A Chip-based Orbital Angular Momentum Transceiver for Underwater Optical Communications

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Abstract: We demonstrate an on-chip orbital angular momentum transceiver operating at visible wavelengths for high-bandwidth low-loss underwater optical communications. Our device achieves an average crosstalk of better than 8 dB from testing in air.

1. Introduction

Underwater communications often utilize sonar technologies that are long-range but low-bandwidth—or optical technologies that are high-bandwidth but short-range. Increasing the range of underwater optical communications is of great interest, however, the main challenge is that water greatly attenuates light propagation, through a combination of optical absorption and scattering. To minimize these losses, blue-green wavelengths are often used to take advantage of their reduced attenuation in typical water conditions [1], where transmission is still limited to around 100 m. Recent work has shown that Laguerre-Gaussian beams carrying orbital angular momentum (OAM) have higher transmission in turbid water conditions compared to traditional Gaussian beams [2]. Such OAM beams contain an azimuthal phase gradient producing twisted wave fronts. Using integer numbers of 2π phase wraps results in a set of integer charge states that form an orthogonal basis, which can be used to spatially multiplex many OAM beams to increase data bandwidth.

In this work, we present our recent progress developing an integrated transceiver module operating at a wavelength of 532 nm for encoding/decoding OAM states for underwater communication. OAM states can be prepared and decoded in several ways including using spatial light modulators and phase-plates [3] or by using phase-wrapping photonic circuits [4]. We employ the latter approach, which offers a compact and manufacturable means to realize these transceivers, all within a small chip-scale package. Fig. 1 outlines our device design, which uses lenses to direct OAM beams between underwater transceiver modules. Each module consists of a photonic integrated circuit that transposes OAM beams with charge states of $-m$, $-m+1 \ldots +m$ into light propagating onto one of the $2m+1$ output waveguides. When used as a receiver, this mode-sorting approach avoids the losses that occur when using a series of beam splitters with discrete phase-plates of different charge, and is thus scalable to higher charge states without incurring additional losses.

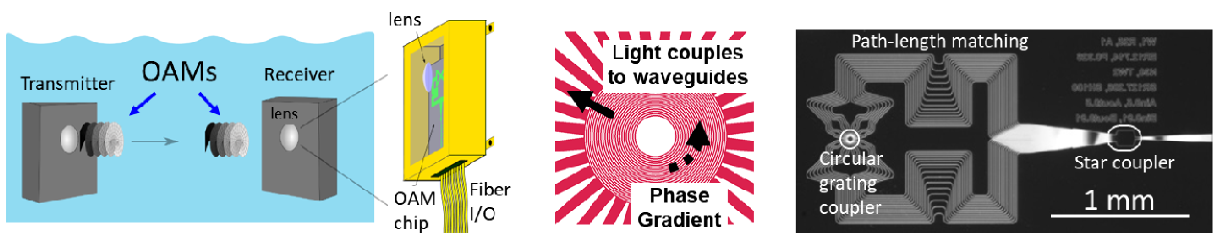

Fig. 1. Module, with optical fiber packaging and an integrated lens, acting as either a transmitter or receiver (left). Each module consists of an OAM chip with a circular grating coupler (center), path-length matched waveguides, and a star coupler (right).

2. Design

Our design consists of three key elements: a grating coupler, a network of pathlength-matched waveguides, and a star coupler. When used as an OAM receiver, light in an OAM state is incident on a circular grating coupler, which scatters the light into 32 radially-oriented waveguides. These waveguides sample the phase profile around the OAM beam and maintain this phase relationship using a network of pathlength-matched waveguides, which effectively unwraps the circular gradient to form a linear gradient. To perform the OAM-sorting operation, the light is sent to a star coupler where the linear phase gradient steers the light into different output ports corresponding to the incident OAM state. These output ports are sent to a series of output waveguides at the edge of the chip, where each output corresponds to a different OAM charge state ($-m$ to $+m$). As our OAM chips operate the same in both the forward and backward directions this approach can be used as a transmitter, a receiver, or a bidirectional transceiver. Our integrated-photonic approach is scalable for accessing higher-order OAM charge states by simply adding more waveguides to both the circular grating coupler and the star coupler. Additional waveguides are needed in the circular grating couplers to better sample the faster spatially varying phase profiles of higher-order OAM states.

3. Results and Conclusions

Measurements of device performance are shown in Fig. 2. Here, we test the transmitter functionality by interfering light emitted from the OAM chip with a Gaussian free-space beam (Fig. 2a) imaged on a camera. The inset in Fig. 2b displays the interferogram, which shows the twisted phase front. To demonstrate receiver mode, we prepare different OAM charge states using a series of OAM phase plates. As the chip uses TE-polarization that is converted to azimuthal polarization by the circular grating coupler, we include a vortex polarization plate to convert our beam from linear to azimuthal polarization (Fig. 2c). We then couple these free-space beams into the OAM chip and read out the charge state by observing the different waveguides at the facet of the chip. Intensity measurements from the receiver-mode tests show that the measured output state correlates well with the known the input state over the range from $m = -2$ to $+2$, with around 8 dB average crosstalk. The design of our grating couplers are critical to the performance of our device. To match the numerical aperture of the incoming OAM beam focused by the lens, we design our gratings to create diverging beams. We do this by adjusting the flair of the tapered waveguides leading to the circular grating and radially chirping the period of the grating elements to produce diverging beams. To optimize the power coupling between chip and free-space, we also apodize the grating couplers to match the radial Gaussian profiles of the OAM beams.

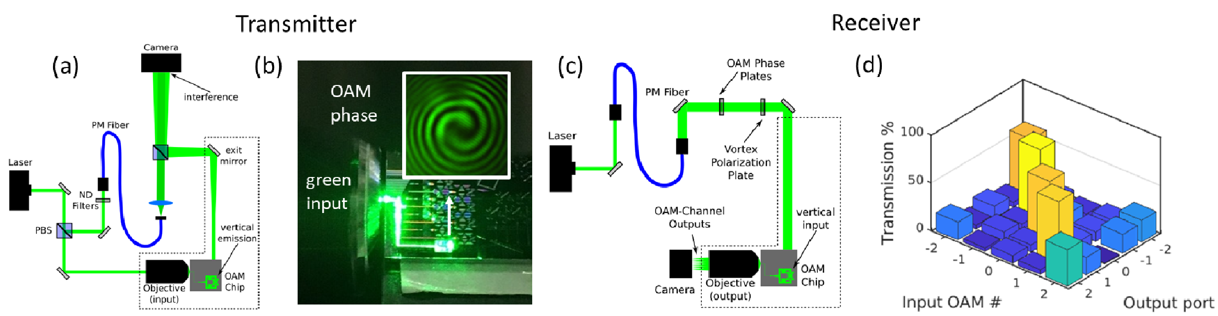

Fig. 2. Chip device operating in transmitter and receiver mode. (a) Optical setup for testing transmitter mode operation. (b) Image of device and an interferogram showing a twisted phase front. (c) Optical setup for testing receiver mode operation. (d) Receiver performance showing desired coupling between an input OAM state and corresponding output waveguide port.

The development of low-loss and high-bandwidth optical transceivers using integrated photonics will enable the exploration of OAM states of light for underwater communications. In addition to the reduced scattering in turbid water and the ability to multiplex data using multiple OAM states, this technology also enables us to explore the advantages of hybrid encoding schemes, such as using coherence between multiple OAM states [5], to potentially increase data rates and link robustness.

4. Acknowledgements

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5. References

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