Experimental Demonstration of 0.4-meter Ranging Through Underwater Scattering with 20-mm Resolution Using z-dependent Angular Rotation of a Spatially Structured Beam

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Abstract: We experimentally demonstrate a 0.4-meter underwater optical ranging with a 20-mm resolution through underwater scattering (extinction coefficient γ up to 9.4 m^{-1}) utilizing the z-dependent angular rotation of a spatially structured beam.

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1. Introduction

There has been increased interest in using optical approaches for ranging applications in underwater moving platforms [1,2]. This is motivated by the relatively limited accuracy of low-loss sonar approaches, and the ability for blue-green light to have low beam divergence and small wavelength resolution over a distance of many meters [3,4].

Typical optical ranging approaches measure the time-of-flight of a transmitted pulse that is reflected from a target [5]. Unfortunately, underwater environments can be highly scattering, such that the optical pulse can spread in time and the ranging performance becomes limited [6,7].

A potential ranging approach might be to use the spatial domain as opposed to the temporal domain, with the possibility that the amplitude and phase spatial distribution of the beam might be more tolerant to highly scattering media [8,9]. The concept of using spatially structured beam for ranging could involve the feature that the angular rotation of the spatial structure changes with different propagation scenarios [10,11].

In this paper, we experimentally demonstrate 0.4-meter ranging through underwater optical scattering (extinction coefficient up to 9.4 m^{-1}) with a 20-mm resolution using angular rotation of a spatially structured beam. We generate a spatially structured beam combining two Bessel modes with (a) different orbital angular momentum (OAM) orders which leads to a petal-like intensity profile [10-12] and (b) different longitudinal wavenumbers and thus the petal-like intensity profile rotates as the beam propagates [10]. Such spatially structured beam is generated, propagates through underwater scattering and reflected back. Subsequently, the reflector distance is retrieved by measuring the petal-like intensity profile of the reflected beam using a camera. The experimental results show that, for the reflector distances ranging from 0 to 0.4 m, (a) through clean water, the measurement error is <10 mm, (b) through underwater scattering with extinction ratio γ < 9.4 m^{-1}, the measurement error is <20 mm, and (c) when the scattering strength increases (γ increases from 1.8 m^{-1} to 9.4 m^{-1}) which results in a relatively higher scattering-induced power loss, the maximum exposure time of the camera detector for a sufficient beam detection increases from ~1.6 ms to ~800 ms with a fixed transmitted optical power of ~-30 dBm.

2. Concept

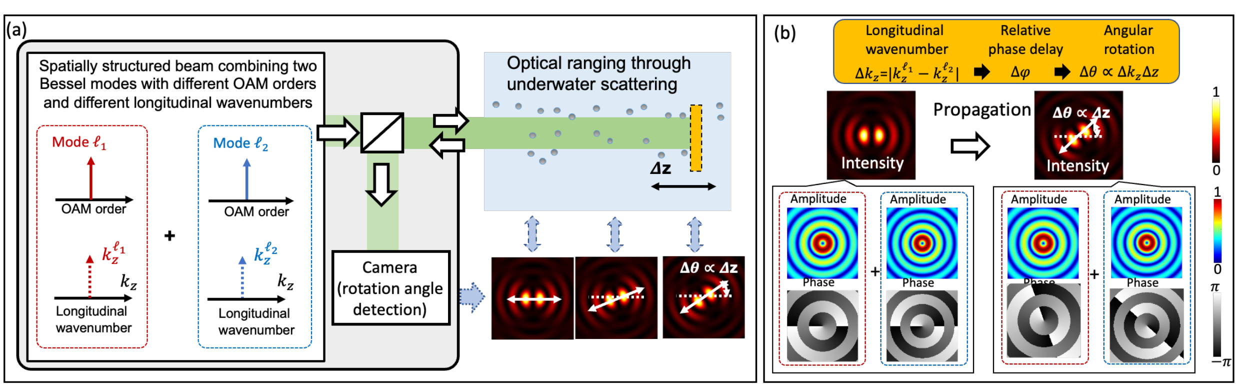

Fig. 1. (a) Concept of utilizing angular rotation of spatially structured beam for underwater optical ranging. The reflector distance is retrieved by measuring the rotating angle of petal-like intensity profile of the reflected beam. (b) Concept of the z-dependent angular rotation of spatially structured beam. The generated spatially structured beam carries two Bessel modes with different orbital angular momentum (OAM) orders and different longitudinal wavenumbers.

