Efficient mirrorlet array based integral field spectrometer for HWO

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ABSTRACT

Habitable World Observatory (HWO) is a NASA strategic mission recommended by 2020 astronomical decadal survey. Integral spectrometers play an important role to verify if the observed exoplanet is habitable. The traditional lenslet array based Integral Field Spectrometer (IFS) has the advantage of simplicity and compactness. However, it does not use detector pixels efficiently in order to prevent wavelength crosstalk among adjacent spectra. The efficient lenslet/mirrorlet IFS combines the advantages from both lenslet based and imager slicer based IFSes—keeping lenslet IFS's simplicity and compactness, concurrently adding slicer IFS's detector efficiency. This paper discusses the principle of efficient lenslet/mirrorlet IFS, design philosophy, and efficient spectral trace layout ideals. It uses HWO NIR IFS requirement as an example to provide an efficiency mirrorlet IFS optical design. The high detector efficiency not only reduces Needed detector pixel numbers, but also reduce the high communication rate demanding for much a large multiple instrument mission.

The basic idea of the efficient lenslet/mirrorlet array IFS is to design a lenslet/mirrorlet array in such a way that the images from multiple mirrorlets are grouped and aligned as a spectrum from a single slit. Therefore, the number of detector rows used to prevent wavelength crosstalk is no longer needed. This paper is also going to address how to lay the traces on the detector and what is the difference from the traditional lenslet IFS. Our goal is to show that such an IFS is capable to lay all spectral traces onto a 2k x 2k detector array using HWO NIR requirement that has a higher spectral resolving power R = 70 and a large Field of View (FOV) of 96 λ/D.

Keywords: Exoplanet, Efficient mirrorlet/lenslet Integral Field Spectrograph (IFS), HWO croronagraph

1. INTRODUCTION

Integral image spectroscopy concept was started from late 1980's. Now it has become a mainstream astrophysical tool in optical to mid-infrared wavelength regions. There are currently three different IFS flavors: image slicer, fiber array, and lenslet array[1]. Each method has its own pros and cons. The lenslet array IFS is the simplest and provides highest throughput, but it has a low detector pixel usage efficiency in order to prevent the wavelength crosstalk between adjacent spectral traces. The image slicer has a high detector pixel usage efficiency but need a complex optics to rearrange the slicer images at the spectral object plane. The fiber array has the flexibility to position spectrometer at a desired position, however, it has a sizeable light loss and poor photometric accuracy and difficult to work in cryogenic environment.

Based on the current status, this paper proposes a novel idea: efficient lenslet/mirrorlet array that maintains the simplicity, compact, and high throughput of lenslet/mirrorlet array IFS, concurrently adding the detector pixel efficiency of the image slicer, which could increase the areal efficiency almost 100%. This impresses that the efficient lenslet/mirrorlet IFS capable to increase the FOV significantly without compromising the special and spectral resolutions. The combined capability is very valuable to space flight missions, which favors light weight, small volume, high performance and low risks.

In this paper we first discuss the concept of the lenslet/mirrorlet IFS. Then using it to design a prototype for HWO coronagraph IFS for NIR channel.

2. LENSLET/MIRRORLET IFS OVERVIEW

2.1 Lenslet/Mirrorlet IFS Concept

Figure 1 shows the effient lenslet IFS in comparison to traditional lenslet IFS and image slicer. The top of figure 1 shows the concept of the efficient lenslet IFS. The main difference from the traditional lenslet array layout is that the efficient layout groups four lenslet in a column to make a pseudo mini-slit, that is, the 4 lenslets focus the light on to a pseudo-slit. The Purpose is to align the 4 PSF in the direction that is perpendicular to the dispersion direction. After the spectrometer disperses spectral traces parallel to pixel rows on detector, the 4 PSFs are always aligned to the same column position for any wavelengths. So, there is no need for adding rows between two adjacent spectra to avoid cross dispersion contamination. This is unlike the traditional lenslet IFS where the spectra are staggered, and additional rows are necessary to isolate them. The same detector was assumed for both traditional and efficient IFS. It is obvious that the efficient lenslet array FOV has increased to 6 x 6 from 4 x 4 in traditional case, which is an increase of 125% areally. The FOV covered by each lenslet/mirrorlet is the same for both cases.

