INVITED PAPER

Optics and Photonics: Key Enabling Technologies

This paper reviews the past, present, and future vision of the technologies of optics and photonics, including lasers, materials and devices, communications, bioimaging, displays, manufacturing, as well as the evolution of the photonics industry.

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ABSTRACT | The fields of optics and photonics have experienced dramatic technical advances over the past several decades and have cemented themselves as key enabling technologies across many different industries. This paper explores past milestones, present state of the art, and future perspectives of several different topics, including: lasers, materials, devices, communications, bioimaging, displays, manufacturing, and industry evolution.

KEYWORDS | Communications; devices; displays; imaging; lasers; manufacturing; materials; optics; photonics

I. INTRODUCTION

The phrase "optics and photonics" is used in the title because of the dual, powerful nature of light. It can be viewed: 1) as a propagating wave, like a radio wave, except that the frequency of the wave is a million times higher (e.g., 200 THz); and 2) as a collection of traveling particles called photons, with similarities to the field of electronics [1, 2].

The impact of advanced light technology on our society is still evolving, with the invention and first demonstration of the laser being roughly 50 years ago [3, 4] and an even greater impact coming in the next few decades. Future opportunities abound for photonics-enabled advances in many fields. The laser provides a source of light that can be both: 1) coherent, meaning that a group of photons can act as a single unit; and 2) monochromatic, meaning that the photons can have a well-defined single color. With laser light:

1) high amounts of energy can be precisely directed with low loss;
2) many different wave properties (i.e., degrees of freedom such as amplitude, frequency, phase, polarization, and direction) can be accurately manipulated;
3) waves can be coherently processed to have high accuracy, speed, and dynamic range.

These basic qualities and the technical advances in the field of optics and photonics have enabled dramatic performance enhancements across many different application areas.

Dramatic advances in optics and photonics technologies have already had a major impact on daily life. For

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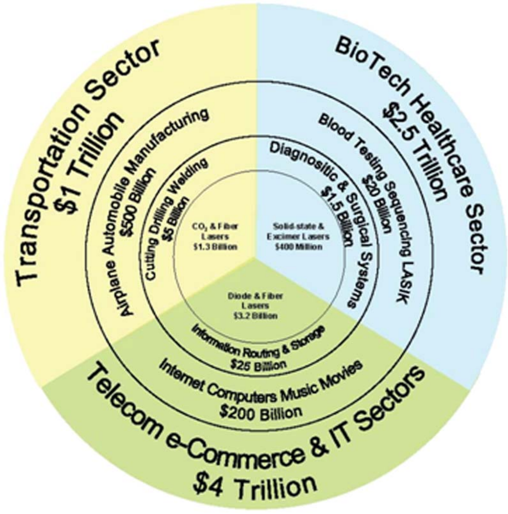


Fig. 1. ***Examples of application sectors that optics and photonics have significantly impacted for the time frame 2009–2010 [6].***

example, advances in optical fiber communications have enabled the amount of information that can be transmitted from place to place to increase by nearly 100-fold over a ten-year period, enabling a society-transforming Internet to thrive. Indeed, the current global internet itself would not exist without optics.

Over the past several decades, optics and photonics have experienced dramatic technical advances and have cemented themselves as key enabling technologies for a myriad of industries. As a small anecdotal indication in the popular press of the breadth and depth of the field, roughly 12 out of the 50 best inventions of 2011 listed by *Time Magazine* had optics as a key technological ingredient of the invention [5].

We can illustrate the "enabling" impact that optics and photonics have made on society by considering not only the direct value of the laser market itself but also the markets in which those lasers play an indispensible role in vibrant market growth. For example, Baer and Schlachter reported that for the time frame 2009–2010, the following sectors were significantly impacted (see Fig. 1): 1) the $1 trillion transportation sector had a laser market of $1.3 billion, 2) the $2.5 trillion biomedical sector had a laser market of $400 million, and 3) the $4 trillion telecom, e-commerce and IT sectors had a laser market of $3.2 billion [6].

Nearly 50 years ago, the IEEE integrated much of the technical work of optics and photonics into the Quantum Electronics and Applications Council. Roughly 12 years later, this council became the Quantum Electronics and Applications Society, later being called the Lasers and Electro-Optics Society and now the Photonics Society. Although the Photonics Society is a hub of activity, the multidisciplinary nature of our field is such that optics and photonics play a key role in many IEEE societies. For example, the IEEE/OSA Journal of Lightwave Technology is cosponsored by seven different IEEE societies.

The fields of optics and photonics are extremely broad in terms of technical topics and application areas. This paper tries to capture the excitement of the past, present, and future vision of these fields. While it is inevitable that we have overlooked key areas of these fields, we have tried in earnest to highlight some areas we thought could represent the advances enabled by our field. This paper is divided into several different subsections, namely:

1) overarching perspective;
2) lasers;
3) materials and devices;
4) communications;
5) bioimaging;
6) displays;
7) manufacturing;
8) evolution of the photonics industry.

In keeping with the spirit of the Centennial Special Issue of the Proceedings of the IEEE, each section is divided further into the following subsections:

1) introduction: context and importance of the topic;
2) past: key past milestones and perspectives;
3) present: state of the art and current thinking;
4) future: speculative vision.

To those people who are interested in topics that we have neglected or whose pioneering work was not referenced in this paper, we offer our sincerest apologies. Such a large topic deserves more than just a few journal pages, but we hope to whet the reader's appetite for the further information that can be found in the abundant open literature.

II. OVERARCHING PERSPECTIVE

Over the last two centuries, striking increases in human science and technology have occurred, with light waves being one of the important areas.

By 1910, the concept of light quanta, i.e., the photon, was beginning to be well-recognized by scientists. High-quality optical mirrors and lenses were being built, with Mt. Wilson's 100-inch telescope being one of the striking examples then under way. Spectroscopy was, of course, important, with increasing resolution and sensitivity. There was as yet no radar, but radiowaves, particularly at long wavelengths, were being used. The theoretical relation of radiowaves to optical waves was recognized, although the technologies involved in transmitting and detecting light and radiowaves were very different.

Today, we have microwaves down to wavelengths of less than a centimeter, and the explosion of work on lasers has provided a wide variety of light sources, making light as well as radio science and technology quite parallel and remarkably similar. The notion of quantized particles is, of course, now quite well accepted throughout the entire electromagnetic spectrum. Lasers produce high intensities, very pure frequencies, excellent directivity, and very short pulses. A remarkable concentration of power can provide enormous effective temperatures, and perhaps power densities large enough to generate atomic particles, e.g., energy. The ability of lasers to amplify and control light now makes the use of light and radiowaves much more similar than before; all electromagnetic waves are more obviously and closely joined together so far as our ideas and applications are concerned.

Modern lightwave developments are helping us both technologically and scientifically. The discovery of the origin of our universe, precise measurements of the distance to the moon, and an enormous increase in the amount of data that can be communicated across a single optical fiber are only a few examples.

What may happen in another hundred years, by 2110? The really new things that may emerge are ones we do not presently foresee. But there is much that we can expect—higher resolution, more accurate measurements, and greater power densities. Will we make and control other waves, such as high-frequency gravitational waves? How high a frequency will we be using—for extremely short pulses, communications, ultrahigh precision measurements, power, information transfer, etc.? However, one thing we can forecast is that there will be many surprises. We can all look forward with pleasure to these very fascinating and exciting developments.

III. LASERS: THE PAST, THE PRESENT, AND THE FUTURE

A. Introduction

Coherent sources of electromagnetic radiation were first generated at radio frequencies in the late 1800s. Within thirty years, 30 million radios had been sold in the United States. Information transmitted and received in the kilohertz frequency region became the new source for news, information, and entertainment [7]. By the mid-20th century, coherent frequencies had increased to the microwave region near 10^9 Hz with applications to Radar [8] during the war years and later in support of commercial aviation. The amplification of microwaves using energy stored in molecules achieved by Gordon, Zeiger, and Townes at Columbia University (New York, NY) in 1955 was a demonstration of Molecular Amplification by Stimulated Emission of Radiation (MASER) [9]. The work was motivated by the need for coherent sources of microwaves to allow high-precision molecular spectroscopy [10]. The demonstration of the MASER led to a concerted effort to extend stimulated emission to optical frequencies [3].

The ruby laser, demonstrated in May 1960 by Ted Maiman of Hughes Research Laboratories (Malibu, CA), caught the world by surprise [11]. The work was rejected for publication but was soon confirmed by research in other laboratories. In a single step, the frequency range was extended by five orders of magnitude to the visible spectral region, and the potential of the laser for light-based weapons caught the public imagination. A new term entered into language that was soon to become ubiquitous: laser.

By 1964, many types of lasers had been invented, including the helium neon laser [12], the diode laser [13], the CO_2 laser [14], the mercury ion laser [15] followed closely by the argon ion laser [16]. At Bell Telephone Laboratory, scientists doped rare earth atoms into crystals and demonstrated a flashlamp-pumped Nd : YAG laser [17]. The leading journal of the field, the IEEE JOURNAL OF QUANTUM ELECTRONICS, listed each new laser and laser wavelength discovered. Schawlow, who left Bell Labs to join the faculty at Stanford University (Stanford, CA), quipped that if you hit anything hard enough, it would lase.

The burgeoning field was recognized by the joint and simultaneous publication of a journal issue devoted to breakthroughs in lasers in October 1966 [18]. Books on lasers, laser types, laser resonators, and laser applications appeared in rapid succession [19], [20]. Years later in 2000, a special issue of the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS [21] focused on the early days of the laser in articles written by the pioneers who participated in the events. Fifty years after the invention of the laser, the world celebrated with LaserFest. It is estimated that more than 1 billion people took part in the festivities, special seminars, and celebrations of the laser.

This section will focus on the laser and its applications to science from the past, the present, and the future.

B. Past Key Milestones and Perspectives

The decade of the 1960s was followed by remarkable discoveries of new lasers that included the visible tunable dye laser, the chemical laser, and the free electron laser. Solid-state lasers, with combinations of laser ions doped into crystal hosts and glasses, were investigated with increasing numbers of solid-state lasers and wavelengths generated.

In 1961, shortly after the demonstration of the ruby laser, Franken and his research group [22] demonstrated that a crystal could be used to double the red ruby frequency into the ultraviolet (UV). This opened up the field of nonlinear optics [23] and the new capability to extend laser wavelengths and to generate tunable wavelengths in a device called a parametric oscillator [24], [25].

At about the same time, laser resonators were being studied and the types of stable resonators were defined [26], [27]. In a remarkable step, Siegman extended the resonator concepts to the consideration of "high-loss" or "unstable" resonator modes for application in high-power lasers, as the mode-volume to gain-volume ratio for unstable resonators can approach [26, 28].

The dye laser provided a tunable output in wavelength regions in the visible part of the spectrum. With the addition of a prism or grating, the dye laser opened the door for laser spectroscopy of atoms and led to precision spectroscopy. A key step was the discovery of Doppler-free spectroscopy, with its increased resolution [31].

The wide bandwidth of the dye laser offered the potential for the generation of ultrafast pulses, limited by the inverse bandwidth of the laser source. The phasing of laser modes had been demonstrated earlier in argon ion lasers, but in dye lasers the results led to sub-picosecond pulse durations setting the scene for advances in ultrafast laser applications [28], [31].

The dye laser was replaced by the titanium sapphire solid-state laser [32] pumped in the green wavelength by a frequency doubled Nd:YAG laser. In short order the pulse duration was reduced from picosecond to femtosecond durations in just one optical cycle in length. The amplification of ultrafast pulses of light was hindered by nonlinear limits until Strickland and Mourou demonstrated pulse broadening followed by amplification and pulse recompression [33]. This approach, called chirp pulse amplification (CPA), led to increasing pulse energy and femtosecond pulse durations to reach very high intensities in the focused laser beam. The electric fields generated by the laser accelerated electrons to relativistic energies in a single optical cycle opening the field of high field physics. Today, laser systems operate at the terawatt and even petawatt power scale (see Fig. 2).

Moreover, measurement and control of the subcycle field and few-cycle light have opened the door to radically new approaches to exploring and controlling natural processes [34]. Remarkable achievements included the controlled generation and measurement of single attosecond pulses of extreme UV light, as well as trains of them, and real-time observation of atomic-scale electron dynamics. Attosecond tools and techniques for steering and tracing electronic motion in atoms, molecules, and nanostructures are being successfully developed.

The invention of the 1-W power level diode bar with 25% efficiency by Scifres *et al.* [36] paved the way for high-power diode lasers and diode laser arrays. In a brief period of 15 years, the diode bar power was increased from 5 W at 25% efficiency to greater than 60 W at 50% efficiency. Simultaneously, the increasing demand for diodes for pumping solid-state lasers [37] led to a decrease in the cost of high-power diode bars. There was rapid advancement, showing exponential cost reduction with continued volume growth. Today, the trend applies to diode lasers. The combination of improved diode performance with lower cost has led to the replacement of lamp-pumped lasers by diode-pumped lasers for manufacturing, defense, space, and scientific applications.

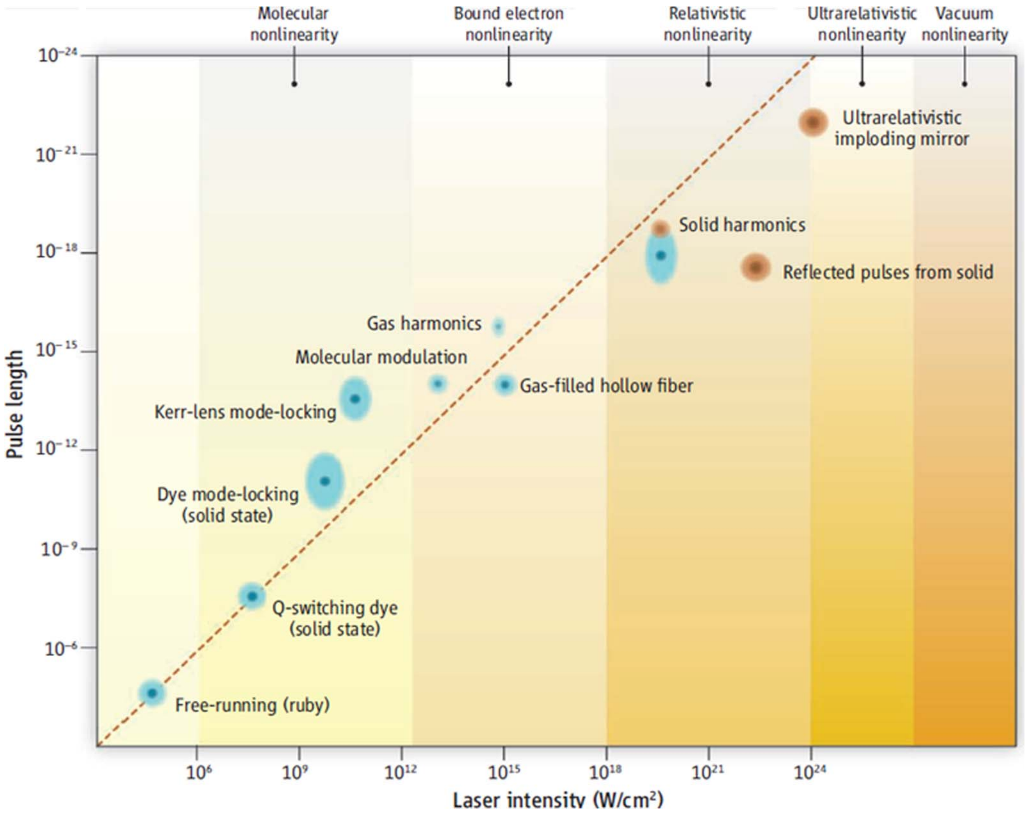


Fig. 2. ***Laser pulse length versus peak intensity with each era denoted by relativistic energies of electrons, protons, and the nucleus [35]. ©2011 AAAS.***

C. Present State of the Art and Current Trends

The state of the art in lasers and laser systems has been reviewed by Injeyan and Goodno [38]. From 2 mW of output power in 1984, the diode-pumped Nd: YAG laser grew to 105 kW of continuous-wave (CW) output power at 20% electrical efficiency in 2009 [39]. This advance was enabled by the tremendous progress in diode bar and diode bar arrays, which led to increases in power per bar to more than 500 W and in efficiency to more than 70%. Furthermore, the brightness of the diode bars improved allowing pumping of fiber lasers and fueling the power output of fiber lasers to greater than 10-kW average power. Current work is focused on combining arrays of fiber devices, each operating at greater than 10-kW average power. The limit for power scaling of a single fiber has been explored by Dawson *et al.* [40]. The power limit appears to be in excess of 30 kW per fiber at near 50% electrical efficiency. The key development was the use of double cladding and a large mode area fiber [41] to decrease intensity to keep nonlinear effects from damaging the fiber.

The exploration of nature at the highest possible electric field strength enabled by CPA has led to the proposal to construct a European infrastructure facility named Extreme Light Infrastructure (ELI) [42]. ELI will use modern CPA techniques and scale to greater than petawatts of output peak power in a Ti: sapphire laser, followed by an optical parametric chirped pulsed amplifier (OPCPA) to reach the shortest possible pulse at the highest intensity [43].

