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Chapter 2

Photonics for Smart Cities

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Abstract

We review the current applications of photonic technologies to Smart Cities. Inspired by the future needs of Smart Cities, we then propose potential applications of advanced photonic technologies. We find that photonics already has a major impact on Smart Cities, in terms of smart lighting, sensing, and communication technologies. We further find that advanced photonic technologies could lead to vastly improved infrastructure, such as smart water-supply systems. We conclude by proposing directions for future research that will have the greatest impact on realizing Smart City initiatives.

Keywords: photonics, nanophotonics, nanotechnology, Smart Cities, sensors, pollution, water supply, infrastructure, metamaterials, nanolasers, optics

1. Introduction

Cities behave as complex and adaptive systems that both require and inspire technology [1, 2]. Photonics—the scientific and engineering discipline dedicated to the generation, transmission, processing, and detection of light—enables much of the information and communication technology that make cities smarter. Nanoscale photonics, also known as nanophotonics, in particular, delivers advanced technologies for improving the quality of life of city inhabitants. In this chapter, we ask and answer two main questions: (1) How are current photonic technologies contributing to the development of Smart Cities? and (2) how can the Smart Cities paradigm inspire a new generation of photonic technologies?

We have surveyed the existing literature on both Smart City initiatives and applications of photonic technologies, with the aim of integrating our findings into a coherent perspective of the current and potential impact of photonics on Smart Cities.

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The chapter is divided as follows. In Section 2, we present our conceptual framework, which identifies relationships between photonics, Smart Cities, and complexity science [3]. We also provide a brief overview of the many applications of photonics in the context of urban development. In Section 3, we address our first primary question in detail. In order to achieve sufficient depth, we focus on several existing application areas of photonics. Namely we focus on smart lighting for human-centric illumination and urban agriculture; smart sensor arrays for environmental and resource consumption monitoring; and smart optical communication and signal processing systems. In Section 4, we address our second primary question in detail, using recent developments in urban water management, that is, the Flint water crisis and Southern California drought, as real-world examples. Again, to achieve sufficient depth, we focus on an exemplary potential next-generation photonic technology, a smart water sensing network. Finally, we propose avenues for further photonics research inspired by the needs of Smart Cities. It should be emphasized that it is impossible to cover all current and potential applications of photonics to Smart City technologies. We do our best to focus on what we believe are, either the most vital to improving urban quality of life, or the least well known to the research community.

2. Conceptual framework

Firstly, we propose a conceptual framework that will guide us throughout this chapter, and beyond, which is illustrated in **Figure 1**. Photonics provides technologies that enable the growth of social networks, the internet of things (IOT) [4], and maintenance of infrastructure, among other applications. Conversely, Smart Cities provide applications for photonics and drive advancement of future generations of materials, devices, circuits, and systems. Simultaneously, data collected by ubiquitous sensor arrays in Smart Cities may be delivered and analyzed not just for immediate actuation but also to researchers who study and predict phenomena that need to be monitored or controlled. Scientists may analyze the data to understand cities as complex adaptive systems of systems (CASoS), which are social–technical–natural networks exhibiting highly nonlinear dynamics [1]. Problems in CASoS are often formalized as optimization problems that require large amounts of processing power. While digital electronic number-crunching is today's norm, future processing of certain problems may be better served by optical and optoelectronic accelerators and/or signal processing systems, in which coupled photonic elements model complex dynamical behavior and augment the capabilities of electronic processors [5]. Solving these problems provides understanding to cities. Additionally, complexity science may inform photonics by solving many-body problems at the atomic, nanoscales, and mesoscales [3]. In this chapter, we focus on the interaction between photonics and Smart Cities. The other interactions illustrated by **Figure 1** form part of our roadmap for future research (Section 4).

While the definition of a Smart City remains somewhat ambiguous, researchers and practitioners do seem to be converging on a common idea [6]. Common features of the various definitions include emphasis on management and organization, technology, governance, policy, people, economy, built infrastructure, and the natural environment. Herein, we focus on technology and loosely follow the definition of Harrison *et al*., who described the Smart City as being instrumented, integrated, and intelligent [7]. In more concrete terms, all Smart Cities must have certain components, namely data collection, integration, and analysis, all leading to some form of decision making that actuates the sensed environment (**Figure 2**). We follow the description of Dirk *et al*., whereby we view the sensed environment as a system of systems, individual systems being people, businesses, communications, transport, water, and energy [8]. Additionally, we add the atmosphere to this list. The entire system is a CASoS [1]. While the size of cities and outward appearance may be extremely different, the properties of cities appear to exhibit common scaling properties that may be understood using the tools of complexity theory [9, 10]. Additionally, recommendations from mayors and researchers participating in IBM's Smarter Cities challenge have common prevailing themes, despite apparent differences in city size, location, and history [11, 12].

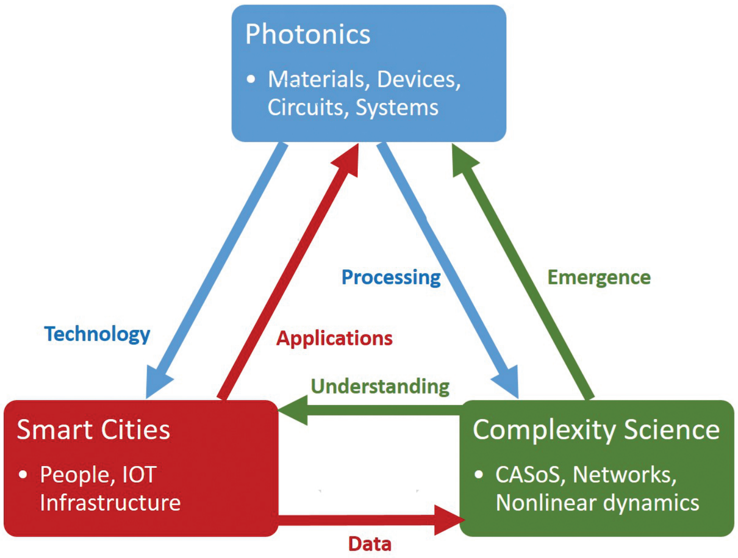

Figure 1. Conceptual framework relating photonics, Smart Cities, and complexity science.

In the context of Smart Cities, photonic sensors and phased arrays enabled data collection from the environment, while communications technologies enable high bandwidth connectivity between all Smart City components. As evidenced by the recently formed American Institute of Manufacturing for Integrated Photonics [13], key application areas of integrated photonics include (1) digital communications within datacenters and between data centers and end-users; (2) analog radio frequency (RF) and microwave communication with fiber optic links; (3) chip-scale chemical and biochemical sensing; and (4) light detection and ranging (LIDAR). Generally, we may classify the first two key applications as communications and signal processing and the last two as sensing modalities (**Figure 2**). Ultimately, through analysis and visualization, decisions are made by both humans and machines that act upon the environment, creating a feedback loop for sensing and actuation of the environment. Additionally, photonics provides lighting for cities, which affects all systems, enabling operation at all hours, and increasingly completely new possibilities, such as energy-efficient vertical farming.

