# Integrated Microwave Photonics

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***Abstract*—Microwave signal generation using the heterogeneous photonic integration platform is described. Preliminary results from a heterogeneously integrated photonic microwave signal generator are shown. Heterogeneous integration, as was recently demonstrated, allows for superior performance of certain devices compared to purely III-V devices and we outline the benefits it brings. Finally, we address narrow-linewidth tunable lasers as one of key components of low phase noise photonic microwave signal generators and show the possibility of achieving sub-kHz linewidths by utilizing on-chip high-*Q* ring resonators.**

***Keywords— Photonic integrated circuits, Heterogeneous integration, RF signals, Tunable lasers, Narrow-linewidth lasers***

## I. Introduction

As the bandwidth of electronic devices continues to increase, generating signals, testing and measuring has become more difficult. Operation of traditional electrical network analyzers, that cover the frequency range up to tens of gigahertz, may be extended to high frequencies by using frequency up-conversion. However, this necessitates use of additional hardware that is bulky, fragile, expensive and difficult to operate. Alternatively, signals may be generated optically using laser outputs that are combined and detected 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. Heterogeneous integration assembles many devices or optical functionalities on a single chip so that all the optical connections are on chip and require no external alignment. 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 devices than what has previously been demonstrated utilizing only III-V materials [1]. We therefore believe that heterogeneous integration platform is an excellent way to realize photonic microwave generators.

## II. Microwave generator

An on-chip photonic microwave generator, in its basic configuration, comprises of two lasers, at least one of which is tunable, a coupler that combines these two signals, booster semiconductor optical amplifier (SOA) and fast photodetector. We show a microscope image of such microwave generator in Fig. 1. Some preliminary measurements are shown in Fig. 2. For optimal performance one requires narrow-linewidth lasers as the width of the RF signal generated by beating the two lasers will be equal to the cross-correlation of the two linewidths. We turn to the specifics of narrow-linewidth lasers in Section III. The underlying waveguide platform should be low-loss. Losses as low as <0.5 dB/cm in C-band [2] and <0.7 dB/cm in O-band [3], with small bend radii, have been demonstrated in silicon platform. The booster SOA should have high-output saturation power and the photodetector should be high-power and high-speed. Heterogeneous platform allows for optimization of all the components due to the ability to individually change the widths of the Si waveguides and III-V mesa. Heterogeneously integrated waveguide-coupled photodiodes on SOI with 12 dBm output power at 40 GHz have been demonstrated [4]. The InP-based modified uni-traveling carrier photodiodes on SOI waveguides have internal responsivity of up to 0.95 A/W and have the highest reported output power levels at multi-GHz frequencies for any waveguide photodiode technology including native InP, Ge/Si, and heterogeneously integrated photodiodes. The added flexibility introduced by the heterogeneous process allowed simultaneous reduction of current crowding and a tailored absorption profile to reduce saturation effects via mode and bandgap engineering. Same flexibility can be utilized in designing the SOA. By changing the width of the underlying silicon waveguide, confinement factor in the active region can continuously be controlled. By increasing the confinement factor (narrow silicon waveguide), small signal gain is increased, while in the opposite end (low confinement factor) high output saturation powers are obtained. Loss and high-quality couplers are provided due to the maturity and high-quality of silicon processing. Finally one can add fast modulators to the microwave generator for more advanced signal generation and measurements. A distributed III-V-on-Si electroabsorption modulator based on an asymmetric segmented electrode with 74 GHz of bandwidth has already been demonstrated [5].

