

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 21-01-2008		2. REPORT TYPE Conference Proceeding Paper		3. DATES COVERED (From - To) 21 Jan 08	
4. TITLE AND SUBTITLE  Towards Silicon-based Longwave Integrated Optoelectronics (LIO)			5a. CONTRACT NUMBER IN-HOUSE		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 61102F		
6. AUTHOR(S)  Richard A. Soref			5d. PROJECT NUMBER 2305		
			5e. TASK NUMBER HC		
			5f. WORK UNIT NUMBER 01		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFRL/RVHC 80 Scott Drive Hanscom AFB, MA 01731-2909			8. PERFORMING ORGANIZATION REPORT		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Electromagnetics Technology Division Source Code: 437890 Sensors Directorate Air Force Research Laboratory 80 Scott Drive Hanscom AFB MA 01731-2909			10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVHC		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RY-HS-TP-2008-0006		
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.					
13. SUPPLEMENTARY NOTES This is a work of the U. S. Government and is not subject to copyright protection in the United States. Published in SPIE Photonics West, Invited Paper 6898-5, Silicon Photonics III, 21 January 2008. Clearance for Public Release by ESC/PA/ESC-08-0015					
14. ABSTRACT The vision of longwave silicon photonics articulated in the Journal of Optics A, vol. 8, pp 840-848, 2006 has now come into sharper focus. There is evidence that newly designed silicon-based optoelectronic circuits will operate at any wavelength within the wide 1.6 to 200 µm range. Approaches to that LWIR operation are reviewed here. A long-range goal is to manufacture LWIR OEIC chips in a silicon foundry by integrating photonics on-chip with CMOS, bipolar, or BiCMOS micro-electronics. A principal LWIR application now emerging is the sensing of chemical and biological agents with an OE laboratory-on-a-chip. Regarding on-chip IR sources, the hybrid evanescent-wave integration of III-V interband-cascade lasers and quantum-cascade lasers on silicon (or Ge/Si) waveguides is a promising technique, although an alternative all-group-IV solution is presently taking shape in the form of silicon-based Ge/SiGeSn band-to-band and inter-subband lasers. There is plenty of room for creativity in developing a complete suite of LWIR components. Materials modification, device innovation, and scaling of waveguide dimensions are needed to implement microphotonic, plasmonic and photonic-crystal LWIR devices, both active and passive. Such innovation will likely lead to significant LIO applications					
15. SUBJECT TERMS Silicon, germanium, longwave infrared, sensors, integrated photonics, waveguides					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Richard Soref
Unclassified	Unclassified	Unclassified	SAR	14	19b. TELEPHONE NUMBER (include area code) N/A

# Towards Silicon-based Longwave Integrated Optoelectronics (LIO)

Richard Soref

Air Force Research Laboratory, Sensors Directorate, AFRL/RyhC  
80 Scott Drive, Hanscom Air Force Base, MA 01731 USA  
[Richard.Soref@hanscom.af.mil](mailto:Richard.Soref@hanscom.af.mil)

## ABSTRACT

The vision of longwave silicon photonics articulated in the Journal of Optics A, vol. 8, pp 840-848, 2006 has now come into sharper focus. There is evidence that newly designed silicon-based optoelectronic circuits will operate at any wavelength within the wide 1.6 to 200  $\mu\text{m}$  range. Approaches to that LWIR operation are reviewed here. A long-range goal is to manufacture LWIR OEIC chips in a silicon foundry by integrating photonics on-chip with CMOS, bipolar, or BiCMOS micro-electronics.. A principal LWIR application now emerging is the sensing of chemical and biological agents with an OE laboratory-on-a-chip. Regarding on-chip IR sources, the hybrid evanescent-wave integration of III-V interband-cascade lasers and quantum-cascade lasers on silicon (or Ge/Si) waveguides is a promising technique, although an alternative all-group-IV solution is presently taking shape in the form of silicon-based Ge/SiGeSn band-to-band and inter-subband lasers. There is plenty of room for creativity in developing a complete suite of LWIR components. Materials modification, device innovation, and scaling of waveguide dimensions are needed to implement microphotonic, plasmonic and photonic-crystal LWIR devices, both active and passive. Such innovation will likely lead to significant LIO applications.

## 1. INTRODUCTION

Portions of the very wide infrared (IR) spectrum are usually described by the terms “near”, “mid”, “long”, “far” and “Terahertz”, but in this paper I shall adopt the shorthand “longwave” to represent all five of those regions-- because I want to discuss a new silicon-based technology that applies to the entire “near-to-Thz” range. This technology consists primarily of an active waveguided optical network on a silicon chip, a chip that can couple readily (edgewise or at normal incidence) to light beams traveling in IR fibers or in free space. There is plenty of work to be done in this new longwave area because a complete suite of on-chip components does not exist. Innovation, sometimes radical, is required to create the components and to integrate them. Optoelectronic integration on Si is a key driver of this new technology, as it is in the telecomm area. For that reason, I would like to introduce the acronym **LIO** to represent this thrust into **Longwave Integrated Optoelectronics**. This paper is organized in sections that cover background considerations, potential applications, proposed approaches, sensing signatures, component integration and suggested chip architectures.

## 2. BACKGROUND DISCUSSION

The prior LIO art consists mainly of longwave camera chips which are focal-plane imaging arrays joined with readout integrated circuits. Those LIOs couple to free space and don't use any waveguides. Although the waveguided LIOs proposed in this paper have never been constructed, there are strong reasons for creating them: (1) low cost, size, weight, and power consumption, (2) high reliability and ruggedness, (3) low optical losses and low electrical parasitics, (4) on-chip sampling of gases, liquids and bio agents, (5) complex longwave functions performed by the on-chip network, (6) adaptable sensing using intelligent electronics, (7) inexpensive Foundry integration of 2D or 3D active-and-passive longwave components, (8) silicon-foundry layered interconnection of CMOS or BiCMOS with photonics to provide the necessary drive, control and readout of the longwave network.

The 2005 vision of LIO articulated in Reference 1 has now come into sharper focus. This vision calls for a new range of platforms for chemical and biological sensing, active imaging, medical diagnostics, environmental monitoring, process control and secure communications. LIO will impact platforms presently limited by cost, size, weight, power and ruggedness. Examples of such platforms in a military context are unmanned aerial vehicles, man-portable and

ground-based systems, satellite and vehicle-borne platforms. Commercial examples include: portable chemical-analysis labs and portable illuminator-imagers.

Some of the key technical objectives are to demonstrate: (1) foundry manufacturing (2) parts per billion sensing within important wavelength bands, (3) cost-effective lab-on-a-chip with integral drive, control, computation and readout. One technical LIO challenge is to demonstrate integration of multispectral or tunable lasers and detectors in the silicon photonics layer(s) with application-specific CMOS-or-bipolar circuitry. The photonics can use, for example, microbolometers and III-V photodetectors as well as III-V interband cascade and quantum cascade lasers evanescently coupled to silicon. Photonics constructed from III-V semiconductors certainly competes with silicon photonics in the longwave region, as it does at 1550 nm. Indeed, it will be quite feasible to construct a longwave photonic integrated circuit made entirely of III-V materials. However, in the realm of electronic-and-photonic integration, the creation of III-V optoelectronic circuits will be more challenging than the manufacture of silicon LIO because the integration of III-V transistors with photonics is more difficult. That is an advantage of Si LIO.

The index contrast in 1.55  $\mu\text{m}$  SOI waveguides is generally larger than that found in 1.55  $\mu\text{m}$  III-V heterostructure waveguides, although at  $\lambda > 4 \mu\text{m}$  where SOI induces too much attenuation (where Ge/Si is preferred), the contrast advantage of Si disappears. Why then do I prefer silicon-based LIO over III-V LIO, and what are silicon's benefits? Two advantages come to mind. The first is the much lower cost of Si LIO (per chip) in high-volume production. (This is based upon the huge Si infrastructure and the larger-than-GaAs/InP silicon substrates). The second is the much larger scale-of-integration for Si CMOS compared to III-V electronics (the silicon circuits will have higher functionality).

