

# Design and demonstration of a foveated imaging system with reflective spatial light modulator

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**Abstract** In this paper, a foveated imaging system using a reflective liquid crystal spatial light modulator (SLM) was designed. To demonstrate the concept of foveated imaging, we simulated with software Code V and established a laboratory prototype. The result of the experiment shows that an SLM can be used to correct the aberration of region of interest (ROI) while the resolution of other area was still very low. The vary-resolution system was relative simple compared to the traditional high resolution system and obviously can reduce the amount of data transmission. Such systems will have wide application prospect in various fields.

**Keywords** optical design, foveated imaging, spatial light modulator (SLM), tolerance analysis

## 1 Introduction

To meet the wider needs, an optical system should have a large field of view (FOV) while maintaining high imaging quality within the whole image. Fast optical systems (with small  $F/\#$  numbers) usually need to add optical elements in order to balance off-axis aberrations at large field angles, which will increase the complexity, size and weight of the system [1]. On the other hand, high resolution images require large data bandwidth. But in many cases, high resolution within the entire FOV is not necessary. That is to say, the resolution through the whole FOV does not need to be the same. If we only correct the aberrations of region of interest (ROI) and keep the other area unclear, the object in ROI will be distinguished while the amount of data is

decreased. Such system is a foveated imaging system. Because of the advantages of simple structure, miniaturization and high data transmission rate, foveated imaging systems have a variety of applications in military and civilian fields including investigation, monitoring, remote control, etc. [2–8].

In this paper, a foveated imaging system was designed. A reflective spatial light modulator (SLM) was used as wave front corrector to correct the aberrations of ROI so the resolution of the entire FOV was variable. A prototype was also established and the results were presented to verify the theory.

## 2 Foveated imaging theory

The FOV of human eye is very large but only limited area called foveal has high resolution while the other area is blurred. Out of foveal area, we still can detect object without its details. When we need to distinguish details, we rotate our eyes and focus on the object. This process is so called foveated imaging. An optical system which has high resolution in ROI and relative lower image quality in peripheral area is a foveated imaging system.

The key elements of foveated imaging systems are active optical components including deformable mirrors (DMs) [9] and SLMs. Considering the cost and convenience, we used a phase-only reflective SLM to control the optical wave front by dynamically changing the optical path difference (OPD) across the aperture. The maximum OPD that can be introduced by the SLM is known as the phase stroke. The phase stroke achievable practically is usually less than  $2\lambda$  ( $\lambda = 632.8$  nm), which is not enough to correct the aberrations in peripheral area. If the wave front aberration exceeds the phase stroke of a SLM, the correction still can be done modulo- $2\pi$  [2,10].

### 3 Optical design and tolerance analysis

To verify the theory of foveated imaging, software Code V was used to design an optical system which contains four spherical lens, a beam splitter and a reflective SLM. The structure of the system is shown in Fig. 1. The FOV is  $\pm 8.7^\circ$  in  $y$  and  $\pm 4.9^\circ$  in  $x$ . Light from infinity objective plane passes through the first lens group and the beam splitter, then is reflected by the SLM and the beam splitter and passes through the second lens group, finally converges on the image plane.

The first lens group is a Kepler telescope consisting of two convex lenses to make the light incident on the SLM almost perpendicular to it. The polarization beam splitter turns the light path to avoid duplication of the light path. The reflective surface is defined by XY polynomial to simulate the SLM. The second lens group consists of a concave lens and a convex lens which can focus the light on the image plane.

Then the wave aberration of a particular field was analyzed to calculate the proper phase diagram. According to the physical optics theory, the differences between practical wavefront and the theoretical wavefront is the wave front aberration. It can be described as follows:

$$W(\sigma, \rho, \phi) = \sum k_{(l+n)(m+n),n} \sigma^{(l+n)} \rho^{(m+n)} \cos^n \phi, \quad (1)$$

where  $\sigma$  is the radius of field (normalized),  $\rho$  is the radius of the aperture (normalized),  $\phi$  is the angle between the principle ray and the rays in the imaging beams,  $k$  is the

