Attenuation of beams with orbital angular momentum for underwater communication systems

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***Abstract*— Beams carrying orbital angular momentum (OAM) have been shown to possess unique properties in scattering environments. However, a limited source of quantifiable data is available on the propagation properties of these beams through turbid water in the context of underwater optical communication systems. In this work we investigate differences in attenuation between beams with and without OAM in line-of-sight geometries.**

Keywords— ***attenuation; orbital angular momentum; scattering; underwater communication***

I. Introduction

There is a growing interest for underwater optical links utilizing laser sources as an alternative to acoustics due to their potentially high bandwidths, data rates, stealth, and significantly lower impact on marine life. While wavelengths typically used for free space communication links, such as radio and microwaves, transmit poorly underwater, light in the blue/green range has been found to exhibit minimal absorption through water and therefore is an attractive alternative choice [1,2].

Scattering due to particulates is a major concern for these underwater optical links. It has been shown that system, geometry, and environmental variables can all contribute to the amount of attenuation and temporal dispersion exhibited by the link [3,4]. This attenuation results in a tradeoff between the range and bandwidth of the signal. Study of the non-scattered and multiple scattered components provides insight into the underlying physics of underwater propagation, which can then be used to optimize the range and bandwidth performance of underwater optical links, including Gaussian beams through turbid media, though there is still little quantitative data to fully explain this behavior.

Spatial division multiplexing (SDM) is one method that can be used to improve range and bandwidth limitations and has been demonstrated in free space and underwater communications [5-8]. One can utilize different Laguerre Gaussian beams known as vortex beams, to spatially multiplex data streams. These vortex beams have a phase given by $\exp(i\ell\phi)$, where ℓ is the azimuthal mode index. This helical profile indicates that the beam is physically orbiting about its propagation axis, giving the beam orbital angular momentum (OAM) proportional to ℓ [9]. This mode, ℓ, can be a positive or negative integer. The magnitude indicates the number of phase fronts, while the sign indicates clockwise or counterclockwise rotation. Additionally, there is a central phase discontinuity in this phase profile, resulting in a helical phase front (Fig 1) from which interference results in an annular intensity profile. It is important to note that OAM is not a result of circular polarization of these beams. These different OAM modes are orthogonal which makes the SDM link possible.

Spatially multiplexing these OAM modes enables a system to use a single wavelength rather than a broad range of wavelengths as in wavelength division multiplexing (WDM). Not only does this enable the signal wavelength to be tailored for minimal absorption through different bodies of water, but it also allows for the minimization of the optical filter bandwidth at the receiver to maximize solar rejection. This method of data multiplexing therefore is much more attractive than WDM in underwater systems. Additionally, beams with OAM have been demonstrated to possess unique properties, such as self-healing capabilities, and can be used as optical tweezers to manipulate small particles and even as a window to measure a weak optical signal in the presence of an intense superimposed beam [10-12]. Therefore, Wang, *et al.* recently suggested that optical vortex beams with large OAM values may exhibit higher transmission relative to those with lower and no OAM through highly scattering media (Fig 2) [13].

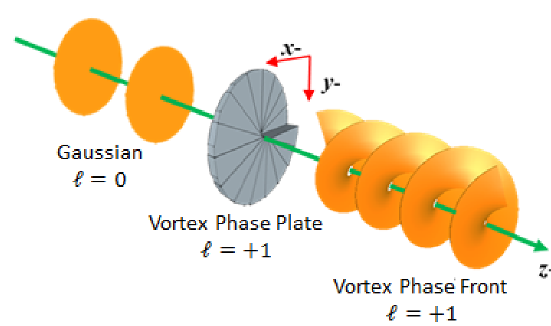

Fig. 1. Generation of a Laguerre Gaussian vortex beam using a 16-step phase plate.

