Photonic Integrated Circuits for Coherent Lidar

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Abstract: A decade ago integrated photonic devices typically consisted of single components that fulfilled one specific function, such as phase modulation or splitting into *N* beams. In the intervening years, photonic integrated circuits (PICs) have undergone a revolution in terms of component functions, loss reductions, and high level functional integration. This has in part been driven by the development of device designs compatible with conventional CMOS fabrication processes. We are now at a point where component diversity, low losses, and low cost fabrication enables us to consider development of coherent laser radar systems based around PIC technology. In this talk we will highlight some of the current developments in the PIC domain, with an emphasis on technology elements applicable to coherent laser radar systems. Examples include narrowband lasers, frequency shifters, beam distribution networks, and large angle photonic beam steering.

Keywords: Photonics, Photonic Integrated Circuits, PIC, Silicon Photonics, Coherent Laser Radar, Lidar, Ladar

1. Introduction

The reduction of optical devices to microscopic dimensions has been underway for decades in the form of fiber optics, CMOS detector arrays, and components like modulators, micro-ring filters, and splitters. The past decade has seen an explosion of development that goes beyond single devices and now encompasses subsystems and systems with hundreds of components [1-4]. The technology typically falls under the name of Photonic Integrated Circuits (PICs). Silicon Photonics is a form of PIC that uses silicon substrates and silicon waveguides for the platform. .

A key enabler in the silicon photonic revolution has been the development of technologies compatible with conventional CMOS fabrication processes and foundries. In an extraordinary coincidence the multi-billion dollar investments in CMOS foundries enable the same fabrication infrastructure to produce devices that propagate light at wavelengths ideally suited for many electro-optic communications and sensing applications. Low propagation losses (<0.5 dB/cm) in waveguide dimensions smaller than the wavelength (220 nm × 300 nm cross-section for 1550 nm wavelength) have enabled integration of large numbers of components in small footprints. The large index step between silicon (n_{Si} ~ 3.5) and waveguide cladding materials like silica glass (n ~ 1.45) and silicon nitride (n ~2) enables tight mode confinement and small bend radii (<10 µm), while supporting low loss and low crosstalk between closely-spaced waveguides.

Silicon is excellent as a materials system for passive components, but is non-ideal for active components like laser sources and detectors. Fortunately heterogeneous integration techniques are maturing, whereby high-performance active components made using InP, GaAs, Ge, and other materials can be integrated with silicon.

In tandem with the development of optical devices, great progress is also being made in the integration of optics with CMOS electronics and efficient thermal management. Flip-chip bonding of PICs with CMOS chips (also known as "2.5D" integration) is routinely done today and full 3D integration of complex photonic/electronic circuitry is undergoing rapid development [3]. These advances enables us to consider construction of lidar systems on a chip.

Figure 1 shows a generic coherent lidar architecture. Aside from the signal processor, the only functional element that has not been demonstrated in PIC form is a high peak power oscillator or amplifier, because of the peak power handling limits of small waveguides. Silicon photonics offers the possibility of fabricating complete coherent lidar systems at the chip level by tailoring components to lidar needs. Until high peak power systems are developed, perhaps based on large arrays of parallel coherent amplifiers, chip-based coherent lidar systems are likely to be developed around modulated CW architectures.

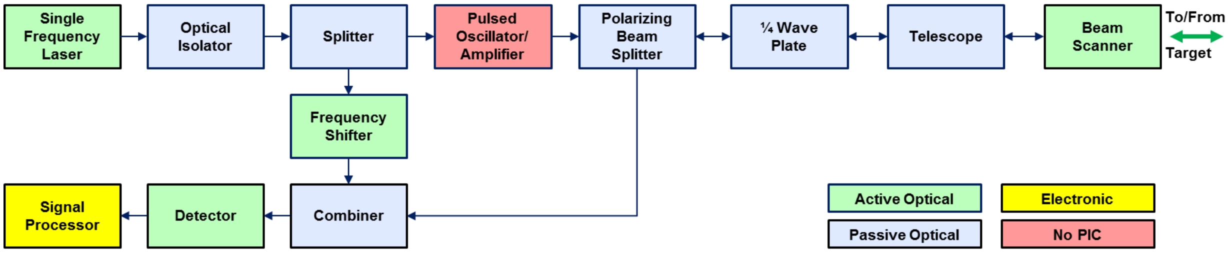

Figure 1. Generic coherent ladar architecture.

