Fully integrated heterodyne microwave generation on heterogeneous silicon-III/V

Jared C. Hulme,[1]* Jin-Wei Shi,[3] MJ Kennedy,[1] Tin Komljenovic,[1] Bogdan Szafraniec,[2] Doug Baney,[2] and John E. Bowers[1]

[1]Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106 USA
[2]Keysight Laboratories, Keysight Technologies, Santa Clara, California 95051, USA
[3]Department of Electrical Engineering, National Central University, Taoyuan City, Taiwan

*email: jaredhulme@ece.ucsb.edu

***Abstract*— We demonstrate a fully integrated tunable photonic millimeter wave generator. Optimized III/V epi for gain, modulator, and photodiodes are bonded to silicon-on-insulator to allow a multi-functional photonic integrated circuit. Microwave signals up to 90 GHz are demonstrated.**

Keywords – microwave generation; millimeter wave generation; semiconductor laser; photodiode; heterogeneous silicon-III/V; photonic integrated circuits

I. INTRODUCTION

As electronic devices continue to expand into larger bandwidths, testing, measuring, and signal generation become increasingly difficult. Traditional electrical network analyzers working at tens of gigahertz are bulky, fragile and expensive. Higher frequencies can be reached through the use of frequency up-conversion but that increases the cost and the complexity of the system.

In recent years, millimeter wave creation on photonic platforms have gained attention. Signals as high as 200 GHz have been generated[1] optically using the heterodyne beat tone at the difference between the two laser output frequencies. By tuning one of these lasers the heterodyne beat can be swept over hundreds of gigahertz, far exceeding the traditional design.

Further work has focused on photonic integration due to the natural desire to drive down costs, power consumption and size. Heterogeneous integration allows many devices and optical functionalities to be integrated onto a single chip without the need for external optical alignment that may result in optical losses and complexity of packaging. Additionally, recent developments in the platform have shown that heterogeneous integration not only allows for reduced costs but also produces devices of equal or superior performance to devices found solely in III/V materials.

In this work we demonstrate a fully integrated micro/millimeter wave generator on the hybrid silicon-III/V platform with generation up to 90GHz. The bandwidth of this device spans microwave and millimeter waves.

II. DESIGN AND FABRICATION

Our chip consists of two tunable lasers with individual phase modulation feeding a fast photodiode through a directional coupler. An off-chip port is also provided for monitoring the laser wavelengths or using an external photodetector. An RF signal is generated from detection of the intensity beat tone of the combined lasers on the photodiode or external detector. The lasers are tuned to generate tones at different frequencies. Modulation applied to one or both of the lasers is mapped on the generated microwave signal.

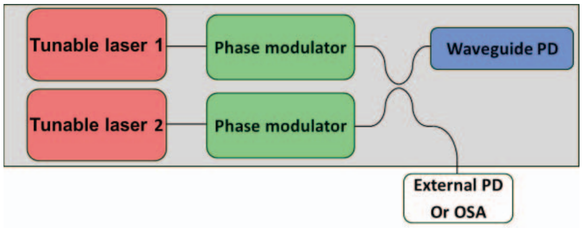

Fig. 1. Design schematic for integrated photonic microwave generator.

The heterogeneous silicon-III/V platform is fabricated by bonding InP epi directly onto waveguides on an SOI wafer with a thin (20 nm) oxide layer in between. The epi is patterned lithographically to create tapers such that the mode transfers adiabatically from being confined mostly in the silicon to an overlap of both.

This research was supported by Keysight Technologies.

Three different epi stacks were designed to optimize for gain, modulation and detection while still being process compatible. These were bonded to the same die and processed simultaneously. The laser epi contains three quantum wells centered at 1545 nm. The modulator epi contains 15 quantum wells centered at 1360 nm. The photodiode epi is a p-i-n structure with a 400 nm absorber region.

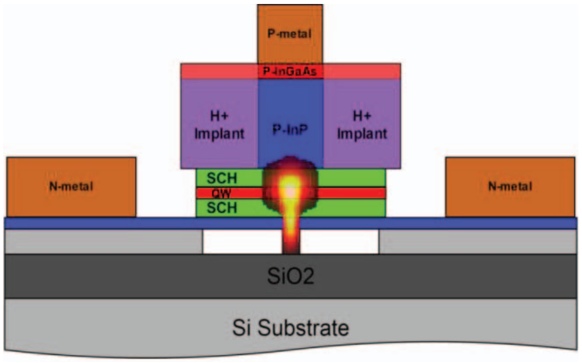

Fig. 2. Illustration of III/V diode cross-section with simulated mode overlay.

