Design of the microlens arrays coupling with imaging fiber bundle*

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To ameliorate the disadvantages of imaging system coupled with imaging fiber bundle, a method by adding square aperture microlens arrays at both entrance and exit ends of the imaging fiber bundle is proposed to increase the system's coupling efficiency. The expressions for solving the parameters of both ends' microlens units are deducted particularly. The microlens arrays used for an infrared imaging fiber bundle with the single fiber diameter of 100 μm and core diameter of 70 μm are designed by this method. The simulation results show that compared with the system without microlens arrays, the fill factor of the imaging fiber bundle coupled microlens arrays system is increased from 44.4% to more than 90%, and the coupling efficiency is doubled too. So the design method is correct, and the introduction of microlens arrays into imaging fiber bundle coupled system is feasible and superior.

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Imaging fiber bundle is widely used in many fields[1]. However, due to it is a discrete sampling element, the imaging quality of imaging fiber bundle coupled system is affected by the resolution, numerical aperture (*NA*), fill factor and transmittance of it[2].

In recent years, the applications of microlens arrays to improve the coupling efficiency of imaging fiber bundle coupled systems have been reported more and more. Arnold Daniels[3] published his experiment of a fiber-optically coupled infrared focal plane array system. Deqing Ren[4] applied a square aperture microlens array in the design of multiple-integral-field-unit telescope. Ren Yang[5] designed a microlens array for two optical fiber bundles coupling. Daniel V. Hahn[6,7] reported a microlens array used in the optical communication receiver, and verified it by experiments. Yan Changling[8] studied the microlens arrays to couple the parallel light into the fiber bundle. Li Jia[9] researched the fabrication of refraction microlens arrays for optical fiber bundles. Wu Zhuo-liang[10] introduced the application of microlens array in external cavity-based spectral beam combing of fiber lasers. Cheng Xin[11] put forward the conception of "fiber-microlens array spectrometer".

Considering the microlens array used in focal plane array can improve its small fill factor and low photosensitive efficiency[12,13], the square aperture spherical microlens array used in the imaging fiber bundle coupled system is designed by numerical calculation and software optimization in this paper.

The typical imaging fiber bundle coupled system is mainly comprised of a fore objective lens, an imaging fiber bundle, a relay lens and the detector assembly. When the fiber bundle is located at the focal plane of the fore objective lens, and the information of the image is sampled discretely, inevitably, a part of the incident rays will irradiate the gap region between the fiber claddings, which results in a loss of light energy, as shown in Fig.1(a). However, as indicated in Fig.1(b), if a microlens array is added at the entrance end of fiber bundle, the microlens unit will image the objective lens' exit pupil onto the entrance surface of each fiber. If the diameter of the microlens unit exactly equals the diameter of each single fiber, the fill factor of fiber bundle will be greatly increased. Meanwhile, if the size of pupil image is smaller than the core diameter, the rays into the gap region will be mostly coupled by the fibers, and the coupling efficiency of the system will be improved too.

For an ideal fiber, the incident rays with a certain solid angle (less than the critical angle) can exit from it with an equal solid angle. However, if there are some defects at the edge of fiber core and cladding, the exit solid angle will be larger, as shown in Fig.2. Disposing *F*# to de-

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scribe this change, then $F\# = 1/(2\tan\theta)$, where θ is the angle between the marginal ray and the optical axis of fiber. As shown in Fig.3, $F\#_{out}$ is smaller than $F\#_{in}$. This is called focal ratio degradation (*FRD*), which is described as $FRD=F\#_{out}/F\#_{in}$. For the relay system, when the aperture angle of incident rays from objective lens equals the *NA* of it, due to the *FRD*, the aperture angle of the rays exiting from the fibers is greater than the object-side *NA* of relay lens, so there will be some energy losses. To reduce the energy losses, it needs to design a relay lens with large relative aperture. This is greatly difficult. If the microlens arrays are added in the entrance and exit ends of the fiber bundle, the aperture angle of the rays coming from the objective lens will become smaller, and the *FRD* of the fibers will become smaller too. Subsequently, the microlens array at the exit end of fiber bundle makes the rays exiting from the fiber bundle telecentric and to be coupled by the relay lens.

