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Photonic integrated circuits for Department of Defense-relevant chemical and biological sensing applications: state-of-the-art and future outlooks

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Abstract. Photonic integrated circuits (PICs), the optical counterpart of traditional electronic integrated circuits, are paving the way toward truly portable and highly accurate biochemical sensors for Department of Defense (DoD)-relevant applications. We introduce the fundamentals of PIC-based biochemical sensing and describe common PIC sensor architectures developed to-date for single-identification and spectroscopic sensor classes. We discuss DoD investments in PIC research and summarize current challenges. We also provide future research directions likely required to realize widespread application of PIC-based biochemical sensors. These research directions include materials research to optimize sensor components for multiplexed sensing; engineering improvements to enhance the practicality of PIC-based devices for field use; and the use of synthetic biology techniques to design new selective receptors for chemical and biological agents. © *The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.58.2.020901]

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1 Introduction

The Department of Defense (DoD) has broad needs to deploy better biochemical sensors for applications in medical diagnostics, environmental monitoring, rapid identification of threats, hazardous materials control, basic scientific research, and more. For example, point-of-care detection of biomarkers of injury or disease can provide rapid health status assessments and quicker medical responses in the field. Standoff detection of chemical and biological threats, such as nerve agents and bioweapons, using long-range sensors is an integral component of force protection strategies as weapons proliferate. Urban environment operations also require monitoring for toxic industrial chemicals and materials to ensure the health and safety of service members. Biochemical sensors capable of tackling these DoD challenges must detect specific molecules within complex mixtures at high confidence; they must also be relatively inexpensive, easy to operate, and sufficiently robust for operational field use. To this end, optical-based sensing using photonic integrated circuits (PICs) has emerged as a promising technology.

PICs are devices analogous to electronic integrated circuits but use light rather than electrons for information signaling and transfer. While electronic integrated circuits are usually constructed as arrays of transistors, PICs employ a range of components (e.g., waveguides) to focus, split, isolate, polarize, couple, modulate, and, ultimately, detect light. Technical advancements in materials fabrication—realized especially over the past two decades—have enabled embedding these numerous functions in a single small-footprint PIC device.[1] PICs are increasingly applied in telecommunications and sensing platforms, and significant research and development (R&D) investments continue to advance a rapidly expanding market (estimated CAGR of 31% from 2016 to 2023).[2]

While various materials are under exploration for use in PIC sensors (discussed further in Sec. 5 of this review), silicon has received considerable attention. The high-refractive index contrast of silicon-on-insulator (SOI) waveguides provides a platform for the design and integration of high-density photonic circuitry. Use of silicon also leverages the existing commercial complementary metal-oxide-semiconductor (CMOS) infrastructure supporting the computing industry. Milestone advancements in this domain have occurred—Intel© announced the first fully integrated wavelength multiplexed silicon-based photonics chip in 2015, a disruptive advancement to present day information technology architectures.[3] Silicon-based PIC development is also driven by the telecommunications industry due to its suitability for transmitting light in the near-infrared (NIR) region of the electromagnetic spectrum (a range relevant to the industry). Nevertheless, silicon is not appropriate for all applications and PICs that operate in the mid-infrared (IR) and other ranges may require different waveguide materials. Another key challenge with silicon is the realization of truly monolithic and portable lab-on-a-chip (LOC) systems, which include integrated optical sources and detectors on-chip.[4]

Innovations of biochemical PIC-based sensors are taking place in the healthcare/biomedical industry.[5] PIC-based biochemical sensors essentially perform three general steps to: (1) prepare light, (2) direct light through a sample of interest, and (3) measure changes of the transmitted light due to the presence of analytes in the sample. This simplified workflow

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provides several advantages over other biochemical sensing modalities, including immunity to electromagnetic interference, smaller footprints, label-free sensing, opportunities for multiplexing, and easier integration into LOC-type systems for rapid sample-to-answer capabilities.[6] While significant progress has been demonstrated, the transition of healthcare PIC sensors to DoD applications is nontrivial. Devices must operate with a low limit of detection (LOD) and high sensor selectivity in a potentially complex environment without access to laboratory-based sample preparations.[7] PICs offer the potential for a direct sample-to-answer sensing workflow for a nontechnical user, eliminating the demand for training and the potential for analysis errors.

In this review, we first describe the fundamental basis for PIC-based biochemical detection, followed by discussions of common PIC sensor architectures for analyte identification and spectroscopic measurements. As work must still be done to realize the full potential of fielded PIC sensors, we discuss recent DoD investments that are providing important fundamental advancements to the field at organizations such as the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research, and the Air Force Office for Scientific Research. Finally, we discuss future research areas of interest to the DoD, including materials research to optimize sensor components for multiplexed sensing; engineering improvements to enhance the practicality of PIC-based devices for field use; and the design of new selective receptors for chemical and biological agents. Notably, these areas of future research broadly apply to biomedical and basic science fields, providing attractive opportunities for synergistic and collaborative work between a range of government and industry stakeholders.

2 Fundamentals of PIC-Based Optical Sensing

All PIC-based biochemical sensors are optical transducers that encode the presence of an analyte onto the properties of light (i.e., intensity, phase, or frequency). As opposed to traditional free-space optics with long atmospheric path-lengths, PIC-based sensors use light that is confined within, and propagates through, a semiconductor or dielectric waveguide. The confinement of light is governed by the principle of total internal reflection at the interface between media with different indices of refraction.[8]

As light propagates within the semiconductor waveguide, it undergoes total internal reflection if the angle of incidence is above a certain critical angle Θ_c (determined by the ratio of the refractive indices by $\sin \Theta_c = n_2/n_1$). Here, n_1 is the refractive index of the waveguide and n_2 is the refractive index of the medium above the waveguide. Note that the definition of total internal reflection requires n_2 to be less than n_1. As the light is reflected from the boundary back into the waveguide, part of the electromagnetic field leaks into and penetrates the sample medium where it can interact with analytes—this interaction is the fundamental mechanism of PIC-based biochemical sensing. The penetrating electromagnetic field, termed the evanescent field, exponentially decays with distance, dependent on material properties and geometry normal to the surface. This effectively confines the detection of analytes to a distance less than a wavelength from the surface (the field becomes too weak to sample the bulk solution farther from the surface). The basic detection principle based on evanescent fields is reviewed in Fig. 1.

