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Underwater power compensated white light source based on synthetic white laser

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ABSTRACT

The semiconductor white laser light source is used as a light source for underwater illumination. The required standard color temperature of white light is obtained at the underwater target surface. We studied the power compensation of a synthetic white laser source and its application to underwater illumination. First, the power ratios of the red (638 nm), green (520 nm), and blue (450 nm) lasers at a color temperature of 6500 K were obtained by using chromaticity theory. Next, the three-color and synthetic white laser parameters were obtained with transmission distance, according to the exponential attenuation characteristics of different light in clear water and seawater medium. The three-color laser power at the output was compensated, and the underwater target illumination surface reached the standard 6500 K color temperature of the white laser, improving the illumination. Finally, an experimental system for underwater white laser illumination based on power compensation was established. The errors between experimental and theoretical results of color temperature and illuminance are no more than 0.43% and 22.15%. This power-compensated synthetic white laser light source has both the advantages of long-range underwater detection and the spectral advantages of LED white light sources. The white laser light source meets specific requirements by compensating for power and optimizing white light characteristics for underwater lighting applications.

1. Introduction

At present, in the context of a robust marine strategy, many countries have invested many resources in underwater lighting and detection. Underwater lighting technology is an important support tool for underwater detection and has essential applications [1,2]. For marine areas, where artificial light is challenging to meet the required depth, underwater exploration relies on active point sources for illumination, so more efficient and accurate instrumentation is urgently needed.

Underwater white light sources include LEDs, tungsten halogen lamps, and monochrome lasers. Shen et al. [3] proposed an underwater LED light source transfer model. Compared to conventional underwater fish attractor light sources, this LED light source has an 81% increase in illumination area efficiency. Qian et al. [4] used PC-LED and RGB-LED as underwater light sources and analyzed the underwater illumination characteristics at different waters and distances. However, the LEDs' limited stability performance and

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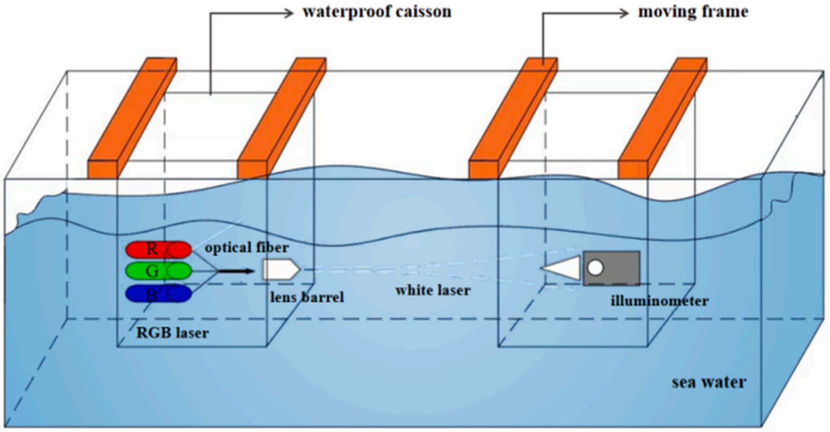


Fig. 1. Synthetic white laser underwater illumination system.

energy density cannot guarantee normal efficient operation. Li et al. [5] proposed a narrow pulse-width Nd:YAG MOPA and a 532 nm frequency-doubling module lidar-radar system for underwater target detection. The 3-D and 4-D images and the resolution of 9 mm of the target underwater across 20 m can be obtained. Monochromatic lasers do not give a true representation of the objective world. Applications have many limitations, such as underwater target identification and spectral analysis.

As a new type of laser, the three-color synthetic white laser uses a combination of red, green, and blue primary color lasers to produce high-brightness white light [6,7]. The high energy and power tunability of white lasers can be used to fill the gaps in other white light source applications. Tian et al. [8] used a high-power RGB trichromatic semiconductor laser to generate white light, and by adjusting the power of the RGB three-color semiconductor lasers, the output white light was 6480 K. The color temperature deviation was less than 3.08% compared to the standard white light D65. Yang et al. [9] proposed an underwater 3D color reconstruction method using an RGB triple laser to improve the LLS system, obtained color texture and data information of the target object on the millimeter scale. Jiang et al. [10] compared the underwater imaging results of a white laser light source from an RGB semiconductor laser with three monochromatic lasers, red, green, blue, and an LED white light source under different conditions, demonstrating the superiority of the white laser as an underwater imaging light source. In previous studies of underwater applications of white laser, the underwater attenuation of the white laser was not considered, which leads to quality deviations of the white laser at the output and the underwater target, with implications for underwater detection.

In this paper, a power-compensated underwater white light source based on a synthetic white laser is used as an underwater illumination source, and the underwater white laser illumination characteristics are investigated for different underwater light source distances in pure water and seawater medium. We compensated the power of the RGB three-color semiconductor laser at the output. A white laser with a color temperature of 6500K at the underwater target surface was obtained. The compensated illumination increases by 44.70% and 104.56% per metre in clear water and seawater. A better quality underwater white light source was obtained. This white laser light source can overcome the short working distance, restricted spectral range, and attenuation of seawater light energy of current underwater detection light sources, and meet the requirement of real-time power adjustment as the light source distance changes. It can improve the category of underwater white light sources and contribute to underwater white laser lighting development. It is of great significance and practical value in developing new underwater equipment and accelerating the development of marine exploration technology.

