Laser and Photonic Systems Integration: Emerging Innovations and Framework for Research and Education

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Abstract

The purpose of this article is to review the key emerging innovations in laser and photonics systems as well as their design and integration, focusing on challenges and opportunities for solutions of societal challenges. Developments, their significance, and frontier challenges are explained in advanced manufacturing, biomedicine and healthcare, and communication. Systems, networks, and integration issues and challenges are then discussed, and an integration framework for networking laser- and photonic-based services and products is proposed. The article concludes with implications and an agenda for education, research and development, and policy needs, with a focus on human, society, science, and technology integration. © 2013 Wiley Periodicals, Inc.

Keywords: Advanced manufacturing; Laser processing; Healthcare; Optical communication; Precision collaboration

1. INTRODUCTION

The purpose of this article[1] is 1) to summarize the key emerging innovations that address solutions for societal grand challenges and 2) to present a framework for research and education priorities and global policy needs, with a focus on human, society, science, and

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technology integration. The goal of the symposium and of this article is to stimulate frontier thinking and to accelerate the delivery of innovations and solutions in the emerging area.

Photonics (the science, engineering, and technology of light) is an important enabling field with diverse applications. Laser and photonics are already considered transformative and potentially as significant for innovations as information technology, steam power, and electronics have been. Over the 50 years since its invention, laser technology has been applied to overcome obstacles in manufacturing, medicine, communication, and other fields, and its economic impact is growing rapidly (e.g., Savage, 2012; Tünnermann, 2012). Definition of some terms related to laser and photonic systems are included in the Appendix; introductory background in books by Quimby (2006), Hecht (2008), and Silfvast (2008); and in handbooks (Kasap, Ruda, & Boucher, 2012; Träger, 2012). Three recent reports by the National Academy of Engineering (2008, 2010, 2012) have also addressed related topics.

The opportunities to solve significant problems and challenges with creative and innovative laser and photonic systems are vast. Examples of the importance of photonics, which have emerged in just the past two decades include:

- In advanced manufacturing, high-power lasers perform precise drilling, cutting, and welding, as well as nanoprocessing; microprocessors are fabricated today by optical lithography; manufacturing of photonics products, such as optoelectronic components, visual displays, and solar equipment could not be possible without the precision and measured energy properties inherent in photonics-based processes and techniques.
- In medicine and healthcare, photonics and optoelectronics enable better, higher-resolution medical imaging for early disease detection, diagnosis, and prevention; brain, eye, skin, and dental surgeries rely on medical lasers to vaporize, ablate, cut, and suture; laser-based DNA sequencing of a single human genome can be completed today in one day, compared with 80 years in the 1990s.
- In communications, photonic integrated circuits imply lower power consumption, better reconfigurability, and faster processing; computer clusters in data centers communicate through high-capacity optical cables, engaging millions of lasers for signaling, to process massive computations; cell phone communications, Internet work, and video chat signals are processed as optical data and transmitted through fiber-optic networks, enabling dramatic improvements in fast, reliable, and cost-effective services.

Three unique features enabled by laser and photonic systems are observed:

1. Processing at multiple scales, from nano-, micro-, to large-scale objects, and from local to remote subjects;
2. Processing and delivery of laser fields at ultrafast speeds and frequencies, and the ability to shape and reshape them; and
3. The ability to bring closer (almost together) the process and its process control by significantly faster sensing and communication.

The following sections describe the development and explain the observations and their significance in advanced manufacturing (Section 2), biomedicine and healthcare (Section 3), and communication (Section 4). Systems, networks, and integration issues and challenges are then discussed in Section 5, followed by implication and agenda for education, research and development, and policy making (Section 6).

2. IMPACT OF LASERS AND PHOTONIC SYSTEMS ON ADVANCED MANUFACTURING

2.1. Overview

With the rapid advent of lasers and laser systems, there has been an explosion in the use of lasers in various manufacturing and materials processing (Steen & Mazumder, 2010). Lasers emit light (electromagnetic radiation) through optical amplification based on the stimulated emission of photons. This emitted light has a high degree of spatial and temporal coherence. There are various properties of laser light that enable material processing applications. These properties include high directionality, tunable wavelength and laser-power density, and selectivity, which enable lasers to be used for precision processing. Lasers can generate high heating and cooling rates in the selected area. In general, the photothermal and photochemical reactions between laser and materials can be used in many laser processing techniques (Majumdar & Manna, 2011), including cutting, welding, brazing, soldering, bending, engraving, marking, cleaning, machining, drilling, trimming, hardening, alloying, shock peening, annealing/crystallization, scribing, cladding, and additive processes. The industrial applications of lasers are still growing at a fast pace. Recently, hybrid manufacturing processes that use lasers and many other energy forms are getting more attention because of their capability to deal with challenges as required by industry, such as large-scale nonvacuum manufacturing, complicated three-dimensional (3D) structures, ultrasmall structures, hard-to-process materials, high-temperature applications, high strength-to-weight ratio, and high fatigue performance and corrosion resistance.

2.2. Challenges and Opportunities for Innovation: Cases in Advanced Manufacturing

With a focus on process innovation, a new perspective on manufacturing could change manufacturing industries (Pisano, 1996). Today's manufacturing industries are facing challenges from advanced difficult-to-machine materials (tough super alloys, ceramics, and composites), stringent design requirements (high precision, complex shapes, and high surface quality), and machining costs. Laser materials processing plays an increasingly important role in modern manufacturing industries due to highly controlled, intense, localized heat sources, which can be used to add, subtract, and transform materials. However, to realize its enormous economic benefits, more research and development should focus on improving the productivity of manufacturing multifunctional materials and structures, optimizing product performance though process design, and more important, innovating manufacturing operations, processes, and systems.

The following are a few examples of laser-based manufacturing innovations with emerging biomedical and energy applications. Current developments and challenges are summarized.

2.2.1. 3D Printing Bio-implants

Manufacturing capabilities of functionally and structurally gradient implant materials with nanocomposites on the surface using 3D laser direct deposition and sintering have been developed at Purdue University (Figure 1). Biocompatible, osteoconductive, advanced compositionally and structurally gradient implant biomaterials are constructed with biocompatible nanocomposites. Laser direct deposition process provides a way of synthesizing structurally and compositionally gradient 3D implants using elemental powders (Halani & Shin, 2012). Multilayer laser sintering process can form functionally gradient nanoscale, nanocomposite coatings on the surface of metal implants (Y. Zhang, Cheng, Erasquin, & Ca, 2011). Multiscale, multiphysics modeling has been developed to simulate the laser direct deposition and laser sintering processes. This process innovation will result in a key enabling technology for integrating advances in biomaterials into manufacturing that leads to significantly improved implants for the orthopedic industry. The team has established critical knowledge and a scientific basis in synthesizing biocomposites that are gradient in function and has brought about an improved understanding of this biocomposite material behavior in the performance of implants.

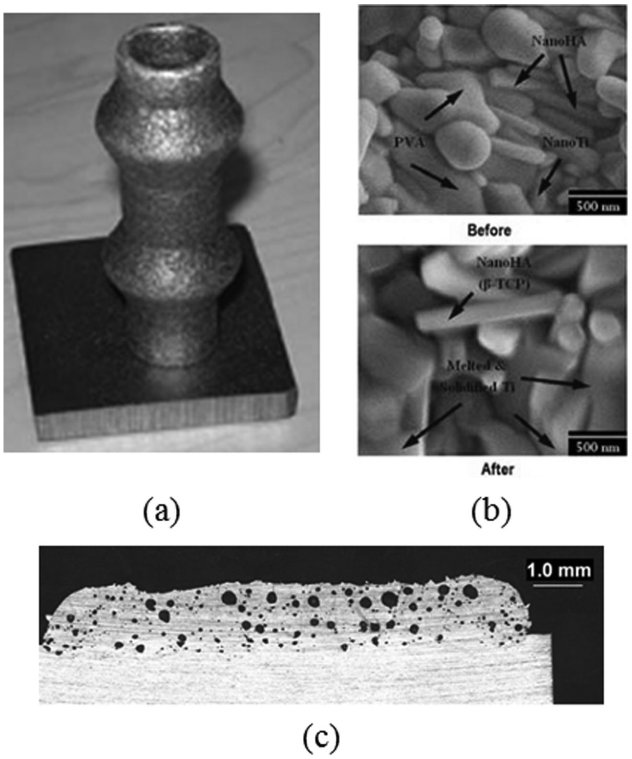
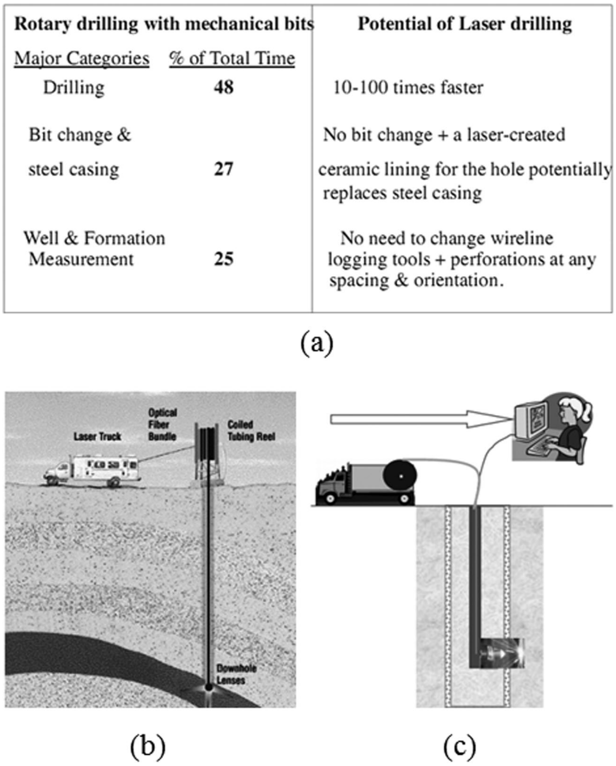


Figure 1 a) 3D metallic structures by laser deposition, b) magnified pictures of coating before (NanoHAp particle, NanoTi particle, PVA) and after (NanoBCP particle, NanoTi) laser processing, c) cross section of porous layer of titanium alloy (Ti6Al4V) deposition.

2.2.2. Laser Rock Drilling: The Drilling Bit of the Future

Argonne National Laboratory (Laser Applications Laboratory) and a group of collaborators are examining the feasibility of adapting high-power laser technology to drilling for gas and oil (Z. Xu et al., 2003). If drilling with lasers ultimately proves viable, it could be the most radical change in drilling technology in the last century. It was at the turn of the twentieth century when rotary drilling supplanted cable tool drilling as the petroleum industry's standard method for reaching oil and gas formations. Using lasers to bore holes offers an entirely new approach. The novel drilling system would transfer light energy from lasers on the surface, down a borehole by a fiber-optic bundle, to a series of lenses that would direct the laser light to the rock face. Because the laser head does not contact the rock, there is no need to stop drilling to replace a mechanical bit. A laser system could contain a variety of downhole sensors, including visual imaging systems, that could communicate with the surface through the fiber-optic cabling. The processing conditions for laser drilling could be controlled to transmit light from surface lasers to as much as 6,700 m (20,000 feet) below the surface (Figure 2).

Another challenge is to determine whether sending the laser light in sharp pulses, rather than as a continuous stream, could further increase the rate of rock penetration. A third challenge of research is to determine whether lasers can be used in the presence of thick fluids—called "drilling muds." Dr. Reed's group at Argonne National Laboratory have developed several approaches and studied the fundamental mechanism of them to realize the high-speed drilling of rocks. A multispot approach has been built to take advantage of rock removal by spallation, low required laser energy, flexible beam fiber delivery, and easy removal of small rock debris or particles. Laser perforation could help realize real-time control and feedback, control downhole beam focusing and motions required for cutting different materials, and flexibility in perforation geometry.



Rotary drilling with mechanical bits		Potential of Laser drilling
Major Categories	% of Total Time	
Drilling	48	10-100 times faster
Bit change & steel casing	27	No bit change + a laser-created ceramic lining for the hole potentially replaces steel casing
Well & Formation Measurement	25	No need to change wireline logging tools + perforations at any spacing & orientation.

Figure 2 a) Study by Gas Technology Institute (1995); b) lasers could play a significant role as a vertical boring and perforating tool in gas well drilling; c) real-time control and feedback in laser perforation.

2.2.3. Laser Processing: Future Manufacturing of Solar Cells

Solar cells are semiconductor devices. However, the stringent requirements for cleanliness and quality control of semiconductor fabrication are more relaxed for solar cells. Manufacturing costs include the cost of energy required for manufacture, materials, productivity. There is a great need for a low-cost, high-speed process to manufacture high-efficiency solar cells. The current target is for costs to be less than $0.50 per watt. Installation cost has also to be considered since many of the costs of a solar power plant are proportional to the area of the plant. Given a power production target (e.g., 50 MWp), a higher-efficiency cell will reduce the installed area and balance of systems costs.