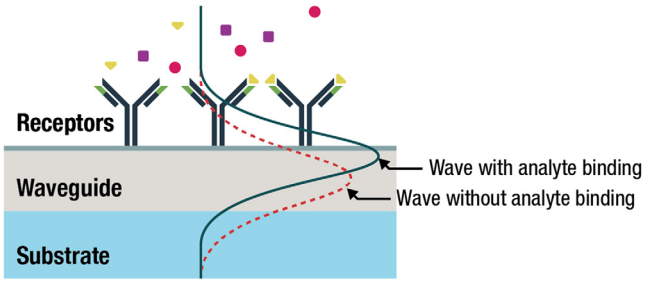

Fig. 1 Evanescent field detection principle. Light traveling through the waveguide produces an evanescent electromagnetic field in the lower refractive index environment above the waveguide. The presence of a target analyte (yellow triangles) bound to receptors (black) in the sampling area modify the properties of the evanescent wave and can be measured. The substrate has structural properties to physically support the waveguide and optical properties to both support the guided mode within the waveguide and the evanescent field above the waveguide.

To better elucidate the physics of PIC-based sensing, consider a simple example: the detection of an optically absorbing analyte using an array of chemically specific receptors affixed to the waveguide surface. The presence of the bound analyte results in an attenuation of the total transmitted optical field [shown in Fig. 2(a)] and, because a chemically specific receptor is used, the optical absorption of the molecular analyte can be known *a priori*.[9,10] The total absorption for an analyte maximally proved by the evanescent field, described by the Beer–Lambert Law, $-\ln\frac{I(\lambda)}{I_0(\lambda)} = a(\lambda)CL$, can then be used to calculate the concentration (C) of the analyte, where I_0 is the input intensity, I is the transmitted intensity, $a(\lambda)$ is the wavelength-dependent attenuation coefficient, and L is the length of the sensing region.[8] Evident here is that sensor performance is determined not only by the analyte and its interaction strength with its receptor, but also by the physical design of the sensor, which determines the total analyte-light interaction (i.e., the length of the devices, the strength of the evanescent field, and its overlap with the optical cross section of the analyte).

Sensor performance can generally be quantified in terms of specificity and sensitivity. In the example above, the use of a chemically specific antibody leads to a fundamentally high specificity and, correspondingly, allows for highly sensitive detectors to be engineered. This type of sensor is termed single-identification (single-ID) as shown in Fig. 2(a). Single-ID sensors have the additional advantage of operating at a single wavelength, thereby relaxing the bandwidth requirements on optical sources. When no receptor is available, or the analyte is not known *a priori*, broadband optical spectroscopy must be used; then through postprocessing, it is possible to mathematically deconvolve the measured spectrum with the spectrum of known analytes to determine the identity and concentration of those present in the sample [shown in Fig. 2(b)].

It is challenging for spectroscopic methods, as just discussed, to achieve the same high specificity and sensitivity of single-ID methods, especially when detecting analytes in a complex mixture with interferents. Furthermore, the stability and bandwidth of the optical source become important factors to collect high-sensitivity and high-resolution spectra. It

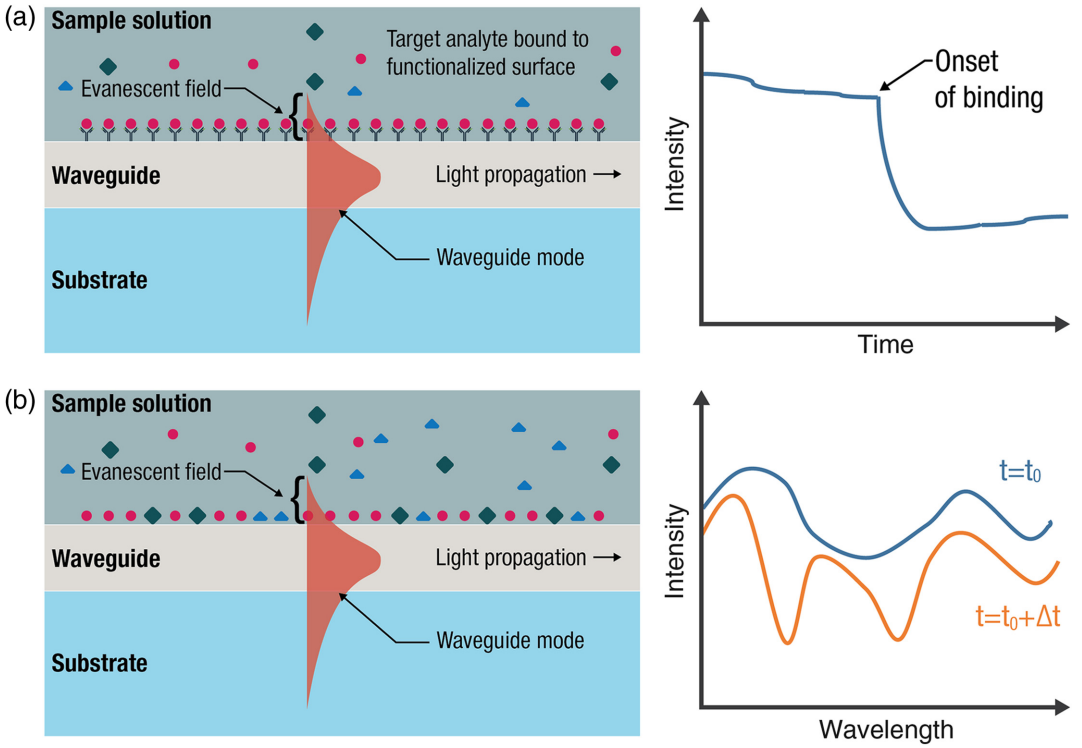

Fig. 2 Analyte detection using single-identification and spectroscopic sensors. (a) Single-ID sensor waveguides are functionalized with a biochemical receptor, which selectively binds to a specific analyte. These sensors operate at a single wavelength that is chosen based on the absorption of the analyte. When the analyte successfully binds to the receptor, the evanescent field interacts with the analyte, and accordingly a reduction in the signal transmitted through the waveguide is detected. (b) For spectroscopic sensors, no receptor is used and a broadband optical source is used to probe the analytes. The resulting evanescent field probes all analytes near the surface of the waveguide. The output spectrum may have multiple features, which need to be deconvolved with known analytes in the environment in order to ascertain their concentrations. These spectra may change rapidly based on the complexity of the environment.

is also important to note that comparing sensitives across reports can be challenging: sometimes units such as mass per volume are given, which is difficult to extend to other analytes, and even if a normalized unit such as refractive index units (RIU) is given, it is not normalized to the physical size of the sensor.