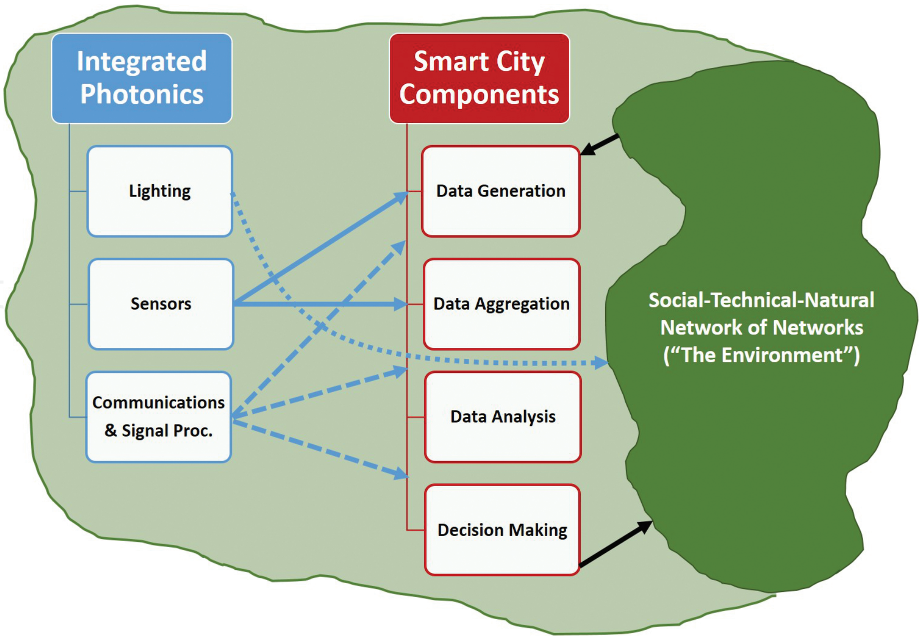

Figure 2. Schematic illustrating general relationships between major applications of integrated photonics and components of Smart Cities.

3. Current applications of photonics to Smart Cities

We broadly classify current major applications of photonics to Smart Cities as (1) lighting, (2) sensors, and (3) communications and signal processing. In the following, we briefly review examples of these application areas.

3.1. Smart lighting

The replacement of incandescent urban lighting for illumination and traffic control with light-emitting diodes (LEDs) is an ongoing application of photonics [14, 15]. LEDs are significantly more energy efficient than older light sources, and their emission wavelength is easily tuned from the UV to infrared through appropriate choice of semiconducting compounds. Several key applications of LEDs that we discuss briefly are human-centric lighting [16] and vertical farming [17].

While often taken for granted, the lighting conditions around residents of a city affect their mood, productivity, sleep patterns, and visual acuity [16]. Human-centric lighting has emerged to address the growing body of knowledge on the effects of lighting on human behavior. Case studies have shown improved learning of school children [18] and increased patient satisfaction in hospitals, when human-centric lighting replaced conventional, static indoor lighting conditions. Human-centric lighting requires dimmable light sources of different emission colors and was originally implemented with fluorescent tubes. However, tunable and dimmable LEDs with an adaptive spectrum and superior performance have become the preferable light source [16]. An additional advantage of LEDs for human-centric lighting is their inherent potential with sensing and communication capability in connected lighting systems [19].

Smart lighting is also important for the illumination of plants. Urban agriculture is the process by which fruits and vegetables for human consumption are grown in indoor greenhouse environments within densely populated cities [20]. The so-called vertical farms increase the crop yield per unit land area, relative to open, “horizontal farming,” substituting energy from the sun with artificial lighting [17]. Additionally, production of food in population centers reduces transportation costs associated with importing food from rural areas. Using LEDs as the illumination source, the wavelength of emission can be tailored for specific plants with minimal waste heat generation and minimal attraction of pests [20]. Currently, Infineon is manufacturing and marketing smart LED systems specifically for urban agriculture [21].

3.2. Smart sensing

The rapid growth of urban areas has a direct impact on the environment, which in turn affects the health and well-being of urban inhabitants. Two important elements that are essentials to humans, and life in general, are air and water. Photonic-based sensors play an essential role in monitoring and controlling air and water pollution [22]. A number of sensors based on optical effects have been demonstrated for monitoring air and water quality. Herein, we provide a brief review. We note that smart water management generally was recently highlighted in [23]. Additionally, in a comprehensive review of advanced sensing networks for Smart Cities, Hancke et al. [24] identified use of optical fibers and lasers in structural health monitoring and electrical transmission line monitoring, respectively.

In the urban environment, determining the quality of air and water is a first step towards improving quality of life for inhabitants. Key analytes of the atmosphere include particulate matter, ground-level ozone, CO, NO_x, SO_2, and lead [25]. Key analytes of water include salinity, pH, chlorine, heavy metals, and bacteria. While necessary, simply determining concentrations of these analytes is not sufficient for reducing potential hazards for urban citizens. Smart Cities ought to strive to connect sensing modalities to integrated collection and decision-making operations to mitigate the source of contaminants in the urban water or oxygen supply [26]. Before discussing smart optical sensors networks, we provide a brief review of photonic technologies for sensing contaminants in air and water. Important parameters for evaluating the performance of a given sensor include sensitivity, selectivity, response time, reversibility, amount of collected information, power consumption, and cost. Sensitivity refers to the minimum quantity of detectable matter in a given volume of gas or water. Selectivity is the ability of the sensor to identify a specific element, molecule, or compound among a gaseous or liquid mixture. Response time can be very important in the cases where real-time detection and monitoring are mandatory, for instance, in areas that are needed to be kept safe from security threats. Also, the response time and amount of collected information have direct implication on the communication bandwidth, important for a network of sensors and actuators. Reversibility refers to whether the matter, upon being sensed, can return to its pre-sensed form. Power consumption and cost becomes especially important if a large number of sensors are implemented throughout a city.

Aside from sensors based on optical excitation, many sensors utilize the electrical response of materials, including metal oxides, semiconductors, and polymers. For instance, the detection of a specific gas can be sensed by measuring the variation in the conductance of a metal oxide [27]. Advantages of sensors based on electronic material properties include low cost and short response time. Disadvantages include low sensitivity, poor selectivity, irreversibility of some materials, and sensitivity to environmental factors, for example, temperature [28].

Most optical sensors are based on spectroscopy. Advantages of sensors based on optical response of materials include high sensitivity, high selectivity, high stability, long life time, short response time for real-time detection, and robustness to environmental factors. Disadvantages tend to include a large footprint and high cost [28].

Spectroscopic analysis mainly involves techniques based on absorption and emission spectrometry. Absorption spectroscopy, based on the Beer–Lambert law, is the concentration-dependent absorption of photons at specific wavelengths. The absorption spectra of specific gases can be found in the HITRAN database [29]. Some techniques based on absorption spectroscopy include differential optical absorption spectroscopy (DOAS) [30], tunable diode laser absorption spectroscopy (TDLAS) [31], light detection and ranging (LIDAR), Raman LIDAR [32], differential LIDAR (DIAL) [33], and intra-cavity absorption spectrometry (ICAS) [34]. These methods tend to be bulky and expensive. Furthermore, most of these techniques employ long wavelengths, requiring tens of meters of open space for operation. For applications in Smart City sensing, optical components must be miniaturized, to approach their practical microscale to nanoscale limit and thereby lead to compact absorption spectroscopy systems.

Fourier transform infrared spectrometry (FTIR) is a powerful technique with applications in environmental monitoring, including pollution at power plants, petrochemical and natural gas plants, waste disposals, agricultural, and industrial sites, and the detection of gases produced in flames, in biomass burning, and in flares [35]. The National Science Foundation's Center for Mid-Infrared Technologies for Health and the Environment (MIRTHE) has been using quantum cascade lasers (QCLs) to monitor air quality, including methane, ammonia, and other “molecular footprints” [36]. For example, the air quality of Beijing before, during, and after the 2008 Olympic Games was measured. QCLs also enable detection of natural-gas leaks and ground-based verification of remote sensors on aircraft and spacecraft. Thus far, measurements require large optical path lengths. Therefore, the technology is currently useful for inter-building distances in a city, but not at the intra-building scale [36].