2. Device Examples

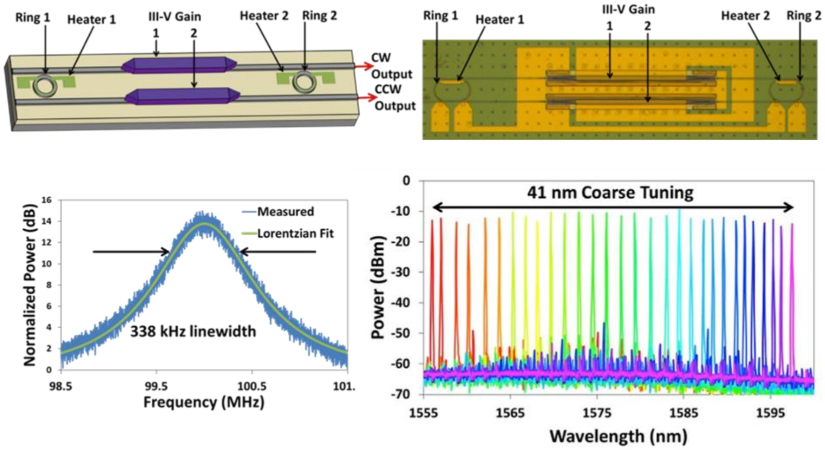

Figure 2. Laser with >40 nm tunability centered at 1575 nm [4].

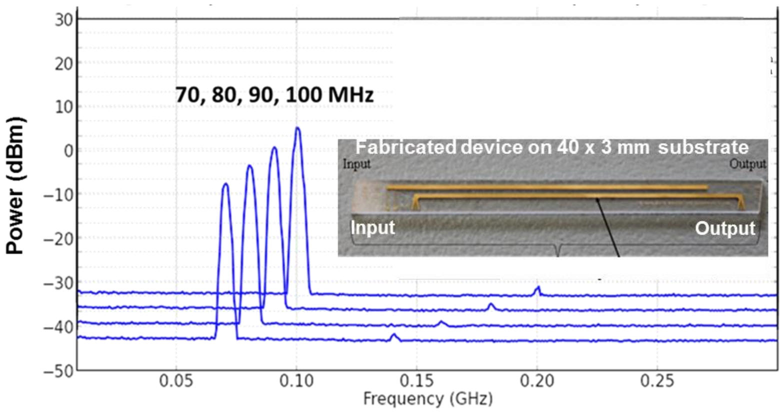

Figure 3. Frequency shifter demonstrated at UCD.

For space reasons we only provide two examples of relevant demonstrated devices. Figure **2** shows a laser developed at UC Santa Barbara comprising two gain elements [5]. Two thermally adjustable micro-rings are used in a Vernier configuration to enable >40 nm wavelength tuning with narrow linewidth and >35 dB side-mode suppression. The output power was >3 mW, which could be increased with on-chip semiconductor amplifiers (SOA) [6]. Other lasers demonstrated at UCSB include broadly tunable lasers with wavelength hopping and stabilization in 30 ns.

Frequency shifting is another important feature of coherent lidar systems as they are frequently used to generate intermediate frequencies (IF) and track out Doppler shifts. This is often accomplished using acousto-optic modulators (AOM), cascaded Mach-Zehnder interferometers, or by offset-locking two lasers. A conceptually very simple direct frequency shifter that emulates a rotating half-wave plate has recently been demonstrated [7] in $LiNbO_3$ at UC Davis – see Figure **3**. Note the absence of the carrier frequency and ~40 dB suppression of the second harmonic. This device type is predicted to enable frequency shifting in excess of 10 GHz.

Many other important components also exist, including optical isolators with >30 dB isolation and 2.3 dB insertion loss [8], low-loss PIC to fiber couplers [9], and methods for writing low-loss 3D waveguides for routing [10]. Numerous additional examples of PICs can be found in reference [11].

3. Non-Mechanical Beam Steering (NMBS)

Beam steering is frequently a SWaP limiting factor in conventional lidar systems. Many means have been devised over the years to eliminate large, heavy, and slow gimbals, Risley prisms, and other steering devices. McManamon reviewed non-mechanical beam steering (NMBS) technologies in 2009 [12]. Silicon photonics is taking beam scanning to a new level by completely eliminating the need for bulk optics. The recent DARPA SWEEPER program developed multiple PIC-based NMBS systems. Figure 4 shows approaches by researchers at UC Berkeley [13] and MIT [14]. The Berkeley approached used MEMS ribbon arrays to on-the-fly reconfigure gratings which diffract light angularly, The MIT approach uses 2D arrays of phase shifters to steer beams by imposing transverse linear phase gradients. Both of these approaches demonstrated fast and efficient beam steering, but also revealed a scalability issue. To address N far field points in two dimensions the number of required controls grows as N^2, which becomes very challenging as N becomes very large.