Figure 1 shows the concept of utilizing z-dependent angular rotation of spatially structured beam for underwater optical ranging. The transmitted spatially structured beam consists of two Bessel modes ($J_{\ell_i}\left(k_r^{\ell_i} r\right) e^{i\ell_i\theta} e^{ik_z^{\ell_i}z}$, $i = 1$ or 2) with different OAM orders (ℓ_1 and ℓ_2) as well as different longitudinal wavenumbers $k_z^{\ell_1}$ and $k_z^{\ell_2}$. The value of OAM order indicates the number of 2π phase shifts around the center of the beam's phase profile. Due to spatial interference between the two modes with the different OAM orders, a petal-like intensity profile is generated as shown in Fig.1(b). The angular rotation of the petal is linearly proportional to the relative phase delay between these two modes [12]. To generate z-dependent angular rotation, the longitudinal wavenumber difference $\Delta k_z = |k_z^{\ell_1} - k_z^{\ell_2}|$ is introduced between the two modes [10]. When the beam propagates, such Δk_z induces a z-dependent relative phase delay between the two modes and thus leads to a z-dependent angular rotation of the intensity profile [10]. Utilizing such z-dependent angular rotation feature of the structured beam after propagation, the distance of the reflector could be retrieved by measuring the corresponding rotating angle as shown in Figure 1(a). The relationship between the angular rotation ($\Delta\theta$) and reflector distance (z) can be represented as $\Delta\theta = \frac{2z\Delta k_z}{n_{water}(|\ell_1 - \ell_2|)}$, where n_{water} is the refractive index of the underwater medium which is calibrated before ranging remeasurement [10,11].

3. Experimental setup and results

Figure 2(a) shows the experimental setup of utilizing z-dependent angular rotation of spatially structured beam for optical ranging through underwater scattering. A spatial light modulator is programmed with a specific phase pattern to convert a free-space Gaussian beam (beam size of ~7 mm) to the desired spatially structured beam. ℓ_1, ℓ_2, and Δk_z are set to +1, -1 and 6.2 m^{-1}, respectively. A 4-f spatial filter is used to filter out the unmodulated light from the SLM. Subsequently, the generated spatially structured beam is then sent to a water tank, propagates through the underwater medium, gets reflected by a reflector, propagates back along the same optical path and the reflected beam is captured by a camera for angular rotation detection. The reflector can be moved along the optical path with a traveling range of up to 0.4 m. The step size of the moveable reflector distance is fixed as 5 mm. The optical power of the spatially structured beam before entering the water tank is set to ~-30 dBm. The scattering medium is emulated by a diluted commercial antacid solution (Maalox®) [13]. Different concentration of the Maalox® solution results in different extinction coefficient γ of the scattering medium. The value of γ can be measured by characterized by propagating a collimated beam through the scattering medium with a path length of L and subsequently measuring the corresponding optical power ($P_{out} = P_{in}e^{-\gamma L}$) based on Beer's law [13]. During the angular rotation measurement, the collimated beam for extinction coefficient characterization is blocked out to reduce the background noise to the camera.