Laser processing has played a crucial role in enabling the commercial production of future generations of photovoltaics (PV) devices because laser holds promises for low-cost, high-efficiency solar cells, with low raw material consumption (Janssen, 2011; Schulz-Ruhtemberg, 2011). The demand for laser systems by the PV industry will increase as the importance and advantages of laser processing are recognized. Laser processing has been realized in manufacturing crystalline silicon PVs and thin-film PVs (see Table 1). In thin-film PV, which is a relatively newer device concept than crystalline silicon PVs, more innovative laser processing is expected to be implemented in the manufacturing line in the near future. For both technology

TABLE 1. Current Key Technologies for Crystalline Silicon PV and Thin-Film PV[1–9]

Crystalline Silicon PV	Thin-Film PV
• Silicon wafer cutting • Laser edge isolation: prevent recombination or current flow toward the edge of the silicon wafer • Via drilling for metal wrap through (MWT) and emitter wrap through (EWT): prevent shading of the silicon by front and back metal contacts[3] • Emitter Contact Formation: Laser Grooving • Laser marking • Laser-fired contacts • Laser annealing and doping[5,7] • Laser surface texturing	• Thin-film patterning: first scribe (P1) is for the front contact; the second scribe is for semiconductor junction (P2); and the last scribe is for the back metal contact (P3)[1,2] • Edge delete: removal or deletion of all the layers around the circumference of the panels • Laser soldering • Laser crystallization[8,9]

Notes: [1]Murison, R. et al. (2010). [2]Patel et al. (2007). [3]Pantsar (2010). [4]Colville (2010). [5]Tjahjono et al. (2010); [6]Kray et al. (2010). [7]Röder et al. (2009). [8]Zhang et al. (2012). [9]Y. Zhang and Cheng (2011).
[4,6]Provide general discussions about the technologies in the table.

families, the overall manufacturing system has to be optimized with integration of laser processing for optimal performance and lowest cost, instead of only focusing on certain individual laser processing. The application of laser processing in organic PVs will be increasing due to the advantages of laser processing, such as flexibility, selective heating, high throughput, and accurate temperature control.

2.2.4. Other Key Laser Processing Techniques

Laser materials processing has become increasingly advantageous to industry both in macroprocessing and in micro-nanoprocessing. To further increase the benefits of laser materials processing for manufacturing, more research efforts in process innovation, process modeling, new material development, quality control and cost reduction, and new laser systems design and integration are needed in the future. To illustrate the state of the field, Table 2 summarizes the current state and future challenges of laser processing techniques currently under investigation in the Laser-based Manufacturing Center and at the Scalable Micro/Nano Manufacturing Laboratory, both at Purdue University.

3. IMPACT OF LASER AND PHOTONIC SYSTEMS ON HEALTHCARE

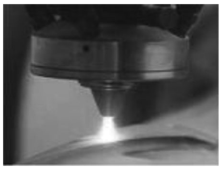
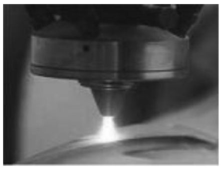
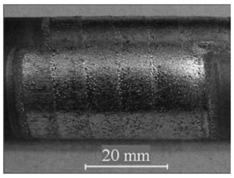
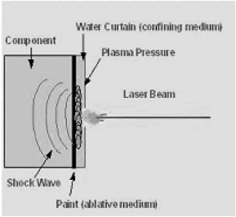
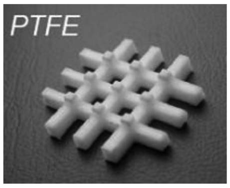
3.1. An Overview

Ever since the invention of the microscope by Galileo Galilei, optics has played a critical role in understanding the nature of life and disease. Since that time, tremendous improvements have been achieved and continue to be made, particularly in terms of the resolution of small, even nanometer-scale features; the imaging of live cells in a natural environment; bright fluorescent probes to clearly illustrate differences between subpopulations; as well as noninvasive, benign imaging techniques underneath live tissues.

From a business and social perspective, laser and photonic systems pose new problems related to the size of the markets and the breadth of products. Diagnostic imaging is dominated today by four major modalities: It has been estimated that x-ray, ultrasound, computed tomography, and magnetic resonance imaging each has an annual market over $3.5 billion and nuclear imaging has an annual market of about $1.5 billion (e.g., marketsandmarkets.com, 2011). These large modalities have a combined annual growth rate of roughly 5% and are typically focused on emerging markets and cost reduction. The biomedical optics space, however, aggregates to more than $2 billion but consists of many smaller markets and unique applications of technology. Some of these new opportunities are growing at more than 30%. As one might expect, the current situation favors large companies in diagnostic imaging and smaller, more agile companies in biomedical optics.

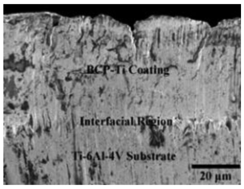
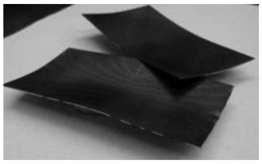
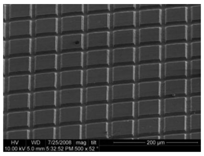
Two of the larger biomedical optics markets that exist today are optical microscopy at roughly $750 million per year, and optical coherence tomography (OCT) at roughly $800 million per year. Optical microscopy benefits from new imaging approaches, including computational, light field, and adaptive optics. Superresolution approaches make possible imaging of structures well below the diffraction limit of light and

TABLE 2. Laser Processing Techniques Developed at Purdue University[1–8]

Name	Figure	Current State	Future Challenges
Laser-assisted machining[1]		• Machining of various ceramics and high-temperature alloys • Significantly higher productivity • Scientific tools for modeling and monitoring	Develop a cost-effective precision fabrication technology for difficult-to-machine materials, such as ceramics and high-temperature alloys
Laser hardening and alloying[2]		• Successful hardening of various steel alloys • Transformation hardening and nitriding of Ti-6Al-4V alloys • Near maximum hardness achievable • Prediction of hardness, stresses, and deformation	Develop a cost-effective laser hardening process and predictive models for process design and optimization
Laser cladding and direct deposition[3]		• Successful cladding using preplaced and blown powder delivery • Scientific tools for modeling and monitoring	Develop a cost-effective direct material deposition processes for surface enhancement and remanufacturing using lasers
Laser shock peening[4]		• Strengthen the surface of metals • Increase surface hardness and compressive residual stress • Improve the fatigue performance and corrosion resistance	Develop a high-speed laser peening for wide range of materials, such as low-ductility materials, composite materials, and superalloys
Laser-assisted micromachining[5]	 	• Picosecond and femtosecond laser micromachining system built • Modeling of laser-matter interaction during ultrashort pulsed laser ablation	• Develop high-throughput laser-based micromachining capabilities applicable to a wide range of materials • Enhance the understanding of ultrashort laser and materials interaction

(continued)

TABLE 2. Continued

Name	Figure	Current State	Future Challenges
Laser sintering[6]		• Multilayer functional gradient coating system has been built • Numerical simulation has been developed and validated by experiments	Develop high-throughput laser sintering process for wide ranges of materials, such as multifunction materials
Laser bending[7]		• Laser bending systems for sheet metal, and thick plate, hard disk cantilever beam have been developed	Develop precisely controlled laser bending system for 3D shaping on various materials
Laser dynamic micro/nanoforming[8]		• Laser dynamic forming system has been built to achieve 3D micro-/nano-structures at room temperature and atmospheric pressure	Develop high-speed manufacturing of optimal 3D nanostructures for functional materials, such as Metamaterials, and semiconductor thin films

Notes: [1]Shin (2011). [2]Bailey, Tan, & Shin (2009). [3]Schoeffel and Shin (2007). [4]Wu and Shin (2007). [5]Hu et al. (2010). [6]G. J. Cheng and Ye (2009). [7]G. J. Cheng and Yao (2002). [8]Gao and Cheng (2010).

the growth of new approaches for spectroscopy is enabling new applications. The two main applications of OCT are ophthalmology and intracoronary imaging, where the ability to see into tissue is critical. OCT can be viewed as an extension of microscopy toward the goal of imaging in a relevant context—seeing inside living tissues and even the patient directly. The ability to perform histopathology measurements inside or at the patient can influence key treatment decisions during surgery.

Biomedical optics is justifiably an area of intense research interest today. From a business perspective, lack of clarity about the maturity and size of many specific markets remains an issue but one that is creating many new and promising entrepreneurial opportunities.

3.2. Challenges and Opportunities for Innovation: Cases in Biomedicine and Healthcare

3.2.1. Applications of Ultrashort Laser Pulses

Ultrashort laser pulses, with durations measured in femtoseconds ($1\ \text{fs} = 10^{-15}\ \text{s}$), have highly desirable properties: 1) They can be used to measure events in the timescale of atomic motion ($10 - 1000$ fs). 2) They reach peak intensities of $10^{15}\ \text{W/cm}^2$. When such intense pulses interact with matter, they vaporize it into plasma on a timescale faster than thermal diffusion. This property allows nonthermal machining of any material. At more moderate intensities, these laser pulses can directly access nonlinear optical properties, such as two-photon absorption and intensity-induced polarization rotation, which are useful for biomedical and other imaging applications. 3) Because of the uncertainty principle, ultrashort pulses have an inherent broad bandwidth that can be used for spectroscopy, metrology, and communications.

These lasers have been available since the 1980s in research laboratories, where a number of proof-of-principle applications have been demonstrated, and two Nobel Prizes have been awarded. Well-known early biomedical applications of ultrashort pulses include two-photon microscopy for resolving subwavelength features, and excimer pulsed lasers for femto-LASIK (laser-assisted in situ keratomileusis) vision correction surgery (known as radial keratomy). Given that most applications of ultrashort pulses depend on their peak intensity elevated to a higher power (quadratic or cubic), the shorter the pulses, the more efficient they are.

However, there are practical limitations preventing the use of ultrashort pulses for applications. A pulse that is 5 fs long has such a broad bandwidth that it becomes dispersed, stretching to 12 fs just by traveling a 1 m path in air. Work with these ultrashort pulses typically requires experts to optimize the source on a daily basis. Harnessing the unprecedented properties of ultrashort laser pulses for industrial and medical applications requires practical means for delivering the shortest possible pulses to the target without the assistance of a laser expert.

One powerful approach to controlling femtosecond laser pulses is known as multiphoton intrapulse interference (MII). Here, the phase of various frequencies of a single high-power pulse is fine-tuned to create constructive interference to maximize the peak pulse power. A robust method for achieving this desirable effect is known as multiphoton intrapulse interference phase scan (MIIPS). It stands for MII phase scan, reflecting the fact that the phase is scanned to allow full characterization of any short pulse waveform. Once characterized, the same apparatus can automatically compress the measured waveform to its shortest possible duration and maximum peak power. Both operations are accomplished in an optical apparatus known as a pulse shaper, discussed further in Section 4.3. The MIIPS-enabled pulse shaper has been tested and demonstrated to be capable of automated pulse compression at the target even for pulses as short as 3 fs (approaching the fundamental limit of one optical cycle in the near-visible spectral range), including commercial applications (B.-W. Xu, Gunn, Dela Cruz, Lozovoy, & Dantus 2006). This device has enabled or enhanced a broad range of exciting applications, including improved biomedical imaging for noninvasive biopsies, improved proteomic sequencing for medical diagnosis and drug discovery, and standoff detection of explosives.

3.2.2. Biomedical Applications of Coherent Light Scattering

When coherent light scatters from displacing objects, the phase of the light shifts according to the direction and magnitude of motion. When there are many scattering objects, moving in random directions, the phase shifts are added randomly, leading to intensity fluctuations in the scattered light. These intensity fluctuations have statistical properties that relate to the type of motion, with different fluctuation signatures for diffusive versus directed transport and with different frequency content for faster or slow motions. Subcellular motions inside live tissue are sensitive indicators of cellular health and cellular response to applied drugs. For live-tissue drug screening, digital holography volumetrically captures these motions during tissue dynamics spectroscopy.

Tissue-dynamics spectroscopy (TDS) combines dynamic light scattering with short-coherence digital holography to capture intracellular motion inside multicellular tumor spheroid tissue models. These spheroids are grown in bioreactors and have a proliferating shell of cells surrounding a hypoxic or necrotic core. The cellular mechanical activity becomes an endogenous imaging contrast agent for motility contrast imaging. Fluctuation spectroscopy is performed on dynamic speckle from the proliferating shell and the hypoxic core to generate drug-response spectrograms that are frequency versus time representations of the changes in spectral content induced by an applied compound or an environmental perturbation. A range of reference compounds have been studied with variable conditions applied to multicellular tumor spheroids (MCT) to generate drug fingerprint spectrograms. These spectrograms can be used for early drug discovery (Nolte, 2011).

3.2.3. Laser-Based Medical Devices

Lasers have already been widely adapted for medical use to solve a variety of medical problems. Laser energy is efficient, controllable, and can be transmitted through tiny optical fibers, making it an ideal energy source for use with catheter-based devices. Two interesting applications of laser technology in clinical practice include the treatment of atrial fibrillation (AF), and the treatment of severe acne.

In patients who suffer from AF, the atrial chambers of the heart rapidly quiver (fibrillate) instead of contracting in a controlled, healthy manner. This is caused by an inappropriate electrical signal received by the atrial tissue, which often significantly reduces cardiac output. This condition was first treated with drugs and surgery, but drugs were ineffective, and surgery involved serious safety issues.

