Heterogeneously Integrated Microwave Signal Generators with Narrow-Linewidth Lasers

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Abstract: *We explore photonic microwave signal generation utilizing the heterogeneous silicon-III/V platform and the benefits and execution of a fully integrated chip. Optimization of device components is discussed, including high-speed waveguide photodiodes and widely tunable lasers. Microwave signal generation is demonstrated beyond 110 GHz. Exploration into dual signal generation with a tracking fixed offset is discussed.*

Keywords: Semiconductor lasers; Tunable lasers; Silicon photonics; Millimeter-wave

Introduction

Frequency agile microwave and millimeter wave microwave sources at frequencies from 1 to 300 GHz are necessary for a variety of military and commercial applications [1]. Generating, testing and measuring such signals is challenging. Conventionally signal generation at millimeter-wave frequencies is done by using frequency up-conversion. For higher frequencies electronic circuitry with many stages of frequency doubling is needed to achieve the desired frequency. The use of additional hardware that is bulky, fragile, expensive and difficult to operate, makes finding an alternative approach beneficial. Another difficulty is the distribution of such very-high frequency signals, as signals in electrical domain encounter high transmission losses in distribution lines, such as a coaxial cable.

Alternatively, signals may be generated optically. Photonic techniques for generating millimeter-wave frequencies provide some key advantages, one being broad tunability and another being ultra-low propagation loss in optical fiber for signal distribution. There are a number of techniques to generate continuous wave RF signals [2], but we will concentrate on using laser outputs that are combined and detected on a high-speed photodetector to generate a heterodyne beat tone at the frequency difference between the laser outputs. At least one of the lasers may be discretely or continuously tuned. The optically generated heterodyne beat tone can be swept over a very wide range of frequencies exceeding hundreds of gigahertz.

Photonic integration brings a promise of significant cost, power and space savings compared to bulk optics approaches. Silicon photonics offers many advantages for microwave photonics, such as large, low cost wafers, low cost processing in volume, and better process control, and low optical loss, to name a few. One serious limitation of silicon photonics is the light generation, and we solve that using heterogeneous integration. Recent developments have shown that heterogeneous integration not only allows for a reduced cost due to economy of scale, but also allows for same or even better performing photonic devices than what has previously been demonstrated utilizing only III-V materials [3].

Microwave generator

A photonic microwave generator based on laser heterodyning, in its basic configuration, comprises of two lasers, at least one of which is tunable, a coupler that combines these two signals and a fast photodetector. One can increase performance and functionality by including booster semiconductor optical amplifiers (SOA) and high speed amplitude and phase modulators. We show a microscope image of an exemplary microwave generator in Figure 1.

For optimal performance one requires narrow-linewidth lasers as the width of RF signal generated by beating the two lasers will be equal to the cross-correlation of the two linewidths. The underlying waveguide platform should be low-loss. A booster SOA should have high-output saturation powers and the photodetector should be high-power and high-speed. The heterogeneous platform allows for independent optimization of all the components. The Si or Si_3N_4 waveguide platform provides low loss. Multiple thin-film epitaxial layers provide optimized gain, modulation and detection performance. The ability to individually change the widths of the Si waveguides and III-V mesa allows for gradual change of confinement factor. We address these issues in remaining sections of the paper.

Narrow-linewidth laser design

The linewidth of semiconductor lasers is inherently broader than e.g. that of solid-state lasers. In a semiconductor laser there are two mechanisms broadening the linewidth: (1) the spontaneous emission which alters the phase and intensity of lasing field and (2) the linewidth enhancement factor α that characterizes the coupling between intensity and phase noise and is specific to semiconductor lasers due to carrier density fluctuations.