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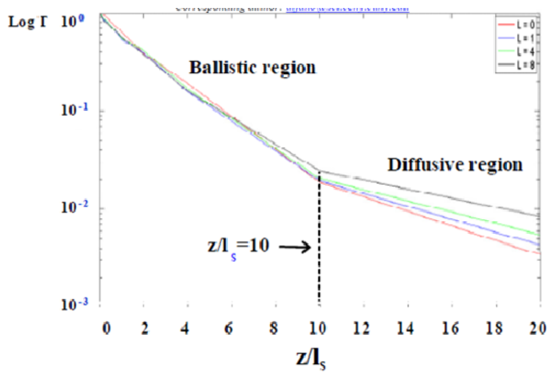

Fig. 2. Transmission of beams with different OAM modes through a scattering medium[10].

The measurements taken by Wang used a setup not fully applicable to underwater communications, and thus the goal of this paper is then two-fold. First, the attenuation of vortex beams with differing OAM modes is compared using a geometry and environment more applicable to underwater communications. Second, it is desirable to understand whether beams with OAM exhibit different properties relative to Gaussian beams such that they may provide a performance improvement for the underwater link. This will provide justification for the use of vortex beams in underwater communications systems.

II. Experimental Design

To verify whether or not OAM beams attenuate at different rates, the set-up shown in figure 3 was used. Here, a diode pumped solid state 532nm laser is transmitted into a water tank measuring 3.6 m long. Mirrors are used to send a vortex beam through the center of the tank and then collected with a 2" diameter photomultiplier tube (PMT) with a 13.13° full angle field of view. The output DC voltage from the PMT was measured with a digital multimeter. By analyzing the rates of attenuation versus turbidity for beams with varying orders of OAM, and comparing to previously well characterized results for Gaussian beams [9,10], any potential propagation differences between beams with and without OAM will be uncovered.

The vortex beams were generated using a corresponding phase plate with $l = 0$ (Gaussian), $l = 8$, and $l = 16$. These phase plates have a 16 step, azimuthally varying height profile (Fig. 1) etched approximately 1.15 microns into a 1 mm thick fused silica wafer using photolithographic methods. This azimuthal height profile generates the phase delay of $\exp(i\ell\phi)$. Collimated coherent light was then passed through the center of a phase plate and was then directed through the turbid water.

Water turbidity was varied by adding Equate antacid to the test tank, which is known to have similar scattering properties to turbid ocean water [3]. The attenuation coefficient, c, was measured in-situ with an AC-9 transmissometer and varied from $0.062/\text{m} < c < 5.64/\text{m}$ ($0.23 < cz < 20.66$). Measurements were taken at each turbidity increment for each vortex beam. In order to account for the dynamic range of the PMT, the laser power was adjusted and ND filters were changed periodically. The data was then scaled accordingly using calibration measurements taken before and after each range change.

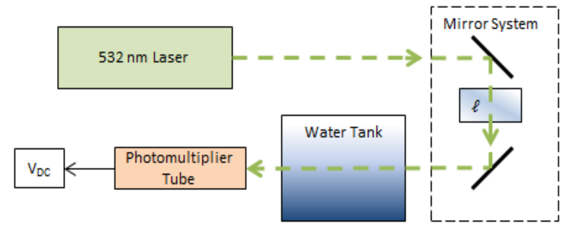

Fig. 3. Experimental setup to compare the attenuation of beams with and without OAM, ℓ – spiral phase plate, V_{DC} – DC output

I. Results and Discussion

Figure 4 plots the attenuation (relative to clear water of c=0.062/m) versus attenuation length for each OAM charge. Also plotted is Beer's Law, which describes the attenuation of non-scattered light. As has been previously observed [3], attenuation can be characterized by two regimes. In the first regime, the ballistic region, non-scattered light dominates and the attenuation follows Beer's Law. In the second regime, the diffusive region, multiply scattered light scatters back through the receiver aperture and field of view, resulting in a lower rate of attenuation. The transition between these two regimes is influenced both by properties of the scattering particles as well as system parameters, and is typically given by the diffusion length. The current transition point in these experiments is consistent with that of other reported underwater measurements.