Progress in free electron lasers (FELs) [44], [45] has also led to significant advances in power and tunability from the terahertz across the visible to the deep UV frequency range. In 2009, an FEL driven by the Stanford Linear Accelerator Center (SLAC, Stanford, CA) operated for the first time in the hard X-ray wavelength region at 8-keV photon energy. Today, the Linac Coherent Light Source (LCLS) is now operating full time to support experimental science studies using coherent X-rays generated at greater than 10-Hz repetition rate and 1 mJ per pulse [46], [47]. Elsewhere in the world, the frontier of this technology is being pushed outward, with new sources of coherent X-rays developed, based on the progress of the X-ray laser at SLAC.

The year 2009 saw the completion of the National Ignition Facility (NIF), a 2-MJ, single shot laser facility at Lawrence Livermore National Laboratory (Livermore, CA) designed to compress targets to generate fusion burns and ignition of a target for energy generation [48], [49]. The NIF laser has now been operating for three years at close to 200 shots per year, with a greater than 95% availability rate for requested shots on targets. The goal in the near term is to achieve ignition defined as 1-MJ output energy from a fusion burn for 1 MJ of laser energy input into the target system. Plans are already underway to define the laser driver for inertial fusion energy applications.

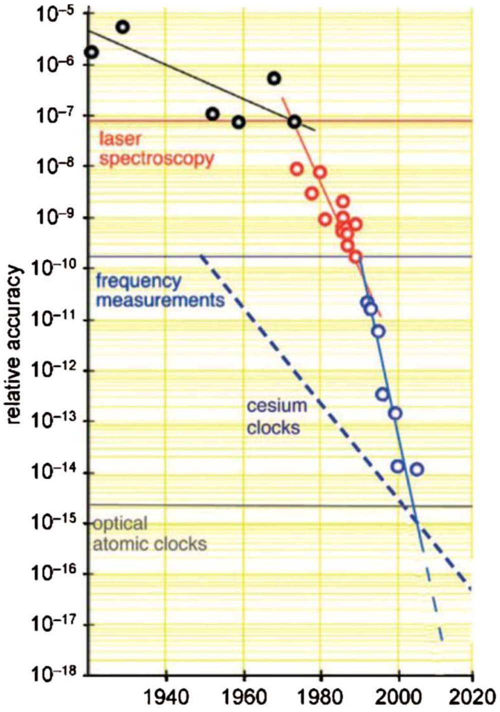


Fig. 3. *Laser clock precision versus year, showing rapid progress in clock performance [51].*

From the early spectroscopic investigations using dye laser and Doppler-free techniques, progress in optical clocks has been stunning (see Fig. 3). Early laser frequency stabilization experiments involved HeNe lasers locked to methane at 3.39 μm or locked to iodine at 633 nm. Clock stabilization of a single laser line took a leap forward when Hänsch [50] and Hall [52] realized that a mode locked frequency spectrum could be used to compare frequencies across a wide spectral gap. The comb of modes, self-referenced by comparison of a comb mode at ω with a comb mode at 2ω led to the use of lasers in precision clocks and spectroscopy. Today, clocks have attained a stability of better than one part in 10^{16}. As the location of the clock in the gravitational potential now matters, the gravitation potential must be known in addition to the clock coordinate system. Modern laser clocks offer the potential for precision measurements that will test our understanding of the pillars of physics and the structure of the universe [53].

D. Future Vision and Possibilities

The laser is now used in many aspects of our lives from medicine, biology, chemistry, manufacturing, to communications, and of course science. In the mid-1990s, a National Academy study was undertaken to understand current applications of the laser and where lasers might be used in the future. Called "Harnessing light, optical science and engineering for the 21st century" and published in 1998, the study was useful but incomplete in its prediction of the future. Some trends could be discerned from what was already known. Rules could be applied to project future trends using rules of thumb in relation to increasing numbers of transistors on a chip and cost reductions achieved from large-volume manufacturing. However, as clairvoyants such as Niels Bohr have said, "*Prediction is very difficult, especially about the future*," and most of all about ideas and concepts that are yet to be discovered. A reading of the National Research Council (NRC) study today shows how often we did not anticipate a key discovery that in turn led to a completely new capability.

With that in mind, we can make some predictions about future capabilities. One more word is in order, however. From a study of the pace at which new technologies are introduced and adopted by society at large, we learn that infrastructure, such as railroads, electrification, and air transportation, takes almost a hundred years to be fully integrated into general use. Derivative technologies that build on existing infrastructure take less time. Computers, the laser, and the Internet took between 25 and 50 years to be adopted. Replication of prior technology by new approaches takes even less time; for example, cell phones, which combine transistor and integrated circuit technology with electronic signal processing to provide a radio receiver electronic processing and a receiver in a handheld device, were adopted rapidly because the relevant infrastructure was already in place.

The laser at half a century is still in its prime and has a considerable life expectancy before it slows in its development and applications. The laser is used in many ways that touch our lives every day, but we often fail to realize it because the laser is a stealth utility and not generally evident. If asked, "what would happen if all lasers stopped working at this moment?", most people would reply, "Not much." However, an inadvertent experiment was run in San Jose, CA, a few years ago, when a key fiber communications link was cut. All banking activity ceased, all street lights stopped working, electricity was cut off, and broadcasting was severely limited. All Internet and telephone services came to a halt as well.

Based on recent progress, we can project that lasers will increase in output power from 0.1 MW in 2009 to greater than 10 MW by 2020. In fact, a laser-driven accelerator useful for particle physics studies at the TeV energy scale would require a laser average power of 10 MW per kilometer of accelerator. Further, the laser would be mode locked and optically phased along the accelerator structure. It would need to operate at greater than 30% electrical efficiency to function with the power available at current laboratory sites.

A laser-based accelerator on a chip is now an active subject of research. Therefore, the prediction of future capability is informed by the exponential plot of accelerator energy versus year first published by Livingston in 1954. Perhaps in 20 years laser accelerators will be used to study matter at the TeV scale. Well before that time, 1-m laser accelerators can drive FELs based on dielectric undulators to generate coherent X-rays on the table top [54], [55]. We can also predict that the same approach will be extended to generate coherent gamma rays of photon energies in excess of 1 MeV. Further, based on the history of lasers, we can be sure that in the next half-century, coherent X-ray lasers will be in widespread use for applications that have yet to become clear. Also, Gamma rays will open up the field of nuclear photonics, giving humankind one more tool with which to explore the universe.

We know that a fusion reaction works at even larger power scales. What we have yet to demonstrate is a nuclear burn in a laboratory under controlled conditions. When this is accomplished, it will be a "man on the moon" moment. Laser inertial fusion will open the possibility of amplifying the laser drive power by 30–100 times and in turn allow the operation of an electrical power plant with GWe output for 35-MWe laser power input. Based on our knowledge of the rate at which new infrastructure is adopted, we can predict that fusion energy will take 25–50 years to make a significant impact on our energy supply. By that time it will probably be known simply as laser energy.

However, yet to be predicted is laser launched space craft, laser fusion energy propulsion [56] for transportation to nearby stars, phased array optical telescopes in space using laser clocks for timing over greater than 1 million kilometer aperture size, laser clocks in the Global Positioning System (GPS) to accuracy improved by four orders of magnitude, laser remote sensing using a comb of modes for precision spectroscopy, coherent X-rays for precision medical imaging, for single shot determination of protein structures from a single molecule, gamma ray remote sensing of nuclear isotopes, gamma ray burning of hot radioactive isotopes, interplanetary communications by coherent X-rays, routine gravitational wave astronomy using phased array antennas in space, and hybrid fusion fission nuclear reactors [57] that burn once through fission fuel to obtain five time more energy and to remove from the inventory all fission depleted fuel. We have enough depleted fission fuel in storage now to provide the United States with energy for 450 years.

Laser science and technology have enabled a flourishing of different areas such as nonlinear optics. In general, nonlinear optics is playing a key role in many applications of frequency mixing, including frequency conversion, parametric amplification [58], supercontinuum generation [59], signal processing [60], and unique light sources in the THz to X-ray regimes [61], [62]. Many of these applications require well-controlled phase matching between the different frequency waves in order to achieve high efficiency [63], which typically requires maintaining a low chromatic dispersion over a large spectral range. Moreover, there are many materials and structures that have high nonlinearity, including lithium niobate, chalcogenide [64], silicon, and photonic crystal fiber [65], [66]. Additionally, nonlinear optics can play a key role in spectroscopy and sensing, including surface-enhanced Raman scattering [67] and fiber Brillouin scattering [68].

IV. MATERIALS AND DEVICES

A. Introduction

Light has long been used by humanity. For example, the Chinese and the Greeks independently developed complex coding schemes to transmit key strategic information about enemy positions. For modern optical communications, however, significant progress was not made possible until the invention of semiconductor lasers in 1962 [69] and the demonstration of heterostructures [70], [71].

Advances of optoelectronic materials and devices have played a critical role in this tremendous revolution, including basic modulation of light [72]–[74]. In addition, optoelectronic materials and devices make it possible to drastically expand the wavelength range and sensitivities of optical sensors, imaging, and lighting capabilities [75], [76]. Discoveries and advances have been made in active materials over a wide wavelength range, with high quantum efficiencies spanning the UV to the far infrared (Fig. 4) [77]–[81]. Nanoscale processing technologies are being developed to facilitate the engineering of optical properties by effects due to the quantization of electron or optical wavelengths. Finally, remarkable progress on the integration of dissimilar materials for new applications has been made. Engineered materials have come of age.

In general, the concept of "integrated optics" [82], [83] has fascinated our community for decades, in which we hope to partially replicate the remarkable progress that integrated electronics has seen, including reductions in cost and size, as well as increased performance and reliability. Typically, however, the "photonic-integrated-circuit" [84], [85] structures we can fabricate tend to be discrete components, components with different sub-elements and enhanced functionality, and arrays of components—all impressive but still not large-scale [86]–[88]. The true vision of integrated optics might still lies ahead, with "silicon photonics" being an exciting new sub-field in this direction.

In this subsection, we briefly outline the role that some key semiconductor materials and devices have played. This is not intended to be complete or comprehensive due to limited space. However, the intention is to highlight some of the new and exciting opportunities.

B. Past Key Milestones and Perspectives

Major advances in epitaxy technologies in the late 1970s, particularly with the inventions of molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), made it possible to precisely control the composition and thickness of epitaxy to nanometer scale [89], [90]. This, in turn, made it possible to realize quantum-well (QW) laser, the first nanodevice [91], [92].

Once 1300- and 1550-nm wavelengths were identified as desirable regimes for long-distance fiber transmission, significant research focused on developing materials and devices operating at these wavelength regime. This led to advances of InP-based III-V compound materials [93]. Single wavelength lasers were recognized to be critical for long-distance transmission in fiber [94], [95]. Distributed feedback (DFB) or distributed Bragg reflector (DBR) structures were introduced to control the emission spectra of diode lasers [96]–[98]. Precision wavelength control in lasers, in conjunction with broadband Er-doped fiber amplifiers (EDFAs), subsequently led to the new era of dense wavelength-division multiplexed (DWDM) systems—a critical step enabling the rapid growth of optical fiber communications [99], [100]. Strain was introduced to QWs to facilitate bandgap engineering and, hence, the associated optical properties [101], [102]. This made it possible to produce reliable, high-power laser with an emission wavelength at 980 nm for pumping the EDFAs.

Vertical cavity surface emitting lasers (VCSELs) were realized because it became possible to grow very complex structures that required hundreds of layers of deposition by MBE or MOCVD (see Fig. 5) [103]–[107]. Due to the

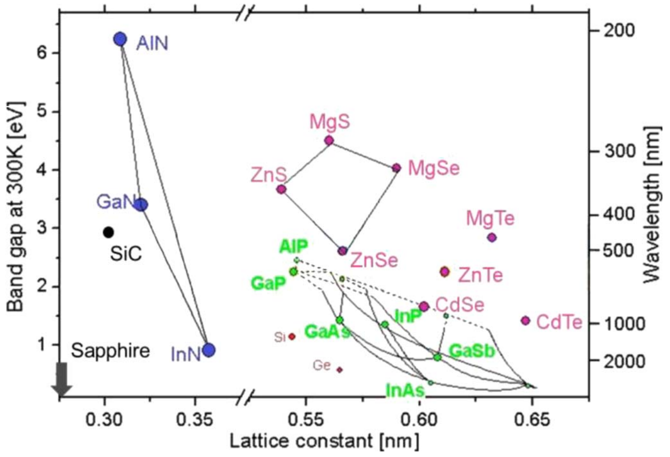


Fig. 4. *Bandgap energy as a function of lattice constant for a wide variety of compound semiconductors for optoelectronic devices [77]–[81].*

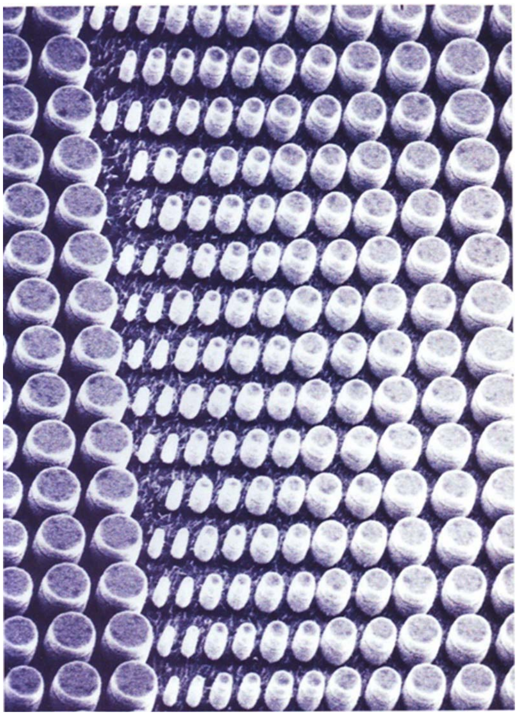


Fig. 5. ***Wafer-scale fabrication of dense array of vertical-cavity surface-emitting lasers (VCSEL). Lasers of different diameters ranging from 1 to 5 μm were demonstrated [129]. ©1991 Scientific American.***

surface-emitting topology, VCSELs can be wafer-scale manufactured and easily fiber coupled. Direct modulation as fast as 25 and 40 Gb/s has been realized in 1550- and 850-nm VCSELs, respectively [108], [109]. In addition, continuously wavelength tunable VCSELs have been demonstrated [110]. These devices are experiencing wide deployment in datacom application and, potentially, may experience deployment in high-speed access network applications.

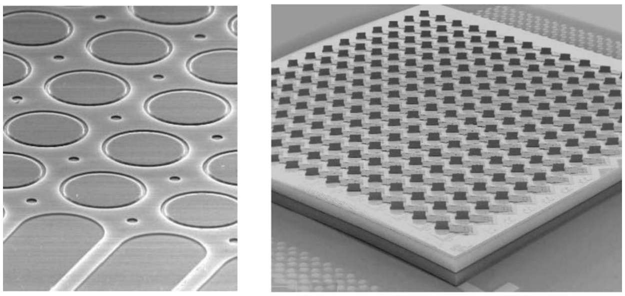
Importantly, the low-loss and high-bandwidth of optical fiber coupled with cost-effective transmitter and receiver arrays has produced a growing area of active optical cables [111]. Such cables are being commercialized by several companies and are a near-ideal replacement for copper cables for connecting computers at multi-Gb/s speeds over tens of meters.

With the advent of nanometer precision epitaxy, not only the interband transitions can be controlled and used as an efficient optical modulator [112], but even the intersubband transitions of QWs [113] can be engineered as detectors [114] and lasers for near-, mid-, and far-infrared wavelengths. The demonstrations of quantum-well intersubband photodetector (QWIP) [115] and quantum cascade lasers (QCLs) [116], [117] are major advances that opened a wide range of applications for optical sensing and imaging.

In addition to GaAs- and InP-based materials and devices, breakthroughs in the growth of high-quality GaN epilayers on sapphire substrates and p-type doping incorporation in GaN led to a revolution in high-brightness blue light-emitting diodes (LEDs), which ignited a vast range of applications in lighting and display [118]–[121]. Now, solid-state lighting technology has the potential to replace inefficient incandescent light bulbs and fluorescent tubes [122]. In addition, UV/blue GaN-based diode lasers are used in high-definition DVDs [123], [124]. The InGaN green laser diode (LD) with a lifetime of many thousands of hours has recently been demonstrated, which opens up the possibility of the miniaturization of full-color laser projection systems and displays. Miniature laser projectors (micro/picoprojectors) can potentially be integrated into laptops and/or cell phones.

Silicon-based photonics started very early with the concept of charge-coupled devices (CCDs) for imaging, first conceived by scientists working on memory applications in 1969 [125]. After the initial experimental demonstration of the concept [126], 8-bit shift registers and imaging devices based on CCDs were shown [127], [128]. Since then, CCDs have attracted enormous interest and proliferated in the form of disruptive new products. Their low-noise characteristics, ability to shift charges, and operational simplicity have keyed innovations in sensors and astronomy. Today, CCDs can be found in most digital cameras. The current state of the art boasts 520-megapixel array of high-performance CCDs specially designed and built for imaging of galaxies in the pursuit of dark energy [129]. In general, high-performance CCDs are proving crucial components for astronomy, while they are steadily being displaced in mass consumer markets by complementary metal–oxide–semiconductor (CMOS) cameras.

