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Sensing Opportunities in Integrated Photonics

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In photonics, light is used as carrier of information similar to electrons in electronics. The field of photonics began with the invention of the laser in 1960 and has revolutionized many applications. For example, optical fiber communication forms the backbone of the internet where signals are transmitted across the globe (Fig. 1a). Another example is in sensing, where photonics is used in scientific experiments that detect gravitational waves. Here, displacements are measured with extreme precision down to 10^{-18} m.

Integrated photonics is the integration of several components in an optical microchip (Fig. 1b) [1]. Light is guided through on-chip dielectric waveguides, similar to optical fibers, but much smaller and in the planar surface of the microchip (Fig. 1c,d). Modern integrated photonic chips can contain laser sources, waveguides, filters, spectrometers, modulators to encode light with electronic signals, photodetectors, and sensors (Fig. 2). Over recent decades, several standardized platforms have been developed which are currently offered by foundries worldwide [2,3]. Such a platform includes a set of material combination, fabrication processes, and library of optical components. Each platform has its own benefits and drawbacks.

Integrated photonic chips have created many opportunities in sensing with only some examples listed here. Solid state lidar using massively parallel on-chip modulation of light for optical phased arrays (Fig. 3a,b) [4]. Optical gas absorption spectroscopy (Fig. 3c), either using novel on-chip dual-comb light-sources (Fig. 3d) [5] or using on-chip spectral filters (Fig. 3e) [6]. Biosensing that detect specific molecules using functionalized waveguides to which these molecules attach (Fig. 3f,g) [7]. Ultrasound sensors that combine integrated photonics with on-chip micromechanics to make waveguides extremely sensitive to acoustical pressure (Fig. 3h) [8,9].

Telecommunication has been the main commercial driver behind integrated photonics, notably for the development of optical transceivers – devices that encode light with binary electronic signals [1,10]. Integrated photonics is becoming a mature technology and market research predicts a strong growth including new applications in sensing. The market volume of bare silicon photonic chips, which is only a fraction of the cost of packaged devices, was in 2020 \$87M with \$83M in datacenter transceivers. In 2026, this market is expected to grow to \$1.1B with \$454M in datacenter transceivers, \$478M in sensing for consumer health, and \$1M in automotive LIDAR sensing [10]. One example of this market trend is that Rockley Photonics announced plans for integrated photonic biosensors in Apple's smart watches [10].

In my opinion, there are interesting opportunities for sensing with integrated photonics, both in technology and in applications. This tutorial will cover the fundamentals of integrated photonic waveguides and components and how these are used to create innovative sensors to enable new applications.

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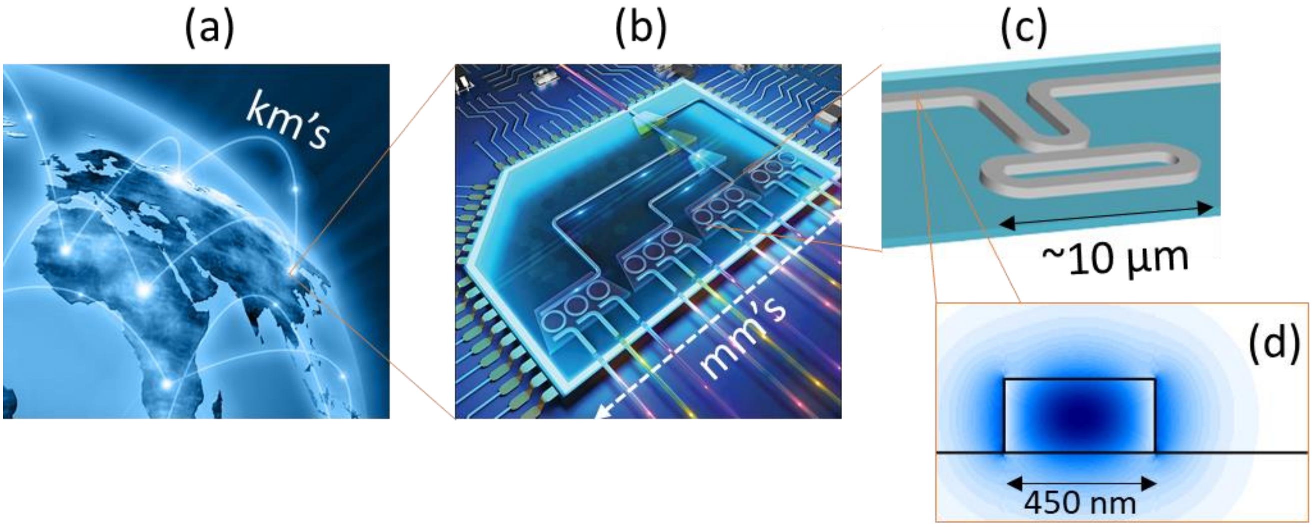