## III. 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 $\alpha$ that

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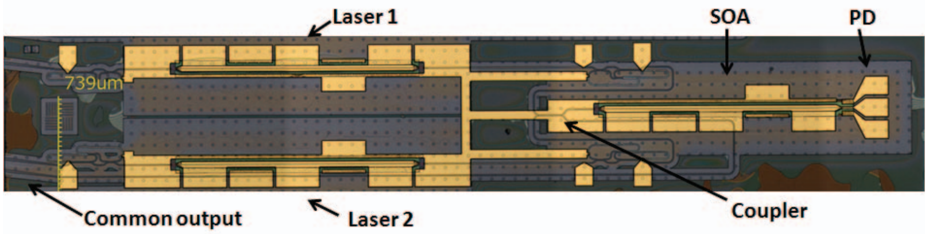
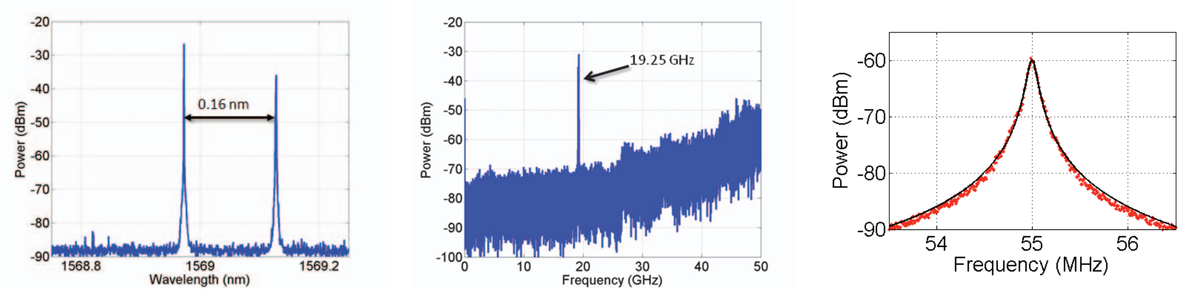



Fig. 1. Microscope image of the photonic microwave generator comprising of two tunable lasers, a coupler, booster semiconductor optical amplifier (SOA) and photodetector (PD). One arm of the 2x2 coupler goes to SOA and PD, other arm goes to the edge facet (common output).




(a) (b) (c)

Fig. 2. (a) Optical spectra of two lasers comprising a photonic microwave generator (captured with high-resolution 20 MHz optical spectrum analyzer) (b) RF beat tone after high-speed detector (c) Measured linewidth and Lorentzian fit (50 kHz) of narrow-linewidth widely-tunable laser with monolithically integrated external cavity [3].

characterizes the coupling between intensity and phase noise and is specific to semiconductor lasers due to carrier density fluctuations.

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 [6]. 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.

### *A. Microring-resonator-coupled semiconductor laser*

Passive microring-resonator-coupled semiconductor lasers were proposed in 2001 [7]. 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 [8].

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

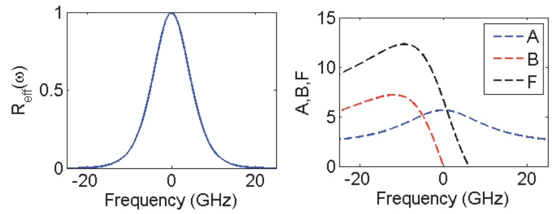



Fig. 3. (left) Normalized reflection of ring-resonator and cavity mirror combination (right) Linewidth reduction factor of the laser as a function of frequency offset from resonance calculated using eqs. 1,2,3 and 4 ($\alpha_H$=4). The combined effect of both contributions is maximized at slight offset to lower frequencies than the ring resonance. [3].

time, but there is an optimal point where the combined influence is maximized. The combination of ring resonators and cavity mirror (facet mirror, loop mirror, etc.) can be thought of as a frequency-dependent passive mirror with complex amplitude reflectivity $r_{eff}(\omega)$. The linewidth improvement due to feedback from this frequency dependant mirror is given by factor $F^2$ where $\Delta\nu$ and $\Delta\nu_0$ are the linewidths with and without the $r_{eff}(\omega)$ mirror (Fig. 22).

