

Design of optical imaging system for full-ocean-depth low-light colors

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ABSTRACT

In this paper, prism beam-splitting structure is proposed in the design of optical system to solve the problem of full-color imaging under low-light environment of the deep-sea. Optimization of optical aberrations is performed considering the specific aberration properties of the sea water and the window materials in the optical system. The designed optical system (field of view 60° and F/4) shows a clear imaging for all fields of view where MTFs is over 0.5 (@77lp/mm). The optical performance demonstrates that the system is very promising for large depth of field and full-color imaging under deep-sea environment.

1. Introduction

Oceans, which occupies almost two thirds of the earth's surface, has been paid extensive attentions due to its rich resources including mineral, biological species and energy reserves. Capturing this comprehensive information of these resources in the deep-sea, leads the advances of optical imaging equipment to high resolution and in-situ recording [1,2]. However, the lack of light penetrating into the deep sea due to the strong scattering in visible spectrum results into active illumination in these optical instruments. To achieve the best imaging performance, the energy efficiency of the illumination in these instruments must be quite high. Note that the low-light performance and the color reproduction [3] are the important challenges that need to be solved in these optical instruments being implemented under deep-sea environment.

In China and other countries, the underwater imaging instruments are directly embedded within land camera systems. The color in these detectors of conventional instruments has limited the efficiency of spectral energy due to the color filtering in the Bayer mode. Furthermore, there is an existing deviation among colors being obtained by the interpolation of the all pixels in the detector. Since there is a tradeoff between the low light and the color performances for the instrument with only one detector, conventional instrument sacrificed its depth of field to improve the vision performance of the low light, the depth of field is related to the F number of the instrument. Even though prism beam-splitters for collecting spectral bands has been used in the radio, televisions and industrial system [4], the underwater imaging instruments still unsuccessfully reach to the requirement of the high-quality performance in low-light color imaging applications due to the small

size the detector chip and the lack of special designed lens for the application in the water environment.

To address the challenge of reproducing the real scenario of a full-ocean-depth underwater, we propose a combination of prism beam-splitters with high-performance low-light chip to realize RGB splitting. It resolves the tradeoff between high dynamic imaging and color reproduction under low-light environment. Based on the analysis of the parameters in the beam-splitting structure, an optical system was designed considering the aberration characteristics of the water body and the optical window. Compared with conventional color chips of Bayer mode, the energy efficiency and the color rendition have been significantly improved. What's more, the actual deep-sea low-light environment can be restored accurately.

2. Design of the beam-splitting system

A beam-splitting prism with three optical wedges was used as a key component in the optical system to realize both low-light performance and color rendition. The prism beam-splitting method [5–8], taking use of the limited energy of the optical window, triples photosensitive area as compared with the single detector design. This strategy greatly implements the high photosensitive performance of the chip. In the optical system, there are three detectors for each pixel position. Since local colors are not obtained by interpolation, the captured image highly resembles a real color. The schematic of beam-splitting prism is shown in Fig. 1.

As can be seen from Fig. 1, there is an air gap between prisms ① and ②, and a cemented surface between prisms ② and ③. Red, green and blue (RGB) incident rays through the optical lens enters surface A of the prism ① and only the blue rays get reflected from surface B, then blue ray is totally reflected from surface A and finally exit the prism. In addition, green and red rays enter prism ②, and the red rays get reflected

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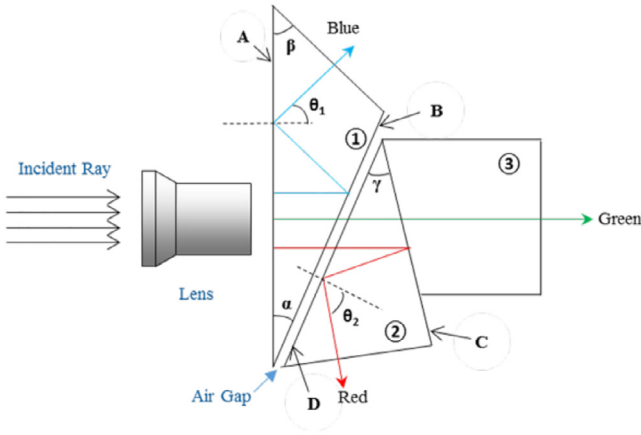


Fig. 1. The schematic layout of beam-splitting Prism.

from surface C, then is totally reflected from surface D and exit prism. Meanwhile, the green rays exit the prism ③.

2.1. Discussion of the total reflection condition

For a total internal reflection (TIR) on surfaces A and D, the incident angle of beam rays of corresponding wavelength must be bigger than the TIR angle θ between optically denser medium and the optically thinner medium (for air medium).

$$\theta = \arcsin\left(\frac{1}{n}\right) \quad (1)$$

Where n is the refractive index of the prism medium.