Silicon micromechanical spatial light modulator arrays and torsion mirrors were first reported in 1977 [130], [131]. This topic has become a thriving field known as optical microelectromechanical systems (MEMS). The first market driver of optical MEMS was in displays [132], [133]. The digital micromirror devices (DMDs) developed by Texas Instruments are one of the most successful MEMS products. They are now widely used in



(a) (b)

Fig. 6. ***(a) Lightconnect's diffractive MEMS variable optical attenuator (VOA). This device was one of the first Telcordia qualified MEMS components, with 40 000 units reportedly shipped by 2005 [138]. (b) scanning electron micrograph (SEM) of OMM. Inc 16 ×1 16 switch (reprinted from [138] with permission).***

portable projectors, large-screen TVs, and digital cinemas [129]. Applications of optical MEMS in telecommunications started in the 1990s [134], [135], including optical switches, filters, variable attenuators [Fig. 6(a)], tunable lasers, wavelength add/drop multiplexers, wavelength-selective switches, and cross connects [136]–[138]. Optical MEMS are naturally suited for optical switches in telecommunication networks, offering provisioning and network management [Fig. 6(b)]. Nodes in ring networks can employ wavelength add-drop multiplexers (WADM) when optical MEMS are combined with wavelength selective components. Other applications of optical MEMS include wavelength-selective switches (WSS), wavelength-selective crossconnect (WSXC), dispersion compensators, and spectral equalizers, filters, and tunable lasers.

Another important silicon photonic device was the Si-based solar cell, first demonstrated in 1954 with conversion efficiencies of 6% [139]. During the 1970s, a series of innovations further improved efficiency by introducing surface texturing for broadband-antireflection coatings, back-surface fields, and surface passivation [140]–[142]. During the 1980s, the first silicon cell exceeding 20% was realized [143]. The record laboratory silicon solar cell now exhibits an efficiency of 25% [144].

It is now understood that, in order to achieve the highest open-circuit voltages and efficiencies, solar cells need to behave like good LEDs due to the thermodynamically dictated re-radiation processes. This means that solar cells should be designed such that they exhibit good light-extraction properties [145].

Recently, the GaAs-based single junction solar cell with a record efficiency of 28.3% was demonstrated. In addition, multi-junction III-V solar cells are shown to exhibit the highest efficiency of 43.5% [144]. The reported timeline of solar cell energy conversion efficiencies is shown in Fig. 7 [146]. High-efficiency solar cells are of significant interest as alternative sources of energy. Photovoltaics [147] holds great potential if "grid parity" can be reached. Of course, the costs of energy for solar cells are expected to drop further in the coming years.

C. Current Trends

Due to space restrictions, we will cover only a few select topics that have attracted much attention lately. First, we will discuss the recent development of nanostructured materials and devices. This subject is of great interest, because of the promise to "tailor" materials' innate physical properties when their sizes are made small enough so that the electron wave functions are significantly confined by the structured boundaries. Thus, the control of matter at nanometer scales would allow the manipulation of absorption, emission, transmission, refraction, transport, energy conversion, and storage in innovative ways that could have profound implications for many applications.

The second topic is on subwavelength metastructures. With the advent of ~100-nm lithography technologies, there

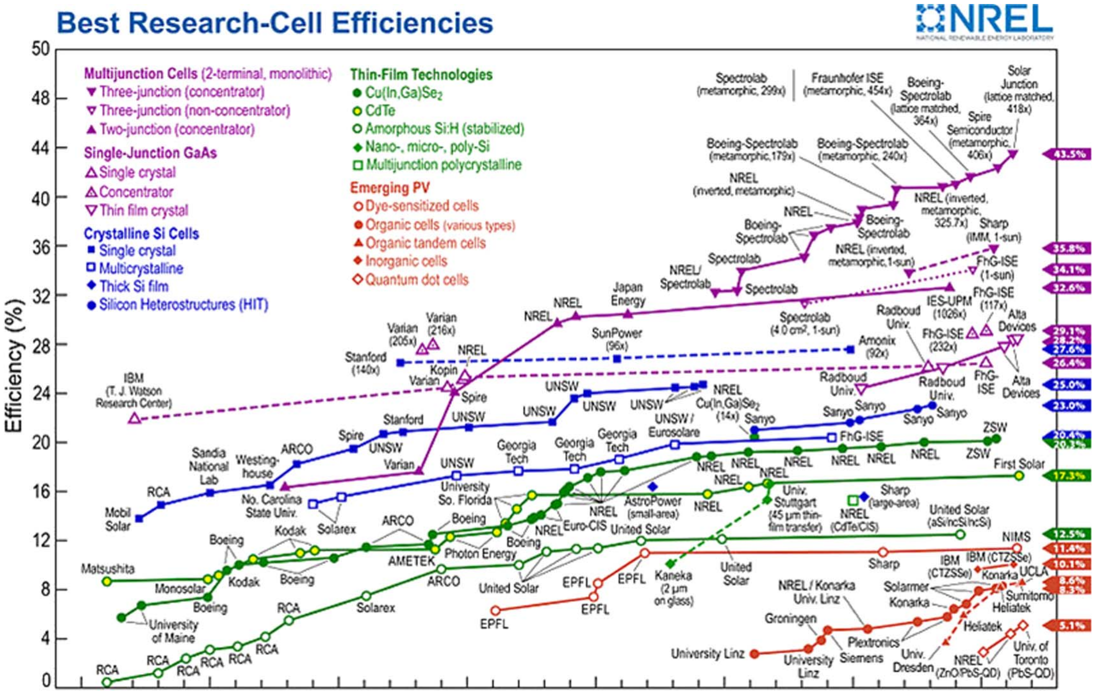


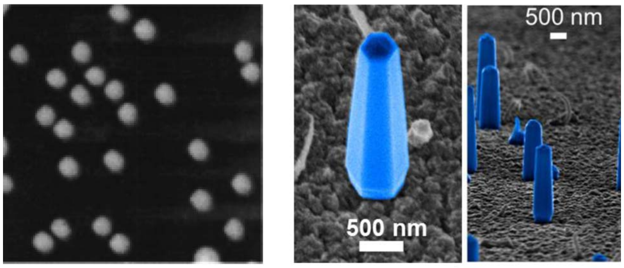
Fig. 7. *Conversion efficiencies of the best research solar cells worldwide from 1976 through 2011 for various photovoltaic technologies; efficiencies determined by certified agencies/laboratories. Source: National Renewable Energy Laboratory (NREL) [146]. ©2011 NREL.*

is much promise in tailoring existing materials in the subwavelength regime to produce new optical properties that the underlying materials themselves would not naturally possess. Such subwavelength structures can be made with metals, semiconductors, or dielectrics, or combinations of more than one of these. The resulting properties include the transmission, refraction, reflection, absorption, and emission of light.

Finally, the monolithic integration of dissimilar materials is believed to be of significant importance in achieving functionalities greater than the sum of their parts. In particular, it is critical to integrate active optical components based on III-V compounds, such as diode lasers and semiconductor optical amplifiers (SOAs), with silicon-based electronic circuits and passive photonics. Such integration can increase the speed and reduce the size, weight, and power consumption of the circuits. It also allows the optical phase to be precisely controlled and used as an additional dimension for signal coding. Nanostructured materials may be particularly promising because of their small footprints, which greatly alleviate the constraints due to mismatches of lattice constants and thermal expansion coefficients.

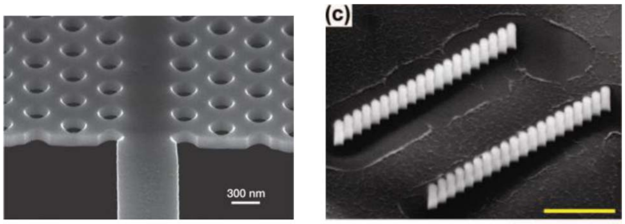
1) *Nanostructured Materials and Devices:* The applications of nanostructures to optoelectronic devices started when 1-D confinement structures, i.e., QWs, were demonstrated in 1974 [148]. Today most semiconductor diode lasers and electroabsorption modulators use QWs as a means to control wavelength, reduce threshold, and provide modulation. Materials with 2-D and 3-D electronic confinements are referred to as quantum wires and quantum dots (QDs), respectively [149], [150]. Due to the strong quantization effect, which changes the density of states of the materials, QD lasers are expected to offer advantages such as temperature-independent threshold, ultralow threshold, low chirp, and very high speed. In addition, QD-SOAs promise ultrabroadband amplification and very low nonlinearities.

There have been intense efforts towards the realization of QDs. A promising approach is self-assembled InAs QDs grown on GaAs substrates via the Stranski–Kransnov growth mode (Fig. 8) [151], [152].



(a) (b)

Fig. 8. ***(a) Self-assembled InGaAs QDs are arranged randomly and vary in size in this micrograph of an area 0.5 μm wide (courtesy [153] ©2005 AIP). (b) InGaAs nanopillar lasers grow on silicon (courtesy [162] ©2011 NPG).***



(a) (b)

Fig. 9. ***(a) Closeup of a silicon photonic crystal waveguide [173]. ©2005 NPG. (b) An ultracompact silicon/polymer laser formed by two parallel high-contrast grating (HCG) reflectors on an SOI substrate [176]. ©2010 ACS.***

The growth of III-V compound nanowires using vapor–liquid–solid (VLS) growth mode with metal as a catalyst was first reported in the early 1990s [154]. The materials and substrates soon expanded to the full spectrum of III-V and II-VI compounds, as well as Ge and Si [155]. Various heterostructures were demonstrated in the axial or radial directions. Quantization effects have been reported in small nanowires, typically having less than a 20-nm core diameter [156], and nanowire-based devices have also been reported [157], [158].

Nanowires are shown to facilitate a larger lattice mismatch with its substrate. In general, for QWs with a given mismatch with the substrate, there exists a critical thickness beyond which the high density of misfit dislocations develops, rendering the material unsuitable as an active material for lasers [159], [160]. The larger the mismatch is, the thinner the critical thickness. Typically, this layer is very thin; for a 2% lattice mismatch, the critical QW thickness is only ∼8 nm. For typical GaAs, InP, or InAs on silicon, the lattice mismatches are 4%, 8%, and 12%, respectively. Such mismatches are so large that the critical QW thicknesses are too small for device applications. Nanowires, too, exhibit a critical dimension in their diameter, above which a single crystalline cannot be obtained.

Recently, a new metastable growth mode has been reported for various III-V on lattice mismatched substrates at a low growth temperature of 380 °C–450 °C. The growth assumes a core/shell nanopillar structure which is scalable with growth time to micrometers in size. GaAs nanopillars were shown to grow on sapphire with a lattice mismatch of 46% [161]. The core/shell layers also accommodate more than ten times thicker lattice mismatched material compared to thin-film epitaxy. This may change the heterostructure material design rules used for thin film, where the combination is limited to the lattice constants close to those of the available substrates.

Various devices have already been demonstrated on such III-V nanopillars grown on silicon, including room-temperature operation of LEDs, avalanche photodiodes, and optically pumped lasers [162]. Such materials are grown at a low enough temperature that they are compatible to wafers with electronic complementary metal-oxide semiconductor (CMOS) circuits. This makes such nanostructured growth promising for the integration of various III-V materials device structures on silicon.

2) Subwavelength Metastructures: Similar to the use of nanostructures for the quantization of the electron wave, optical structures that are on the order of the optical wavelength have been used to change the optical properties of structures. The DBR is perhaps the simplest 1-D example of such structure, with alternating layers of quarter-wavelength-thick dielectric (or semiconductor) materials to yield high reflectivity [96], [98]. DBRs have been long used in commercial products for reflectors, interference filters, or antireflection coatings.

The 2-D and 3-D versions of periodic structures are referred to as photonic crystals (PhCs) because the structure shows effects on the motions of an optical wave similar to the way a semiconductor crystal affects an electron wave [163], [164]. Since its inception, rapid progress has been made. Complex PhC structures with varied dimensions have been reported, allowing the control of properties such as spectral and polarization dependence in transmission, refraction, reflection, absorption, and emission of light [165], [166]. Interesting metal patterns have been added to such periodic structures that result in a negative refractive index and super lens effects [167], [168], which can focus light below the conventional diffraction limit. Photonic crystal devices are also being actively deployed in biosensors, semiconductor lasers, and hollow-core fibers [169]–[172].

A new class of dielectric subwavelength gratings has emerged to exhibit very different properties from PhCs or traditional gratings. This grating leverages a high contrast in the refractive indices for the grating medium and its surroundings and subwavelength period to lead to unique properties, and hence the name high-contrast grating (HCG) [173], [174]. They can be readily designed to exhibit broadband, high-reflectivity mirrors for light incident in surface-normal and, at a glancing angle, ultrahigh-Q ($> 10^6$) resonators with surface-normal output, planar high focusing power reflectors and lenses (numerical aperture > 0.9), ultralow-loss hollow-core waveguides, slow light waveguides [175], and high efficiency vertical to in-plane waveguide couplers [176]. HCG is poised to be a promising platform for integrated optics with applications for lasers, filters, waveguides, sensors, and detectors [173]–[175].

3) Monolithic Integration of III-V Compounds on Silicon: Rapid progress has recently been made for photonic devices on a silicon substrate using silicon foundry processes. These devices include high-speed modulators, low-loss passive devices, and silicon germanium (SiGe) photodetectors [177]–[180]. This family of devices is referred to as Si-photonics. Si-photonics is attractive for high-speed low-power interconnects for interchip and intrachip communications [181], [182].

The excitement of silicon photonics is, of course, the potential to leverage the highly advanced and vast lithographic infrastructure that is commercially available, such that high volume, high integration, and low cost could come to integrated photonic circuits. Indeed, conventional wisdom [183] had long considered III-V materials to be of greater interest, and silicon was not the material of choice for photonic applications due to the relatively low electrooptic coefficient and the indirect bandgap structure. However, dramatic progress at high-speed operation was made in the past several years, [184] with modulators [185]–[188] and highly nonlinear waveguides [189]–[191] being demonstrated; many other structures have also been demonstrated, including detectors, filters, and couplers.

To facilitate the dense integration of optoelectronics and electronic circuits, it is desirable to include active components, lasers and amplifiers, on a silicon substrate with a process that is compatible with silicon-based CMOS circuits. The fundamental roadblock facing the monolithic integration of lasers has been a large mismatch of lattice constants and thermal expansion coefficients between the III-V materials and silicon. Recently, a new material, Ga(NAsP)/GaP QWs, has been strain engineered to match a silicon substrate [192]. Diode lasers directly grown on silicon have been demonstrated at a low temperature with an emission wavelength of ~850 nm [193], [194]. With future bandgap engineering to a longer wavelength, this approach represents a promising active material for Si-photonics.

Direct transfer of III-V epitaxial layers onto a prepatterned silicon-on-insulator (SOI) wafer was also demonstrated using a molecular bonding technique [195]. Evanescent optical coupling between III-V thin film and silicon waveguide was achieved, enabling integration with silicon-based photonic devices. Discrete single frequency and tunable laser sources, as well as modulators and filters, have been demonstrated [196].

In addition to III-V on silicon, the recent advancement of Ge or GeSn grown on Si has enabled optoelectronics devices operating in the telecommunication band, i.e., 1.3–1.6 μm [197]–[200] to be fabricated in a way that is compatible with CMOS electronic device fabrication. Strong optical modulation mechanisms that previously were only practically observed in III-V materials have been demonstrated in Ge QW layers grown on silicon. Such Ge-based materials and structures on silicon are thus potential candidates for dense integration of optoelectronics and electronics in applications such as optical data interconnections.

Finally, as discussed in Section IV-C1, nanostructures enable the growth of single crystalline III-V materials on silicon, substantially relaxing the lattice matching and high growth temperature requirements found in typical III-V thin-film epitaxy.

D. Future Vision and Possibilities

Although a camera is only a simple optoelectronic device, its incorporation into cell phones has already transformed our society—making every person a reporter. We envision that the wafer-scale monolithic integration of a wide range of optoelectronic and electronic integrated circuits will enable a far wider spectrum of functionalities otherwise unattainable, bringing capabilities that have not yet been conceived.

Nanofabrication technology will hopefully be a key enabler to such integration, reducing power consumption, size, and weight while simultaneously increasing speed. All processes, i.e., synthesis, deposition, patterning, additive and removal processes, and metrology, must have nanometer control, repeatability, precision, and accuracy. It will be crucial to achieve a better understanding of physics and materials science in order to control this new class of nanostructures by design, including their placement, doping, size, and scalability. We will also need to obtain a full understanding of the fundamental properties of nanostructures, including their electronic, transport, mechanical, thermal, optical, and crystalline properties. New devices and integration techniques will be needed to continue this revolution, with many exciting new opportunities awaiting us.

V. COMMUNICATIONS

A. Introduction

Mankind has used optical messaging since ancient times. However, it was the prospect of coherent light generated by lasers that excited visionary communications researchers. They appreciated that the carrier frequency of visible or near-infrared light was more than 200 THz and even a small fraction of this would provide a bandwidth vastly exceeding the limited spectrum of radio waves and microwaves [201]. An early example of this vision is the patent for the optical MASER by Schawlow and Townes filed in 1958 including communications in its title and a communication system in its claims [202].