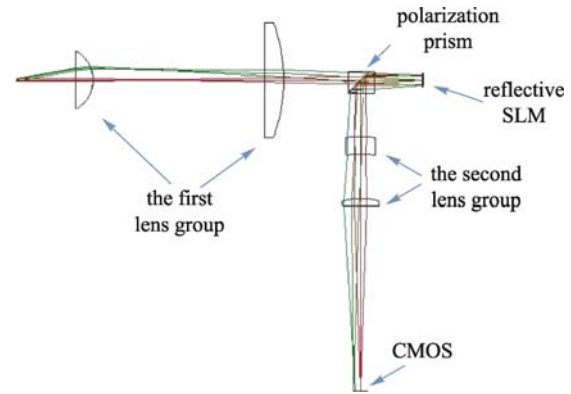


Fig. 1 Structure of foveated imaging system

coefficient and  $l, m, n$  are natural numbers. Then the wave front aberration of any field can be calculated so that the wave front map of ROI can be achieved. A foveated imaging system is a system that has minimum aberration in ROI and relative larger aberration in other area. By calculating the wave front error of ROI, the phase diagram that need to be loaded on the SLM can be achieved.

The aberration of field  $(-4^\circ, -4^\circ)$  and  $(4^\circ, 4^\circ)$  then is corrected and the simulation results is illustrated in Figs. 2–4. Figure 2 is the original modulation transfer function (MTF) before any modulation, which indicates the image quality of the whole FOV is not good. Figures 3 and 4 show the MTF of field  $(-4^\circ, -4^\circ)$  and field  $(4^\circ, 4^\circ)$  after correction. The wave front errors before and after correction are also shown below the MTF. It can be seen