Based on Eq. (1), if increasing the RI of the prism material, it results into decreasing the TIR angle. Actually, The RI depends on the wavelength of light so that the shorter wavelength leads to small TIR angle. So, TIR is easier to be realized. H-ZF7LAGT is selected as the prism material. The TIR condition is satisfied by controlling the incident angle of light on all surfaces. Incident angles θ_1 and θ_2 of the ray on surface A and surface D must satisfy the TIR condition to successfully split the R/G/B beams Eqs. (2) and (3). The design should be emphasized on controlling the maximum deflection angle δ in the incident ray beam during the optimization design. What's more, maximum deflection angle is associated with the incident angle and the image beam aperture angle of marginal rays. The following conditions must be satisfied for realize the RGB tri-wavelength ray split of the prisms ①, ② and ③:

$$\text{Surface A : } \beta - \delta > \theta_B \quad (2)$$

$$\text{Surface D : } \alpha + \delta < \theta_R \quad (3)$$

where θ is the total reflection angle of the ray.

2.2. The relationship between the total reflection condition and the wedge angle

The schematic of the beam-splitting system in Fig. 1 illustrates the structure of the three prisms. A and B are the upper and lower surfaces of the prism ①; D and C are the upper and lower surfaces of the prism ②; α and β are the wedge angles of both ends of the prism ①, and γ is the wedge angle of the acute end of the prism ②. To split the red (R), green (G), and blue (B) rays, the following conditions should be satisfied [9] Eqs. (4), (5) and (6).

Surface A:

$$\theta_1 = 2\alpha - \arcsin NA \geq \arcsin(1/n) \quad (4)$$

Table 1
Specifications of Optical System.

Parameters	Value
Spectral range	400–650nm
Resolution	2048 × 1152
Pixel size	6.5 × 6.5μm
Imaging distance	0.5 to 15m
Field of view	38.4° × 21.6° (underwater)
F/#	4
Optical window material	High borosilicate glass (HBG)

Surface B:

$$\alpha + \arcsin NA < \arcsin(1/n) \quad (5)$$

Surface D:

$$\theta_2 = 2(\gamma - \alpha) + \alpha \geq \arcsin(1/n) \quad (6)$$

3. Design of the optical system

The main system parameters are shown in Table 1. Note that the image space F/# is 4, which not only solve the tradeoff between the system depth of field and the low-light performance of the small relative aperture, but also meet the need for observation in wide-range scenes.

To realize desired optical performance, it is necessary to consider two important factors during the optical design, such as refractive index and the dispersion properties of the seawater [10]. Importantly, due to the large target surface and the large relative aperture in the optical system, the image quality at the edge field of view is very distinct. To solve these challenges, a reasonable combination of materials for optical lens was implemented. Through optimizing system parameters, a system design with an equalization correction of the aberrations is obtained. The optimized design has four lens materials including low dispersion fluor crown glass H-FK61 (497,816), crown glass H-K9L (517,642), dense crown glass transparent H-ZK14 (603,606) and flint glass F2 (620,364). These optical lens materials have over 97% transmission in the visible working band from 400 nm to 650 nm.

An inverted telephoto lens system is used, which is characterized by having a long back focal length (BFL) being compared with its short effective focal length(EFL).The lenses consist of a negative front lens group and a rear positive lens groups. In the design, the focal power of front lens groups should be as small as possible, and the rays almost parallel passes through the aperture stop, which is favorable to reduce the impact of focusing, and then the rays is converged to the focal plane by the rear elements. The incident angle of each field on each lens surface should be controlled to minimize monochromatic aberration, the index of object space is set the refractive index of the water and the splitting prism is design as a parallel plates in the lens optimization, the last lens surface is design as flat plane to avoid the convergence of stray light on the focal plane of the detector. The final 2D optical model in optical simulation software is shown in Fig. 2.

The image quality evaluation standard for optical design is based on MTFs at the Nyquist frequency (@77 mm/lp). As the position of the relative prism of the detector is fixed, clear imaging within the entire working distance can be guaranteed using the movement of front group. MTF at a typical imaging distance of 3 m is greater than 0.3@77lp/mm, as shown in Fig. 3 Spot Diagram of the optical system as shown in Fig. 4 Maximum illumination variation is less than 5% over the entire field of view.

4. Experimental results

In Fig. 5 the prototype of the designed optical system with three CMOS detector chips has been integrated and calibrated. The prototype

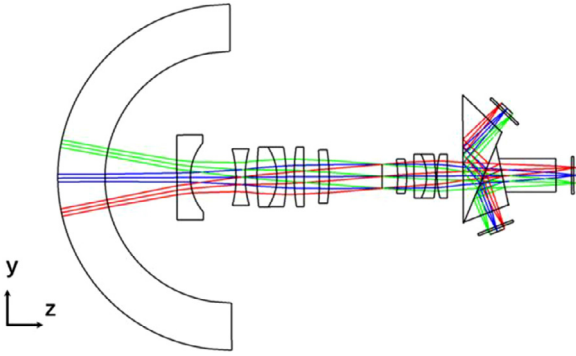


Fig. 2. Layout of Optical Structure.