2. Theoretical basis of the model

Underwater illumination is low during underwater detection, so that artificial lighting will be involved. According to the attenuation characteristics of water, the optical power at the output is compensated. A model for white light underwater illumination based on three-color power compensation is established. This model achieves the required white light 6500 K standard color temperature at the underwater illumination surface and increases the illumination on this surface. Fig. 1 shows a power-compensated underwater white light model based on a synthetic white laser.

Due to the theory of attenuation transmission of light of different wavelengths in water, the attenuation of the light consists of the direct beam transfer function $g_{1\lambda}(l)$ and the scattered beam transfer function $g_{2\lambda}(l)$ [11]. The transmission function of the whole beam in the water medium is represented by (1):

$$g_{\lambda}(l) = g_{1\lambda}(l) + g_{2\lambda}(l) = e^{-cl} + \left(2.5 - 1.5\lg\frac{2\pi}{\varphi}\right)\left[1 + 7\left(\frac{2\pi}{\varphi}\right)^{\frac{1}{2}} \times e^{-kl}\right]\frac{ble^{-kl}}{4\pi} \tag{1}$$

where $g_{1\lambda}(l)$ is the direct beam transfer function, $g_{2\lambda}(l)$ is the scattered beam transfer function, which is expressed by Duntley's semi-empirical formula. λ is the wavelength, l is the laser transmission distance, φ is the laser divergence angle, c is the direct light attenuation coefficient, k is the scattered light attenuation coefficient. $a = c + k$, where a is the overall attenuation coefficient of absorption and scattering [12].

The red, green, and blue semiconductor lasers are used as the light source. After power is proportioned, the white laser output is achieved through spatial and wavelength combined beam coupling to an optical fiber. Based on the principle of the three primary colors, the ratio of the three primary colors can be calculated after the target color has been determined, and this ratio is represented by the three stimulus values. When two or more colors with known luminance values and color coordinates are mixed, the luminance and color coordinates of the mixed light are obtained [13].

X, Y, and Z are three stimulus values for a certain color. (x, y) is color coordinates. L is luminance. The relationship is represented by (2):

$$\begin{cases} X = \dfrac{x}{y}L \\ Y = L \\ Z = \dfrac{z}{y} = \dfrac{1 - x - y}{y}L \end{cases} \tag{2}$$

The relationship between the three stimulus values and the color coordinates is represented by (3):

$$\begin{cases} \dfrac{X}{X+Y+Z} = x \\ \dfrac{Y}{X+Y+Z} = y, \\ \dfrac{Z}{X+Y+Z} = z \end{cases} \tag{3}$$

The red, green, and blue semiconductor lasers are synthesized into a white laser. (x_R,y_R), (x_G,y_G), and (x_B,y_B) represent the color product coordinates of red, green, and blue light, respectively; (X_R,Y_R,Z_R), (X_G,Y_G,Z_G), and (X_B, Y_B, Z_B) represent the stimulus value of red, green, and blue light, respectively. The relationship between the stimulus value of white light and the stimulus value of the three colors is expressed by (4).

$$\begin{cases} X_0 = X_R + X_G + X_B \\ Y_0 = Y_R + Y_G + Y_B \\ Z_0 = Z_R + Z_G + Z_B \end{cases} \tag{4}$$

The color coordinates of white light (x_0,y_0) can be represent by (5)

$$\begin{cases} x_0 = \dfrac{X_0}{X_0 + Y_0 + Z_0} \\ y_0 = \dfrac{Y_0}{X_0 + Y_0 + Z_0} \end{cases} \tag{5}$$

The power ratio of three-color laser can be represent by (2), (4), and (5)

$$\begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix}^{-1} \begin{bmatrix} \dfrac{x_0}{y_0} \\ 1 \\ \dfrac{1 - x_0 - y_0}{y_0} \end{bmatrix} Y_0 \tag{6}$$

Equations (2)–(6) can be obtained from Tian et al. [14]. The wavelengths of the red, green, and blue semiconductor lasers are 638 nm, 520 nm, and 450 nm, respectively. According to the CIE 1931 XYZ standard chromaticity system, the chromaticity coordinates and spectral stimulus values of the three-color corresponding to synthetic white light with a color temperature of 6500 K can be obtained [14]. $P_R : P_G : P_R = 0.4789 : 0.3307 : 0.1904$ is the three-color power ratio.

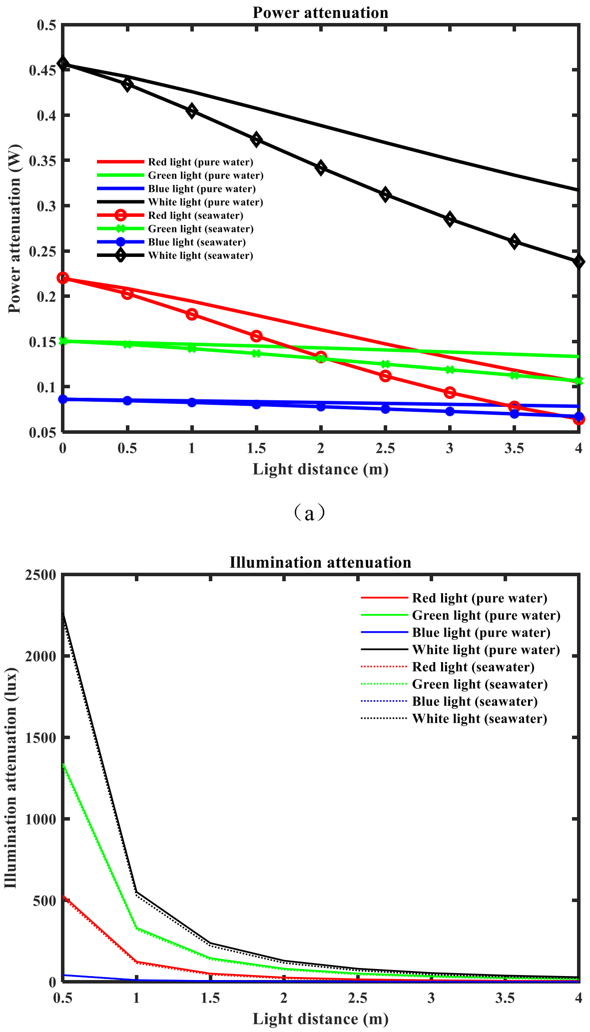
When light is transmitted in the water medium, the true power of the synthetic white laser at the underwater target surface is related to the laser transmission distance and the attenuation coefficient at different wavelengths due to the absorption and scattering properties of light to water [15]. The power of the red, green, and blue laser at the underwater target surface $P_1(\lambda)$ is obtained from (7)