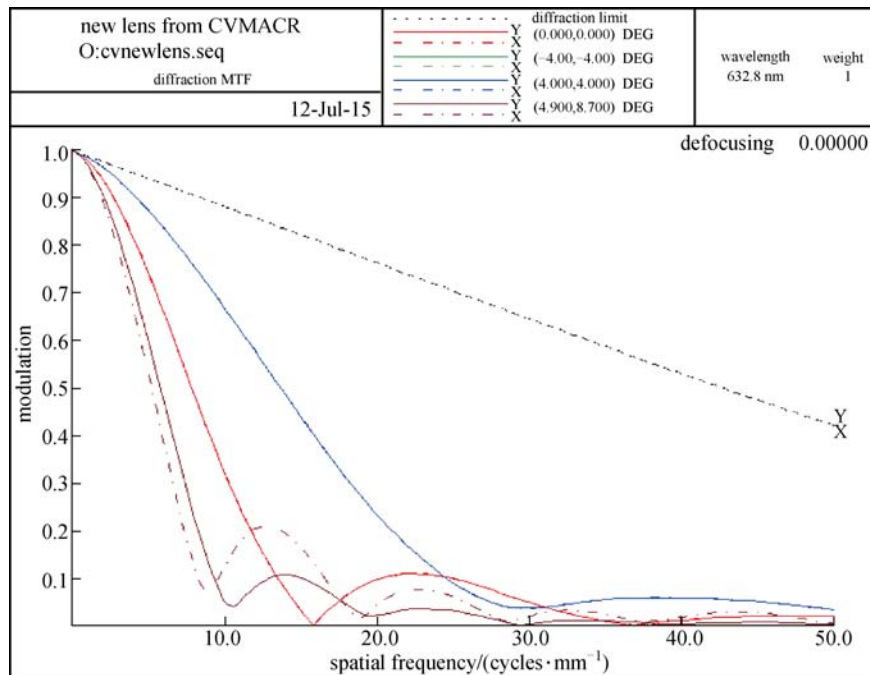


Fig. 2 MTF of the system before correction

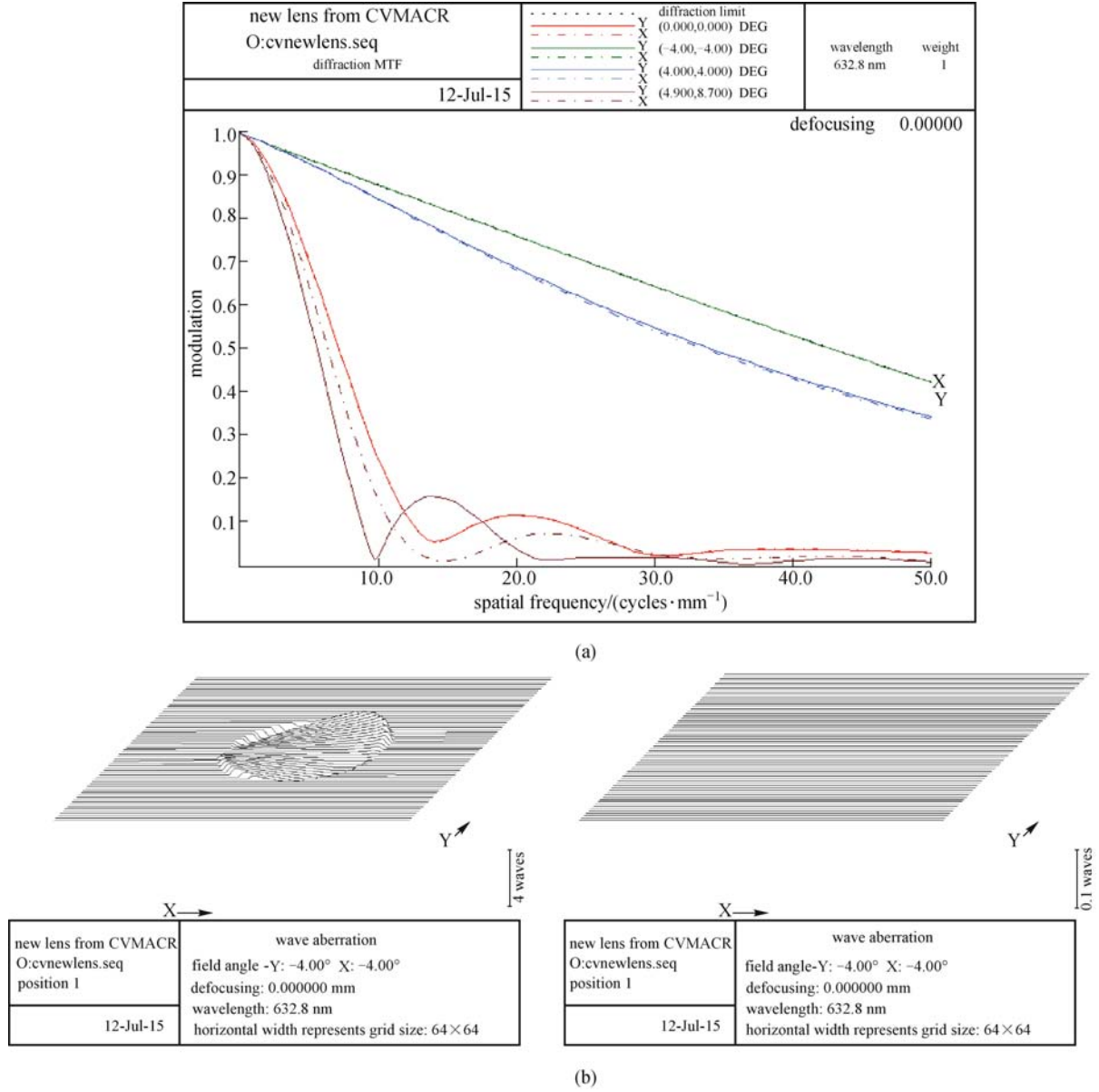


Fig. 3 (a) MTF after correction and (b) wave front errors before and after correction of field ( $-4^\circ$ ,  $-4^\circ$ )

that these two fields have a near diffraction-limitation performance while other fields still have residual aberration.