Below, we give a brief overview of the state-of-the-art for single-ID and spectroscopic sensors, principles of detection unique to each type, and relative advantages and disadvantages of each type.

3 Single-ID PIC-Based Biochemical Sensors

As discussed above, single-ID sensors use functionalized waveguide surfaces to capture and detect target analytes. This type of detection is performed at a single wavelength because the optical properties of the analyte are known *a priori* and changes in the transmitted optical signal can be directly attributed to that analyte. Three PIC-based sensor designs using evanescent field detection have been the most prevalent over the past two decades: (i) integrated interferometers, (ii) ring resonators, and (iii) photonic crystal (PhC)-based sensors. We briefly discuss the architectures of each device type and compare their relative performance characteristics in the context of biochemical sensing, when applicable.

3.1 *Integrated Interferometers*

Interferometers are historically established as highly sensitive sensors based on the phase-sensitive detection of minute optical path differences; a striking recent example is the detection of gravitational waves.[11] Interferometric PIC-based sensors, like their traditional free-space counterparts, split light from one waveguide into two separate arms, a reference arm and a sensing arm, functionalized for analyte capture. If a target analyte is present in a sample, it will bind to receptors on the sensing arm, and, as a result, light passing through the sensing arm will be phase shifted relative to the reference light. The interference pattern formed when light from both arms is recombined can then be measured to determine the relative optical phase delay and calculate the amount of analyte present. Two standard configurations exist for interferometers[12] integrated on a chip: the Mach–Zehnder interferometer (MZI)[13] [Fig. 3(a)] and the Young interferometer (YI) [Fig. 3(b)], which is similar but out-couples the light in both arms allowing the light to interfere in free space, instead of using a junction on-chip.

Several demonstrations of MZI-based PIC biosensors are reported in the literature, with LODs reaching as low as 1×10^{-7} RIU or, equivalently, LOD of 10 pM of DNA.[15] Various waveguide designs, such as slot and bimodal waveguides (BiMW), have also been explored to improve sensor

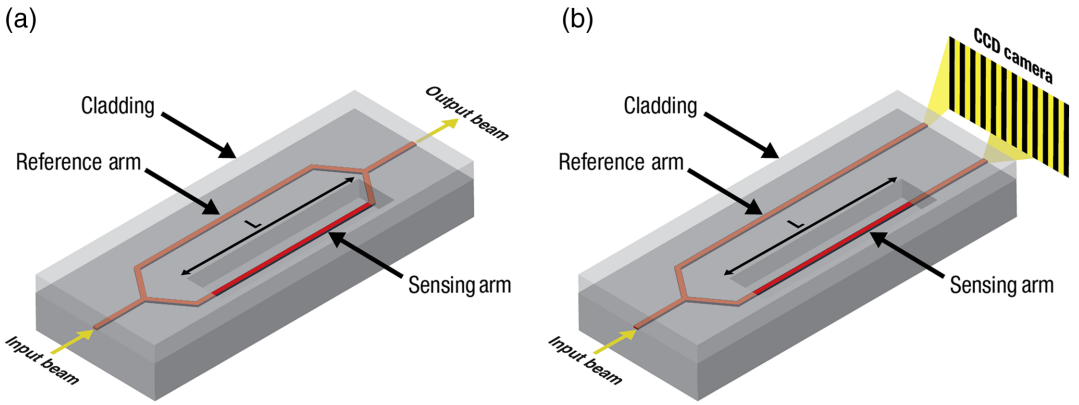

Fig. 3 Interferometric PIC sensors. A standard (a) MZI (a) and (b) YI configurations. Light enters the interferometers on the left and is split into the sensing and reference arms. In the MZI case, the arms are recombined in a Y-junction and the interference measured in the output is used to quantify the presence of an analyte in the sensing arm. In the YI configuration, the light is not coupled, but is outcoupled from sensing and reference arms and interfered in free space to create interference pattern. The presence of an analyte and its concentration is identified based on the interference pattern, reproduced from Ref. 14.

accuracy. In the slot design, the sensing arm is split into two waveguides separated by a nanometer-scale, low-refractive index "slot" region for light confinement. This design greatly enhances the light–matter interaction yielding higher sensitivity to the refractive index of the analyte; an LOD of 5.4×10^{-6} RIU and 1 pg/mL of streptavidin was recently demonstrated.[16] The same slot design was also recently integrated into an LOC-type point-of-care medical device that used a multiplexed approach to detect specific microRNAs in human urine with an LOD of 1 nM.[17] In the BiMW configuration, a step junction in a single-mode waveguide excites two transverse modes, in a single waveguide, which interact with the sample before being measured by a photodetector. The sensitivity level of the BiMW sensor is comparable to other integrated interferometers; LODs down to 5.9×10^{-4} experimentally were recently demonstrated for bovine serum albumin (BSA), with a theoretical LOD limit of 2.5×10^{-7} RIU.[18]

To the best of our knowledge, the most sensitive biochemical interferometric sensor is a YI device with two Ta_2O_5 slab waveguides, which achieved a sensitivity of 9×10^{-9} RIU and a surface coverage of 13 fg/mm^2 for both bulk solution and surface sensitivities to immunoglobulin G.[19] However, the YI configuration requires off-chip detection and analysis, which may impact operationally relevant considerations for DoD applications.