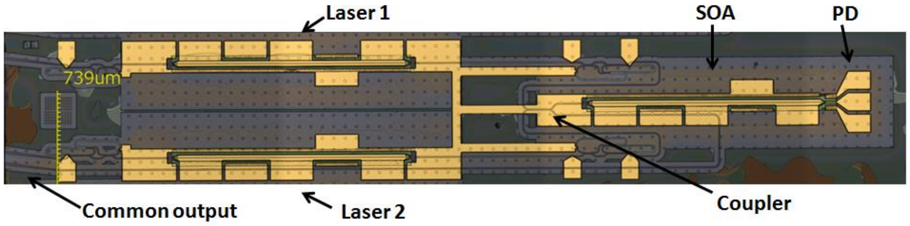

Figure 1. Microscope image of the photonic microwave generator comprising of two tunable lasers, a coupler, booster semiconductor optical amplifier (SOA) and photodetector (PD). One arm of the 2x2 coupler goes to SOA and PD, other arm goes to the edge facet (common output).

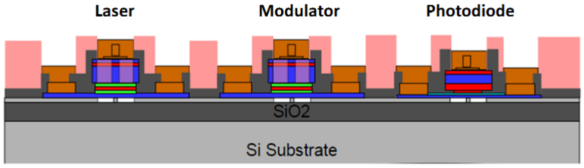

Figure 2. A illustration showing optimized thin-film epitaxial structures for different photonic devices, which is one of key strengths of the heterogeneous integration.

The heterogeneous silicon photonics platform opens up a new possibility in improving the coherence by providing a mechanism to separate the photon resonator and highly-absorbing active medium [4]. The III-V active medium allows for efficient electrical pumping, while the low loss silicon waveguides allow for an increased total Q of the laser cavity. Lower losses reduce the number of excited carriers needed to reach threshold, which combined with the confinement factor optimization can reduce the spontaneous emission into the lasing mode. The transverse confinement is controlled by changing the widths of Si and III/V waveguides, and by changing the number of quantum wells in the active region. The longitudinal confinement is controlled by adjusting the length of passive section inside the cavity.

Microring-resonator-coupled semiconductor laser

Passive microring-resonator-coupled semiconductor lasers were proposed in 2001. In such a structure, an active region in the conventional Fabry–Perot cavity is coupled with a passive ring resonator. This is different from conventional ring lasers, where the active traveling wave ring resonator replaces the standing wave Fabry–Perot cavity. The ring inside the cavity improves side mode suppression ratio, linewidth, and decreases the frequency chirp. The concept can be extended to two or more rings, significantly improving the single-mode tuning range by utilizing the Vernier effect [5].

Using rings inside the cavity benefits the linewidth in two ways: (1) increasing the photon lifetime due to effective cavity length enhancement, and (2) providing negative optical feedback by slight detuning from the ring (resonator) resonance. Both mechanisms cannot be maximized at the same time, but there is an optimal point where the combined influence is maximized [6].

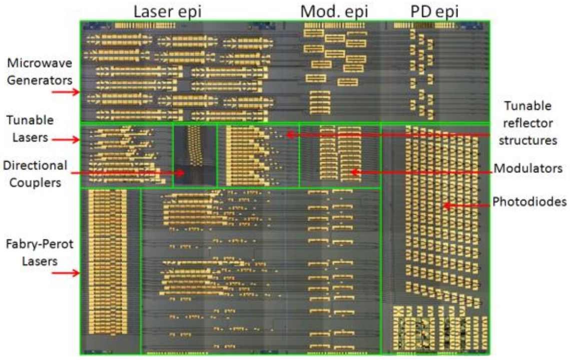

Figure 3. Microscope image of a die with marked regions using different thin-film epitaxial structures. Some devices are also labeled.

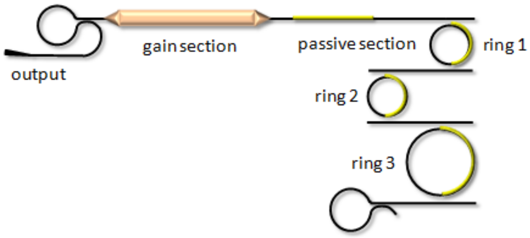

Figure 4. Schematic of narrow-linewidth laser with a high-Q ring inside the cavity. Theoretically such laser could have instantaneous linewidth below 1 kHz. [8]

