Space photonics roadmap: current and future challenges

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Abstract: This paper reports the characterization at device-level of micro-transfer-printed III-V-on-Silicon semiconductor optical amplifiers implemented on a hybrid photonic integrated circuit enabling distributed multiband coherent MIMO radar system for Earth observation.
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1. Introduction

Recently, photonics is leading to a profound transformation of different sectors such as telecommunications, Earth and space observation, defence, and remote sensing. In this context, microwave photonics represents a key field of expansion, offering various advantages over radio frequency (RF) systems such as very large bandwidth, electromagnetic immunity, and efficient RF distribution via radio-over-fiber systems [1]. These advantages, together with the low size, weight, and power consumption given by photonic integrated circuits (PICs), is also having a significant impact on photonic-based distributed Synthetic Aperture Radar (SAR) systems [2]. High-resolution images are constructed by fusing radar images acquired at different satellite positions in space. However, the lack of correlation among radar signals acquired by satellites stationed at different positions poses a significant challenge, particularly affecting the accurate detection of moving targets. To address this problem, an innovative strategy has emerged, aiming to enhance resolution, especially concerning dynamic objects. This approach involves merging radar backscattered signals obtained from a constellation of satellites observing the same Earth region from diverse angles, thus implementing a multi-static Multi Input Multi Output (MIMO) SAR systems in space [3]. However, achieving this requires precise synchronization of radar signals, a task that traditional methods like GPS timing struggle to accomplish. Therefore, we have recently proposed a multi-static MIMO SAR system based on a centralized generation and distribution of radar signals between the satellites of the constellation using photonics techniques (Fig.1(a)) [4]. This ensures coherence among signals across the radar constellation, eliminating the need for additional synchronization methods and increasing system resolution by enabling simultaneous generation and reception of multi-band signals. The system operates on two hierarchical levels: the primary satellite distributes/collects radar signals via free-space optical (FSO) links to/from secondary satellites, while the secondary satellites transmit/receive radar signals to/from the Earth's surface, relaying them back to the primary satellite through free-space optical links. The architecture of the PIC implementing the system functionalities is shown in Fig.1(b) for primary and secondary satellites. The circuit, designed to support up to three secondary satellites, includes complex functions realised through integrated photonics that require the compensation of the insertion losses of the different system components. In this context, semiconductor optical amplifiers (SOAs) can be employed to reduces such losses.

2. Preliminary PIC characterization

Among the different PIC technology materials, SOI is the most mature platform as it exploits established CMOS foundry processes (i.e., higher reliability and performance) while allowing low propagation loss and supporting highly confined optical modes. On the other hand, it lacks integrated light sources and amplification. A solution

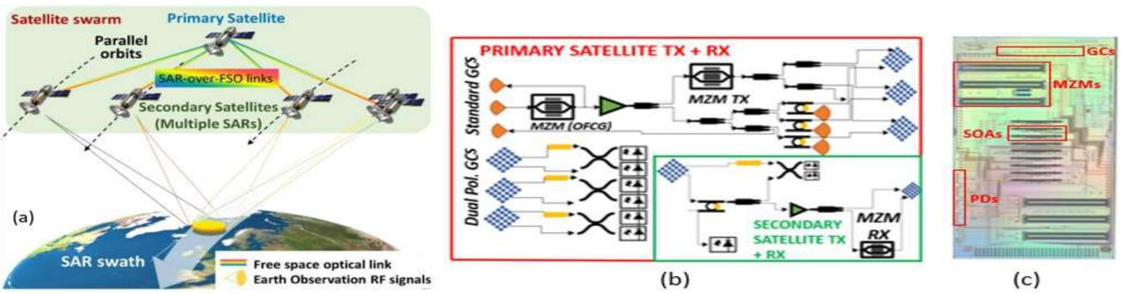

Fig. 1. (a) Proposed multi-static MIMO SAR approach; (b) Primary and secondary satellite architecture; (c) Image of the fabricated PIC.

to overcome this limitation is to integrate different material platforms (e.g., SOI and InP) into a single packaged PIC. Hybrid integration of various PICs offers the benefit of exploiting the unique properties of each material to provide specific functionality within photonic systems. The main drawbacks of this technique are that the assembly generally involves larger dimensions than other integration methods and introduces additional losses due to the coupling between PICs. Furthermore, it requires precise package alignment, which could potentially limit its application in harsh environments such as space. Conversely, heterogeneous integration combines two