The development of devices to treat AF rapidly evolved, and catheter-based systems using radio frequency (RF) energy became the standard of care. The

RF energy is deployed to create a burn, or lesion, of small round dots, on the inside of the heart tissue, thus making it impossible for an electrical signal to cross the lesion. Connecting the dots to wall off the errant electrical signal is time consuming and often unsuccessful if all the dots do not result in a completely continuous line. CardioFocus Company was created to address both limitations of RF catheters by employing a laser to reduce the total treatment time and increase the efficacy of the procedure. The CardioFocus catheter is serially positioned into each of the pulmonary veins, and a compliant balloon is inflated so that it is pressing circumferentially against the pulmonary vein wall. A channel inside the catheter contains fiber-optic strands, and the distal tip of this cable is perpendicular to the centerline of the catheter inside the balloon at the end of the catheter system. When the laser is fired through the fiber-optic cable, the tip is rotated inside the balloon in separate arcs, eventually creating a lesion that is a circle around the diameter of the pulmonary vein. This lesion then blocks the errant electrical signal from reaching the tissue of the atrium, thus curing AF.

A second laser-based company, Sebacia, was started at the Innovation Factory to address the needs of patients with severe acne. The condition is caused by the sebaceous glands producing an excess of sebum that clogs the pores and causes a blemish on the surface of the skin. The drug Accutane is the standard treatment. It is effective but can have several serious side effects. Sebacia set out to develop a nonsystemic approach to the treatment of acne. To avoid the need for lengthy, expensive, and complex FDA approval of a new drug, an innovative device treatment was preferred. A solution infused with gold nano-shells is worked into the skin area to be treated. The shells are worked down into the pores and near the sebaceous glands. A laser, tuned to the gold nano-shells is fired onto the surface of the skin. The laser energy is not absorbed by the skin and passes through the upper layers to reach the nano-shells. The shells become excited by the laser energy and radiate heat, which in turn kills the sebaceous glands.

This potentially represents a cure for acne.

Both of the VC-funded companies mentioned above have employed lasers in creative ways to address poorly met clinical needs. The use of lasers in medical device applications will continue to evolve, because of the unique advantages of the energy source, and the precision and flexibility of its delivery. Over time, hopefully many other poorly met clinical needs can be better addressed using creative approaches, such as the examples described above.

4. IMPACT OF LASER AND PHOTONIC SYSTEMS ON COMMUNICATIONS AND ULTRAFAST SYSTEMS

Since the invention of the radio by Guglielmo Marconi in 1895, electromagnetic waves have been used to rapidly transmit information over long distances. Enabled by mid-twentieth-century advances in optical generation, transmission, and detection, a marked shift from radio to commercial fiber-optic networks began in 1976. In more recent years, a hybrid approach has become prevalent, with a rich mixture of fiber-optic backbones, wireless cellular communication, Wi-Fi local area networks, and optical interconnects for data centers and high-performance computing.

High-speed, long-distance communications using light waves is empowered fundamentally by several distinctive properties of electromagnetic radiation in the optical range. These include 1) the very high frequency of optical waves ($>10^{14}$ Hz), which means that even bandwidths as small as a few percent of the optical frequency can carry very high data rates in the hundreds of billions of bits per second (Gb/s) or even trillion of bits per second (Tb/s) range; 2) the ability of glass fiber-optics waveguides to guide light with extremely low propagation loss (only a few percent per kilometer, hundreds to thousands of times lower than the propagation loss of Gigahertz frequency electrical signals on conventional metal cables); and 3) the nearly noninteracting character of photons, which means that light-wave signals are largely immune to the electromagnetic interference and pickup that severely challenge signal fidelity for densely packed electrical wiring operating at high frequencies and data rates. The high-frequency and high-bandwidth properties of optical waves also makes possible ultrafast laser systems generating pulses as short as several femtoseconds (a few times 10^{-15} seconds), much faster than any other known technology, including electronics. In the following subsections, we first discuss examples of key optical communication technologies and then discuss a few interesting examples of ultrafast photonic technologies and applications.

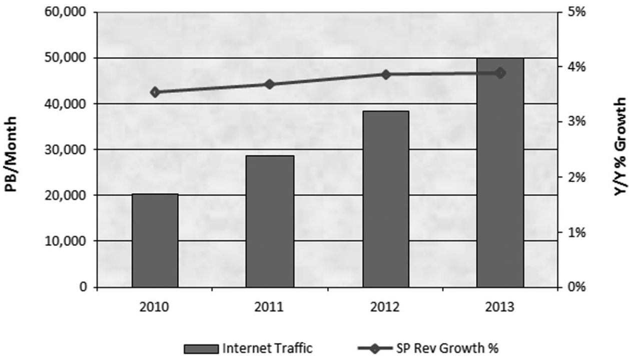


Figure 3 Recent growth of Internet traffic (left-hand scale) and service provider revenues (right-hand scale). Figures for 2012 and 2013 are estimated. A petabyte (PB) is $\sim 10^{15}$ bytes (Odlyzko, 2012).

4.1. High-Speed Optical Communications

High-speed, long-haul fiber-optic systems play an essential role in telecommunications today. They function by generating a laser beam at a specified wavelength, usually around 1.55 μm, which is sent down a low-loss, fiber-optic cable over a long distance. The laser beam is modulated at a predetermined rate to encode digital information in the optical beam, which can then be picked up at the other end by a receiver. Fiber optics offers enormous advantages in terms of speed, data capacity, security, and scalability, compared with alternatives such as copper wires or radio waves. Once it became possible to transmit fiber-optic signals across the ocean floor, starting with the Atlantic Ocean in 1988, fiber-optic systems became the backbone of the Internet, now accounting for the majority of traffic on the Internet.

As shown in Figure 3, Internet traffic has grown in recent years at a compounded annual growth rate of 40–50% per year. At the same time, service provider revenue is currently growing more than an order of magnitude more slowly, around 3–4% per year. In practice, this has meant that service providers are expected to achieve dramatic improvements in data transmission performance while revenues only match inflation. Historically, this target has been met through increases in the modulation rate; increasing the number of laser wavelengths used in communications, known as wavelength-division multiplexing, or WDM; and improvements in the information density and bit error rate for the analog encoding scheme used to transmit the digital source data.

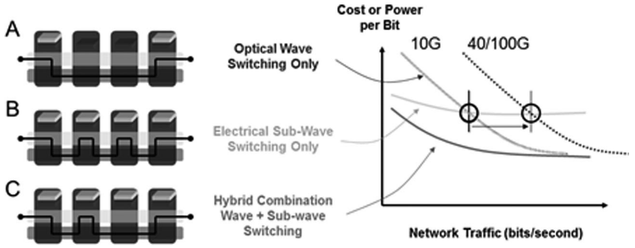


Figure 4 Illustration of the cost of communication network capacity per bit for three types of networks: A) optical wave switching (dynamic WDM) only; B) electrical subwave switching only; C) hybrid optical and electrical switching combination. The hybrid network is generally expected to yield the lowest costs over all network traffic levels of interest now and in the near future. 10 G: transport systems operating at 10 Gb/s per wavelength; these have been commercially deployed for over a decade. 40/100 G: systems operating at 40 or 100 Gb/s per wavelength, characteristic of many current deployments.

Moving forward, the three most important criteria for optical network performance will be convergence, reconfigurability, and scalability. Convergence refers to the trend toward combining network layers, both within the optical domain as well as joining them to the electronic transport layer; such combinations are expected to simplify the amount of hardware required and bring costs down. As shown in Figure 4, while optical switching approaches may be cost-effective for very high bandwidths, electrical switching approaches work best for smaller bandwidths, due to lower fixed costs of each operation. However, hybrid optical and electrical switching is expected to be much more powerful and cost-effective than either approach in isolation. Reconfigurability refers to flexibility to adapt to the rise and fall of new services, and to dynamically reallocate resources where they are needed, such as when Instagram attracts 10 million new users in 10 days (Burns, 2012). Scalability refers to putting a higher-capacity infrastructure in place capable of accommodating increasing volumes of data, as an increasing number of devices using more bandwidth-intensive services come online. As illustrated in Figure 5, benefits of scalability include fiber relief, rapid service turn-on, better economics, and high-performance applications such as computationally intensive research.

High-speed communication infrastructure based on photonics empowers many topics of interest in modern industrial and systems engineering research, such as collaborative manufacturing and collaborative biomedical operations. Optical communication

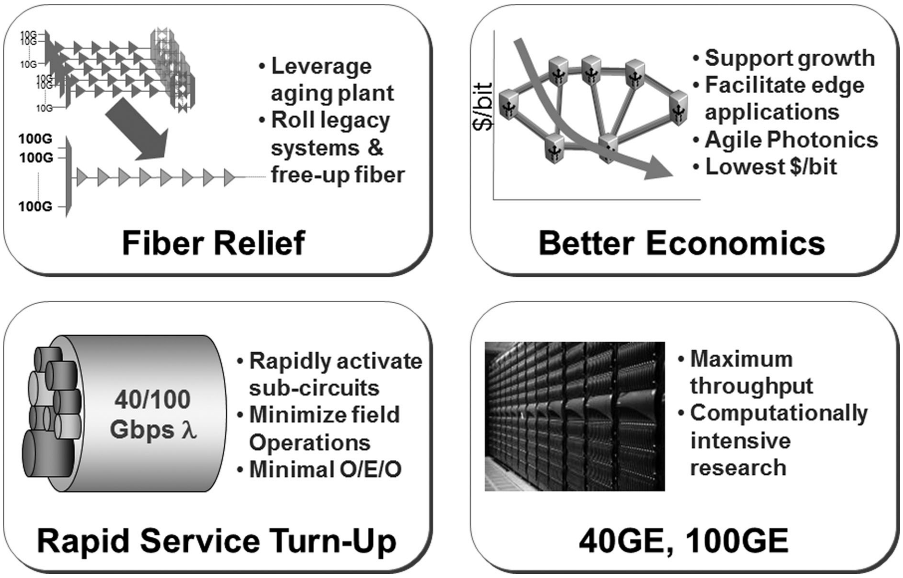


Figure 5 Illustration of the advantages of scalability to higher-capacity transport, which include fiber relief, rapid service turn-up, better economics, and enabling high-performance applications.

networks may also prove to be an interesting research topic to which industrial engineering researchers may contribute.

Two areas of particular significance are 1) multilayer network planning and 2) real-time network monitoring and optimization. Most real networks have multiple hierarchical layers, such as the optical layer, the OTN/SONET layer, and the ethernet/IP layer. Data are routed, controlled, and transported across these layers, for example, the IP layer may be most suited for routing, while the optical layer may be most suited for transport. Having multiple layers generally provides better network control, better network resiliency, and availability, but also adds to the cost. Multilayer network modeling is important for two reasons. First, given a network with multiple layers an efficient modeling program determines how best to deploy the physical assets at each layer to achieve the same network performance with respect to control, resiliency, and availability and to minimize costs. Second, if an opportunity exists to converge or eliminate one or more layers, an efficient modeling program can best determine how to converge the layers again with minimal impacts to network performance. Such network convergence not only can significantly reduce cost but also can result in operational simplicity due to a reduction in deployed hardware.

Real-time network monitoring and optimization is important since networks are dynamic with traffic and network loading changing on day to day. While some trend analysis can be done on historical network traffic and these traffic models extrapolated out to predict future traffic growth and flows, most models are found to be inadequate in making good future predictions. This inadequacy presents a fundamental problem in network design with respect to future-proofing a network. A way around this problem is to perform real-time network monitoring of traffic flow and optimization of the deployed assets based on this real-time traffic information. Such monitoring and optimization assumes that the network can be probed without disturbing its behavior and the optimization does not result in network disturbances while the optimization is ongoing. Such ongoing optimization is important since networks are live when they are monitored and optimized. Most state-of-the-art networking hardware allows for such in situ nondisturbing network monitoring. The optimization part on live networks has to be done with much care and with highly sophisticated algorithms. However, as with multilayer network planning, a good real-time monitoring and optimization model can provide significant benefits in network operation.

4.2. Optical Interconnects

Recently, several research groups have been exploring whether any of the successes in long-haul fiber-optic telecommunications can be adapted to improve the performance of shorter-haul high-bandwidth applications, including high-performance computing and data centers. An important point is that the performance of modern electronic computing systems is fundamentally limited much more severely by challenges in high-speed, high-density communications, even at short length scales, and by high-power consumption than by challenges in achieving higher clock speeds. Photonic approaches offer a potential solution to overcoming severe communications bottlenecks while lowering power consumption. Applying the concepts of Figure 4, we can expect that a hybrid approach that incorporates both optical and electronic components when appropriate would have the highest overall performance. One promising approach to achieving that overall strategy is known as silicon nanophotonics (Vlasov, 2012). In this approach, one employs CMOS-compatible fabrication processes to manufacture optical components that vertically interconnect with a conventional electronic layer as seen in a microchip. Much like in the long-haul telecommunication application, key optical components include optical sources and passive waveguide components (analogous to fiber-optic cables). At a higher level, packaging and assembly of nanophotonic systems with other subsystems, potentially including electronic, micromechanical, and microfluidic systems, as well as integration of heterogeneous materials, including III-V compounds, quantum dots, and nanoplasmonic materials, pose novel challenges. Given the likelihood that tightly spatially constrained and multifunctional systems will see rapidly increasing adoption in the future, increasingly flexible components will be key to successful deployment and scaling.

4.3. Pulse Shaping

As introduced briefly in Section 3, ultrafast laser systems now routinely generate pulses of light with durations deep into the femtosecond range, much shorter than available in any other engineered system. Although this opens up many new opportunities, it also raises new technical challenges. As one example, reshaping ultrashort pulses produced by femtosecond lasers into user-specified waveforms for specific applications becomes difficult, because the relevant timescale is too fast for direct modulation under electronic control. Femtosecond pulse shaping refers to a process, implemented using special optical hardware, of taking an ultrafast input optical signal and modifying it to produce a desired output signal with features controllable on an ultrafast timescale (Weiner, 2009). The process can have applications in a wide range of areas, ranging from high-speed optical telecommunications to ultrafast optical science, nonlinear microscopy, and life sciences and engineering applications (as mentioned in Section 3). Future potential uses of interest include ultra-broadband radio-frequency photonics, single-shot biochemical detection, optical particle acceleration, and even quantum computing.