Figure 1. (a) With photonics, light is used as carrier of information, rather than electrical signals. Optical fiber connections form the backbone of the internet where information is communicated across the globe. **(b)** Artist impression of an integrated photonic microchip. Many optical functionalities are combined in a single microchip. (Reproduced from: Advanced Material Technologies, 5, 2020) **(c)** Integrated photonic waveguide and ring resonator. Light is guided on the microchip through tiny waveguides. The ring-shaped waveguide forms a photonic resonator filter. **(d)** Cross-section of silicon photonic waveguide. Electric field profile plotted in blue.

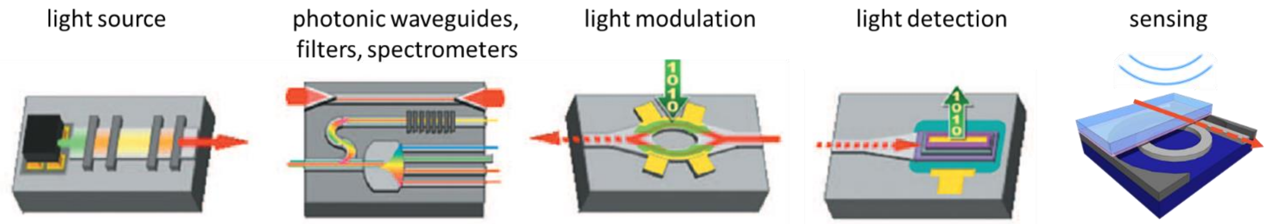

Figure 2. Optical functionality which can be combined in a integrated photonic microchip. **(1)** Light generation, **(2)** passive photonics including waveguides, filters, and spectrometers, **(3)** light modulation with electrical input, **(4)** light detection, and **(5)** photonic sensing. (Figures 1-4 adapted from David Geer, Computer 39, 16, 2006. Figure 5 adapted from Westerveld, Nature Photonics 15, 341, 2021).

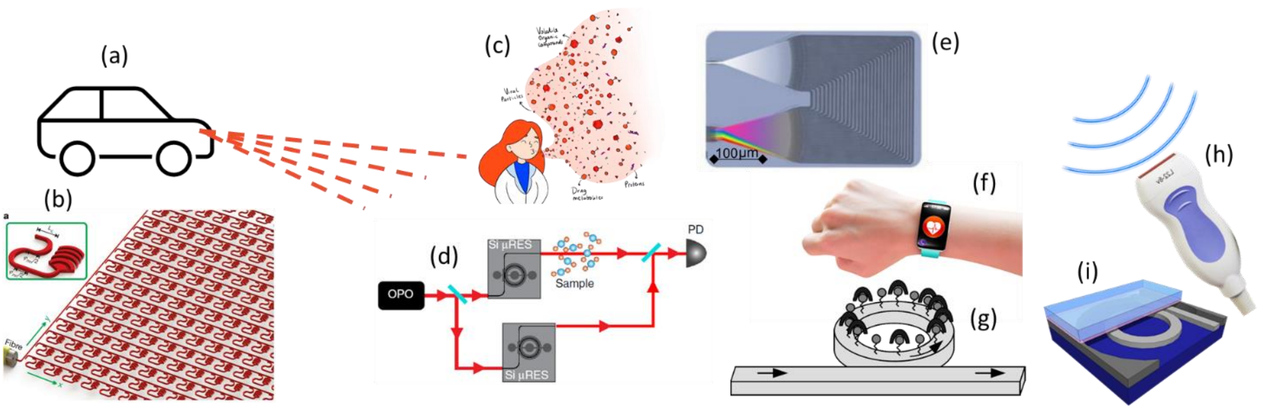

Figure 3. Opportunities for sensing with integrated photonics. (a) Lidar in automotive industry using (b) optical phased array using on-chip light modulation and routing [4]. (c) Medical gas spectroscopy using (d) on-chip dual-comb light source [5] or (e) on-chip filters [6]. (f) Photonic biosensor using functionalized sensing waveguide [7]. (h) Medical ultrasound sensing using (i) opto-mechanical waveguide [8].