After a decade of worldwide R&D and breakthroughs the two key enablers of lightwave communications emerged: low-loss optical fiber and a semiconductor laser capable of continuous operation at room temperature. After another decade of significant R&D innovations the technology was ready for commercial long-distance transmission and kept growing in capability. Soon the marriage of the optical fiber with the semiconductor laser revolutionized the way people communicate, industry operates, and society functions. It provides the transmission network for the Internet, the backbone of the modern information infrastructure. Even wireless signals from common cell phones must be routed through the fiber network after detection at a local cell tower. Communications ranging from real-time video chats to data center searches, telemedicine, and online gaming were all the realm of science fiction until optical fiber transmission enabled the fantastic growth in the capacity of the Internet. There are now over 1 billion kilometers of fiber deployed worldwide, and continuing R&D innovations have resulted in several orders-of-magnitude increases in transmission capacities, such that 10 Tb/s can now be deployed in commercial systems in one fiber over long distances (see Fig. 10) [203].

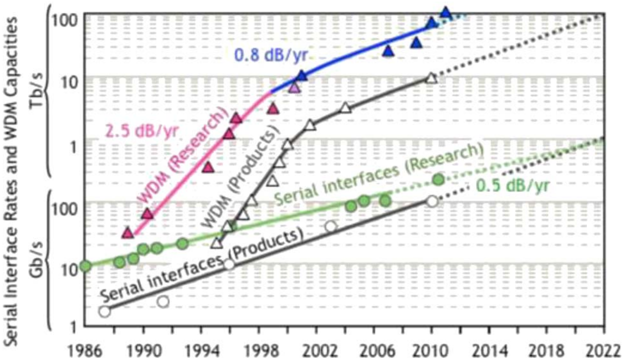


Fig. 10. ***Historic serial bit rate and wavelength-division-multiplexed system capacity scaling in research and products [203].***

The importance of optical fiber communications was highlighted when Charles Kao was awarded the Nobel Prize in Physics for this innovation. Indeed, during the introduction to Kao's 2009 Nobel Prize Lecture, it was stated by the physics committee chair that "the work has fundamentally transformed the way we live our daily lives" [204].

B. Past Key Milestones

1) Two Enablers: Fibers and Semiconductor Lasers: The concept of guiding light by total internal reflection was established in the mid-19th century. Moreover, the idea of a high-index glass core surrounded by a lower index glass cladding was well known in the early part of the 20th century. However, glass fibers were deemed impractical for communication systems as attenuation losses were > 1000 dB/km. Early theory by Hondros and Debye had established that guided "modes" could propagate inside a dielectric cylindrical waveguide without experiencing radiative loss [205]. More detailed theory followed. Around 1970, Snyder [206] and Gloge [207] reported the important linear-polarization (LP) approximations for the modes in a fiber with small index differences.

Materials breakthroughs started in 1966 when Kao and Hockham published a paper that showed that glass could pave the way to the future of telecommunications [208]. Subsequently, they measured the attenuation of various types of glasses at different optical wavelengths [209], [210]. They showed that glass was not fundamentally lossy but was lossy due to impurities and demonstrated that glass could achieve losses of ~ 5 dB/km. They reported that fused silica could have the lowest losses and set a benchmark of 20 dB/km as a threshold for realizing a practical communication system.

A 1970 publication by Kapron *et al.* reported fiber losses of 16 dB/km [211]. The team pursued an approach of trying to deposit high-purity, fused-silica glass using chemical vapor phase deposition. The base glass was converted into a vapor, and this vapor would collect inside a glass rod and form a pure, low-loss glass core upon cooling.

Fibers were brittle, and the method described above was not reproducible or scalable for large-volume manufacturing. Different solutions emerged. In 1974, MacChesney *et al.* [212] reported the modified chemical vapor deposition (MCVD) process that increased the ability to reproducibly fabricate long lengths of uniform optical fiber at < 2-dB/km attenuation. Schultz achieved outside vapor deposition (OVD) by reaction of highly pure constituents to form ultrapure particles [213]. Finally, Izawa and Inagaki developed vapor-phase axial deposition (VAD), which enabled the production of long, large-diameter preforms [214]. Ultimately, highly reproducible fabrication of single-mode silica fibers that exhibit ~0.2 dB/km of loss was achieved.

Small, reliable, power-efficient light sources are needed for optical communication, with their wavelength in the infrared range where fiber losses were lowest. Moreover, glass has chromatic dispersion, such that light of different frequencies propagates down the fiber at different speeds. This necessitates a narrow optical spectrum to reduce the temporal spreading of an optical data pulse as it propagates.

It was, therefore, extremely fortuitous that breakthroughs in semiconductor lasers happened during the same time frame as breakthroughs in fiber technology. GaAs semiconductor pn-junction lasers operating at low temperatures were demonstrated nearly simultaneously in 1962 by the three groups of Hall [69], Nathan [215], and Quist [216]. Finally, in 1970, Hayashi *et al.* demonstrated a double-heterostructure laser that limited nonradiative recombination and operated continuously at room temperature [217]. Later developments used different materials, such as InGaAsP, to achieve lasing at the optimum wavelengths near 1.55 μm.

The desire for compact narrow-linewidth lasers resulted in an advance by Kogelnik and Shank [96]. By creating a Bragg reflection distributed throughout the semiconductor gain medium, they produced the ubiquitously used distributed feedback laser (DFB) that made use of coupled modes and lased at a single wavelength. With the above innovations, a small, power-efficient, nearly monochromatic, and coherent source was achieved for easy deployment in optical communication systems.

2) Early Fiber Transmission Systems: The first generation of systems introduced in 1980 used multimode fiber, multifrequency Fabry–Perot 0.8-μm lasers, and had a data rate of 45 Mb/s [218]. The second generation systems of the mid-1980s generally used single-mode fiber, multifrequency 1.3-μm lasers, and had a data rate of several hundred megabits per second. The third generation of the late 1980s used single-mode fiber, single-frequency 1.5-μm DFB lasers, and had data rates in the few gigabit per second range. The decade culminated in the deployment of the 1988 fiber-optic trans-Atlantic cable, called TAT-8, that operated at 280 Mb/s, an order of magnitude faster than the copper-based cable that it replaced (see Fig. 11) [219]. This was a major step forward in the acceptance of optical communications for reliable deployment.

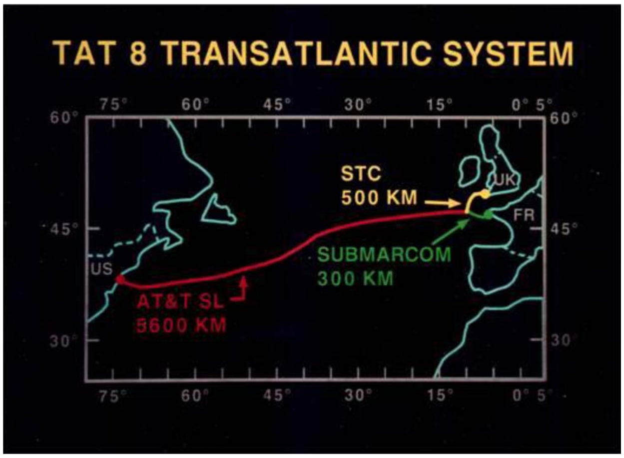


Fig. 11. ***Map of the TAT-8 fiber-optic trans-Atlantic 280-Mb/s cable deployed in 1988 [219].***

Since 1980, a series of rapid innovations have kept lightwave technology on a "Moore's-law-like" growth path, such that the capacity per fiber has been increasing, roughly, by a factor of 100 every ten years. Commercial systems were generally five to seven years behind the laboratory demonstrations. Key innovations included single-mode fiber, single-frequency lasers, Erbium-doped fiber amplifiers (EDFAs), and wavelength division multiplexing (WDM).

3) WDM and Amplifiers: Two key advances that allowed lightwave technology to continue in its exponential growth were optical amplifiers and WDM.

In 1964, Koester and Snitzer constructed a glass fiber amplifier by doping optical glass with rare-earth metals for the gain medium [220]. However, it was not until 1987 that the use of doped fibers emerged as an optical amplifier in communication systems. The revolutionary advance was made possible by recognizing that the rare-earth metal of Erbium had critical advantages. First, Erbium produced gain at the 1.55-μm low-loss minimum of the fiber. Second, Erbium contained a "meta-stable" energy state that had a recombination time closer to milliseconds (orders-of-magnitude longer than semiconductors) and would produce: 1) a near-quantum-limit low noise [221] figure for the amplifier; and 2) gain saturation effects would occur slowly over micro- to milliseconds and not change during a single or multiple bit times. In late 1987, two groups published work demonstrating high-gain EDFAs: first by Mears *et al.* [222], and then by Desurvire *et al.* [223]. The gain bandwidth of EDFAs is at least 3 THz wide. A single high-data-rate channel would experience gain, and, importantly, multiple data channels on different wavelengths as in WDM could be amplified simultaneously. Indeed, deployment-ready EDFAs with superior characteristics were achieved rapidly in the early 1990s.

A major leap forward occurred with the development of WDM systems in the 1990s [99]. As radio systems can use the frequency spectrum to simultaneously transmit multiple channels over the same medium, independent data streams can each be located on a single wavelength and propagated down the same fiber simultaneously dramatically increasing capacity. Among the components necessary to enable WDM transmission is the wavelength multiplexer to efficiently combine closely spaced wavelengths from different inputs onto a single output fiber. The arrayed waveguide grating (AWG) multiplexer could combine up to 100 channels spaced 50 GHz apart [224].

In addition to advances in components, a new systems approach was needed, since transmission systems were significantly hampered by fiber chromatic dispersion and nonlinearities. On the one hand, chromatic dispersion will cause temporal spreading of an optical pulse since: 1) a pulse has a finite information bandwidth; and 2) the fiber has a frequency-dependent speed of light. This argues for lower dispersion. On the other hand, the fiber's glass is slightly nonlinear, such that two waves propagating at the same speed will interact with each other in a deleterious fashion. This argues against low dispersion and for higher dispersion in order to reduce the phase matching. The concept of dispersion management enabled the mitigation of both these problems. The positive dispersion of the transmission fiber is compensated periodically by a negative dispersion element, such as dispersion compensating fiber. In this manner, there is no region of zero dispersion and phase matching, thereby limiting accumulation of nonlinear effects. An early R&D demonstration of this is the 1993 experiment of Chraplyvy *et al.* demonstrating WDM transmission of eight channels at 10 Gb/s per channel [225].

WDM, EDFAs, and dispersion management were also the keys to the simultaneous demonstration in 1996 by three groups of transmitting one terabit per second of data over a single fiber, a true milestone in optical fiber transmission [226]–[228]. This was accomplished by the groups of Onaka *et al.*, Gnauck *et al.*, and Morioka *et al.*

Although WDM enabled dramatic advances in capacity, it also ushered in an era of highly efficient networking. Given wavelength-selective components, a data signal's wavelength can be used as an address, such that nodes in a network would add or drop only that color of light. Such an optical add/drop multiplexer (OADM) would only detect the channel wavelength that is meant for that node, thereby reducing the speed of the detecting electronics and allowing the nondropped channels to pass through without any added latency [229]. OADMs could also be reconfigurable by using space switches, and many metro area networks deployed capacity where needed by using WDM-based reconfigurable OADMs.

C. Present State of the Art and Current Trends

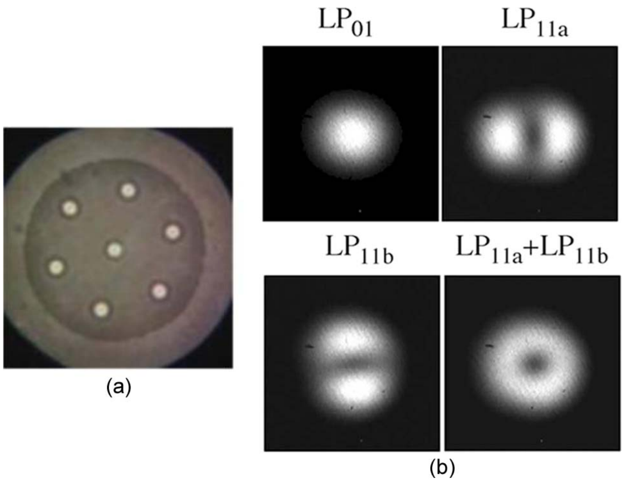
The years since 2000 have produced very exciting advances in the field of optical communications, especially toward lower cost, higher data rates, longer distances, lower power consumption, more functionality, and more stability. In the quest for more capacity, techniques long used in the radio field [230] have been applied to optical communications, including forward error correction (FEC) coding. The following technical advances have produced dramatic increases.

1) *Advanced modulation formats*: Until recently, deployed systems employed amplitude-keyed data encoding. However, phase-shift keying (PSK) of the optical wave is more robust to degrading nonlinear effects. Given that we are rapidly filling up the available fiber spectrum, spectral efficiency in terms of bits per second per hertz becomes critical; as another benefit, spectrally narrow channels are more tolerant to chromatic dispersion effects. Quadrature phase-shift keying (QPSK) enables two independent bits of data to be transmitted within one symbol time, thereby doubling the spectral efficiency. This can be extended to much higher in-phase/quadrature (I/Q) data constellations, e.g., quadrature-amplitude-modulation (QAM) transmission up to 512 [231]. Additionally, independent data can be transmitted along the two orthogonal fiber polarization axes, doubling the capacity and spectral efficiency again [232]. Another complementary advance is orthogonal frequency-division multiplexing (OFDM), which uses a single carrier wave and multiple orthogonal subcarrier waves. Each subcarrier carries independent data, and the subcarriers can be densely packed in the spectrum since orthogonality is maintained by advanced transmitter/receiver electronic processing [233], [234].
2) *Coherent systems using electronic digital signal processing*: Heterodyne receivers are ubiquitous in the radio world, in which a weak data signal is mixed with a powerful local oscillator. The corresponding optical approach uses a narrow linewidth laser to mix with a weak incoming optical data signal. The balanced detectors are square-law devices and recover not only the amplitude but also the phase information, i.e., the time history of the data channel's wave. Coherent systems not only exhibit better receiver sensitivity than direct detection, but also they can utilize sophisticated electronic digital signal processing (DSP) to equalize many impairments, such as chromatic- and polarization-based degradations [235].

The above two technical advances have been combined to produce significant results, including: 1) 1 Tb/s "superchannel" over a single 50-GHz channel [236]; 2) 100 Tb/s over a single fiber [237]; and 3) 200-Gb/s in a single channel over 12 000 km [238]. Commercial systems are now being deployed that transmit: 1) 100-Gb/s (as an Ethernet standard) per 50-GHz spectral channel using polarization-multiplexed QPSK and coherent detection at 25 Gbaud; and 2) 10-Tb/s total capacity per fiber.

According to Shannon [230], high signal power produces high capacity. Unfortunately, optical fiber nonlinearities limit the total signal power. The next dimension that has the potential for dramatic capacity increases is space multiplexing, i.e., transmitting independent data channels that are each on an orthogonal spatial dimension. As shown in Fig. 12, two approaches that are emerging include the transmission of independent data streams: 1) within each individual core of a special multicore fiber [239]; and 2) on orthogonal spatial modes within a few modes of a multimode fiber [240]. In both these approaches, crosstalk is a key challenge. Unique challenges for multicore systems include: 1) increasing the number of cores/modes; 2) decreasing the intercore/mode nonlinear effects; and 3) developing multicore/mode network elements. For multimode systems, mode mixing of the different LP modes is a natural occurrence which can be partially solved by utilizing multiple-input–multiple-output (MIMO) approaches; MIMO is a popular technique in radio-frequency (RF) systems and can untangle some of the crosstalk between modes using digital signal processing [240].

In terms of hardware, one area of intense R&D advances is photonic integrated circuits, which holds the promise of lower cost, higher performance, and reduced power consumption. Many of the innovations that produce better systems performance require more components that are evermore complex. For example, higher order modulation formats in coherent transceivers require multiple modulators, lasers, couplers, and balanced detectors. This scenario has benefitted greatly from advances in photonic integrated circuits on both III-V [241] and silicon [242] materials; Fig. 13 shows an example of an integrated 100-Gb/s coherent receiver. In terms of the ability to interact with light, III-V materials are generally superior. However, silicon-based photonics opens up the possibility to make use of the massive silicon manufacturing infrastructure to produce cost effective integrated photonics circuits in both data communications and telecommunications.



(a)

(b)

Fig. 12. ***Spatial division multiplexing of orthogonal, independent data streams each transmitted on a different: (a) core in a multicore fiber [239]; and (b) mode in a multimode fiber [240].***

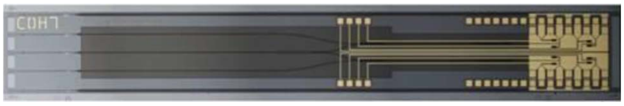


Fig. 13. ***Photograph of a monolithically integrated InP dual-port coherent receiver for 100-Gb/s PDM-QPSK. The chip size is 8 × 1.2 mm^2 [241]. ©2011 OSA.***

Another exciting development has been the emergence of massive data centers that enable Internet searches and "cloud-based" services. Data centers require large-capacity, short-distance fiber "pipes" connecting the high-speed servers, and optical communications has enabled data centers to flourish. Indeed, a data center can employ as many as one million lasers, a truly amazing development.

Also in the past 20 years there have been exciting and promising advances in the quantum information sciences. An emerging early application of this is the safely encrypted quantum key distribution (QKD) over optical fiber transmission links [243].

