Underwater Wireless Optical Communications Using Integrated Optical Phased Arrays

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***Abstract*—Underwater wireless optical communications using integrated optical phased arrays is demonstrated for the first time, enabling chip-scale visible-light beamforming for submersible communications. We demonstrate a 1-Gbps on-off-keying link and an electronically-switchable point-to-multipoint link through water.**

Keywords—integrated optical phased arrays, underwater communications, silicon photonics

I. Introduction and Motivation for Underwater Wireless Optical Communications

Underwater wireless communications systems are a ubiquitous need in maritime applications such as submarine operations, underwater sensor networks, and unmanned underwater vehicle controls. However, conventional underwater communications are limited to acoustic and low-radio-frequency (RF) systems [1], which are severely hindered by low carrier-wave frequencies and, hence, cannot realize high-speed, low-latency data links. For this reason, extensive research has been thrust towards the implementation of optical systems for underwater wireless communications, which enable orders of magnitude higher capacities than underwater acoustic and RF systems [2]. However, current high-speed, dynamic, and unguided optical data links require the use of bulky mechanically aligned and steered lenses or mirrors, which are not well suited for harsh environments, such as those weathered by underwater wireless optical communications (UWOC) systems.

As an alternative to bulky optical systems, silicon-photonics-based integrated optical phased arrays (OPAs) have been demonstrated for free-space optical communications (FSOC) in air [3-5], where the OPA's electronically-tunable beam-steering capabilities mitigate the need for mechanically adjusted lenses. However, these demonstrations have been limited to infrared wavelengths, which are suitable for terrestrial FSOC, but not UWOC due to heavy absorption of infrared light through water. In contrast, for an OPA-based transmitter to be suitable for underwater applications, it must operate at a visible wavelength to fall within the transparency window of water. However, a visible-light integrated-OPA-based transmitter has yet to be shown.

In this work, we show the first visible-light integrated-OPA-based FSOC transmitter and use it to demonstrate the first integrated-OPA-based UWOC link. We experimentally demonstrate a 1-Gbps on-off-keying (OOK) link through water and leverage the non-mechanical active beam-steering capabilities of this OPA architecture to establish an underwater point-to-multipoint link.

II. Visible-Light Integrated Optical-Phased-Array Architecture and Performance

The visible-light integrated OPA [6] was fabricated in a CMOS-compatible foundry process at the SUNY Polytechnic Institute and postprocessed at MIT. The OPA, depicted in Fig. 1b, consists of a silicon-nitride-based cascaded-phase-shifter architecture that linearly controls the relative phase applied to an array of antennas via electrically-tunable liquid-crystal (LC) birefringence [7]. An on-chip input edge coupler couples light from an off-chip current-modulated 637-nm-wavelength diode laser into an on-chip silicon-nitride waveguide. A 100-μm-long adiabatic layer-transition structure then couples light into a bus waveguide. From the bus, evanescent tap couplers with a pitch of 20 μm and increasing coupling lengths uniformly distribute the light from the bus region to 16 grating-based 400-μm-long antennas with a 2-μm pitch. The OPA emits a beam with a 0.4° × 1.6° power full width at half maximum, 8-dB sidelobe suppression, and second-order grating lobes at ±18.8°.

III. Underwater Wireless Optical Communications Setup and Experimental Results

To enable a one-way simplex UWOC demonstration, digital data is superimposed onto an optical signal by modulation of the forward current through a laser diode, which results in an intensity-modulated optical signal that serves as an OOK digital signal. This modulated optical signal is coupled onto the photonic chip via an optical fiber, and the resulting beam formed by the OPA is emitted out of the surface of the chip. The beam propagates through free space, through a 75-cm-long glass tank filled with tap water, and again through free space, as depicted in Fig. 1a. At the far end of the tank, avalanche photodetectors (APDs) are used to recover the information in the transmitted beam.

To characterize the link performance, we first use the integrated OPA passively (without beam steering) and recover the beam on the far side of the water-filled tank using a single 1-inch spherical lens and a high-speed APD. The recovered signal-to-noise ratio (SNR) is measured by sweeping the frequency of an RF signal generator that modulates the laser-diode current.