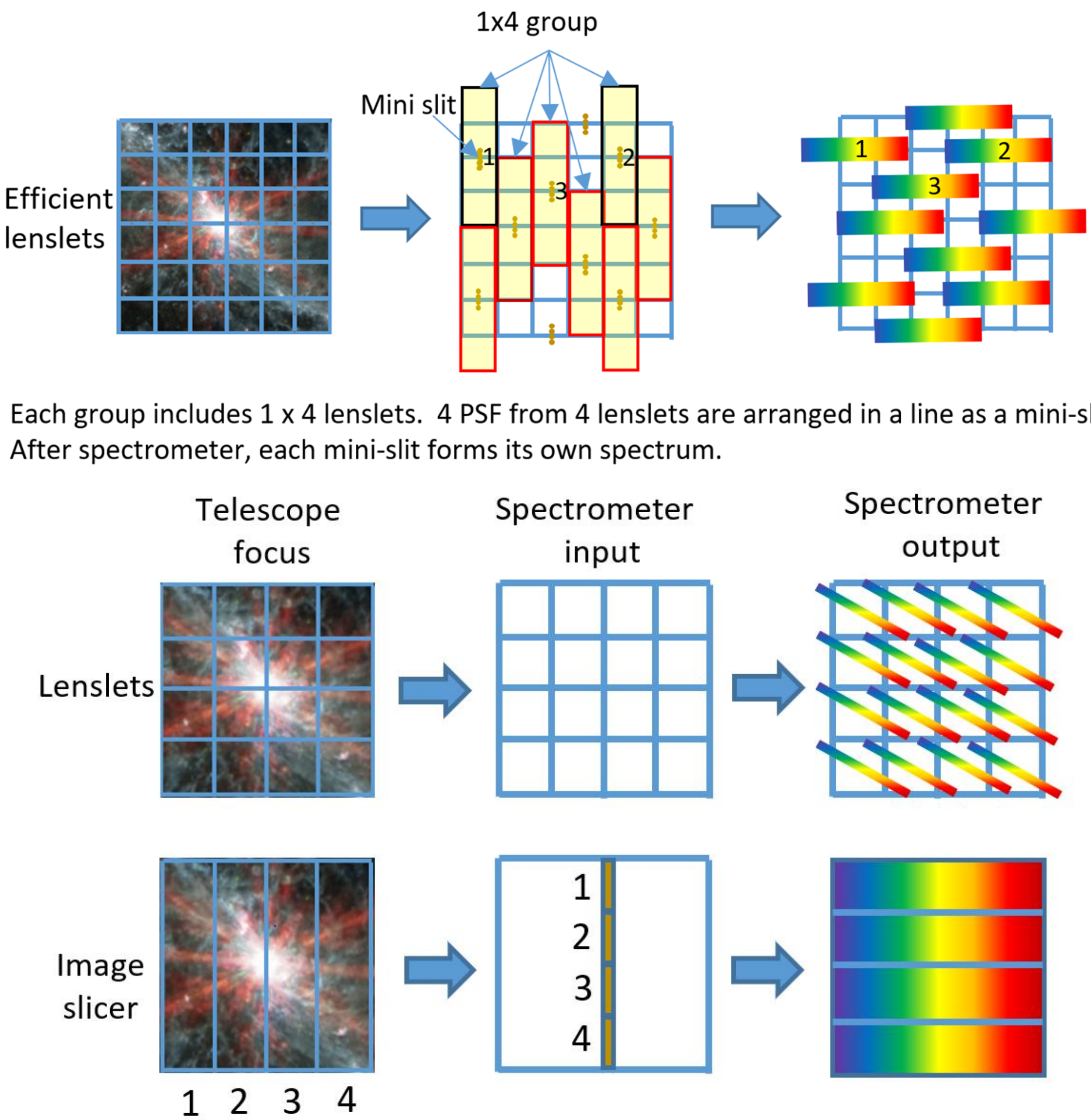

Figure 1. Efficient lenslet/mirrorlet array IFS[2] with comparison to traditional lenslet array and image slicer IFSes.