$$P_1(\lambda) = P_0(\lambda) \times g_\lambda(l) \tag{7}$$

The power value at the laser output $P_0(\lambda)$ is used as a reference point, and the attenuation is zero. $P_1(\lambda)$ is the power value of the underwater target surface. When illuminating with a single-direction laser, the power compensation value $\Delta P(\lambda)$ is the difference between the power value of that wavelength at the output and the target surface. $\Delta P(\lambda)$ is obtained from (8)

$$\Delta P(\lambda) = P_0(\lambda) - P_1(\lambda) \tag{8}$$

In order to obtain a white light with a standard color temperature of 6500 K at the target illuminated surface. The power compensation result $P(\lambda)$ can be obtained from Equation (9) by adding the compensation value $\Delta P(\lambda)$ to the output power $P_0(\lambda)$,



（a）

（b）

Fig. 2. Three-color and synthetic white light parameters versus underwater light source distance: (a) power attenuation; (b) illumination attenuation.

$$P(\lambda) = [P_0(\lambda) - P_1(\lambda)] + P_0(\lambda) \tag{9}$$

$P(W)$ is the compensated power of synthetic white laser at the output [4]. $P(W)$ is obtained from (10)

$$P(W) = P(R) + P(G) + P(B) \tag{10}$$

The total illuminance of the synthetic white laser $E(l)$ is the sum of the direct illuminance $E_1(l)$ and scattered illuminance $E_2(l)$. The synthetic white laser illumination at the underwater target surface within the transmission range is represented by Equation (11).

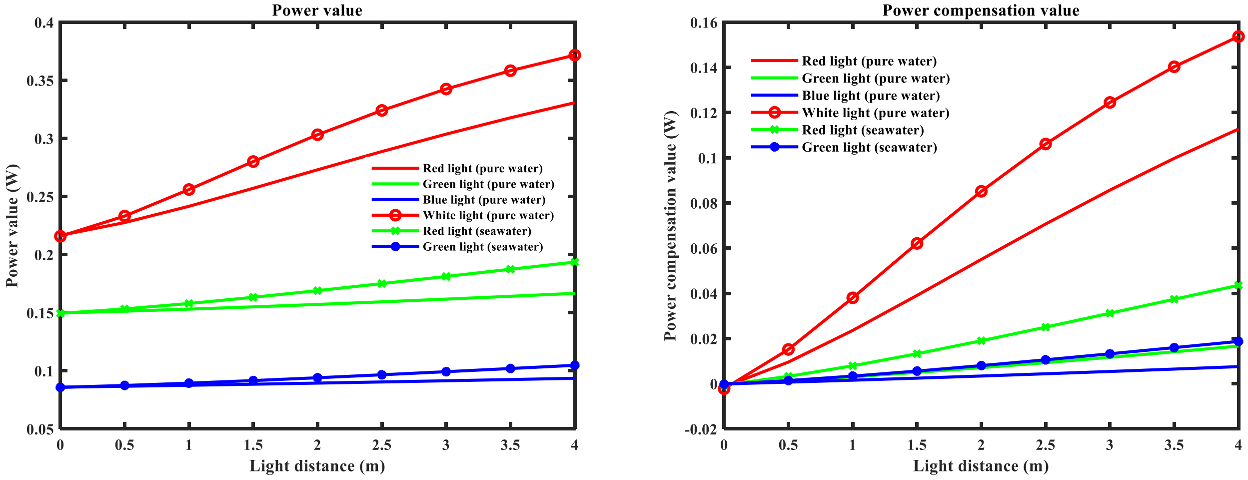
$$E(l) = E_1(l) + E_2(l) = \frac{I(\lambda)}{l^2}[g_1(l) + g_2(l)] = \frac{P(\lambda)\cdot K_M \cdot V(\lambda)}{\Omega_\varphi \cdot l^2}[g_{1\lambda}(l) + g_{2\lambda}(l)] \tag{11}$$

$I = d\varphi/d\Omega_\varphi$, φ is the luminous flux (lm), $\varphi = P(\lambda)\cdot K_M \cdot V(\lambda)$. $K_M = 683lm/W$ is the maximum luminous efficacy, $V(\lambda)$ is the spectral optical performance. Ω_φ is the stereo divergence angle (sr) of the laser, $\Omega_\varphi = \pi \sin^2 \varphi$.

In summary, synthetic white laser illumination of the required color temperature at the target surface can be obtained at any distance within the underwater transmission range through power compensation.