Complementing the transmission of information optics, we have the development of information storage in optical discs, such as CDs, DVDs, and Blu-rays [244]. These discs were introduced in 1982, and several hundreds of billions have been sold worldwide since then. In the disc players, semiconductor lasers read the information stored on the discs. These lasers number in the hundreds of millions.

D. Future Vision and Possibilities

"Computer power and optical transmission power have scaled up now, for . . . 30 years, by about a factor of 100 every 10 years. . . . And it would be foolish to predict that it will suddenly stop, although it will take amazing breakthroughs to keep it going" [245].

The modern era of optical communications is only about 50 years old. In fact, even the original paper on optical communications predicted that communication systems using optical fiber could have "an information capacity in excess of 1 Gc/s" [208], which has already been surpassed by five orders of magnitude. Given the technical advances and society changes wrought by our field, it is tempting to be bold about the future. A few possible

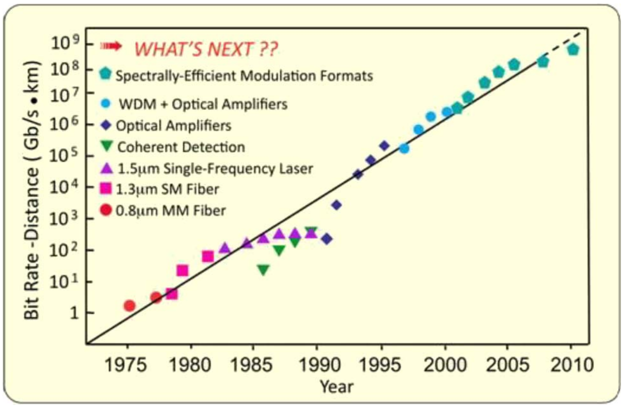


Fig. 14. ***Bit-rate distance product for transmission over a single optical fiber, highlighting the different key technologies that enabled the advances.***

scenarios that may unfold over the coming decades include, some more bold than others, the following.

- Will fibers be deployed to nearly all homes and offices, providing ubiquitous 10-Gb/s bandwidth to all users?
- Will optics become pervasive inside computers, providing low-cost, power-efficient, and high-capacity interconnects, potentially using silicon-photonics-based integrated chips?
- Will all-optical networks be fully transparent, adaptable to operational changes, provide flexible bandwidth allocation, accommodate heterogeneous traffic, and be functionally reconfigurable in much the same way that wireless networks operate?
- Will satellite communications be dominated by optical free-space links that provide high data-rate and low size-weight-power characteristics?
- Will novel optical components and architectures be used to dramatically reduce the ever-growing power consumption in generating and switching of data?

If past is prolog and the capacity grows by a factor of 100 every ten years (see Fig. 14), will the capacity be a billion-fold higher in 50 years? If even a fraction of that does occur, what will be the effect on society? It is exciting to speculate on the impact and also on the technologies that will enable these advances.

E. Companion to Communications: Important Related Technologies

Although this section focused specifically on communications, there are several important topics that are thematically related in terms of enabling technologies or applications focus. A brief treatment of some of these areas is described below.

1) *Sensors:* Optical sensors play an ever-expanding role as we are able to detect ever-smaller changes in some property of the optical wave itself. Infrared sensors have been used for decades to control TVs, open elevator doors, detect thermal changes, and enable disruptive night-vision goggles [246]–[248]. Fibers have also made major advances in terms of highly accurate gyroscopes [249], [250]. More recently, sensors have been expanded into the biological and chemical realm (e.g., optofluidics) [251], and oftentimes small optical wave phase changes in an interferometric device can sense minute changes [252]. Implications of these advances are vast, such that optics might be used extensively to accurately and rapidly diagnose medical conditions [253] and detect unwanted, dangerous elements in homeland security [254]. Finally, reflections from optical fibers and fiber Bragg gratings can also be used to measure changes (e.g., pressure, mechanical, temperature, stress) with high accuracy [255]–[257].
2) *Light detection and ranging (LiDAR):* Lasers can produce waves with orders-of-magnitude smaller wavelengths than are used for traditional radar, and laser light can be confined to a much narrower beam than can radio waves [258]. Therefore, radar that is based on light can produce exquisite detail of images at standoff distances of many kilometers that far exceed traditional radar (see Fig. 15) [259]. By transmitting light and coherently measuring the phase of the reflected signal, large geographic areas can be mapped in fine detail, which has become quite important for military applications [260], [261].
3) *Image processing:* Images today are commonly detected by an array of optical pixels using different types of technologies (e.g., CCDs, CMOS) [262]–[264]. Advances in pixels include: increased

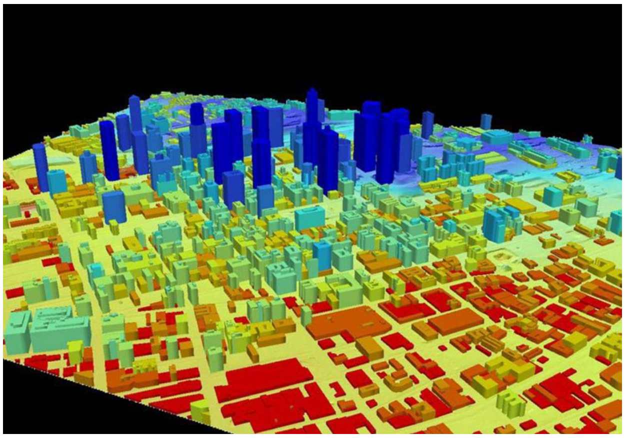


Fig. 15. ***Science Applications International Corporation (SAIC) can convert vast quantities of information contained in raw LiDAR data into detailed urban feature data to support analysis and mission planning [259]. ©2011 SAIC.***

density, decreased size, increased dynamic range, and increased signal-to-noise ratio [265]. Moreover, these pixels can access ever-broader spectral ranges and resolutions, and can include more functionality due to intimate coupling with sophisticated electronics [266], [267]. Given that close to a billion people around the globe carry megapixels in their pocket cell phones, it is inevitable that the capabilities of optical pixels will continue to increase in the future [268, Fig. 4.10].

4) *Microwave and terahertz photonics:* Information transfer, sensing, and imaging can all make critical use of microwaves and terahertz waves for achieving excellent performance [269], [270]. However, efficiently generating, transmitting, and detecting these waves can make critical use of the dramatic optical technologic advances that have occurred; this can be justified when considering that the optical wave starts out at a much higher 200-THz frequency. For example: a) highly linear optical elements (e.g., optoelectronic modulators) can be used to imprint a microwave signal as a subcarrier onto an optical wave that travels with low loss through a fiber [271]; and b) wave mixing of two stable optical waves in a nonlinear element can efficiently produce sum and difference frequencies, which can then be used to generate and detect terahertz waves that have many of the desirable properties of the original optical waves [272].

5) *Signal processing:* Whereas optics is considered the mode of choice for transmitting high-capacity data, VLSI electronics has been the domain for the parallel processing and manipulation of that data. If we speculate into the future, there is the potential for applications of optics in signal processing at very high serial data speed [273] and with low power consumption [274]. Depending on the relative advances of electronic- and photonic-integrated circuits, optical signal processing might be used to perform some specific, limited functions, possibly including: a) pattern recognition [275]; b) data impairment compensation [276]; and c) simple logic functions [277], [278].

VI. BIOIMAGING, HEALTH, AND MEDICINE

A. Introduction

Light has been used for medical diagnosis since before the days of Hippocrates; early practitioners of the art used visible cues to categorize maladies of the human body. The application of optics in medicine expanded significantly with the invention of the microscope in the late 16th century, which allowed physicians to see structures, such as cells, that the eye could not resolve natively. The microscope gave rise to histopathology, the "gold standard" for disease diagnosis, where fluids/tissues are extracted from the patient, made into thin sections, stained, and examined for the presence of microscopic structural patterns that are indicative of a particular disease. This diagnostic paradigm is prevalent today and has remained relatively unchanged for more than 100 years.

Driven largely by the information technology revolution, optics in medicine has undergone a renaissance over the past 30 years. The advent of the laser, optical fiber, and fiber-based telecommunication technologies, optical detectors, and computers have made it possible to consider more advanced forms of optical microscopy that may be used to improve disease diagnosis. Accompanying this massive technology influx, a new transdisciplinary field called biomedical optics originated and has grown exponentially. Biomedical optics combines the knowledge and talents of engineers, physicists, and clinicians to create new ways of using light to visualize the body and treat disease. Research conducted in this new field has opened up opportunities for improving medical diagnosis now and revolutionizing it in the future.

The use of optics in biomedical sciences has exploded over the past several decades. Some of the major advances include:

- super-resolution microscopy [279], [280], where the diffraction limit of the optical microscopy has been broken, enabling nanometer-resolution imaging of cells;
- confocal and nonlinear microscopy [281]–[284] and genetic/molecular imaging [285]–[287], which, among others, provide the capability of imaging within animals to enable the study of disease on the molecular/genetic basis;
- optogenetics [288], [289], which provides a means for genetically modifying cells so that light may be used to open ion channels, thereby enabling the investigation of diverse physiological processes associated with action potentials and bioelectrical conduction;
- spectroscopy [290]–[295], where new forms of absorption, autofluorescence, light scattering, and Raman spectroscopy have been developed to unravel the native chemical/molecular composition of cells and tissues;
- diffuse tomography [296]–[298], in which a body is illuminated, diffuse light is collected, and the inverse problem is solved to recover the macroscopic optical properties of tissues inside the body that are correlated to disease states such as cancer;
- photoacoustics [299]–[301], which illuminates tissue with a short pulse of light that, when absorbed inside the body, creates an ultrasound signal, thereby providing a noninvasive imaging tool with optical contrast and ultrasound resolution;

- light-based therapy [302]–[306], where lasers have been used to ablate disease, and selectively target vessels and tumors based on native absorption or optical excitation of an injected phototoxic agent [e.g., photodynamic therapy (PDT)]. Recently, low levels of light in the near-infrared region have also been shown to decrease programmed cell death (apoptosis), mitigating damage caused by anoxia and traumatic injury [307], [308].

These and many other techniques pioneered during this period promise to change the way in which basic biological research and medicine is conducted. Perhaps there is no better example of the potential of optics in medicine than the change in the paradigm for tissue diagnosis that will take place through the development and adoption of *in vivo* microscopy techniques.

B. Past Key Milestones and Perspectives

High-resolution optical imaging of human tissue is challenged by the scattering of photons once they enter the tissue, making it difficult to obtain detailed images when the body is illuminated externally. Three important milestones in optics have helped to overcome light scattering for internal tissue diagnosis: the invention of the endoscope, the confocal microscope, and optical coherence tomography (OCT). The fiberoptic endoscope, pioneered by Basil Hirshowitz in the late 1950s [309], enabled clinicians to see macroscopic structures inside the body under white light illumination—subsequent CCD camera-based endoscopes and laparoscopes are now used routinely in many clinical subspecialties. Confocal microscopy, invented by Marvin Minsky in 1955 [310], uses a pinhole placed in front of the detector to reject the majority of multiply scattered light from a tightly focused beam within tissue. Detailed optical sections or transverse microscopic images are obtained when the beam or pinhole is scanned. OCT was conceived circa 1990 in the laboratory of James Fujimoto at the Massachusetts Institute of Technology (MIT, Cambridge, MA) [311]. As opposed to confocal microscopy, OCT utilizes low coherence interferometry and optical ranging to detect singly scattered light from within tissue. This mode of imaging provides cross-sectional images when the OCT beam is scanned across the tissue. Because the eye and skin are externally accessible, confocal microscopy and OCT were first applied to the diagnosis of these organs in the early 1990s [311], [312]. The development of flexible confocal microscopy/OCT probes that were compatible with endoscopy made it possible to see inside the body at microscopic resolutions [313], [314]. The first demonstrations of endoscopic OCT and confocal microscopy emerged in the late 1990s and early 2000s [315], [316].

C. Present State of the Art and Current Trends

Endoscopic confocal microscopy and OCT have now entered the medical arena as state-of-the-art imaging techniques [317], [318]. These methods fall under a new field termed *in vivo* microscopy, whose goal is to obtain microscopic images from human tissue without excising it from the body. The medical applications of *in vivo* microscopy are many—the ability to extract these images minimally or noninvasively is safer, saves time and cost, and *in vivo* microscopic imaging can be far more comprehensive than conventional excisional biopsy. Currently, there are many different devices that use OCT and confocal microscopy to image internal organ systems: representative images obtained from two such instruments are presented in Fig. 16.

One particular improvement that *in vivo* microscopy affords is the capability to image extremely large areas of tissue at microscopic scale. Currently, the conventional biopsy only allows the physician to obtain a small snippet of tissue, which is then subsequently examined under a microscope. However, many diseases are heterogeneously distributed over a large tissue area or even an entire organ and cannot be seen by the naked eye. In these situations, physicians blindly take multiple biopsies at random locations, which can lead to nondiagnostic samples or specimens that do not accurately represent the patient's disease state. Imaging large regions of tissue (> 1 cm^2 surface area) at the microscopic scale is now possible with high-speed *in vivo* microscopy techniques and has been coined comprehensive volumetric microscopy [319]. With comprehensive volumetric microscopy, images of entire coroary arteries, the esophagus, skin, eye, etc., can be obtained in a realistic procedural time (Fig. 17), giving clinicians something they need, but have not had access to before—the ability to screen a large region of tissue at the microscopic scale *in vivo*. This capability allows full microscopic assessment of entire organ surface tissues and enables the selection of biopsy sites to be guided by these advanced optical imaging modalities.

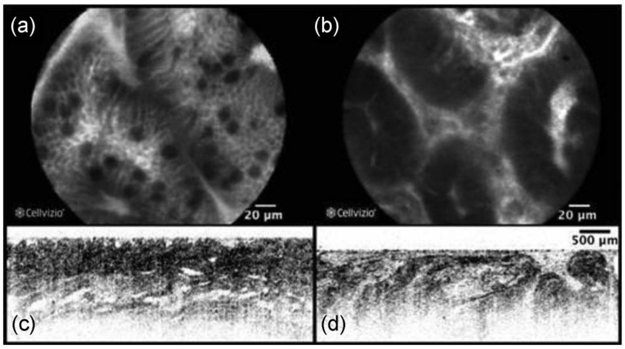


Fig. 16. ***Endoscopic confocal microscopy (a) and endoscopic OCT (c) images, obtained from patients with Barrett's esophagus, a condition of the esophagus that puts patients at risk for developing esophageal cancer. Confocal (b) and OCT (d) images of Barrett's that has undergone progression to high-grade dysplasia, a cancer precursor (b), and frank esophageal cancer (d). Image panels (a) and (b) were provided courtesy of Dr. Emmanuel Coron, Nantes University Hospital (Nantes, France).***

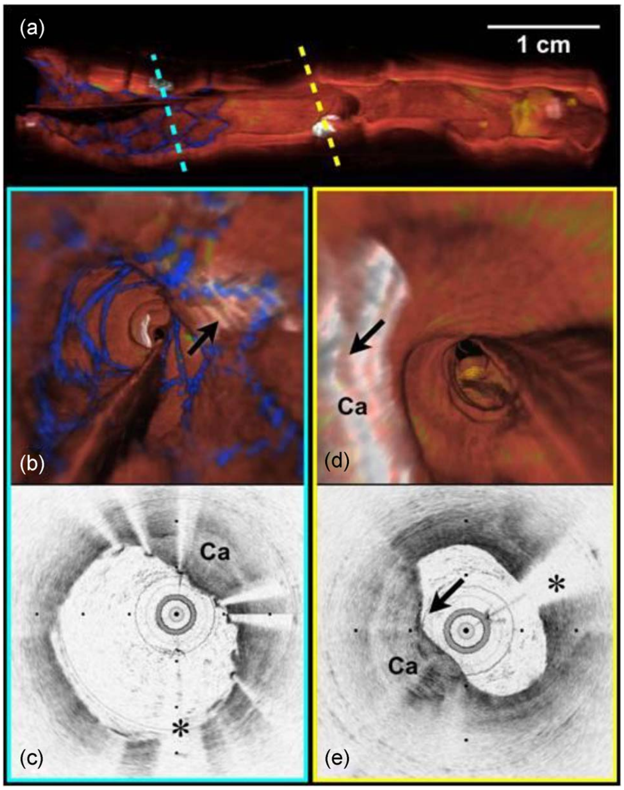


Fig. 17. *Comprehensive volumetric microscopic images of the coronary artery of a living human patient, obtained using OCT in vivo and displayed as a 3-D cutaway view (a), fly-through views (b) and (d) and individual cross-sectional images (c) and (e). Color scale for (a), (b), and (d): red—artery wall; green—macrophages; yellow—lipid core; blue—stent; white—calcium; Ca and black arrows—denote calcium; *—guidewire artifact [320].*

In addition to OCT and confocal microscopy, a host of other interesting optical imaging modalities have been conceived and are under active investigation. Nonlinear microscopy techniques offer additional high-resolution imaging capabilities with deep tissue penetration [321]. Methods for measuring the details of the light scattering spectrum have been shown to provide insight into subcellular structure [322]. Autofluorescence and spectroscopy have been incorporated into instruments for uncovering images of the chemical and molecular composition of tissue [323], [324]. These techniques can be standalone or can be added to OCT and confocal devices for the multimodality imaging of different organ systems.