The efficient lenslet/mirrorlet array is amendable to a variety of configuration. The number of the lenslets being grouped is arbitrary. The more lenslets in a group, the higher the efficiency. However, the number of the lenslets is limited by the "equivalent f/#", which limits the optimal lenslet numbers to 3 – 5 in most cases. The optimal lenslet numbers, along with other parameters, such as lenslet size, detector pixel size, FOV, spectral resolving power, instantaneous bandwidth, etc., are detailed in the following sections of this paper. Generally speaking, the efficient lenslet/mirrorlet IFS provides much more flexibility for designers to optimize the efficiency. On the other hand, it is also more challenge for designers.

2.2 Efficient Lenslet/Mirrorlet Array Design and Fabrication

The advanced photo-lithography and dry etch technology have provided us the opportunity to shape each individual lenslet/mirrorlet surface differently. The key of the efficient lenslet IFS is to put multiple PSFes from each lenslet group on a line with selected spacing. For 1:1 magnification spectrometer, the spacing usually matches the detector array pitch. This implies that many lenslets are off-axis, their vertex could even be off the lenslet area.

In order to maximize the efficiency, the PSF separation should match the detector pitch. In this design example, we are using the efficient lenslet array configuration shown in Figure 1, that is, the pseudo mini-slit is parallel to each lenslet group and the dispersion direction is parallel to rows of the lenslet array. The following are the layout of the lenslet and mirrorlet versions from Zemax ray trace. In the design, the first thing we need to think about is the f/# of each lenslet. Based on our past experience, the PSF size (FWHM) should be Nyquist sampled to detector pixels. After the lenslet size is determined by the required spectral resolution, the f/# is controlled by the focal length of the lenslet. The equivalent group $f/\#_{group}$ is approximately the lenslet f/# multiplying the number of grouped lenslets. The $f/\#_{group}$ value is optical designer's choice. However, when the $f/\#_{group}$ is less than 2, more optical elements might be needed for controlling the spectrometer aberrations.

It should be briefly mentioned that two other factors can be used to the efficiency optimization: spectrometer magnification and the spectrum laying angle relative the mini-slit direction. It could also be used to relax optical design challenges.

