BIGRE: a new double microlens array for the integral field spectrograph of SPHERE

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ABSTRACT

IFS is the Integral Field Spectrograph for SPHERE, a 2nd generation instrument for VLT devoted to the search of exoplanets.

To achieve the performances required for the IFS a new device sampling the focal plane has been designed, prototyped and tested in laboratory. This device named BIGRE consists of a system made of two microlens arrays with different focal lengths and thickness equal to the sum of them and precisely aligned each other. Moreover a mask has been deposited on the first array to produce a field stop for each lenslet. Laboratory tests confirmed that specifications and properties of the prototype are met by state of the art on optics microlens manufacturing.

To characterize the device, a simulator of IFS has been built in laboratory and the BIGRE properties have been tested in real working conditions, showing that the design of the double array fulfills IFS requirements.

Keywords: lenslet arrays, integral field spectroscopy, exoplanet search

1. INTRODUCTION

SPHERE is a 2nd generation VLT instrument devoted to Exoplanets studies using high contrast images. It foresees an Integral Field Spectrograph (IFS) to implement accurate subtraction of speckles in the near Infrared range [0.95, 1.70] μm. A complete description of IFS and SPHERE is presented elsewhere in these proceedings [1, 2, 3]. From the design point of view the limiting factor for the planet detection with an instrument that uses adaptive optics, as in the SPHERE case, is the speckle noise. This problem is overcame using differential techniques such as methane band differential imaging. The subtraction of an image at the wavelength of an absorption band from an image at a continuum wavelength eliminates the speckles to first order, but leaves the planet signal intact. The wavelength dependence of the speckles [4] set the limits on the noise reduction achievable in this way, but it has been shown that double difference schemes employing images at two or three wavelengths can be very effective [5]; even better results can be obtained by using speckle deconvolution techniques [6]. These methods can be implemented via software if a hyper-spectral data set is available. The basic idea of IFS is the spatial sampling of the field of view around the target in order to obtain a 2 dimensional spectroscopy that can be used in differential imaging. In principle various ways to obtain hyper-spectral data can be used, with advantages and drawbacks related to the techniques, above them we can remember *image slicers*, *tunable filters* and *microlens arrays*. See [7] and [8] for examples of implementations for the first two methods. If one does not need to have high spectral resolution data, as in the exoplanet rearch, a good sampling can be obtained using microlens arrays as in the TIGER design [9]. In this case an array of thick microlenses with only one surface getting optical power samples the PSF on the focal plane or the re-imaged focal plane of the telescope. Due to significant cross

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talk, this design does not permit to fulfill the high contrast requirements of the technical specifications for the SPHERE IFS, so an alternative solution has been considered. This is the BIGRE, a double lenslet array: differently from the TIGER a second surface reforms a reduced image of the sampled PSF of the focal plane.

In this paper the first section will describe the concept of the BIGRE, the second the characteristics of the model designed and realized, the third the optical setup used to characterize the device, the fourth the tests performed to analyze the performances reached and the last will be devoted to the conclusions on the results obtained.

2. BIGRE OPTICAL CONCEPT

Cross talk is a critical parameter for IFS. This is true in particular for IFS in high contrast, diffraction limited imagers. In this case two critical parameters of the system to maximize the contrast performances are the coherent and incoherent cross talk levels. They can be defined in the following way:

- The incoherent cross talk is signal due to the Point Spread Function (PSF) of each lenslet, at a location of an adjacent spectrum; this is generally closer than the location of the adjacent lenslet, by a factor depending on the geometry adopted for the IFS
- The coherent cross talk is the signal due to interference between beams passing through different lenslets. This is essentially given by the square root of the products of the PSF of the lenslets, computed at a given location, times a phase term. Neglecting the phase term (which oscillates on a quite short space scale, generally smaller than the detector pixel size on practical IFS designs), the coherent cross talk is then essentially the square root of the PSF computed at the location of the adjacent lenslet

Cross talk can be estimated using the Fraunhofer approximation (for a full description, see [3]). Essentially, for a classical TIGER design the PSF generated by a single micro-lens is the Fourier Transform of the signal on the lens itself. Assuming this is circular and uniformly illuminated, this is an Airy disk, which declines quite slowly at large distances from center: this produces a high cross talk level (the coherent cross talk being in general the dominant term), at a level of several per cent. Consideration of non circular and not uniformly illuminated apertures only makes cross talk larger.