LIO does, however, have a "real estate" problem. The photonic-device length and the waveguide cross-section dimensions scale with wavelength, meaning that longwave photonics requires much more area than telecomm photonics. Also, the mismatch between transistor area and photonic-device area becomes larger as the wavelength increases. Nevertheless, LIO components have micrometer dimensions, or at worst, lengths of a millimeter or two, and a silicon die has centimeter(s) scale.

### 3. THE IMMEDIATE AND POTENTIAL APPLICATIONS OF LIO

I would like to discuss LIO applications using "short wave" applications as a reference. I list the 1550 nm, 1310 nm and 850 nm applications of silicon optoelectronics in a forthcoming online article<sup>2</sup> as follows: (1) **interconnects**: send-and-receive transceivers for broadband core-, metro- and access-networks (fiber to the home, internet box, Ethernet LAN, FTTX); transceivers for supercomputers, high performance computers, enterprise networks, and data centers (active cables as computer patch cords; optical interconnects for cabinet to cabinet, board to board, chip to board and chip to chip); transceivers for avionic-automotive-shipboard communication and control links; transceivers for microwave photonics (optical control of a phased-array antennas); nano-transceivers for intra-chip communications and electrooptically switched (reconfigured) optical networks. (2) **sensors**: infrared spectrometer-on-a-chip; photonic laboratory-on-a-chip for sensing chemical and biological agents; lab-on-a-chip for environmental monitoring or process control or medical diagnosis. (3) **signal processing**: wireless hand-held multi-function "phone-like" device; optical time-delay beam-steerer for a phased-array microwave antenna; RF-optical receivers for RF spectrum analysis, ultrafast analog-to-digital converters; reconfigurable wavelength-division multiplexers and demultiplexers; reconfigurable optical filters; electronic warfare processors; photonically enhanced microwave and millimeter-wave circuits; optical buffer memories; electrooptical logic that operates on phase-coherent light beams; quantum communication-cryptography-metrology-computing; photonic testing of electronic ICs; bionic signal processors; neural network processors; data-fusion chips using inputs from several sensors. (4) **imaging**: focal-plane-array imager with integral readout, infrared-to-visible image converter chip, (5) **displays**: chip-scale electrooptical display with integral scanning, (6) **energy conversion**: highly efficient group IV photovoltaic solar cells with integral signal processing-- perhaps with thin-film supercapacitors for energy storage. (7) **illumination**: efficient group IV solid-state lighting devices. (8) **optical storage**: read/write chips for ultradense CDs and atom-scale memories (9) **gaming**: ultrafast graphic computation chips for Nintendo and Playstation.

Turning now to longwave applications, I have three comments: (1) LIO is not truly appropriate for the displays, energy conversion, illumination, storage, and gaming listed above, (2) There are several unique, longwave-specific applications that are not on this shortwave list. (3) Most LIO applications do overlap with interconnects, sensors, processors and imagers on the shortwave list--but there is a caveat about high-speed signal processing. If we look at the available and projected LIO photodetectors and electrooptical modulators, we see that they have inherently

lower detectivity and lower speed capabilities than the corresponding shortwave devices. This means that we would not choose LIO for ultrafast communication and computation.

Now let's highlight the most probable LIO applications. I have identified applications that require group IV waveguides on the chip, and applications that don't need waveguides. The guided uses are: (1) Sensing chemical and biological molecules in a lab-on-a-chip, (2) Communicating securely over short distances using two on-chip LIO transceivers linked by an infrared specialty fiber, (3) Detecting weak longwave signals with a LIO heterodyne receiver that contains a local-oscillator laser—signals coming from space, as in astronomy. The second group consists of (4) Imaging nearby targets “actively” using a LIO chip that combines a target illuminator with an image sensor, (5) Sensing or ranging nearby targets with a LIO chip that has a point sensor and light sources, (6) Sensing longwave images with the human eye using a longwave-to-visible image converter “cube”, (7) Generating infrared “scenes” in miniature with a LIO emitter-array chip that is intended to calibrate an off-chip imaging device. In application (4), edical diagnosing and threat warning are important. Application (5) would include multispectral LADAR, environmental monitoring and process control.

#### 4. CHEMICAL AND BIOLOGICAL SIGNATURES AT LONGWAVE

Identifying trace gases is an example of our LIO chem.-bio sensing. The fundamental vibrations of many important gases are found in the 3 to 14  $\mu\text{m}$  spectral region with associated rotational-vibrational spectra as illustrated in Fig. 1. Rotational signatures are found at wavelengths in the Terahertz region, and we can see the complicated absorption lines of water vapor and other atmospheric constituents in the THz transmission diagram of Fig. 2 which shows narrow “windows” that might be used for communication within the 0.5 to 5 THz regime.

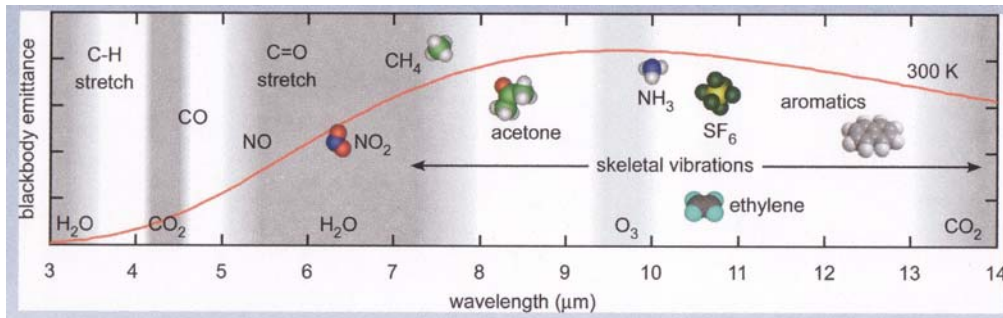


Fig. 1. Vibration lines of significant trace gases within the 3 to 14  $\mu\text{m}$  wavelength range.

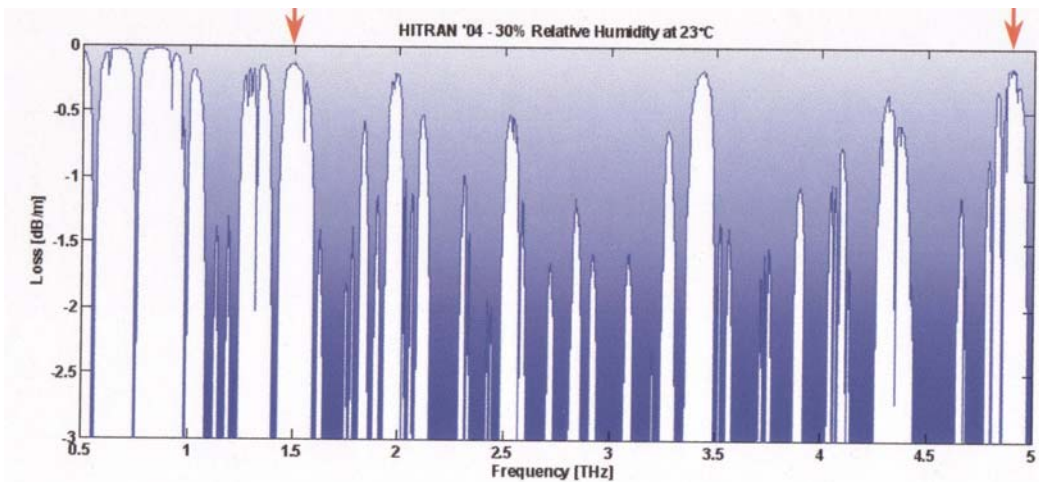


Fig. 2. Infrared transmission of the atmosphere over the 0.5 to 5 THz frequency range.