3.2 *Ring-Resonator Sensors*

Ring-resonator transducers are becoming more common for biochemical sensing applications due to their high sensitivity and potential for multiplexing; the detection of multiple analytes is vital for testing complex fluids (e.g., blood, saliva, and urine) in diagnostics, monitoring, and toxicity screening.[20] PIC ring-resonator sensors use at least one linear waveguide to couple light to a closed-loop waveguide (the ring resonator) and, through evanescent-wave coupling, excite resonant modes in the loop waveguide. On resonance, constructive interference is generated in the multiple round-trips over the ring circumference; however, off resonance the transmission rapidly decreases. This resonance effect considerably enhances sensor sensitivity.[21] Analytes captured on the functionalized surface of the ring resonator shift the resonant wavelength only slightly, but this change is detected as a relatively large decrease in output intensity at a specific wavelength [Fig. 4(a)].[10]

The number of revolutions light takes around the ring resonator yields an optical path length (OPL) orders of magnitude larger than the sensor's physical footprint, which is generally described by the resonator's quality (Q) factor.[21] High Q-factors—considered to be at least 106—indicate low optical loss and correspondingly long photon lifetimes, which is translated into narrow linewidths and often high peak resolution (i.e., high sensitivity). Q-factors in the 106 range have been reported for resonators around 50 to 200 μm in circumference, which has an OPL equivalent to a linear waveguide measuring several centimeters. In practice, a Q-factor of 108 effectively means a molecule will be sampled more than 100,000 times, given by $L_{\text{eff}} = \frac{Q\lambda}{2\pi n}$, where L_{eff} is the effective free-space path length, Q is the Q-factor, λ;is the free-space wavelength, and n is the refractive index of the resonator.[21]

Other important characteristics of resonators are the free spectral range (FSR) and the finesse. The FSR is the inverse of the round-trip time of an optical pulse around the resonator and defines the optical frequency range over which the resonator can be utilized. The finesse, which is determined by the resonator losses and in independent of the resonator circumference, is defined as the FSR divided by the full-width at half-maximum bandwidth of the resonance. Hence, L_{eff} can also be defined as the finesse times the ring circumference, which is a useful metric as the sensitivity generally scales with finesse for most sensing applications.

Therefore, despite the small physical size of the ring resonator, it can achieve higher sensitivities than straight waveguides while using orders of magnitude less surface area. Li and Fan[23] have demonstrated LOD as low as 2.5×10^{-7} in RIU, or equivalently detected 1.6 pg/mm^2 of biotin, using a ring resonator with a diameter of just 70 μm. Smaller waveguide sizes also facilitate the development of more complex, integrated devices. For example, Iqbal et al. demonstrated an arrayed device using 32 ring-resonator sensors to detect

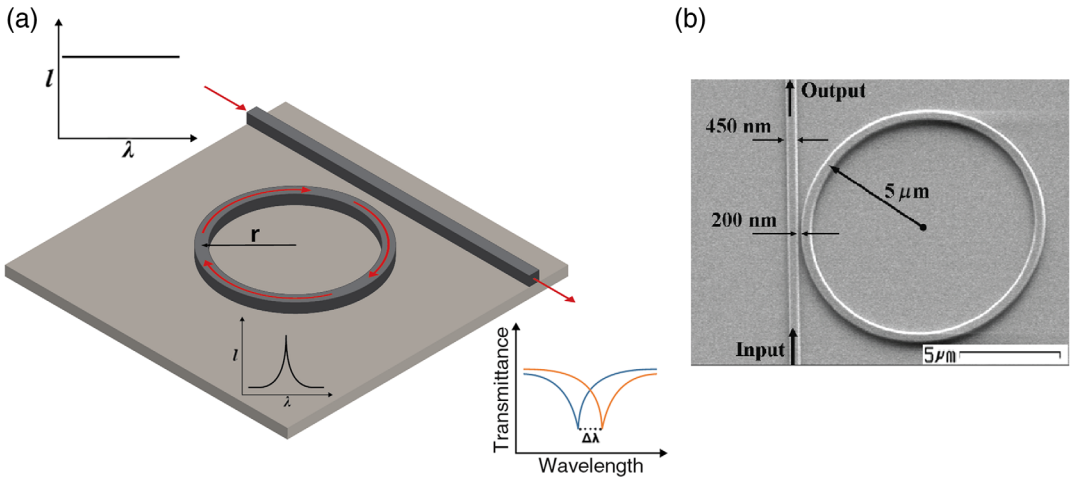

Fig. 4 Ring-resonator sensor. (a) Schematic of a ring-resonator sensor. The linear waveguide provides input light to the loop waveguide at the coupling zone and captures output light from the loop for measurement. The presence of analyte will shift the resonance wavelength within the loop, which is detected in the output spectra, adapted from Ref. 10. (b) Micrograph of a fabricated ring resonator, adapted from Ref. 22.

streptavidin diluted in BSA with an LOD of 60 fM. Furthermore, pushing the technology toward detection of analytes in complex environments, Iqbal et al.[24] demonstrated simultaneous detection of two DNA oligonucleotides. Isolating 8 of the resonators to use as control sensors, they separated the remaining 24 sensors into two groups and functionalized each for a specific oligonucleotide and successfully demonstrated multiplexed sensing. More recently, there have been demonstrations of functionalizing ring resonators with sorbent polymers to efficiently bind vapor-phase compounds, such as acetone and DMMP, and achieve LODs as low as a few ppb.[25]

3.3 *Photonic Crystal-Based Sensors*

PhC are structured matrices of materials that possess different dielectric constants, resulting in photonic bandgaps that determine the frequencies of light, which are reflected or transmitted by or through the substrate.[26] The simplest type of PhC structure is a perfect array of holes, which was in fact one of the earliest geometries for PhC biochemical sensing;[27] the PhC was designed to reflect a single wavelength of light and, upon analyte binding to immobilized receptors on the surface (e.g., immunoglobulins, streptavidin, and BSA), a change in the reflected light wavelength was measured with a reported detection limit of 500 ng/mm^2.[28]