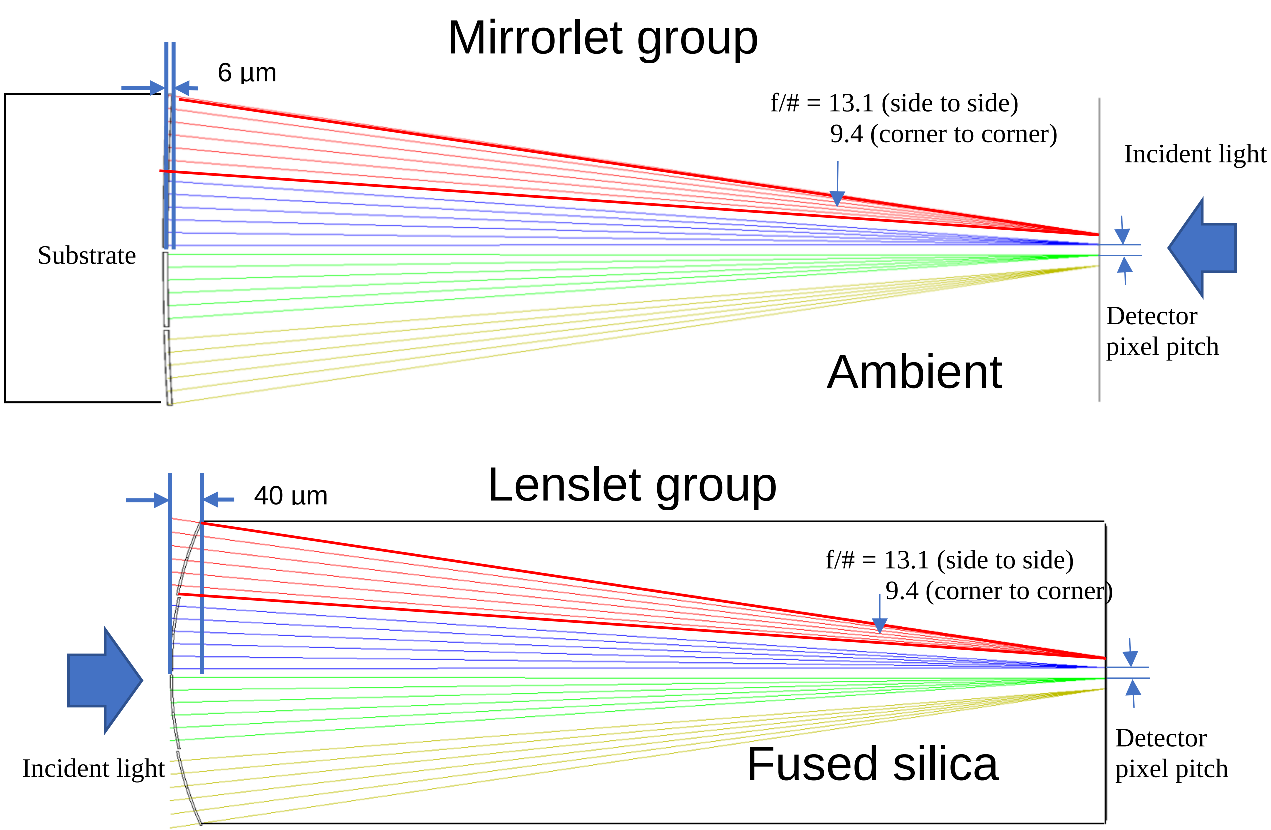

Figure 2. lenslet and mirrorlet group ray trace. Same design parameters are used for both designs. For the mirrorlet array on top, the substrate is on the back of the mirror. For lenslet at the bottom, substrate extended to the lenslet focus.

2.3 Lenslet Array versus Mirrorlet Array

Both lenslet and mirrorlet arrays could provide similar performance in visible and near IR range, similar to all other optical systems. Selecting mirrorlet for the efficient IFS is mainly due to the limitation of lithography and dry etch technique. The commonly used lenslet/mirrorlet array are made of fused silica. Fused silica is a preferred material among the transparent lens materials due to the following reasons: (1) It is non-crystal, that provides a smoother surface finish. (2) It has a good photoresist/fused silica selectivity that provides faster etch rate, deeper etch depth, and good surface figure control. (3) it has a very matured fabrication process compared to other materials in kind, such as CaF2, etc. However, even using fused silica substrate and the state of art lithography and etch technique, to have a etch depth more than 20 µm is a challenge. To compare the sags of mirrorlet group and lenslet group in Figure 2, the mirrorlet sag is only 6 µm but the lenslet sag is 40 µm, which is beyond manufacturer's comfortable zone. Besides, both surface figure error and surface roughness are a function of etch depth: the deeper the depth, the rougher the surface, the higher the surface error. Further more, the mirrorlet is achromatic, but lenslet isn't. For applications with wide wavelength range, mirrorlet's achromatic nature helps.

3. CHALLENGE OF TRADITIONAL LENSLET IFS FOR HWO CORONAGRAPH

The exoplanet study has been started in early 1990. It has attracted so many scientists and astronomers to this field trying to find the exoplanets orbiting the stars and to characterize them[3, 4]. However, most of the exoplanets were found using indirect imaging methods and not in habitable zone.[5] Driven by the interests from different study perspectives and try to catch the unique opportunity provided by HWO mission, the requirement for IFS becomes more and more challenge. With the technology advancing on deformable mirror (DM) and wavefront sensing and control, the required FOV for IFS has increased significantly. This motivated us to develop a more efficient way to pack the IFS spectral traces on detectors with finite number of pixels.

In the rest of this paper, we are using the HWO NIR IFS as an example to address how to meet the challenge.