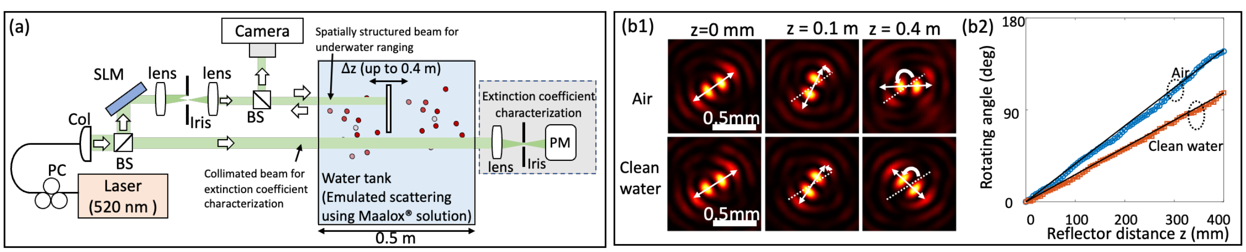

Fig. 2. (a) Experimental setup of the underwater ranging utilizing z-dependent angular rotation of the spatially structured beam. PC: polarization controller. Col: collimator. BS: beam splitter. SLM: spatial light modulator. PM: optical power meter. Measured (b1) intensity profiles and (b2) rotating angle of the generated spatially structured beam (Δk_z = 6.2 m^{-1}) propagated through air or clean water at different reflector distances. The solid black lines indicate the linear relationship between the angular rotation (θ) and reflector distance (z) in the air and clean water.

Figure 2(b1) shows the measured beam profiles at different reflector distances. The rotating angle of the reflected spatially structured beam changes at different reflector distances. At the same reflector distance, the rotating angle of the same transmitted beam (*i.e.*, same Δk_z) in air and clean water is different. Figure 2(b2) shows that the measured slope of the distance-dependent rotating angle between the case of air and clean water is ~147°/400mm and ~106°/400mm, respectively. The difference of rotating angle between these two cases indicates that angular rotation ($\Delta\theta$) at given propagation distance changes in the medium of different refractive index [11].

Figure 3(a1) shows the measured beam profiles through underwater scattering with different extinction coefficients γ. When the extinction coefficient γ increases from 1.8 m^{-1} to 9.4 m^{-1}, the angular rotation and the corresponding measured distance of the reflected beam remains similar at the same propagation distance as shown in Fig. 3(a1-a2). This is to be expected since in our scattering cases with a small-field-of-view system, the ballistic scattering dominates, leading to that (a) the relative phase delay between the two modes tends not to be distorted during propagation and thus (b) the petal-like intensity profiles maintain its shape and angular rotation [8, 14, 15].

Figure 3(a3) shows the measured beam center when the reflector moves from z =0 m to 0.4 m. Such beam wandering effect is mostly compensated after the beam detection. Figure 3(a4) shows the measurement error under various scattering strengths. In clean water, the measurement error at the reflector distance from 0 to 400 mm is <10 mm. Through underwater scattering with the increasing scattering strength (*e.g.*, γ increases or z increases), the measurement error tends to increase. With the extinction coefficient γ up to 9.4 m^{-1} and reflector distance up to 400mm, the measurement error is <20 mm. It should be noted that the exposure time of the camera is automatically adjusted during the range measurement. The increased measurement error could potentially be due to that when the extinction coefficient (γ) increases or propagation distance (2z) increases; (i) scattering-induced power loss increases; (ii) longer exposure time is needed to ensure sufficient beam detection; (iii) the beam wandering affects the beam detection (*e.g.*, "blurred" intensity profile in measurement) for a longer exposure time, and thus (iv) a relatively higher measurement error is observed.

Figure 3(b1) shows the adjusted exposure time under various extinction coefficients. When γ increases from 1.8 m^{-1} to 9.4 m^{-1}, the maximum exposure time of the camera detector increases from ~1.6 ms to ~800 ms with a fixed transmitted optical power of ~-30 dBm. It should be noted that the increased exposure time could potentially affect the refresh rate of the measurement in a practical ranging system. Figure 3(b2) shows the measured beam profile (normalized) through underwater scattering (γ = 6.2 m^{-1}) with/without adjusting exposure time. As the reflector distance increases and the corresponding scattering-induced power loss increases, the beam profile is less likely to show a petal-like shape if the exposure time is not sufficient for beam detection. Figure 3(b3) shows that, through underwater scattering (γ = 6.2 m^{-1}), the case with a fixed exposure time of 0.2 ms tends to fail to retrieve the distance when z increases to ~200 mm.