By optimizing the design, we have constantly improved the performance of semiconductor lasers in terms of linewidth. The first generation of ring lasers featured a linewidth of 330 kHz. Second generation coupled ring resonator lasers have shown linewidth of 160 kHz and monolithically-integrated external-cavity lasers have brought the linewidth below 100 kHz across full tuning range with the record integrated linewidth of 50 kHz for a single-chip semiconductor laser [3]. An assembled hybrid design using butt-coupling between InP and Si chips with ring resonators have shown even better performance with linewidths lower than 15 kHz along the entire C-band and with record values at 5 kHz [7]. A possibility of further improving the linewidth by utilizing an integrated high-Q ring cavity-on-chip was explored [8]. Three potential strategies: with the high-Q ring used as an external cavity with optical feedback in all-pass or drop configurations, and with the high-Q ring being an integral part of the laser

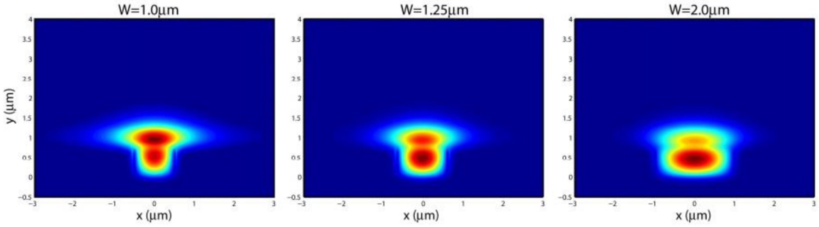

Figure 5. Simulated mode-profiles of heterogeneous silicon/III-V waveguide show control of mode profile and of confinement factor in active region by changing the width of underlying silicon waveguide.

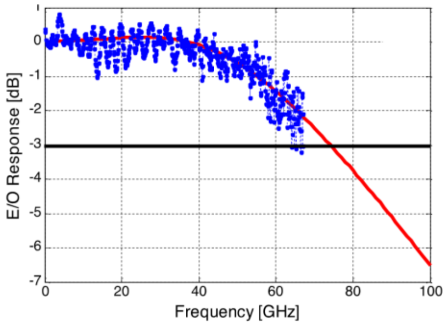

Figure 6. Measured (blue) and fitted (red) electro-optical response of distributed III-V on Si electroabsorption modulator showing extrapolated 3 dB bandwidth of 74 GHz. [9]

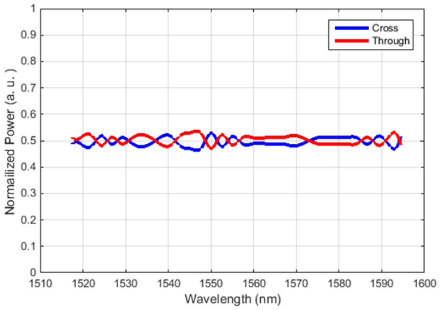

Figure 7. Measured performance of adiabatic coupler showing flat response in > 75 nm of bandwidth (limited by measurement setup)

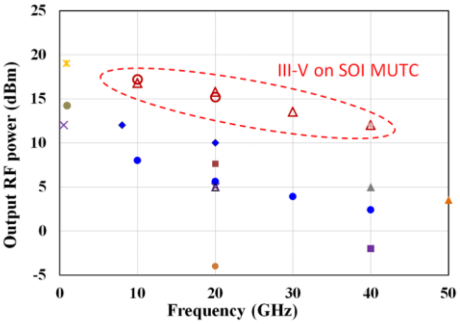

Figure 8. Output RF power of waveguide photodiodes at 1.55 µm wavelength. [10]

cavity (Figure 4) were studied. It was shown that sub-kHz linewidths should be attainable by using high-Q rings with ~0.5 dB/cm of propagation loss [8].

Semiconductor optical amplifier

Tunable lasers benefit from the addition of an SOA, since it allows the laser bias condition to be optimized for emission wavelength and side mode suppression ratio independently from the output power. Another advantage of introducing SOAs for microwave generator is the control and boosting of optical power before the detector providing higher RF powers. A key benefit of heterogeneous silicon photonics for this application is the ability to control the confinement factor by changing the width of underling Si waveguide (see Figure 5). With increase in confinement factor, the gain is increased, while with reduction, output saturation power is increased. The confinement factor also influences the spontaneous emission into the laser mode. As the confinement can gradually be controlled, a single optimal amplifier can be made. We have demonstrated unsaturated gains of 25.5 dB, input saturation power of 4.25 dBm, 65 nm of 3 dB bandwidth and 16 dBm of maximum output power.