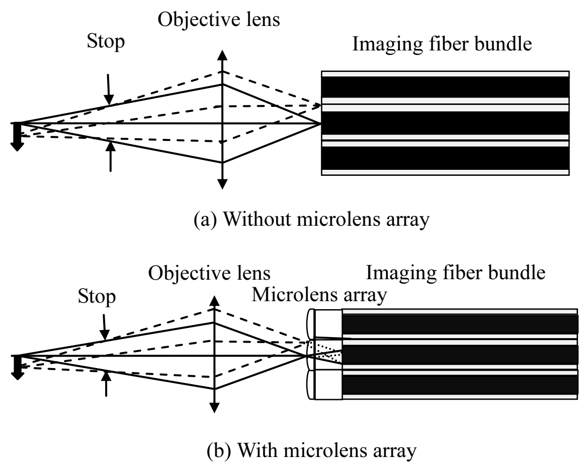


Fig.1 Schematic diagram of the objective lens coupled with imaging fiber bundle

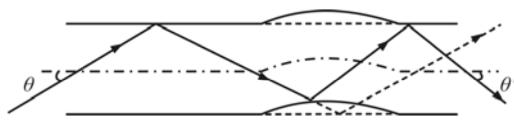


Fig.2 The beam angle change caused by fiber defects

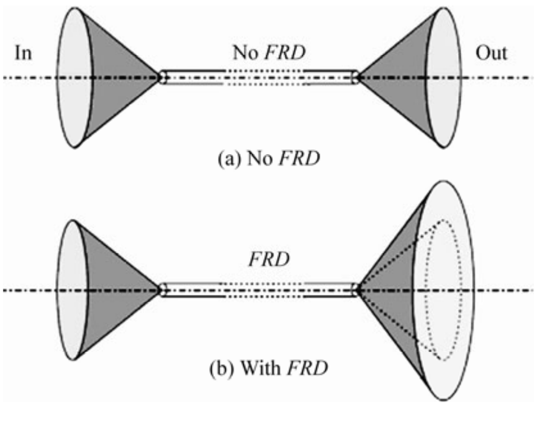


Fig.3 Schematic diagram of the fiber *FRD*

The structure of square aperture spherical microlens array is shown in Fig.4.

The entrance end microlens unit is a plano-convex lens, as shown in Fig.5. The objective lens' field of view is split into a number of miniature sub-fields, and the converging rays are coupled into the core of the single fiber respectively.