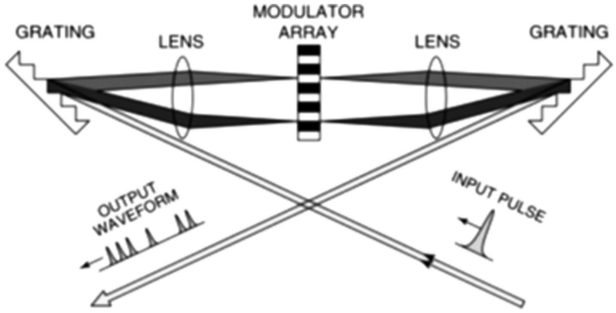


Figure 6 Illustration of the Fourier-transform pulse shaping technique. A programmable spatial light modulator in the middle allows each input frequency to be shaped individually (adapted from Weiner, 2011).

Pulse shaping requires the convolution of an input signal with a filter function, which is most commonly implemented in the optical frequency domain using a so-called Fourier-transform pulse shaping approach (Weiner, 2009, 2011). As illustrated in Figure 6, the different optical frequencies (or colors) that make up the input field are first separated using well-known optical components, such as a diffraction grating and lens. At the back focal plane of the first lens, the amplitude and phase of each frequency component may be independently adjusted using a complex spatial mask. After passing through another lens and grating, the different optical frequencies are reassembled into a single spatial beam. The resulting waveform in the time domain is given by the inverse Fourier transform of the complex pattern transferred from the spatial mask onto the optical spectrum. The first pulse shaping masks were arrayed in space to match the range of expected frequency inputs with a fixed amplitude and phase modulation. However, for the greatest versatility, it is quite useful to have the ability to program the Fourier pulse shaping waveform dynamically. The technology capable of achieving this functionality is known today as the spatial light modulator (SLM). Commonly used types of SLMs include liquid-crystal SLMs, acousto-optic SLMs, and deformable mirrors and micro-mirror arrays based on MEMS technology (Weiner, 2011). The Fourier transform pulse shaper concept exploits parallel manipulation of optical frequencies to overcome severe speed limitations of (opto)electronic modulator technologies, resulting in generation of complex photonic signals modulated on a femtosecond timescale according to user specification.

One area in which programmable pulse shaping systems have been heavily deployed is in the optical communications industry. The most common connection comes from the necessity of using multiple optical wavelengths in high-capacity optical networks, known as wavelength-division multiplexing (WDM), where each wavelength carries an independent high-speed communications channel. It has been demonstrated that pulse shaping techniques can be used to operate on all optical communications frequencies in WDM in parallel. This general approach is known as dynamic wavelength processing. One application is known as dynamic gain equalization, important because optical fiber amplifiers have a gain factor that varies with optical frequency. Repeated passage through such fiber amplifiers in an optical network results in a strong intensity difference between different WDM frequencies, which may seriously degrade data transmission. As an example, in one early precommercial experiment, 36 WDM channels spread over a frequency range of nearly 4 THz centered on 1.55 μm exhibited a spread of 7.1 dB between the intensity of each channel; the intensity spread was reduced by a factor of 10 under pulse shaping action (J. E. Ford et al., 2004). An important point is that because this approach is programmable, such equalizers can track slow changes in the channel intensities. Pulse shapers have also been generalized to realize wavelength-selective switches, in which different WDM channels can be routed, programmably and independently, to different output fibers. Such capability allows network operators to implement different network connections simultaneously on a single fiber infrastructure by using wavelength as an independent variable.

In most common telecommunications applications, a key goal is to prevent interference between transmitted symbols over a long-distance link. One major source of such interference is the presence of dispersion—propagation of different frequencies at different speeds through the transmission link. One solution, which is employed in most high-speed light wave systems, is to concatenate a dispersion compensating element, such as a special dispersion compensating fiber, after the main propagation fiber. As sketched in Figure 7(a), a short pulse traveling through conventional single-mode fiber (SMF) experiences "anomalous" dispersion, such that bluer wavelengths (higher frequencies) travel more rapidly than redder wavelengths (lower frequencies), leading to pulse spreading in time. The dispersion compensating fiber (DCF) is designed and manufactured such that it provides "normal" dispersion, with blue traveling slower than red. With proper matching of the length ratios, the pulse is compressed close to its original duration. However, because it is generally not possible to perfectly match the SMF and DCF, some amount of distortion remains. Such distortion may become especially serious for ultrashort pulses that are of interest to support very high data rates per channel. In such cases, a pulse shaper may be programmed to compensate the remaining distortion. Such compensation is possible because there is a very close link between dispersion, that is, variation of delay with frequency, and variation of phase with frequency—the latter of which can be controlled directly with a programmable pulse shaper.

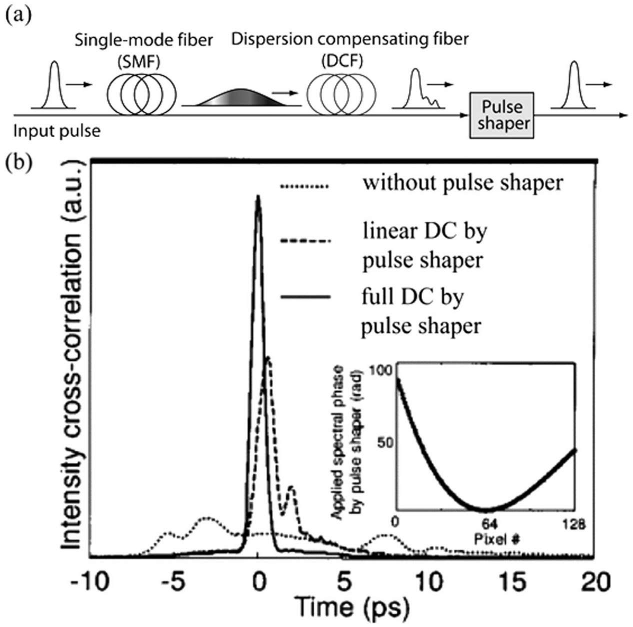


Figure 7 a) Propagation through long lengths of fiber often distorts signals, but the distortion can be reversed with dispersion compensating fiber; b) experimental demonstration of the concept from part (a) (adapted from Weiner, 2011).

Figure 7(b) shows an example in which pulses 500 fs in duration (significantly shorter than those used in current commercial light wave systems) are sent through a 50-km link of conventional SMF fiber followed by a "matched" DCF module. With propagation in the SMF alone (not shown), dispersion broadens the pulses to 5 ns, a broadening factor of 10^4. With the DCF module, the output is shortened to roughly 15 ps, an impressive 99.7% compression, but still an unacceptable 30 times longer than the input! Programming the pulse shaper for either linear (linear variation of delay with frequency) or full dispersion compensation leads to progressive improvement, with the final pulse essentially indistinguishable from the input. The inset shows the final programmed phase profile, amounting to nearly 100 radian phase variation across the 128 control pixels of the spatial light modulator. This example illustrates the strong degree of waveform control available.

The basic dispersion compensation approach described above is applicable in a broad range of scenarios (Weiner, 2011). Within optical fiber communications, a number of researchers have investigated pulse shaping–based dispersion compensation for commercial WDM systems operating at 10 or 40 Gb/s. Here the individual bit durations are in the range 10–100 ps, substantially longer than in the femtosecond example above. In some of the approaches, the dispersion compensation function can be fine-tuned from one WDM channel to the next. Within ultrafast optics, a similar pulse shaping approach (without the fibers) is frequently applied to compensate dispersive broadening of extremely short pulses down to the few femtosecond regime, as noted in Section 3.2. With such extreme pulse durations, passage of the ultrashort pulse, even through a single lens, can have deleterious effects when left uncompensated. Finally, a similar approach has been adopted to compensate dispersion encountered by ultrabroadband electrical pulses when radiated by certain classes of broadband antennas for wireless applications (McKinney, Peroulis, & Weiner, 2008). In this scenario, the pulse is first shaped optically and then converted into an electrical signal to drive the antenna by a fast photodetector.

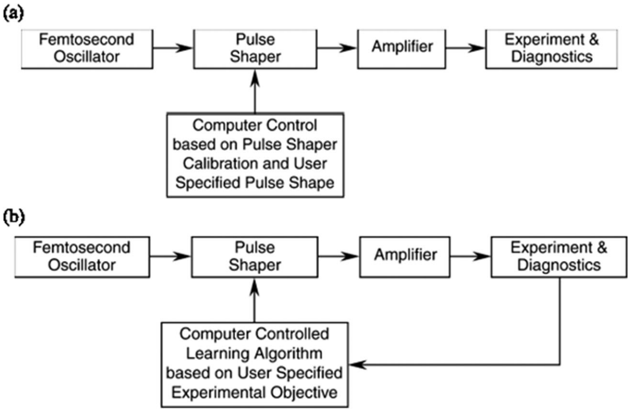


Figure 8 Illustration of two strategies for programmable pulse shaping: a) open-loop control; b) feedback (adaptive) control (adapted from Weiner, 2011).

Finally, it is worth commenting on two contrasting control strategies for programmable pulse shaping, namely, open loop control and feedback (adaptive) control, both of which are depicted in Figure 8. In the open loop configuration, the desired output waveform is specified by the user, and reasonable knowledge of the input pulse is also usually available. Therefore, the desired transfer function is known, and one simply programs the pulse shaping SLM to provide this transfer function. The dispersion compensation examples discussed above fall into this class. The ability to program a pulse shaper under computer control leads also to an alternative adaptive control strategy. In these experiments, one usually starts with a random spectral pattern programmed into the pulse shaper, which is updated iteratively according to a stochastic optimization algorithm based on the difference between a desired and measured experimental output. In this scheme, there is no need to explicitly program the pulse shaper. This adaptive control scheme is less intuitive but is often viewed as especially suitable for optimization of strongly nonlinear processes or for manipulation of quantum mechanical motions in systems, such as molecules, where knowledge of the dynamics is not sufficiently accurate. In such cases, the adaptive control approach can be used to search for the laser waveform, which gives the best experimental result, as judged according to a user-defined metric. Such adaptive optimization schemes are well known to the industrial engineering community. Experimental examples are reviewed briefly in (Weiner, 2011) and include laser-controlled chemistry, selective enhancement of short wavelength radiation from atoms driven by strong laser fields, manipulation of energy flow in light harvesting molecules, and spatially selective excitation of subwavelength metallic nanostructures.

Figure 9 (Left) Photograph of racketball bat. (Middle) Photograph of racketball bat in case. (Right) Terahertz image of racketball bat in case (X.-C. Zhang & Xu, 2009).

4.4. Terahertz Wave Sensing[2]

Terahertz (THz) waves discriminate strongly between material types and offer the potential to see "inside" certain materials without ionizing radiation, thus offering a powerful yet safe window into a large range of phenomena. Nestled in a formerly rarely used portion of the electromagnetic spectrum between microwaves and infrared—the "terahertz gap"—new techniques for generating and detecting THz waves have recently been developed (Zhang & Xu, 2009). One popular generation technique relies on semiconductor or electro-optic devices that radiate THz electromagnetic waves in response to illumination by ultrashort laser pulses. Ultrashort pulses are needed for this purpose because the illuminating laser pulse must be shorter than a single cycle of the desired radiation; at a frequency of 1 THz (10^{12} Hz), each cycle is only 1 ps (10^{-12} s) in duration, so the exciting laser pulses must be in the femtosecond range. The generation and/or detection of THz waves is now of great interest in areas such as astronomy, global environmental monitoring, and homeland security. An example of the potential is illustrated in Figure 9, which shows that a racquetball bat in an optically opaque case can be clearly imaged with a THz probe. Because of the potential to find otherwise obscured objects, THz imaging is already being tested in Australia for secondary scanning of suspicious individuals at airports to enhance security for all passengers. THz imaging also enables spectroscopic sensing of specific molecules, which can help with the detecting foreign pathogens, measuring levels of pollutants in the environment, finding hazardous chemical agents reliably, and providing quality control for food and drinks. THz probes are also suitable for detecting varying levels of water in samples of interest, including biological samples, and in the environment, using component contrast imaging. Overall, THz imaging enables a broad range of important and useful applications in a safe and increasingly cost-effective manner.

However, remote broadband THz sensing can be limited by atmospheric water vapor absorption. The previously developed technique of THz air-biased-coherent-detection (ABCD) provides ultra-broadband sensing capability. However, it requires electrodes or wires near the target, so it cannot be used for remote, or "standoff," measurements (X.-C. Zhang & Xu, 2009). Examples of recent research approaches that involve innovative mixes of ultrafast laser and THz technologies, termed "THz wave air photonics," have begun to suggest viable options for broadband THz remote sensing: "seeing" THz-enhanced fluorescence with radiation-enhanced emission of fluorescence (REEF), or "hearing" THz-enhanced acoustics (TEA; X.-C. Zhang & Xu, 2009). The THz spectrum recovered through ultraviolet fluorescence in the REEF method can contain spectroscopic information about the environment and objects that the THz wave has propagated through or interacted with. If the THz wave interacts with a material that has a strong or distinctive spectroscopic feature within the very broad generation bandwidth that information will be encoded on the THz pulse and may be extracted and analyzed. The ability to extend THz to remote sensing scenarios is especially relevant to standoff detection of explosives and hazardous agents and environmental monitoring applications.

