III-V on silicon micro-photonic circuits for the frequency downconversion of RF signals

III-V ON SILICON MICRO-PHOTONIC CIRCUITS FOR FREQUENCY DOWNCONVERSION OF RF SIGNALS

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I. INTRODUCTION:

RF frequency downconverters are of key importance in communication satellites. Classically, this is implemented using an electronic mixer. In this paper we explore the use of photonic technology to realize the same functionality. The potential advantages of such an approach compared to the classical microwave solutions are that it is lighter weight, has lower power consumption and can be made smaller if photonic technology is used. An additional advantage is the fact that the optical local oscillator (LO) reference can easily be transported over longer distances than the equivalent LO signal in the microwave domain due to the large bandwidth and low loss and dispersion of optical fiber. Another big advantage is that one can envision the use of short pulse trains as the LO – starting off from a sinusoidal RF reference – in order to exploit subsampling. Subsampling avoids the need for high frequency LO references, which is especially valuable if a downconversion over several 10s of GHz is required. In this paper we present the operation principle of such a photonic frequency downconverter and describe the performance of the developed micro-photonic building blocks required for this functionality. These micro-photonic building blocks are implemented on a III-V semiconductor-on-silicon photonic platform. The components include a micro-photonic hybridly modelocked laser, a 30GHz electroabsorption modulator and an intermediate frequency (1.5GHz) photodetector.

II. OPERATION PRINCIPLE OF THE ELECTROPHOTONIC FREQUENCY CONVERTER:

The electrophotonic frequency converter consists of a short-pulse source (driven by an RF local oscillator signal) that is injected into a high-speed modulator that is driven by the signal to be downconverted. Effectively this implies that the intensity of consecutive optical pulses at the output of the modulator is proportional to the applied RF signal (when the modulator is used in its linear regime). In other words, the RF signal is sampled by the short-pulse train, which hence, after envelope detection on a photodetector results in an RF spectrum that contains replicas of the original RF signal spectrum spaced by the repetition frequency of the modelocked laser [1]. By selecting a proper repetition rate an aliasing-free downconversion can be realized this way. In this project we target the downconversion of Ka-band signals (27.5-30 GHz) to L-band (1.25-1.75GHz). A 5^{th} harmonic downconversion was selected for the implementation, requiring a pulse repetition rate in the range of 5Gsamples/s.

The conversion efficiency of such an electro-photonic frequency converter unit can be calculated to be

$$G_{IF}(\omega) = \frac{R_i}{R_0} R_L{}^2\, G_{FE} G_{IF} |H_{RF}|^2 |H_{IF}|^2 . \left(R.A.\frac{\pi}{V_\pi(0)} S_{21,MOD}(\omega) S_{21,Det}(\omega). P_0\right)^2 e^{\left(\frac{-(2\pi N f_s t_0)^2}{2}\right)} \tag{1}$$

in which R_i, R_o and R_L are the load impedances (all assumed 50Ω), G_{FE} and G_{IF} are the front-end and IF amplifier gains, $|H_{RF}|^2$ and $|H_{IF}|^2$ represents the insertion loss of the input image rejection filter and IF output filter respectively. The second part of the equation comprises all parameters of the photonic building blocks: the photodetector responsivity R, the insertion loss of the modulator A, the V_{pi} of the modulator, the S21 parameter of the modulator (at 30GHz in our specific application) and that of the photodetector (at 1.5GHz in our specific application). P_0 is the average output power from the pulsed laser source. The last term describes a conversion penalty due to the finite duration of the pulses, corresponding to a power reduction of the Nth RF harmonic of the pulse train envelope compared to the fundamental one.

III. MICRO-PHOTONIC BUILDING BLOCKS

A. III-V on silicon photonic platform

The components required for the electro-photonic frequency converter can all be implemented on a III-V semiconductor platform (InP/InGaAsP). However, better performance can be expected when integrating such III-V devices on a passive silicon photonic platform that provides low-loss passive waveguide circuits and high-resolution lithography for the definition of e.g. grating structures. The integration of III-V material onto such a platform is done through adhesive die-to-wafer bonding in which a III-V die, comprising the III-V epitaxial layer stack is bonded epi-side down onto the silicon waveguide circuit using DVS-BCB as the transparent polymer bonding agent. After bonding, the III-V substrate is removed and the III-V component is fabricated lithographically aligned to the underlying silicon photonic circuit [2]. The optical coupling between the 400nm thick silicon device layer and III-V layer (and vice versa) is done through an adiabatic taper structure [3]. In this project 3 basic components are developed: a hybridly modelocked laser, an electroabsorption modulator and an IF-band photodetector, which we will detail in the following subsections.