For this reason, we have developed an alternative concept, the BIGRE. Figure 1 shows the optical concept of BIGRE.

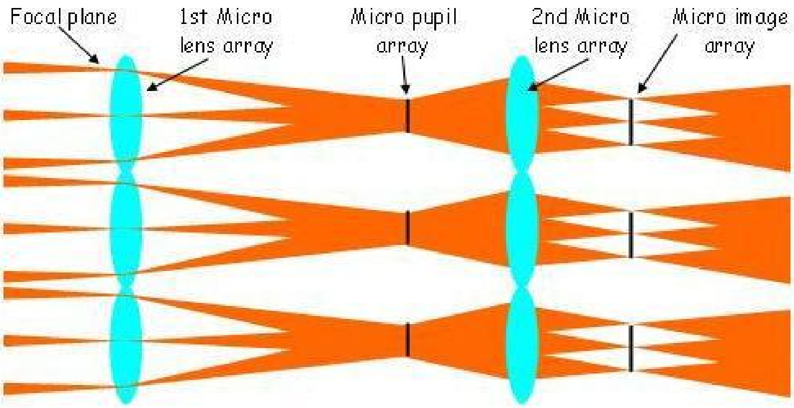

Figure 1: Optical concept of a BIGRE IFU: The first lenslet array, located on the input focal plane, forms a set of micro pupils; a second lenslet array forms a set of micro-images of the telescope Focal Plane on the IFS Slits Plane. The magnification of the system is less than 1, so that there is room for spectra given by a dispersive element using the space between the monochromatic micro-images.

In this Figure the BIGRE concept is schematized by an array of pairs of thin lenses (cyan objects). In the real world, a BIGRE IFU is made with a single array of thick lenses, each one having two powered optical surfaces. Each microlens on the input face of the IFU concentrates the flux corresponding to a spatial pixel on the sky into a small image of the pupil, referred to as a micro pupil. The second microlens reforms a reduced image of the sky pixel itself, referred to as a micro image. An array of bright spots on a dark background is formed, playing the role of entrance slits to a classical dispersive spectrograph. Between the two dioptric surfaces in the focal plane of the first we can individuate the micro pupil plane of the system. It is possible to decrease the impact of stray-light onto adiacent lenslets by filtering the system with a pupil stop array; moreover this pupil stop acts as a spatial frequencies filter. In addition, a mask in front to the first lenslet array may be used, to mask the dead area between lenslets (reducing straylight). If this mask is circular, it further reduces the diffraction spikes that else would be present in the direction of adjacent micro-images. A detailed description of the BIGRE optical principle is in [3].

Both in the case of TIGER and BIGRE the crosstalk levels depend on the optical parameters defining the single lens composing the arrays. However, in BIGRE designs we can reduce cross talk by an order of magnitude with respect to the TIGER case; further gains could be obtained by apodizing the micropupils. However, this is not requested in the case of the SPHERE IFS, where the BIGRE design already fulfills cross talk specifications.

In order to work properly, BIGRE might be manufactured within optical specifications: the most critical items are the relation between the radii of curvature and the thickness of the IFU, and the alignment between the two array of lenses.

To check the state of the art in the production of double lenslet arrays as the BIGRE, an IFS simulator prototype has been designed and mounted on laboratory and a BIGRE array with the required optical parameters to meet the crosstalk levels necessary has been manufactured by Advanced Microoptic Systems (AμS) company [10].

The BIGRE array has been manufactured with multistep photolithography technology (wet chemical etch) with further *smoothing* of the preliminary etched. After etching the microlenses were *smoothed* with a special method which permits to remove rests of the photolithographical steps or irregularities.

In the following sections the aspects regarding the characteristics of the manufactured arrays will be addressed.

3. BIGRE AND IFS PROTOTYPING

A complete prototype of the IFS has been realized in the laboratories of the Osservatorio Astronomico di Padova (OAPD). The spectral working range has been blue shifted in the visible region [0.55, 0.80] μm to simplify the issues related to the detector and qualification of the device. This implied a tuned rescaling of the IFU parameters with respect to the IFS-SPHERE case. The BIGRE array has been mounted on the telescope simulator focal plane The main characteristics of this BIGRE prototype are reported in Table 1. It is composed by two lenslet arrays of suprasil glued together and with a mask in front of the first array with a filling factor of 0.82.