5. SYSTEMS, NETWORKS, AND INTEGRATION ISSUES

The integration of laser and photonics technology is essential for enabling engineering solutions to grand societal challenges, as described above. It is used for new medical processes and new manufacturing processes, with promising new solutions. It enables new techniques of better and faster communications. It is used for material processing to create unique characteristics for more efficient and economical energy systems, such as solar energy. Integration of all the technologies required for a power station is planned for mid-2020s. Laser technology is an inseparable part of computer-created virtual realities and advanced personalized learning that aim at furthering engineering's contributions to the joy of living. Furthermore, a major motivation to integrate laser technology and photonic systems is the inherent need of scientific discoveries to investigate the vastness of the cosmos or the inner intricacy of life and atoms. The laser and photonics technologies, however, have to be seamlessly integrated at the system and network level in order to fully achieve their promise. This section addresses the emerging approaches and challenges in the systems, networks, and integration issues to further advance the knowledge, application, and education in this frontier.

5.1. A Collaboration Network for Laser and Photonic Services and Products

As laser technology and various photonic systems continue to mature, their coherence and integration with humans and other systems and tools pose significant challenges. For instance, current laser technology is limited by the useful transmission range of nonlinear optical materials; longer wavelength materials have been developed but are incompatible with mature laser systems. To fully explore their potential, scientific and engineering challenges must be addressed (Li, 2010). Some of the challenges stem from the development of laser technology, while others are related to its implementation and integration in various manufacturing and service systems. Laser has the potential of being a leading technology in precision collaboration of robotic systems and human-robot systems due to its diversified abilities and high efficiency. It can improve the collaboration quality in various types of systems and tasks, for example, more effective path teaching tasks of laser welding robots; better and faster human-robot collaborative task sharing systems for selective agricultural harvesting; and more precise interactions through virtual manufacturing and virtual medical procedures. Several challenges have to be addressed to accomplish such progress.

5.1.1. Challenges

5.1.1.1. System-Oriented Structure

The first challenge is the local versus networked system-oriented structure. Hundreds of thousands of laser- and photonic-based systems have already been developed and more advanced ones are emerging in manufacturing, healthcare, transportation, logistics, and other services. In certain cases, it is costly to maintain these stand-alone systems and an untold number of system-to-system interfaces, both within local facilities (communication facilities, hospitals, monitoring and rescue installations, laboratories, test and repair installations, microelectronics factories, and other facilities), and between facilities. The local system-oriented structure is challenged by the need to rationally scale up application solutions, network them on a broader basis where it is useful, enable adaptive rerouting in and between systems and networks, and eliminate unnecessary duplications. A service-centric platform is needed, which enables collaboration between product/service providers and between providers and customers.

5.1.1.2. Inherent Sequential Process

The second challenge is the inherent sequential process. Even with concurrent design, product development must undergo several sequential, repetitive steps, for example, design, prototyping, and testing. The sequential process is vulnerable to changes in a product life cycle and in technology innovation. For instance, a relatively small design change discovered during the testing stage can be costly and may not be accommodated. A network-centric process will increase parallelism and help flatten the manufacturing, development, and integration process. Innovative and flexible aspects of the laser and photonic technologies would promote parallelism, and it is important to carefully explore this opportunity from a network-centric perspective.

5.1.1.3. Integration of Laser-Based and Traditional Processes

The third challenge is the integration of laser- and photonic-based processes with traditional manufacturing, healthcare, and other processes. Both types of processes can be applied to a variety of products and services. In many cases, laser- and photonic-based processing is more energy efficient and provides better quality than traditional processing, for example, in manufacturing and in healthcare. In practice, however, many objectives such as affordability, process time, safety, system sustainability and vulnerability, recovery, and recycling must also be considered. While emerging laser and photonic systems are still maturing, the characteristics of certain laser-based processes are difficult to predict. Therefore, to overcome such difficulties, the integration needs to be planned in an open

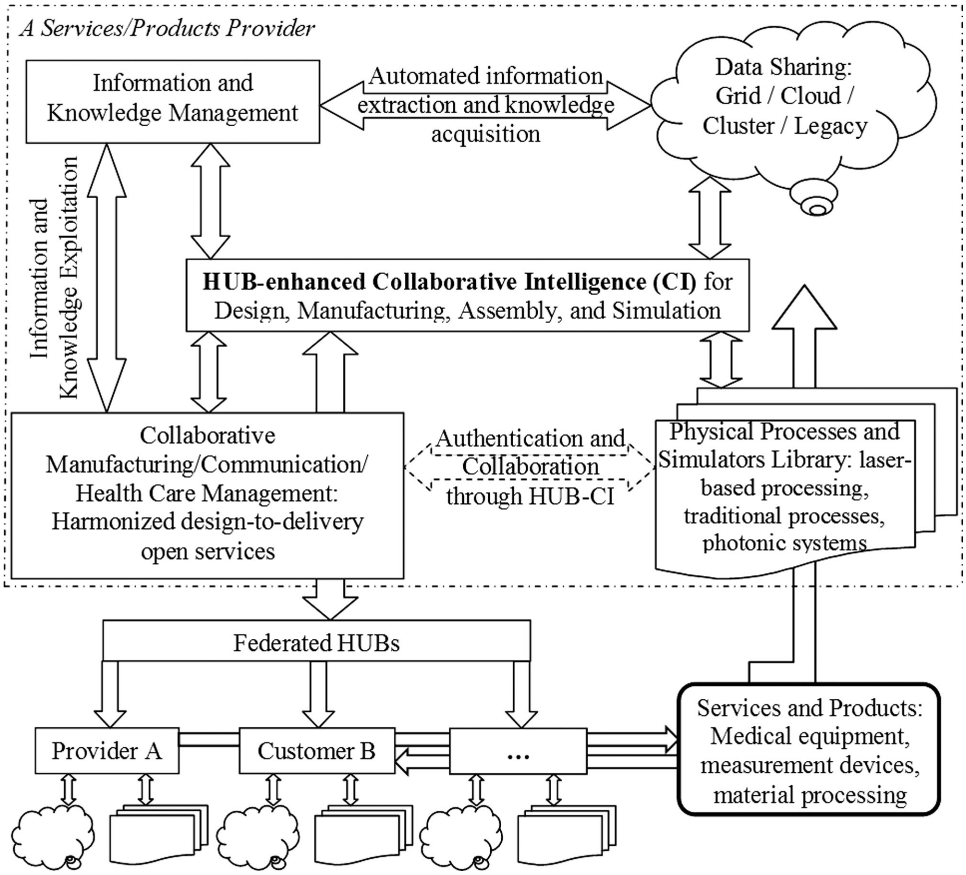


Figure 10 Integration architecture (framework) of a collaboration network for laser- and photonic-based services and products.

architecture (Figure 10). For instance, the integration of different manufacturing processes, logistic services, and other services is emerging as being enabled by an open manufacturing and service environment supported by a library of physical processes, simulators and virtual manufacturing, virtual medical, or other virtual service tools.

5.1.1.4. System Modeling and Analysis

Successful integration of laser and photonic technologies into manufacturing, healthcare, and service systems through the open architecture (Figure 10) gives rise to new system models that may not yet have been investigated. New photonics-based processes can introduce different behaviors and interactions within and across processes and systems. For instance, the closer and faster integration of information and decision flows with processing steps and control are becoming feasible. For example, multiphysics simulation tools were developed to simulate the multilayer laser sintering of nanomaterials for bio-implant (Y. Zhang et al., 2011) and laser crystallization of thin films on various substrates (M. Y. Zhang, Nian, & Cheng, 2012). This model could predict the optimal laser processing conditions for ideal microstructure and performance of the product. The system modeling works could significantly reduce the trial and errors during production. When the simulation tools are combined with online monitoring tools, the quality control and processing effectiveness could be significantly improved. A related example of combining laser-based processing with laser-base process control is described below (Informatics for laser and photonics based processing.) Therefore, the fourth challenge is to define the system models emerging from the photonics and laser technologies, thereby developing tools and techniques of optimally designing and controlling the systems.

Though photonics technologies have a great potential in enhancing the performance of systems in terms of cost, timeliness and quality, if these processes are not integrated from a broad systems perspective, the

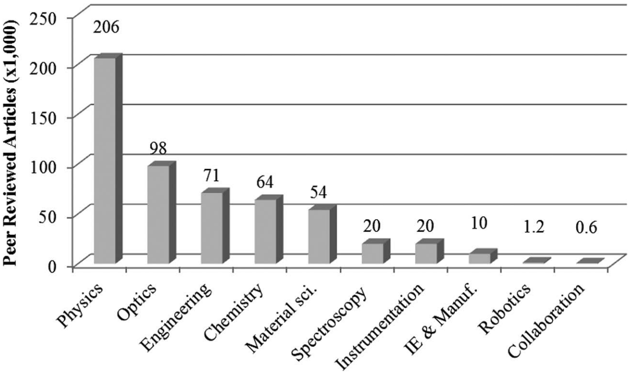


Figure 11 Peer-reviewed articles on laser technology and photonic systems (Source: Web of Science, accessed in March 2012; Bechar, Wachs, & Nof, 2012).

promise they can provide would be diminished. On the other hand, successful integration at the system and network level will prove the usefulness of the technology, enabling its fruitful diffusion into society at an accelerated rate.

Figure 10 depicts a service- and network-centric collaboration platform for laser and photonic systems. A Hub-enhanced collaborative intelligence (HUB-CI) integrates systems for a provider and aligns their functions to services requested by customers. Service and product providers and customers collaborate with each other through a network of cyber-hubs. The objective is to establish a network of sustainable, resilient, and collaborative laser and photonic technology providers and customers for better solution of societal problems.

5.2. Research Highlights

The amount of research related to laser technology is vast (Figure 11), whereas relatively little is dedicated to integration represented in two categories: industrial engineering and manufacturing and collaboration (Nof, 2003, 2007; Zhong, Wachs, & Nof, 2013). One of many applications of laser technology is precision collaboration, which integrates communication, synchronization, control, geometrical environmental data, and information collection. Laser technology is used to operate each of these components because of its unique ability to transfer data, information, and energy with no spatial or temporal residuals. Laser is used as a tool, an information media, an energy source, a marker, or a sensor in precision collaboration such as in metal welding, tissue welding, chemical detection (Yoo, Gilbert, & Broderick, 2010) and target recognition systems of the types described by Bechar, Meyer, and Edan (2009). In the latter study, laser technology can be integrated into the system and increase efficiency, quality, and effectiveness. Similar to the use of lasers in military and aviation, in areas such as manufacturing, healthcare, agriculture, transportation, and other services, to improve the overall system performance, laser scanners and sensors can be used for mapping a target environment, for example, for the detection and recognition of targets, fruits, organs, and parts; for marking the detected objects by laser pointers; and for communicating and applying precise collaboration by laser and photonics communication systems. Recent advances in laser and photonics technology increase the potential feasibility of harnessing them for new and improved collaboration processes and systems.

The advantages of laser and photonics for collaboration are numerous. In comparison to radio-based systems, it has lower cost and higher flexibility and reliability, wider bandwidth, and lower power requirements; it is lightweight and points accurately and has increased potential for covert data links. Furthermore, it can be designed with better tracking abilities and with inherent precision, leading to better quality and precision of the command and control decisions. These advantages enable precise collaboration and elimination of errors, resulting in faster, more effective interaction and less effort and time of interactions and commands required to achieve the goal, compared with less precise interaction and collaboration techniques.

The opportunities in applying advanced laser techniques for precision collaboration are determined mainly by the type of collaboration, interaction, task, the application, and the environment. Emerging laser applications in precision collaboration (Figure 12) include mapping the environment, detecting objects, targeting, localization, and interactions. In particular, laser technology is used to track fingers for gesture recognition in human–computer interfaces (Jacob, Li, & Wachs, 2011; Wachs, 2010; Wachs, Kölsch, Stern, & Edan, 2011). For instance, a sterile finger tracker has applications in various areas, including interactive medical imaging for healthcare, safety and security applications, and other tasks relying on noncontact precision measurements by laser interferometry.

Precision collaboration and integration can be classified along five main dimensions that characterize the functions and roles in Figure 12 (Bechar et al., 2012):

1. *Virtual shared surfaces among users*: In conceptual design, sketching, and planning, designers

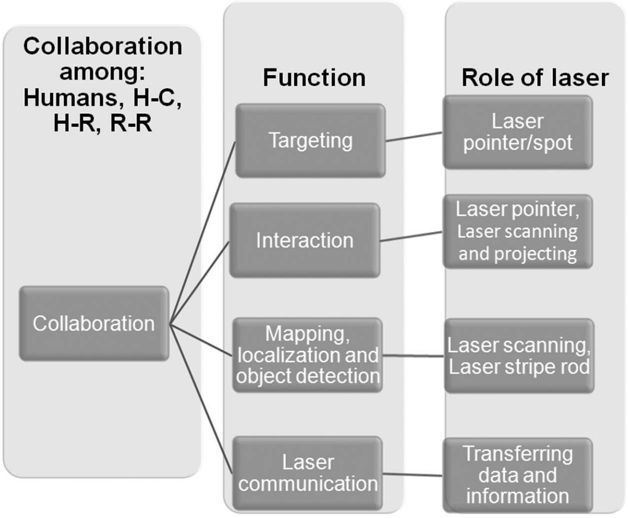


Figure 12 Emerging laser applications in precision collaboration among humans, human–computer, human–robot, and robot–robot.

can be distributed and share a virtual model for a conceptual design, reflecting the characteristics of the true physical objects and locations.