Table 1. HWO coronagraph NIR IFS capability requirement

Parameter	Unit	Capability
Wavelength range	nm	1000 - 1800
Full FOV (based on traditional lenslet IFS)	mas (λ/D at 1000 nm)	3030 (88)
Spectral resolving power	At 1000 nm	R = 70
Spectral sampling	nm	7
Spatial sampling	Spaxel[a] at 1000 nm	2
Lenslet/mirrorlet angular size	mas in sky	17
Instantaneous bandwidth	%	20
Detector array	LMAPD	2k x 2k
Deformable Mirror (DM)	pixel	96 x 96

Table 1 shows that the FOV is limited to 88 λ/D at λ = 1000nm with traditional IFS, which prevents the IFS from sampling the entire area of 96 λ/D where the Deformable Mirror (DM) can control the wavefront. Moreover, the FOV in λ/D is a function of wavelength. At the longest wavelength 1800 nm, the FOV is only 49 λ/D. On the other hand, DM's FOV is independent of wavelength: 96 λ/D for the entire wavelength range from 1000 nm to 1800 nm.

Figure 3 shows the traditional IFS FOV range with respect to DM FOV in λ/D. It is seen that for the entire NIR wavelength range, DM's FOV is not fully utilized.

3.1 How does efficient lenslet/mirrorlet array increase IFS FOV

Using the NIR IFS specification in Table 1, the following lenslet/mirrorlet array parameters are derived;

[a] A spaxel is one element (lens or mirror) in lenslet/mirrorlet array.

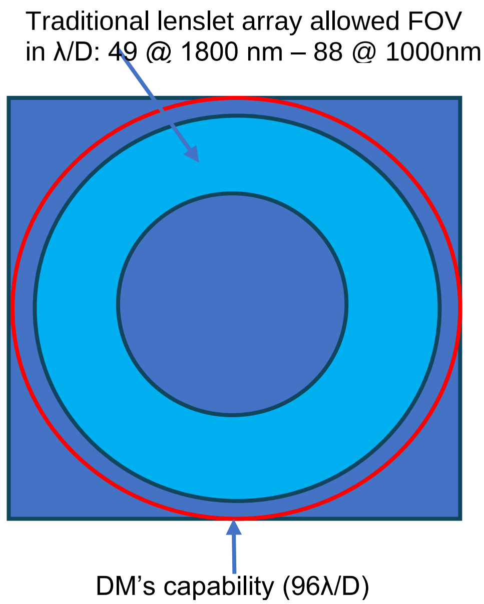

Figure 3. Efficient lenslet/mirrorlet array IFS with comparison to traditional lenslet array and image slicer IFSes.

1. Based on the spectral resolving power R = 70, the required number of pixels on detector is 29 per spectrum for covering 20% instantaneous bandwidth.
2. In order to prevent contamination of two adjacent spectral traces in the same row, two additional pixels on each sides are added, which makes the total trace length 33 pixels long (see figure 4 (a)).
3. For this particular efficient elnslet/mirrorlet array with 4 lenslets/mirrorlets as a group, the pixel numvers becomes 4 * 33 = 132 pixels (Figure 4 (b)).
4. To prevent the contamination in cross dispersion direction, two additional rows are added, which makes the total detector pixel per group 264 pixels (Figure 4 (b)).
5. The 264 pixels includes 4 spectral traces, that is, each trace needs 66 pixels to lay the spectrum. In other words, each lenslet/mirrorlet covers at least 66 detector pixels. If the spectrometer's magnification is 1:1, the lenslet/mirrorlet size will be $\sqrt{66} \approx 8.12$. Considering the possible spectrometer distortion and all tolerances, this number is relaxed to 8.5.