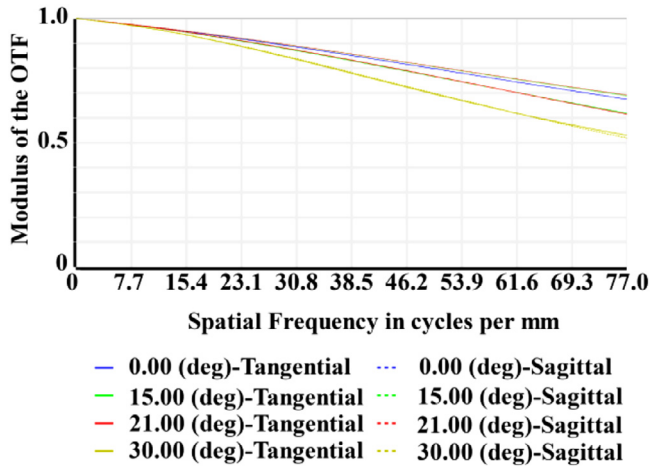


Fig. 3. MTF of the optical system@3 m.

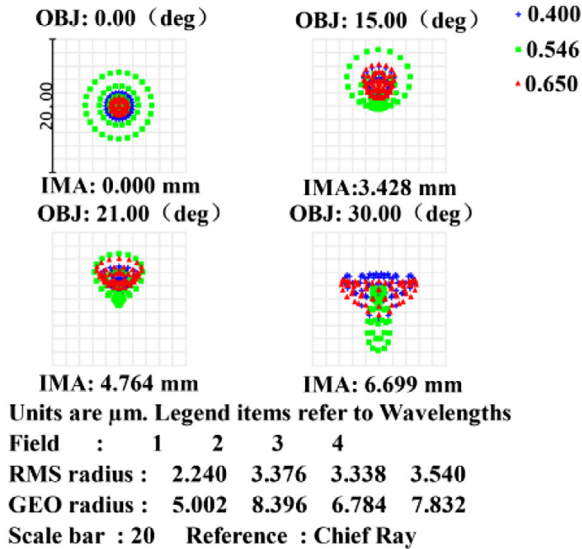


Fig. 4. Spot Diagram of the Optical System.

includes two parts: lens and beam-splitting prism, in which the RGB images are independently formed in the prism. The final image can be synthesized by RGB channel, which can set different weights. It can resolve the color restoration problem caused by varied attenuation in different wavelengths of seawater. The real performance and the transmittance curve of 3D Prism is shown in Figs. 6 and 7.



Fig. 5. The optical system prototype. The imaging effect in the water was carried out by standard color, which is put in the water under the distance of 0.5 m. The final image is demonstrated in Fig. 8 which shows very high color reducibility.

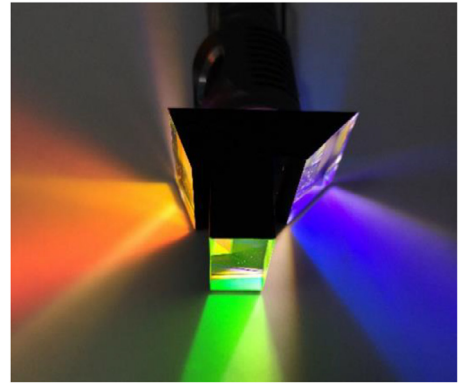


Fig. 6. Real performance of beam-splitter Prism.

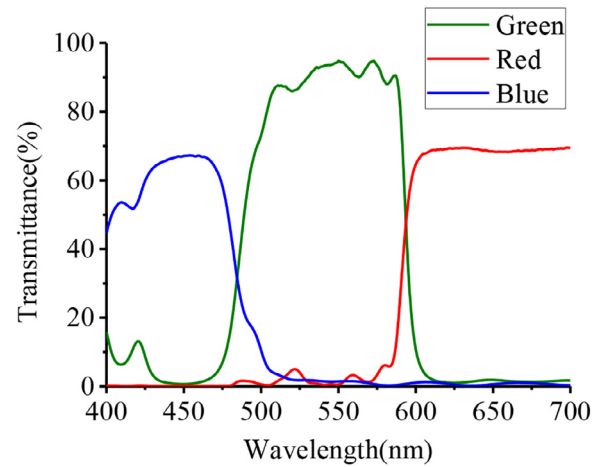


Fig. 7. Transmittance Curve of the Prism within visible band.



Fig. 8. The imaging performance using standard color card.

5. Conclusions

In this paper, we proposed the prism beam-splitters in a typical optical system for underwater application to realize low-light sight and color performances as well as guarantee a larger optical imaging depth of field. The optical system, which was designed with a diagonal field of view of 60° and $F/\#$ is 4, MTFs of all fields of view are greater than 0.5 (@77lp/mm), can ensure a clear imaging at a large depth of field. Independent imaging of the three RGB channel has a larger operating space for image color restoration in the later stage, which is useful in the seawater imaging. The effect of working distance in water media on color reproduction will be further studied in the engineering implementations.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yang Jiang: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft. **Xiang-qian Quan:** Data curation. **Yan**

Xing: Validation. **Li Da-yong:** Investigation. **Zheng Xiong:** Writing – review & editing. **Qiang Sun:** Supervision.

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