2. *Shared spaces with robots (co-work)*: Pointing to targets, assistive, service, and surveillance robots interact with human operators through gesture and speech commands. In such situations, a laser device is mounted on the human's wrist to define unambiguous target locations and positions.
3. *Shared gestures and pointing gestures*: Sketches are designed and interacted on a projected surface or in the air, using a special glove. This glove projects a single point generated by a laser, which is installed on the operator's palm. The trajectories represented by the movement of a finger or hand are translated into fine, thin lines.
4. *Augmented reality*: Operators interact with virtual objects as if they are interacting with real ones. It has also been used to project virtual textured patterns over real objects which do not yet have any pattern (having just uniform colors) to express an illusion of how the object would appear if it had that pattern.
5. *Shared patterns*: Patterns are shared through projected structured light from individual sources to assess depth, pattern, and position and to enable planning and operations. For this purpose, lasers can be used to generate beams of light for projection on surfaces in the environment and for assessing distance and relations of objects within the environment, enabled for both indoor and outdoor applications.

Although initial progress has been reported along these dimensions, further research is needed, specifically

1. For display Groupware interfaces and synchronization, and a framework that supports multiple pointing devices;
2. For graphical representation and rendering using lasers;
3. For gesture recognition using lasers;
4. For human factors of integrated laser systems for collaboration;
5. For augmented reality: Laser projectors have been previously used to create augmented reality, instead of the standard head-mounted displays. This technology overcomes problems such as small field of view, limited resolution, multiple focus planes, and eye fatigue; and
6. For enhanced depth sensor technology for indoor/outdoor use: Monocular cameras using structured light are cheap, reliable, and do not require calibration. While some cameras deliver satisfactory performance indoors using infrared structured light, other devices use laser-structured projections to deliver depth information.

Research on networks and systems integration has kept up with the development of the framework proposed in Figure 10. The association/dissociation and join/leave/remain protocols aim at creating an ad hoc, responsive service-centric network of best-matching information resources and physical suppliers/sources and customers/receivers. Task administration protocols (Ko & Nof, 2012; Nof, 2007) have been designed to manage and control the coordination and collaboration workflow among multiple network or swarm entities. An interactive prognostics and diagnostics network (Chen & Nof, 2012) was invented to effectively and efficiently detect and prevent conflicts and errors in complex networks. Many complex networks, for example, random networks, scale-free networks, and Bose-Einstein condensation networks with quantum communication of computation, have been investigated to

TABLE 3. Contribution and Challenge Areas for Systems Interaction, Collaboration, and Integration with Lasers

Area/Application	Function/Device	Dimension[1]
Mobile robots / communication	Laser communication, development of pointing, acquisition, and tracking for laser communication	1
Robot control	User interface, specifying command and target location; laser pointers	1–2
User interface and display groupware	Computer-controlled laser pointers; input device for collaboration	2
User interface and display groupware	Input device for collaboration, laser pointers	2
Mobile robots/intelligent space	Cooperative positioning, laser scanning, mapping, people detection	2
HRI	Dismantling interior facilities in buildings, pointing to a target in the task space with the laser pointer	2
Assistive robot (chronic stroke)	Selection of objects with laser pointer	2
Mobile/service robots, HRI	Pose/ gestures detection, laser range scanner, detection	2–3
HRI, wearable collaborative systems	Collaboration/interface, point to real objects in the task space with laser spot, laser pointer	2–3
Industrial robots, positioning tasks	Mapping objects, point to a work piece in the task space with a laser pointer	2–3
Industrial robots, laser welding, path teaching	HR collaboration, augmented reality, laser scanning, laser spotting for marking, and laser welding	4
Dental operations and surgery/AR	Projecting surgical plans onto patient, laser scanning, projecting and marking	4
HRI, manipulator control, robot guidance	HR collaboration, user interface, gesture and posture detection	5
HRI, teleoperation guidance	HR collaboration, user interface, gesture detection	5
Mobile robots	Multirobot collaboration, mapping and object detection	5

Note: Survey by Bechar et al. (2012).

[1] Dimensions as defined above in the five dimensions of precision collaboration and integration.

identify the most resilient collaboration platform and optimize service performance (Chen & Nof, 2012).

Various challenges addressed and areas in which researchers have been found to apply laser devices and techniques for interaction and collaboration are shown in Table 3. In these cases, lasers have been used as part of the collaboration process or collaborative system or as a means of controlling the collaborative system, with the laser device applied as a tool, information medium, energy source, pointing device, and as sensor to collect data.

Collaborative control for sustainability is critical to the long-term effectiveness of laser and photonics industry. Decision support tools have been developed to reduce the cost of materials, energy, and human resources and reduce the duplication of hardware and software resources at the user end. Another important integration issue is the management of interactions between physical manufacturing processes, robots and human operators, and integration of human operators in virtual manufacturing through the reconceptualization of the work cell for operators, automated workflow management, human-in-the-loop process simulators, and centralized collision avoidance. The direct impacts of laser-based interactions in different areas and the required dimensions, as defined above, are presented in Table 4.

Virtual models and tool libraries, for example, virtual manufacturing and virtual medical procedures provide predictive modeling capabilities for traditional and laser-based processes. It implies an iterative simulation and prediction process based on kinematics and dynamics of machines and tools. It also enables better training of operators, technicians, surgeons, and nurses by learning and practicing first in virtual environments. For instance, virtual surgeries enable surgeons to prepare for complex procedures before execution by first training and experimenting on virtual models built precisely based on timely images taken from the patient. Distance learning and training opportunities are enabled for complex surgical procedures, involving master surgeons, who can take over virtually when required. Similarly, in virtual manufacturing, designers can predict and select desirable processing and material parameters without going through expensive and time-consuming experiments with the actual hardware. A

TABLE 4. Direct Impacts of Laser-Based Interactions Anticipated in Emerging Collaborative/Interactive Systems and Networks

Impacts on Safety, Security, Productivity, and Quality	Examples	Dimensions of Sharing Among Interacting Operators/Participants				
		1. Virtual Surfaces	2. Space with Robots	3. Gestures	4. Augmented Reality	5. Patterns
Manufacturing	Collaborative CAD/CAM, production; collaborative processing	■	■		■	
Production	Facility monitoring for safety and quality	■	■	■		■
	Sensor automation for safety and productivity	■	■			■
Agriculture	Precision human–robot tasks	■	■	■	■	■
Transportation	Airport security and safety	■		■		■
Supply chains	Supply chain security	■	■		■	■
Training	Security training	■			■	■
Healthcare	Operating room image browser, robotic scrub nurse		■	■		
Environment	Environmental monitoring by laser-based wireless sensor networks		■	■		■

Note: Bechar et al. (2012). The required precision collaboration and integration dimensions for each direct impact are marked by filled square.

number of approaches have been developed for virtual manufacturing, for example, a numerical framework for simulating the microstructural evolution in machining was developed using Thirdwave AdvantEdge.

At Purdue University, the HUB-CI initiative (Seok & Nof, 2011) has taken steps to establish a collaboratorium platform for product and service development that enables enhanced parallel, coordinated development of low-volume, high-value products. The HUB-CI initiative is integrated with HUBzero (McLennan & Kennell, 2010), which has also been developed at Purdue University to enable scientists and engineers to share data and resources and develop simulation and modeling tools collaboratively. Cloud computing enriches the HUB-CI by enabling participants to access data and applications from anywhere on demand.

5.3. Challenges and Opportunities for Innovation: Systematization Considerations

5.3.1. Role of Humans

Whenever humans are involved in any system, comprehensive human factors analyses need to be performed to optimize performance and maximize safety. Much is known from experimental and social psychology that is relevant to design and implementation of laser technology. From the former comes understanding of the processes that underlie sensation and perception, cognition, retrieval and manipulation of information, and selection and control of action (Proctor & Vu, 2012). From the latter comes a large body of literature on the influence of group interactions on attitudes and behaviors of people (Van Lange, Kruglanski, & Higgins, 2012).

One general implication from human factors research is that any specific application of laser technology needs to be designed to accommodate the human users. The following examples illustrate this point. The first concerns human interaction with imaging systems and the display of imaging information. A company that specializes “in laser communications, satellite sensors, fiber optic gyros, and vision systems” emphasizes as a selling point that they also work “with world renowned experts in human factors . . . [and] night vision” (SA Photonics, 2012). There is no doubt that these specialists see human factors as important to the design and implementation of their photonics products. The second example is a study by Blankenbach and Buckley (2012) that examined perceptual effects of laser-based head-up displays (HUDs). These researchers compared the readability and color performance of laser-based HUDs and light emitting diode (LED) displays under several ambient lighting conditions. Their main finding was that the laser-based HUDs exhibited better readability and chromaticity performance than the systems based on LEDs. This study illustrates that, for any application involving laser-based visual displays, there is a need for human factors and perceptual analyses to evaluate and hopefully establish the value for users of the LED-based system.

A second general point is that adoption of new technology requires consideration of factors that influence user perceptions of the technology and resistance to adoption. One example of this point is the concept of perception-based engineering, introduced by researchers at Purdue more than 10 years ago. The goal of this approach is "to integrate into the design of engineering systems, the ways in which people perceive and are affected by machinery outputs" (Perception-Based Engineering Research Group, 2012, p. 2). Clearly, whether and how users of all types perceive their interactions with laser technology is central to widespread adoption of the technology. Another example is the affect in risk perception and its role in decision making (e.g., Visschers et al., 2012). Users of virtually any technology will vary in their perceptions of risk, and these perceptions of risk will determine in part how likely the user is to engage in certain actions, such as downloading an app to an Android mobile device. Finally, it is well known that users are resistant to new technology. Many factors enter into this resistance, but as Haymes (2008) emphasized, "a technology must be easy to use to avoid rousing feelings of inadequacy."

5.3.2. Safety Applications

Laser technology also plays an increasingly large role in a wide variety of safety applications, particularly with respect to developing sophisticated warning and alerting systems. Illustrating this trend, most automobile manufacturers currently offer collision avoidance systems as an option for higher-end vehicles. Emerging evidence, including recent simulator studies, suggests such systems can be effective (Muhrer, Reinprecht, & Vollrath, 2012). Real-world data also support this conclusion. In particular, a recent study conducted by the US insurance industry found that the frontal collision warning systems offered on Acura, Mercedes-Benz, and Volvo vehicles reduced crashes by 10 to 14 percent (Highway Loss Data Institute, 2012). Laser technology is particularly effective in these and a wide variety of other collision avoidance applications since lasers can be used to quickly and accurately obtain real-time measures of position, velocity, and acceleration. Some other applications of collision avoidance warning systems where laser technology plays an important role include laser collision warning systems for overhead crane and hoists now offered by manufacturers and laser helicopter warning systems that warn pilots of power lines and other obstacles when flying at low altitudes.

Laser technology is a critical element in many other safety devices, including interlocks or emergency braking systems. For example, presence sensing and interlock devices are sometimes used in installations of robots to sense and to react to potentially dangerous workplace conditions. Laser light curtains are often used in such applications to determine whether someone has crossed the safety boundary surrounding the perimeter of the robot. Perimeter-penetration will trigger a warning signal and in some cases will cause the robot to stop. Laser and other types of end effector sensors detect the beginning of a collision and trigger emergency stops. In more sophisticated applications, computer vision and other methods of data fusion can play an important role in detecting safety problems during robot motion planning and collision avoidance.

A presence sensing system, such as a safety light curtain device, is often installed for point of operation, area, perimeter, or entry/exit safeguarding. By reducing or eliminating the need for physical barriers, such systems simplify access to the robot system during setup and maintenance. By providing early warnings prior to entry of the operator into the safety zone, such systems can also reduce the prevalence of nuisance machine shutdowns. Furthermore, such systems can prevent accidents by providing warning signals and alerts to personnel on the production floor.

Two commonly cited technical challenges for collision warning and avoidance systems are the development of reliable and all-weather target detection systems and the trade-off between false/nuisance alarms (false-positive) and missed detections (false-negative). From a short-term perspective, false alarms are merely a nuisance to the operator, but over time, false alarms create mistrust in the system and encourage people to ignore the warnings or even disable the systems (Lehto, Lesch, & Horrey, 2009). The solution is to increase the quality of the information provided, by reducing the number of false alarms and misses. Better quality can be obtained by either improving sensor technology or creating better algorithms. Simply adjusting the warning threshold to a more meaningful (less conservative) setting that reduces the number of false alarms can have a large benefit by encouraging drivers to behave more rationally (Lehto, Papastavrou, Ranney, & Simmons, 2000). However, ultimately the best solution is to build on advances in laser technology to develop systems capable of accurately detecting imminent collisions under all foreseeable conditions. Advances in sensor fusion and image recognition in which laser technology is combined with other methods of sensing environmental and operator states is an important step in developing truly intelligent warning systems with capabilities well beyond those currently available.