In the intra-building scale, sensing of gases by photonic technologies was reviewed generally in [37]. Commercially available technologies include palm-size optical dust sensors [38] and dangerous-particle detectors [39]. Particulate matter less than 2.5 μm in diameter is especially prone to cause problems in urban environments. Such small particles come from industrial and automotive exhaust and often lead to cardiac and lung diseases [39]. In [38], an infrared emitting diode and a phototransistor are combined to enable detection of light scattered from airborne dust. The output of the sensor is an analog voltage proportional to the measured dust density, with a sensitivity of 0.5 V/0.1 mg/m^3. Shorter wavelengths could increase sensitivity [38]. Mitsubishi Electric recently claimed that a unique, double-sided mirror design is able to collect nearly twice as much scattered light as conventional single-sided designs for small-particle detection [39]. A proprietary algorithm is then able to distinguish between pollen and dust, based on the respective differences in the optical characteristics of their scattered light. The air-quality sensor prototype is based on a laser diode, aspheric lens, light-collecting mirror, photodetector, and airflow controller. The prototype measures just 67 x 49 x 35 mm, and the company says that it can detect particle sizes down to 0.3 μm in diameter ($PM_{2.5}$). The smaller $PM_{2.5}$ is produced by various combustion processes, including those in motor vehicles, power plants, and residential wood burners [39]. In [40], a sensor for sulfur dioxide was presented based on differential absorption spectroscopy of UV light. The device had a reported temporal resolution of 3 s, optical path length of 19.6 m, and minimum detection limit of 75 ppb SO_2. Applications for detecting levels of vehicle exhaust were discussed. In [41], sensing agents coated on the surface of bent optical fiber probes were analyzed for the detection of ammonia and carbon dioxide, and sensing humidity.

Concerning water sensing, recently, in [42] a real-time in-line bacteria sensor was demonstrated based on 3D image recognition. The device showed a 10-min temporal resolution and classified particulates as bacterial or abiotic based on over 50 image parameters. Field trials demonstrated that rapid changes in bacteria composition could be detected, in both pure and mixed solutions. In [43], the absorption of light in water was measured for wavelengths in the 300–800 nm range, as a function of both salinity and temperature. The resulting data provide a baseline for sensing local changes to water conditions. In [44], a water pollution monitoring system was demonstrated utilizing a water-core waveguide and UV illumination. Traces of nitrate and chlorine as low as 22 μg/L and 26 μg/L were detected, respectively. In [45], it was demonstrated that a cavity could significantly improve the absorption sensitivity of FTIR spectrometry by increasing the effective path length. This is important for achieving high sensitivity, while maintaining a small footprint for the detection of pollution in low-volume samples.

Aside from discrete devices, photonic sensors have benefited significantly from the maturity of CMOS technology, pushing on-chip integration toward microscale and nanoscale footprints. The emergence of CMOS sensors is attractive not only for the integration purposes but also due to incomparable advantages related to high-sensitivity, high-speed response, electromagnetic immunity, and low cost. Numerous high-performance integrated devices have been developed for chemical, biochemical, and gas detection. These sensors are based on various topologies that utilize changes to the local refractive index, including high-quality factor resonators [46, 47], Mach-Zehnder interferometers [48], 2D photonic crystal microcavities [49], and surface plasmon resonances [50, 51].

3.3. Smart communications and signal processing

Because of its unmatchable propagation velocity and carrier frequencies, light is the physical medium of choice through which information is carried over long distances [52]. Gradually, the meaning of “long distances” has evolved, as the miniaturization of optical components has enabled cost-effective optical links over smaller and smaller distances, while the demand for bandwidth has increased. As internet traffic becomes increasingly dominated by activity within data centers, the need for inexpensive, compact, fast, and efficient integrated optical components will increase. Fiber optic networks (FON) are already essential to the operation of cities, providing two-way communication between residents, businesses, and the rest of the world.

FON are smart systems that correct themselves when error or failures on the network arise. The transceivers used on FON contain detectors that monitor back-reflections from the fibers through optical-time domain reflectometry (OTDR) [53]. If there is a failure, back-reflections increase and an upper electronic layer is programmed to re-route the network, reducing errors and delays. We believe OTDR can inspire a new generation of self-controlled networks of sensors for efficient real-time decision making.

Fiber-to-the-home (FTTH) is the final leg of a FON and has become a critical component of Smart Cities [54]. Because a Smart City contains an extensive network of sensing and actuating nodes, fast and efficient communications between nodes are essential for effective operation. FTTH provides the fastest communication links currently conceivable and is only expected to become more widespread, interfacing with wireless communication and mobile platforms [54].

LEDs were mentioned previously as main components in smart lighting. Additionally, LEDs can simultaneously function as a communication channel, making a host of systems in the city smarter [55, 56]. Visible light communications (VLC) were first proposed decades ago for indoor communications [57], and experienced a resurgence of attention in 2004 [58]. Soon thereafter, the networking benefits of light-fidelity (Li-Fi) networks relative to RF-based Wi-Fi networks were demonstrated [59], followed by data rates exceeding 500 Mbps [60], and by a comprehensive analysis of the potential of VLC [56]. A multiplexed VLC system based on individual red, green, and blue LEDs exceeding a data rate of 3 Gbps was demonstrated in [61].

In addition to high-speed and high-capacity data transmission, data processing increasingly occurs in the optical domain [62, 63]. Photonic signal processing (PSP) enables multi-GHz sampling of RF or microwave signals, bypassing the inherent time-bandwidth limitations of electrical systems, with immunity to electromagnetic interference [64]. Widely tunable filters, waveform generators, Hilbert transformers, wave mixers, and signal correlators built from photonic devices have all been demonstrated, with inherent compatibility with fiber optics communications [62]. Furthermore, use of plasmonic materials suggests avenues for PSP elements in nanoscale footprints [65]. In the context of Smart Cities, compact PSP systems should ensure the processing of large amounts of information from arrays of sensors monitoring the urban environment.

4. Potential applications of photonics to Smart Cities

Having reviewed existing photonic technologies in the application areas of lighting, sensing, and communications and signal processing for Smart Cities, we now explore advanced applications. For concreteness, we use the recent water crisis in Flint, MI, USA, as well as the ongoing drought in San Diego, CA, USA, as real-world examples for proposing a smart network of integrated optical water resource sensors. We then discuss how Smart City concepts will drive long-term research goals in the photonics community.

Figure 3 summarizes a roadmap for photonic technologies for addressing urban water problems. Existing optics-based sensors have the ability to independently measure concentrations of pH, salinity, and bacteria, as well as the amount of water consumed. We propose to integrate these discrete sensors into a compact, cost-effective, energy-efficient system with graphical user interface (GUI) and connectivity to the outside world enabled by RF or optical transmitters (Tx) for wireless or plastic optical fiber (POF) communications. Finally, we anticipate that Smart City initiatives may drive research goals in photonics, including towards chip-scale spectrometers utilizing nanoscale light sources and metamaterials.