Table 1
Three-color laser compensation power value.

L/m		0 m	0.5 m	1 m	1.5 m	2 m	2.5 m	3 m	3.5 m	4 m
pure water	PR/W	0.218	0.229	0.243	0.259	0.275	0.290	0.305	0.319	0.332
	PG/W	0.150	0.151	0.153	0.155	0.157	0.159	0.161	0.164	0.164
	PB/W	0.085	0.086	0.087	0.088	0.089	0.090	0.091	0.092	0.093
sea water	PR/W	0.218	0.236	0.259	0.283	0.306	0.327	0.345	0.360	0.374
	PG/W	0.150	0.153	0.158	0.163	0.169	0.175	0.181	0.187	0.193
	PB/W	0.086	0.087	0.089	0.091	0.094	0.096	0.099	0.102	0.105



(a) (b)

Fig. 3. Light source distance versus power compensation value: (a) power value; (b) power compensation value.

3. Analysis of simulation results and power compensation design

3.1. Simulation parameters

The optical parameters are substituted into the model and then simulated to obtain the power, brightness, and illumination of the synthetic white laser.

From the CIE 1931 standard chromaticity table, R: G: B = 638 nm: 520 nm: 450 nm is the commonly used trichromatic wavelength combination; Laser divergence angle is $\varphi = 0.52\ rad$, the light intensity distribution is a Gaussian distribution; $l = 0 \sim 4\ m$ is laser transmission distance; $P_W = 0.45\ W$ is white laser output power. The power of red, green, and blue laser are $P_R = 0.218\ W$, $P_G = 0.15\ W$, $P_R = 0.086\ W$; Pure water medium, the direct light attenuation coefficient of the three-color light are $c_R = 0.238\ m^{-1}, c_G = 0.06\ m^{-1}$ and $c_B = 0.045\ m^{-1}$, with the scattered light attenuation coefficient of $k_R = 0.0932\ m^{-1}$, $k_G = 0.024\ m^{-1}$, and $k_B = 0.016\ m^{-1}$, respectively; Offshore seawater medium, the direct light attenuation coefficient of the three-color light are $c_R = 0.36\ m^{-1} c_G = 0.135\ m^{-1}$, and $c_B = 0.105\ m^{-1}$, with the scattered light attenuation coefficient of $k_R = 0.146\ m^{-1}$, $k_G = 0.154\ m^{-1}$, and $k_B = 0.042\ m^{-1}$, respectively. Experimental measurements of red, green and blue light illuminance at different light source distances were made and substituted into Equations (1) and (11). $c/k = (2,3)$. A range of values for the attenuation coefficients of direct and scattered light were taken according to Zhang et al. [11]. The experimental inversion method was used to obtain the attenuation coefficients for direct and scattered light. The optical analysis surface of the underwater target is set to fully absorb the ideal light-sensitive surface.

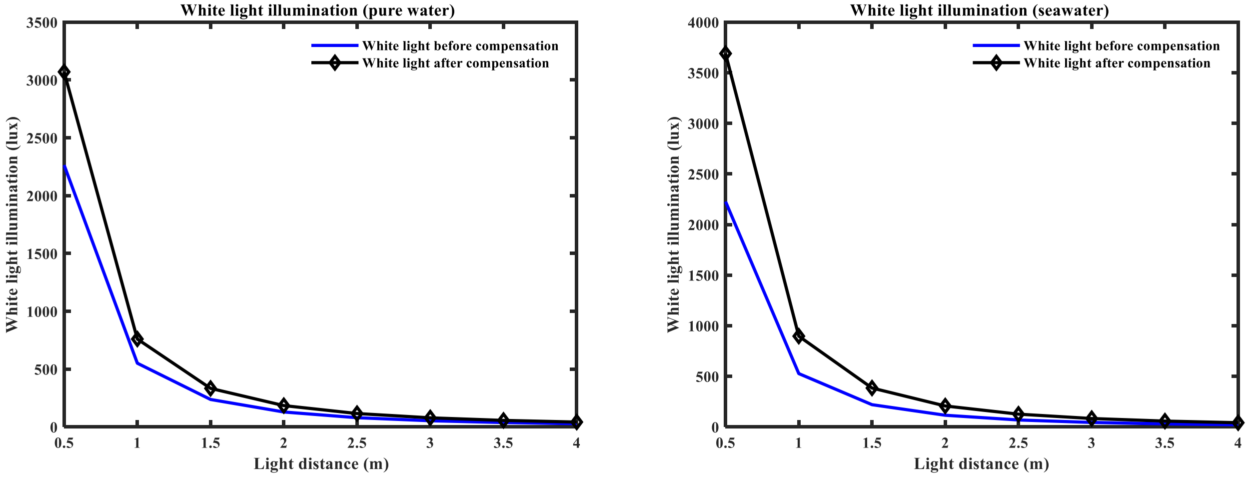
3.2. Attenuation effect

In pure water and seawater medium, the power and illuminance of the underwater target surface are obtained from the distance attenuation of red, green, blue, and white lasers.

Fig. 2(a) shows the relationship between the three-color powers, synthetic white laser powers, and light source distance under different water mediums. When the laser distance is increased to 4 m, the light power of red, green, blue, and white decays by 0.1142 W, 0.017 W, 0.008 W, and 0.139 W, respectively in pure water medium. The red, green, blue, and white light power decays by 0.1551 W, 0.0436 W, 0.0187 W, and 0.217 W, respectively in seawater medium. The attenuation of red light power is greater than that of green and blue light. In addition, the attenuation of the laser power of each color in seawater is greater than in pure water, indicating

Table 2
Illuminance of the synthetic white laser at the target before and after power compensation.