5.3.3. Uncertainty Management in Integrated Laser and Photonic Systems

The dispersion compensating mirror has become an enabling technology for modern ultrafast lasers. Solid-state mode-locked lasers can only operate at or below few-cycle pulse widths when the total cavity dispersion is reduced to nearly zero, with only a small amount of residual second-order dispersion. While prisms can be used to compensate for second- and third-order cavity dispersion, their relatively high loss and inability to compensate for arbitrary dispersion limit their use; pulse durations below 10 fs were not possible directly from oscillators until the development of high-performance double-chirped mirror pairs (Kärtner et al., 1997).

As bandwidths increase, so do the number of layers required to produce a mirror with the high reflectivity needed for an intracavity mirror. For bandwidths exceeding an octave, mirror pairs with more than 200 total layers are generally required. The sensitivity of a dielectric stack to manufacturing errors increases with the number of layers, and dispersion compensating mirrors push the limits of manufacturing tolerances, requiring layer precisions on the order of a nanometer. Currently, this challenges even the best manufacturers.

While the nominal optimization of layer thickness has lead to successful design of dispersion compensating dielectric mirrors, allowing dispersion and reflectivity control over nearly an octave bandwidth, in practice the performance for such complicated mirrors is limited by the manufacturing tolerances of the mirrors. Small perturbations in layer thickness not only result in suboptimal designs, but due to the nonlinear nature of mode-locking, such perturbation may completely destroy the phenomenon. Even though manufacturing errors often limit the performance of thin-film devices (Sullivan & Dobrowolski, 1992), there has been little work on optimizing thin-film designs to mitigate the effects of errors.

Recently, a novel robust optimization algorithm was demonstrated that attempted to account for expected coating errors as they can occur in manufacturing of mirrors for ultrafast lasers (Nohadani, Birge, Kärtner, & Bertsimas, 2008). This optimization method explicitly takes the possibility for layer errors into account, compromising nominal performance to improve robustness against layer perturbations. In theory, one could attempt to optimize a coating merit function, which involves a full Monte Carlo simulation of manufacturing statistics. However, such an approach would be computationally infeasible for all but the simplest designs. The introduced approach is a *deterministic* method that explicitly considers the effects of manufacturing tolerances, while retaining the fast convergence properties inherent to a deterministic algorithm. Furthermore, this method is generic and, hence, can be applied to many problems that are solved through numerical simulations. The advancements in performance in the presence of manufacturing errors were performed on a proof of concept antireflection coating design (Birge, Kärtner, & Nohadani, 2011). It was shown that the robust algorithm produced an antireflective coating with a higher manufacturing yield when root mean square layer tolerances were above approximately 1 nm.

The essence of this approach showcases that, while the nature of manufacturing error usually may pose performance limitations, robust optimization methods offer remedies that are beyond sensitivity analysis or other postdesign approaches and can directly impact the outcome as well as the manufacturing yield at a moderate computational cost.

5.3.4. Risk Analysis

Integration of laser and photonic systems requires a careful risk analysis in the early stage of the project, with the objective to select and create high-value outcomes. In defense and homeland security applications, it has become increasingly more common to employ laser-based technologies to perform critical tasks. For example, it is becoming more advantageous to perform tracking of extended targets such as missiles or aircraft via laser range sensors. The latter offer high resolution and are equipped with sophisticated signal processing apparatus, designed to improve the accuracy of the target kinematical estimates (position, velocity, acceleration, etc.).

Companies that produce such technologies can obtain higher revenues from the innovation, sale, and commercialization of these products but are at the same time exposed to risks. When designing a product, such as a laser-based sensor system, highly specialized companies would prefer to have a systematic methodology to identify all risks. Such risks are incurred because of the uncertain business environments, and a timely prediction allows the company to take the necessary measures to be partially hedged against them.

As an example, in 2002, the NASA Earth Science Technology Office created a new program to address the risks of developing laser and lidar (light detection and ranging) technologies for space-based remote sensing applications. The laser risk reduction program employs probabilistic risk methods to assess the reliability of laser diode arrays, the effect of radiation on diode performance, and the degradation mechanisms of diode lasers.

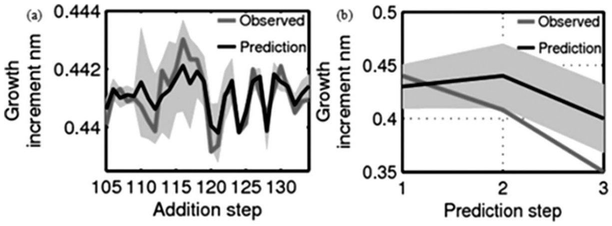
Useful financial tools that may be used to perform such an analysis are real options. Those instruments allow to value opportunities arising in such strategic environments, and to proactively manage the investments made. The valuation formulas are aligned with financial markets and enable managers the ability to start, to stop, or to modify a business activity at a future time. This ability is highly relevant in the current context of rapid integration with laser and photonic systems, where launching and manufacturing a new product may lead to unpredictable outcomes.

To this extent, applications of real options enable organizations to consider high-return projects, while becoming more agile in an uncertain business environment. Advanced laser systems technologies call for targeted research, which should leverage on existing real options techniques and develop them specifically to deal with integrated laser and photonic systems. Such efforts should be conducted through partnerships between academia and industry and can generate high returns.

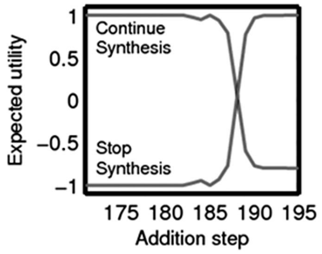
5.3.5. Systems and Networks Optimization

The integration of different processes in manufacturing, healthcare, and communication, for instance, as in the HUB-CI architecture (Figure 10), imposes new challenges in the processes. As the service-centric platform requires that physical processes of different nature must be systematically integrated, for example, manufacturing resources can be effectively drawn and assembled in a timely manner when needed. For example, suppose a customer needs to harden the surface of a piece of metal, which can be performed by laser shock peening or by conventional shock peening. The service-centric platform ensures that the customer communicates through one channel with different service providers and receives high-quality services at reasonable costs; the nature of the process selected, that is, laser shock peening, conventional shock peening, or the combination of both, can be transparent to the customer. In addition, dynamic time sharing among different people, assets, and processes in both remote and proximal environments should be handled automatically by monitoring programs, enabling smart allocation of critical resources and efforts on the tasks with different levels of priorities.

Examples of optimization and simulation-based design and control of laser and photonics applications include the coating of mirrors for ultrafast lasers (Nohadani et al., 2008) mentioned above and simulation-based process control of microfabrication techniques discussed below (Figure 13). The flexibility and efficiency features enabled by laser and photonic systems provide new opportunity to expand the boundary of traditional systems and networks. However, the size of the problems with which we have to deal will accordingly become significantly more large scale, complex, and difficult to handle by current analytical models. Therefore, the primary strategies for meeting these challenges call for innovation in simulation tools and optimization techniques that can be directly incorporated into the design-to-deliver process. Simulation tools are expected to quickly assemble smaller, encapsulated process modules to construct the targeted process and should be capable of evaluating the system performance in both transient and steady state. On the basis of the evaluation provided by simulation, the optimization tools at different system hierarchies facilitate seamless collaboration among a network of resources in real time and provide necessary data and control feedback to future simulation runs. The tight link between simulation and optimization on HUB-CI platform are also expected to significantly broaden the research frontier of the joint research domain such as simulation-based optimization.



a. Comparison of growth increment from simulation and LGP prediction model; the shaded region represents the 95% confidence interval: (a) one-step-ahead prediction; (b) three-step-ahead prediction



b. Utility function for synthesis of CNT with desired lengths as 90 nm

Figure 13 Process optimization for laser-based nanomaterials fabrication (C. Cheng, Bukkapatnam, Raff, & Komanduri 2012).

Simulation-based optimization has already been successfully applied in applications of manufacturing and service-centric systems (Shi & Ólafsson, 2008). Decision support tools in healthcare service platform, for instance, have been developed for both long-term and short-term planning to reduce the operational cost while at the same time maintaining a reasonable service level. For laser-based applications, recent research has applied simulation-based optimization as an optimal control strategy to address complex relationships between the quality of weld and control parameters. Also, research along the line of laser polishing process (e.g., Vadali, Ma, Duffie, Li, & Pfefferkorn, 2012) has demonstrated great potential for implementing simulation-based optimization techniques in helping to improve the quality of the product manufactured.

5.3.6. Systems and Networks Scheduling

Scheduling is an important tool in optimizing manufacturing and service systems and networks. There exist various models and solutions according to the characteristics of individual problems (Baker & Trietsch, 2009; Pinedo, 2008). Innovations of processes by the laser and photonic technologies have a significant potential to enhance the performance of systems and networks. Traditional scheduling models may not be able to represent the system behaviors emerging from the laser- and photonic-based processes and their interactions with other system or network components.

In laser cosmetic surgeries, for example, laser surfacing is widely applied to renew human skin. During surgery, which imperfections are treated first and related decision variables such as the type of laser to use, laser energy dissipation, and duration must be determined to optimize multiple objectives, including skin appearance and health, the number of imperfections treated, and recovery time. This planning is a challenging scheduling problem, and its complexity is compounded by many constraints, for example, the particular areas of human body being treated. Such problems require attention and solution as laser surgeries and other processing are needed and applied significantly more widely.

Scheduling models have to be carefully examined and extended to comply with the new needs. Also, scheduling problems are, in general, computationally hard, and it is common to apply heuristic algorithms to solve them. The evaluation of different heuristic algorithms is usually conducted in a set of practical problem instances; the best algorithm chosen is then expected to perform best when it is applied to the current practical settings. However, the emergence of fast, high-quality processes by laser and photonic technologies, such as those listed in Section 2, for example, laser drilling 10–100 times faster than rotary drilling, can fundamentally change the region of practical problem settings, and the algorithm known to be the best so far may become ineffective and inefficient in the laser- and photonic-based domains. Such change can be similar to the way laser technology has already enabled optical communication, revolutionizing information delivery and rendering many communication techniques obsolete. The industrial applications of laser and photonics are growing at a fast pace; the associated systems and networks that schedule optimization has to keep pace with the innovations to deliver synergistic benefits from the technological advances.

5.3.7. Informatics for Laser- and Photonics-Based Processing

Informatics, including automated extraction, processing, and utilization of information from different measurements and sensor systems and networks, is viewed as the next frontier in advancing the time-series understanding and prediction of the states of complex dynamic systems.

Applications of informatics are emerging in nonmanufacturing and other laser-based processes. In recent years, new lines of products with at least one dimension in the nanometer range have been developed. They include new generations of semiconductor chips, air purifiers that trap a variety of dangerous chemicals in the air, high-performance lithium-ion and nanotitanate batteries, microchannel heat exchangers for refrigerators and automobile radiators, paint and coating treatments to enhance durability and surface properties, as well as advanced light emitting diodes (LED) and electroluminescent displays. Such material structures and products are considered vital for niche applications in a broad spectrum of industries, including automotive, aerospace, defense, biomedical, and security sectors. Earlier reports from governmental and private organizations project the market for such products to grow beyond $1 trillion in the next 10 years.

Technologies used for fabricating nanoscale components and structures are collectively termed "nanomanufacturing" (NM) processes. These novel technologies offer opportunities for developing material structures, such as tubes, films, powders, large (macro) molecules, and multimaterial honeycombs, and porous solids with unprecedented combinations of physical, chemical, and mechanical properties. Lasers have emerged as a primary energy source for material/phase transformation, removal, or addition in manufacturing and material processing, as well as in bioprocessing and other application areas (Taniguchi, 1983). Their unique advantage is the ability to realize atomic-scale precisions and nanometric-scale features in various macromolecular structures and a variety of nanostructures (Bukkapatnam, Kamarthi, Huang, Zeid, & Komanduri, 2012). For example, pulsed laser deposition with subsequent surface treatment of catalyst films forms a critical step in the process discussed below to grow dense, vertically aligned carbon nanotubes (CNTs). Besides serving as the energy source, lasers have also been employed for in situ monitoring of nanoprocessing. In particular, optical systems typically based on splitting the primary laser beam have been attempted for in situ measurement of nanostructure geometries in laser-based nanofabrication processes (Li et al., 2011). Together with signals from the sensors of the process variables (e.g., temperature, chamber pressure, flow rates), these in situ measurements can usher real-time monitoring and control of NM processes.

As these technologies begin to mature, the system issues necessary to translate them into technologically and economically viable industrial processes have become necessary. Quality considerations are becoming critical too. For instance, in microelectronics fabrication, device features are decreasing to sub-20-nm regimes, associated with an increase in the number of levels and layers processed. Process control for assurance of planarity of patterned thin films of interconnects and interlayer dielectrics on a silicon wafer are becoming important for improving wafer yield and advancing device densities.

Advanced nanoscale processes, many of which use lasers as energy sources for material transformation, are becoming data intensive. Incorporation of informatics (e.g., Bukkapatnam et al., 2012) is anticipated to improve process and system control, increase productivity, and speed up innovation (C. Cheng, Bukkapatnam, Raff, Hagan, & Komanduri, 2012; Huang, 2011; Park et al., 2012). Unlike conventional manufacturing systems, nanomanufacturing systems exhibit complex dynamics due to the inherent nonlinear and nonstationary characteristics of the synthesis processes. Hence, time-series informatics provides a means to their modeling, simulation, and control through accurate state prediction, model identification, structure reference, and parameter estimation.