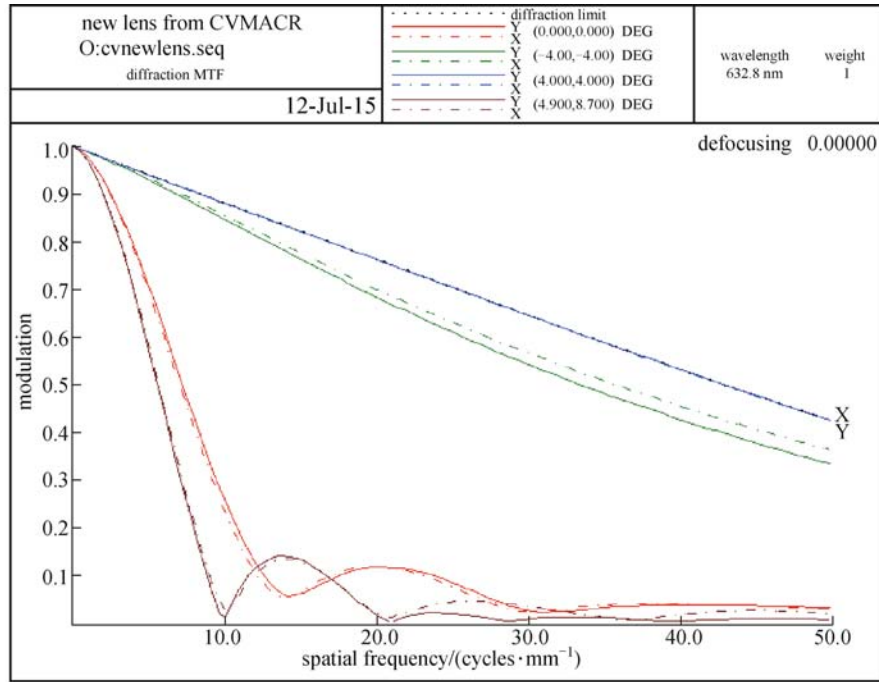
The structure of the first lens group can be treated as an inverted Kepler telescope. An obvious advantage of this structure is that it avoids large incident angle which will cause strict tolerances since parallel beam is less sensitive to the distances between elements compared with convergent beam in Ref. [1]. In a foveated imaging system using an SLM, the experimental accuracy directly affects the practical wave front aberration of the system. If the difference between the actual aberration and the calculated value is too large, the phase diagram created by the software cannot be used in the experiment. So the tolerance analysis is needed.

Since the elements are all off-the-shelf, the tolerances of their dimensions are given by the manufacturer. We analyzed the centered and decentered tolerances by Code V and the results are shown in Table 1.

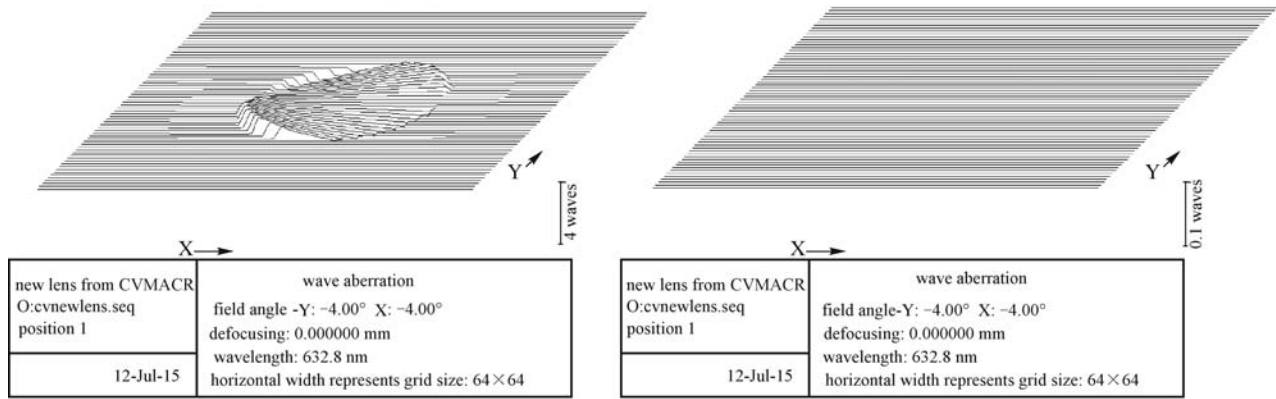
From Table 1, we can find that the tolerances near the SLM and the decentered tolerances are quite loose. That is to say, the prototype established in laboratory can be quite close to the theoretical one. This also can be demonstrated by the experiment. This is an obvious advantage compared with the system designed in Ref. [1].