### 5. LONGWAVE COMPONENTS AND THEIR INTEGRATION

Before I present specific chip designs, I would like to discuss the possibilities for key components such as waveguides, laser sources, detectors and wavelength-division demultiplexers.

**a. Waveguides:** Because SOI is not viable beyond 3.6  $\mu\text{m}$  due to the  $\text{SiO}_2$  absorption<sup>1</sup>, other kinds of longwave guides must be developed<sup>1</sup>. Some credible possibilities are: the silicon membrane, the Ge membrane, undercut SOI, undercut GeOI, the Ge-on-Si heterostructure, the chalcogenide-on-Si heterostructure<sup>3</sup>, the hollow waveguides<sup>1</sup>, the asymmetric composite surface-plasmon waveguide and the metal-semiconductor-metal plasmon waveguide<sup>4</sup>. Membrane refers to a suspended slab Si or Ge (usually containing a ridge structure) that is clad below and above by air. Figure 3 illustrates the “undercut” SOI waveguide which is equivalent to a membrane.

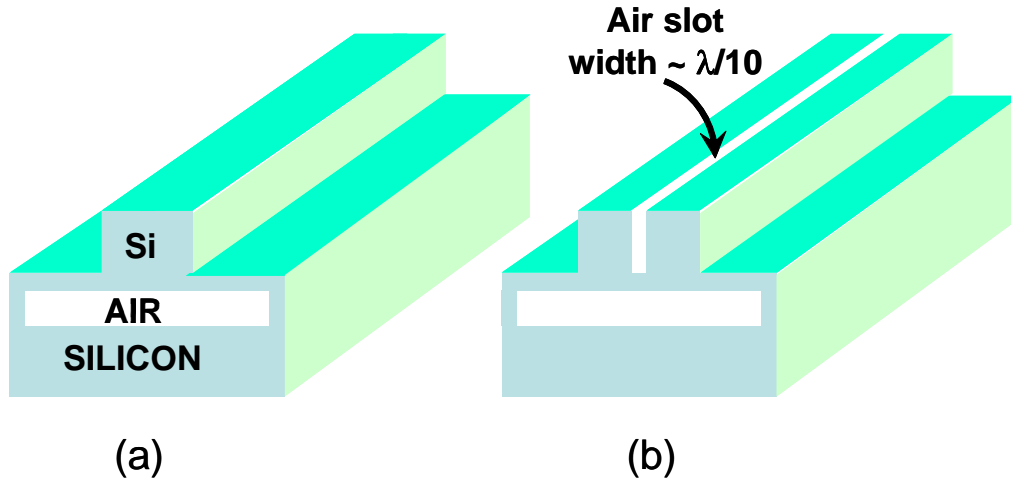


Fig. 3. Undercut SOI strip waveguide with the buried  $\text{SiO}_2$  layer etched away locally under the silicon rib: (a) solid rib, (b) slotted rib.

The slotted silicon rib has the feature of very high electric fields within the air slot. If the slot is filled with a gas to be tested, the high fields offer added sensitivity to the waveguided sensor device. As discussed earlier<sup>1</sup>, intrinsic crystal Si has less than 2 dB/cm propagation loss from 1.2 to 8.0  $\mu\text{m}$  and from 24 to 200  $\mu\text{m}$ . In addition, the Si loss is less than 13 dB/cm over 8.0 to 24  $\mu\text{m}$ , apart from a 39 dB/cm spike at 16.1  $\mu\text{m}$ . These numbers apply to undercut SOI and to the Si membrane. Intrinsic Ge has less than 2 dB/cm loss from 1.9 to 16.8  $\mu\text{m}$  and from 140 to 200  $\mu\text{m}$ . In addition, the Ge loss is less than 17 dB/cm from 1.9 to 23  $\mu\text{m}$  and from 42 to 200  $\mu\text{m}$ -- and all of these Ge numbers apply to undercut GeOI and to the Ge membrane. The index difference between crystal Ge and crystal Si is approximately 0.6 across the

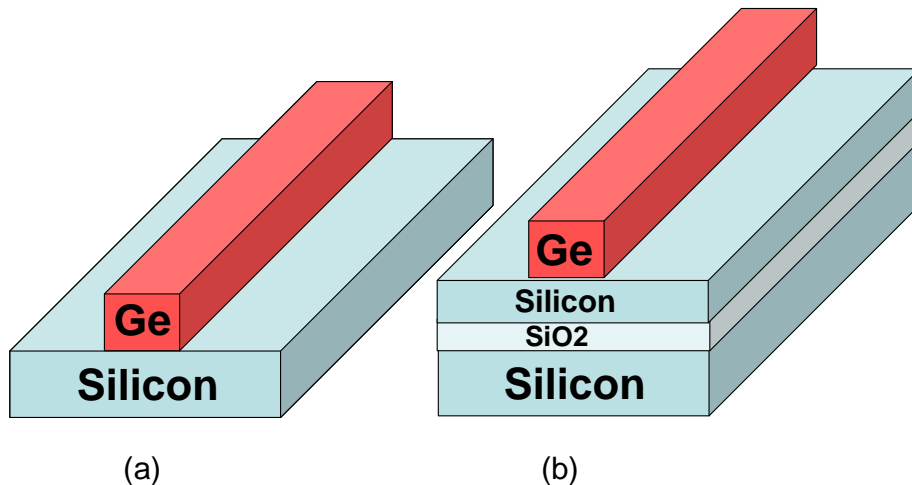


Fig. 4. Ge/Si heterostructure longwave channel waveguide: (a) on bulk Si, (b) on SOI.

1.6 to 200  $\mu\text{m}$  range, and the art of growing Ge upon Si is now well known (the dislocations are pinned mainly at the Ge/Si interface while the Ge film itself has good crystallinity). For those reasons, the Ge strip upon Si illustrated in Fig. 4(a) looks like a very good candidate for longwave waveguiding. Because most of the fundamental mode will be in Ge, with small fringing into the underlying Si, the spectral ranges in which the Ge/Si heteroguide offers high transmission will be quite similar to those of the above-mentioned Ge rib-membrane waveguide. Also, the Ge-upon-SOI waveguide of Fig. 4(b) will perform much like Ge/Si. It is indeed feasible to make low-loss chalcogenide waveguides on Si, but that is not an all-group IV solution, and that's why I do not gravitate towards it.

**b. One chip or two?** One chip of silicon is the preferred embodiment of the LIO system (or subsystem). An alternate scenario is to put the system on two chips: one for the optoelectronic network and the other for the light source(s). The two-chip solution is not ideal but will be necessary in cases where the source is too "hot" literally or figuratively.. Note that the light source on chip #2 could be either the primary laser or a shorter-wave laser "pump" that excites longwave Raman lasers and amplifiers located on chip #1.

**c. The issue of cryogenic cooling:** As the wavelength of operation moves beyond 10  $\mu\text{m}$  towards 200  $\mu\text{m}$ , the need for cryogenic cooling of sources and detectors becomes more urgent. However, cryo cooling of LIO should be avoided if at all possible. Uncooled operation is ideal. Generally, the strategy for obtaining room temperature operation is to sacrifice performance for the sake of 300K. For example, an uncooled microbolometer could serve instead of a cryo-cooled QWIP, albeit at 10x to 100x-reduced detectivity. A laser running CW at 77K might operate at 300K when pulsed.