L/m		0.5 m	1 m	1.5 m	2 m	2.5 m	3 m	3.5 m	4 m
pure water	E/lux	2264	551	237	129	79	53	37	28
	E1/lux	3070	760	333	184	116	79	56	42
	ΔE	806	209	96	55	37	26	19	14
sea water	E_s/lux	2227	527	220	115	69	44	30	21
	$E1_s$/lux	3689	897	384	207	126	83	60	47
	ΔE	1462	370	164	92	57	39	30	26



（a） （b）

Fig. 4. White illuminance at the underwater target surface before and after power compensation: (a) pure water; (b) seawater.

that there are impurity particles in seawater, which have an absorption and scattering effect on light.

The illuminance in Fig. 2(b) can represent the energy decay effect, in which the laser transmission distance decays exponentially with illuminance. However, seawater has a "see-through window" for the green light and has excellent penetration capabilities, so the illuminance of green light is greater than red light and blue light. The illuminance of synthetic white laser consists of the three-color.

When the total synthetic white light power is only 450 mW, the light source can be transmitted up to 4 m, realizing longer distance lighting and efficient white laser light underwater use.

3.3. *Power compensation design*

Due to the attenuation of light in the water medium with the transmission distance, the power of the synthetic white laser is reduced at the underwater laser illumination target, and there is an error with the standard synthetic white laser at the output. The result is a reduction in illumination, which affects the actual observation and judgment of the target. Based on the law that the red, green, and blue light decays exponentially with light distance, the power of the three-color is compensated for every 0.5 m of transmission distance.

From Table 1, the three-color power value at 0 m is the reference value, which is the power value of the standard color temperature white laser. PR, PG, and PB result from the compensated three-color output power.

The power values for red, green, and blue light at distances from 0 m to 4 m were summarized in Table 1, and the curve changes were shown in Fig. 3(a). In pure water, the red, green, and blue light power values compensate from 0.218 W to 0.332 W, 0.150 W–0.164 W, and 0.085 W–0.193 W, respectively. In seawater, the red, green, and blue light power values compensate from 0.218 W to 0.374 W, 0.150 W–0.193 W, and 0.086 W–0.105 W, respectively. The light power compensation result for seawater is greater than for pure water at the same transmission distance because seawater is more turbid and weakens the energy of the light. In order to obtain a standard white light at the underwater target, the output light power should be increased as the transmission distance and the turbidity of the water increase.

Furthermore, from Fig. 3(b), we can also obtain the rate of change of power compensation for red, green, and blue light per 0.5 m in both water mediums. The power compensation value per 0.5 m for red light is greater than for green and blue light, indicating that the water medium attenuates the red wavelengths to a greater extent.

According to the illumination results before power compensation in Table 2, the illumination at the underwater targets in pure water and seawater decreases from 2264 lux to 28 lux and from 2227 lux to 21 lux as the transmission distance increases. Obviously, the longer the transmission distance, the greater the attenuation and the weaker the illumination of the underwater target surface.