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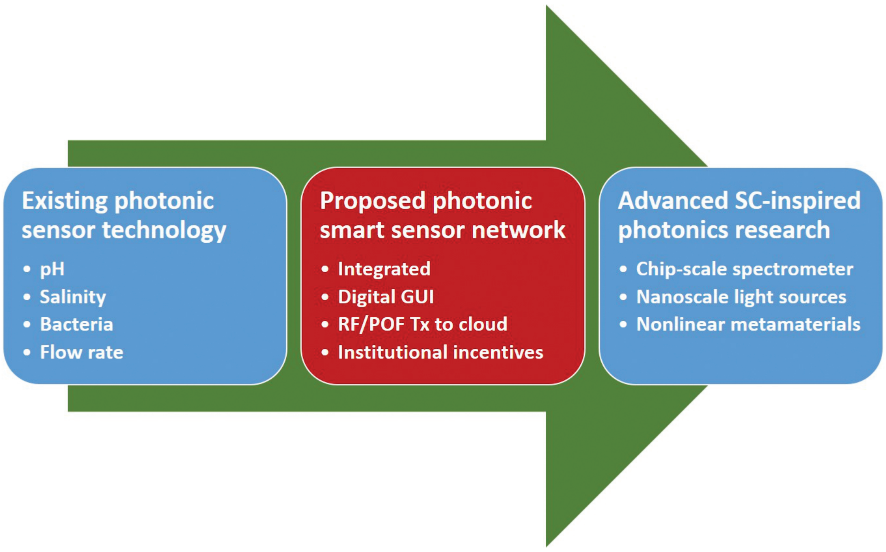

Figure 3. Technology roadmap of smart optical network for water-supply monitoring, highlighting existing sensing modalities, and potential intermediate, and long-term research topics.

4.1. Flint water pollution and the southern California drought

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The recent drinking water crisis in Flint, Michigan, stands as a reminder of the fragility of civil infrastructure and poor decision making [66]. Century-old lead pipes leached lead into the drinking water supply after the source of the water was switched from Detroit to the Flint River. While elevated lead levels were noticed and reported by residents, local and state officials ignored changes to the water chemistry that caused leaching and eventual lead pollution [66]. Could this crisis, and situations like it, be avoided in the future with smart sensor networks? How can this crisis inspire future photonic technologies, in both the near and long terms?

Southern California has experienced an ongoing drought that affects over 34 million people (see **Figure 1a**) [67]. Because much of the population lives in arid regions, coastal cities in the region rely on imported water. This is exemplified by the water supply of San Diego, about

85% of which is imported from outside sources, such as the Colorado River and Sacramento Bay Delta (**Figure 4b**) [68]. Reduced water consumption has, therefore, become a major strategy for the region to retain a sufficient long-term supply [69]. Additionally, water from the Colorado River contains elements from old mining and industrial sites, while the water from the State Water Project contains traces of pesticides, herbicides, and high bromide levels. Efficient water-quality monitoring again becomes fundamental for the safety of urban dwellers [68]. How can smart sensor networks enable more efficient use of water? How can the longstanding drought conditions inspire future photonic technologies? How can smart sensors assist on water quality real-time monitoring?

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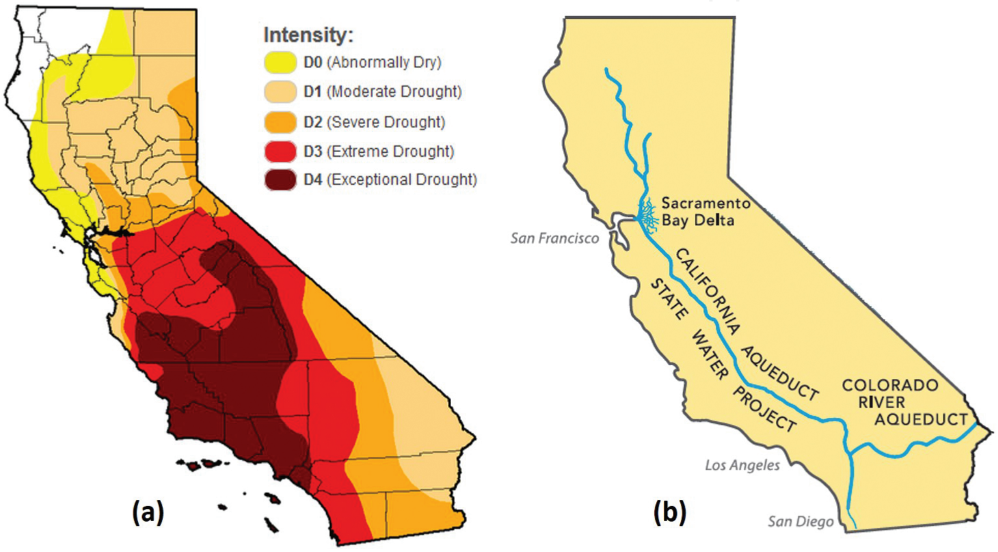

Figure 4. (a) Map of drought conditions in state of California as of May 24, 2016 [67]. (b) Map of California highlighting the main sources of water supplying the San Diego region [68].

4.2. Preventing future crises

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To prevent the occurrence of pollution or resource-driven water crises, we propose an example of a smart water-supply system enabled by integrated optical sensors and communications. Recently, the city of Na Ding, Vietnam, modernized their water-supply system, installing sensors for salinity, pH, turbidity, and chlorine, to improve water treatment options [70]. Our proposed system goes further, detecting bacteria and consumption rates and relaying information directly to residents.

The proposed smart water system is shown in **Figure 5**. Integrated photonic sensors (red circles) simultaneously monitor pH, salinity, bacteria, and flow levels, and transmit this information to data aggregators and individual users. The transceiver architecture depends on data requirements, as outlined in [24]; we illustrate the possibility of wireless data transmission to residents and fiber links between regional level sensors and the aggregator. Note that wireless transmission may be either RF or VLC. Aggregated data are analyzed, creating information upon which decisions may be made, affecting the water supply and/or water treatment. All information is stored on the cloud for meta-analysis and eventual formation of knowledge, as advocated in [2].

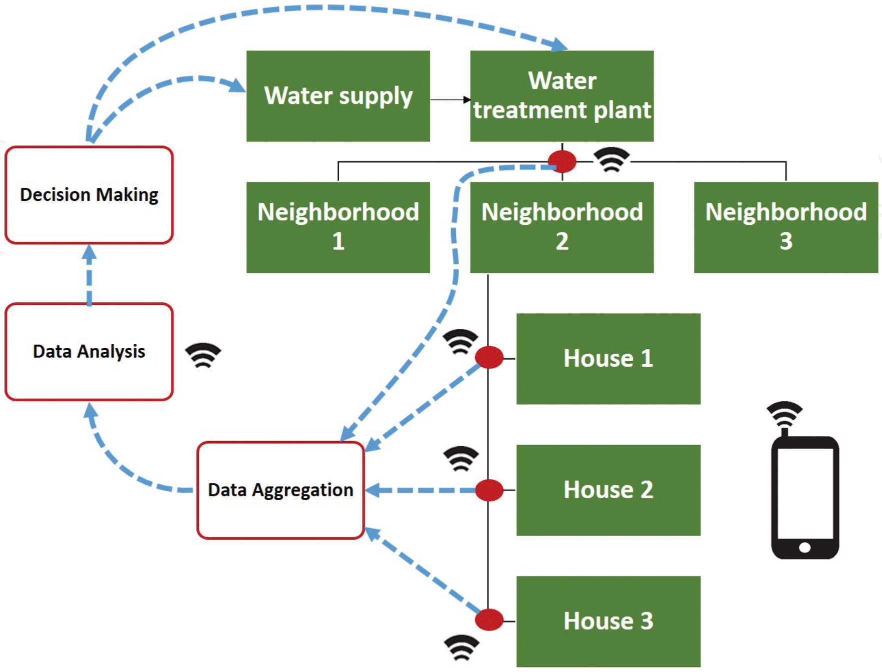

Figure 5. Schematic of smart water-supply system enabled by integrated optical sensors and optical communications. Integrated optical sensors (red circles) generate data on water quality and consumption. Data are transmitted by RF or optical communications links, depending on data rate requirements. Optical links transmit aggregated data for analysis. Decision is made based on analysis to actuate water supply or treatment plant appropriately, for example, alter salinity levels. Additionally, generated local data are transmitted to citizens via smart phone app and analyzed aggregate data are made accessible via public database.