One of the benefits of the heterogeneous platform is the low loss waveguides possible in silicon. Utilizing these low losses, high Q ring cavities can be realized, allowing for low linewidth lasers. Our laser consists of a 1200 μm long gain section with a loop mirror designed for 100% reflectivity and a coupled-ring resonator (CRR) mirror, similar to that demonstrated in [3][4]. Previous results for a two-sided CRR showed linewidths as low as 160 kHz. With the 1xCRR design we expect low linewidths as well as greater simplicity in wavelength tuning. The rings are design to be 337 and 368 μm in circumference with $\kappa 1 = 36\%$ and $\kappa 2 = \kappa 3 = 2.25\%$.

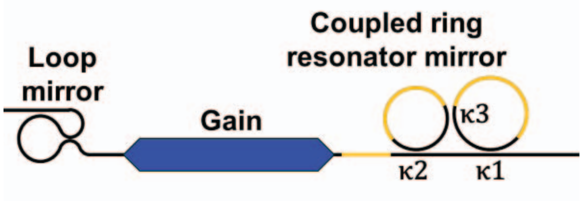

Fig. 3. Illustration of a 1x coupled-ring resonator laser.

The photodiodes for this chip have a 4 μm wide, 30 μm long and 400 nm thick absorber region.

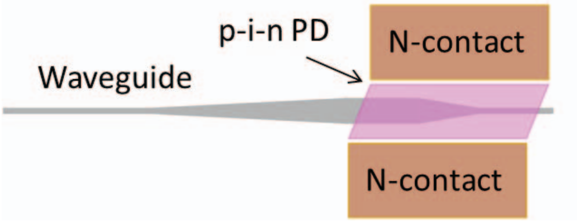

Fig. 4. Cartoon of p-i-n waveguide photodiode design.

III. RESULTS

A. *Lasers*

The CRR tunable lasers showed promising results. They had a side mode suppression ratio (SMSR) greater than 45 dB and approximately 40 nm of tuning. Narrow tuning over 1 nm was also demonstrated which is sufficient to cover our photodiode bandwidth.

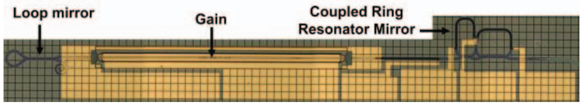

Fig. 5. Optical microscope image of CRR laser.

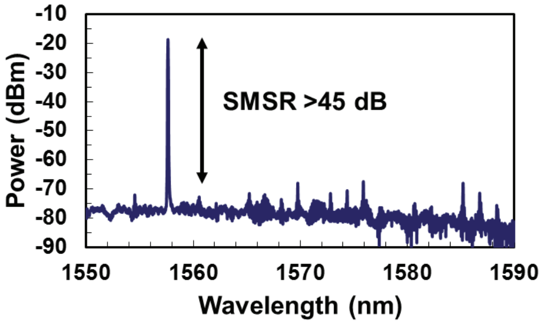

Fig. 6. Optical spectral of a 1xCRR laser showing 48 dB SMSR.

B. *Photodiodes*

The photodiodes were characterized from near DC to 67 GHz using a high-speed probe and a lightwave component analyzer (LCA). Additional measurements were performed with a 60-90 GHz waveguide probe and power sensor. At 1mA of photocurrent and -5V bias, photodiodes showed a 3dB bandwidth of 67 GHz (Fig. 8). The saturation output power was -8.2dBm at 70 GHz with a saturation current of 9 mA. The DC internal responsivity was between 0.4 and 0.5 A/W from 1520 nm to 1600 nm (Fig. 9).