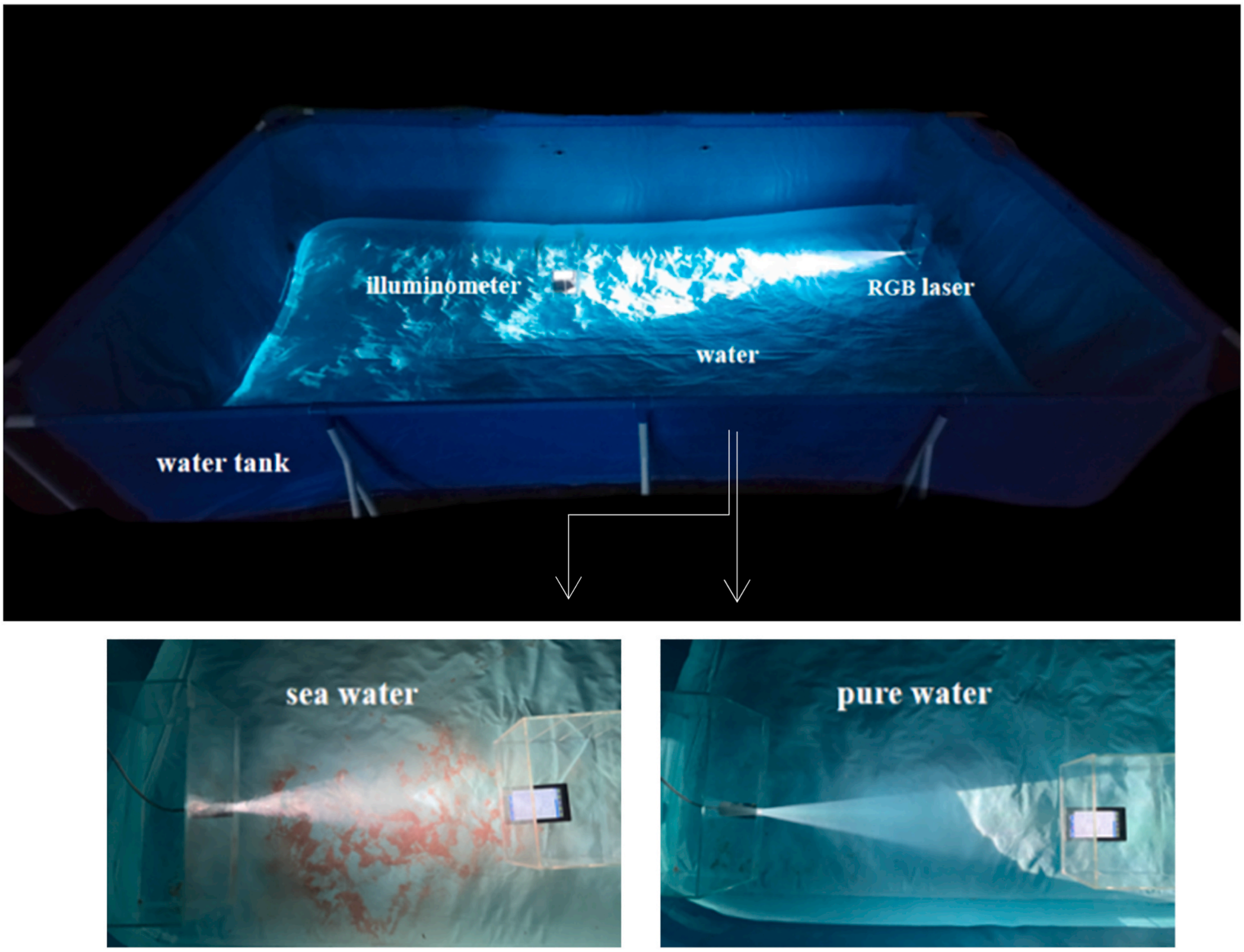
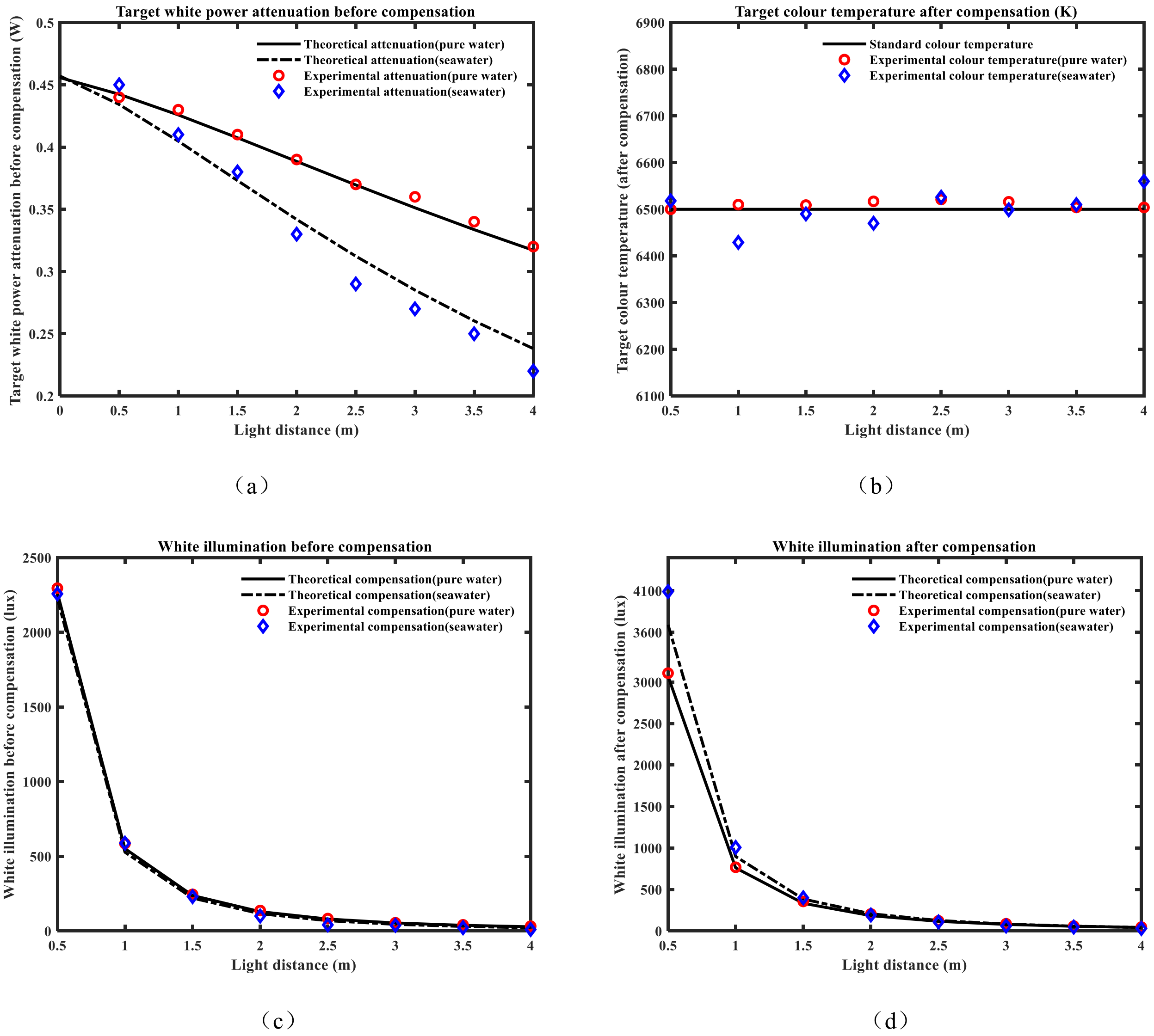


Fig. 5. White laser underwater illumination experiment.

Fig. 6. Laser control device.