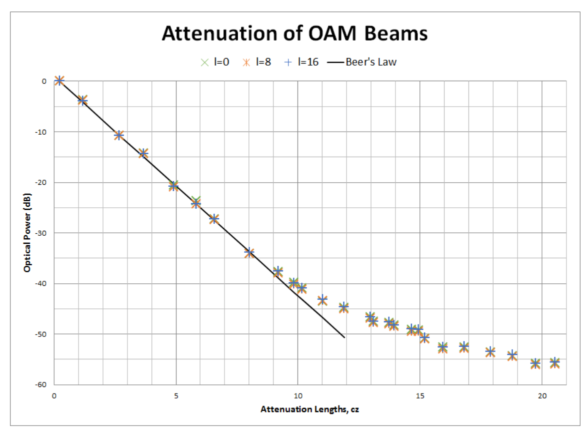

Fig. 4. Attenuation curves for $l = 0$ (Gaussian), $l = 8$, and $l = 16$ through turbid water.

These results differ from that in Wang, *et al.*. Further scrutiny into their data shows that only one data point was taken beyond the transition point between the non-scattering and multiple scattering regimes. Noise in the measurement could therefore skew the true nature of the attenuation in the multiple scattering regime observed by Wang. Alternatively, the differences between these two works might also be attributed to differences in the scattering particle, as the irregular shapes and particle size distributions of the antacid (typically Magnesium Hydroxide) are likely to differ to the calibrated beads used by Wang. This is certainly an area worthy of further investigation.

III. Conclusions

In this paper, the attenuation of beams with OAM propagating underwater is studied. It was observed that the vortex beams exhibit the same amount of attenuation as Gaussian beams in both the ballistic and diffusive regions, contrary to other reported experiments. By using OAM to multiplex data, SDM systems can be designed using a single wavelength which can have several potential benefits over WDM systems. In future works, the temporal response of OAM with high frequency modulation up to 1.0 GHz will be studied underwater to demonstrate a high speed underwater link using OAM to further explore the current limits of these systems.

IV. Acknowledgment

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References

1. G. M. Hale and M. R. Querry, "Optical constants of water in the 200-nm to 200-µm wavelength region," *Applied Optics*, vol. 12, no. 3, pp. 555-563, 1973.
2. R. M. Pope, *et al*. "Absorption spectrum (380–700 nm) of pure water. II. Integrating cavity measurements." Applied optics 36.33 (1997): 8710-8723.
3. B. M. Cochenour, *et al*,. "Characterization of the beam-spread function for underwater wireless optical communications links," *IEEE J. Ocean. Eng.*, vol. 33, no. 4, pp. 513-521, Feb. 2009.
4. B. M. Cochenour, *et al*., "Temporal response of the underwater optical channel for high-bandwidth wireless laser communications," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 730-742, Oct. 2013
5. P. Martelli, et al. "Free-space optical transmission with orbital angular momentum division multiplexing." Electronics letters 47.17 (2011): 972-973.
6. G. Gibson, *et al*. "Free-space information transfer using light beams carrying orbital angular momentum." Optics Express 12.22 (2004): 5448-5456.
7. J. Baghdady, *et al*. "Spatial multiplexing for blue lasers for undersea communications." SPIE Defense+ Security. International Society for Optics and Photonics, 2015.
8. K. S. Morgan, *et al*. "Design and fabrication of diffractive optics for orbital angular momentum space division multiplexing." SPIE OPTO. International Society for Optics and Photonics, 2015.
9. Allen, Les, et al. "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes." Physical Review A, Vol. 45, No. 11, pp. 8185-8189, 1992
10. J. E. Curtis, *et al.* "Dynamic holographic optical tweezers," *Optics Communications,* vol. 207, no. 1, pp. 169-175, Jun. 2002.
11. D. Palacios, *et al.,* "Observed scattering into a dark optical vortex core," *Physical review letters*, vol. 88, no. 10, pp. 103902, 2002.
12. M. V. Vasnetov, *et. al.*, "Self-reconstruction of an optical vortex," *JETP Lett,*. vol. 71, no. 4, pp. 130-133, Feb. 2000. W. B. Wang, *et al*. "Propagation and transmission of optical vortex beams through turbid scattering wall with orbital angular momentums," SPIE BiOS, pp. 931805-931805, Intl. Society for Optics and Photonics, 2015.