The introduction of defects into the PhC structure (i.e., shifting or removing holes, or changing hole diameters) results in the confinement of light to the defect with high Q-factors, enabling highly sensitive detection of extremely small sample volumes (e.g., a few μm^3). The prospect of high Q-factors and small sample volumes has led to significant effort to explore the potential of PhCs for biochemical sensing, beyond the mirror geometry discussed above.[29] Increasingly complex structures, such as that shown in Fig. 5 where the use defects (i.e., the absence of holes) introduces a waveguide, have been demonstrated to confine sensing volumes and increase sensitivity. For example, slot waveguides have been integrated in PhCs to boost sensor

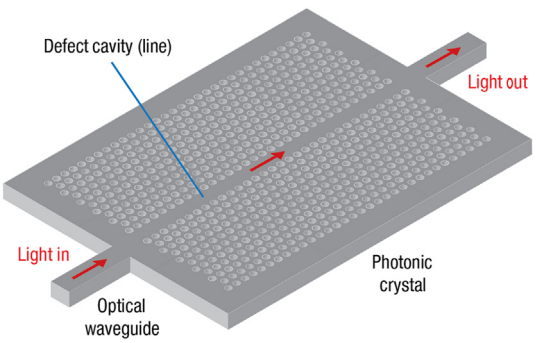

Fig. 5 A 2-D PhC waveguide adapted from Ref. 30. The top and bottom milled areas form a PhC with a photonic bandgap. Light is confined to defects which, here, is the region absent of holes, which forms the central waveguide. Introducing analytes near the PhC changes the RI and the cutoff frequencies of the bandgap.

performance, enabling a Q-factor of up to 50,000, a sensitivity of 1500 nm/RIU, and an LOD of 7.8×10^{-6} RIU.[31] While analyte detection was not demonstrated with the device in Ref. 31, similar PhC devices have been used to detect lung cancer cells down to 2 cells/μL, to measure biotin–streptavidin binding (a common analyte/receptor pairing to demonstrate biochemical assay viability), and to probe the binding kinetics of immunoglobulin G proteins.[32] More recently, PhC biosensor devices have been developed for detection of HIV,[33] biomarkers for iron deficiency anemia,[34] and glucose monitoring.[35]

3.4 *Summary and Comparison of Single-ID PIC-Based Sensor Characteristics*

As with all technologies, specific features and designs of single-ID PIC-based sensor types carry a cost/benefit trade-off, particularly for operationally demanding DoD use cases. Interferometric devices look very promising as they are inexpensive to fabricate and are the most sensitive PIC sensors, achieving LODs as low as 9×10^{-9} RIU; however, interferometric detectors with high sensitivities are physically large,

provide enough functionalized surface area, and currently rely on off-chip excitation and detection schemes.

Ring resonators and PhCs have good miniaturization potential, a feature almost universally coveted for DoD biochemical sensing applications but also have challenges. As with all high-Q resonant devices, both are susceptible to thermal drift, or a thermally induced change of the refractive index given by the thermo-optic coefficient.[36,37] The inherent high sensitivity of the resonant condition to refractive index makes thermal drift the primary detuning mechanism. Several methods have been identified to mitigate thermal drift, including making devices thermal using core and cladding materials with opposite signs in their thermo-optic constants, or using a reference resonator, which is identical to the sensing elements but placed in a separate fluidic channel. The latter method can be utilized for PhC-based sensors as well,[38] with more sophisticated methods encoding a reference resonance that is robust to environmental changes.[39] It is important to note that interferometric PIC-based sensors are less susceptible to temperature drift, which makes them a highly attractive platform for field-based sensing applications.

Still, ring resonator and PhC sensors both have advantages. Ring resonators can be easily integrated into multiloop detector circuits for multiplexed and LOC-type applications, which will likely be critical for fielded devices. PhCs, likely the least proven of the three PIC types for biochemical detection within integrated devices, are perhaps of greatest interest for simple and rapid chemical or biological agent detection since detecting color changes in applications such as wearable sensing, despite fabrication challenges.[29] Such colorimetric sensors could function with a simple LED as an optical source, further emphasizing the simplicity and utility of PhC sensors. For ease of reference, Table 1 summarizes bulk and surface sensitivities of various PIC-based sensors and the representative analyte detected.

While many varieties of PIC sensor designs being explored, it is unlikely that there will be a single design globally favored. Instead, application-specific single-ID PIC sensors will be developed to ensure that specific DoD mission-needs are satisfied.

Table 1 Comparison of PIC-based sensors for biochemical detection. Adapted from Gavela et al.[10]

Sensor type	Mass detection limit (pg/mm^2)[a]	RIU[b]	Waveguide material	Exemplar analyte	Ref #
MZI	0.06	1×10^{-7}	Si_3N_4	DNA	9
YI	0.013	9×10^{-9}	Ta_2O_5	IgG	19
BiMW	0.05	2.5×10^{-7}	Si_3N_4	BSA	18
Ring resonator	1.5	7.6×10^{-7}	SOI	DNA	23
PhC	0.42	3.4×10^{-5}	Si_3N_4	Proteins	27[c]

[a]Measure of surface sensitivity (waveguide core surface).
[b]Measure of bulk sensitivity (whole sensing area).
[c]Not the highest LOD in RIU reported in the literature, but highest LOD achieved in detecting an analyte.

4 Spectroscopic Sensors

Spectroscopic PIC-based sensors, in contrast to single-ID sensors, do not use a chemically specific receptor to capture a known analyte; instead, all molecules near the waveguide surface are measured and their respective properties are encoded into a broadband optical field. The resulting optical spectrum can then be postprocessed to mathematically deconvolve the spectral signatures of known molecules. While it is challenging for spectroscopic methods to achieve the same high specificity and sensitivity of single-ID methods, this type of sensing is well-suited for DoD-relevant applications such as environmental and air-quality monitoring, greenhouse-gas sensing, medical diagnostics, and standoff detection for chemical, biological, radiological, nuclear, and explosive (CBRNE) agents.[40]

Based on free-space spectroscopic detection geometries and leveraging silicon photonics technology, there have been demonstrations of IR spectroscopy [such as tunable diode laser absorption spectroscopy (TDLAS) or Raman spectroscopy] on integrated CMOS-compatible platforms for gas sensing. For example, Tombez et al.[41] demonstrated IR TDLAS on-chip using a dense spiral network of silicon waveguides to increase OPL on a SiO_2 platform to achieve sub-100 ppm methane gas sensing. The top of the spiral waveguide was exposed to the ambient atmosphere allowing the evanescent field of the optical mode to probe the rovibrational transitions of the surrounding environment directly. Optical absorption of the rovibrational transitions, in accordance with the Beer–Lambert law, provides an absorption spectrum that can be used for spectroscopic identification.