This cadre of optical bioimaging techniques now has a commercial presence and is gaining a foothold in the medical application space. To date, there are over 20 companies putting forth products for *in vivo* microscopy or optical diagnosis. Reimbursement is in place or in process for confocal microscopy and OCT and real-world medical applications are beginning to emerge. The most important remaining challenge for widespread adoption is conducting clinical studies to demonstrate that the introduction of these technologies in the patient management workflow will improve outcomes in a cost-effective manner.

D. Future Vision and Possibilities

High-tech *in vivo* microscopy methods are here today and can be used to complement or in some cases supplant existing medical imaging modalities and improve certain diagnostic paradigms. Thinking about the next steps for these technologies, can we foresee a day when conventional microscopes are no longer used by pathologists and the final diagnosis is rendered instantly from images obtained from living patients? While OCT and confocal provide very high-resolution images, the resolution is still not quite as good as bench microscopy, where images are acquired from thin sections under very controlled conditions. Newer, high-resolution optical technologies, such as full-field-optical coherence microscopy (FFOCM) [325] and 1-μm resolution OCT (μOCT) [326] bring us a step closer, but have not yet been demonstrated for internal organ imaging *in vivo*. Another challenge is image contrast. Currently, greater than 90% of histopathologic diagnosis is based on a single stain combination, hematoxylin and eosin (H&E); hematoxylin stains nuclei blue and eosin stains the cytoplasm and many extracellular molecules pink. Because most human *in vivo* microscopy tools use natural contrast or the U.S. Food and Drug Administration (FDA) approved fluorescent dyes, such as fluorescein, they are not currently able to completely recapitulate the contrast afforded by an H&E stained slide. Therefore, it is likely that *in vivo* microscopy techniques will need further resolution and contrast improvements before the conventional biopsy and microscopic analysis can be rendered obsolete.

One advantage of optical *in vivo* microscopy is its potential to provide on-the-fly diagnosis. Not only does this allow the diagnosis to be obtained rapidly, but it also opens up the possibility of a "see and treat" paradigm. By combining imaging with near-simultaneous and colocalized therapy, such as laser or RF ablation, a patient could come into the office, be diagnosed, and then treated in the same session. The treatment could precisely conform to the boundaries of the disease, leaving no abnormal tissue behind, while at the same time preserving as much of the unaffected tissue as possible [327]. Optical bioimaging devices integrated with therapy could enable a far more efficient process of patient management, could reduce the number of visits, and provide more effective patient care.

Beyond microscopic imaging, the field of pathology is trending toward molecular/genetic diagnosis; this more granular molecular/genetic information may be used to narrow diagnostic categories and tailor individual therapeutic management strategies. Wide utilization of molecular and genetic diagnosis from extracted fluids and excised tissues is on the horizon. In order to conduct molecular/genetic imaging *in vivo*, molecular reporters or labels must be administered and then imaging, such as fluorescence confocal microscopy, can be conducted. A tremendous amount of progress in molecular imaging has been made in the field of intravital confocal/multiphoton imaging in animals [328], [329]; the primary challenge for human implementation is regulatory approval of these new molecular and genetic diagnostic agents.

Most current case use scenarios for *in vivo* microscopy modalities occur when a patient is known, via symptoms or other tests, to already have a medical problem. A wider vision that would make a greater impact on healthcare would be to use these devices to screen asymptomatic patients to determine if they have occult disease or if they are at risk to develop it in the near future. Currently, most *in vivo* microscopy probes and instrumentation are relatively expensive and need to be administered during an endoscopy or an interventional procedure. Looking toward the future, there may come a time when *in vivo* microscopy may be implemented in the outpatient setting. The recent clinical introduction of swallowed capsule endoscopy is a first foray into this domain [330], but it is possible that many of the more advanced optical diagnostic technologies discussed here could also be incorporated into a pill that can be swallowed. Positional control of these devices would be a requirement for many diseases and organ systems; multiple groups are working on external methods for navigating small endoscopic capsules [331] that could be adapted for *in vivo* microscopy capsules as well.

In sum, light has been used for diagnosis since the beginning of medicine, but the most recent information technology revolution has significantly expanded the scope of *in vivo* optical imaging and its potential role in clinical medicine. In the near term, it is likely that *in vivo* microscopy techniques will complement current diagnostic strategies and in some cases will supplant existing medical practices. The future of optical bioimaging will afford even greater capabilities, where we will be surpassing what has previously been thought to be possible for the betterment of healthcare.

VII. FLAT PANEL DISPLAYS: ENABLING THE AGE OF MOBILITY

A. Introduction

Displays are undergoing revolutionary changes. Only two decades ago, most homes had only a single, fixed information display: a television that used a bulky and power-consumptive cathode ray tube (CRT) as the imaging element. But liquid crystal displays (LCDs), despite their poor image quality, slow speed, and viewing angle dependence, were rapidly developed to eliminate the CRT's shortcomings, and would soon replace the CRT, which had dominated the world of displays for more than 50 years.

B. Past Key Milestones and Perspectives

Originally, LCDs were monochrome and front-lit (i.e., reflective) such that they could only be viewed in lighted environments. Hence, their use was primarily confined to small, handheld electronic appliances such as calculators. Nevertheless, LCDs were lightweight, compact, operated at very low voltages, and consumed considerably less power than a CRT. With the introduction of fluorescent-tube backlit, color LCDs fabricated on inexpensive amorphous Si transistor backplanes [332] that were used to rapidly address each display pixel, the image quality and other performance factors considerably improved. This ultimately ushered in the current age of mobile electronics, spearheaded by the introduction of laptop computers. These changes were made in the context of a highly diverse array of alternative display technologies that were competing for to replace CRTs, including plasma displays, thin-film electroluminescent displays, and electrophoretic displays [333]. But LCDs continued to improve rapidly in terms of image quality and color gamut, viewing angle capabilities, and response speed, resulting in their emergence as the single most cost-effective and ubiquitous display technology both at home and in the workplace. Ultimately, high information content, active matrix LCDs (AM-LCDs) have enabled a plethora of handheld, portable devices that only a decade ago were unimaginable: the smartphone and the computer tablet being chief among the appliances that have connected users to the Internet at almost all times and regardless of location.

But by the mid-1990s, yet another display technology based on organic light emitting devices (OLEDs) emerged [334]. Extremely rapid advances in OLED displays over the last decade are now, once again, creating a revolution that is poised to displace LCDs from the marketplace, much as LCDs eliminated CRTs two decades ago.

C. Present State of the Art and Current Trends

A LCD is segmented into pixels, each consisting of a liquid crystal light valve employing molecules that rotate the polarization of light when aligned in an applied electric field [335]. If placed between crossed polarizers, the liquid crystal can be aligned to either block the incident light (typically supplied using fluorescent lamps or white light emitting diodes on the display back plane), creating a dark pixel, or to pass the light, creating a white pixel. Color is introduced at the pixel level using cyan, magenta, and yellow color filter arrays. Hence, the display is "color-subtractive": starting with an illuminated white background, color content is removed at each subpixel by switching the light valve from on to off. This introduces a power penalty since the backlight is always on, with the brightness and segments of the color spectrum locally set by the state of the light valve. The speed of image refresh is determined by how fast the liquid crystal orientation can be varied: typically a few milliseconds which is marginally sufficient for following rapidly moving images on a display with a frame rate of 30 per second. The viewing angle dependence, which has been significantly reduced over the last decade, arises from the use of polarizing optics.

Whether illuminated by fluorescent tubes or LEDs, the color subtractive nature of the LCD limits their color gamut and contrast ratio, making images noticeably less rich than the now-obsolete CRT display. However, these issues are avoided by OLED displays, which like CRTs, are emissive (i.e., color-additive) [336]. Furthermore, due to the elimination of the backlight and the relatively complex optics of LCDs (i.e., OLED displays do not require crossed polarizers or color filter arrays), OLED displays are extremely thin (2–3 mm), power efficient, and lightweight. Their images are vivid due to a wide color gamut and very high contrast ratio. That is, when the OLED pixel is turned off, there is no light emitted, which differs from the LCD which is incapable of blocking 100% of the backlight emission when the pixel is off. Finally, the efficiency of an OLED display is typically four times that of LCDs since light is emitted only on demand by a given pixel, and the devices themselves can have internal quantum efficiencies as high as 100%. This is of considerable importance for mobile applications where extended battery life is required when the user is "on the move."

The basic OLED structure is shown schematically in Fig. 18. Here, "ETL" is the organic electron transport layer that moves electrons from the cathode metal contact to the light emissive layer, or "EML." The EML is typically composed of two different molecules, a charge-conductive "host" into which it is doped at very small concentration (~1%–8% by weight) of a "guest" molecule that gives off light of the desired color (or wavelength). The "HTL" is the hole transport layer that delivers holes from the anode contact to the EML. The transparent conducting anode through which the light is viewed comprises indium tin oxide (ITO), and the cathode is a metal (such as Al doped with Li) capable of forming an ohmic contact with the ETL for the efficient injection of electrons. Typical OLED structures used in high-efficiency and high-reliability applications are considerably more complex than this basic structure, but in most cases, the total thickness of organic layers rarely exceeds 100 nm.

When an electron and hole are conducted to the same molecule within the EML, they put the molecule into a mobile excited state (or exciton) that, after a few nanoseconds to microseconds, can radiatively recombine to emit light. By changing the composition or structure of the molecule, the emission wavelength is varied. In fact, only slight chemical modifications can result in the color emission being changed from the UV, through the blue and green, to the red and near-infrared. A sample of the gamut of colors currently available to phosphorescent light-emitting molecules is shown in Fig. 19. For all colors, light emission can be extremely efficient. Indeed, 100% conversion of electrons to photons has been reported across the visible light spectrum using so-called electrophosphorescent, or "triplet emitting" dopants [337]. However, when mounted on flat glass substrates, as shown in Fig. 18, total internal reflection limits the light emitted into the viewing direction to ~20%. To increase light extraction, many schemes have been demonstrated, including the use of high index of refraction substrates, surface roughening, lenses, and methods to outcouple waveguide modes trapped within the organic films themselves [338]. Perhaps the most cost-effective outcoupling method is to apply arrays of polymer microlenses on very thin (~0.5-mm) substrates. Arrays of low-cost hemispherical microlenses ~5–10 μm in diameter can increase the external efficiency to as high as 40% [339].

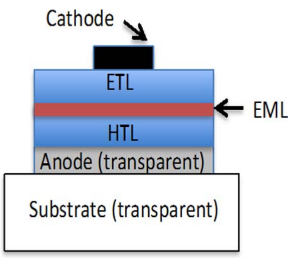


Fig. 18. ***Archetype OLED structure.***

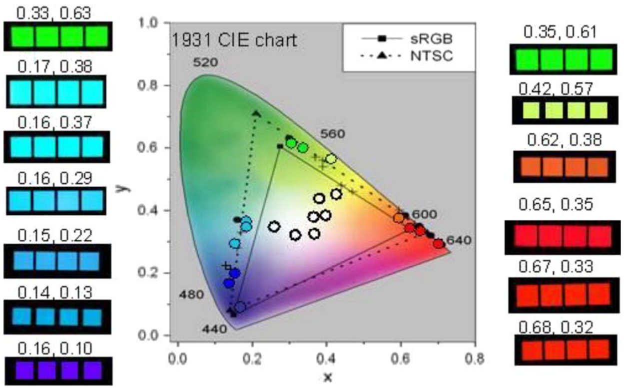


Fig. 19. ***Chromaticity chart showing sample phosphorescent OLED color coordinates for the test devices shown on the periphery. Each color coupon (actual emission colors shown) shows its color coordinates (X,Y), with a corresponding dot marking its location on the chart. By mixing more than one color, white OLEDs can be realized, as shown by the white dots. Courtesy, Universal Display Corp.***

Very high efficiency is only one feature of a successful display technology. For OLED displays to gain widespread acceptance they must also have a long operational lifetime and be priced at a level acceptable to the consumer. The primary barrier to long lifetime is the stability of the blue phosphorescent OLED (or PHOLED) subpixel element. Due to molecular excited state energy-driven molecular degradation, PHOLED displays today have lifetimes of 10 000–20 000 h, as shown in Table 1.

A substantial cost barrier arises from the active matrix (transistor) backplane that rapidly addresses and illuminates each pixel. In contrast to LCDs which are voltage activated, OLEDs require current drivers. Hence, the very low-cost amorphous Si LCD backplanes are incapable of supplying sufficient current to OLEDs, and hence have been

Table 1 Representative Commercial PHOLED Performances. Source: Universal Display Corp.

PHOLED Color	CIE Color Coordinates	Luminous efficiency (cd/A)	Operating Lifetime (Khr, LT 50%)
Deep red	(0.63, 0.31)	17	250
Red	(0.64,0.36)	30	900
Green	(0.34, 0.62)	78	400
Light blue	(0.18, 0.42)	47	20

All data corresponds to an initial luminosity of 1000 cd/m^2. LT 50%=Time for luminosity to decrease by 50% from its initial value.

replaced by the somewhat more costly low-temperature polysilicon (LTPS) active matricies [340]. Nevertheless, LTPS backplanes have now achieved production on large-area substrates, leading to rapid decreases in cost.

The final major challenge to producing low-cost, large-area OLED displays is in pixel patterning. To create a full color display, red, green, and blue emitting pixels must be positioned within only a few micrometers, with each OLED subpixel only 30 μm wide in a high-definition display. Since all OLED displays currently consist of vacuum-evaporated "small molecule" materials, patterning is typically achieved via deposition through shadow masks. While this technology is currently used in large-scale production, it has many shortcomings such as the tendency for masks to become clogged, fragility to continued handling, and complexity when used in large-scale manufacturing environments. Hence, alternative, direct-printing technologies are currently being explored including inkjet printing of molecular materials suspended in solution, and its "dry processing" analog, organic vapor jet printing [341]. Other printing technologies, such as physical transfer printing (i.e., "stamping") and laser-induced pattern transfer are also of interest.

The manufacturing experience gained as OLEDs have emerged as an increasingly important display technology that competes with LCDs provides the confidence to also move this technology into the lighting market in the near future. As of this writing, one company alone [Samsung Mobile Displays (SMD)] is producing 7–8 million such displays per month for use in smartphones, with plans to scale these devices to larger, 3-D displays. SMD claims that it will produce 1 billion displays in the next five years.

Another manufacturer is LG Display that is positioning itself to introduce active-matrix OLED (AM-OLED) TVs in the near future. Current manufacturing primarily employs Gen 5.5 mother glass substrates (Gen 5.5 corresponds to 1.3 m × 1.5 m × 0.6 mm substrate blanks). Production on large substrates is resulting in a rapid decrease in cost of OLED displays while increasing their performance as the industry grows.

Today, AM-OLEDs are poised to enable a second revolution in mobile electronic appliances. Indeed, the next generations of smartphones, tablets, and laptops will almost certainly employ OLED displays.

D. Future Vision and Possibilities

The next step in information display technology is migration to 3-D television. Today, 3-D AM-OLED displays are entering pilot manufacturing. This application is particularly attractive to display manufacturers due to their very vivid colors, high response speed, and large on–off contrast ratios that make 3-D images particularly vivid. The image is created via a stereoscopic illusion, and hence provides a false impression of depth. However, there are emerging technologies based on holographic image formation where an object is truly captured in 3-D, with its various features revealed as the observer's viewing position changes, just as if viewing the actual object. Until recently, holographic displays have been confined to fixed images. However, using rapid refresh-rate electrorefractive polymers, moving 3-D images have recently been demonstrated [342], suggesting the possibility that future displays will enable complete 3-D image viewing in real time. However, there is considerable work to be done before this prospect becomes reality. Currently, holographic images are low contrast and have very poor (if any) color depth. Furthermore, early demonstrations of moving holographic images are slow, and hence are not yet capable of providing a real-time visual experience. Last, the equipment needed to create and to view a high-quality image is extremely bulky, complex, and costly, making such displays inaccessible to commercial markets.

The extreme thinness of OLEDs and their ability to be deposited on flexible plastic or metal substrates suggest that they will eventually enable full color, full motion, ultralight weight roll-up displays, creating the next major paradigm shift in high-information content, mobile electronics. Early demonstrations of this technology have already produced extraordinary results [343], suggesting that their commercialization will occur in the near future.

It is now clear that, starting with the LCD, mobile electronic devices with high information content and high fidelity image reproduction are now an ubiquitous feature of our everyday lives. But this "mobile device" revolution, which has also been enabled by high bandwidth wireless technology, is only in its infancy. More complex and flexible interactive displays based on AM-OLEDs, and eventually refreshable 3-D holograms, are just on the horizon. Their potential for generating realistic images with a large color gamut using ultrahigh efficiency electronics promises to open up entirely new and yet-to-be envisioned possibilities in our world of high information content mobile electronics.

VIII. PHOTONICS IN MANUFACTURING

A. Introduction

Manufacturing is the process of converting raw materials and components into useful products. The story of photonics in manufacturing is intimately intertwined with the story of lasers. Although the reforming and even destructive power of light, as epitomized by the ingenious use of Archimedes "burning" mirrors, was recognized from ancient times, its practical and widespread use was realized only much later with the first laser demonstration by Maiman in 1960 [4]. Initially described as "a solution looking for a problem," lasers quickly turned from scientific curiosity to powerful tools that shaped technologically the second part of the 20th century. Owing to the stimulated emission process, compared to other sources, lasers are intense, directional, largely monochromatic, and coherent, making them the most versatile and accurately controlled form of energy sources. In addition to providing the energy, photonics supply the optics for beam shaping, beam delivery, process sensing, control, and measurements with unprecedented accuracies.

