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# Supplementary information

#### S1 Fabrication process of the ACMC



Figure S1 Schematic diagram of the fabrication process of the ACMC.

Figure S1 shows the fabrication process of the ACMC with each layer of the ACMC been fabricated from PMMA sheets (Asahi, Kasei) using CO<sub>2</sub> laser ablation process. Within the experiments, the commercially available CO<sub>2</sub> ablation system with a 50w laser generator (JinBoshi JBSCO2-50) was used and the laser system is equipped with a laser head containing a field lens and two swivel-mounted mirrors. The lens can focus the laser beam to a 0.05mm diameter spot at a focal distance of 30mm. For the microchannel layer, the pattern of the microchannel and the microlens was scanned through the 500µm thick PMMA sheet, producing microfluidic channel and the microlens of a height dictated by this thickness. The CO<sub>2</sub> laser scanning speed was 40mm/s and the laser power was 25w. Subsequent to the CO<sub>2</sub> laser ablation process, microchannel side walls and the microlens surface were sequentially sanded with 800, 1000 and 2000 grit sandpapers and finally polished with a specialized polymer polishing paste (SONAX30500, Germany). For the cover layer and the substrate layer, the CO<sub>2</sub> laser scanned the outline of the microchannel onto the 1mm thick PMMA sheet with the laser scanning speed of 20mm/s and the laser power of 30w. Under such laser parameters, the PMMA sheet was not cut through and a small bulge, which was called laser bulge (LB), was formed in the rim of the laser-ablated groove (LG). The LB was designed to be at a distance of 800µm from the microchannel. On one hand, the LB can concentrate the ultrasonic energy, which was prepared for the ultrasonic bonding process. On the other hand, during the ultrasonic bonding process, the melted LB can flow into the LG, avoiding the clog of the microchannel. After the laser ablation process, the three layers were stacked at the given sequence, put into the bonding clamp and bonded together with the pressure of 0.4MPa and ultrasonic time of 1s using an ultrasonic bonding system (Dizo-ultrasonic NC-1800P).

### S2 Fluorescence image processing method on the smartphone

Figure S2 shows the schematic diagram of the image analysis method. The image captured by the smartphone was compromised by a pixel matrix and the pixels are saved by 3 byte 24 bit, for example, the 16-23 bit representing red (R), the 8-15 bit representing green (G) and 0-7 bit representing blue (B). Therefore, first of all, a pixel point (i, j) is extracted from the image and the selected pixel is separated into RGB value according to their respective bit address mentioned above. Then the RGB value is converted into luminosity according to the expression: I=0.30R+0.59G+0.11B. Finally, the luminosity values of all the pixels are added and their average value is taken as the fluorescence intensity of the image. The code to accomplish the above functions is shown as follows.

```
private double[] getRGB(Bitmap bitmap) {
```

```
int i=j=rgbG=rgbR=rgbB=rgbR=min=mix=0;
double fluo =0;
double A[];
A=new double [5];
int width = bitmap.getWidth();//Image width
int height = bitmap.getHeight();//Image Height
```

```
for (i = minx; i < width; i++) {
```

```
for ( j = miny; j < height; j++) {
    int pixel = bitmap.getPixel(i, j);</pre>
```

```
// Exact (i, j) and converted into RGB format
```

```
rgbR =(pixel &0xff0000) >> 16;
```

```
rgbG = (pixel \& 0xff00) >> 8;
```

```
rgbB = (pixel & 0xff);
```

```
RGBR=RGBR+rgbR;
```

```
RGBG=RGBG+rgbG;
```

```
RGBB=RGBB+rgbB;
```

```
double fluo= (double)(0.3*rgbR+0.59*rgbG +0.11*rgbB);
```

```
Fluo=Fluo+fluo;
```

```
//Converted to luminosity
```

```
Gray=Gray/(i*j);
```

```
RGBR=RGBR/(i*j);
```

```
RGBG=RGBG/(i*j);
```

```
RGBB=RGBB/(i*j);
```

```
A[0]=Gray;
```

```
A[1]=Gray;
```

```
A[2]=RGBR;
```



Figure S2 Schematic diagram of the image analysis method

## S3 Matlab code for fluorescence intensity measurement

A MATLAB code was used to analyze the RGB value and fluorescence intensity of the images taken by a smartphone. The MATLAB code is shown below. im=imread('1.jpg'); s=size(im); R=im(:,:,1); G=im(:,:,2); B=im(:,:,3); R=reshape(R,[s(1),s(2)]); G=reshape(G,[s(1),s(2)]);B=reshape(B,[s(1),s(2)]);r=mean(mean(R)); g=mean(mean(G)); b=mean(mean(B)); I=0.3\*r+0.59\*g+0.11\*b; The following MATLAB code is used to generate the fluorescence intensity profile. d=double(x3(:,:,1)); mesh(d); a=double(x3(:,380,1)); plot (a);

### S4 Theoretical analysis for the geometry of the SOF lens



Figure S3 Theoretical analysis for the geometry of single lens.