Table 1: Main specifications of the BIGRE array manufactured and tested

Wavelength range	0.55 ÷0.80 μm
Refraction Index	≥ 1.4585 @ 633 μm (SUPRASIL)
Lenslet number	70×70
Pitch	(200.0 ± 0.3) μm
Curvature Radius: 1st array surface	(2.00±0.10) mm
Curvature Radius: 2nd array surface	(0.367± 0.014) mm
Center Thickness (CT)	(7.53±0.28) mm
Decenter-X 2nd wrt 1st	<10 μm
Decenter-Y 2nd wrt 1st	<10 μm
Tilt-X 1st lens	<1 deg
Tilt-Y 1st lens	<1 deg
Tilt-X 2nd lens	<1 deg
Tilt-Y 2nd lens	<1 deg

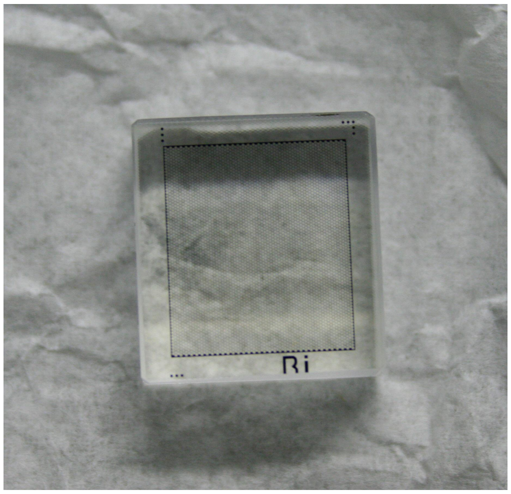

Figure 2: An image of one of the lenslet arrays manufactured with the characteristics of Tab. 1

The IFS prototype is depicted in Fig. 3. it is composed by the light source arm, the telescope simulator and the IFS simulator.

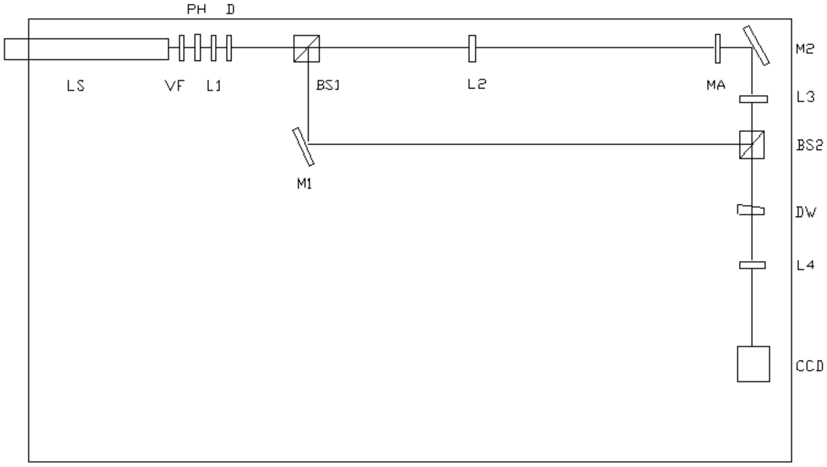

Figure 3: Experimental setup simulating IFS prototype

- The light source arm permits to illuminate the setup with a He-Ne Laser or with a white light source.
- The telescope simulator simply simulates an unaberrated PSF from the telescope using two lens and a diaphragm.
- The IFS simulator is a classical collimator and camera system and the two places where is placed a disperser near the pupil, and the BIGRE mounted in the focal plane of the telescope simulator.