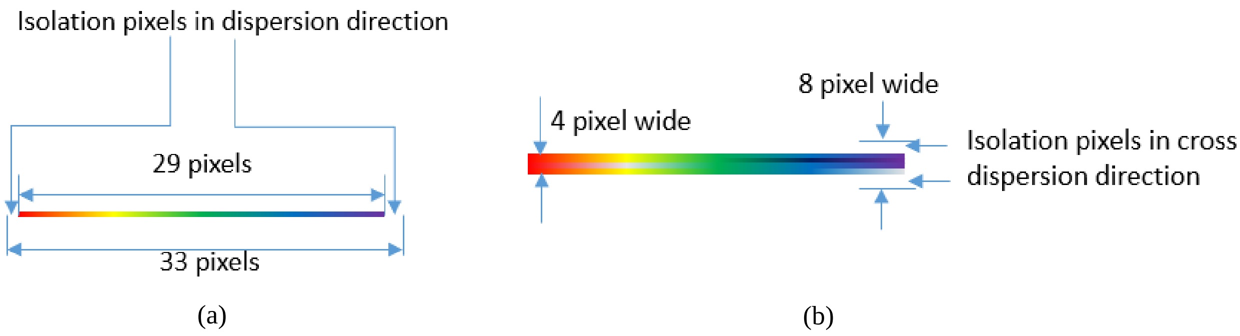

Figure 4. Efficient lenslet/mirrorlet spectra layout geometry.

Summarize the calculation above, the efficient lenslet array can have 242 x 242 lenslets for a 2k x 2k detector array, which makes the FOV 121 λ/D at 1000nm. The equivalent sky/detector FOV is 4114 mas x 4114 mas, which is the same for all wavelengths.

The comparisom of FOV in λ/D between traditional lenslet IFS and effiecient lenslet/mirrorlet for the same specification and detector. It is noted that the sky/detector FOV is independent of wavelength. The reason that coronagraph design prefers λ/D is that almost all coronagraph sensitive elements, such as DM, focal plane mask, Lyot stop, etc. have strong dependent on wavelength due to the nature of the diffraction is a function of wavelength. Therefore, the elements being used to suppress the diffraction are wavelength dependent, such as focal plane masks.

Table 2. FOV comparison in λ/D between efficient and traditional lenslet arrays

λ (nm)	Efficient	Traditional	DM
1000	121 λ/D	88 λ/D	96 λ/D
1260	96 λ/D	70 λ/D	96 λ/D
1800	67 λ/D	49 λ/D	96 λ/D

The graphis version of Table 2 is shown in Figure 5.