A large number of lasers using different host and active materials were developed ever since, as discussed in Section III. However, only a few, the most power scalable, have been used as energy sources in manufacturing to date. These include CO_2, Nd : YAG, Nd : Glass, Yb : YAG, Yb : YVO_4, Er : YAG, excimer, diode, and the more recent disk and fiber lasers. Industrial lasers can be continuous wave (CW) or pulsed, ranging from millisecond to nanosecond and femtosecond, and cover wavelengths from UV to far infrared (FIR). Currently, use of lasers in material processing and manufacturing accounts for $\sim$30% of total laser revenues, and amounts to a total of $\sim$3 billion. Lasers continue finding an ever increasing number of applications, contributing to wealth creation and life quality improvements.

B. Past Key Milestones and Perspectives

Right from the start, it was realized that lasers could be used in previously unimaginable ways and systematic studies of lasers in material processing applications began almost concurrently with the first laser demonstration [344], [345]. It was soon found that such lasers could drill very small holes and cut different types of material, and inevitably interest arose in their potential applications for weaponry and manufacturing.

A key development in the industrial use of the newly developed laser technology took place in 1967 in the U.K. Welding Institute (Cambridgeshire, U.K.), where a consortium was formed to develop a laser system for a new industrial process, namely cutting metal sheets. In the electronics industry, by 1971, Motorola had started to use lasers to adjust circuit components by evaporating sections of them. In 1973, General Electric introduced laser turbine-hole drilling in aerospace applications. In 1978, the Ford Capri II was the first car to have laser-cut parts, while in early 1980s, initial work in the Osaka University (Osaka, Japan) and MIT on laser forming resulted in stereo-lithography as a means of 3-D rapid prototyping. A revolution that was bound to change the landscape of modern manufacturing had just started, with lasers rapidly replacing traditional manufacturing techniques. In addition and more importantly, new techniques were developed using the novel properties and accurate control offered by lasers [346], [347].

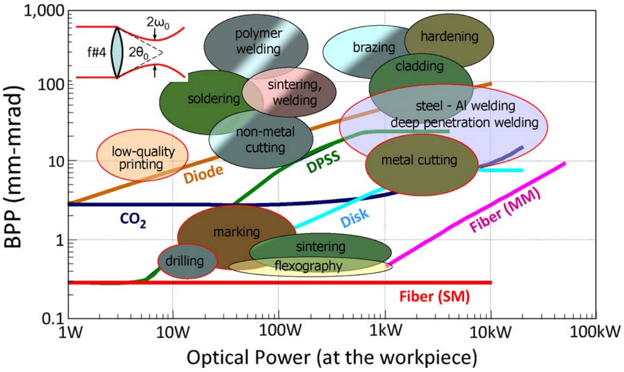


Fig. 20. ***BPP and average power requirements for laser applications and BPP versus average output power for main industrial lasers (adapted from [346], [348]).***

C. Present State of the Art and Current Trends

Major modern manufacturing sectors, such as automotive, aerospace, and electronics, are now heavily dependent on lasers and photonics to perform an ever increasing number of large-scale industrial processes.

Fig. 20 shows typical beam quality, quantified by the beam-parameter product (BPP $= \omega_0\theta_0$; see inset for definitions), and power requirements for the most common laser applications in material processing and manufacturing to date. The majority of these processes are based on thermal effects, such as heating, melting, and vaporization. It is evident that lasers cover a large application parameter space with vastly diverging requirements spanning about three orders of magnitude in beam quality and four orders of magnitude in optical power. They cover low average power-high beam quality applications, such as marking and drilling, and multi-kilowatt low beam quality applications, such as hardening. In addition to replacing traditional mechanical or chemical techniques, lasers have also enabled a number of novel processes. Laser cutting, for example, allows repeatable high-precision flat or 3-D patterns, creating features at high speeds that cannot be produced via conventional methods. Also use of laser enables welding of dissimilar materials like steel and aluminum, or processing of composite materials, such as carbon fiber-reinforced plastics, known to be impossible with traditional techniques.

Fig. 20 also shows a comparison of the beam quality achieved at different average output powers, for the main industrial-grade lasers. Applications appearing higher and left of the curves in Fig. 20 are covered by the corresponding laser technology. Fiber lasers are the latest entry to the manufacturing arena, arising out of the late 1990s telecom "boom and bust." They capitalized on the fiber

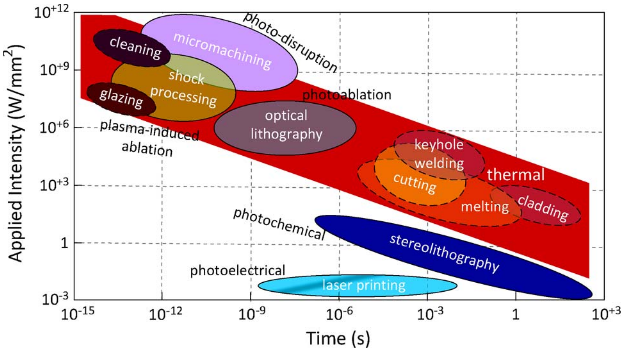


Fig. 21. ***Applied intensity and interaction time requirements for thermal (dashed contours) and athermal (solid contours) material processing techniques (adapted from [350]).***

and diode pump technological advances and reliability of the telecom industry, demonstrating the importance of "cross pollination" and interaction between industries. They offer single-mode (SM) near-diffraction-limited outputs up to 10-kW level. This allows focusing into smaller spots with higher intensities and enables remote processing. Also, they can be spatially combined into multimode (MM) fibers to reach multi-kilowatt powers still with record beam quality, stability, and wall-plug efficiency (30%–40%) [345], [349].

In addition to raw power, efficient laser/material interaction is also critically determined by the interaction time. Among the various manufacturing technologies, accurate interaction time control, down to femtosecond level, is a feature provided uniquely by photonics. Fig. 21 shows absorbed intensities and time requirements for an extended range of industrial applications. In addition to the previously mentioned thermal processes, the figure includes processes of athermal nature, involving photoelectrical, photochemical, or photophysical (photo-ablation, plasma-induced ablation, and photo-disruption) mechanisms [320]. The laser provides enough energy, either through single highly energetic UV photons or multiphoton absorption in high peak-power ultrashort (subnanosecond to femtosecond) pulses to break or create chemical bonds or create ionizing plasma and open up entirely new application domains.

There is hardly any manufacturing sector that has not benefitted from the introduction of photonics. In the automotive industry, welding car bodies, transmission and engine components, air bags, exhaust systems, etc., are now made robotically using laser systems. In healthcare, lasers are employed for welding deep brain stimulator implants, pacemakers, and prosthetics. In the electronics industry, lasers are used for drilling and cutting printed circuit boards; in photovoltaics for scribing, drilling, and cutting of Si-wafer, ablation of conduction or dielectric layers of thin-film solar and crystalline Si solar cells. More recently, in additive manufacturing, 3-D rapid prototyping and manufacturing by selective sintering, melting, and 3-D cladding directly from Computer Aided Design (CAD) files is enabled by lasers. Rapid prototyping has evolved from polymer components to tool-free rapid manufacturing of high-quality metallic parts using titanium, aluminum, and cobalt chrome powders.

So far most of the industrial applications are based on lasers operating predominantly in CW or relatively long pulse mode. Recently, advances in laser technology have resulted in industry-worthy ultrashort laser systems capable of efficient material processing. Femtosecond pulses can extend the laser processing capabilities into materials inaccessible by traditional lasers. For example, transparent materials can be processed efficiently by focusing femtosecond pulses tightly to induce nonlinear absorption through a combination of athermal effects, such as multiphoton absorption, tunneling ionization, and avalanche ionization. As a result, the induced structural changes are confined into tiny volumes with nanometer precision and are ideal for enabling efficient 3-D micromachining.

D. Future Vision and Possibilities

Following the spectacular progress and widespread use of lasers so far, the next century is destined to be revolutionized by photonics in the same way last century was reshaped by electronics. With today's more than 100 kW in CW DPSS laser powers [351] and 1.8 MJ, 500 MW in 3-ns UV pulse capabilities [352], it is hard to envisage what can stand in the way of photonics. Novel enabling technologies are expected to keep branching out from photonics laboratories into the industrial manufacturing sector with increasing pace.

Further improvements are expected by utilizing largely unexplored laser characteristics, such as spatial and temporal coherence, narrow linewidth, and tunability. Lasers with wavelength (spectral) and coherent (phased array) combined outputs [353] can provide an efficient way of not only power scaling but also accurate and fast beam steering and waveform control which will enhance further the remote material processing and manufacturing capabilities. Fast and widely tunable lasers, such as free-electron lasers, are expected to mature and enter the manufacturing arena, moving laser manufacturing to new levels of sophistication.

"Fiber-to-the-workstation" architectures, employing new large-mode area and hollow-core photonic crystal fibers designs (HC-PCF) [354], will enable distribution of high average and/or peak power high brightness beams over long distances from a central "power hub" to multiple points throughout the manufacturing site, resulting in efficient sharing of resources and cost reduction. Efficient fiber delivery can also enable radically new future applications such as drilling oil and gas wells, replacing 150-year-old mechanical techniques.

Novel gas-filled, Kagome-lattice HC-PCFs can potentially provide powerful and efficient fully fiberized deep UV and high-harmonic generating sources. Advances in photonic elements will enable solar-powered lasers to power scale for direct material processing or enable far-fetching applications, such as magnesium combustion engines for renewable energy generation [355]. Such innovations can potentially transfer manufacturing and empower underdeveloped sunny countries in Africa and elsewhere in the world.

Advances in laser-assisted formation of nanomaterials, with techniques such as pulsed-laser ablation and deposition, offer significant promise for bottom-up structural engineering (multilayers, graded layers, composite crystals, etc.). Investigations into advanced techniques, such as combinatorial pulsed laser deposition, have only just begun [356].

The next frontier will inevitably involve understanding better and exploiting underlying quantum effects. Making use of N entangled photons, for example, focusing resolutions N times greater than the Rayleigh limit can be achieved, allowing one to write a factor of N^2 more elements on a semiconductor chip [357] and keeping up with Moore's law for years to come. The fast developing field of metamaterials [358] can also potentially be used in future high-resolution imaging systems for near-field manipulation and focusing below the diffraction limit [359].

Direct phase and amplitude control of femtosecond laser pulses for molecular and cluster dynamics manipulation is fast maturing and can be used to monitor and control the material/light interactions in a fully automated way with yet unimaginable consequences for future manufacturing [360], [361].

It seems also inevitable that large-scale manufacturing will eventually take the "plunge" into the nano-cosmos. Nanotechnology and nanomanufacturing is coming to age and photonics once again is expected to play a critical role, providing the extraordinary precision needed at this scale. New engineering and manufacturing technologies will be needed to ensure that atoms or molecules, instead of macroscopic components, are placed accurately and in a prescribed order achieving fundamentally new functions and eventually removing all manufacturing barriers.

Within this regime, optical lattices can potentially be an enabling technology for diverse applications including multiple trap optical tweezers, optical trapping of cold atoms, sorting of molecules, and patterning in holographic lithography [362], [363]. Optical forces resulting from interacting optical modes and specially designed cavities can scale to remarkably large values and show great promise as a means for nanomechanical control in microelectromechanical and nanoelectromechanical systems [364]. Fundamental properties of light such as orbital angular momentum can possibly be used to drive such micromachines [363]. Optical-lattice trapping, as well as direct laser writing and Extreme ultraviolet (EUV) photolithography can be used to nanofabricate metamaterials, which in turn can play a pivotal role in building systems for nanomanufacturing [365].

It seems now is the time to be bold and accept R.P. Feynman's prophetic "*invitation to enter a new field of physics*" and use photonics and plasmonics in tackling "*the problem of manipulating and controlling things on a small scale,*" since it has become apparent that "*there is plenty of room at the bottom*" [366].

IX. EVOLUTION OF THE PHOTONICS INDUSTRY

A. Introduction

Photonic devices have created huge new markets. The market value created by photonic components and the systems which they enable is currently about $750 billion globally and is forecast to exceed $1.3 trillion by 2020 [367]. These systems have been key enablers of the Digital Revolution that has been underway and continue to reshape the world economy and how people live and work. In fact, we might well call the new age the Photonic Age because many world changing products and services— ranging from the Internet to cellular phones and large-scale integrated circuits—would not exist without photonic devices.

New industries based on technological innovations start with invention but succeed with in creating economic value when new products are introduced which meet price, reliability, and availability requirements dictated by the market. The path from proof of concept to major product is always a long and costly one. Pessimists do not get to the finish line because the hurdles which must be overcome appear insurmountable until original ideas, commonly from unpredictable technological sources from around the globe, come to the rescue.

These valuable products and services are the result of enormous work performed over the years in refining devices, and in developing production equipment and process controls to ensure that the needed device performance and cost have been met as applications have proliferated. For photonics, the new markets created exceed the expectations of even the most aggressive visionaries of 40 years ago. In fact, they are as important as they are unpredictable. If we are living in the Photonic Age it is because thousands of technologists in all continents have made their contributions.

There is a virtuous circle in industrial technology: totally unexpected markets develop as device performance increases creating market interest. Higher volumes of production lead to lower costs. Lower costs in turn open new markets and further increased device volume leads to further cost reductions. This has been the history of photonics since the late 1960s.

B. Past Key Milestones and Perspectives

1) The Laser Diode, LCDs, and CCDs: But how did this amazing industrial process start? It is perhaps simplistic, but, as historians identify the steam engine as the key equipment enabler for the start of the Industrial Revolution

[368], perhaps the key innovations and their commercial feasibility which enabled the Digital Age include: the transistor, magnetic disk storage, CMOS integrated circuits, heterojunction laser diodes, fiber optics, LCDs, and CCD imagers [369]. Of the seven, three are photonic devices—the heterojunction laser diode, the liquid crystal display, and the CCD imager. Of course, many other components, such as LEDs, made unique contributions so there is no claim of exclusivity in this list. We will discuss high-power "white" LEDs that are revolutionizing global lighting by replacing incandescent and fluorescent lamps with much more efficient and reliable devices.

The laser, LCDs, and CCDs all had serious deficiencies for real-world applications. Without enormous investment by talented technologists, these devices would have remained laboratory curiosities rather than world changers. Here are examples of the early problems.

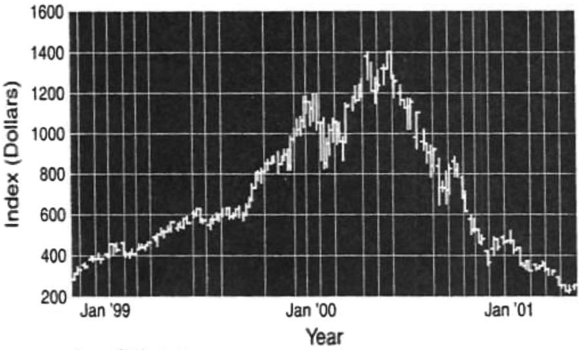
- Liquid crystal displays were small and had low resolution. They also had a very limited temperature operating range and did not last long in operation. After some improvements, they found a limited market in the 1970s in small calculators and watches. Nobody dreamed that 25 years later LCD TV receivers would hang on walls around the world having replaced CRTs.
- CCD imagers could not be produced with sufficient pixel quality because too many defects ruined the image. In fact, when engineers at RCA Laboratories built the first portable television camera in 1980 for NBC TV news field teams, using CCD imagers instead of cathode ray imagers, only a few good devices were selected out of thousands produced in the Lancaster, PA, factory; this camera got television people excited about the potential of solid-state imagers but the cost was simply too high for commercial deployment. This came later. But who dreamed that solid-state imagers would be found in billions of handsets and digital cameras 25 years later—and that Kodak would stop making film?
- The laser diode was an exciting device in the 1960s but it was not commercially useful owing to erratic reliability. Its handicaps were overcome over a period of years and lasers eventually became sufficiently reliable to be used even in undersea communications cable systems [370]. Of course, no one dreamed that laser diodes would enable the global communication systems by the 1990s and thus enable the Internet.

2) Telecommunications "Bubble": It is instructive to discuss one of the strangest periods of our industry in which we experienced rapid and growing pains. As a community, we went through the so-called "telecommunications/Internet tech bubble and bust" of the late 1990s and the early 2000s.

The Telecommunications Act of 1996 triggered one of the largest speculative investment bubbles in history [371]. The Act effectively opened access to local phone lines owned by the Regional Bell Operating Companies (RBOCs, separated from AT&T under the Consent Decree of 1984). For the first time, non-Bell System companies (CLECs) could offer services directly to consumers and businesses. CLECs were funded by an enormous wave of private and public capital from people seduced by the hope of gaining a piece of the $100 billion market previously controlled by the RBOCs. The emergence of the Internet only added fuel to the speculative fever. Investors had visions of unlimited demand for communications capacity, and hence unparalleled growth in revenues [369].