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or more material platforms into a single PIC, providing functionalities similar to monolithic integration. In this context, several approaches have been pursued for wafer-level light source/amplification integration, such as flip-chip, die and wafer bonding, direct growth and deposition, and micro-transfer printing (μTP), each with their own advantages and drawbacks. The concept of μTP, illustrated in Zhang et al. [5], combines advantages from both flip-chip and wafer bonding integration techniques, enabling the production of large-scale photonic integrated circuits. Moreover, μTP C-band SOAs on a Si PIC has been recently demonstrated by Haq et al. [6], showing the potential of this technique for the scalable integration of III-V SOAs on a SOI wafer. In the following, we propose the characterization of the μTP SOAs reported in Fig 1(c). The PIC is placed on a temperature-controlled stage at 10°C and optically probed with a vertically coupled fiber array, using grating couplers to inject/extract light to/from the PIC. The loss of the trench hosting the SOA is 2 dB before μTP. The angle of the fiber array has been optimized to set the maximum transmission wavelength of the gratings on the SOA gain peak obtaining that, at 1550nm, the coupling loss per grating coupler is 5.5dB. In Fig.2(left), the SOA input power is varied measuring the output power for different bias current values, at T=10°C. The SOA gain saturates at a bias current value of 120mA, reaching a gain of 9dB for input power <-15dBm. In order to measure the spectral gain of the SOA, the wavelength of the input light is swept while the input power is kept at -10dBm, and the optical spectrum is observed. In Fig.2(right), an example of SOA spectrum is shown, with a bias current value of 100mA and T=10°C. The maximum output power is -14.3dBm, while the optical signal-to-noise ratio (OSNR) is 31.5dBm, with a resolution bandwidth of 0.1nm. Moreover, the temperature variation of the SOA gain as function of the wavelength is reported in Fig.3(left), keeping the input power at -7.7dBm and the bias current at 120mA. As expected, increasing the temperature leads to a decrease in gain, with a change of 8dB for a temperature variation from 5°C to 25°C. Finally, the SOA gain at a fixed temperature of 10°C and input power of -7.7dBm is observed in Fig.3(right), for different bias current values. A gain variation of 0.5dB is measured in the range 1550-1560 nm at 120mA. Once again, increasing the bias current value beyond 120mA results in a decrease in gain. Further activity will be on the characterisation of the performance at the system level and on the optimization of the PIC performance also considering the space qualification aspects.

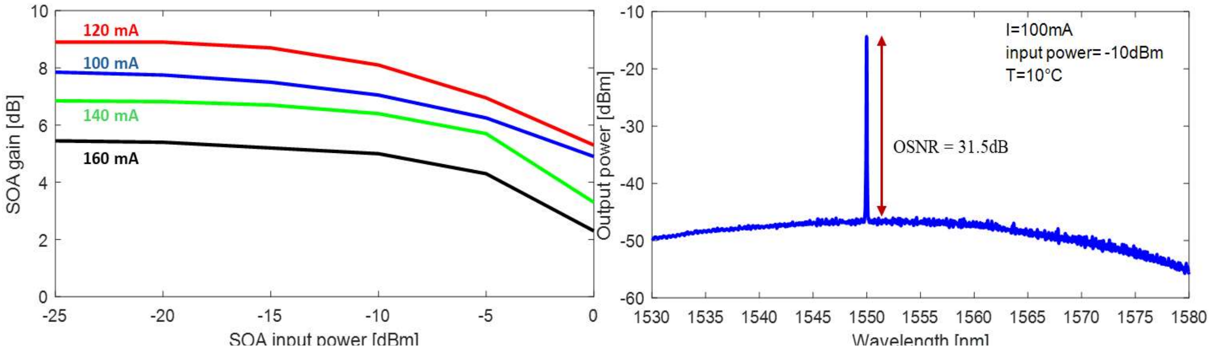

Fig. 2. (Left) Variation of the SOA gain with the SOA input power for various bias currents at T=10 °C and λ=1550nm; (Right) SOA output spectrum measured with an input power of -10dBm, bias current of 100mA and T=10 °C.

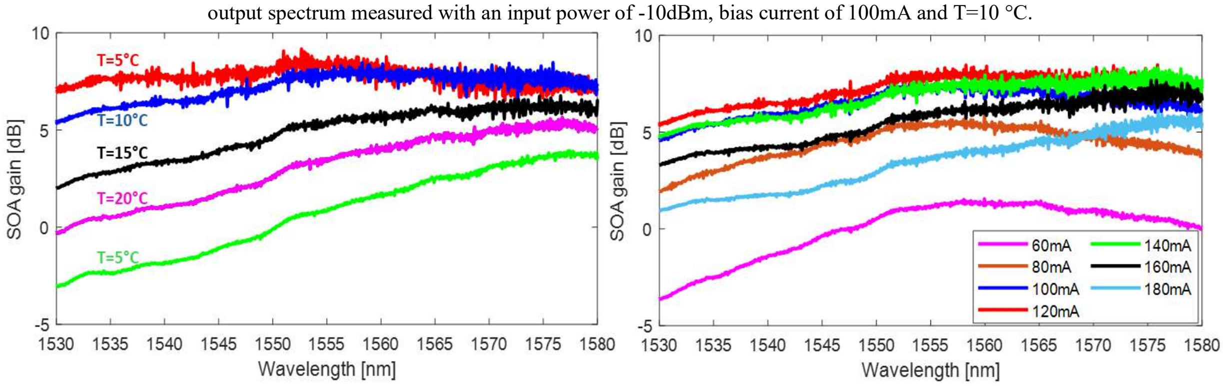

Fig. 3. (Left) Variation of the SOA gain with wavelength for various temperatures at bias 120 mA and input power of -7.7dBm; (Right) Variation of the SOA gain with wavelength for various bias currents at T=10 °C and input power of -7.7dBm.

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