Faculty Fellows FY24 Application

Basic Information:

1. Title: Miniaturized & Real-time Water Quality Monitoring Using Photonic Sensing Chips

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Affiliation: Texas A& University, Department of Electrical & Computer Engineering Associate Professor. Director of **M**id-Infrared **I**ntegrated **P**hotonics and **R**emote **S**ensing (**MiPRoS**) Laboratory. 10th Congressional district of Texas.

3. Agency and Programs for Submission:
(i) U.S. Geological Survey (USGS), The Water Availability and Use Science Program (WAUSP), April 2024. *To improve the collection process or quality assurance of water-use data, or improve the transfer of water-use data to the USGS*
(ii) National Science Foundation (NSF), PD-20-1440, Full proposal accepted anytime. *Protection of water. Innovative approaches to smart and adaptive management of surface water, groundwater, and urban watersheds and storm water to maintain/improve quality and prevent downstream impacts from nutrients and other water constituents.*

4. Abstract: A good management plan of water resource relies on accurate and continuous monitoring of water quality. Rapid, early detection of water contamination can be addressed by low-cost and improved in-line monitoring of water quality. Currently no in-line continuous biochemical sensor exists in any water system. This project will demonstrate an on-chip microphotonic sensors for the sensitive and specific detection of blue-green algae, methane, and e-coli, three most common pollutants in water. We will focus on several critical features of a water sensor, including *(i)* enhanced sensitivity by using high quality factor (Q) micro-resonator sensors. High Q allows stronger interaction between the light and the water sample, hence providing higher sensitivity to pollutant detection; *(ii)* high specificity for chemicals by using functionalized polymers on sensor surfaces; and *(iii)* real-time monitoring by adding fluidic channels that continuously deliver μL water to the sensor.

5. Description of planned proposed research, emphasizing how it will address water resources-related concerns (particularly how, if possible, it will benefit Texas), including:
5a. *Statement of critical regional or state water problem.* Texas Commission on Environmental Quality created the Surface Water Quality Monitoring (SWQM) Program to evaluate physical, chemical, and biological characteristics of aquatic systems. Accurate, continuous, and distributed monitoring of water quality over the state is imperative for daily operation of public water systems, including the maintenance of the drinking-water quality, water conservation and drought, assessing and protecting groundwater operating, wastewater treatment plants, etc. Nevertheless, such an in-line monitoring system with a high density of monitoring spots is not currently available. Current water quality monitoring methods consist of sampling occasionally and waiting 3-4 days for sample results. The task of this project, therefore, is to develop in-line and low-cost on-chip water quality sensor devices which are highly sensitive and specific, and which can be adapted to larger scale deployment in Texas urban water distribution systems and drinking water plants. Table1 compares TAMU-MiPRoS technology from PI's laboratory, including sensing mechanism, pollutant detected, sensitivity, size, portability and price with state-of-art water monitoring devices. Our innovative photonic sensor chips offer a pathway to obtain continuous in-line and wireless sensing of multiple contaminants with the highest sensitivity (ppb) for the lowest price (<$50), highly demanded by the state and federal environmental protection agencies and private manufacturing industries.

Table 1. Comparison of water monitoring technology from TAMU-MiPRoS and others

	Technology (Sensing mechanism)	Pollutant detected	Sensitivity	Size (Portability)	Price /unit
TAMU-**MiPRoS**	**Photonic chip** (*Resonance enhanced* fluorescence & index sensing)	Chemicals	ppb	< 1cm^2 (In-line)	<$50
		Algae E-Coli	19 cells/mL		
YSI	Fluorometry (Fluorescence)	Algae E-Coli	220 cells/mL	50x10 cm (In-line)	>$2000
Thermo Scientific	Spectrophotometry (Absorption)	Chemicals	60 mg/L $K_2Cr_2O_7$	15.7x11.8x9.8 in. (Off-line)	>$3000
Agilent	Spectrophotometer (Fluorescence)	Algae E-Coli	200 cells/mL	22x30 x32 in. (Off-line)	>$3000

***5b.** Nature, scope and objectives of the research, including a timeline of activities.* The objectives of this proposed work is to demonstrate the use of optical micro-resonators with a battery-powered light source and detector for in-situ water quality monitoring. Typically the detection of three contaminant categories are crucial for water quality control, including *organic and inorganic chemical compounds, biological hazards, and dissolved gases.* We will design and fabricate our micro-sensor system to detect pollutants in two of the categories – biological hazards (algae, e-coli) and dissolved gases (methane), and conduct following key experiments:

<u>Task 1. Develop coated optical micro-resonator sensors.</u> The sensor module is composed of a "photonic circuit" coupled to a "micro-fluidic channel". For the photonic circuit, light from a battery powered light emitting diode is coupled into an optical bus waveguide and into a micro-ring resonator shown in Fig. 1. This resonator causes strong light confinement – it is designed to have a high Quality (Q) factor (10^6), thus causing light to couple into the resonator making multiple round trips before being coupled out again. The interaction between the probe light and pollutant is therefore greatly enhanced and amplifies the detection by 5 or 6 orders of magnitude. In addition to a sensing resonator, an encapsulated resonator will be fabricated on the chip to serve as a reference, thereby ensuring that any changes monitored are attributable only to the presence of the pollutant. Specificity of the sensor is enhanced by using an enriching/discriminating polymer coating which concentrates only the target pollutant on the micro-ring resonator. Standard micro-fabrication will be used to build micro-resonator arrays. The dimensions of the resonators and waveguides (w and h shown in the figure) will be designed for single mode transmission at visible (algae, e-coli) and near IR (methane) wavelengths. Next step, we will develop polymer film coatings to demonstrate discrimination between two species (for example methane vs hexane).