In the collimated beam before the second lens of the telescope simulator has been placed a beam splitter to used a Mach-Zender interferometer that is close with another beam splitter in the IFS pupil. In this way it is possible to check if the aberrations of the systems are inside design predictions and at the focal plane of the IFS simulator it is possible to obtain a integral field spectroscopy useful to check the properties of the simulator and BIGRE itself (see Figure 4)

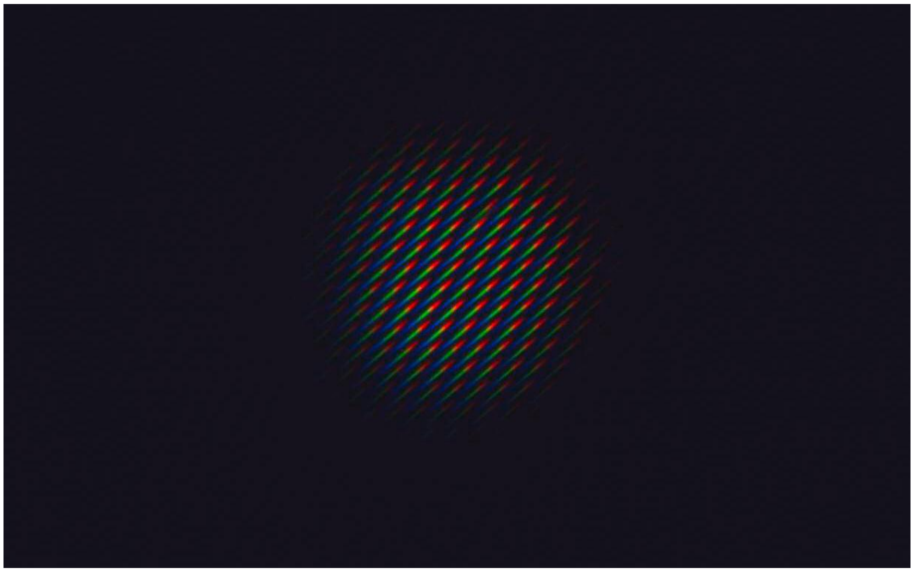

Figure 4: The typical image obtained in white light with IFS simulator and the BIGRE mounted on the simulated telescope focal plane

4. BIGRE CHARACTERIZATION

The characterization tests for the BIGRE array has followed the list below:

- Visual Inspection at the microscope
- Optical transmission
- Verification of geometrical quantities (lenslet pitch and filling factor)
- Verification of optical quantities (magnification of the system, cross talk between lenslets and PSF measurement).

4.1 Microscope inspection

In Fig. 4 an image taken with a Nikon ZMS-1 microscope on a BIGRE heavily handled to check the hardness of the mask coating. The samples observed at microscope show good regularity in the mask deposited on the arrays. In particular the sample of Fig. 5 has demonstrated a good resistance of the microlenses and of the masks to the sometimes rough usage, and only some scratch is visible.

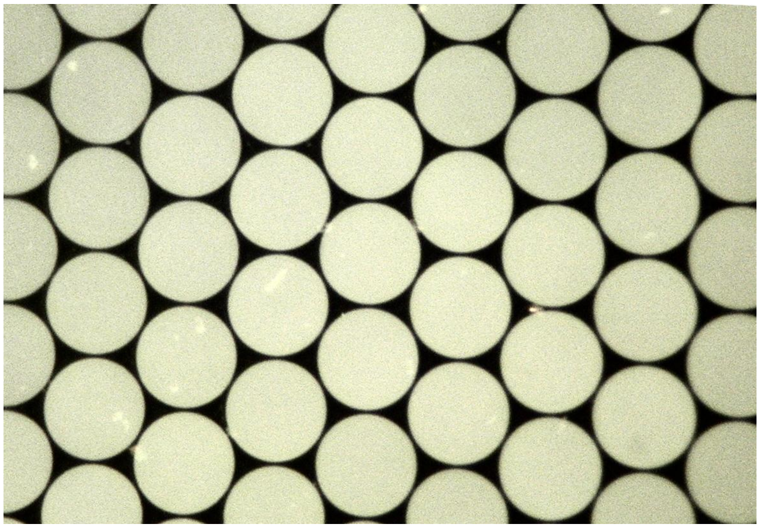

Figure 5: BIGRE Array at microscope after a heavy use

4.2 Optical Transmission

In order to estimate the optical transmission of the double array a Varian Cary 5000 UV/Vis/IR spectrophotometer has been used. The transmission spectrum obtained in the range 180-2300 nm is shown in Fig. 6.