Reflecting on the case of Flint, Michigan, the proposed smart water system could in principle prevent widespread pollution created by human error [66]. Firstly, the system could be implemented with autonomous decision making and actuation such that the water chemistry would be altered in response to measurements throughout the network. Through iterative sensing and actuation, lead levels would decrease in response to reaching a water chemistry wherein leaching would not occur. Secondly, real-time transmission of data to individual users and online databases would enable greater citizen participation in resource management. Consequently, local and state officials could be more easily held accountable for their actions or inactions in response to system problems.

For San Diego, California, the proposed smart water system could significantly reduce water consumption, a primary goal of the city's Climate Action Plan [69]. Transmission of real-time water use to customers would enable them to quantify wasteful practices. Employers could incentivize environmentally conscious behavior by awarding employees who make their water use data available and meet resource consumption goals [71]. A smart water system thereby enables the gamification of resource management, much like step-counters incentivize employees to practice preventive healthcare.

The smart water-supply system proposed here shares features with smart air-quality monitoring systems. For example, in Amsterdam, Netherlands, a start-up named TreeWiFi installed smart birdhouses to monitor the amount of combustion particles (NO_2) in the air [72]. LED lights placed on the roof of the birdhouse show real-time levels of pollution, and if the lights go green, which means improved quality of air, the network makes free Wi-Fi spots available. The next step is to make the collected data available to researchers, governmental departments, and the public, as we have also proposed in our smart water-supply system.

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4.3. Advanced photonic technologies for Smart Cities

Sensing and monitoring systems for Smart Cities present a continuous cycle of operation: sensing—communication—decision making—sensing. Returning to **Figure 1**, Smart City requirements will inspire the development of advanced photonic technologies such as detectors and sensors, light sources, modulators, and optical hardware accelerators offering unprecedented speeds for communication and decision making, while consuming low power in a small footprint. Based on these requirements, we briefly describe our vision on how Smart Cities can drive research in advanced nanophotonic technologies.

In the example of the birdhouses, the sensors are purely electronic, presenting a large footprint for detecting just one type of molecule. However, in Section 3(b), we have shown examples of water-quality monitoring through absorption of light in water, where different choice of wavelengths allows probing different properties of water, such as temperature, salinity, pH, and traces of nitrates and chlorine. In the same way, different wavelengths can monitor different molecular constituents of air. Photonics then brings a new concept to sensing, sensor fusion. In data processing, this concept is related to combining sensory data from different sources to reduce the uncertainty in the resulting data. Here, we extend the concept to a sensor that simultaneously probes different properties of the desired environment. An array of five semiconductor nanolasers [73, 74], each one with all spatial dimensions less than 1 μm, placed 1 μm from each other, could provide light emission in five different wavelengths on an array pitch of 10 μm. A semiconductor laser, if reversed biased, can act as photodetector, which means a similar compact array could be used for power detection. Inserting now a medium to be monitored between these two arrays, one can sense five different properties of the medium, where each property is addressed by one wavelength. Recent advances to increase the efficiency of these semiconductor nanolasers operating at room temperatures will make this technology available in the near future [73].

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After detection, a communication channel is necessary. Here, current optical communications technologies can play a major role from which we can learn. Previously, we explained the concept of FTTH, where the objective is replacing existing copper infrastructure for telecommunications by optical fibers, providing vastly higher bandwidths and enabling more robust internet services to the end consumer. We envision an active optical network that we name fiber-to-the-sensors (FTTS). All fused sensors, in the near future, are connected by optical fibers using the same protocols and fiber optic cable infrastructure already used on communication systems. In FTTH, information from different users can use different channels (frequencies), which are multiplexed, transmitted across long distances, and then demultiplexed to reach the final users. On FTTS, information of different frequencies (measured water or air properties) are multiplexed and transmitted with fiber optics to a central node, where information is demultiplexed to be classified and used on a decision-making process. The information on quality and quantity consumed is also returned to the user. Multiplexers [75], demultiplexers, efficient laser sources for transmitters [76], efficient and sensitive detectors for receivers, fast switches and routers based on nonlinear optical process [77], and other photonics technologies are needed to increase the bandwidth and reduce power consumption in optical interconnects that allows FTTH, and possibly FTTS [78]. If the number of sensors in a Smart City starts to increase, fast communication, and data processing is necessary for fast decision making. In this case, all technology that has been developed for fast, robust, and low power consumption optical interconnects in data centers can be applied on a FTTS network [73, 79, 80]. Here, central nodes that collect information from different sensors are the data centers. Furthermore, OTDR systems used for fiber fault detection can be applied to detect sensor failures and reroute the network.

Besides smart sensors networks, there are several other Smart City needs than can benefit from photonics. Continued progress is needed in the area of mid- and far-infrared photonics for developing optical sources emitting in atypical frequencies, such as within the Terahertz window. Working in these frequencies allows monitoring optical absorption of elements that cannot presently be monitored, resulting in ubiquitous sensing capabilities for monitoring air and water pollution. Consequently, detection in these frequencies regimes will also be necessary. One of the candidates for enhanced emission and detection in these regimes is III–V semiconductors coupled to plasmonic inclusions [81–83]. The first luminescent hyperbolic metamaterial was developed recently by our group, operating at the C telecommunication band [84–86]. However, the capability of tuning the constituent materials allows, in principle, absorption and emission in the required atypical wavelengths. Other application of metamaterials includes perfect absorbers for solar cells that can enhance the energy harvesting and super-lenses for imaging with higher resolutions [87].

More progress is also needed in the engineering of light-matter interactions, for increasing the fundamental speed limit and efficiencies with which optoelectronic devices may be modulated [88]. While devices based on stimulated emission, for example, semiconductor lasers, are limited to less than 100 GHz modulation bandwidth due to relaxation oscillations, it is conceivable to design faster devices based on spontaneous emission [89]. No devices have yet approached the fundamental limits to the enhancement of linear radiative processes [90] or nonlinear processes [91], necessitating that engineered nanostructures and metamaterials remain an active focus of research for the benefit of all Smart City applications.

4.4. Mitigating deleterious effects of future crises

Finally, efficient decision making is extremely necessary, as we can remember from the Flint case; a human decision making, or rather negligence, led to a catastrophic scenario. In the last few years, there is a trend on researching optical hardware accelerators to solve large-scale, high-complexity problems using brain inspired architectures for efficient pattern recognition with low power consumption. Examples of proposed and demonstrated devices include nonlinear coupled semiconductor lasers for pattern recognition and decision making [5] and photonic time stretching for processing images and information [92]. It is expected that analog computers and hardware accelerators will advance significantly in the next few years. While the current focus is to assist electronic-based computation, there is plenty of space for developing new architectures designed for Smart Cities.

