Commercialization Analysis & Roadmap

Title: Multiple Layer Graphene Optical Modulator **Date: Nov. 16th, 2012**
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Driving Forces

According to the International Data Corporation (IDC) the total amount of digital data generated in 2020 is estimated to be over 40 times more than that created in 2009. High-energy consumption and data jams at I/O interfaces are common results of modern computers' widespread use of multicore CPUs. Optical communication is believed to be a solution to such problems. This graphene modulator technology with its low power consumption, high-speed, broad bandwidth and stability over a range of temperatures makes it a promising candidate for next generation architectures of high volume and high speed data communication/storage.

Technology

Researchers at Berkeley Lab, led by Prof. Xiang Zhang, have demonstrated a new graphene-based technology that could break the current speed limits in digital communications. Modulators play a vital role in communications due to their switching ability, because this controls the speed at which data packets travel through networks. As the speed of data pulses sent out increases, greater volumes of information can be transmitted. Graphene is the thinnest, strongest crystalline material yet known, and graphene optical modulators have significant advantages over other modulators. This technology has a compact footprint, broad operation bandwidth, fast modulation speed, low insertion loss, and is insensitive to environmental temperature flux. Optical modulators, even integrated ones, are not a new research field. Nonetheless, this breakthrough modulator is the first of its kind to include all of the advantages listed above.

Labeled the world's smallest optical modulator, the technology performs at speeds up to ten times faster than current technology allows, thereby facilitating ultrafast optical communication and computing [1]. In addition to high-speed operations, graphene-based modulators could lead to unconventional applications due to graphene's flexibility and ease of integration with different kinds of materials. Graphene can also be used to modulate new frequency ranges, such as mid-infrared light, that are widely used in molecular sensing.

Compared to traditional devices with limited bandwidth range, up to 10 nanometers, the Berkeley Lab optical modulator operates at a 1.2 GHz (at 3dB) and at a broad optical bandwidth— from 1.35mm to 1.6mm under ambient conditions. The speed for a single modulator could, theoretically, reach 500 GHz. The device has a 25 square micron footprint, offering a wide potential for integration. With such attributes, graphene-based modulators could soon allow consumers to stream full-length, high-definition, 3-D movies onto a smartphone in a matter of seconds [1].

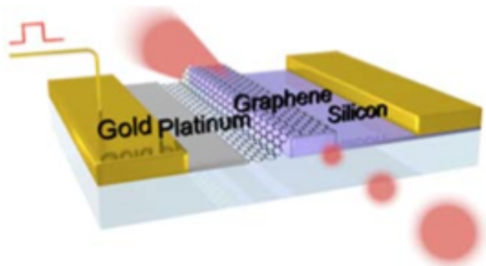

Figure 1. Schematic illustration of the Graphene-Based Optical Modulator (GBOM).

Applications

- Optical modulator for on-chip data communication

The multi layer graphene system boosts the transmission and switching speed of optical modulators - the building blocks of routers that form the backbone of the Internet. From an ExtremeTech interview, Professor Xiang Zhang put it this way: "Instead of broadband, we will have 'extremeband.'" — if graphene modulators can actually operate at 500GHz, we could soon see networks that are capable of petabit or exabit transmission speeds, rather than megabits and gigabits [2].

- Optical modulator for long-haul telecommunications

The graphene modulator would work as one the key elements in FTTX architecture. Such systems incorporate optical modulators in the last kilometer or so of the telecommunications fiber.

- Flexible modulators

The flexibility of graphene permits application on a curved surface, including the possibility of graphene or optical fibers.

- Biosensors

Lin et al. have demonstrated a DNA-Graphene optical nano-biosensor with facile design, excellent sensitivity, and improved selectivity and biostability [5]. Functionalized graphene allows high efficient DNA sorption, complementary DNA induced desorption and exceptional fluorescence quenching ability, which in turn permits advanced future biomedical applications including biosensors [5].

- Polarizers
- Mode-locked lasers
- Optical switches

Market

According to a new market research report, 'Global Silicon Photonics Market (2010 - 2015), the total global silicon photonics product market is expected to be worth US$2.02 billion by 2015, and the U.S. market will account for nearly 52.9% of the total revenues [3, 6]. The estimated five-year compound annual growth rate (CAGR) is 78.2% from 2010 to 2015 [3]. In particular, modulators are expected to have a relatively higher market share and growth rate after multiplex filters, as optical modulators form a part in the building block of complete optical circuit and are essential components for integration with telecommunications networks [3]. Xiang et al. report that the global market of optical modulators already grew with an average annual rate of 22.1% over the past 5 years.