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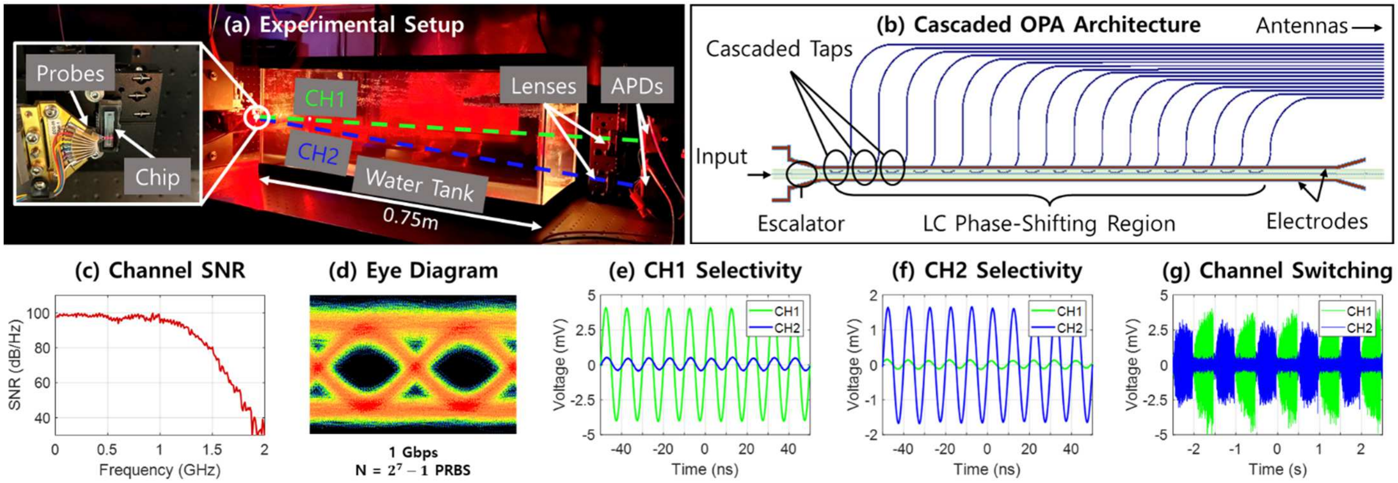

Fig 1. (a) Photograph of the experimental setup with the chip-based transmitter system on the left, water-filled tank, and a photodetector array on the right (inset showing photograph of photonic chip and probes). (b) Partial simplified top-view schematic of the integrated optical phased array highlighting major components [6]. (c) Signal-to-noise ratio of the underwater wireless optical channel as a function of frequency. (d) Recovered digital eye diagram through the underwater wireless optical channel at 1 Gbps. Signals recovered from CH1 and CH2 APDs showing spatial channel selectivity for (e) OPA steered to CH1 and (f) OPA steered to CH2. (g) PRBS recovered from CH1 and CH2 APDs showing electronically-switchable time-division multiplexing of the two spatially distinct wireless channels.

At each frequency, both the RF power in the recovered signal and the noise floor of the detector are measured to calculate the SNR, depicted in Fig. 1c. Next, we use a pattern generator to modulate the laser with an N = 2^7-1 pseudo-random binary sequence (PRBS) at 1 Gbps, where N is the number of bits in the PRBS. The OOK signal recovered from the APD was measured using an oscilloscope to generate an eye diagram, shown in Fig. 1d.

To demonstrate an actively tunable point-to-multipoint link, we apply a 10-kHz square-wave control voltage to the integrated electrodes on the photonic chip and – by varying the peak voltage – steer the beam emitted by the OPA [6] to an array of two separate APDs and matching lenses on the far side of the water-filled tank. These two APDs are vertically stacked, such that the first APD (CH1) is positioned boresight to the OPA (corresponding to a control voltage of 0 V) with the second APD (CH2) approximately 7 cm below the first (corresponding to a square wave peak voltage of approximately 2.5 V). The laser diode is modulated with a 100-MHz RF sinusoid and both APD voltages are captured with an oscilloscope, resulting in two spatially distinct wireless channels, as shown in Fig. 1e-f, with 19-dB and 22-dB channel-to-channel isolation for CH1 and CH2, respectively.

Finally, to demonstrate the utility of this modality, we replace the 100-MHz test tone with a 100-Mbps PRBS and toggle the control voltage from 0 to a 2.5 V_p square wave at 1 Hz to multiplex the transmitted data between the two detectors, shown in Fig. 1g. This adaptive modality represents time-division multiplexing of two beam paths (i.e. two channels) with one instantaneous active channel.

IV. Conclusions and Future Outlook

Here, we have presented the first visible-light integrated-OPA-based FSOC transmitter and used it to demonstrate the first integrated-OPA-based UWOC link. We experimentally demonstrated a 1-Gbps on-off-keying (OOK) link and an electronically-switchable point-to-multipoint link with channel selectivity of greater than 19 dB through a water-filled tank. This integrated OPA transmitter chip can reduce the size, weight, and mechanical complexity of apparatus for UWOC systems. Moving forward, we intend to scale this architecture for longer-range communications, extend its functionality to shorter green-blue wavelengths for further reduced water absorption, and explore multi-beam emitters for underwater and free-space MIMO (multiple-input, multiple-output) optical communications.

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