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Photonic integration improves on current technologies

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With recent advances in materials and device concepts, integrating photonic components has the potential for strong societal impact.

Chip-scale integration has dramatically increased the performance, reflected in Moore's law, of electronic devices such as personal computers, cell phones, MP3 players, and other devices, with no significant increase in price. Less well recognized by the general public, but just as important, is the effect of electronic integration on transportation, medicine, business, and defense. In many ways, the technology has proven to be the most influential of the 20th century. In the first decade of the second millennium, the question is whether the time has come for photonic integration, and whether, together with hybrid electronic and photonic integration, it will exert the same force. This question is certainly being asked by federal advisory panels, by various industries, and by professional societies. Their interest is motivated by the emergence of silicon photonics and advances in nonlinear optical materials.

It is becoming increasingly well recognized that combining photonic components can provide size, weight, and power (SWAP) reductions together with better performance—for example, in speed and bandwidth, and reliability—analogous to electronic integration. At this point, photonic systems do not lend themselves to monolithic consolidation (as with silicon CMOS). But silicon affords many desirable photonic properties at telecommunication wavelengths.[1] Moreover, exceptional SWAP reductions and performance enhancements have recently been realized combining III-V semiconductors and organic nonlinear optical materials with silicon photonic circuitry.[2,3] Such hybrid integration, while losing some of the cost advantages of single foundry manufacture, suggests the possibility of revolutionary new technology.

Over the last decade, protocols have been developed for combining organic linear and nonlinear optical circuitry, both vertically and horizontally, with very large scale integration (VLSI) semiconductor chips.[4] This was accomplished with no degradation in the operation of either electronic or photonic

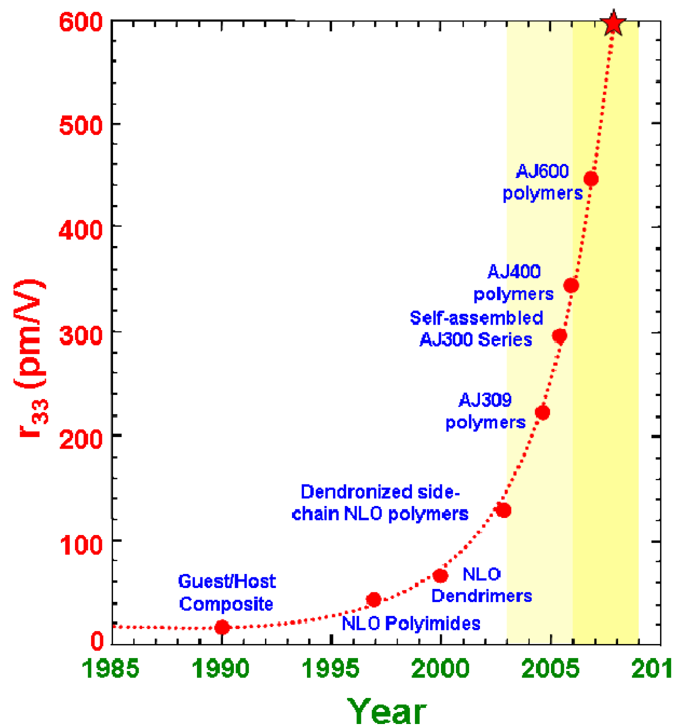

Figure 1. *The increase in electro-optic activity (r_{33}) of organic materials is shown as a function of time.[3] The 'AJ series' are binary chromophore organic glasses produced by Alex Jen and his students at the University of Washington. Shaded areas indicate the time frames of the Defense Advanced Research Projects Agency's Super Molecular Photonics (DARPA MORPH) phase I (300pm/V goal) and II (600pm/V goal) programs,[11] while the star indicates the DARPA MORPH phase II goal. The MORPH program aims at 'lossless' conversion or even gain in the electrical-optical-electrical signal transduction process. NLO: Nonlinear optical. pm: Picometers.*

circuitry. Moreover, the production of 3D photonic circuitry,[5] clever marrying of organics with silica,[6] and production of high-density photonic circuitry by an array of processing methods, including nanoimprint lithography,[7] has also been demon-

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strated. It was, however, the advent of silicon photonics that provided the real driver for bringing electronics and photonics together. The high index and good transparency of silicon at telecommunication wavelengths tightly confined light and substantially reduced photonic circuitry to sizes compatible with high-density photonics on electronic wafers (chips). Silicon also enabled greater flexibility in circuit layouts, as light could be guided around tight bends. Nevertheless, because silicon is not yet a good light source, and its nonlinear optical properties do not provide all the needed characteristics, the hybrid approach still appears to be the most reasonable. Good progress has been made combining silicon photonic circuitry with III-V lasers,[2] fiber optics, and organic nonlinear optical materials.[3]