Measuring the IR absorption spectrum requires a broadband or tunable source, and Raman spectroscopy uses a monochromatic source to excite molecular vibrational transitions and identify them in a broadband optical output. Recently, there have been several demonstrations of Raman spectroscopy on-chip using silicon nitride platforms for evanescent-field Raman scattering. In addition to being a mature CMOS-compatible photonic integration platform, silicon nitride provides a high-refractive index contrast that could enhance the Raman signal by at least a factor of 500 per cm of waveguide length, as compared to free-space optical systems.

One challenge with spectroscopic detection is concentration analytes on the waveguide surface. Recently, Holmstrom et al.[42] used sorbent polymers designed to reversibly sorb organophosphates (OPs) and concentrate them by as much as 10^8, to functionalize PICs for trace gas Raman spectroscopy. By designing the waveguide mode to propagate within the sorbent polymer, in contrast to the previously described evanescent interactions, the light–analyte interaction and the resulting Raman scattering is enhanced along the length of a high-index Si_3N_4 waveguide; this design achieved single ppb detection limits for identifying trace compounds, such as dimethyl sulfoxide. Just earlier this year, Tyndall et al.[43] utilized a hyperbranched carbosilane sorbent polymer on silicon nitride waveguides for detection of four vapor-phased chemical warfare agent simulants as low as 5 ppb.

While these demonstrations on-chip are quite exceptional, in each case the laser source and the detector were off-chip. Hence, although these devices achieved high detection sensitivity and specificity, they are not yet fieldable. Moving farther into the IR would not only provide a larger class of

material platforms for on-chip integration but also yield higher sensitivities by probing fundamental rovibrational modes rather than the weaker overtones in the NIR. We discuss some of these current challenges, as well as current and near-term DoD investments aimed at addressing these challenges, in the next section.

5 Current PIC-Based Research Areas for the DoD

The DoD is investing in the development of mission-critical PIC-based sensor technologies through basic and applied research programs spanning a diverse set of DoD organizations. In this section, several of these programs are highlighted in the fields of fully integrated devices, long-wavelength broadband sources, and data analysis.

5.1 *Fully Monolithic Photonic Chips*

Although significant advancements have been made in the CMOS compatible fabrication of PIC technologies, fully integrated monolithic silicon photonic/electronic chips with on-chip sources, detectors, and amplifiers have yet to be demonstrated. This is primarily a material limitation because silicon is an indirect bandgap semiconductor with extremely low light emission efficiency. Given the vast knowledge and infrastructure for silicon device fabrication and the extensive role of silicon in electronics, it is desirable to find ways to use a silicon platform for all-optical devices.

To that end, several efforts have been made to enhance silicon emission efficiency to demonstrate on-chip lasers, such as growing successive layers of indium arsenide on silicon to form quantum dots as demonstrated through the DARPA Electronic-Photonic Heterogeneous Integration (E-PHI) program.[44,45] This demonstration is now serving as a foundation for the development of other photonic components such as optical amplifiers, modulators, and detectors.

Current efforts are now focused at large-scale integration of electronics and photonics, such as the recent DARPA Photonically Optimized Embedded Microprocessors (POEM) program.[46] This program is developing chip-scale integrated photonic technology to enable seamless intrachip and off-chip photonic communications. This program has already had several groundbreaking demonstrations, including the first single-chip microprocessor with 70 million transistors and 850 integrated photonic elements, all fabricated using the standard microelectronics foundry process, to work together to provide logic, memory, and interconnect functions.[47] This is significant because the silicon fabrication requirements for electronics and photonics are orthogonal—while electronics requires very thin silicon materials (order of single nm) to quickly dope and transition the silicon between conducting and insulating states, photonics requires much thicker silicon (order of 100 nm) to confine light efficiently. Earlier this year, the same group demonstrated, for the first time, integrated photonics (optical waveguides and resonators, transceivers, high-speed optical modulators, and sensitive avalanche photodetectors) with silicon nanoelectronics in polycrystalline silicon operating at 10 Gbits/s, all on the same chip.[48] These developments are pushing the technological limits of integrated photonics, but they do not yet include on-chip optical sources.

While the on-chip integration of sources, detectors, and electronics, may be possible in the near-IR, there is still much interest in integrating different material platforms, which may also enable devices operating at longer wavelengths, such as the mid- and long-wave IR. For example, photonic systems based on III–V materials operating in the mid-IR such as GaAs, InP, and GaN already have a complete set of photonic components, including on-chip monochromatic lasers, amplifiers, and modulators.[49] These platforms are continually being developed to create hybrid platforms with silicon photonics.

5.2 *High-Volume Manufacturing of PIC Devices*

The prospect of single-chip, multitechnology integration opens an array of opportunities. While on-chip PIC components are still under development and being optimized using several material platforms, the National Network for Manufacturing Innovation has founded the American Institute for Manufacturing Integrated Photonics (AIM Photonics) to advance large scale manufacturing of CMOS-compatible PICs. This institute serves to leverage existing CMOS electronics infrastructure and fabrication technologies to develop a complete PIC ecosystem within the United States; this includes foundry access, automated design tools, resources for packaging, assembling and testing devices, and a domestic workforce.[50]

AIM Photonics is currently focusing on achieving a manufacturing readiness level 7, as defined by the DoD Manufacturing Technology program, for CMOS-compatible integrated electronic and photonic devices, such as the device shown in Fig. 6.[51] CMOS devices based on both silicon and indium phosphide would span applications in telecom, RF analog circuits, and PIC sensors and array technologies. Integrated devices should serve to increase both the capacity and reliability while decreasing the cost, size, weight, and power (SWaP) consumption of devices.[52] AIM also receives funding from the Navy, to advance their multiproject wafer assembly and packaging service, which provides access to the most advanced 300-nm semiconductor fabrication facilities and a suite of passive and active PIC wafer processing technologies. This infrastructure, largely funded by the Government, will ensure that the necessary manufacturing resources are available for mission-critical technologies.