Modulators

We have demonstrated III-V-on-Si electroabsorption modulator based on an asymmetric segmented electrode with measured modulation response that shows a 2 dB drop at 67 GHz and an extrapolated 3 dB bandwidth of 74 GHz (Figure 6) [9]. Large signal measurements show clearly open eye diagrams at 50 Gb/s. An extinction ratio of 9.6 dB for back to back transmission and an extinction ratio of 9.4 dB after 16 km transmission were obtained with a drive voltage of 2.2 V.

Photodetectors

For RF photonic applications low noise figure is crucial. One of the most straightforward methods to achieve low noise figure is to utilize photodiodes that operate at high photocurrent with high linearity. InP-based modified uni-traveling carrier (MUTC) photodiodes on SOI waveguides using a wafer-bonding technology with exceptional performance have been demonstrated [10]. The devices have low dark current <10 nA, internal responsivity of 0.95 A/W, 48 GHz bandwidth, and >12 dBm RF output power at 40 GHz. Using the same technology balanced photodiodes and photodiode arrays reached bandwidths of 14 GHz and 20 GHz, respectively, and 17 dBm RF output

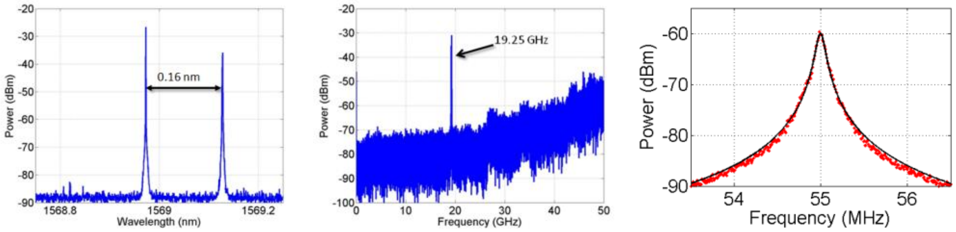

Figure 9. (left) Optical spectra of two lasers comprising a photonic microwave generator (captured with high-resolution 20 MHz optical spectrum analyzer) (center) RF beat tone after high-speed detector (right) Measured linewidth and Lorentzian fit (50 kHz) of narrow-linewidth widely-tunable laser with monolithically integrated external cavity [6].

power at 10 GHz. These are the highest RF output power levels at multi-GHz frequencies reported for any waveguide photodiode and photodiode array technology including native InP, Ge/Si, and heterogeneous integration.

Couplers

Couplers are a critical passive component for realizing integrated components. For the microwave generator, ideally one needs a 50:50 coupler to photodiodes and coupling in the range of 5-25% for the ring resonators used in tunable lasers. Various couplers have been demonstrated including directional couplers, multimode interference (MMI) couplers and adiabatic couplers. All passive devices benefit from the maturity of silicon processing. We believe that adiabatic or MMI couplers are a best choice for 50:50 split as they have greater process tolerance and are broadband. We have internally demonstrated adiabatic 50±3.3% couplers with < 0.5 dB insertion loss and more than 75 nm of bandwidth (limited by measurement setup) as shown in Figure 7. The downside of the adiabatic coupler is its fixed splitting ration and relatively long length of 600 µm. For the ring resonator coupling, we use directional couplers that allow for arbitrary splitting ratios and are much smaller, typically < 100 µm in length.

Conclusions

We believe that heterogeneous integration is the optimal way to realize photonic microwave generators as it allows for combination of low-propagation loss in Si (or Si_3N_4) waveguides with efficient light generation in III-V materials, gives the ability to continuously control the confinement factor and allows the utilization of different thin-film epitaxial layers for different components, allows optimization and fine-tuning the performance of each photonic microwave generator component.

Future work will be concentrated on improving the phase purity of lasers used to generate heterodyne beat signal, increasing the speed of photodiodes (e.g. traveling wave designs), increasing photodiode power handling capabilities at high frequencies, increasing the bandwidth of electroabsorption modulators above 100 GHz (reducing the metal loss) and using quantum-well lasers with higher output powers.

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