As an example, we consider the application of optical computing to problems in infrastructure resiliency. The resiliency of a system is a measure of its ability to withstand external forces, respond quickly to damages, and return to a normal state of operation [93]. Negative external forces include natural disasters, industrial accidents, and terrorist attacks. Quantitative descriptions of resiliency provide a means for optimizing the system by minimizing the costs associated with disruptions and system downtime [94]. These optimization problems are often formalized in terms of a multimode resource-constrained project scheduling problem [95], which may be solved using the simulated annealing algorithm [96, 97].

Physical implementation of simulated annealing with optical components was first investigated decades ago [98, 99]. Recently, optical hardware accelerators have gained more traction for assisting electronic digital information processing, for particular classes of problems wherein the difficulty scales nonlinearly with problem size, such as modeling metastable heteroclinic channels [100]. An initial concept with this focus in mind was recently proposed in [5]. We believe that continued co-optimization of nanophotonic materials, devices, and system architectures could make photonic hardware accelerators competitive for solving urban management problems of the future.

5. Conclusion

We have identified the major applications of photonics to Smart Cities and outlined topical areas for future research. It is hoped that this chapter serves simultaneously as a review of the impact of photonics on Smart Cities and as a roadmap for photonics research inspired by the demands of Smart Cities. As the global population becomes increasingly urban, photonics-based solutions are increasingly needed for improving the lives of all urban-dwellers.

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References

[1] R. Glass, A. L. Ames, W. A. Stubblefield, S. H. Conrad, S. L. Maffitt, L. A. Malczynski, D. G. Wilson, J. J. Carlson, G. A. Backus, M. A. Ehlen, K. B. Vanderveen, and D. Engi, A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative, Sandia National Laboratory, Albuquerque, NM (2008).

[2] A. Ramaswami, A. G. Russell, P. J. Culligan, K. R. Sharma, and E. Kumar, "Meta-principles for developing smart, sustainable, and healthy cities," Science 352, 940–943 (2016).

[3] M. Mitchell, Complexity: A Guided Tour, Oxford University, New York (2009).

[4] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities," IEEE Internet Things J. 1, 22–32 (2014).

[5] S. Shahin, F. Vallini, F. Monifi, M. Rabinovich, and Y. Fainman, "Heteroclinic dynamics in photonic cognitive motif network," in Conference on Lasers and Electro-Optics, OSA (2016), p. ATu3O.3.

[6] H. Chourabi, J. R. Gil-Garcia, T. A. Pardo, T. Nam, S. Mellouli, H. J. Scholl, S. Walker, and K. Nahon, "Understanding smart cities: An integrative framework," in 45th Hawaii International Conference on System Sciences, Honolulu, HI (2012), pp. 2289–2297.

[7] C. Harrison, B. Eckman, R. Hamilton, P. Hartswick, J. Kalagnanam, J. Paraszczak, and P. Williams, "Foundations for smarter cities," IBM J. Res. Dev. 54, (2010).

[8] S. Dirks and M. Keeling, A Vision of Smarter Cities: How Cities Can Lead the Way into a Prosperous and Sustainable Future, IBM Institute for Business Value, North Castle, NY (2009).

[9] L. Bettencourt, J. Lobo, D. Helbing, C. Kuhnert, and G. West, "Growth, innovation, scaling, and the pace of life in cities," Proc. Natl. Acad. Sci. 104, 7301–7306 (2007).

[10] L. Bettencourt, "The origins of scaling in cities," Science 340, 1438–1441 (2013).

[11] How to Transform a City: Lessons from the IBM Smarter Cities Challenge, IBM Smarter Cities White Paper (2012).

[12] How to Reinvent a City: Mayors' Lessons from the Smarter Cities Challenge, IBM Smarter Cities White Paper (2013).

[13] "Key technology manufacturing areas," http://www.aimphotonics.com/key-technology-manufacturing-areas/, American Institute for Manufacturing, Albany, NY (2016).

[14] A. Sabapathy and J. Whittaker, "An Assessment of Energy Efficiency and Carbon Reductions from Replacing Halogen Lamps with Light Emitting Diodes in Traffic Lights – A Case Study of Gloucestershire County's Initiative," Energy Environ. 22, 361–374 (2011).

[15] J. Lai, J. Qiu, J. Chen, Y. Wang, and H. Fan, "Application of wireless intelligent control system for HPS lamps and LEDs combined illumination in road tunnel," Comput. Intell. Nueroscience 2014, 429657 (2014).

[16] S. Walerczyk, "Human-centric lighting," http://humancentriclighting.org/, Lighting Wizards (2012).

[17] D. Despommier, The Vertical Farm: Feeding the World in the 21st Century, Macmillan, New York (2011).

[18] M. S. Mott, D. H. Robinson, A. Walden, J. Burnette, and A. S. Rutherford, "Illuminating the effects of dynamic lighting on student learning," SAGE Open, http://dx.doi.org/10.1177/2158244012445585 (2012).

[19] T. Herbst, "Why lighting systems will become more connected," in 2015 Connected Lighting Systems Meeting, U.S. Department of Energy, Washington, D.C. (2015).

[20] M. Rozenfeld, "Indoor farms could revolutionize agriculture: No soil, sunlight, or pesticides required," IEEE Institute, http://theinstitute.ieee.org/technology-topics/life-sciences/indoor-farms-could-revolutionize-agriculture (Published online May 23, 2016).

[21] Infineon, "LEDs in urban farming," https://www.infineon.com/cms/en/about-infineon/company/our-contribution/urbanfarming/, Infineon (2016).

[22] T. Kjellstrom, M. Lodh, T. McMichael, G. Ranmuthugala, R. Shrestha, and S. Kingsland, Air and Water Pollution: Burden and Strategies for Control, The International Bank for Reconstruction and Development/The World Bank, Washington, D.C. (2006).

[23] T. A. Larsen, S. Hoffmann, C. Lüthi, B. Truffer, and M. Maurer, "Emerging solutions to the water challenges of an urbanizing world," Science 352, 928–933 (2016).

[24] G. P. Hancke and B. de C. E. Silva, "The role of advanced sensing in smart cities," Sensors (Basel). 13, 393–425 (2013).

[25] S. Devarakonda, P. Sevusu, H. Liu, R. Liu, L. Iftode, and B. Nath, "Real-time air quality monitoring through mobile sensing in metropolitan areas," in Proceedings of the 2nd

ACM SIGKDD International Workshop on Urban Computing – UrbComp'13, ACM Press, Chicago, IL (2013), p. 1.

[26] K. Pretz, "An urban reality: Smart cities," IEEE Institute, http://theinstitute.ieee.org/technology-focus/technology-topic/an-urban-reality-smart-cities (Published online 2014).

[27] A. Fioravanti, A. Bonanno, S. Gherardi, M. C. Carotta, and A. N. Skouloudis, "A portable air-quality station based on thick film gas sensors for real time detection of traces of atmospheric pollutants," IOP Conf. Ser. Mater. Sci. Eng. 108, 12005 (2016).

[28] X. Liu, S. Cheng, H. Liu, S. Hu, D. Zhang, and H. Ning, "A survey on gas sensing technology," Sensors 12, 9635–9665 (2012).