Fig. 4(a) and (b) show comparative curves and three-dimensional plots of underwater target surface illumination in pure water and seawater. In both water conditions, the power-compensated illumination is better than before compensation. The greatest increase is achieved at a distance of 0.5 m, up to 806 lux and 1462 lux.

Table 2 and Fig. 4(a) and (b) shows that before power compensation, the luminosity under seawater is lower than that of pure water due to the influence of impurities in the seawater. After compensation for the three color powers, the white light power value at the output of the seawater medium is greater than that of the clear water. At each distance stage after compensation, the white illumination of seawater is greater than that of pure water, and standard white light is obtained. The three-color power compensation can adjust light color conveniently and thus can produce white light of the required color temperature at different underwater distances.



（a） （b）

（c） （d）

Fig. 7. Comparison of experimental with theoretical results for different water mediums: (a) target white power attenuation before compensation; (b) target color temperature after compensation; (c) white illumination before compensation; (d) white illumination after compensation.

This is the advantage of a three-color semiconductor laser as a source of underwater white light.

4. Underwater experiments

Experiments to measure the illuminance and color temperature of underwater target surfaces at different light distances in pure water and seawater medium. The experiments were carried out in a dark field environment with an ambient illumination of less than 1 lx. Optical instruments are shown in Fig. 5. The experimental pool is 4 m long, 3 m wide, 1 m high, and 1 m deep. Seawater source: Clearwater Bay, Lingshui Lizu autonomous county, Hainan Province, China (latitude and longitude: 109.87605, 18.40063). The three-color laser is the LWRGB-F-FTP laser (LaserWave, China), which has the advantages of being smaller, adjustable power, etc. The mirror barrel is connected to the fiber optic outlet, and the white light is finally output through the mirror barrel. The spectral illuminance meter (OHSP-350, Hopoocolor, China) measures the illuminance and color temperature of the white laser at the underwater target. The laser control device regulates the current of the red, green, and blue laser separately. The optical power meter (LI-P50W, LaserWave, China) is used to measure the required output monochromatic laser power. The white output laser is obtained by fixing the above three base color currents and coupling them via fiber optics.

The laser control device is shown in Fig. 6. Serial number 1 is the potentiometer that adjusts the current level. (Clockwise current increases, counterclockwise current decreases. The light can be emitted individually or in any combination). Serial number 2 is the status display lamp, when the switch is turned on, the laser enters into the self-test, when the self-test is normal, “Laser” lights up,

Table 3
Comparison of experimental with theoretical results for before compensation.

Before compensation (theoretical vs experimental)									
L/m		0.5 m	1 m	1.5 m	2 m	2.5 m	3 m	3.5 m	4 m
pure water	PW	0.44/0.44	0.42/0.43	0.40/0.41	0.38/0.39	0.36/0.37	0.35/0.36	0.33/0.34	0.31/0.32
	white illumination	2264/2295	551/585	237/245	129/137	79/83	53/55	37/41	28/32
sea water	PW	0.43/0.45	0.40/0.41	0.37/0.38	0.34/0.33	0.31/0.29	0.28/0.27	0.26/0.26	0.23/0.22
	white illumination	2227/2257	527/588	220/230	115/100	69/41	44/38	30/22	21/10

Table 4
Comparison of experimental with theoretical results for after compensation.

After compensation (theoretical vs experimental)									
L/m		0.5 m	1 m	1.5 m	2 m	2.5 m	3 m	3.5 m	4 m
pure water	color temperature	6500/6500	6500/6510	6500/6509	6500/6517	6500/6541	6500/6516	6500/6504	6500/6504
	white illumination	3070/3107	760/768	333/356	184/205	116/122	79/87	56/59	42/47
sea water	color temperature	6500/6518	6500/6429	6500/6490	6500/6470	6500/6526	6500/6499	6500/6510	6500/6560
	white illumination	3689/4090	897/1007	384/400	207/192	126/109	83/60	60/47	47/30

otherwise it does not light up. Serial number 3 is the switch, which is responsible for controlling the power on and off. The laser control device regulates the current of the red, green, and blue laser separately. The optical power meter (LI-P50W, LaserWave, China) is used to measure the required output monochromatic laser power.

The laser's drive current is changed to adjust the three colors' power output and to compensate for the power at the phase distance, measuring the illuminance and color temperature of the synthetic white laser. The experimental results were obtained by averaging five measurements.

The comparison between the theoretical target white power attenuation and the experimental target white power attenuation for different water mediums is shown in Fig. 7(a) and Table 3. The white power attenuation relative errors in pure water and seawater were 2.4% and 3.8%, respectively. The comparison between the standard 6500K color temperature and the compensated experimental target color temperature for different water mediums is shown in Fig. 7(b) and Table 4. The target color temperature relative errors in pure water and seawater medium were 0.16% and 0.43%, respectively. In addition, the theoretical and experimental illumination errors before and after compensation are shown in Fig. 7(c) and (d) and Table 4. Before compensation, the relative illumination errors in pure water and seawater were 6.37% and 22.15%, respectively. After compensation, the illumination errors in pure water and seawater were 6.01% and 15.14%, respectively. By comparing the data before and after the illumination compensation, the error is reduced by 0.36% in pure water and 7.01% in seawater.