$$\Delta\nu = \frac{\Delta\nu_0}{F^2} \tag{1}$$

$$F = 1 + A + B \tag{2}$$

$$A = \frac{1}{\tau_{in}} \mathrm{Re}\left\{ i \frac{d}{d\omega} \ln r_{eff}\left(\omega\right) \right\} \tag{3}$$

$$B = \frac{\alpha_H}{\tau_{in}} \mathrm{Im}\left\{ i \frac{d}{d\omega} \ln r_{eff}\left(\omega\right) \right\} \tag{4}$$

where $\alpha_H$ is the linewidth enhancement factor. $\tau_{in} = 2n_{eff}L_a/c$ where $n_{eff}$ is the effective index of the gain section, $L_a$ is the length of active region and $c$ is the speed of light. The $A$ term, corresponding to the linewidth reduction from reduced longitudinal mode confinement, is often denoted as the ratio of the external (passive section) cavity path length to the gain

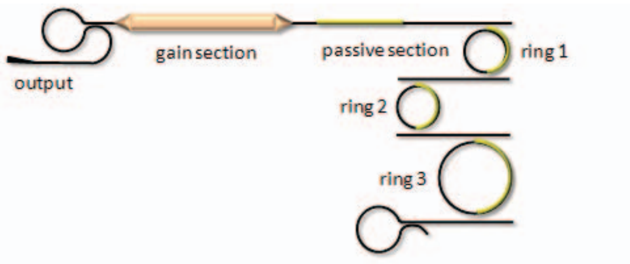



Fig. 4 Schematic of laser with high-$Q$ ring (ring 3) inside the cavity.

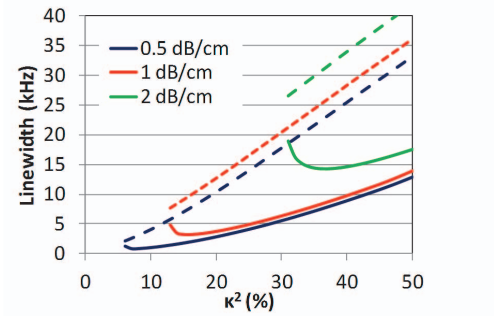



Fig. 5 Instantaneous linewidth as a function of high-$Q$ ring coupling strength for various propagation losses. (Full lines) Minimum linewidth with detuning, (Dashed lines) Linewidth at ring resonance. [11]

section path length. As the effective length of a ring resonator is maximized at the resonance, the $A$ factor is maximized when the ring is placed exactly at the resonance. For a weakly coupled rings ($\kappa << 1$), the effective length will be largely extended and can even dominate the total cavity length.

The $B$ term corresponds to the reduction from the negative feedback effect where a decrease in wavelength increases reflectivity (increasing photon density in the cavity) and hence decreases carrier density, which in turn causes the wavelength to increase due to the carrier plasma effect. The phase condition in the cavity can be used for a slight detuning of the laser oscillation with respect to the minimum cavity loss condition (resonator resonance). This negative feedback effect occurs only on the long wavelength side of the resonance and is optimum at the wavelength of highest slope in the transmission spectrum. At the ring resonance, i.e. the optimal condition for the $A$ term, it is equal to zero. On the short wavelength side of the resonance, the effect is reversed and operates in positive feedback, broadening the linewidth. The combined effect of $A$ and $B$ is at maximum when the laser is slightly detuned on the long wavelength side (lower frequency), as shown in Fig. 3. We believe that these two mechanisms - the effective cavity length enhancement and the negative optical feedback - are responsible for the exceptional linewidth results shown by ring-coupled lasers. As the loss in rings ultimately limits the performance (obtainable $Q$), the low-loss silicon waveguide platform is the key enabler of the exceptional performance shown by recent devices.

By optimizing the design, we have constantly improved the performance of semiconductor lasers in terms of linewidth. First generation of ring lasers featured a linewidth of 330 kHz [9], coupled ring resonator lasers have shown linewidth of 160 kHz [10] 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 [2].

### *B. Toward sub-kHz linewidth*

A possibility of further improving the linewidth by utilizing an integrated high-$Q$ ring cavity-on-chip was explored [11]. 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 cavity (Fig. 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 (Fig. 5).

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