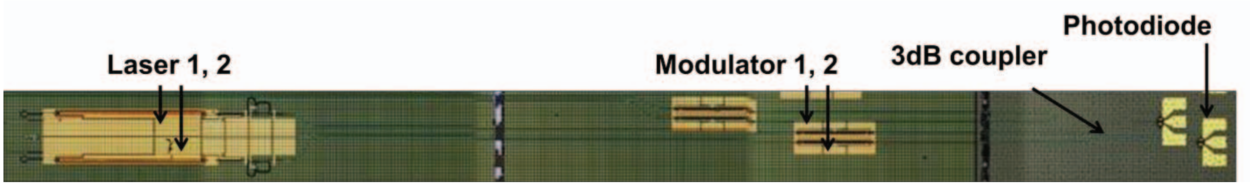

Fig. 7. Optical microscope photo of completed integrated microwave generator including two 1xCRR lasers, phase modulators, a 3dB directional coupler, and on-chip photodiode.

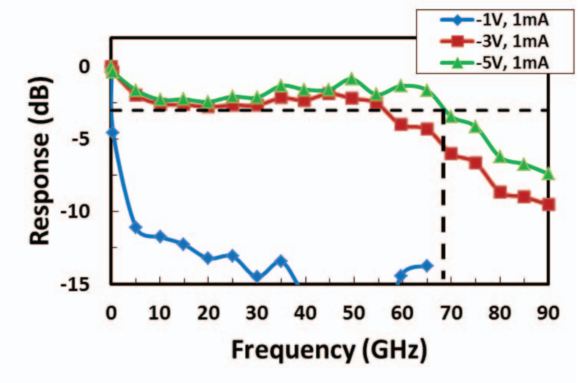

Fig. 8 Frequency response of a 4x30 µm photodiode. At -5V bias a 3dB bandwidth of 67 GHz is shown.

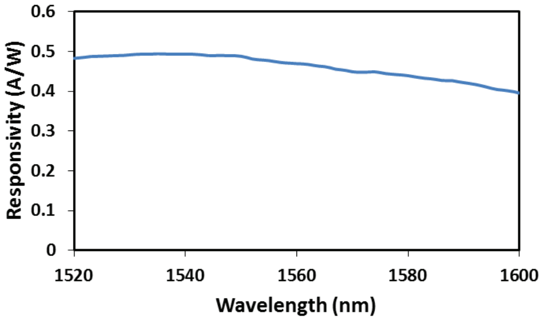

Fig. 9. Responsivity of the photodiode at DC.

C. *Integrated Chip*

Testing of the integrated chip included probe cards for the lasers and high-frequency probes for the photodiodes. The signal for the integrated device was generated on-chip, so an electro-spectrum analyzer was used instead of the LCA for measurements up to 50 GHz. The 60-90 GHz waveguide probe and power sensor were used for higher frequency measurements. A lensed fiber was coupled to the external port of the 3 dB coupler to monitor wavelength and relative laser powers. The test setup is shown in Fig. 10.

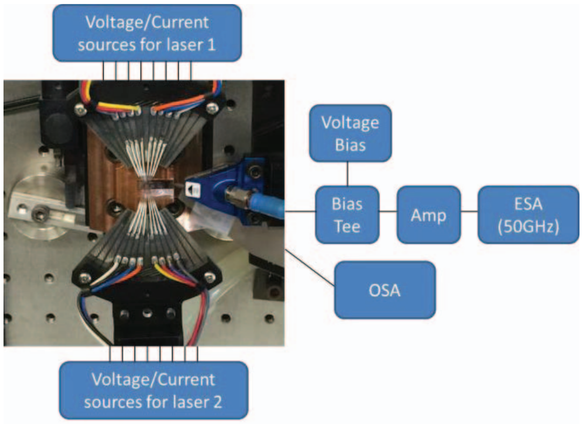

Fig. 10. Measurement setup for microwave generation.

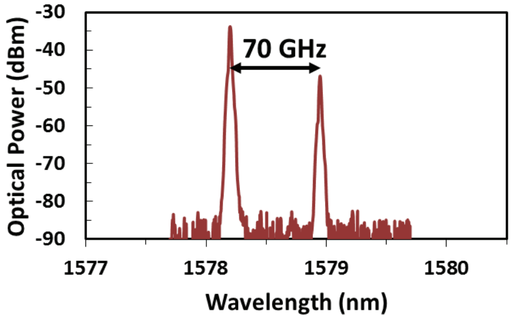

Fig. 11. Optical spectrum of two lasers tuned to a 70 GHz difference in frequency and observed from external port.