According to a new technical market research report, the global market for graphene-based products is projected to reach $122.9 million in 2017 and $986.7 million in 2022, increasing at a five-year CAGR of 51.7% [4]. With graphene's intrinsic properties tailored for data communication applications, and the rapid market expansion opportunity for optical modulators, this technology prevails in many aspects of commercialization.

Economics

Mainstream modulators, which use nonlinear optical material (mainly LiNbO3), are sold at high prices (≥ $4K). Unlike graphene, the raw nonlinear material (LiNbO3) requires extensive fabrication processes that are not compatible with existing silicon industry infrastructure. LBL's multiple layer graphene modulator has less critical fabrication requirements and is projected to cost much less than the market dominant LiNbO3 modulators.

In addition the innovative architecture of graphene modulator does not require a light source behind each modulator – another cost effective feature of this technology. Nonetheless, although the technological superiorities of the graphene based optical modulator are unquestionable, the cost of the modulator module is approximately only 20% of transreceiver units.

Competitive Landscape

The main competition is silicon-based modulators. However, disadvantages of this technology include a large footprint and stringent fabrication tolerance. Another contender, the Mach Zehnder (MZI) modulator, requires careful control of fabrication, as the two paths/waveguides must be perfectly symmetrical, while the quantum well modulator only works at the edge of the band-gap and is very temperature dependent. LBL's graphene modulator is transparent regardless of voltage direction, and its production and maintenance costs are projected to be much lower than its rivals (including the high Q-factor cavity modulator and LED single channel modulator whose frequency shifts when switched off/on). The table below shows a comparison of LBL's graphene-based optical modulator with other state-of-the-art modulators.

Table 1 - Comparison of the LBNL graphene optical modulator with other top tier modulators

Modulation principle	Structure	Device footprint (μm^2)	Speed (Gbit s^{-1})	Modulation voltage (V)	Insertion loss (dB)	Working spectrum (nm)
Graphene modulator	WG	<25	1~100	1~4	<4	> 250
Horizontal p-n junction	MZI	~10,000	40	6.5	~7	> 20
Forward-biased diode	MZI	~1,000	10	7.6	12	–
Forward-biased p-i-n diode	Ring	~100	3	0.5	1	0.2
Reverse-biased p-n junction	Ring	~1,000	10	2	2	~ 0.1

Intellectual Property

Provisional patent application filed. Available for licensing or collaborative research

Readiness

Encouraged by preliminary results, the team is now working to improve the speed of its device to 10-100 GHz, reduce insertion loss to 3dB or less and moderate the operating voltage. In addition, future work includes the systematic integration of the prototype's performance both optically and electrically. Based on laboratory results, the graphene modulator is anticipated to be compatible with current silicon industry infrastructure.

Licensing Strategy

The following US companies are some of the main contributors to the optical modulator market:
Kotura (http://www.kotura.com)
Luxtera (http://www.luxtera.com)
IBM (http://www.ibm.com)
Lightwire (Recently acquired by Cisco in 2012 – http://www.cisco.com)
Intel (http://www.intel.com)
HP (http://www.hp.com)

Other players include:
Corning (http://www.corning.com)
Gigoptix (http://www.gigoptix.com)
Infinera (http://www.infinera.com)
Aurrion (http://www.aurrion.com)
NanoPrecision Products (http://www.nanoprecisionproducts.com)
Oclaro (http://www.oclaro.com)
Acacia (http://www.acacia-inc.com)
Ciena (http://www.ciena.com)

Next Steps

With regard to commercialization, the next steps involve optimization of the current prototype, software integration, and the systematic calibration of the prototype both optically and electrically (including electromagnetic field calculations of the system).

Companies interested in licensing this technology may contact ttd@lbl.gov or call 510-486-6457.

References

[1] http://newscenter.berkeley.edu/2011/05/08/graphene-optical-modulators-ultrafast-communications/

[2] http://www.extremetech.com/computing/84114-graphenepowered-optical-networks-could-lead-to-petabit-and-exabit-transmission-speeds

[3] http://www.electronics.ca/presscenter/articles/1429/1/Global-Silicon-Photonics-Market-Expected-to-Record-a-CAGR-Of-827-from-2009-to-2014/Page1.html

[4] http://www.electronics.ca/presscenter/articles/1870/1/Global-Market-For-Graphene-Based-Products-To-Reach-9867-Million-In-2022-/Page1.html

[5] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6144492

[6] http://www.marketsandmarkets.com/Market-Reports/silicon-photonics-116.html