A case study is used to illustrate the application of time-series informatics in modeling and control of CNT synthesis process. CNTs are one of the promising nanostructure materials considered for various solutions. Efforts have been made to optimize the chemical vapor deposition (CVD) and other processes used for CNT synthesis; yet, current production and yield rates remain too low for wider applications. Time-series informatics-based fast and computationally efficient atomistic Monte Carlo simulation was developed to study and predict the carbon nanotube synthesis mechanism in CVD (Bukkapatnam & Cheng, 2010; C. Cheng, Bukkapatnam, Raff, & Komanduri, 2012). Among the predictive models, recurrence-based local Gaussian process (LGP) models were found advantageous in terms of prediction accuracy and computational speed (Figure 13a). The LGP can capture the drifts and variations in the CNT growth increment with high prediction accuracy. The results indicated that it can save more than 70% of the simulation time for the conventional atomistic simulation, which led to one of the longest CNTs (∼194 nm) from atomistic simulations.

Such speeded-up simulations can be used for CNT in situ length control over a larger length and timescales than were possible earlier. The utility function plot at different synthesis process steps to realize CNTs of length 90 nm is shown in Figure 13b. The red (light) curve shows the variation of the utility over time (addition steps) as one decides to continue synthesis, and the blue (dark) curve captures the variation of utility when the synthesis process is stopped at different times. When the two curves intersect, it is the recommended end point for realizing desired CNT length. Numerical studies indicate that CNTs generated through such time-series informatics–based procedure are within the 1 nm variation of the specifications. Thus, time-series informatics can be useful for advance simulation, monitoring, and control of plausibly laser-based, nanoprocesses.

6. CONCLUSION: IMPLICATION TO EDUCATION AND RESEARCH AGENDA, PRIORITIES, AND GLOBAL POLICY

6.1. Education Implications

While laser technology has already had a tremendous impact in certain areas of manufacturing, healthcare, and telecommunications, many other promising applications are still in the early stages. The ultimate impact for those cases is difficult to predict. The impact will certainly emerge, but how rapidly it does will greatly depend on acceptance. In the United States, this rate will be paced by the education of future industrial, systems, and manufacturing engineers and engineers in general. Clearly, the rate of impact in the United States and globally will be a function of education. Europe, especially Germany, is leading globally in the use of laser technology in manufacturing and has set the bar high for others to reach. It is important to examine current educational programs in engineering and technology in the United States. The manufacturing program needs to be modified to change the traditional images of manufacturing lines, such as dingy, dirty, and dangerous. Manufacturing engineering programs should be revitalized if these images are to be realigned to increase the number of high-quality students. To do this, advanced manufacturing techniques, such as laser-based manufacturing, should be included in undergraduate and graduate curricula. The complex nature of manufacturing engineering requires highly talented students, who like to design new products, are well rounded, have solid analytical skills, and theoretical background to optimize process and design and able to make correct decisions on manufacturing processes and systems.

Traditionally, industrial and systems engineering students learn tools and techniques to analyze and optimize manufacturing and service systems. The integration of laser and photonic technology into such systems will be accompanied with new and revised system and network models, and those models have to be introduced in engineering courses so that students can be provided with new insights into the emerging technology. Students will also have to be more knowledgeable and better prepared for addressing the impact of these technologies on industry and more broadly on society.

The related objectives for the industrial and systems engineering professionals are

1. To capitalize on promising new technology developments;
2. To reach out to other engineering and scientific disciplines; and
3. To bring a systems perspective to leverage new technologies, such as the integration of laser and photonic systems. The curricula will need to adapt at both the undergraduate and graduate levels. These adaptations are typically encouraged by ABET Inc., the Accreditation Board for Engineering & Technology, as helping fulfill its required engineering student outcomes as follows:
    1. An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
    2. An ability to function on multidisciplinary teams; and
    3. An ability to identify, to formulate, and to solve engineering problems.

Before establishing expectations on students and researchers in developing and integrating laser and photonic systems, they must first be educated in systems integration and then acquire domain knowledge (in laser and photonics) to be able to contribute effectively to a multidisciplinary team. Systems integration and systems development is currently an explicit emphasis in most industrial engineering department curricula. However, to acquire domain knowledge in laser and photonics, some fundamental nontraditional coursework is necessary. This may include courses such as:

- Fundamental of Lasers (can be offered at the undergraduate level)
- Laser Theory and Design
- Laser Applications and Advanced Optics
- Modern Optics Lab (Basic and Advanced)
- Photonics (Basic and Advanced)
- Photonics and Microelectronics

These course examples do not necessarily represent new course offerings for academic institutions since they are typically part of existing coursework for students in physics or electrical and computer engineering, depending on the focus of these departments. Further, most industrial engineering programs allow some flexibility (typically in the form of four to six technical electives as part of their curricular requirement). It can therefore be seen that, for industrial engineers to participate actively in the integration of lasers and photonics systems, some adaptations to existing curricula are necessary, but these can be built into existing curriculum requirements with relatively minor additional effort.

6.2. Advances in Research and Development

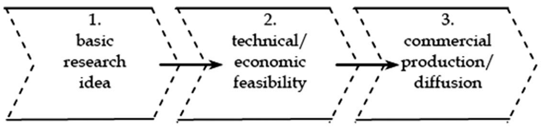
Systems, networks, and integration are important for the healthy growth of laser and photonic systems beyond local application impacts. Future advancement in laser and photonic systems integration will focus on the following priorities:

1. Designing and developing collaboration and communication protocols to enable seamless, service-centric collaboration among a network of entities, including research, education, service and industry participants;
2. Establishing open manufacturing, healthcare, and service environments that facilitate sustainable development and application of all processes, including laser- and photonics-based manufacturing, processing and services;
3. Enhancing virtual design for manufacturing, medical, and other services to further shorten development time and provide access to distributed laser and photonic systems;
4. Enabling human-in-the-loop control through human-centered design of laser and photonic systems, new concepts of interactive work-cells for operators, and streamlined organization structure and workflow;
5. Modeling and optimizing laser technology and photonic systems and their potential for improving quality, effectiveness, efficiency, and robustness in implementation and integration;
6. Providing digital service and digital manufacturing to integrate and optimize finite global resources and meet the increasing demand for laser technology and photonic systems without the limit of time and space; and
7. Promoting policies that balance scientific exploration and discovery, technology advancement, service sustainability, and economic considerations.

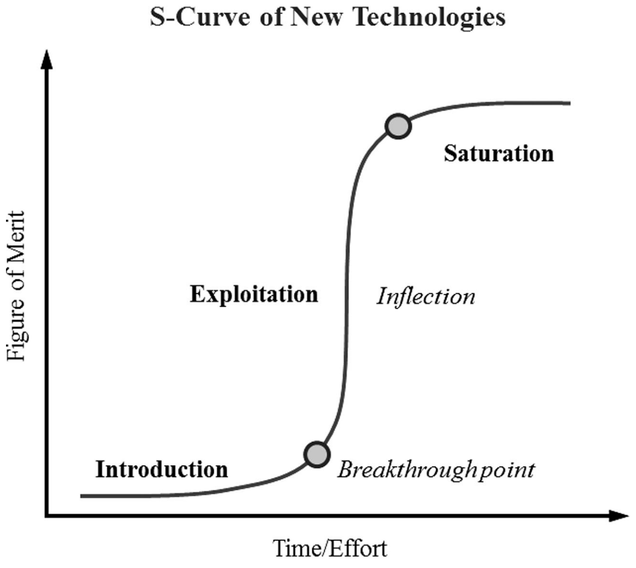
The majority of the current and emerging research advancements in laser- and photonic-based processes for traditional and nanoscales have focused on the synthesis and processing techniques for building structures and delivering outcomes of varying complexities. So far, few efforts have attempted to integrate these processes with interface and networking approaches addressing interaction, collaboration, and nanoinformatics for modeling and control purposes. There has been, however, a noticeable growth in the development and deployment of in situ sensing methods to gather information spread over multiple scales of nanomanufacturing and other nanoscale processes (e.g., National Science Foundation report; Morse et al., 2009). It is anticipated that such developments in and deployment of the sensing methods would be precursors to the advancements in nanoinformatics methods for in situ process and quality control. In conjunction, the development of associated advanced statistical models and interaction protocols, and the integration of engineering knowledge will become part of the future, largely laser-, photonics-, and energy-based nanosystems, where closer, ultrafast sensing and decision making are applied closer to the process.

6.3. New Paradigms for Policy Making

Government funding and public policy in general will play a critical role in helping accelerate the research



a. Sequence of Innovation (following Ford *et al.,* 2007)



b. New Technology Adoption Process

Figure 14 a) Sequence of innovation development. b) New technology adoption process.

on laser and photonic systems and realize their societal benefits, as it is well known that the private sector has less incentive for R&D than welfare-maximizing social planners (Tirole, 1988). With a multitude of uncertainties and risks faced by policy makers, a new policy-making paradigm is needed to meet the grand challenges. Such a paradigm should include the following characteristics.

6.3.1. Dynamic Innovation and Adoption Processes Require Dynamic Policies

As the innovation and adoption processes of laser and photonic systems are inherently dynamic (Figure 14), a static or a onetime policy cannot serve well to promote the research and deployment. A dynamic policy should contain at least two aspects. The first is that specific policies need to target a specific stage of the innovation or adoption stage. For example, to overcome the well-known “valley of death” that bridges the basic research and full commercialization of a technology, funding policies that encourage public–private sector partnerships, such as a university research center with industrial members and supporters, are likely to be more effective than a single-sector targeted policy. The second aspect is that a complete policy needs to cover the entire process of innovation and adoption. To accelerate the diffusion of a new technology, for instance, a onetime subsidy for early adopters may not be as effective as an adaptive policy that fades out gradually, depending on the saturation rate of the new technology.

6.3.2. System Issues Require a System Approach for Policy Making

One of the emerging application areas of lasers is manufacturing solar energy devices. Such innovation holds great potential in lowering solar cells’ costs and promoting broader adoption of the renewable technology for electricity generation. However, as demand is the ultimate driver for any technology adoption, energy-system-wide analyses are warranted for any public policy in directly funding solar technology. The focus of such analyses should be to determine long-term market competitiveness, subject to both demand and market uncertainties.

6.3.3. Public Goods Require Public Policy to Account for Externalities

Advancements in laser and photonic systems, presented earlier in this article, can bring substantial benefits to society through their real-world applications. Some of the benefits, however, are in the form of positive externality; that is, while all society benefits from the advent of a new technology, such benefits are not included in the compensation to the entity responsible for making such technology available. Renewable technologies, including solar energy devices, all exhibit positive externality, as by replacing fossil fuel power plants, such technologies reduce air pollution, which has positive health benefits to people. Laser and photonic systems also play an important role in smart grid, which is the vision of the next-generation electricity grid characterized by its integration of electrical, communication, and information networks. Optical current and voltage sensors, and fiber-optical-based transformers and converters, all outperform current technologies. They can be at the backbone of the smart grid that will make the electricity grid more reliable and resilient to natural and man-made disasters. A good policy should design mechanisms to quantify such societal benefits and reward the entities that are responsible. To achieve such societal benefits, a system approach, as outlined above, is also needed to actually account for system-wide welfare gain.

APPENDIX

Basic Terminology

A1. Optics

The science and technology of the generation, transmission, and propagation of light, mainly pertaining to imaging and vision. Scientific work in optics began in the seventeenth century.

A2. Photonics

The science, engineering and technology of light (its basic unit is the photon).

Photonics and electronics join in optoelectronic integrated circuits. Photonics application examples: data storage (e.g., optical disks and holograms), data transmission via fiber optics, optical switches and light modulators for signal processing and for communication, photonic gyroscopes in commercial aircraft that have no moving parts. Photonics covers applications of light over the entire spectrum (from ultraviolet through visible to the near-, mid- and far-infrared). Most applications have been in the range of visible and near-infrared light. Photonics as a field began with the invention of the laser in 1960, and the term "photonics" emerged after practical semiconductor light emitters were invented in the early 1960s and optical fibers were developed in the 1970s.

A3. Laser

Light amplification by stimulated emission of radiation. A device generating and transmitting such visible and invisible radiation (light). It is a key technology within photonics, first demonstrated in 1960.

Laser beams: Light beams propagating mostly in one given direction in free space.

Laser marking: Methods for labeling materials with lasers.

Laser mirrors: High-precision mirrors used in laser resonators and various optical setups.

Laser pointers: Appliances using laser beams for pointing at objects.

Laser resonators: Optical resonators designed as basic building blocks of lasers.

Laser safety: Safety of those who use laser devices.

Optical data transmission: Transmission of information using light, for example, via optical fibers.

Optical fiber communications: Technology for information transmission via optical fibers.

Optical filters: Devices designed with a wavelength-dependent transmission or reflectivity.

Optical metrology: Measurements with light.

Optical modulators: Devices enabling manipulation of light beam properties, for example, the beam optical power or phase.

Optoelectronics: Interaction of electronic devices with light, also known as electro-optics.

Output couplers: Partially transparent laser mirrors, designed to extract output beams from laser resonators.

Optical resonators: Optical components designed and arranged to enable a beam of light to circulate.

Optical tweezers: Techniques for capturing, holding, and moving particles with laser beams.

Photons: Quanta of light energy.

Photonic integrated circuits: Integrated circuits with optical functions.

Photonic metamaterials: Materials with nanostructure that have special optical properties.

Power over fiber: Power delivery to electronic devices by light through an optical fiber.

Pulsed laser: Laser-emitting light in the form of pulses (flashes of light).

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Endnotes

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2. Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.