**d. Monolithic integration:** Lasers, amplifiers, detectors, modulators and switches made entirely of Group IV materials are "factory compatible" or "monolithic" as desired for silicon LIO. Work on monolithic SiGe/Si quantum cascade *emitters* has been successful, both at  $\sim 10 \mu\text{m}$  and  $\sim 100 \mu\text{m}$ , but lasing has not been shown yet. This laser quest continues at the University of Glasgow and the University of Leeds. The stumbling blocks for monolithic lasing seem to be low gain and the "immaturity" of SiGe materials epitaxy. However, the new tin-containing-alloy heterostructures offer brighter prospects than SiGe for IV-IV lasing. The Si-based GeSn/SiGeSn and Ge/SiGeSn heterostructures offer higher gain, less strain, larger design space and more favorable band structure<sup>5</sup>. A promising design for a strain-free Ge/SiGeSn QCL grown upon SiGeSn-buffered Si was published recently<sup>6</sup>, and since the research investment in SiGeSn structures is growing, I think we will witness SiGeSn band-to-band lasing at 2 to 5  $\mu\text{m}$ , and intersubband lasing at  $\sim 50 \mu\text{m}$  during the next five years.

**e. Hybrid integration:** While we are waiting for monolithic IV-IV lasers and sensors to emerge, what is the most expedient way to attain on-chip LIO semiconductor light sources and detectors? The answer is hybrid or

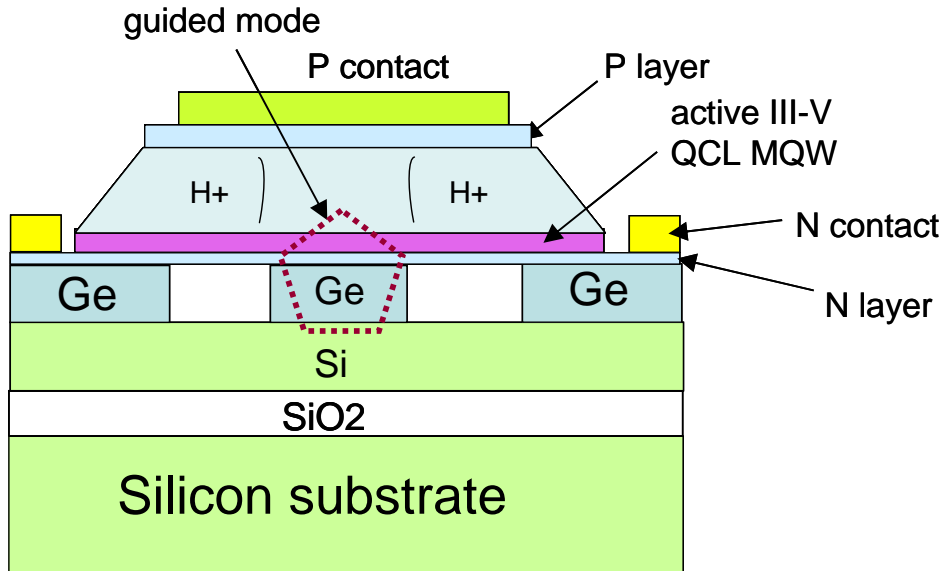


Fig. 5. End view: SOI-based quantum-cascade laser in Ge/Si waveguide. The hybrid-integrated III-V QCL gain structure is bonded to the Ge/Si waveguide network for evanescent coupling of MQW gain to the Ge resonator.

heterogeneous integration of III-V or II-VI devices on group IV waveguide networks. Examples of III-V sensors and sources relevant to LIO are MQW photodetectors, type II interband cascades and QCLs. I would integrate the cascades in LIO using a technique similar to that developed by John Bower's group. Here, the bottom n-type layer of the n-i-n QCL would be specially thinned to facilitate strong "leakage" of IR into the underlying Ge strip, as illustrated the Fig.-5 end-view of the device--which shows the central Ge waveguide and the outer Ge supports. The FP or DFB laser cavity is defined in Ge. Looking at the longwave mode profile within the composite guide of Fig, 5, about 80 % of the fundamental mode is in Ge. The mode overlap with the III-V gain hetero-region is about 20 %, and the overlap factor with the high-gain multiple quantum wells is about 5 %, adequate for long-wave lasing.

**c. Photodetectors:** As in the case of lasers, hybrid integration of longwave II-VI or III-V photodiodes on group IV--such as GaAs/AlGaAs QWIPs evanescently coupled to Ge/Si—is good approach.. The problem here is that QWIPs and Schottky diodes have greatly reduced (unusable?) sensitivity at 300K. However, there are several types of viable uncooled bolometric detectors that are monolithically integrateable on silicon. In the cases where the chip requires higher detectivity, then the LIO chip with hybrid-integrated detectors could be mounted in a closed-cycle cooler.

**f. Micro-photonics convergence:** In my review articles on silicon photonics<sup>7,8</sup>, I describe the new convergence of plasmonic optics, photonic crystals, and nano-photonics—meaning that these structures can co-exist, combine, couple to each other and complement each other in their functioning. I believe these techniques can converge synergistically at long wavelengths to advance the capabilities of micrometer-scale opto-electronics.

**g. Plasmonics:** Longwave plasmonics is a rather new endeavor. The term refers here to group IV semiconductors combined with metals or doped semiconductors or silicides to form "composite" longwave components with sub-wavelength cross-section dimensions and unique physical properties. Already, metal-semiconductor-metal and metal-semiconductor-dielectric waveguides are making useful contributions at 50 to 200  $\mu\text{m}^5$ , and I think that active-and-passive plasmonic-waveguided components will soon make important inroads into the 5 to 50  $\mu\text{m}$  domain. In other words, I believe that the migration of integrated polaritonic structures from the near infrared into the 5 – 200  $\mu\text{m}$  infrared will prove to be a new paradigm for plasmonics.

**h. Photonic crystals:** These are readily scaleable to longer wavelengths where the lithography and dimension control become much easier. In the far infrared "reststrahl" region of the III-V semiconductors, it is interesting that a practical 2D photonic crystal can be constructed from lattice-matched Si and GaP, or from Ge and GaAs<sup>9</sup>.

**i. Amplifiers:** A novel 3.39  $\mu\text{m}$  waveguided image amplifier was demonstrated in silicon by Bahram Jalali's group<sup>10</sup>. This uncooled optically pumped Raman device is probably extendable to longer wavelength operation.

#### 4. PROPOSED APPROACHES TO THE LONGWAVE LAB-ON-A-CHIP

Before I propose waveguide layouts and components for the Lab, I would like to categorize the sensor according to its electrical readout and proximity to the chem./bio analyte. Contact sensing means that the CB agent touches the chip. A second category is "remote" sensing (actually nearby standoff sensing) of CB material located several meters away from the lab-chip. In the standoff case, we would probably use a small remote-sampling cell to collect light from excited molecules and send those photons back to the chip over a special infrared fiber.

**a. Electrical readout of sensor:** There are three kinds of electrical readout of the lab: (1) local electrical signals coming directly off the chip, (2) near-infrared readout signals emitted by the chip and transmitted over a telecom fiber to a receiving chip far away from the LIO, and (3) RF readout signals emitted by the chip into free space where those radio waves travel to a "distant" RF receiver chip that gives local electrical readout. We have illustrated these in Fig. 6. An essential aspect of Figs 6(b) and 6(c) is the integration of LIO with EPIC and the integration of LIO with RF—which is done for cost, weight, and power reasons. Thus, in Fig 6(b), we want to construct within LIO a 1.55  $\mu\text{m}$  transceiver of the type developed on the DARPA EPIC program. Then, as shown, a second EPIC provides the remote readout of LIO. The RF wireless case is shown in Fig. 6(c) where we construct an RF transmitter upon LIO using, for example, Si or SiGe bipolar transistors that send microwave LIO-readouts to an antenna. A remotely located wireless chip picks up the LIO signals and provides a local readout as indicated.

