Multifunctional Photonic Integration for the Agile Optical Internet

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ABSTRACT

An agile, transparent optical network is emerging. This paper enumerates the functions that will be needed at nodes in order to add transparency and agility to the network while robustly assuring optical fibre channel performance. One key requirement will be scalable integration of multiple functions on a platform. The paper presents recent results along one strategic axis for integration – the use of functionalized self-organized photonic crystals and heterostructures thereof to control the flow and features of light.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Enabling technologies.

General Terms

Experimentation, Theory.

Keywords

Agile optical networks, reconfigurability, optical performance monitoring, optoelectronic integration, photonic crystals, optical nonlinearity, electro-optics, optical polymers, semiconductor nanocrystals.

1. STATE OF THE OPTICAL NETWORK

Fibre-optics has made available tremendous bandwidth for long-distance, high-speed communications. Increasingly, fibre-optics is making its way toward the network edge, with significant commercial activity in metropolitan-area networks and a reemergence of interest in access and local-area optical networking.

Bandwidth breakthroughs – exponentially-growing time-domain rates and dense wavelength-division multiplexing – engender new bottlenecks. An electronic implementation of a switch so massive as to enable grooming and routing of the information contents of multiple fibres, each conveying terabits of data per second, would be onerous. Some degree of data forwarding may in the future be executed in the optical domain.

2. CHALLENGE: ENABLING THE AGILE OPTICAL NETWORK

In the emerging agile optical network, much of the traffic not originating at or being consumed by a given node will pass through, largely untouched, in the optical domain.

Agility is needed in this network as traffic patterns evolve and new nodes are added. The ability to establish new lightpaths – optically transparent links across multiple physical nodes to an intended destination – is in part enabled by the introduction of optical switches which can route optical signals to different spatial ports. Combined with wavelength-domain multiplexers and demultiplexers, these allow switching of different wavelength-domain channels among fibres. Some degree of wavelength conversion may be used to resolve conflicts in wavelength use in a given fibre. Optical switches are reaching maturity and seeing commercial deployment; reconfigurable wavelength conversion is farther from being a widespread practical reality.

These building-blocks of optical switching – cost-reduced multiplexers and demultiplexers, reliable large-port-count 3-D MEMS switches, and wavelength converters – introduce a new set of challenges. Optical transparency along a diversity of paths of time-varying lengths, losses, dispersions, and accumulated nonlinearities implies a need to groom signals dynamically along multiple performance axes. Some components – optical amplifiers are one example – may introduce interchannel interactions following reconfiguration events.

Switching may not be executed without awareness of and sensitivity to its implications on channels sharing a link.

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3. NEED: INTELLIGENT OPTICAL SWITCHING NODES

In addition to raw switching, mux/demux, and wavelength conversion capabilities, the agile optical network requires nodes which combine and interconnect a multiplicity of further functions, among them:

- power monitoring and adjustment
- chromatic dispersion monitoring and compensation
- polarization mode dispersion monitoring and compensation
- channel add/drop which is adiabatic on the scale of fibre amplifier response times
- optoelectronic transmit/receive
- control plane interface, logic, and protocol implementation.

At the level of more basic optical and electronic functionalities, these may entail, across a prospectively broad spectral range:

- photodetection and time-domain gating
- light emission
- optical amplification and attenuation
- modulation of refractive index
- low-loss waveguiding
- electronic transistor action
- microwave-frequency guiding.

4. ENGINEERING A SEMICONDUCTOR FOR LIGHT

In some, though admittedly not all, respects, what is needed is a semiconductor for light.

Semiconductors provide a versatile foundation for electronics. Electronic Bloch waves propagate or ar forbidden in a periodic crystal. Energy-momentum dispersion relations for electrons in periodic media give rise to bandgaps, and in turn to the possibility of carrier confinement and anticonfinement through heterostructures. Bandgaps – regions of forbidden energy – give leverage to small levels of impurities in influencing the type and extent of conductivity in donor-rich (n-type) and acceptor-rich (p-type) materials.