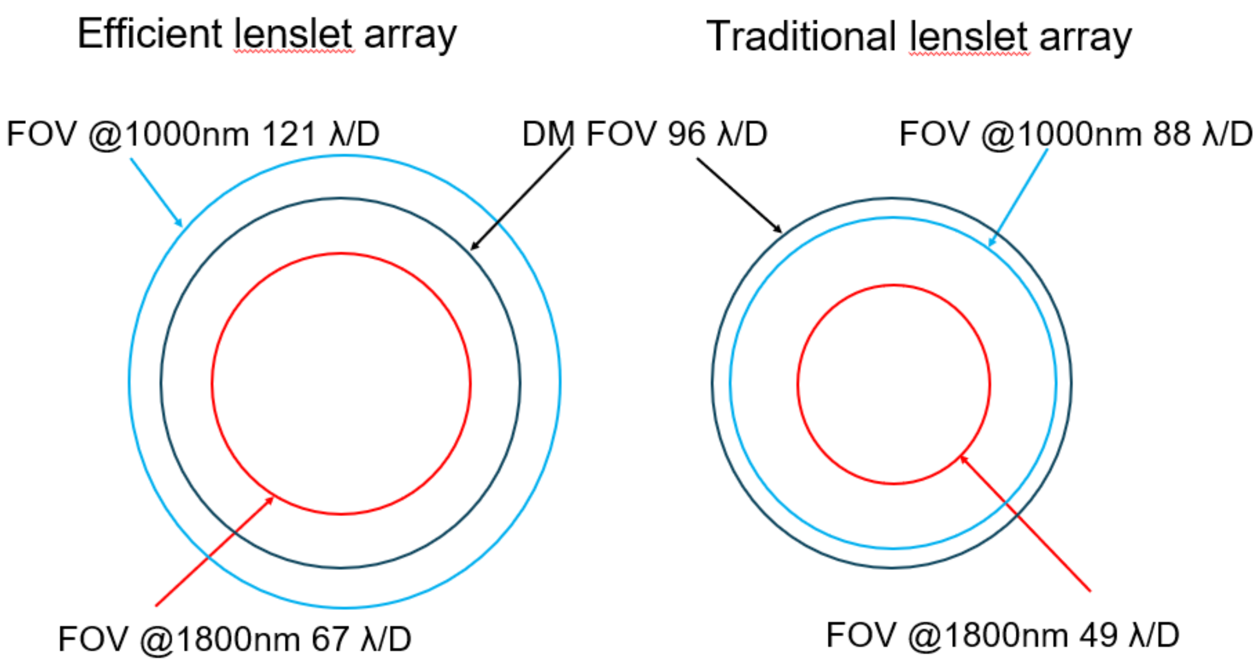

Figure 5. FOV comparison in λ/D between efficient and traditional lenslet arrays. The black circle is the DM capability of digging the dark hole. It is seen for efficient array, more than half FOV (area) fully utilizes DM's capability, and for traditional array, none of FOV fully utilizes DM capability.

3.2 Optical design

The optical design of efficient lenslet/mirrorlet IFS is similar to other lenslet based IFSes. It includes a "relay" optics to adjust the final beam f/# on lenslet/mirrorlet to form a PSF with its size meet the Nyquist sampling at defined wavelength. One thing that should be noted is that the footprints of the efficient IFS is no longer symmetric in the x and y direction. This is because the equivalent $f/\#_{group}$ in the two directions becomes approxiately 1:4 (See Figure 2). The 4 beams in figure 2 (YZ plane) are separated. But in the orthogonal plane (XZ plane), 4 beams are overlaped. Figure 6 shows the 2 views of IFS ray trace in YZ and XZ planes. It is obvious, the footprints in the two planes are quite different. Even though the footprints are different, it does not add too much additional challenge to optical design and aberration contral, because the f/# from each lenslet/mirrorlet is still the same.

The detailed optical design and analysis is out of the scope of this paper. It will be published in another paper soon.

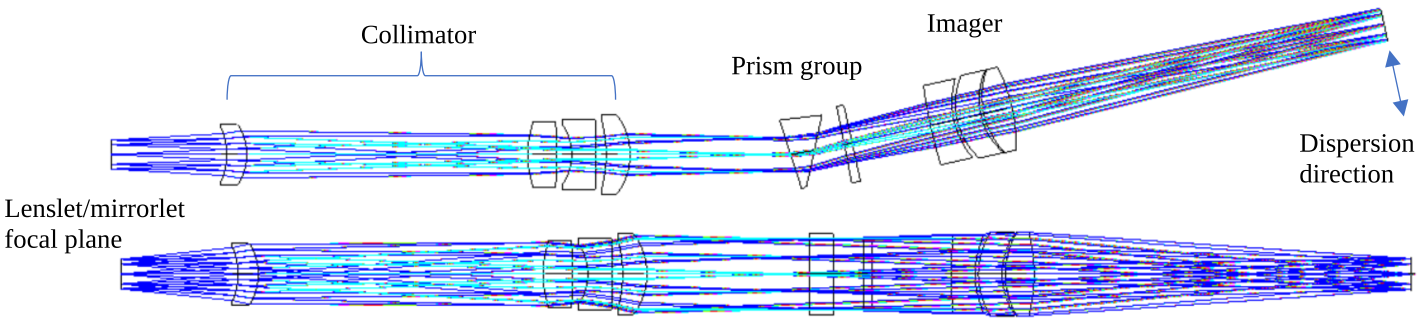

Figure 6. IFS optical design for efficient lenelet/mirrorlet array. On the top is the layout in YZ plane. At the bottom is the layout in XZ plane.

4. CONCLUSION AND FUTURE WORK

We have shown that efficient lenslet/mirrorlet array increases the detector pixel packing efficiency 38% linearly or ~90% in areal coverage without adding additional optics. The next step is to use HWO coronagraph NIR IFS specifications to perform optical modeling and carry out prototype testing.

The preliminary optical design was also conducted. It indicates that the geometric optical design for the 1x4 efficient lenslet.mirrorlet group can be smoothly handled without adding much additional challenge.

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