With regard to remote sensing of molecules, we could, for example, provide a remote double-pass absorption chamber linked to LIO by an exotic (but currently available) longwave fiber as illustrated in Fig. 7. A fairly flat spectrum of infrared is sent into the chamber. The idea here is to have a partially open cylinder in which molecules congregate. An internal mirror at the far end of the chamber reflects the longwave exciting light back towards the

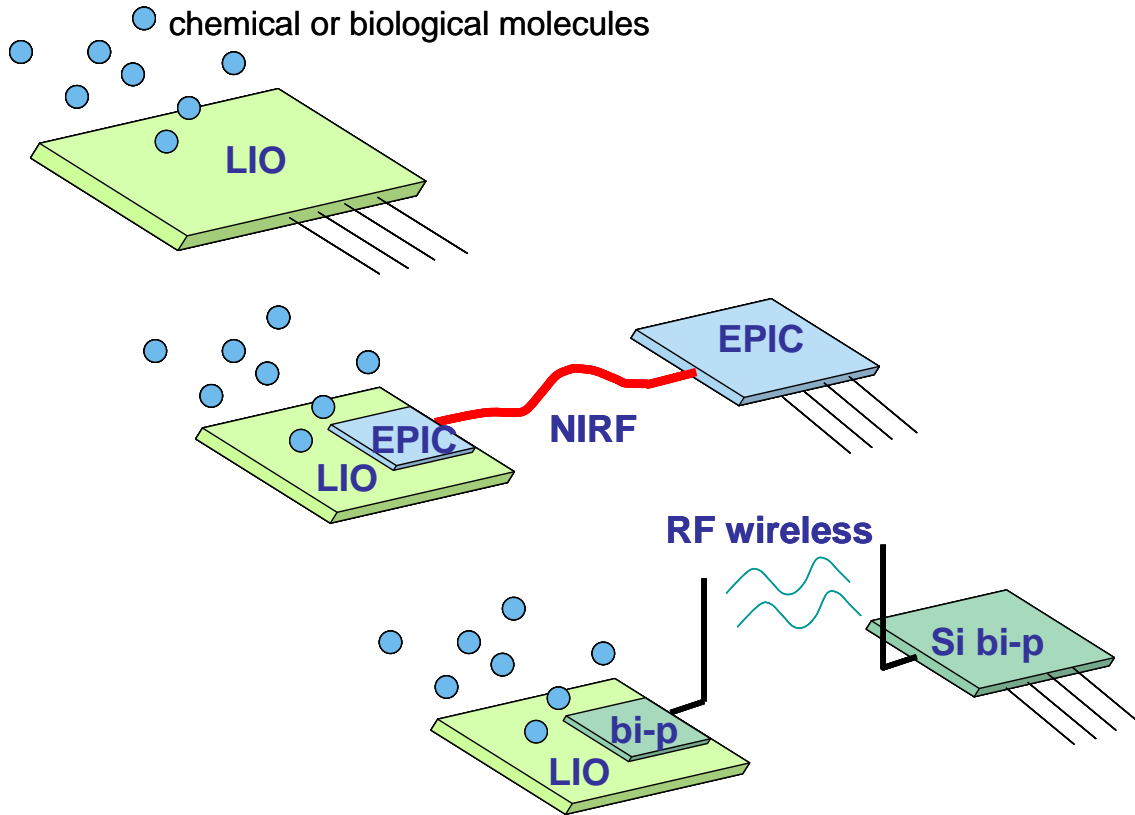


Fig. 6. Three kinds of electrical readout of a chem.-bio “contact” sensor: (a) local, (b) remote with fiber, (c) remote with RF wireless. Chem-bio molecules shown by dots.

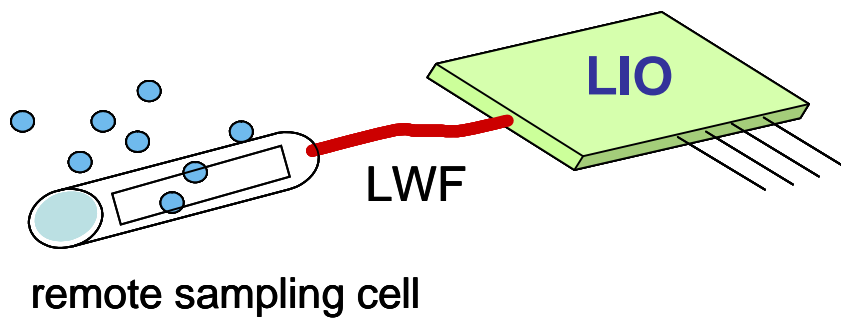


Fig. 7. Remote sensing of C-B agents using a longwave fiber linked to the LIO Lab. In lieu of this local readout, the readout can be remote with NIR fiber or RF wireless as in Fig. 6.

collection fiber. The returned spectrum contains two encounters with the molecules. For remote sensing (or two-way communication) using free-space transmission of the longwave “probe” beam, a surface grating on LIO will couple long waves in and out of the chip via the “telescope lens” shown in Fig. 8.



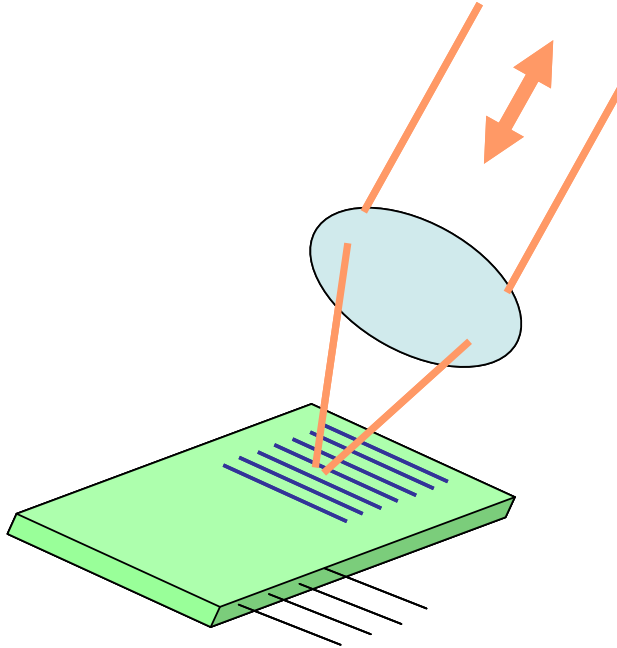


Fig. 8. Remote sensing and/or duplex communication using free-space longwaves lens-coupled to the LIO chip via a surface-relief grating.

**b. Details of the Lab:** There are several possibilities for the lab's on-chip light source: a laser, a broad-spectrum LED diode, a silicon black-body emitter and a multi-spectral laser array<sup>11</sup>. Most of the labs that I envision will perform some sort of longwave spectroscopy on-chip<sup>12,13</sup>. The prime spectroscopic candidates (architectures) for this integrated LIO Lab are: the differential-absorption spectrometer (DAS), the surface-enhanced Raman spectrometer, the surface-plasmon interferometer sensor<sup>14</sup>, the fluorescence spectrometer, the photo-luminescence spectrometer, the laser-photoacoustic spectrometer and the Fourier transform infrared spectrometer (FTIR). The above-mentioned DAS is usually a non-resonant device, although we can readily build resonant absorption structures on-chip for high sensitivity within a small spectral range as discussed in the Sensors section of Optics Express for November 27, 2007.

Figure 9 shows the proposed layout of a fully integrated optoelectronic DAS that employs a widely tunable laser.. The reference and signal photodiodes have broad response over that range. An alternative to the Fig-9 laser is a "globar-like" broad-band source consisting of a resistance-heated silicon bar with a "textured" surface to enhance the blackbody-like emission in certain spectral bands<sup>15,16</sup>. (The silicon is micro-machined<sup>17,18</sup> or macro-porous, as in a photonic crystal). This alternative Lab is shown in Fig. 10. The blackbody (BB) source is located on a second chip in order to isolate the BB thermally and optically from the spectrometer chip. In Fig. 10, we use two banks of broad microbolometers. Each microbolometer ( $\mu\text{B}$ ) input is resonated via a waveguided microring to a different, narrow slice of the BB spectrum in order to detect features in that "bin". The idea is to have the chem bio (CB) absorption lines overlap bins of the wavelength-multiplexed detectors. To ensure that strong absorption takes place, long serpentine paths are again used, and the CB analytes flow inside a narrow slot of width  $\lambda/20$  etched into the length of the folded Group IV waveguide. The high fields within the slot give intense interaction with the analyte.