## 4 Demonstration

To demonstrate the theory, a laboratory prototype was



(a)



(b)

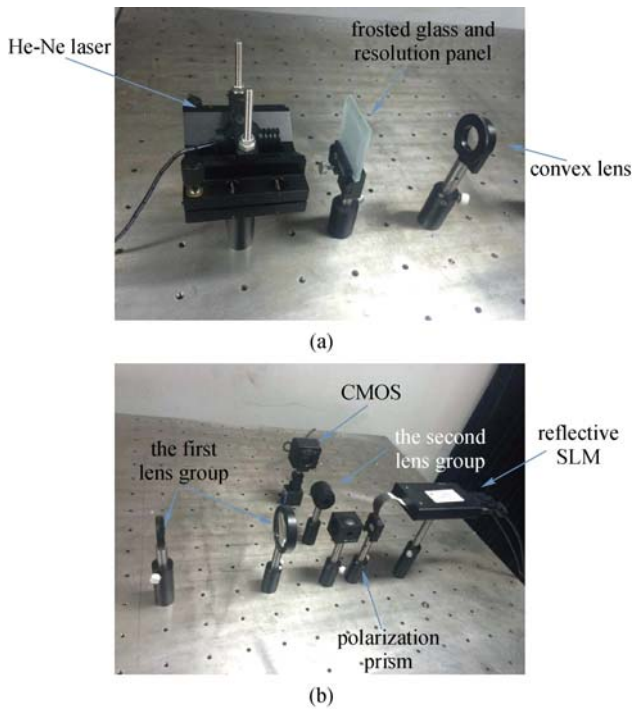
Fig. 4 (a) MTF after correction and (b) wave front errors before and after correction of field (4°, 4°)

Table 1 The centered and decentered tolerances of foveated imaging system

elements No.	distance tolerance/mm	tolerance wedge		tolerance tilt	
		total indicated runout (TIR)	arc minute	total indicated runout (TIR)	arc minute
1	—	0.01	3.4	0.015	5.2
2	1.00	0.04	8.4	0.041	8.6
3	5.00	0.04	11.2	0.062	17.2
4	5.00	0.07	23.7	—	—
5	5.00	0.04	11.2	0.062	17.2
6	1.00	0.01	2.4	0.029	6.9
7	1.00	0.10	21.5	0.032	6.9

established. All of the components are off-the-shelf. The simulation part of infinity object consists of a He-Ne laser

was used as the light source ( $\lambda = 632.8$  nm), a frosted glass to uniform the light and a resolution panel as the object.



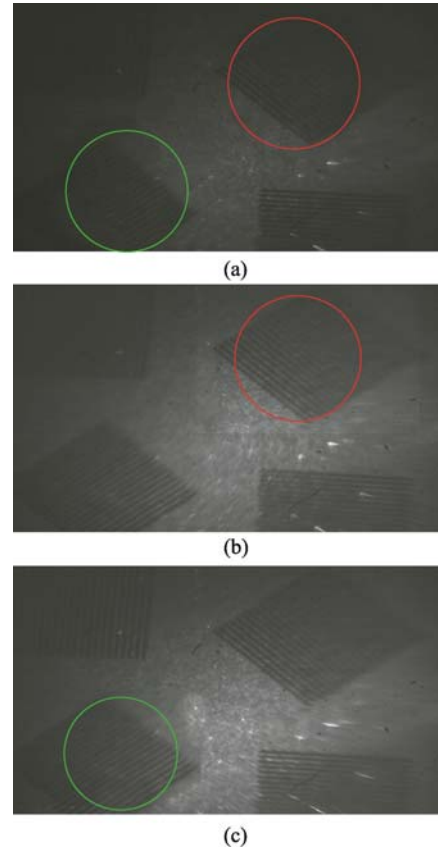
**Fig. 5** Structure of (a) the simulation of an infinity object and (b) a foveated imaging system

The resolution panel is on the focal plane of a convex lens so that the exit light beam is parallel. Figure 5(a) shows the structure of this part.