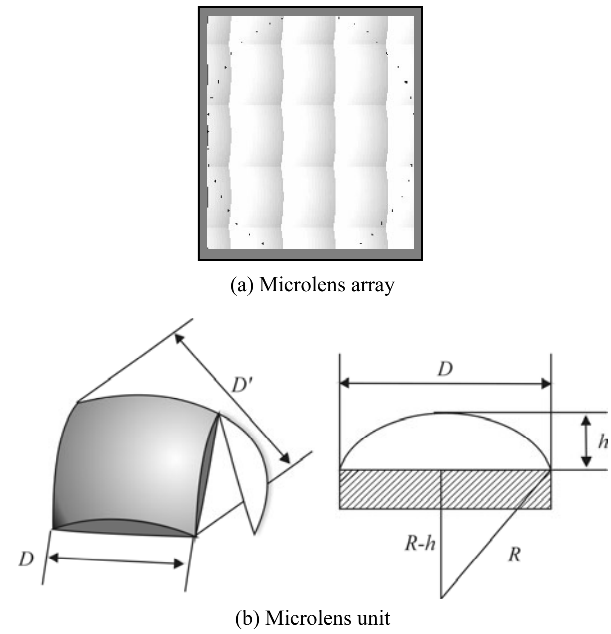


Fig.4 The structure of square aperture spherical microlens array

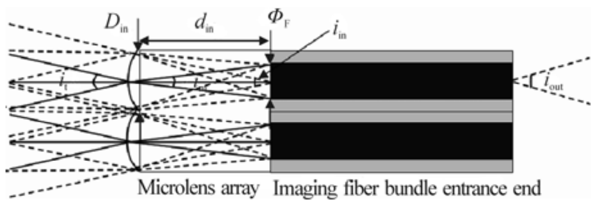


Fig.5 Schematic diagram of the entrance end of imaging fiber bundle coupled with microlens array

Assume that i_t is the aperture angle of the converging rays, n is the refractive index of the microlens, i_m is the aperture angle of the rays refracted by the microlens, i_{in} is the aperture angle of the rays incident into the fiber bundle, R_{in} is the radius of microlens unit, d_{in} is the thickness of microlens substrate, D_{in} is the side length of the square aperture, which is equal to the diameter of the single fiber, and the pupil image height should be equal to the diameter of fiber core Φ_F. According to the geometrical optics, we have

$$i_m = \frac{i_t}{n}, \tag{1}$$

$$d_{in} = \frac{n\Phi_F}{i_t}. \tag{2}$$

For a single refractive spherical microlens, we have

$$R_{in}=\frac{n-1}{n}f_{in}=\frac{n-1}{n}d_{in}\ ,\tag{3}$$

where f_{in} is the focal length of microlens, and $f_{in}=d_{in}$. From Eqs.(2) and (3), we can obtain

$$R_{in}=\frac{(n-1)\Phi_F}{i_t}\ .\tag{4}$$

From the geometric relationships in Fig.4, the unit hat height of h_{in} can be solved by

$$h_{in}=R_{in}-\sqrt{R_{in}{}^2-\frac{D_{in}{}^2}{4}}\ .\tag{5}$$

From Eqs.(2), (4) and (5), in which i_t, Φ_F and D_{in} are known, the structural parameters of entrance end microlens array can be solved.

The exit end microlens unit is also a plano-convex lens, as shown in Fig.6, where f_{out} is the focal length of microlens

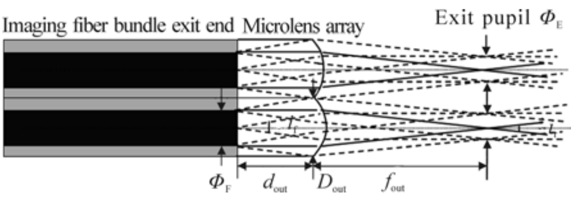


Fig.6 Schematic diagram of the exit end of imaging fiber bundle coupled with microlens array

unit, R_{out} is the radius of microlens unit, n is the refractive index, d_{out} is the thickness of microlens substrate, D_{out} is the side length of the square aperture and is equal to the diameter of the single fiber, Φ_F is the diameter of fiber core, Φ_E is the diameter of exit pupil, i_{out} is the aperture angle of the rays exiting from the fiber, f_d is the *FRD* of the fibers, and i_r is the aperture angle of the refraction rays from the microlens array. Then the following relationship can be obtained,

$$d_{out}=\frac{D_{out}-\Phi_F}{i_f}\ ,\tag{6}$$

where i_f satisfies the following relationship as

$$i_f=\frac{i_{out}}{n}\ .\tag{7}$$

According to the definition of *FRD*, $f_d = i_{out}/i_{in}$. From Eqs.(6) and (7), we can obtain