We should mention that there are alternatives to slot sampling. One method (not shown) is unguided microfluidic delivery of analytes in an on-chip trench that cuts across waveguides. Another approach (not shown) is to flow analytes in contact with the exposed top (the evanescent mode tail) of a line-defect waveguide formed in a photonic crystal membrane. The PC guide is engineered for slow-light transmission so as to increase the interaction length.

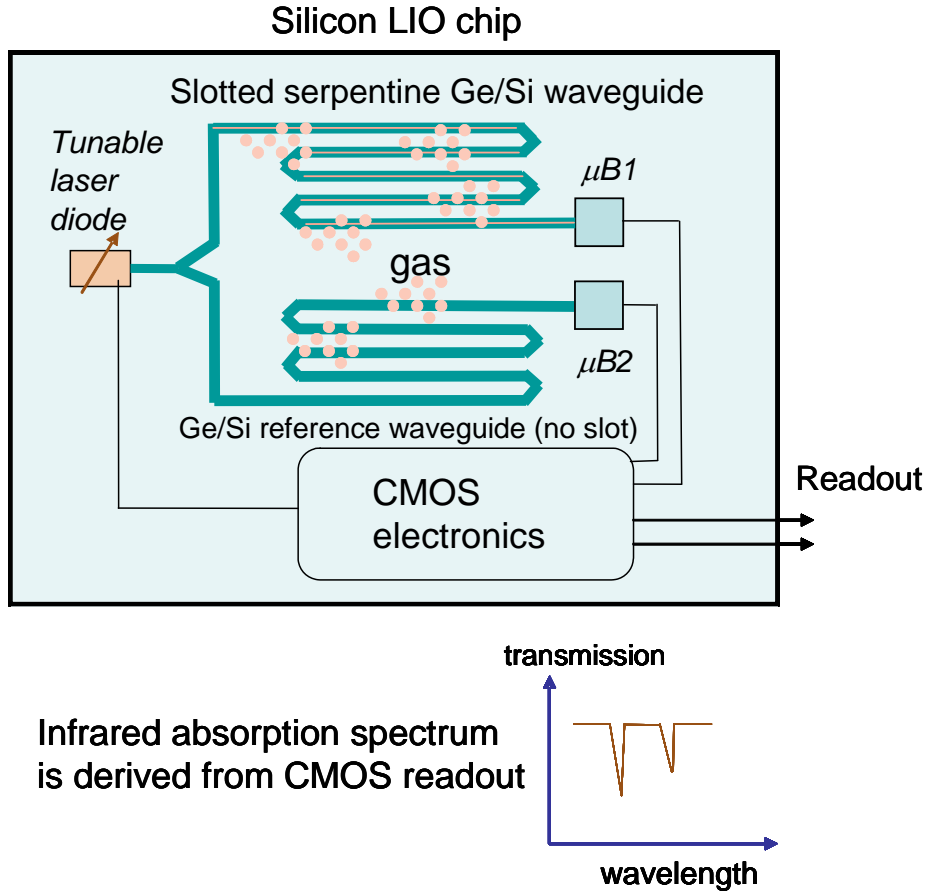


Fig. 9. Lab-on-a-chip: Top view of waveguided differential absorption spectrometer using a tunable on-chip source. The molecules being analyzed infiltrate the slot in the "lengthy" Ge/Si (or undercut-SOI) strip waveguide.

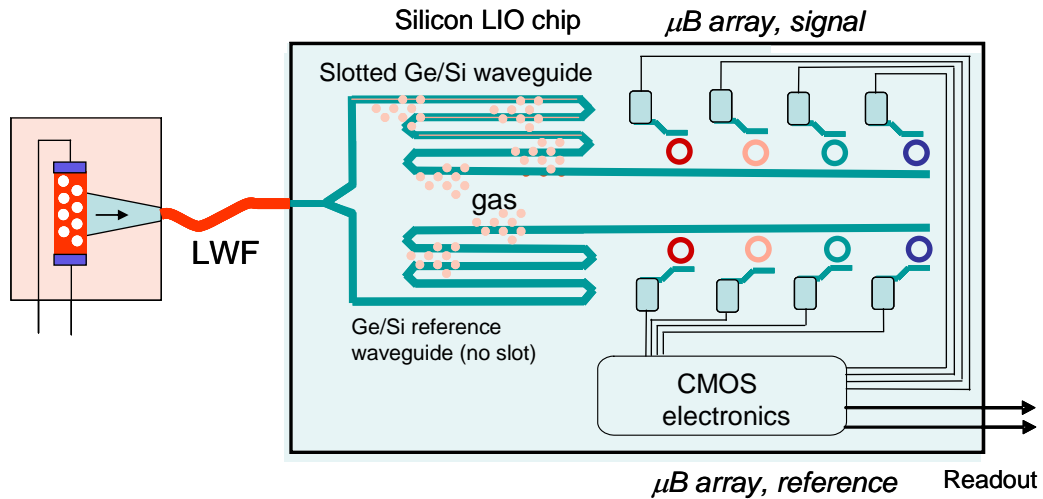


Fig. 10. Lab-on-two-chips: DAS similar to that in Fig. 10, except that the source is spectrally broad. Two banks of longwave sensors detect discrete portions of the spectrum with the aid of resonant wavelength-drop filters.

Continuing on the theme of the "discretized" DAS raised in Fig. 10, a third type of lab-on-a-chip utilizes a wavelength-multiplexed laser array as the source, such as the 32 DFB-QCL array-on-an-InP-chip developed by Capasso and co-workers<sup>11</sup>, an array available for LIO by hybrid InP-on-Ge integration. This lab is illustrated in Fig. 11.

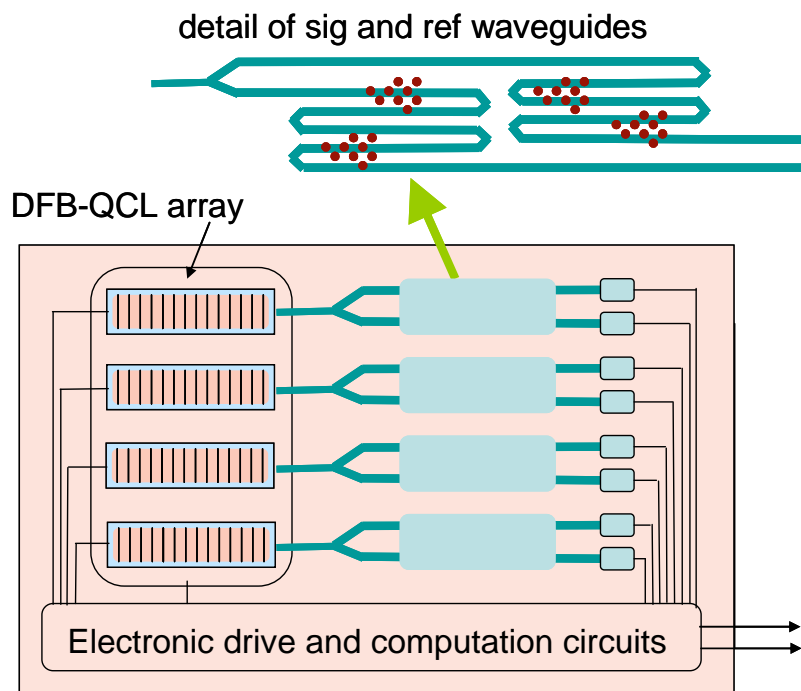


Fig. 11: Lab-on-a-chip: DAS with arrayed-laser wavelength-multiplexed source for discrete sampling of analyte absorption spectrum.