B. III-V on silicon modelocked laser

Semiconductor mode-locked lasers generating short (~ps) optical pulses at GHz repetition rates are of interest in a range of applications due to their compact size, low power consumption and ruggedness. In the electrophotonic frequency converter application low phase noise performance is of paramount importance. Fundamentally, the noise performance is determined by the spontaneous emission generated in the amplifier section of the mode-locked laser. Therefore, limiting the length of the semiconductor optical amplifier and realizing a low-loss optical cavity, consisting for a large part out of passive waveguides is key. This can be realized on a III-V semiconductor platform by active-passive integration. However, the passive waveguide losses on a III-V semiconductor platform are typically in the 2-3dB/cm range, thereby inducing substantial loss when long cavities (low repetition rates) are required. Replacing the III-V passive waveguide circuit by a silicon photonic integrated circuit can reduce the cavity loss, due to the well-developed CMOS fabrication technology, used to realize such waveguides. Moreover, at telecom wavelengths also the two-photon absorption losses are substantially lower in silicon compared to InP-based waveguides, thereby creating less excess loss due to the high peak power nature of the optical pulses traveling in the mode-locked laser cavity.

Two types of modelocked lasers were compared: a linear cavity geometry with a central saturable absorber to work in colliding pulse mode and a ring based geometry, also working in colliding pulse mode, but where both pulse trains couple to a separate output, as shown in Fig. 1. The longitudinal cross-section of the III-V semiconductor optical amplifier and saturable absorber is shown in Fig. 2. A III-V/Si taper structure is used to couple the III-V amplifier sections to the silicon waveguide circuit. Since in the passive modelocking regime the phase noise specs for the EPFC could not be reached, hybrid modelocking was required using an external LO. In this approach the residual phase noise from the modelocked laser was very low. Depending on the driving conditions, 2 to 5ps wide optical pulses were generated and the average output power of the modelocked laser reached 6dBm. The output spectra of both the linear cavity and ring-based cavity over a wide frequency range are shown in Fig. 3 (a) and (b) (50 GHz and 25 GHz) respectively. From these wide range spectra stronger spurious signals can be seen in the linear cavity geometry. Therefore, a linear cavity geometry will be used in the final EPFC. The generated RF comb is relatively flat, due to the short pulse duration.

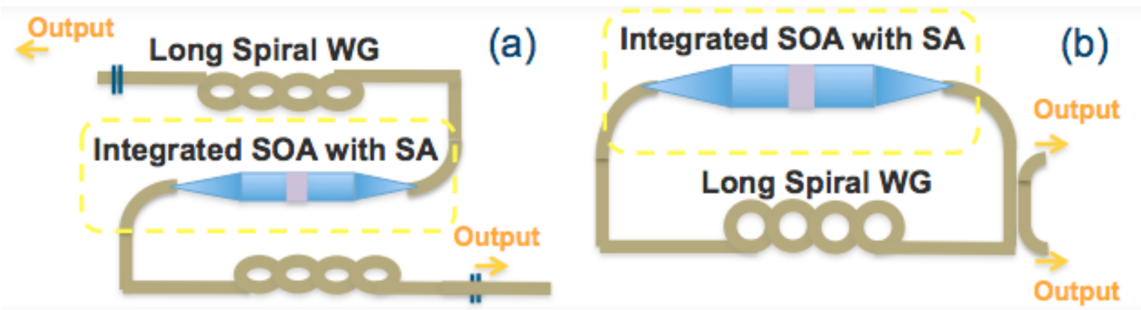

Fig. 1. Modelocked laser configurations: linear cavity based structure (a) and ring-based cavity (b)