Figure S3 shows the theoretical analysis for the geometry of the single lens. For the single lens, the derivation distance  $\delta_L$  between the abaxial ray and the paraxial ray can be derived as follows. The symbols and their meanings during the derivation process can be seen in table S1.

Symbol	Meaning	Unit
Ia	Incident angle of the abaxial ray	(°)
$I_p$	Incident angle of the paraxial ray	(°)
I'a	Refraction angle of the abaxial ray	(°)
$I'_p$	Refraction angle of the paraxial ray	(°)
$arphi_a$	Radius angle of the abaxial ray	(°)
$arphi_p$	Radius angle of the paraxial ray	(°)
$U_a$	Image aperture angle for the abaxial ray	(°)
$U_p$	Image aperture angle for the paraxial ray	(°)
R	Radius of the lens	(mm)
$L_a$	Image distance of the abaxial ray	(mm)
$L_p$	Image distance of the paraxial ray	(mm)
$\delta_L$	Derivation distance	(mm)
п	Refractive index	-

Table S1 The symbols and their meanings for the single lens.

From the refraction law, it can be known:

$$\frac{\sin I_a}{\sin I_a} = n \tag{1}$$

$$\sin I_a = \frac{\sin I_a}{n} \tag{2}$$

From figure S3(a), it can be found:

$$\varphi_a = I_a = I'_a + U_a \tag{3}$$

Insert Eq.(2) into Eq.(3), the image aperture angle for the abaxial ray  $U_a$  can be derived:

$$U_a = I_a - I'_a = I_a - \arcsin(\frac{\sin I_a}{n})$$
(4)

In  $\triangle$ ABC, based on the Law of Sines, the length of  $\overline{AB}$  can be yielded:

$$\overline{\frac{AB}{I_a}} = \frac{R}{\sin U_a}$$
(5)

$$\overline{AB} = \frac{R\sin I_a}{\sin U_a} = \frac{R\sin I_a}{n\sin U_a} = \frac{R}{n} \frac{\sin I_a}{\sin U_a} = \frac{R}{n} \frac{\sin I_a}{\sin[I_a - \sin^{-1}(\frac{\sin I_a}{n})]}$$
(6)

In the same way, the length of  $\overline{AE}$  can be evaluated:

$$\overline{AE} = \frac{R}{n} \frac{\sin I_p}{\sin[I_p - \arcsin(\frac{\sin I_p}{n})]}$$
(7)

From Eq.(6) and Eq.(7), the derivation distance  $\delta_L$  can be given as:

$$\delta_{L} = \overline{AE} - \overline{AB} = \frac{R}{n} \left\{ \frac{\sin I_{p}}{\sin \left[ I_{p} - \arcsin(\frac{\sin I_{p}}{n}) \right]} - \frac{\sin I_{a}}{\sin \left[ I_{a} - \arcsin(\frac{\sin I_{a}}{n}) \right]} \right\}$$
(8)



Figure S4 Theoretical analysis for the geometry of compound lens.

For the compound lens, the derivation distance  $\delta_{L2}$  is obtained using the analytic geometry method. The rectangular coordinate system is defined as shown in figure S4 and the meanings of the symbols are illustrated in table S2. It should be noted that because the thickness of the lens has little influence on the derivation distance  $\delta_{L2}$ , here, we neglect the effect of lens thickness, considering that the light directly transfers to the second lens.

Symbol	Meaning	Unit
I <sub>al</sub>	Incident angle of the abaxial ray (the first lens)	(°)
$I_{pl}$	Incident angle of the paraxial ray (the first lens)	(°)
I'al	Refraction angle of the abaxial ray (the first lens)	(°)
$I_{a2}$	Incident angle of the abaxial ray (the second lens)	(°)
$I_{p2}$	Incident angle of the paraxial ray (the second lens)	(°)
I' <sub>a2</sub>	Refraction angle of the abaxial ray (the second lens)	(°)
$\varphi_{a2}$	Radius angle of the abaxial ray (the second lens)	(°)
$arphi_{p2}$	Radius angle of the paraxial ray (the second lens)	(°)
$U_{al}$	Image aperture angle for the abaxial ray	(°)
$R_I$	Radius of the lens (the first lens)	(°)
$R_2$	Radius of the lens (the second lens)	(mm)
$L_{a2}$	Image distance of the abaxial ray (the second lens)	(mm)
d	The distance between the first and second lens	(mm)
$L_{p2}$	Image distance of the paraxial ray (the second lens)	(mm)
$\delta_{L1}$	Derivation distance (the single lens)	(mm)
$\delta_{L2}$	Derivation distance (the compound lens)	(mm)
п	Refractive index	-

Table S2 The symbols and their meanings for the compound lens.