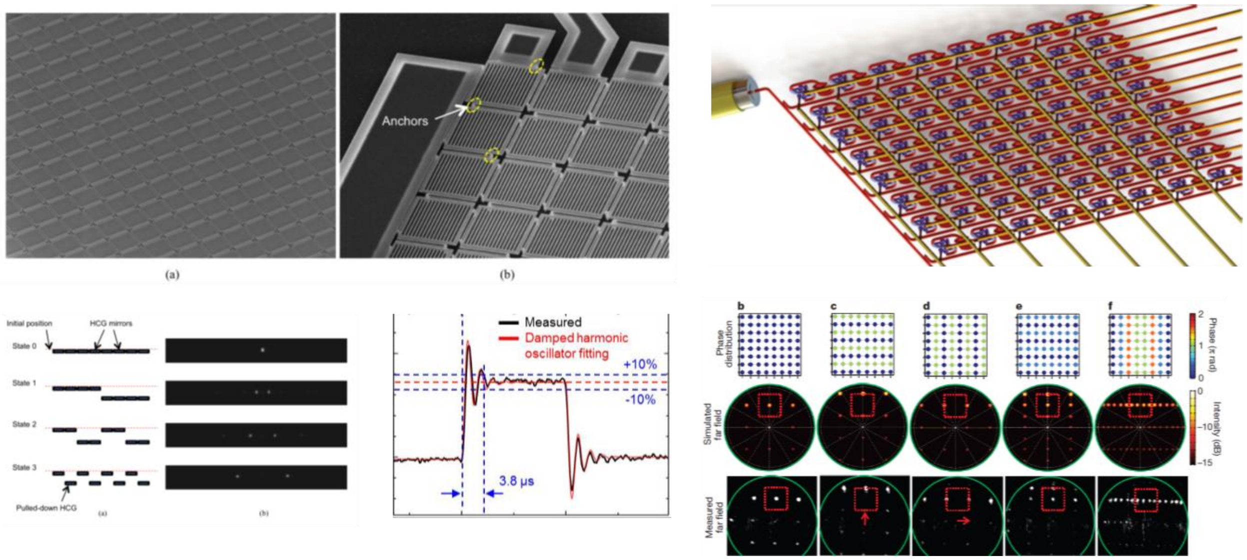

Figure 4. PIC-based NMBS demonstrated by UC Berkeley (left) [13] using MEMS ribbon arrays and by MIT (right) [14] using 2D arrays of phase shifters.

Figure 5 shows an alternative approach developed by UCSB [15,16]. In this approach laser tuning over ~43 nm combined with a fixed grating is used to steer beams in one dimension. Transverse phase gradients steer in the second dimension. This approach reduces the number of control elements to *N*+1, the 1 being the laser wavelength control.

