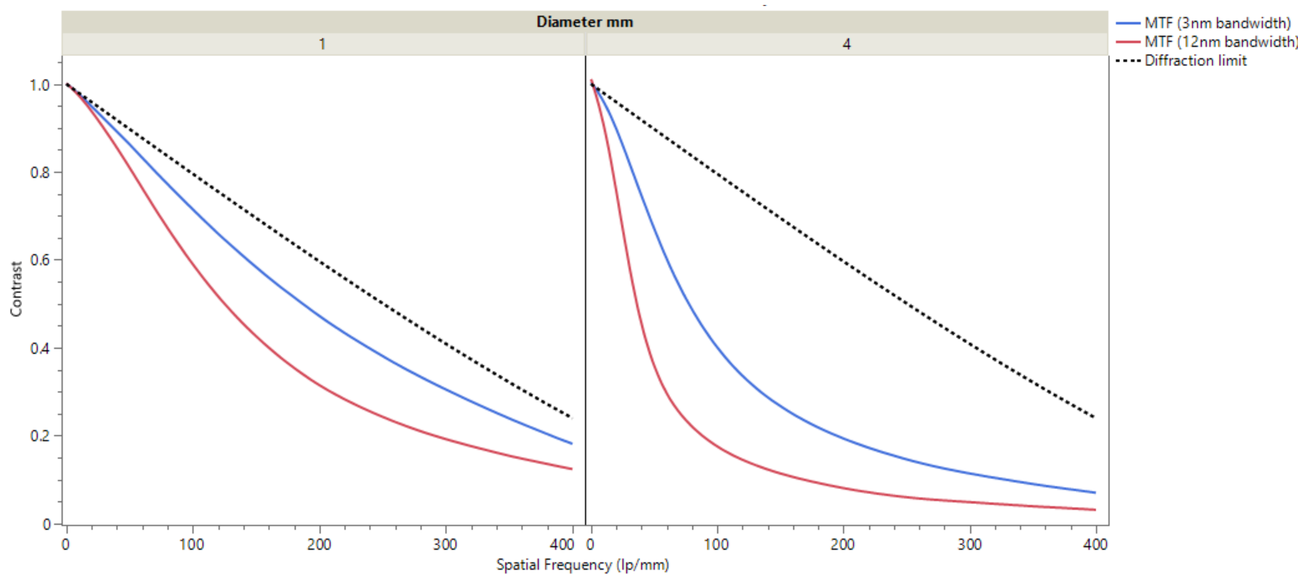


Figure 11. MTF curves for 1mm and 4mm diameter lenses designed for 633nm and measured with two bandpass filters centered at 633nm with 3nm and 12nm bands.

Conclusions

Metalens metrology differs from conventional metrology in some important ways. Focusing efficiency is very important for metalenses while being considered unimportant for conventional lenses. However, conventional lens metrology tools can measure these parameters. Chromatic focal shift is strong in metalenses, but very closely follows theoretical values.

Moxtek's metalens metrology processes have been described. MTF and absolute efficiency are standard automated measurements that can be performed on 100% of all fabricated lenses. Distortion, relative illumination, chromatic aberration measurements have been demonstrated as well. with capability to control the FOV within 105°. More complex measurements, such as measuring the footprint of an off-axis imaging lens, can be performed as well. Measured wavelengths can be easily expanded by installing new bandpass filters within the visible-NIR range.