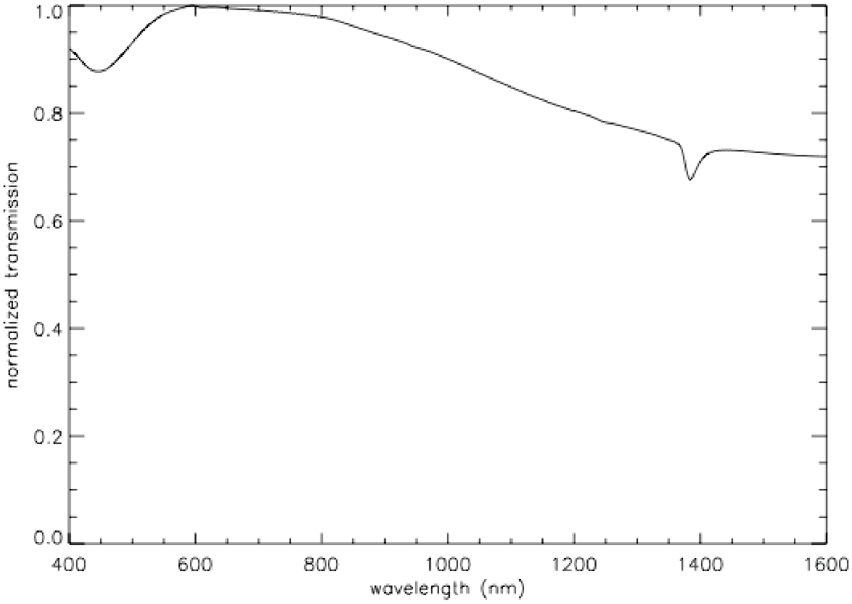

Figure 6: The BIGRE transmission curve obtained with the Varian Cary 5000 spectrophotometer.

The feature well evident at 1.4 µm is due to water absorption and is a characteristic of the kind of material use to build the prototype of the BIGRE (Suprasil). The arrays for the IFS-SPHERE will be optimized in the IR region (0.95-1.7 µm) and will use Infrasil instead of Suprasil to overcame this problem.

4.3 Lenslet pitch and filling factor

Lenslet pitch and filling factor have been measured using the same image of Fig. 5. In the case of lens pitch an autocorrelation has been obtained. This is shown in Fig. 7.

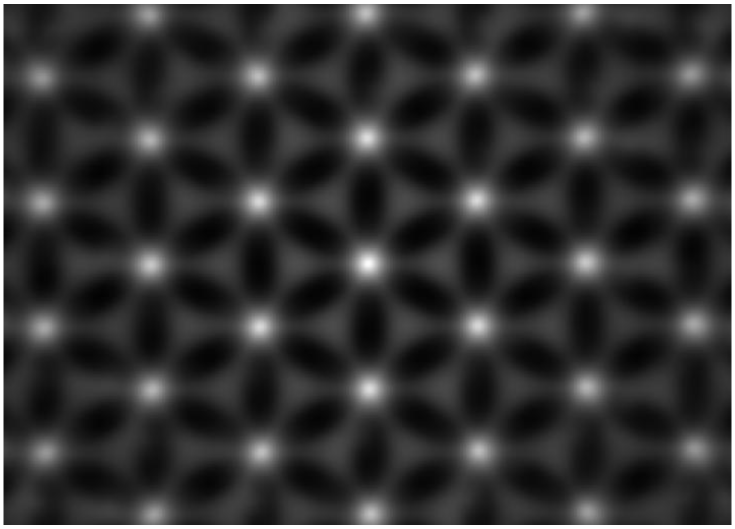

Figure 7: Autocorrelation of Fig. 5 used to obtain lenslet pitch.

The grid follows the hexagonal pattern of the lenslet array and is in perfect agreement with specification of Tab. 1. To measure filling factor a two level image with respect to a threshold from Fig. 4 has been obtained. The filling factor is simply the ratio between the number of pixels with signal greater than a defined threshold to the total number of pixels. Also in this case the specification has been respected.

4.4 Magnification of the BIGRE

The ratio between the two focal lengths of the microlenses in front and behind the BIGRE is the most important parameter of the BIGRE and is the magnification of the device; we named its inverse the K factor. The BIGRE by design is afocal and for this reason an estimation of its value by a separate measurement of the two focal lengths of the lenslet arrays is not possible. On the other hand using the interference and diffraction properties of the double array it is possible to obtain good estimations of the K factor. In our characterization three methods have been used:

- Measurement of the diffraction Airy disk of the lenslets;
- Counts of the number of the interference spots inside the Airy disk seen in the IFS intermediate Pupil images;
- Measurement of the dimension of the PSFs of the lenslets in the focal plane of the IFS simulator.