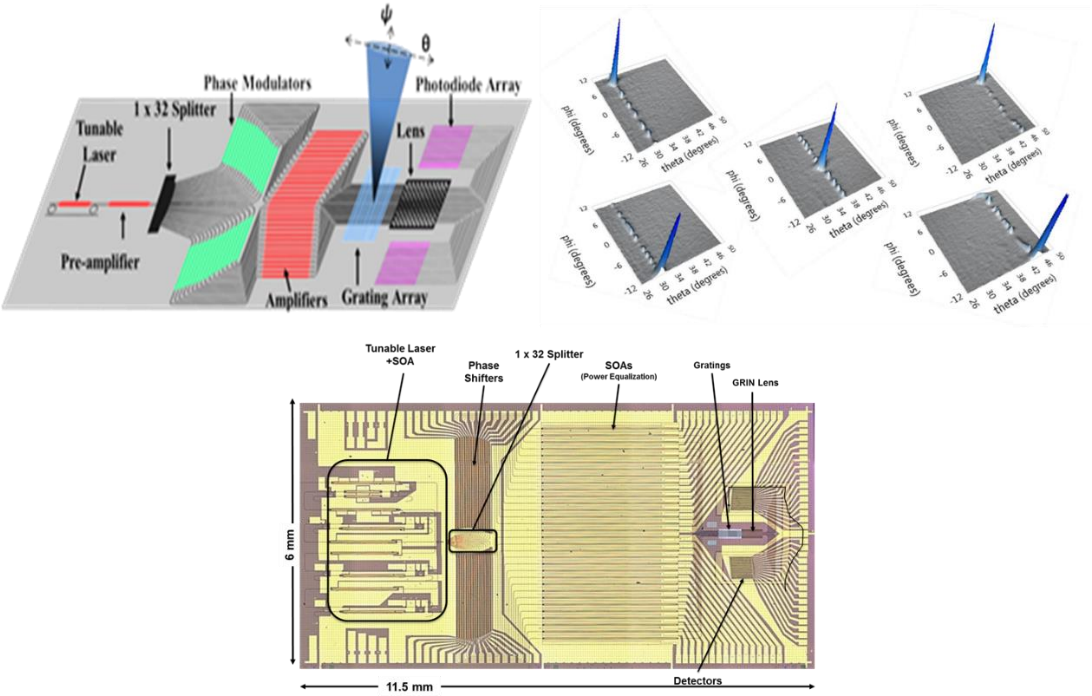

Figure 5. 2D NMBS approach developed by UCSB [15]. Top left – functional architecture. Top right – 2D beam steering demonstrated to date. Bottom – physical layout on 6 × 11.5 mm^2 chip.

4. Coherent Lidar Example

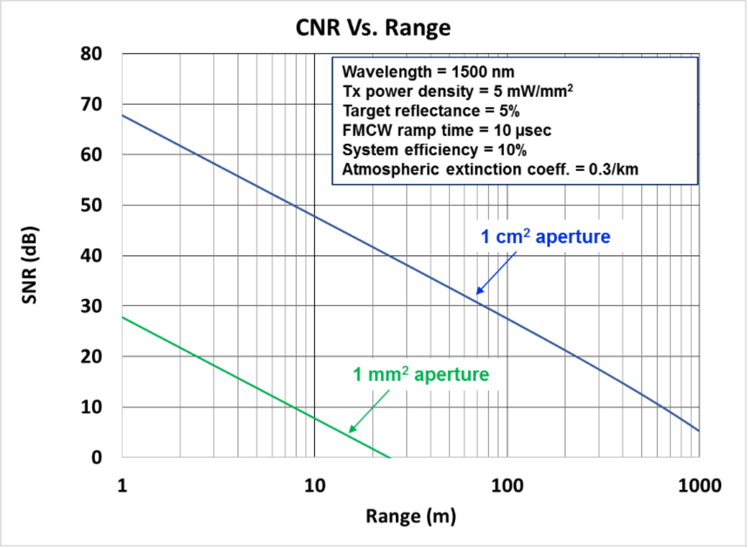

Figure 6. FMCW lidar CNR vs. range prediction for realistic sensing scenario at two aperture sizes with the same

transmitted power density of 5 mW/mm^2.

Many versions of coherent lidar systems can be constructed as variations on the generic architecture shown in Figure 1. Frequency-modulated continuous wave (FMCW) operation is one approach to perform lidar functions like range finding at low peak powers and simple signal processing [17]. In this technique the laser frequency is ramped linearly in time and the time delay associated with the round-trip time to the target produces a beat signal with frequency proportional to range. Up-down frequency ramps can be used to unambiguously distinguish range and velocity. Figure 6 illustrates an example of the anticipated SNR achievable with a coherent FMCW single point sensor operating with a single shot measurement time of 10 µs, i.e. up to 100 kHz data points per second rate. The green curve corresponds to a 1 × 1 mm coherent transmit/receive aperture while the blue curve corresponds to a coherent 1 × 1 cm aperture. Multi-point simultaneous sensing similar to that used in commercial 3D lidar instruments [18] can also be incorporated into the same chip. A non-mechanical steered single-chip sensor of this type could be constructed by incorporation of the technology elements described in this paper. As seen in Figure 6 such a sensor could provide rapid 3D mapping to km ranges with a modest ~1 cm^2 coherent aperture.

Looking into the future it is not far-fetched to envision future large aperture coherent lidar systems fabricated at low cost in very small form factors. These may incorporate all photonic components, the associated signal processing, as well as efficient heat removal.

5. References

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