Nanotechnology for the Optical Network

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Abstract

Instead of maximizing information rate alone, future optical communications will need to be simultaneously sensitive and responsive to the competing needs of many users. Optical switches will route beams of light from different points of origin into the many different fibers, amplifiers, and nodes of the network. A smart and sophisticated strategy is needed to bring order and reliability to this potentially chaotic environment. Nanotechnology may, through new functions, offer the path to harmony. It may add new dimensions and directions to the progress of networking using light. It harnesses new and fundamental physics, chemistry, and engineering to enable not just higher speeds, but new capabilities. This nanoscale science could exploit the ways in which matter organizes into regular shapes and structures to integrate many such functions onto a single chip. The diverse functional possibilities of engineering on the nanoscale may deliver a new agility to the optical network.

I summarize the results of our recent investigations of function-property relationships in multi-quantum well semiconductor lasers as explored through novel electronic scanning probe microscopy techniques. I present our picture of photonic heterostructures, combinations of photonic crystals designed to act upon optical signals in the temporal, spectral, and intensity domains. I finish with a perspective on the potential of nanotechnology in the agile optical network.

Sommaire

En plus de maximiser le débit de transmission de l'information, les communications optiques devront aussi à l'avenir être conscientes de la présence d'une multitude d'utilisateurs concurrents et réagir à leurs besoins. Des commutateurs optiques conduiront des faisceaux lumineux partant de différents endroits à travers les nombreuses fibres, amplificateurs et noeuds du réseau. Une stratégie adroite et sophistiquée est requise pour mettre en ordre cet environnement potentiellement chaotique et pour assurer sa fiabilité.

Les nanotechnologies peuvent, par les nouvelles fonctions qu'elles permettent, apporter au réseau une nouvelle harmonie. Elles ajouteront de nouvelles dimensions et directions à l'évolution de la gestion de réseau par la lumière. Elles exploitent de nouveaux principes fondamentaux en physique, en chimie et en ingénierie pour permettre non seulement des vitesses plus élevées, mais aussi de nouvelles aptitudes. Cette science à l'échelle du nanomètre peut exploiter la façon dont la matière s'organise en formes et en structures régulières pour intégrer plusieurs de ces fonctions sur une seule puce. La fonctionalité diverse possible à l'échelle du nanomètre pourra donner au réseau optique une agilité sans égale.

Je résumerai les résultats de nos récentes études sur les rapports fonction-propriété dans les lasers à semi-conducteurs avec puits multiquantiques, obtenus grace à de nouvelles techniques de microscopie à sonde électronique de balayage (electronic scanning probe microscopy). Je présenterai notre vision d'hétérostructures photoniques, combinaisons de cristaux photoniques conçues pour agir sur les signaux optiques dans les domaines temporel, spectral et d'intensité. Je terminerai en offrant notre perspective sur le potentiel des nanotechnologies dans les réseaux optiques agiles.

1.0 Introduction

Fiber-optic communications systems (Figure 1), which transmit vast quantities of information over a thin strand of glass, advanced telecommunications dramatically from the 1970's to the present time.

The enabling technologies and architectures of the decade to come have the potential to revolutionize the optical network. Instead of maximizing one parameter - speed - future optical communications systems will need to be simultaneously sensitive and responsive to the competing needs of many users. Optical switches will route information-bearing beams of light from different points of origin into the many different fibers, amplifiers, and nodes of the network. We call these proposed networks agile optical networks - their dynamism is achieved within the optical domain, rather than through electronic switches and routers.

A smart and sophisticated strategy is needed to bring order and reliability to this potentially chaotic environment. Nanotechnology may, through new functions, offer one important path.

For the past ten years, the number of bits of information which can be communicated over a fiber-optic link per unit time - its transmission capacity - has grown at an astonishing rate.

Nanotechnology adds new dimensions and directions to the progress of networking using light. It uses engineering to harness physics and chemistry to enable not just higher speeds, but new capabilities. This nanoscale science could exploit the ways in which matter organizes into regular shapes and structures to integrate many such functions onto a single chip. The diverse functional possibilities of engineering on the nanoscale may help to deliver a new agility to the optical network.