[29] L. S. Rothman, I. E. Gordon, Y. Babikov, A. Barbe, D. Chris Benner, P. F. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L. R. Brown, A. Campargue, K. Chance, E. A. Cohen, L. H. Coudert, V. M. Devi, B. J. Drouin, A. Fayt, J.-M. Flaud, R. R. Gamache, J. J. Harrison, J.-M. Hartmann, C. Hill, J. T. Hodges, D. Jacquemart, A. Jolly, J. Lamouroux, R. J. Le Roy, G. Li, D. A. Long, O. M. Lyulin, C. J. Mackie, S. T. Massie, S. Mikhailenko, H. S. P. Müller, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. Perevalov, A. Perrin, E. R. Polovtseva, C. Richard, M. A. H. Smith, E. Starikova, K. Sung, S. Tashkun, J. Tennyson, G. C. Toon, V. G. Tyuterev, and G. Wagner, "The HITRAN2012 molecular spectroscopic database," J. Quant. Spectrosc. Radiat. Transf. 130, 4–50 (2013).

[30] Z. Haiming, "Experiment study of continuous emission monitoring system based on differential optical absorption spectroscopy," in 2008 International Workshop on Education Technology and Training & 2008 International Workshop on Geoscience and Remote Sensing, IEEE, Beiging, China (2008), Vol. 1, pp. 175–177.

[31] Y. Miao, Q. Yao, N. Qiu, and J. Zhang, "Application research of laser gas detection technology in the analysis of sulphur hexafluoride," CICED 2010 Proc. 1–3, Nanjing, China (2010).

[32] H. Miya, T. Shiina, T. Kato, K. Noguchi, T. Fukuchi, I. Asahi, S. Sugimoto, H. Ninomiya, and Y. Shimamoto, "Compact Raman lidar for hydrogen gas leak detection," in 2009 Conference on Lasers & Electro Optics & The Pacific Rim Conference on Lasers and Electro-Optics, IEEE, Shanghai (2009), pp. 1–2.

[33] S. Kuang, J. F. Burris, M. J. Newchurch, S. Johnson, and S. Long, "Differential absorption lidar to measure subhourly variation of tropospheric ozone profiles," IEEE Trans. Geosci. Remote Sens. 49, 557–571 (2011).

[34] K. Liu, T. Liu, J. Jiang, G. D. Peng, H. Zhang, D. Jia, Y. Wang, W. Jing, and Y. Zhang, "Investigation of wavelength modulation and wavelength sweep techniques in intracavity fiber laser for gas detection," J. Light. Technol. 29, 15–21 (2011).

[35] Z. Bacsik, J. Mink, and G. Keresztury, "FTIR spectroscopy of the atmosphere part 2. Applications," Appl. Spectrosc. Rev. 40, 327–390 (2005).

[36] P. Daukantas, "Air-quality monitoring in the mid-infrared," Opt. Photonics News 26(11), 26–33 (2015).

[37] J. Hodgkinson and R. P. Tatam, "Optical gas sensing: a review," Meas. Sci. Technol. 24, 12004 (2013).

[38] "Optical dust sensor – GP2Y1010AU0F," Sparkfun product sheet (2016), https://www.sparkfun.com/products/9689.

[39] "Mitsubishi air quality sensor detects dangerous particulates," Optics.org (Published online February 9, 2016), http://optics.org/news/7/2/13.

[40] J. T. Pisano, C. G. Sauer, J. Robbins, J. W. Miller, H. Gamble, and T. D. Durbin, "A UV differential optical absorption spectrometer for the measurement of sulfur dioxide emissions from vehicles," Meas. Sci. Technol. 14, 2089–2095 (2003).

[41] L. Xu, J. C. Fanguy, K. Soni, and S. Tao, "Optical fiber humidity sensor based on evanescent-wave scattering," Opt. Lett. 29, 1191 (2004).

[42] B. Højris, S. C. B. Christensen, H.-J. Albrechtsen, C. Smith, and M. Dahlqvist, "A novel, optical, on-line bacteria sensor for monitoring drinking water quality," Sci. Rep. 6, 23935 (2016).

[43] W. S. Pegau, D. Gray, and J. R. V. Zaneveld, "Absorption and attenuation of visible and near-infrared light in water: dependence on temperature and salinity," Appl. Opt. 36, 6035 (1997).

[44] P. Dress, M. Belz, K. F. Klein, K. T. V. Grattan, and H. Franke, "Water-core waveguide for pollution measurements in the deep ultraviolet," Appl. Opt. 37, 4991 (1998).

[45] A. A. Ruth, J. Orphal, and S. E. Fiedler, "Fourier-transform cavity-enhanced absorption spectroscopy using an incoherent broadband light source," Appl. Opt. 46, 3611 (2007).

[46] X. Fan, I. M. White, H. Zhu, J. D. Suter, and H. Oveys, "Overview of novel integrated optical ring resonator bio/chemical sensors," in A. V. Kudryashov, A. H. Paxton, and V. S. Ilchenko, eds., International Society for Optics and Photonics, San Jose, CA (2007), p. 64520M.

[47] H. K. Hunt and A. M. Armani, "Label-free biological and chemical sensors," Nanoscale 2, 1544 (2010).

[48] F. Prieto, B. Sepulveda, A. Calle, A. Llobera, C. Dominguez, A. Abad, A. Montoya, and L. M. Lechuga, "An integrated optical interferometric nanodevice based on silicon technology for biosensor applications," Nanotechnology 14, 907–912 (2003).

[49] B. Troia, A. Paolicelli, F. De, and V. M. N. Passaro, "Photonic crystals for optical sensing: A review," in Advances in Photonic Crystals, InTech, Rijeka, Croatia (2013).

[50] J. Homola, "Surface plasmon resonance sensors for detection of chemical and biological species," Chem. Rev. 108, 462–493 (2008).

[51] B. Sepúlveda, P. C. Angelomé, L. M. Lechuga, and L. M. Liz-Marzán, "LSPR-based nanobiosensors," Nano Today 4, 244–251 (2009).

[52] G. Agrawal, Nonlinear Fiber Optics, Academic Press, San Diego, CA (2007).

[53] M. K. Barnoski, M. D. Rourke, S. M. Jensen, and R. T. Melville, "Optical time domain reflectometer," Appl. Opt. 16, 2375 (1977).

[54] R. Jones, "FTTH at the heart of a smart city," white paper, Fiber to the home council of Middle East and North Africa, Amman, Jordan (2015).

[55] H. Haas, "High-speed wireless networking using visible light," SPIE Newsroom (Published online April 19, 2013), DOI: 10.1117/2.1201304.004773.

[56] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," IEEE Commun. Surv. Tutorials 17, 2047–2077 (2015).

[57] F. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," Proc IEEE 67, 1474–1486 (1979).

[58] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Trans. Consum. Electron. 50, 100–107 (2004).

[59] M. Z. Afgani, H. Haas, H. Elgala, and D. Knipp, "Visible light communication using OFDM," in 2nd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, 2006. TRIDENTCOM 2006, IEEE, Barcelona, Spain (2006), pp. 129–134.

[60] J. Vucic, C. Kottke, S. Nerreter, K.-D. Langer, and J. W. Walewski, "513 Mbit/s visible light communications link based on DMT-modulation of a white LED," J. Light. Technol. 28, 3512–3518 (2010).

[61] F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, and H. T. Huang, "Performance comparison of OFDM signal and CAP signal over high capacity RGB-LED-based WDM visible light communication," IEEE Photonics J. 5, 7901507–7901507 (2013).

[62] R. A. Minasian, E. H. W. Chan, and X. Yi, "Microwave photonic signal processing," Opt. Express 21, 22918 (2013).

[63] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, "Microwave photonic signal processing," J. Light. Technol. 31, 571–586 (2013).

[64] R. A. Minasian, "Photonic signal processing of microwave signals," IEEE Trans. Microw. Theory Tech. 54, 832–846 (2006).