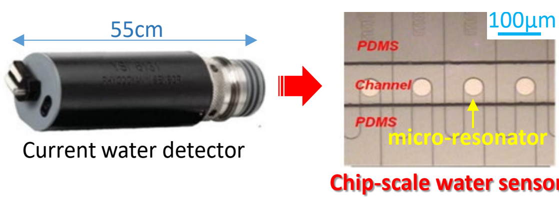

Fig. 1 Current bulky water detector vs. our miniaturized water sensor.

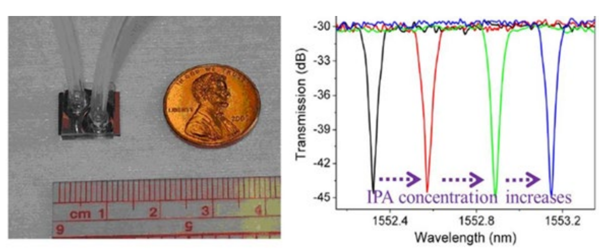

Fig. 2 Prototype of a water sensor chip. The optical spectrum shifts as the IPA concentrate changes.

Optimized specificity-enhancing polymer coatings will be coated within the windows, directly on the micro-resonators.

Task 2. Selection and integration with micro-fluidics: The fluidic channel is the flow cell that delivers the raw water from the water pipes or the reservoir to the coated surfaces of the optical resonator. From our prior study shown in Fig. 2, we have successfully demonstrated the fabrication of fluidic channels using PDMS and the spectrum shifts as the isopropyl alcohol (IPA) concentration changes.[6 7 8] We will apply this developed technology for in-line water quality sensing, with the added feature of optimized fluidic cell dimensions to minimize clogging caused by biofouling. Additionally, we will also apply anti-biofouling procedures. The timeline of this project is shown in Table 2.

Table 2. Timeline of activities

	Milestone	**Deliverable**
Month 3	Using optical chips to monitor (a) fluorescence from algae and e-coli and (b) Index change due to methane.	Design, fabrication and test using optical micro-resonators for sensing algae, e-coli, and methane in water.
Month 6	Evaluate (a) coating polymers enhance specificity (methane:hexane) and (b) fluidic channels for pollutant delivery.	Optimized coating material to differentiate between two chemicals in water (methane vs. hexane).
Month 9	Perform evaluation applying the sensor parameters, including sensitivity, fluorescence, absorption, response time	Optimization of the sensing parameters such as response time, durability, specificity.
Month 12	Develop a compact sensor prototype with light source, sensor/coating and detector on a single platform	Demonstration of water monitoring using a single platform. Build partnership and technology transfer.

5c. *Methods, procedures and facilities.* The testbed to characterize the water sensor chip is illustrated in Fig. 3. The workstation is used to measure the waveguide and the micro-resonator transmission spectra. It has a tunable near-IR light source and is used to detect resonant peak shifts caused by the presence of target chemical analytes in the water sample. The testbed can also be converted to a photoluminescence measurement system equipped with a $\lambda = 532$ nm laser and spectrometer, thus enabling the detection of algae and e-Coli which emit fluorescence after laser excitation. PI's MiPRoS Lab has equipped all the necessary components, including the light source, detectors, spectrometers, optical stages, signal collection and analysis software, to evaluate the performance of the water sensor chip. In addition, the PI's group has full access to AggieFab Nanofabrication Facility, which host the instrument to fabricate the devices.

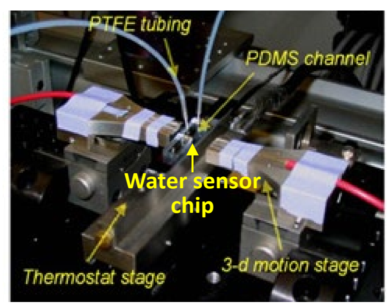

Fig. 3 Station to characterize the water sensor chip.

5d. *Statement of expected results or benefits.* This project provides the critical technology to build on-chip water sensors enabling real-time chemical, biological matter and gas detection. The result can improve the conservation of water resources, the quality control, and efficient management. Our sensor chip can develop a baseline of environmental data and a network of monitoring stations linked together to assist in making informed decisions. From the collected data, models will be built to minimize/prevent damage caused by natural disasters such as flooding leading to malfunctioning of water treatment systems.

6. *Potential collaborator/partner.* Dr. Shankar Chellam in Civil & Environmental Engineering.