Integration of these last materials merits special mention, as it illustrates new concepts. First, the performance of organic electro-optic materials has shown a rate of improvement consistent with Moore's law for the last 10 years (see Figure 1). This is driven by theory-inspired design based on a quantitative understanding of intermolecular electrostatic interactions.[3] A new class of electro-optic materials, binary chromophore organic glasses, has been introduced, and new processing methods, such as laser-assisted Bessel (2D) and Ising (1D) lattice generation, have been proved.[3] Moreover, theory has been applied to design new silicon photonic device structures. For example, incorporating organic nonlinear optical materials into 60–100nm slots in silicon waveguides (see Figure 2) permits low-loss transition of light from high index of refraction silicon to the low index of refraction organic material, for active control of light by applied electrical or optical fields. The ultrafast response times of organic nonlinear optical materials (tens of femtoseconds, defined by the phase relaxation time of the π-electrons of the organic materials) allow terahertz bandwidths to be achieved when not limited by some other material in the device structure.[8,9]

The small dimensions of silicon photonic circuitry, and particularly of the organic material–containing slots, promote low-loss amplification of electrical and optical fields. This leads to nonlinear optical behavior that is better by orders of magnitude. Indeed, field concentration coupled with improvement in the optical nonlinearities of organic materials has made millivolt electro-optic modulation, microwatt optical rectification, and microwatt all-optical signal processing feasible.[8–10] Of course, the concept evident in slotted waveguides is readily extended to a variety of photonic bandgap or metamaterial periodic structures, creating practical routes to superprisms and other 'nontraditional' and negative index of refraction devices.

Note that not all problems have been solved with hybrid silicon photonic integration, and particularly not for exotic device

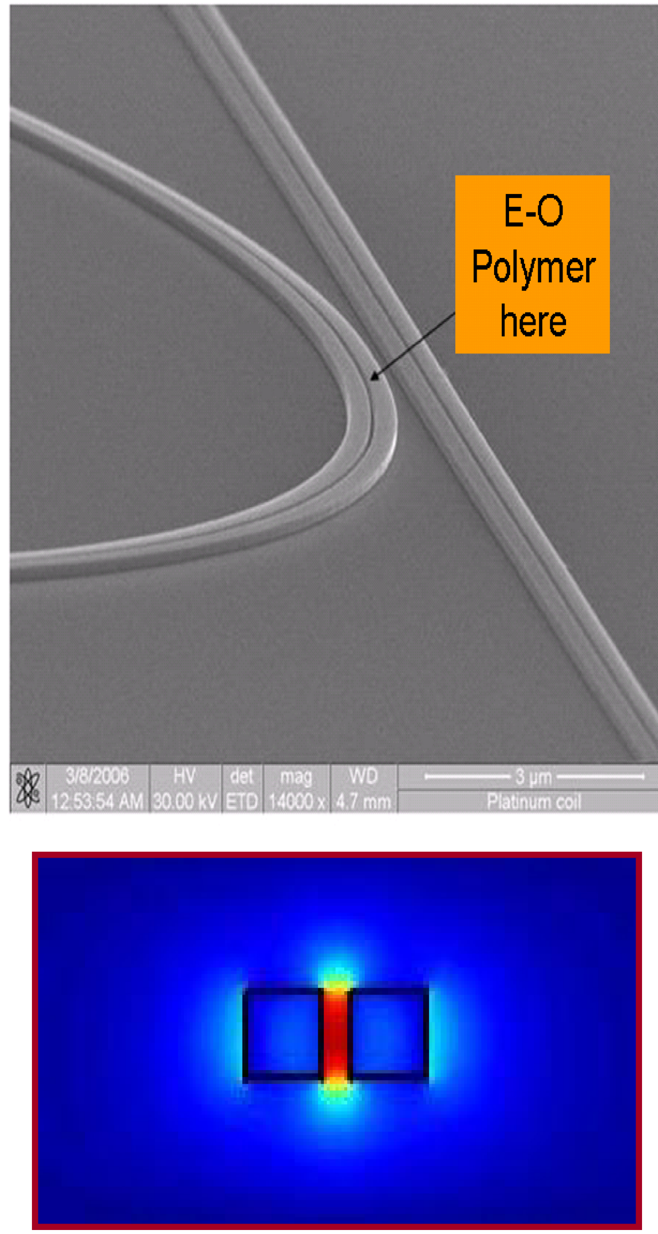

Figure 2. *(Top) A portion of a slotted waveguide silicon ring microresonator, filled with an organic electro-optic (E-O) material. (Bottom) The concentration of the optical field in the organic material–containing slot.*

structures. For example, optical loss continues to be a challenging issue. While they do not achieve the full cost advantages of monolithic consolidation, CMOS foundries can still be used to fabricate the basic silicon photonic circuitry, and an ever-

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increasing array of automated hybrid technologies suggest that cost savings, as well as SWAT and performance advantages, can be achieved.