Based on Eq.(6), the coordinate of point B can be obtained:

$$B(R_{1} + \frac{R_{1}}{n} \frac{\sin I_{a1}}{\sin[I_{a1} - \arcsin(\frac{\sin I_{a1}}{n})]}, 0)$$
(9)

Assuming that the analytic expression of line DB is y=kx+b, then

$$k = \tan U_{a1} = \tan \left[ I_{a1} - \arcsin\left(\frac{\sin I_{a1}}{n}\right) \right] = \xi_a \tag{10}$$

Inserting the coordinate of point B (4) into the analytic expression of line DB, the intercept b can be obtained:

$$b = -kx_{B} = -\tan[I_{a1} - \arcsin(\frac{\sin I_{a1}}{n})] \cdot \{R_{1} + \frac{R_{1}}{n} \frac{\sin I_{a1}}{\sin[I_{a1} - \arcsin(\frac{\sin I_{a1}}{n})]}\} = \eta_{a}$$
(11)

Then the analytic expression of line DB can be expressed as

$$y = \xi_a x + \eta_a \tag{12}$$

Assuming that the equation of the second lens is

$$(x - d - R_2)^2 + y^2 = R_2^2$$
<sup>(13)</sup>

Then inserting Eq.(12) into Eq.(13), the x coordinate of the intersection point can be evaluated:

$$x = \frac{-2(\xi_a \eta_a - d - R_2) \pm \sqrt{4(\xi_a \eta_a - d - R_2)^2 - 4(1 + \xi_a^2)(d^2 + 2R_2d + \eta_a^2)}}{2(1 + \xi_a^2)}$$
(14)

From figure S4, it can be seen that the x coordinate of point D can be expressed as

$$x_{D} = x_{\min} = \frac{-(\xi_{a}\eta_{a} - d - R_{2}) - \sqrt{(\xi_{a}\eta_{a} - d - R_{2})^{2} - (1 + \xi_{a}^{2})(d^{2} + 2R_{2}d + \eta_{a}^{2})}{(1 + \xi_{a}^{2})} = \varepsilon_{a}$$
(15)

Inserting Eq.(15) into Eq.(12), the y coordinated of point D can be obtained

$$y_D = \xi_a \varepsilon_a + \eta_a \tag{16}$$

Then the coordinate of point D is

$$D(\varepsilon_a, \xi_a \varepsilon_a + \eta_a) \tag{17}$$

According to the coordinate of point D and point E (d+R2, 0), the slope of line DE can be expressed as:

$$\tan \varphi_{a2} = \frac{y_D}{x_E - x_D} = \frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a}$$
(18)

So, the radius angle of the abaxial ray (the second lens) can be given as

$$\varphi_{a2} = \arctan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a})$$
(19)

Then, the incident and refraction angle of the abaxial ray (the second lens) can be yielded:

$$I_{a2} = \varphi_{a2} - U_{a1} = \arctan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a}) - I_{a1} + \arctan(\frac{\sin I_{a1}}{n})$$
(20)

$$I_{a2}' = \frac{I_{a2}}{n} = \frac{1}{n} \left[ \arctan\left(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a}\right) - I_{a1} + acr \sin\left(\frac{\sin I_{a1}}{n}\right) \right]$$
(21)

In  $\Delta DEF$ , based on the Law of Sines, the length of  $\overline{AE}$  can be obtained:

$$\frac{\overline{EF}}{\sin I'_{a2}} = \frac{\overline{DE}}{\sin U_{a2}}$$
(22)

$$\overline{EF} = \frac{R_2 \sin\{\frac{1}{n} [acr \tan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a}) - I_{a1} + \arcsin(\frac{\sin I_{a1}}{n})]\}}{\sin[acr \tan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a})]}$$
(23)

For the paraxial ray, the derivation process is the same with the abaxial one. So the derivation process will not be repeated. And the length of  $\overline{EG}$  is directly given as:

$$\overline{EG} = \frac{R_2 \sin\{\frac{1}{n} [\arctan(\frac{\xi_p \varepsilon_p + \eta_p}{d + R_2 - \varepsilon_p}) - I_{p_1} + \arcsin(\frac{\sin I_{p_1}}{n})]\}}{\sin[\arctan(\frac{\xi_p \varepsilon_p + \eta_p}{d + R_2 - \varepsilon_p})]}$$
(24)

The derivation distance for the compound lens  $\delta_{L2}$  can be given as:

$$\delta_{L2} = \overline{EG} - \overline{EF} = \frac{R_2 \sin\{\frac{1}{n} [\arctan(\frac{\xi_p \varepsilon_p + \eta_p}{d + R_2 - \varepsilon_p}) - I_{p_1} + \arcsin(\frac{\sin I_{p_1}}{n})]\}}{\sin[\arctan(\frac{\xi_p \varepsilon_p + \eta_p}{d + R_2 - \varepsilon_p})]}$$

$$-\frac{R_2 \sin\{\frac{1}{n} [\arctan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a}) - I_{a_1} + \arcsin(\frac{\sin I_{a_1}}{n})]\}}{\sin[\arctan(\frac{\xi_a \varepsilon_a + \eta_a}{d + R_2 - \varepsilon_a})]}$$
(25)

From Eq.(25), it can be found when the  $I_{al}$ ,  $I_{pl}$ , n,  $R_l$ ,  $R_2$  and d are given, the derivation distance for the compound lens  $\delta_{L2}$  can be calculated.