Photonic crystals are three-dimensionally periodic materials which may potentially be used to enhance control over the flow of light. Increasingly well-ordered photonic crystals have been demonstrated in recent years. However, a high degree of ordering is a necessary but not a sufficient condition to control the flow of light. Also needed is a means of placing and shaping the photonic crystals to build mesoscopic devices and connect them together.

Colloidal crystals – arrays of spherical particles – provide a self-organizing basis for the realization of photonic crystals, analogous to atomic crystal growth techniques. Polymer spheres are synthesized to have a diameter similar to the period of lightwaves. These materials may be tailored to resonate with certain colours of light, including the wavelengths used in fibre-optic communications systems.

Recently, successful growth of colloidal crystals on textured substrates has been reported to result in long-range ordering in photonic crystals [1]. Holography was used to pattern a photosensitive polymer covering a conductive substrate in order to produce conductive and dielectric features on the surface.

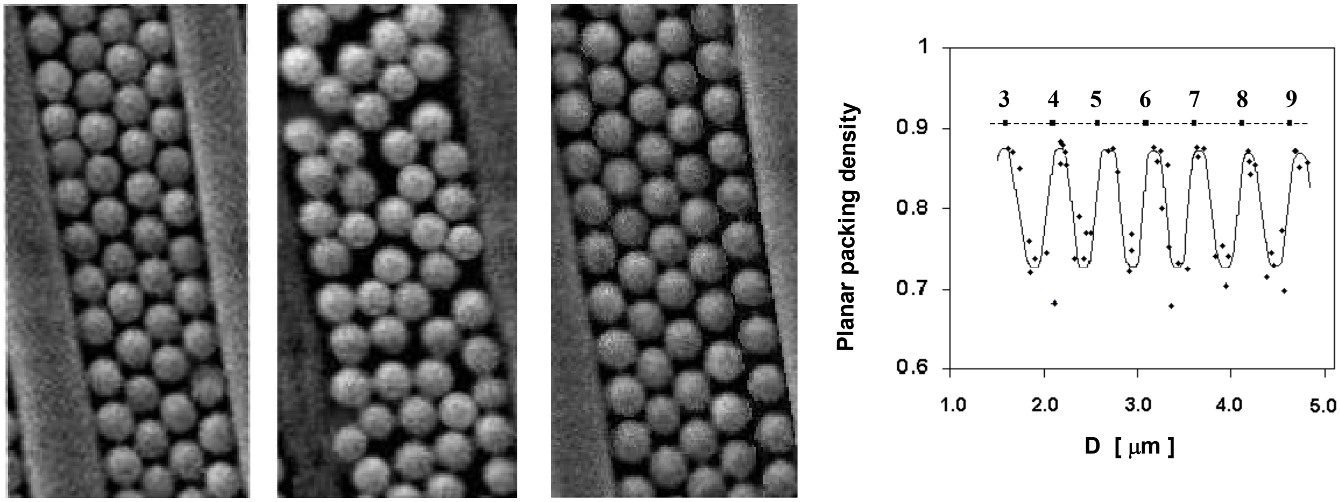

Figure 1. Colloid deposited on mesoscopically patterned substrate. *Left:* From left to right, the width of the groove are 2.22, 2.51 and 2.22 μm The particle diameter is 0.58 μm. *Right:* Planar packing density as a function of the groove width.

Charged colloid particles were deposited on the substrate by electrophoresis. The particles assembled only on in the conductive areas of the substrate.

The work makes possible precise control over sphere placement and ordering in the crystal through the use of a suitable pattern.

In the absence of any surface pattern, the colloid particles assembled in a random close-packed fashion. However, when grooves were used which were sufficiently large to accommodate several spheres, the presence of a surface pattern induced a hexagonal ordered packing of the particles in the grooves. This occurred only when the groove width corresponded to the width of an integer number of rows of spheres. When this condition was not met, the arrangement of the spheres was not periodic, and the planar packing density decreased below the maximum theoretical value of 0.907, as shown in Fig. 1(b).