$$d_{out}=n\frac{D_{out}-\Phi_F}{f_d i_{in}}\ ,\tag{8}$$

where $i_{in}=D_{in}/d_{in}$. By the object-image relationship, we have

$$f_{out}=\frac{d_{out}}{n}\ .\tag{9}$$

Meanwhile, for the single spherical lens, we have

$$f_{out}=\frac{R_{out}}{1-n}\ .\tag{10}$$

From Eqs.(8), (9) and (10), we can obtain

$$R_{out}=(1-n)\frac{D_{out}-\Phi_F}{f_d i_{in}}\ .\tag{11}$$

From Fig.4, the unit hat height h_{out} can be solved by

$$h_{out}=R_{out}-\sqrt{R_{out}{}^2-\frac{D_{out}{}^2}{4}}\ .\tag{12}$$

From Eqs.(8), (11) and (12), where D_{out} and Φ_F are known, and f_d can be measured by experiment, the structural parameters of exit end microlens array can be solved. Meanwhile, $i_r=\Phi_F/f_{out}$, which determines the *NA* of the relay system.

For the selected regular hexagonal arrangement fiber bundle with the parameters shown in Tab.1, the structure parameters of the designed microlens arrays are shown in Tab.2.

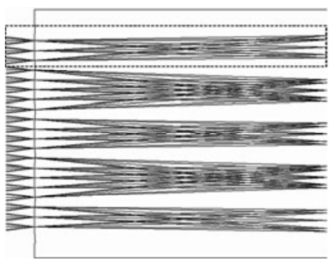
Tab.1 The parameters of the imaging fiber bundle

Material	Core radius	Cladding thickness	*NA*	Spectrum
As-S	0.035 mm	0.015 mm	0.28	3–5 μm

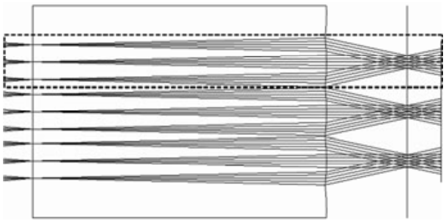
Tab.2 The parameters of the designed microlens arrays (units: mm)

Radius	Thickness	Diameter	Hat height	Focal length
0.683	0.965	0.1	0.00185	0.282
-0.583	0.825	0.1	0.00214	-0.241

The microlens arrays are designed and optimized in the software of Zemax. The final design is shown in Fig.7, where the dotted line portion is a microlens unit. The materials of the microlens arrays and substrates are Si. Fig.7 (a) shows that the rays within the aperture angle of the objective lens are mostly coupled into the core with 70 μm diameter at the entrance end of fiber bundle. Fig.7(b) shows that the rays exiting from the exit end of fiber bundle become telecentric after being refracted by the designed microlens array and easy to be connected by the relay system. Fig.8 is the simulation result of the entrance end microlens unit coupled with a single fiber in the software of Tracepro.



(a) Entrance end



(b) Exit end

Fig.7 Layouts of the imaging fiber bundle coupled with microlens arrays

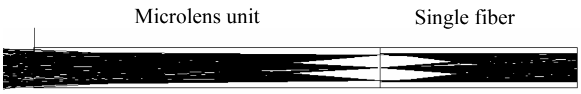


Fig.8 Simulation result of a single fiber coupled with a single microlens unit in Tracepro

The fill factor of the imaging fiber bundle in this instance is about 0.907×0.72=44.4%. The front view of the microlens array coupled with the fiber bundle is shown in Fig.9. As the fill factor of the square aperture microlens array is more than 90%, the collection efficiency of the system is doubled, and the coupling efficiency is further improved too.

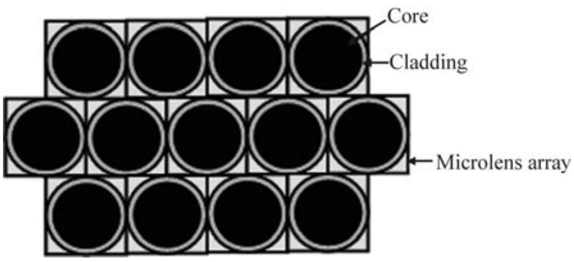


Fig.9 The front view of the imaging fiber bundle coupled with microlens array

Hot-melt molding method is suitable for the fabrication of square aperture microlens array[14]. The following work of us is about the production and validation experiment of the designed microlens array.

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