By tuning of one of the lasers we were able to demonstrate a swept microwave signal. Spectra of coarse tuning are shown in Fig. 12. Spectrum analyzer plots are shown from 1 to 45 GHz where it hits the ESA noise floor; measured microwave power is shown from 60 to 90 GHz. The noise floor of the high frequency power sensor is -60 dBm.

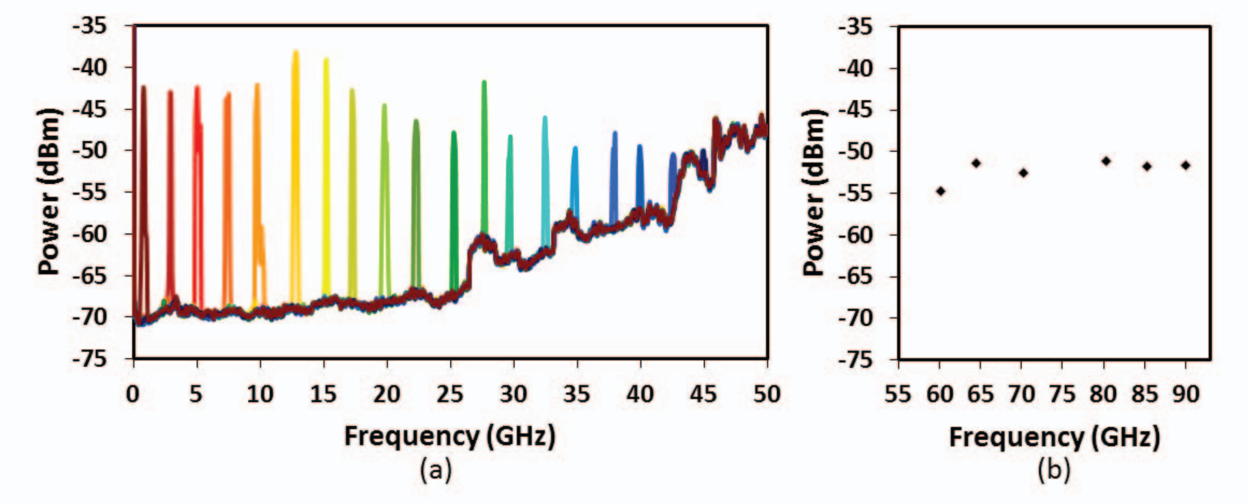

Fig. 12. (a) Measurements using an electro-spectrum analyzer demonstrating photonic microwave generation up to 45 GHz. (b) Additional measurements were made on a power meter using a 60-90 GHz high speed probe showing generation across that band.

IV. CONCLUSION

We have demonstrated a fully integrated microwave generator on a heterogeneous silicon-III/V platform utilizing three optimized bonded epi stacks. On-chip photodiodes show a 3dB roll-off at 67 GHz. Microwave signals as high as 90 GHz have been demonstrated.

ACKNOWLEDGEMENT

We thank Doug Baney and Bogdan Szafraniec of Keysight Technologies for their helpful discussion.

REFERENCES

[1] Rouvalis, E., Cthioui, M, van Dijk, F., Carpintero, G., Renaud, C.C., Seeds, A.J., “170 GHz Photodiodes for InP-based photonic integrated circuits,” IEEE Photonics Conference, (2012)

[2] Tin Komljenovic, Michael Davenport, Jared Hulme, Alan Y. Liu, Christos T. Santis, Alexander Spott, Sudharsanan Srinivasan, Eric J. Stanton, Chong Zhang, and John E. Bowers, "Heterogeneous Silicon Photonic Integrated Circuits," J. Lightwave Technol.34, 20-35 (2016)

[3] S. Srinivasan, M. Davenport, T. Komljenovic, J. Hulme, D. T. Spencer and J. E. Bowers, "Coupled-Ring-Resonator-Mirror-Based Heterogeneous III–V Silicon Tunable Laser," IEEE Photonics Journal, vol. 7, no. 3, pp. 1-8, (2015).

[4] J. E. Bowers, T. Komljenovic, J. C. Hulme, "Using narrow-linewidth lasers for rapidly tunable microwave signal generators," Invited Talk, Proc. SPIE 9836, Micro- and Nanotechnology Sensors, Systems, and Applications VIII, 983611 (2016)

[5] John E. Bowers, “Integrated microwave photonics”, Plenary Talk International Topical Meeting on Microwave Photonics, (2015)