2.0 Physics into novel function

2.1 Linking electrons and photons

Nanotechnology has the capacity to probe the structure and composition of atoms, molecules, and materials. Scientists are now investigating the function of matter and its constituents.

The prospective power of functional imaging in nanotechnology is brought out by a comparison with a breakthrough area in medical research. Functional magnetic resonance imaging (fMRI) allows researchers to follow and localize subtle internal metabolic changes as they occur in response to external stimuli. Structure-function relationships may be traced out and the workings of the brain progressively uncovered.

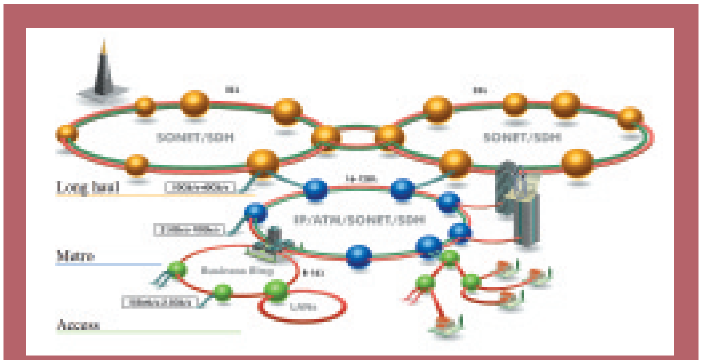

Figure 1: An image of the evolution of the optical network. The reach of the network is extending its reach from long-distance communications toward metropolitan- and local-area networks. Increased dynamism is needed in connecting disparate points in the network as network usage changes in time.

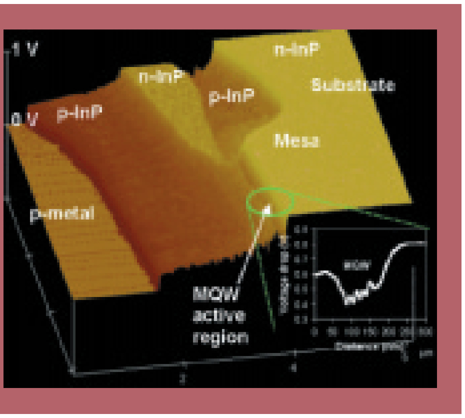

Figure 2: Electrical potential image of a laser while it is producing light. The profile shows the forces which electrons experience in traversing the laser active region

Our research group has recently used a nano-sized probe to study the potential and flow of electrons in a laser emitting an intense beam of light. We have observed - with nanometer resolution - the detailed flow of electrons to and from the laser's active region, and have witnessed how healthy lasers successfully concentrate electron flow into the active region, while electrons bypass the region in unhealthy lasers (Figure 2). Our team uncovered blockages to electron flow and has traced their origins to the early stages of laser crystal growth.

The work illuminates the inner workings of lasers whose performance is critical in building better networks. Fiber-optic communications systems, connecting buildings within a metropolitan area, demand lasers which convert electrons efficiently and rapidly into photons. With the aid of functional imaging of lasers, we can now diagnose and treat impediments to the efficient production of light.

Researchers are turning physics into novel function on many other fronts as well. One research thrust involves the controlled merging of electronic and photonic materials. Materials that control the quantum behavior of electrons must confine these particles to a few nanometers. Quantum dots, or boxes, do just this, since they have dimensions in the dozens of atoms.

In order to control the flow of photons, light must be confined to sizes more on the scale of a micrometer, or one millionth of a meter. Photonic crystals, tiny lattice-like structures that may be able to manipulate light waves just as semiconductors manipulate electrical current, are the prototype for such optical control.