For clarity, only four of 32 lasers are shown. The approach here is to take many samples of the CB spectral profile with the closely spaced laser lines.

I believe that a waveguided LIO FTIR-on-a-chip that has no moving parts can be constructed as shown in Fig. 12 where a separate blackbody source-on-a-chip is employed. The CB molecules, as illustrated, infuse the slot of an

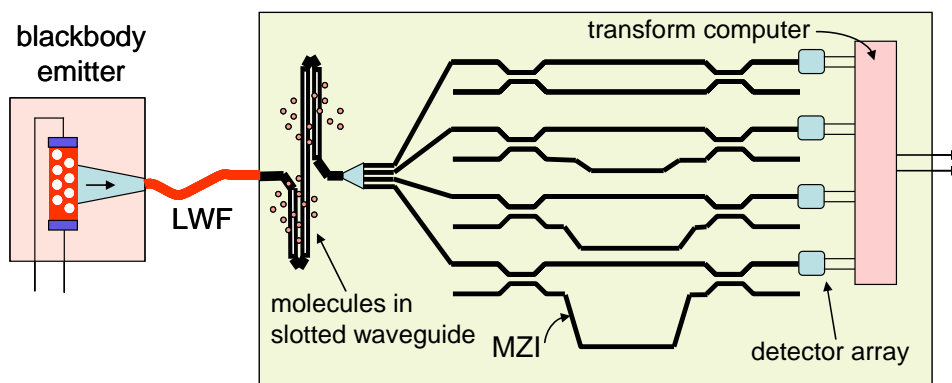


Fig. 12. Lab-on-two-chips: Waveguided FTIR with its on-chip CMOS computer. Only four of the N unbalanced interferometers are shown

elongated waveguide whose output is sub-divided N-fold. Those “polychromatic” waveguides then feed in parallel a set of N progressively unbalanced MZIs as envisioned by Cheben *et al* (Fig. 3b of Ref. 19). On-chip processing of the N-fold detected Fourier waveforms would complete this FTIR system-and-readout

I do not have space to discuss the other spectrometers mentioned above, except to comment briefly upon a technique for taking the spectra of individual molecules. This would be done by placing a nano-scale metal antenna<sup>20</sup> on the output facet of a tunable QCL to concentrate its light into a  $\sim \lambda/40$  region. Then a flat, negative-index lens, quite adjacent to the metal, would focus that light to a  $\sim \lambda/40$ -diam spot in the CB sampling zone where the photons that pass through individual molecules would be collected at the nano-point of a tapered plasmonic waveguide (“transformer”) that feeds the longwave detector. Room-temperature bolometric detectors are discussed below.

## 6. NON-WAVEGUIDED LIO APPLICATIONS

The illuminator/imager pair is the prime example of unguided LIO as illustrated in Fig. 13. This chip sends longwaves out to a nearby target and images the light reflected therefrom. In Fig. 13, the longwave source is a surface-emitting laser or an array such of lasers for multi-spectral sensing. In the near term, those III-V VCSELs would be hybrid integrated on Si. As before, there are cooled and uncooled scenarios. If a cooled chip is acceptable, then the LIO imager can be any one of the well-known 2D focal-plane arrays (FPAs) hybrid-integrated on LIO; FPAs made of HgCdTe or InSb or GaAs/AlGaAs, etc.

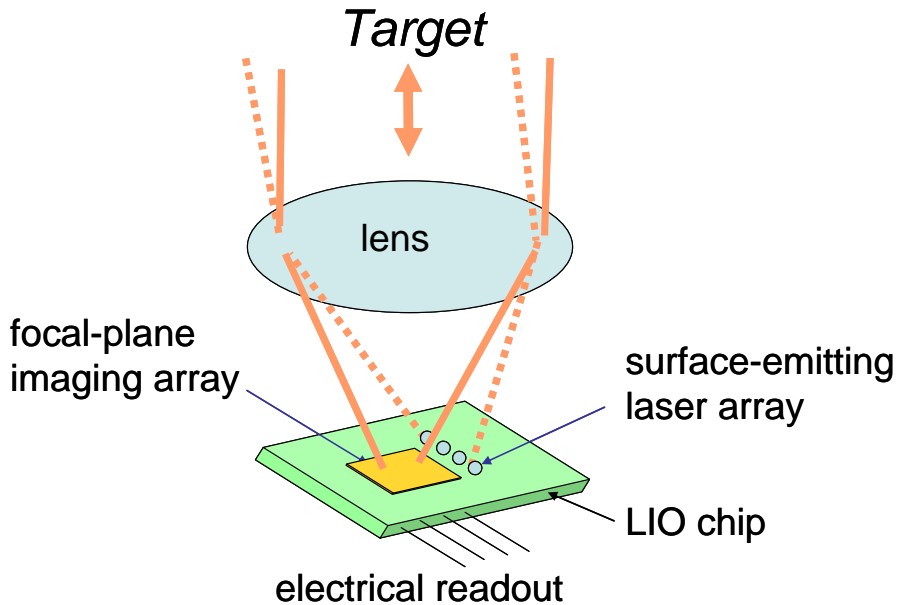


Fig. 13 Illuminator-imager chip for bio-medical, ladar, and other applications.

Uncooled microbolometers can play a role as the 2D FPA in Fig 13, or as point sensors in Figs. 9-12. Regarding the latter, the speed and sensitivity of state-of-the-art microbolometers are probably adequate for the point detectors in the foregoing Labs. The art of vanadium dioxide microbolometers-on-silicon is well known, and enhanced CMOS-factory-compatible microbolometers are coming on-stream now. For example, an innovative Si-based “controlled cantilever” microbolometer array is being developed at ImageSys<sup>21</sup>. Following their 2007 experimental validation of the operating principles, their early projections of performance include an uncooled NETD of less than one milliKelvin, irradiance dynamic range of four orders-of-magnitude, no requirement for thermoelectric temperature stabilization, detection optimized for 8 to 20  $\mu\text{m}$ , and frame rate capability up to 300Hz. Speaking generally about microbolometers, the wavelength range of maximum detectivity is determined by the longwave absorption properties of the bolometer coating. If a “gold black” film is deposited on the bolometer surface, the sensor’s spectral response can be maximized for whatever range desired (8 to 14  $\mu\text{m}$ , 50 to 100  $\mu\text{m}$ , etc) by adjusting the deposition parameters.

Another good example of “unguided” free-space LIO is the Longwave-to-Visible image converter cube shown in Fig. 14. which has an FPA on the input face and a reflective, low-power liquid crystal display on the output face of the silicon 3D microelectronic cube. The transistors in this thick-chip cube are integrated in the chip body in such a way that there is electrical access to the scanning voltages on both the front and back faces of the die. Complicated, large-scale computations are avoided by internal scanning of the FPA and LCD simultaneously with the same simple algorithm.