The most obvious beneficiaries of the new chip-scale integrated photonic and electronic technologies will be telecommunication, computing, defense, and transportation sectors. However, this integration is critical in enabling embedded network sensing, providing sensor, microprocessor, telecommunication, and actuator capabilities on a single chip. Such developments have the potential for broad societal impact, ranging from environmental monitoring to controlling buildings, bridges, and the electrical power grid. A particularly intriguing area of intelligent sensing is point-of-care diagnostics, which can benefit from the compatible dimensions of laboratory-on-a-chip microfluidics and silicon microphotonic circuits. With its potential improvements in performance and SWAP reductions, photonic integration promises potential repercussions comparable to those of its very large scale electronic counterpart.

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References

1. M. Lipson, *Overcoming the limitations of microelectronics using Si nanophotonics: solving the coupling, modulation, and switching challenges*, **Nanotechnology 15**, pp. S622–627, 2004.
2. A. W. Fang, H. Park, Y. Kuo, R. Jones, O. Cohen, D. Liang, O. Raday, M. N. Sysak, M. J. Paniccia, and J. E. Bowers, *Hybrid silicon evanescent devices*, **Mater. Today 10**, pp. 28–35, 2007.
3. L. R. Dalton, P. A. Sullivan, B. C. Olbricht, D. H. Bale, J. Takayesu, S. Hammond, H. Rommel, and B. H. Robinson, *Organic photonic materials*, in **Tutorials in Complex Photonic Media**, SPIE, Bellingham, WA, 2007.
4. L. R. Dalton, A. W. Harper, A. Ren, F. Wang, G. Todorova, J. Chen, C. Zhang, and M. Lees, *Polymeric electro-optic modulators: from chromophore design to integration with semiconductor VLSI electronics and silica fiber optics*, **Ind. Eng. Chem. Res 38**, pp. 8–33, 1999.
5. S. M. Garner, V. Chuyanov, S.-S. Lee, A. Yacoubian, A. Chen, W. H. Steier, F. Wang, A. S. Ren, M. He, and L. R. Dalton, *Three dimensional integrated optics using polymers*, **IEEE J. Quantum Electron. 35**, pp. 1146–1155, 1999.
6. Y. Enami, C. T. Derose, D. Mathine, C. Loychik, C. Greenlee, R. A. Norwood, T. D. Kim, J. Luo, Y. Tian, A. K. Jen, and N. Peyghambarian, *Hybrid polymer/sol-gel waveguide modulators with exceptionally large electro-optic coefficients*, **Nat. Photon. 1**, pp. 180–185, 2007.
7. Y. Huang, G. T. Paloczi, A. Yariv, C. Zhang, and L. R. Dalton, *Fabrication and replication of polymer integrated optical devices using electron-beam lithography and soft lithography*, **J. Phys. Chem. B 108**, pp. 8606–8613, 2004.
8. T. M. Baehr-Jones, M. M. Hochberg, G. M. Wang, R. Lawson, Y. Liao, P. A. Sullivan, L. Dalton, A. K. Jen, and A. Scherer, *Optical modulation and detection in slotted silicon waveguides*, **Opt. Express 13**, pp. 5216–5226, 2005.
9. M. M. Hochberg, T. M. Baehr-Jones, G. M. Wang, J. M. Parker, K. M. Harvard, J. M. Liu, B. M. Chen, Z. M. Shi, R. M. Lawson, P. A. Sullivan, A. K. Jen, L. R. Dalton, and A. M. Scherer, *All optical modulator in silicon with terahertz bandwidth*, **Nat. Mater. 5**, pp. 703–709, 2006.
10. M. M. Hochberg, T. M. Baehr-Jones, G. M. Wang, J. Huang, P. A. Sullivan, L. R. Dalton, and A. Scherer, *Toward a millivolt optical modulator with nano-slot waveguides*, **Opt. Express 15**, pp. 8401–8410, 2007.
11. Overview page for the DARPA Super Molecular Photonics program http://www.darpa.mil/mto/programs/morph/index.html