All these methods take use of the IFS simulator shown in Fig. 3. Since interference and diffraction is exploited, for these measures we use a He-Ne laser source.

The Airy disk due to the lenslet diffraction is easily obtained in the pupil plane of the IFS simulator and is shown in Fig. 8. While the pattern given by a single lenslet (which is masked) is itself circular, it is modulated by the hexagonal pattern due to interference between lenslets (since the array of lenslets is itself hexagonal), because the laser beam illuminated several lenslets each time. This originates the complex pattern shown in the Figure.

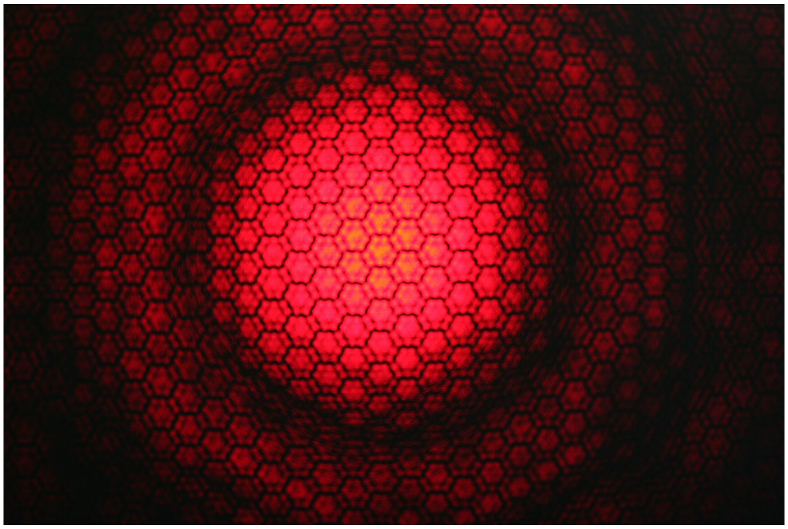

Figure 8: BIGRE Airy disc in the IFS simulator pupil plane

The relationship between the dimension of the disc (first zero's) and the K factor is simply:

$$\phi = 2.44\frac{\lambda K}{d}F_{coll} \tag{1}$$

Where:

λ = wavelength

F_{coll} = collimator focal length

d_{lens} = diameter of the single lenslet

ϕ = measured linear diameter of the Airy disc in the pupil plane

K = magnification of the BIGRE

The second method takes into account the interference effects that produces a grating effect inside the Airy disk on the pupil plane. The number of interference spots inside the Airy disk can be calculated as:

$$n = \frac{\frac{2.44\lambda K}{PM}}{\frac{\lambda}{P}} = 2.44\frac{K}{M} \tag{2}$$

Where:

n = number of interference spots inside the Airy disk

λ = wavelength

K = magnification of the BIGRE

P = pitch of the lenslet array as measured previously

M = mask in front of the lenslets

The third method is obtained considering how the BIGRE works both in magnification (K factor) and interference on the IFS simulator focal plane. The typical image obtained in monochromatic light is shown in Fig. 9.