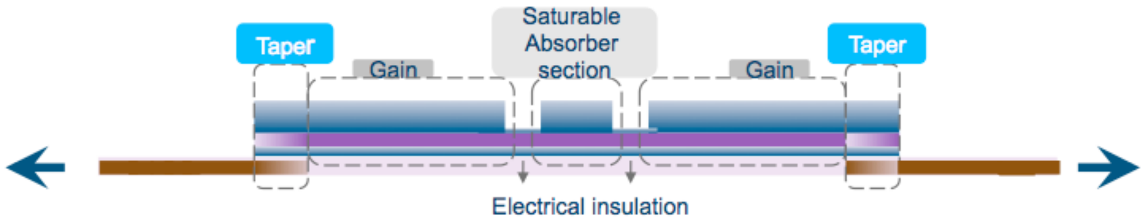

Fig. 2. Longitudinal cross-section of the III-V on silicon SOA/SA section

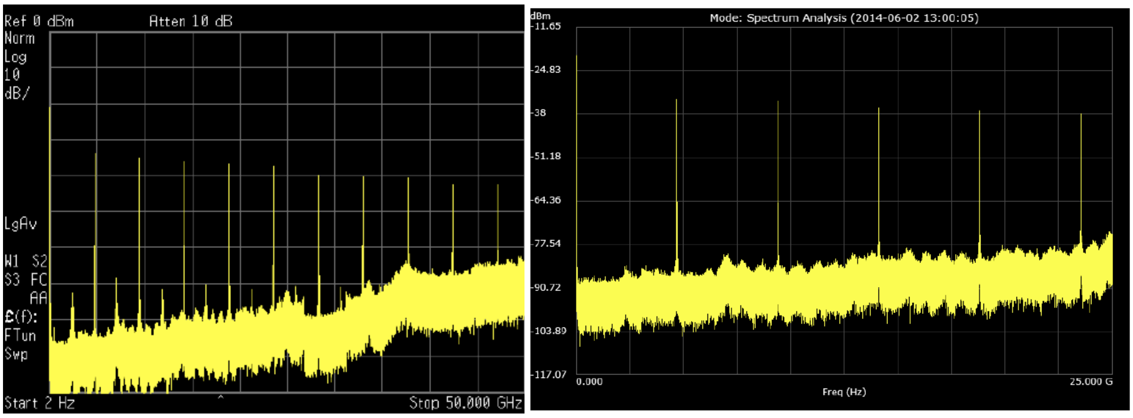

Fig. 3. RF output spectra of the linear cavity based structure (a) and the ring-based cavity (b)

C. III-V on silicon electroabsorption modulator

As the signal that is to be downconverted is in the 30GHz range, the optical modulator should support such bandwidth. This was realized by implementing a traveling wave electro-absorption modulator integrated on a silicon photonic platform. The cross-section of the III-V on silicon electro-absorption modulator is shown in Fig. 4. The traveling wave structure is terminated by a 50Ω impedance. The DC response of the fabricated electroabsorption modulator is shown in Fig. 5(a), while the normalized $|S21|^2$ response as a function of frequency is shown in Fig. 5(b) at -1.2V bias. From the DC response curves an equivalent Vpi of 8V can be deduced. The reason for such a high Vpi is not yet understood. The epitaxial layer structure is different from that of the modelocked laser. This can be accommodated by double die-to-wafer bonding and collective processing of the modelocked laser and EAM.

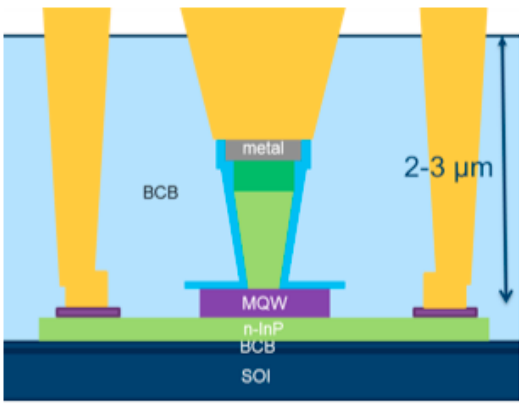

Fig. 4. Structure of the III-V on silicon electro-absorption modulator

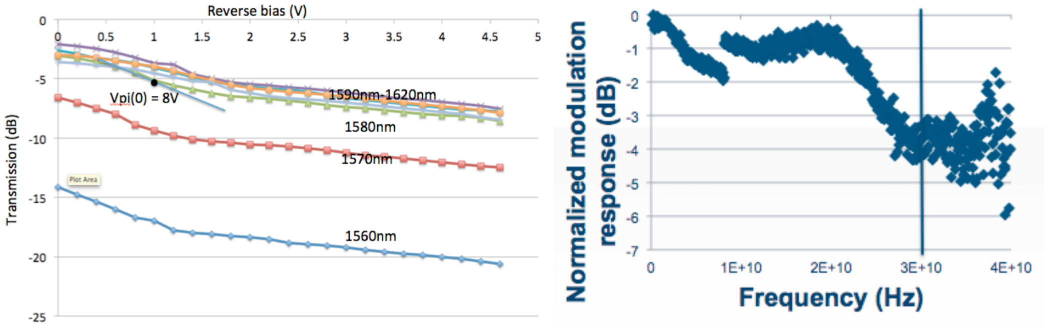

Fig. 5 Electroabsorption modulator characteristics: (a) DC response; (b) RF response.

D. III-V on silicon photodetector

The IF-band photodetector is implemented in the same layer stack as the laser, allowing straightforward co-integration of both opto-electronic components. A responsivity of 0.8A/W and a bandwidth far exceeding 2 GHz at 1V reverse bias was obtained.

IV. CONCLUSIONS

In this paper we present the development of the building blocks required to implement an electro-photonic frequency converter based on micro-photonics. A low phase noise modelocked laser, high bandwidth electroabsorption modulator and high responsivity photodetector is demonstrated on a III-V on silicon platform. All building blocks can be co-integrated to realize an ultra-compact Ka to L-band downconverter. A different topology can also be considered, where the optical LO signal is centrally generated and distributed to an array of electrophotonic mixers.

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