[65] A. V. Krasavin and A. V. Zayats, "Photonic signal processing on electronic scales: Electro-optical field-effect nanoplasmonic modulator," Phys. Rev. Lett. 109, 53901 (2012).

[66] M. Torrice, "How lead ended up in Flint's tap water," Chem. Eng. News 94, 26–29 (2016).

[67] D. Simeral, "United States drought monitor: California," http://droughtmonitor.unl.edu/Home/StateDroughtMonitor.aspx?CA, The National Drought Mitigation Center, Lincoln, NE (Published online May 24, 2016).

[68] E. Symons, Municipal report, City of San Diego 2014 Annual Drinking Water Quality Report, San Diego, CA (2015).

[69] F. Faulconer, Municipal report, City of San Diego Climate Action Plan, San Diego, CA (2015).

[70] J. Andrews, "Da Nang opens smart control centre," Cities Today, http://cities-today.com/da-nang-opens-smart-control-centre/ (Published online August 16, 2013).

[71] L. Galli, P. Fraternali, C. Pasini, G. Baroffio, A. Dos Santos, R. Acerbis, and V. Riva, "A gamification framework for customer engagement and sustainable water usage promotion," in 36th IAHR World Congress, Delft, Holland (2015).

[72] "In Amsterdam, clean air gets free wifi from trees," Springwise Intelligence Ltd., http://www.springwise.com/amsterdam-clean-air-free-wifi-trees/, (Published online June 3, 2016).

[73] Q. Gu, J. S. T. Smalley, M. P. Nezhad, A. Simic, J. H. Lee, M. Katz, O. Bondarenko, B. Slutsky, A. Mizrahi, V. Lomakin, and Y. Fainman, "Subwavelength semiconductor lasers for dense chip-scale integration," Adv. Opt. Photonics 6, 1 (2014).

[74] Q. Gu, J. S. T. Smalley, J. Shane, O. Bondarenko, and Y. Fainman, "Temperature effects in metal-clad semiconductor nanolasers," Nanophotonics 4, 26–43 (2015).

[75] D. T. H. Tan, A. Grieco, and Y. Fainman, "Towards 100 channel dense wavelength division multiplexing with 100GHz spacing on silicon," Opt. Express 22, 10408 (2014).

[76] O. Bondarenko, C.-Y. Fang, F. Vallini, J. S. T. Smalley, and Y. Fainman, "Extremely compact hybrid III-V/SOI lasers: design and fabrication approaches," Opt. Express 23, 2696 (2015).

[77] M. Puckett, J. Smalley, M. Abashin, A. Grieco, and Y. Fainman, "Tensor of the second-order nonlinear susceptibility in asymmetrically strained silicon waveguides: analysis and experimental validation," Opt. Lett. 39, 1693–1696 (2014).

[78] Y. Fainman, M. P. Nezhad, D. T. H. Tan, K. Ikeda, O. Bondarenko, and A. Grieco, "Silicon nanophotonic devices for chip-scale optical communication applications [Invited]," Appl. Opt. 52, 613 (2013).

[79] Y. Fainman and G. Porter, "Directing data center traffic," Science 342, 202–203 (2013).

[80] A. Grieco, G. Porter, and Y. Fainman, "Integrated space-division multiplexer for application to data center networks," IEEE J. Sel. Top. Quantum Electron. 22, 1–6 (2016).

[81] J. Lee, M. Tymchenko, C. Argyropoulos, P. Chen, F. Lu, F. Demmerle, G. Boehm, M. Amann, A. Alu, and M. Belkin, "Giant nonlinear response from plasmonic metasurfaces coupled to intersubband transitions," Nature 511, 65–69 (2014).

[82] O. Wolf, S. Campione, A. Benz, A. Ravikumar, S. Liu, T. Luk, E. Kadlec, E. Shaner, J. Klem, M. Sinclair, and I. Brener, "Phased-array sources based on nonlinear metamaterial nanocavities," Nat. Comm. 6, 7667 (2015).

[83] L. M. Freeman, A. Smolyaninov, L. Pang, and Y. Fainman, "Simulated Raman correlation spectroscopy for quantifying nucleic acid-silver composites," Sci. Rep. 6, 23535 (2016).

[84] J. Smalley, F. Vallini, B. Kante, and Y. Fainman, "Modal amplification in active waveguides with hyperbolic dispersion at telecommunication frequencies," Opt. Exp. 22, 21088–21105 (2014).

[85] J. Smalley, F. Vallini, S. Shahin, B. Kante, and Y. Fainman, "Gain-enhanced high-k transmission through metal-semiconductor hyperbolic metamaterials," Opt. Mat. Express 5, 2300–2312 (2015).

[86] J. S. T. Smalley, F. Vallini, S. Montoya, E. E. Fullerton, and Y. Fainman, "Practical realization of deeply subwavelength metal-dielectric nanostructures based on InGaAsP," in Proc. SPIE 9544, Metamaterials, Metadevices, and Metasystems 2015, San Diego, CA (2015).

[87] L. Ferrari, C. Wu, D. Lepage, X. Zhang, and Z. Liu, "Hyperbolic metamaterials and their applications," Prog. Quantum Electron. 40, 1–40 (2015).

[88] J. B. Khurgin and G. Sun, "Comparative analysis of spasers, vertical-cavity surface-emitting lasers and surface-plasmon-emitting diodes," Nat. Photonics 8, 468–473 (2014).

[89] M. S. Eggleston, K. Messer, L. Zhang, E. Yablonovitch, and M. C. Wu, "Optical antenna enhanced spontaneous emission.," Proc. Natl. Acad. Sci. U. S. A. 112, 1704–1709 (2015).

[90] O. D. Miller, A. G. Polimeridis, M. T. Homer Reid, C. W. Hsu, B. G. DeLacy, J. D. Joannopoulos, M. Soljačić, and S. G. Johnson, "Fundamental limits to optical response in absorptive systems," Opt. Express 24, 3329 (2016).

[91] M. Kuzyk, "Fundamental limits of all nonlinear-optical phenomena that are representable by a second-order nonlinear susceptibility," J. Chem. Phys. 125, 154108 (2006).

[92] C. L. Chen, A. Mahjoubfar, and B. Jalali, "Optical data compression in time stretch imaging," PLoS One 10, e0125106 (2015).

[93] C. S. Holling, "Resilience and stability of ecological systems," Annu. Rev. Ecol. Syst. 4, 1–23 (1973).

[94] E. D. Vugrin, M. A. Turnquist, and N. J. K. Brown, “Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks,” Int. J. Crit. Infrastructures 10, 218–246 (2014).

[95] F. F. Boctor, “Resource-constrained project scheduling by simulated annealing,” Int. J. Prod. Res. 34, 2335–2351 (1996).

[96] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, “Optimization by simulated annealing.,” Science 220, 671–80 (1983).

[97] V. Černý, “Thermodynamical approach to the traveling salesman problem: An efficient simulation algorithm,” J. Optim. Theory Appl. 45, 41–51 (1985).

[98] A. J. Ticknor, Optical Computing in Boltzmann Machines, University of Arizona (1987).

[99] N. Farhat, “Optical computing based on neuronal models,” Report for Program Review, University of Pennsylvania (1988).

[100] M. Rabinovich and P. Varona, “Transient brain dynamics,” in Principles of Brain Dynamics: Global State Interactions, M. Rabinovich, K. Friston, and P. Varona, eds., MIT, Cambridge, MA (2012), pp. 71–92.

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