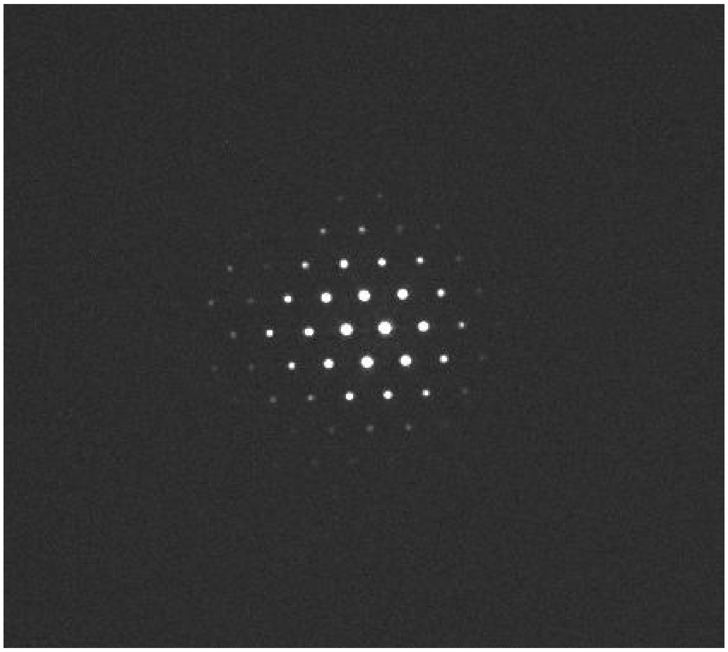

Figure 9: Focal plane image on the IFS simulator at 632.8 nm of wavelength

While the dimension of the PSFs of the spots is directly linked to the K factor, the pitch of the spots is function of K and of the pitch of the lenslet array. In particular:

$$K = \frac{l_{pitch}}{\vartheta} \tag{3}$$

Where:

l_{pitch} = distance between two PSFs in pixel on the detector

ϑ = Diameter of the PSF

Anyway we have to consider that in principle the method allows to give only an upper limit to the magnification factor because the PSF measured on the focal plane of the IFS simulator is the result of the convolution of the PSF of the BIGRE with the PSF of the simulator. Any degradation in the optical quality of the simulator is therefore confused with the magnification of the BIGRE. However if the simulator is well designed and built this effect is negligible.

Using the three methods we measured a K factor for our device of 5.27±0.09 against a required value of 5.44±0.34, so the manufacture array fulfill the specifications.

4.5 Cross talk between lenslets

In principle direct measurement of the cross talk level, that is the intensity level due to a lenslet at the location of the closest lenslet, is not possible. In fact, this should be obtained by subtracting the light from the adjacent lenslets. However, illumination of a single lenslet would result in canceling the interference component (that is the coherent cross talk) between adjacent lenslets, invalidating the result. We can only measure the intensity in regions between the two apertures and compare this result with models for the cross talk. In the cross talk measurement to have valid results the level of straylight must be low. Also in this case we use the IFS simulator. Due to the characteristics of CCD used a dynamic range as large as a few 10^4 has been obtained by summing up hundreds of images. Only few lenslets has been illuminated by the He-Ne Laser beam, a situation very similar to the case of speckle pattern illumination in the case of IFS-SPHERE. So the simulation is very realistic. Two setups have been considered. In a case we put a stop in the IFS intermediate pupil position, about at the DW position in Fig. 3. This stop permits to suppress the light outside the first Airy ring. The second configuration is without the stop. The comparison between the two set-ups allows to evaluate the importance of having this aperture stop in the IFS. In Fig. 10 the images on the IFS simulator focal plane are reported. On the top panels we show the full scale images, while in the bottom one we show the images on a logarithmic scale to show up the low levels structures due to the cross talk. Faint hexagonal-like structures are visible in those images obtained with set-up first setup (the one with the pupil stop): these are due to ghosts created by reflection on the back surface of the mask deposited on the first surface of the BIGRE. Those obtained with the second setup have a much higher background level, and no small scale structure is obvious. Figure 11 compares the plot along a portion of a detector row shown in the right panel of the previous figure, with predictions obtained from our model for cross talk (both coherent and incoherent). The agreement is excellent