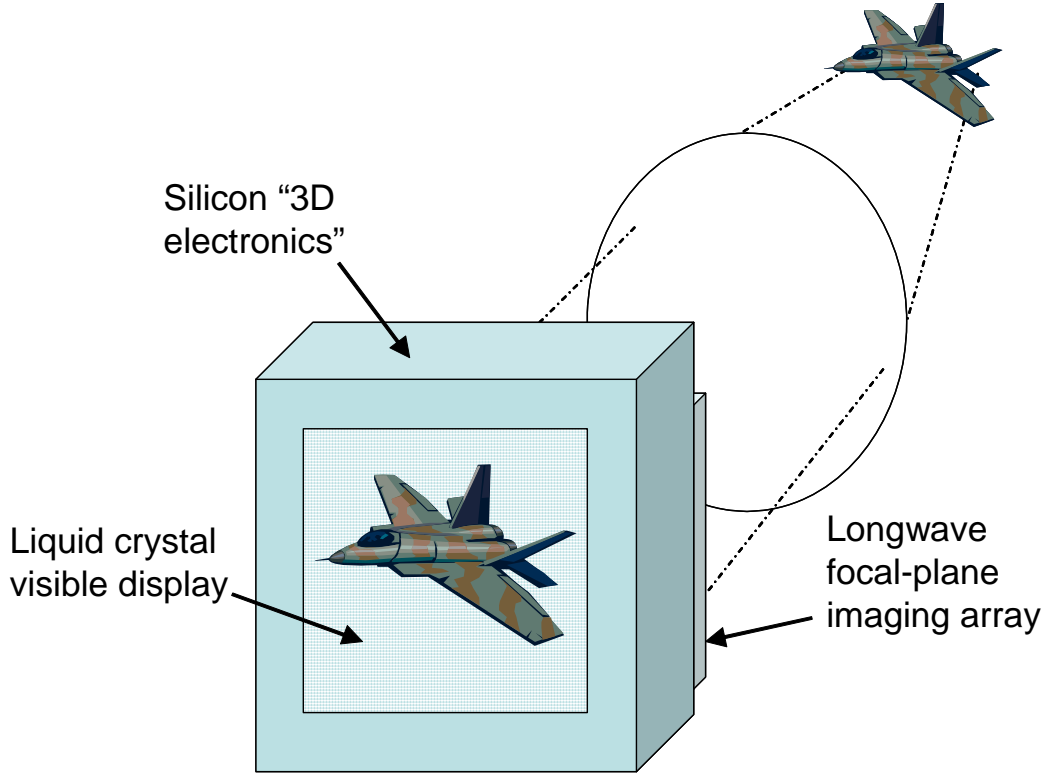


Fig. 14. Longwave-to-visible image converter cube. Complicated algorithms are avoided by scanning the 2D imager array and 2D display-pixel array simultaneously in “electrical unison”.

## 7. CONCLUSION

Longwave systems today are made of discrete components and various electronics chips; however, in principle, many of those systems can be foundry-integrated onto one or two silicon OE chips using hybrid integration, waveguiding and other techniques described in this paper. When actualized, this optoelectronic integration will yield new capabilities and new applications on new platforms. It will take ingenuity to realize this LIO vision, but the resulting savings in cost, size, weight and power will be worth the effort.

## ACKNOWLEDGEMENT

The author wishes to thank AFOSR, Dr. Gernot Pomrenke, Program Manager, for sponsoring his inhouse research at Hanscom AFB.

## REFERENCES

1. R. A. Soref, S. J. Emelett and W. Buchwald, “Silicon waveguided components for the long-wave infrared region”, *Journal of Optics part A* (IoP Publishing, UK) vol. 8, pp. 840-848 (2006).
2. Richard Soref, “The achievements and challenges of silicon photonics”, invited lead article in *Advances in Optical Technology* (Hindawi, online), special issue on silicon photonics (2008).

3. J. Hu, V. Tarasov, N. Carlie, N. -N. Feng, L. Petit, A. Agarwal, K. Richardson, and L. Kimerling, "Si-CMOS-compatible lift-off fabrication of low-loss planar chalcogenide waveguides," *Opt. Express*, vol. 15, 11798-11807 (2007)
4. Benjamin S. Williams, "Terahertz quantum-cascade lasers", *Nature Photonics*, vol. 1, pp 517-525 (Sept. 2007)
5. R. A. Soref, J. Kouvetakis, J. Tolle, J. Menendez and V. D'Costa, "Advances in SiGeSn technology", (outstanding meeting paper), *Journal of Materials Research*, vol. 22, paper 0415, (December 2007).
6. G. Sun, H. H. Cheng, J. Menendez, J. B. Khurgin and R. A. Soref, "Strain-free Ge/GeSiSn quantum cascade lasers based on L-valley intersubband transitions", *Applied Physics Letters*, vol. 90, 251105 (2007).
7. Richard Soref, "The past, present and future of silicon photonics", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 6, pp. 1678-1687 (November/December 2006).
8. Richard Soref, "Introduction—The opto-electronic integrated circuit", invited lead chapter in the book *Silicon Photonics—The State of the Art*, Graham T. Reed, Editor, John Wiley & Sons UK (2008).
9. R. A. Soref, Z. Qiang and W. Zhou, "Far infrared photonic crystals operating in the Reststrahl region", *Optics Express*, vol. 15, pp.10637-10648 (20 August 2007).
10. V. Raghunathan, D. Borlaug, R. Rice, and B. Jalali, "Mid-infrared silicon Raman amplifier" OSA Topical Meeting on Advanced Solid-State Photonics, Nara, Japan, (27-30 Jan 2008).
11. B. G. Lee, M. A. Belkin, R. Audet, J. MacArthur, L. Diehl, C. Pflugl, F. Capasso, D. C. Oakley, D. Chapman, A. Napoleone, D. Bour, S. Corzine, G. Hofler, and J. Faist, "Widely tunable single-mode quantum cascade laser source for mid-infrared spectroscopy". *Applied Physics Letters*, vol. 91, 231101 (2007).
12. B. Momeni, J. Huang, M. Soltani, M. Askari, S. Mohammadi, M. Rakhshandchroo and A. Adibi, "Compact wavelength demultiplexing using focusing negative index photonic crystal superprisms", *Optics Express*, vol. 14, 2413-2422 (March 2006).
13. A. Lambrecht, S. Hartwig, S. L. Schweizer and R. B. Wehrspohn, "Miniature infrared gas sensors using photonic crystals", *SPIE Proceedings*, vol. 6480, ISBN 978-0-8194-6593-1, (2007).
14. P. Debackere, S. Scheerlinck, P. Bienstman, and R. Baets, "Surface plasmon interferometer in silicon-on-insulator: novel concept for an integrated biosensor," *Optics Express*, vol. 14, 7063-7072 (2006)
15. J.T. Daly, A.C. Greenwald, et. al., "Nanostructured surfaces for tuned infrared emission for spectroscopic applications," *SPIE Photonics West*, vol. 3937, paper 14, San Jose, CA (2000).
16. M. U. Pralle, N. Moelders, M. P. McNeal, I. Puscasu, A. C. Greenwald, J. T. Daly, and E. A. Johnson T. George and D. S. Choi I. El-Kady and R. Biswas, "Photonic crystal enhanced narrow-band infrared emitters", *Applied Physics Letters*, vol. 81, pp. 4685-4687 (December 16, 2002)
17. W. Konz, J. Hildenbrand, M. L. Bauersfeld, S. Hartwig, A. Lambrecht, V. Lehmann and J. Wollenstein, "Micromachined IR-source with excellent blackbody-like behavior", *SPIE Proceedings*, vol. 5836, pp 540-548, ISBN-0-8194-5831-7 (May 2005)
18. Irina Puscasu, M. Pralle, M. McNeal, J. Daly, A. Greenwald, E. Johnson R. Biswas and C. G. Ding "Extraordinary emission from two-dimensional plasmonic-photonic crystals", *J. Applied Physics*, vol. 98, 013531 (2005).
19. P. Cheben, A. Delage, A. Densmore, M. Florjanczyk, S. Janz, B. Lamontagne, J. Lapointe, E. Post, I. Powel, J. Schmid, P. Waldron and D.-X. Xu, "Silicon photonic arrayed waveguide grating devices and sub-wavelength structures", invited paper, *Proceedings of the ICTON'07 Conference*, pp 92-95, Rome, Italy (1-5 July 2007).
20. N. Yu, E. Cubukcu, L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Hofler, K. B. Crozier and F. Capasso, "Bowtie plasmonic quantum cascade laser antenna", *Optics Express*, vol. 15, 13272, (1 Oct 2007)
21. Oliver Edwards, "High-resolution long wavelength focal-plane array", *Third Monthly Status Report by ImageSys Corp. on US Special Operations Command contract number: H9222207P0052*, (11 September 2007).