Through a combination of new theory and experiments, our group recently combined engineering on both the electron and photon length scales. Collaborating with the University of Toronto's Dr. Eugenia Kumacheva and her research group, we have grown nanometer-sized quantum dots on the surfaces of micron-sized polymer spheres, and have induced the spheres to organize into regular arrays. Recent developments predict that these structures can enable functions urgently needed in the optical network - in particular, switches which automatically limit the power on an optical signal to a safe level, and which can restore and recalibrate optical pulses that have traveled over different distances. A dynamic optical network urgently requires components which can stabilize the network and groom the optical signals which it conveys.

3.0 Chemistry for integration:

3.1 Planting the seeds to orchestrate growth

The agile optical network needs not only new and complex functions. It needs to combine the monitoring and control of many disparate optical signals onto a convenient platform. Optical integration, wherein many different devices and their associated functions are conveniently combined on a planar substrate, could do for agile optical networks what the electronic integrated circuit did for computing: it could create the foundations of a technology which grows in performance and decreases in cost.

Photonic crystals could be a platform technology for optics just as crystals of silicon are at the foundation of electronic integrated circuits. The crystals allow scientists to control the flow of light. While researchers have been successful in creating a stable photonic crystal, they need to be able to control its placement, order, and configuration on the surface of materials.

Our group recently showed that we could specify how photonic crystals grow on a glass or silicon substrate, determining the pattern of crystal growth or its absence (Figure 3). We also discovered that the shape and size of the openings in their templates governed the properties of the crystals - whether they organized themselves according to square or hexagonal symmetries. These symmetries determine which wavelengths of light will be trapped and which ones will flow inside photonic crystals. Controlling this flow is the basis for developing a successful photonic circuit.

4.0 Science-Technology Convergence:

4.1 Chemistry and Physics for Information Technology and Medicine

Nanotechnology can do much more than enable a dynamic optical network. It creates an abundance of connections between biological and physical sciences and engineering. Living organisms are a triumph of the genesis of complex macroscopic structure and function out of nano-sized genetic material. Optical networks engineers have much to learn from the genius of the biological world in creating robust complex function out of nanoscopic building blocks. At the same time, they have much to give: with healthcare costs and expectations rising rapidly, integrated advances in information and medical technology offer a solution to enhancing quality of life in a world with finite resources. Nanotechnology may play an important enabling role - from the bottom up.

5.0 Further Reading

[1]. Reprints of the research papers discussed herein: http://light.utoronto.ca/reprints

[2]. U.S. National Nanotechnology Initiative http://nano.gov/nsetrpts.htm

[3]. Nanotechnology: National Consultation on the Nanotechnology Industry in Canada - within Canada's Innovation Strategy http://www.innovationstrategy.gc.ca/cmb/innovation.nsf/SectorReports/Nanotechnology

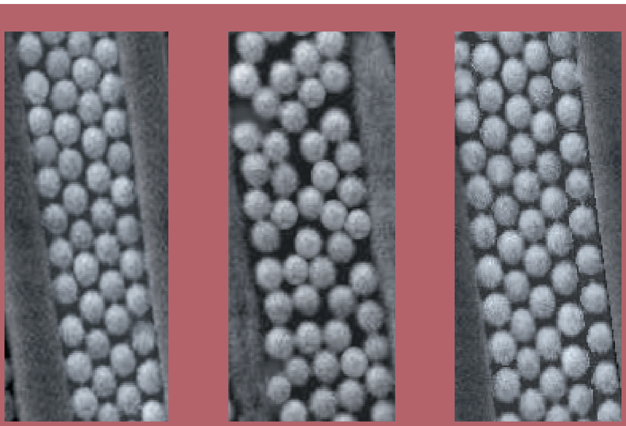

Figure 3: Bottom-up self-organized spheres whose placement and order are programmed by top-down templating.

About the author

Ted Sargent holds the Nortel Networks - Canada Research Chair in Emerging Technologies at the University of Toronto. In 2002, the Canadian Institute for Advanced Research named Prof. Sargent one of the nation's top twenty researchers under age forty across the natural sciences, engineering, and the social sciences. In 2002, he won the IEEE Canada Outstanding Engineer Award for "for ground breaking research in applying new phenomena and materials from nanotechnology towards transforming fibre-optic communications systems into agile optical networks."