Error in seawater is greater than in pure water, indicating that uncontrollable seawater impurities affect the light transmission. The experimental illumination is slightly greater than the theoretical calculation. This is because the light energy outside the experimental system is not negligible and causes errors. In addition, the theory only considers a single scattering. The body of water scatter several times as the laser transmission distance increases, and a few photons are distributed beyond the measurement range with each scattering, which explains the result that the greater the distance of the light source, the smaller the error. The waterproof equipment of the laser and illuminance meter affects the actual color temperature and illumination results, which is a cause of the error. The optical instruments are placed manually. Another cause of the error is that the instrument does not ensure positive light incidence during the measurement.

5. Conclusion

This paper uses the three-color semiconductor laser as the underwater illumination source. The power, brightness, and illuminance of the monochromatic and synthetic white laser at the underwater target surface decrease as the laser transmission distance increases. The white laser color temperature and illuminance of the target surface are obtained at underwater distances using the three-color power compensation method in clear water and seawater medium. In both water mediums, errors between the experimental and theoretical results for target color temperature and illuminance are not more than 0.43% and 22.15%, respectively.

This power-compensated synthetic white laser light source has both the advantages of long-range underwater detection and the spectral advantages of LED white light sources. It is a new laser technology for underwater lighting. In addition, the output power of the three single-color lasers can be controlled to achieve power-adjustability for different transmission distances, obtain a white laser light source for specific needs, and optimize the white light characteristics in underwater lighting applications. It proves the superiority of white lasers as an underwater illumination source, which is conducive to promoting subsequent research on underwater optical imaging systems. It is of great significance to the development of underwater detection technology.

Author contribution statement

Wei-Yu Cai: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Zi-Qi Jiang: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Xiao-Mei Liu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Hua Liu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Xiao-Juan Ma; Rong-Nian Tang: Contributed reagents, materials, analysis tools or data.

Xiang Li: Performed the experiments; Analyzed and interpreted the data.

Data availability statement

Data will be made available on request.

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.

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References

[1] M.B. Lucena, T.C. Mendes, M.C. Barbosa, C. Cordeiro, L.M. Eggertsen, C.E.L. Ferreira, Does the colors of light matter? Testing different light color in nocturnal underwater visual censuses, Mar. Environ. Res. 166 (2021), 105261.
[2] B.K. Lubsandorzhiev, R.V. Poleshuk, B.A.J. Shaibonov, Y.E. Vyatchin, LED based powerful nanosecond light sources for calibration systems of deep underwater neutrino telescopes, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 602 (2009) 220–223.
[3] S.C. Shen, H.J. Huang, C.C. Chao, M.C. Huang, Design and analysis of a high-intensity LED lighting module for underwater illumination, Appl. Ocean Res. 39 (2013) 89–96.
[4] Z. Qian, X. Cui, Z. Wang, G. Zhou, R. Lin, E. Gu, P. Tian, Characteristics of underwater lighting based on white LEDs, Optik 245 (2021).
[5] G. Li, Q. Zhou, G. Xu, X. Wang, W. Han, J. Wang, G. Zhang, Y. Zhang, Z.a. Yuan, S. Song, S. Gu, F. Chen, K. Xu, J. Tian, J. Wan, X. Xie, G. Cheng, Lidar-radar for underwater target detection using a modulated sub-nanosecond Q-switched laser, Opt Laser. Technol. 142 (2021).
[6] Y. Yang, S. Zhuang, B. Kai, High brightness laser-driven white emitter for Etendue-limited applications, Appl. Opt. 56 (2017) 8321–8325.
[7] M. Cantore, N. Pfaff, R.M. Farrell, J.S. Speck, S. Nakamura, S.P. DenBaars, High luminous flux from single crystal phosphor-converted laser-based white lighting system, Opt Express 24 (2016) A215–A221.
[8] J.Y. Tian, J. Zhang, H.Y. Peng, W. Wang, Y.X. Lei, L.J. Wang, High power white laser source based on RGB diode laser, Chin. J. Lumin. 40 (10) (2019) 1254–1260 (in chinese).
[9] Y. Yang, B. Zheng, L.Y. Kan, J. Yu, J.C. Wang, 3D color reconstruction based on underwater RGB laser line scanning system, Optik 125 (2014) 6074–6077.
[10] Z.Q. Jiang, X.M. Liu, F.H. Cai, D. Zhang, W.Y. Cai, H. Liu, Imaging comparison experiment of an underwater imaging system with a semiconductor white laser, a monochromatic laser and an LED white light as the light source, Chinese Optics 16 (2023) 466–478.
[11] L. Zhang, C.D. Sun, J.H. He, Impact of light source angle on imaging quality of underwater imaging systems, J. Appl. Optics 31 (2010) 579–583 (in chinese).
[12] Z. Zeng, S. Fu, H. Zhang, Y. Dong, J. Cheng, A survey of underwater optical wireless communications, IEEE Communications Surveys & Tutorials 19 (2017) 204–238.
[13] J. Yang, Z. Liu, B. Xue, Z. Liao, L. Feng, N. Zhang, J. Wang, J. Li, Highly uniform white light-based visible light communication using red, green, and blue laser diodes, IEEE Photon. J. 10 (2018) 1–8.
[14] M. Sun, J. Zhu, Y. Bi, Color matching and real-time color temperature control in laser display, Chin. J. Lasers 47 (2020), 0704001 (in chinese).
[15] X. Zhao, T. Jin, S. Qu, Deriving inherent optical properties from background color and underwater image enhancement, Ocean Eng. 94 (2015) 163–172.

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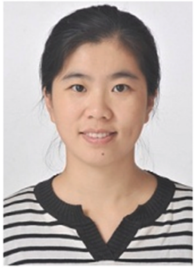

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