AIM Photonics is already making an impact on mission-relevant technologies, including the successful development of a chip-scale Sarin gas photonic sensor.[53] The team achieved the necessary high sensitivity by developing

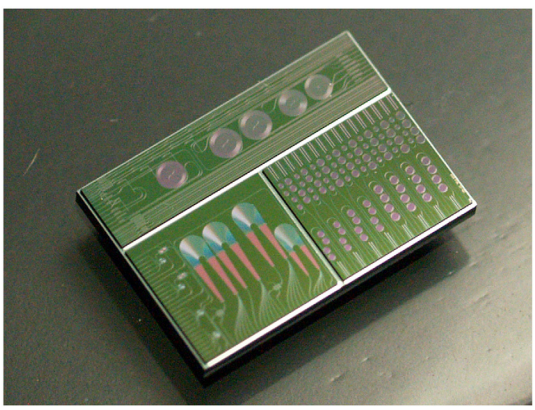

Fig. 6 PIC sensor device with integrated photonics and electronics manufactured by the AIM Photonics teams.

a long-path on-chip waveguide and coating it with a polymer to concentrate the simulated Sarin agent. Their next steps are to develop a fully integrated sensor with on-board spectrometers and lasers and to apply such monolithic sensors for non-defense applications.

In collaboration with the MIT Microphotonics Center and the International Electronics Manufacturing Initiative, AIM released their 2017 Integrated Photonics Systems Road Map in March 2018.[54] The roadmap, which serves to drive technology development, identifies several grand challenges, including: the drastic improvement in power efficiency, the development of tools for large-scale PIC system design, new manufacturing and material technologies, and standards for interoperability to broaden market potential. AIM has already solicited and funded several proposals for R&D efforts to overcome these challenges, including a new effort to develop a CMOS-compatible waveguide platform for integrating mid-IR and long-wave IR on-chip laser sources (spanning 3 to 14 μm). The large wavelength range would enable several DoD-relevant applications including detecting atmospheric trace gases. We discuss the importance of these integrated sources further below.

5.3 *Broadband, On-Chip IR Sources for Biochemical Detection*

Looking specifically toward spectroscopy-based biochemical sensing platforms, there is a clear need for broadband sources with extremely high-spectral resolution, different from the on-chip monochromatic lasers mentioned above: increasing the bandwidth will allow for more properties of each analyte to be measured, resulting in improved specificity and multiplexing. One promising technology is optical frequency combs, which have emerged in the past decade as powerful and precise tools with coherent, equidistant spectral lines spanning a broad range with unprecedented precision in frequency in timing.[55] Several programs across the DoD have been pushing the development of frequency combs spanning the visible and IR ranges for applications in biochemical sensing, time-frequency transfer, and metrology, such as DARPA Spectral Combs from UV to THZ (SCOUT),[56] DARPA program in Ultrafast Laser Science and Engineering (PULSE),[57] and the DARPA Direct On-Chip Digital Optical Synthesizer (DODOS)[58] programs. These programs continue to push the limits of frequency combs in terms of power generation, bandwidth, spectral resolution, and detection.

One major challenge of optical frequency combs is their requirement for large spectrometers to spectrally resolve each individual comb tooth. However, by interfering two combs with slightly different repetition rates, one can generate an RF comb composed of heterodyne beat pairs, which contain all the relevant spectral information and is easily accessible with RF electronics.[59] This technique, termed dual-comb spectroscopy (DCS), has several advantages over conventional spectrometers, including a broad spectral coverage, high-frequency resolution, high-sensitivity/signal-to-noise ratio, and fast acquisition speed; as additionally, DCS performance is not limited by the instrument OPL, which may enable ultracompact systems. Hence, DCS is proving to be an invaluable tool for biochemical detection in the near- and mid-IR.

There is also a strong push to move sources for chemical detection to longer wavelengths in the mid-IR and long-wave IR ranges as it allows for probing much stronger fundamental molecular vibrations, as opposed to the overtones excited in the near-IR. Programs such as SCOUT have specifically pursued the development of mid-IR frequency combs for DCS-based biochemical sensing and have demonstrated significant enhancement in sensitivity and limits of detection. Earlier this year, Ycas et al.[40] at the National Institute of Standards and Technology demonstrated a mid-IR dual-comb system spanning 2.6 to 5.2 μm with sub-MHz frequency precision. While this is an open-path-based system, recently developed chip-scale battery-operated frequency combs have the potential to revolutionize the SWaP of DCS systems.[60] Just this year, Gaeta et al. have demonstrated high-SNR absorption spectroscopy with an on-chip DCS for the first time in the NIR, with a 170-nm bandwidth and a 20-μs acquisition time. Further broadening of the spectral coverage of this on-chip system and shifting to longer wavelengths could enable truly disruptive chemical and biological sensing technologies relevant to DoD applications. However, moving to the mid-IR does introduce several operational challenges including limited achievable Q-factors and increased water vapor absorption, which, respectively, reduce sensitivity and increase background signatures, making the detection and quantification of analytes in native environments more difficult. We discuss the challenges with detection in native environments in further detail below.

5.4 *Analyte Identification in Native Environments*

As PIC-based sensors transition from the lab to native environments for field use, metrics for assessing utility must go beyond sensitivity alone to also include concepts of device robustness and trustworthiness, such as the probability of correct detection, false alarm rate (FAR), and the response time.[61] FAR is defined as the number of false alarms per unit time and defines how well the sensor identifies analytes amidst a background and interferents. For biochemical detection, false negatives are far more dangerous than false positives, though a high false positive rate undermines the detection system trustworthiness (a challenge to combat operational and response fatigue). The sensor's receiver operating characteristic (ROC) curve captures the performance trade-off between sensitivity, probability of correct detection, and FAR and dictates an implicit associated detection confidence.[61] Additionally, metrics for long-term stability of devices, such as the Allan variance or Allan deviation, will be required to understand device stability to noise processes and drift and assess their ability to transition to DoD-relevant missions. We direct the reader to Ref. 61, a government-issued study with in-depth analyses of chemical and biological sensor metrics, testing, and recommendations.