The use of narrower grooves designed to accommodate a single sphere in each groove was also demonstrated. Figure 2 shows different packing scheme, square and hexagonal, observed on the same sample where the ratio of the grating period to the sphere diameter is approximately 0.81, between the theoretical values for the square packing arrangement, 0.707, and the hexagonal close-packed arrangement, 0.866

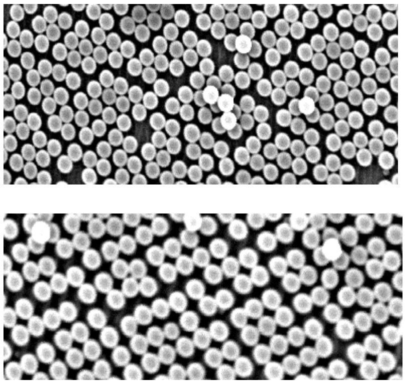

Figure 2 Colloid deposited on microscopically patterned substrate, where the period of the grating is approximately 0.81 sphere diameter. From top to bottom: the grating before colloid deposition, hexagonal packing and square packing.

Thus, photonic crystals can be placed where they are needed and surrounded by a variety of different polymers and glass materials as required. Not only can the degree of order now be controlled, but also the nature of photonic crystal packing – hexagonal versus square, for example. The nature of the photonic crystal lattice determines how waves of light interact with the photonic crystal.

To complement experimental progress/progress in fabrication, a set of tractable design principles and methodologies is needed. In semiconductors, this is available through spatial band diagrams. The energy-momentum bandstructure is captured through a small number of parameters, such as band edge positions, effective masses, the energetic structure seen by charge carriers in devices. In semiconductor heterostructures, band offsets provide an additional degree of freedom in guiding, manipulating, and confining charge carriers.

The analogous picture is rapidly emerging in the photonic case. An envelope approximation formalism was recently developed for 3-D photonic crystal heterostructures [3, 4]. It requires knowledge only of the bulk bandstructure and heterostructure design. The method is mathematically analogous, but distinct from, the envelope formalism widely deployed throughout semiconductor quantum electronic engineering. The method has been applied to photonic crystal waveguides (Figs. 3 and 4), predicting within 1% accuracy [4] the frequencies of guided modes and providing excellent agreement in the shapes of waveguided mode shapes, compared with results from full, computationally-intensive 3D electromagnetic vectorial solution. Guided modes have been shown to be allowed for wavevectors where the curvature of a band in a direction perpendicular to the plane of the waveguide has the same sign as the refractive index contrast between the core and the cladding. Elementary waveguide theory has been shown to provide the basis for the computation of mode shapes and dispersion relations.

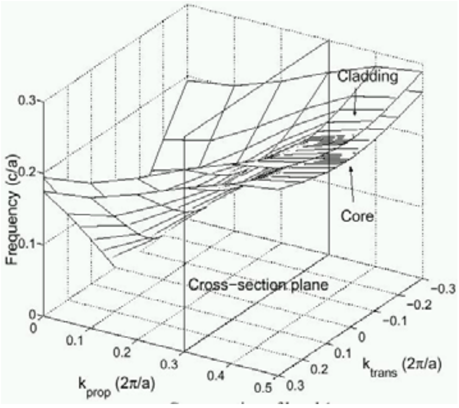

Figure 3. Photonic crystal waveguiding - confinement and modes with the envelope formalism.

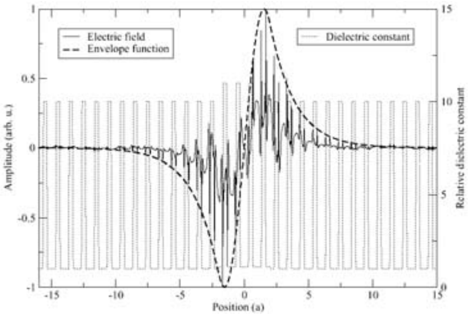

Figure 4. Odd mode of the first band through exact numerical and approximate envelope analyses.

5. CONCLUSIONS

Optoelectronic integration has been discussed and explored since the 1970's. Its time may finally have come, for the agile optical network will rely on scaling optoelectronic functions and densities far beyond what is currently available. Photonic crystals may play a role in increasing control over the flow of light, and in processing the information-bearing signals which it conveys.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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