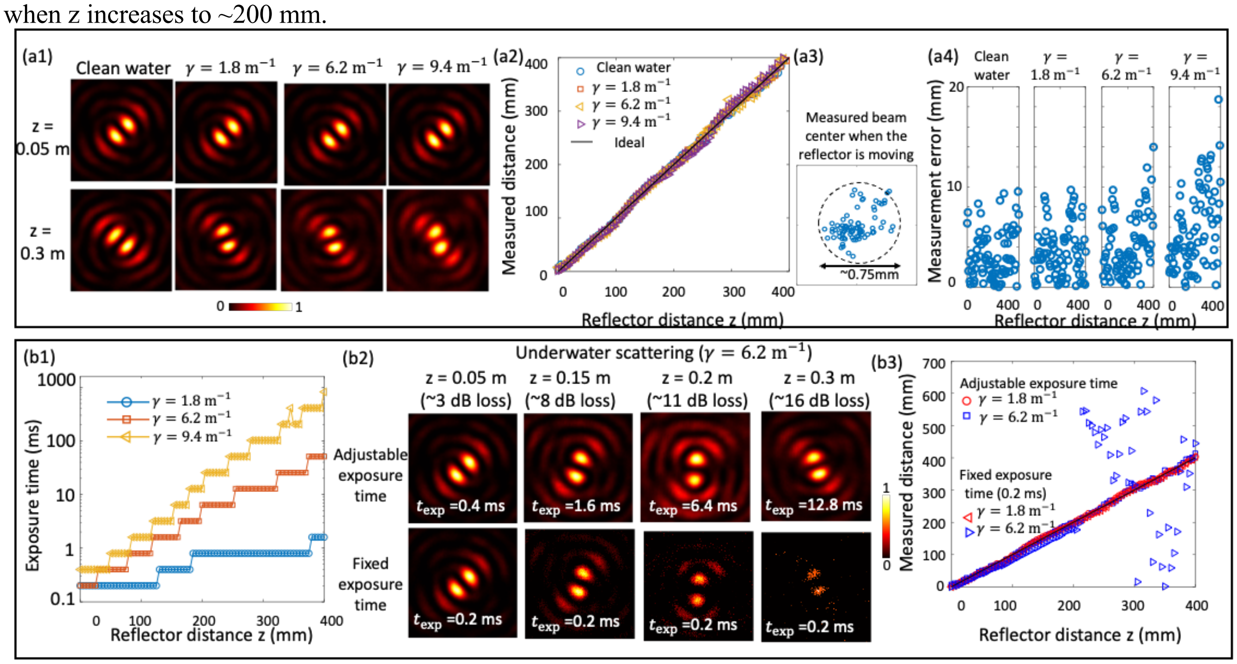

Fig. 3. (a1) Measured intensity profiles of the reflected spatially structured beam through scattering with different extinction coefficients at different reflector distances. (a2) Measured distance with different extinction coefficients. (a3) Measured beam center when the reflector is moving. Such beam wandering is measured and compensated after beam detection. (a4) Measurement error as a function of reflector distance. (b1) Exposure time (adjustable) of the camera for different extinction coefficients at different reflector distances. (b2) Measured intensity profiles of the reflected spatially structured beam with and without adjusting exposure time. The inset number shows the exposure time for capturing the intensity profile. (b3) Comparison of the distance measurement with and without adjusting exposure time.

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References

[1] L. Paull et al., IEEE J. Ocean. Eng. 39, 131 (2014)
[2] B. Zha et al., Opt. Comm. 431, 81 (2019)
[3] X. Lurton, London: Springer. (2002).
[4] S. Q. Duntley et al., J. Opt. Soc. Amer. 53, 214 (1963).
[5] P. Zhan et al., Appl. Phys. Lett., 104, 769 (2014).
[6] J. Snow et al., Proc. SPIE Ocean Opt. XI 1750, 418 (1992).
[7] B. Cochenour et al., IEEE J. Ocean. Eng. 38, 730 (2013).
[8] K. S. Morgan et al., J. Opt. 18, 104004 (2016).
[9] A. Jantzi et al., JOSA A 38, 10 (2021).
[10] A. H. Dorrah et al., Phys. Rev. A 93, 063864 (2016).
[11] A. H. Dorrah et al., Light Sci. Appl. 7, 1 (2018).
[12] G. Xie et al., Opt. Lett. 42, 991 (2017).
[13] B. Cochenour et al., Opt. Lett. 35, 2088 (2010).
[14] N. A. Ferlic et al., App. Opt. 61, 6383 (2022).
[15] R. Zhang et al., Opt. Lett 44, 691 (2019).