The structure of the imaging system is illustrated in Fig. 5(b). We chose Holoeye PLUTO SLM to demonstrate our theory. The key part of PLUTO SLM is an active matrix reflective mode phase only LCD with  $1920 \times 1080$  resolution. It measured  $15.36 \text{ mm} \times 8.64 \text{ mm}$  with  $8.0 \mu\text{m} \times 8.0 \mu\text{m}$  pixels and 87% fill factor. A polarizing prism from which the exit light was polarized is used as the beam splitter to meet the polarization requirements of the SLM. A 1/2" black-and-white CMOS was put on the image plane for image acquisition.

Then the phase diagram calculated before was loaded on the SLM. Figure 6 shows the original image and the image after correction at field  $(-4^\circ, -4^\circ)$  and field  $(4^\circ, 4^\circ)$ . In Fig. 6(a), there is no voltage applied to the SLM and the whole image is blurred. The red circle is field  $(4^\circ, 4^\circ)$  and the green one is field  $(-4^\circ, -4^\circ)$ . In Figs. 6(b) and 6(c), phase diagrams were loaded to the SLM. Phase diagram is a grayscale image and each gray scale has a corresponding voltage value which will change the OPD of SLM.

After correction, the areas in the red circle and green circle become clearer separately while other area becomes worse. That is because the SLM is located in the aperture surface while the phase diagram loaded to the SLM is for the specific area. So when the ROI is corrected, the image quality of other area becomes worse.



**Fig. 6** Images (a) before and (b,c) after correction at fields  $(-4^\circ, -4^\circ)$  and  $(4^\circ, 4^\circ)$

## 5 Conclusion

An optical system which can realize foveated imaging was designed. The system consisted of two groups of lenses, a beam splitter and a reflective SLM. The SLM was used to correct the aberrations of the ROI so that the image quality of this area can have a near diffraction-limitation performance while the resolution of other area decreases. We also analyzed the tolerances of this system and found it very loose. This analysis illuminated that this system is easy to be assembled and this conclusion was also verified in the experiment. Using an SLM, the foveated imaging system can achieve a high resolution of the ROI and relative lower resolution of other area. Such systems will have wide application prospect in various fields.

**Acknowledgements** This research work was financially supported by the National Natural Science Foundation of China (Grant No. 61178041)

## References

1. Wick D, Martinez T, Restaino S, Stone B. Foveated imaging demonstration. *Optics Express*, 2002, 10(1): 60–65
2. Curatu G. Analysis and design of wide-angle foveated optical

systems. Dissertation for the Doctoral Degree. Florida: University of Central Florida, 2009

3. Du X, Chang J, Zhang Y, Wang X, Zhang B, Gao L, Xiao L. Design of a dynamic dual-foveated imaging system. *Optics Express*, 2015, 23(20): 26032–26040
4. Feng C, Chang J, Yang H. Design of dually foveated imaging optical system. *Acta Phisica Silica*, 2015, 64(3): 034201
5. Zhao X, Xie Y, Zhao W. Wide field-of-view foveated imaging system. *Chinese Optics Letters*, 2008, 6(8): 561–563
6. Curatu G, Harvey J E. Lens design and system optimization for foveated imaging. In: *Proceedings of the Society for Photo-Instrumentation Engineers*. 2008, 7060: 70600P-1–70600P-9
7. Curatu G, Harvey J E. Analysis and design of wide-angle foveated optical systems based on transmissive liquid crystal spatial light modulators. *Optical Engineering (Redondo Beach, Calif.)*, 2009, 48(4): 043001
8. Peng Q, Chang J, Feng S, Wang R. Reflective foveated optical imaging system based on liquid crystal spatial light modulator. In: *Proceedings of the Society for Photo-Instrumentation Engineers*. 2010, 7849: 78911-1–78911-7
9. Xie Y, Zhu S, Hu S, Zhao H, Zhena M A, Chen R, Qiu Y, Gao W, Fan X, Zhao B, Li Y. Space-based telescope with variable resolution at any field angle by active optical zoom. *Guangzi Xuebao*, 2011, 40(11): 1619–1624
10. Love G D. Wave-front correction and production of Zernike modes with a liquid-crystal spatial light modulator. *Applied Optics*, 1997, 36(7): 1517–1520



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