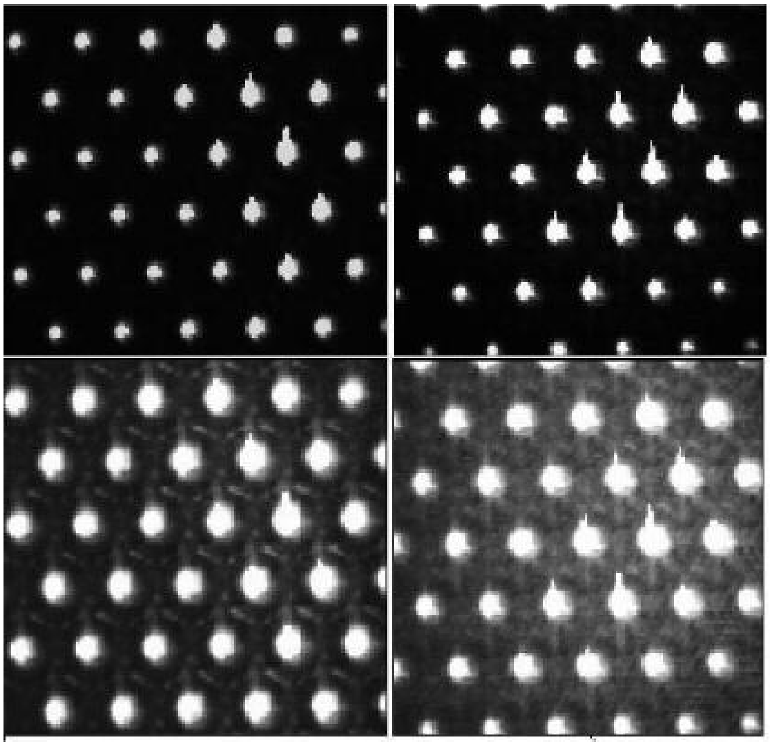

Figure 10: Cross talk images taken with a diaphragm in the pupil (left panel) and without it (right panel). Note that some images of the spots appear elongated: this is due to saturation of the CCD and inefficiency of charge transfer. The images are on a logarithmic scale to enhance visibility of faint structures.

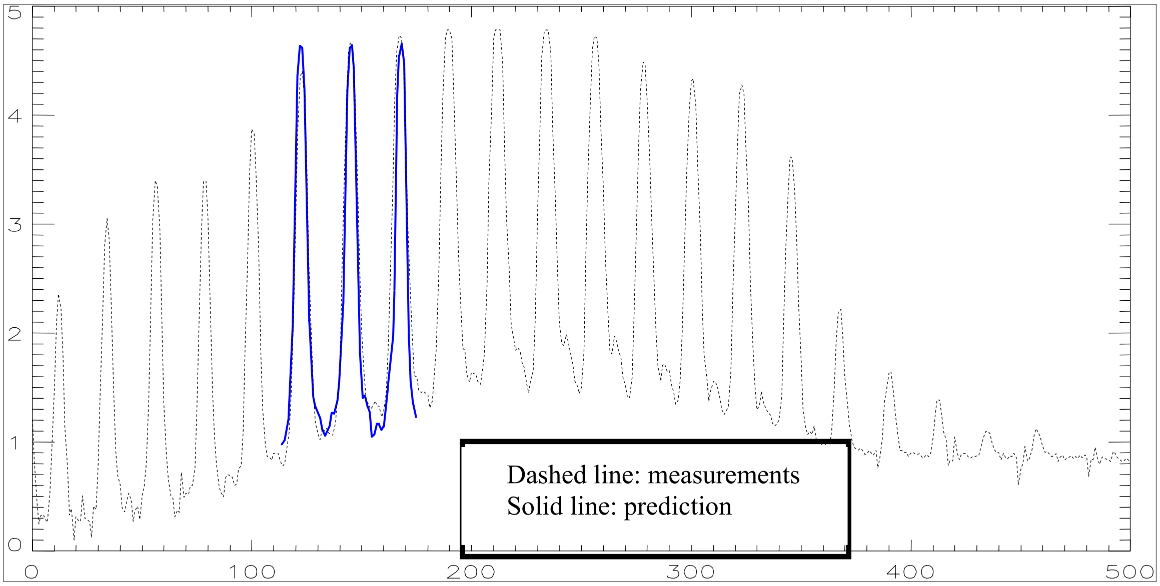

Figure 11: horizontal profile of the central part of the left image of Fig. 10. Solid line shows prediction on Cross talk for the BIGRE+IFS prototype. Units of the plot are arbitrary.

4.6 PSF and Encircled Energy measurements

These measurements, have been obtained for the K factor estimation and can be used as comparison with the values expected by the prototype IFS optical design.

The measurements a PSF with a FWHM of 26.16±0.25 μm. This value is in good estimation with the design prediction that is about 23 μm.

5. CONCLUSIONS

The double lenslet array named BIGRE represents an improvement in the design of high contrasts integral field spectroscopic instrumentation, with respect to the traditional systems TIGER like. Due to the fact that the manufacturing of such a device is complex for the presence of the mask and the alignment between the two microlens arrays a prototype of the system IFS and BIGRE has been manufactured, mounted on the optical bench and tested.

Measurements of the magnification of the array and of the cross talk arising between the lenslets demonstrate that the system performs as the design predictions and that technological state of the art in microarrays manufacturing permits to produce devices with the required high performances specifications required to satisfy high demand IFS technical specifications.

6. ACKNOWLEDGEMENTS

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