Many equipment vendors soon emerged, offering new products to equip this growing industry. There was a herdlike rush of private and public capital into the market, launching a classic speculative boom/bust cycle. Inevitably, massive business failures followed. It is estimated that more than $2 trillion of public value in publicly traded securities was lost between 2000 and 2003. A good proxy for this cycle is Fig. 22, which shows the public-market Telecom Networking Index rising to 1400 in October 1998 and dropping to 200 in October 2001 [369], [372].

In terms of technology, the opening of the communications market to newcomers in 1996 started a race to build new fiber-optic communications systems worldwide. Companies that supplied semiconductor lasers for these systems finally began to look like attractive investments. As Fig. 23 shows, sales of lasers began rising sharply in 1998 [369], [373]. Looking at the laser business in 1997, a shrewd investor would have projected rising demand and a resulting industry order backlog. The investor would have valued a laser business opportunity on the basis of a $6 billion market, which it actually reached in 2000.



Source: BigCharts.com

Fig. 22. ***The "bubble" in the U.S. Telecom Networking Index October 1998 to October 2001. From BigCharts.com quoted by Dr. A. Bergh [369], [372].***

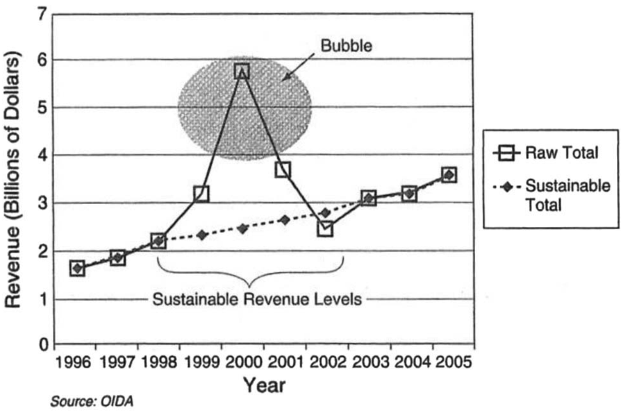


Fig. 23. ***Worldwide laser diode sustainable revenues. Removal of bubble (1999–2002) in worldwide laser diode market history to show sustainable revenue levels [369], [373].***

As it happened, this demand was not sustainable. It represented the peak of a rapid buildup in capacity. Demand was sure to level off or even decline as fiber-optic systems deployment slowed. At that point there would be a huge amount of overcapacity in the laser industry. Investors believed that the build-out of new systems could be driven indefinitely by the insatiable demand for Internet traffic bandwidth, which was erroneously believed by some to double every few short months. As the downturn came when the market ran out of steam, component suppliers saw their revenues drop sharply. Indeed, the $145 share of JDS Uniphase fell to $3, all during 2000 [369].

This "tech bubble" was a painful but quite valuable lesson for our industry. Over the past decade, our industry has regained much of its footing, we and our customers are learning how to properly gauge our value, and we have emerged from the bubble a little wiser and perhaps in better shape to mature into a multi-industry-enabling technology.

C. Present State of the Art and Current Trends

The ultimate success of optoelectronic devices in enabling new systems required many years of costly research and development conducted in many establishments around the world. It also required that other technologies advance. Notably, the quality of optical fibers greatly improved while their cost dropped by orders of magnitude—a key factor in enabling long-distance fiber-optic communications. Likewise, the cost of integrated circuits and computers dropped while their performance improved thus enabling digital packetized data transmission systems built around laser diodes and high-speed InGaAsP detectors.

Making a few devices in the lab is both fun and interesting. Making such devices in the millions and billions at affordable cost is totally different and requires entirely different skills which can be financed only by organizations committed to the ultimate markets. The successful history of these and other devices also shows the importance of multidisciplinary efforts where production and equipment engineers are teamed with materials and device scientists to solve enormously difficult problems.

1) Laser Diodes: The evolution of the laser diode is a good illustration of this process. The first heterojunction lasers of AlGaAs exhibited two failure modes. One was facet damage correlated with the optical power density at the facet; the second was a loss of efficiency because of the growth of nonradiative ("dark lines") crystal defects inside the device related to the operating current density. The reliability problems appeared to be so serious that many laboratories abandoned work on laser diodes in the belief that, like GaAs tunnel diodes [374], these devices were fated to remain laboratory curiosities due to incurable reliability problems.

In fact, the reliability issue was brought under control by a combination of novel device heterojunction structures to meet system needs, lower operating current densities, novel facet coatings, and a better understanding of realistic operating conditions. By 1969, RCA announced the first commercial heterojunction AlGaAs laser diode for pulsed high-power operation, which was used in military systems such as air-to-air missiles and infantry training simulators [375].

However, the CW laser diodes with the most far-reaching impact were those designed for optical communications, but this was also the most challenging application because many years of reliable operation is mandatory. This objective was achieved some years later. By 1980, tests were devised at RCA for screening commercial CW lasers, which allowed devices with projected 100 000 h of operating life to be commercially available [376].

Over the years, the family of heterojunction laser diodes was greatly expanded with new materials and more complex structures extending their emission wavelengths from the infrared into the blue along with output powers ranging from milliwatts of output to hundreds of watts. As a result, component costs were achieved ranging from a few dollars to thousands of dollars per unit depending on its sophistication. These expanded capabilities enabled new system level products. In addition to optical communications using fibers, consumer applications such as DVDs became practical as well as applications in instrumentation [377].

2) Liquid Crystal Displays: The history of these devices has been reviewed by Kawamoto [378]:

> "The history of liquid-crystal developments has been the history of competition among institutions

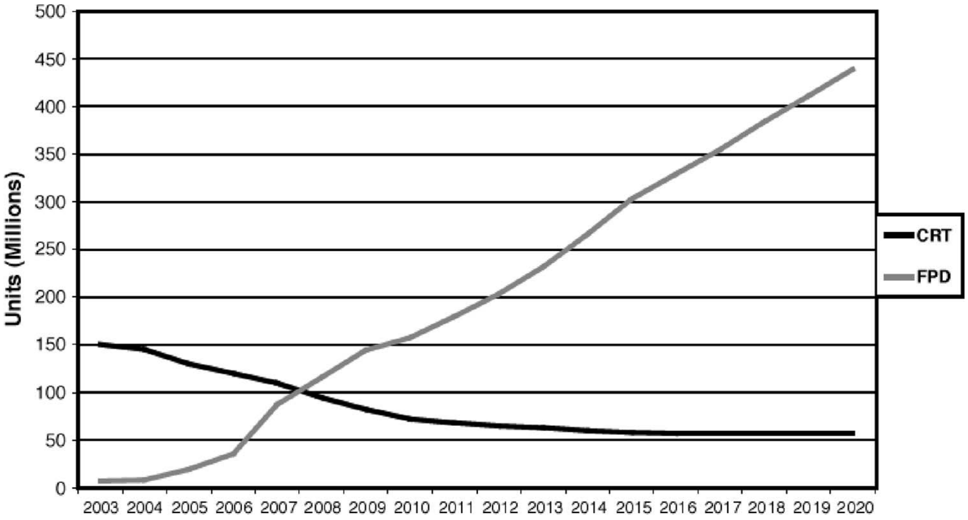


Fig. 24. ***The number of liquid crystal displays and CRT displays between 2003 and 2020. The crossover in volume of LCDs shipped occurred in 2007.***

> and companies scattered over three industrialized regions: 1) the U.S.; 2) Europe; and 3) Japan. At the same time, these competitors assisted each other. The success of liquid-crystal devices could not have been achieved without such competition. As for the regions' contributions, the U.S. contributed to all the early attempts: particularly, RCA Laboratories to the Williams domain, guest-host mode, DSM, active-matrix TFT drive, Schiff's bases, the digital clock and others to the analysis of limitation of simple-matrix drive and digital watches. . . . We now recognize that America's strength was in its speed in creating new ideas and then demonstrating their feasibility. Europe's strength was in fundamental science and synthesizing basic materials. Japan's strength was in perfecting the implementation and moving it to mass production."

What better proof of success is needed than the fact that, in 2007, the number of flat panel LCD displays exceeded CRT unit shipments as shown in Fig. 24 [379].

3) Imagers: The progress in CCD and CMOS imagers enabled digital cameras and eventually led to the demise of the film industry. Thanks to improvements in the manufacturing of CMOS integrated circuits, mass production of low defect imagers became possible. Device costs for mass market applications dropped to the low dollar range and billions of such imagers are now produced every year.

Fig. 25 shows the market value of components and systems which are enabled by photonic devices [380]. This market is expected to reach $1.3 trillion in 2020. In order to understand the nature of the market, Fig. 26 shows the applications where photonic devices are key enablers [381]. Consumer displays based on LCDs are the largest sector (48%) followed by applications in data processing for interconnections (20%).

Although the communications sector appears relatively small (8%), its impact on mankind is enormous. For example, in extended range optical communications, the total market value of the laser diodes used is only about $1.3 billion, but this enables system level products worth about $30 billion.

The same can be said about other laser types. For example, excimer lasers emitting in the UV spectrum enable the most advanced photolithographic equipment for semiconductor production without which Moore's law would not exist. And without the constantly increasing chip capacity and cost reductions, we would not have wireless handsets for the masses or any kind of portable computing devices. We certainly would not have smartphones.

While some of the markets are maturing, one emerging growth market will have enormous impact on energy utilization in the world, and this is general lightning. The shift to LED lighting from incandescent and fluorescent lighting is just starting as component costs are decreasing and in some cases by as much as 40% a year. The ability to make "white light" emitting LEDs owes its origin to the development of heterojunction devices emitting in the blue based on GaN alloys in the 1990s [382]. The high-power LED market was very small in 1995 but in 2008 it reached $8 billion and is forecast to reach $18 billion in 2020 with over 200 billion devices sold worldwide. What drives this expansion is the fact that these devices have

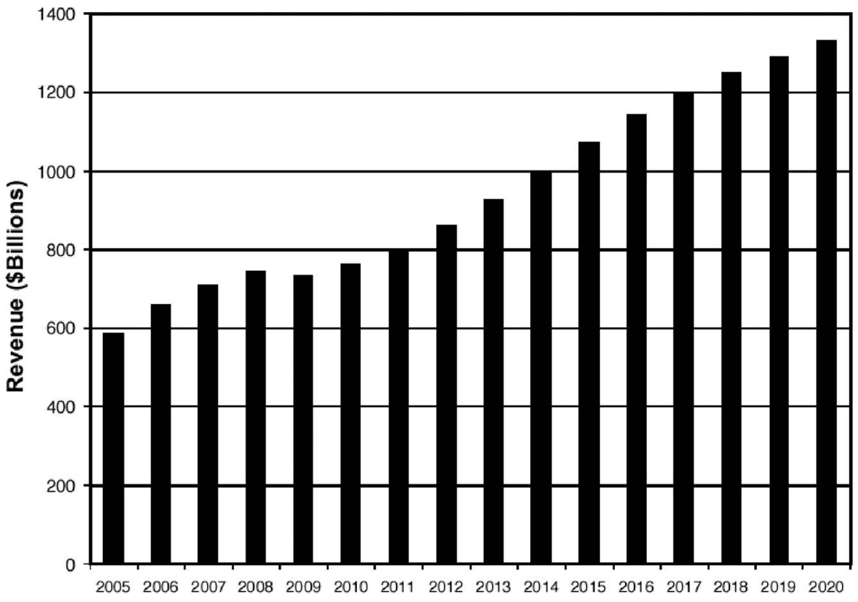


Fig. 25. ***The global value of market enabled by photonic devices projected to 2020.***

electrical conversion efficiencies in excess of 50% (much superior to other mass produced light sources) and have much longer lifetimes than conventional lighting sources—which translates into much lower lighting maintenance costs in addition to lower energy consumption. Street lights are an important application. In addition, LEDs are replacing other lighting sources as backlights for LCD displays in TV receivers.

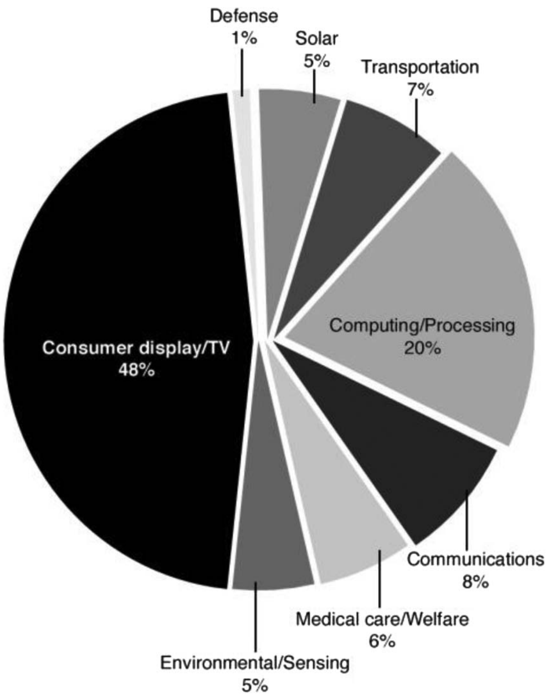


Fig. 26. ***Global photonic device—enabled market sectors in 2008 (components and systems).***

There is no single source for electronic products in the modern global economy. This makes it difficult to assign a single geographical location to the value created by such products. Many products incorporating photonic devices such as cameras, communications equipment, medical, and other instruments are designed in Japan, the United States, or Europe with component and subassemblies produced in Asia. However, the proprietary system software is developed in the developed countries. So where is the value created? It is noteworthy, however, that high-volume photonic components produced in low-cost countries might represent less than 10% of the system level product value.

The emergence of large markets, particularly those targeting consumer applications, puts enormous pressure on product cost. Big markets invite big competitors and competition drives prices down. Photonic component manufacturing has followed this trend and production facilities have largely migrated from high-labor cost locations such as the United States, Europe, and Japan, to Taiwan and South Korea and now China. At this time, there are practically no LCD displays produced in the United States, although Japan has retained significant production capabilities.

Bucking this trend has been the production of CMOS imagers which are still produced in large quantities in the United States and Japan because the processes are compatible with standard CMOS integrated circuit production and require very little direct labor for production. Other photonic devices, on the other hand, which require dedicated facilities and involve a substantial amount of hand labor, will remain in low-cost countries.

D. Future Vision and Possibilities

Just as we were incapable of forecasting the fantastic future of photonics 40 years ago, so we should be humble enough to acknowledge that the future is unknowable, particularly the development of technology. However, we do know that certain developments will continue. Primary among these is the continuing cost reduction and performance improvement of LED lighting. We are familiar with LEDs in portable devices as indicators. In the future, LED lamps will be found in homes, cars, and streets and practically every place where lighting is needed. Just as photonics have obsoleted film, they will obsolete other lighting sources for most applications.

While we might think that LCD displays are invincible, a competing technology is emerging as its performance and reliability improves: OLEDs. Just the same old story: there are no lasting monopolies in technology-based industries as innovations threaten all incumbents. These display devices, which do not require backlighting, are finding their way in small displays where saving space is important. Migration to large systems is inevitable.

While we have not discussed solar cells, they are photonic devices and will play an increasing role in the generation of electricity without fossil fuels. Costs are dropping with volume production and such solar energy installation costs are within reach of the cost needed for widespread grid electricity generation. This will provide a valuable and economic complement for other nonrenewable energy sources.

One continuing trend is the integration of photonic devices with silicon devices and other components as a means of improving performance and reliability while reducing cost. The literature describes many promising innovations [383], [384]. Which of these innovations translate into important products will depend on their value creation compared to other solutions. Applications that are too small to warrant manufacturing in volume can be justified only by quite outstanding value creation on the system level. But such has been the history of photonics: start with limited applications and they blossom into huge markets. This will keep happening.

Finally, a word about economic value creation in various geographies. High-volume component production will remain in low-cost countries, but system design and even their production will be global because much of the value created is by software and features that fit various regional markets. However, the fact that component production is concentrated in high-volume production plants ensures that the lowest cost components are available for system use. As component costs decline and performance improves, an ever increasing number of system level products will be designed by clever people all over the globe. And that is a very good thing for all of us.

X. SUMMARY

As we hope that it has been conveyed by this paper, the fields of optics and photonics have produced dramatic technological advances and have cemented themselves as key enablers for many important industries. The technical advances over the past several decades are typically measured in orders of magnitude (e.g., clock accuracy, communications capacity, machining power), and many applications areas could not readily be tackled by other technologies (e.g., coherence tomography, semiconductor lithography, terabit per second long-distance communications).

It is quite exciting to imagine reading our paper in another 20 or 50 years. Will our future vision prove too timid or too bold? Will we master the "photon" across an ever-larger spectral range in a way that is similar to or even exceeds the way we have mastered the electron? Undoubtedly, new technical areas that have not yet been contemplated will vibrantly emerge and enable applications that are now simply the realm of science fiction.

How many of us could have imagined 40 years ago: 1) the likes of social networking, which relies on optics to flourish; 2) printing 3-D objects at will; 3) bending light "unnaturally" using metamaterials; or 4) that commerce pervasively relies on the use of optics for displays, manufacturing, and communications in order to compete? On the other hand, many of us do have an inherent intellectual faith that in 50 years it will be optics that provides the energy for our planet—we just do not know which specific technology will prevail. We might look back and say that we were now only starting to harness the power of the photon.

What might a future article on optics and photonics for the 150th anniversary of the PROCEEDINGS OF THE IEEE contain? More exciting possibilities, we hope. ■

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