The DoD is actively using machine learning algorithms that are trained with experimental data to reduce FAR by identifying analyte signatures amidst a strong background and interferents; this includes water absorption in the mid-IR, which obscures real-time analyte identification. In terms of fielded devices, DHS S&T first responders group is actively looking at machine learning and artificial intelligence technologies for wearable sensor technologies.[62] Their new platform, assistant for understanding data through reasoning, extraction, and synthesis, collects data from various

sensors and notifies first responders of any necessary actions to be taken, as well as any contextual insight of similar events that occurred elsewhere in the country.[63]

In addition to machine learning algorithms, networking orthogonal sensing platforms to reduce the overall FAR across a network are a capability being developed at DARPA through the SIGMA+ program.[64] SIGMA+ is focused on both developing highly sensitive detectors and advanced intelligence analytics to detect minute traces of substances related to CBRNE threats. By fusing CBRNE data, as well as local weather and external contextual data across a network infrastructure, SIGMA+ aims to develop a persistent, real-time early detection system to monitor a city-wide region (km^2) with maximum sensitivity and minimum FAR.

6 PIC-Based Sensor Research Horizons

Current and future research initiatives across a range of disciplines provide opportunities to improve the functionality of PIC-based biochemical sensors. Advances could enable the development of novel synthetic receptors, the exploitation of new material platforms for on-chip detection, the development of protocols for higher precision waveguide surface functionalization, and more generally identify methods to design sensors with improved operational utility.

New synthetic biology tools may enable the development of receptors with both high affinity and high selectivity, capable of filling the existing technological void of differentiating chemically similar small DoD-relevant toxic chemicals. For example, detecting chemical warfare agents using acetylcholinesterase or butyrylcholinesterase as the receptor will not provide selectivity across a variety of OPs.[65] Gene editing tools such as CRISPR-Cas9 and directed evolution approaches could be used to quickly and efficiently construct chimeric receptors or receptor complexes with varied allosteric properties and substrate binding kinetics to functionalize waveguide surfaces. Ancillary research would likely include the development of surface chemistries for immobilization of new receptor types.[66]

Along with the development of novel receptors and surface chemistries, the spatial selectivity of waveguide surface functionalization must also be improved. Traditionally, waveguide functionalization for multiplexed sensing[4,20] is performed following photonic structure fabrication; however, *in situ* functionalization may improve spatial control and reduce contamination of other photonic components, increasing the sensors multiplexed capacity.[4,67] The capability of click chemistry and silanization to attach binding sites to silicon surfaces may provide an additional benefit.[68–70] These approaches, however, have not been demonstrated or developed for PIC sensor specific technologies.[4]

New material platforms, such as porous silicon, could be exploited to enhance detection via larger transducer area and molecular size selectivity in PIC sensors, as demonstrated in a DNA sensor and an interferometer-based nerve agent sensor.[71,72] Additional on-chip optical control could be enabled by nanoscale structured surfaces. Referred to as metasurfaces,[73] such surfaces have demonstrated an unprecedented control of light in wavelength and polarization, offering a route not only to improve devices but offer novel on-chip functionality. For example, an ultrathin metasurface that efficiently separates left-hand and right-hand circular polarizations at visible wavelengths was recently reported[74] and demonstrated to function as an ultracompact circular dichroism (CD) spectrometer; traditional CD spectrometers were large, mechanically slow, and expensive instruments with no on-chip counterpart. The integration of metasurface-based spectrometric methods on a chip platform could enable the ultrafast detection of complex, mission-relevant molecules.

Usability advances could be enabled by transitioning PIC sensors from a hard silicon substrate to flexible, biocompatible material platforms that would enable PIC-based wearable and implantable sensors for both physiological monitoring and the continuous interrogation of the immediate environment. Several reports demonstrate PIC sensors embedded in polymers such as poly(dimethyl)siloxane (PDMS) or photoresists such as SU-8 via device transfer methods.[75] However, the mechanical and thermal durability of these sensors is not yet fully understood. PDMS-only sensors may offer an ideal platform in terms of combined robustness and flexibility, however, current devices suffer from low-sensitivity attributable to challenges refractive index control during fabrication. Recently, Cai et al.[76] developed a fabrication method for tuning the refractive index of PDMS by adjusting the ratio of base and curing agent and demonstrated waveguides with a transmission loss of about 1.1 dB/cm at 460 nm. Independently, methods to mass-manufacture polymer-based PIC devices with high Qs, such as roll-to-roll nanoimprint lithography,[77] need to be further developed.

Beyond optimizing fundamental design and detection approaches, PIC-based sensors for DoD applications still need to achieve practical field and operational utility. Research to improve shelf-life and sensor reusability without a degradation in precision or sensitivity[4] is required. Reporting ROC curves and Allan deviation plots to understand FAR and long-term drift of PIC-sensors will be required to assess operational utility. Fielded sensors also require a simple sample preparation procedure at a minimum and ideally will work with native samples. Research into microfluidics may provide sample preparation solution; for example, magnetic and digital microfluidics are of considerable interest for field-based LOC applications due to their high precision, power-free operation, and utility as a functional substrate for molecular capture.[78,79]

7 Conclusions

Integrated photonics technology is paving the way toward truly portable LOC platforms and highly accurate sensors for applications outside the laboratory. Significant efforts have been made to develop ultrasensitive PIC-based sensors, but limitations of integrating all components into sample-to-answer microsystems, and the challenges associated with the real-world implementation of such devices, need to be overcome. The DoD need for such technologies has led to several research programs spanning basic research to integrated devices, as discussed in this paper, to drive the development of disruptive PIC sensors. To have a significant impact in advancing PIC-based sensors toward field-ready technologies, future research can develop reliable functionalization protocols for chemical and biological agents, use synthetic biology techniques to design new selective receptors, and optimize sensors for multiplexing.

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