Single-Chip Silicon Photonic Processor for Analog Optical and Microwave Signals

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A silicon photonic signal processor is presented, which consists of several subcircuits: two tunable laser sources with micro-transfer printed III-V amplifiers, a reconfigurable modulator capable of both phase modulation and amplitude modulation, and a programmable optical filter bank. With different configurations, we can use our signal processor to implement a variety of functions on both microwave signals and optical signals, including optical and radio frequency (RF) signal generation and filtering, electro-optical and opto-electric conversion, and RF signal multiplexing.

Introduction

Photonic integrated circuits (PIC) are widely used for optical signal transmission and manipulation of light on the surface of a chip. Among the various PIC platforms, silicon photonics offers low-loss passive components, high-speed modulators and germanium photodiodes, which makes it suitable for optical communications, signal procession and photonic sensors. Furthermore, silicon photonics is compatible with mature complementary metal oxide semiconductor electronics fabrication technology, which makes it easy to scale-up with a low cost in a massive production.

Silicon has an indirect bandgap, therefore the integration of III-V materials in silicon photonic circuits has been extensively explored. Among various technologies, transfer printing technology has emerged as a promising method that optimizes the utilization of costly III-V epitaxial substrates without changing the manufacturing of silicon photonics.

Benefiting from a large bandwidth and low propagation loss, photonic systems have been widely investigated for the generation, distribution, filtering and measure high-speed radiofrequency (RF) signals, which is called Microwave Photonics. By utilizing compact optical modulators, flexible optical filters, and low-noise photodiodes (PDs), PICs enable the implementation of complex RF signal processing with multiple functions. However, a fully integrated single-chip solution has not been presented yet.

In this work, we report the first single-chip signal processor developed with silicon photonics technology, capable of implementing programmable operations on both optical and RF signals, and the conversion between the two domains. The chip contains two widely tunable lasers, a reconfigurable modulator, optical switches, a fully tunable Mach-Zehnder interferometer (MZI) loaded with 4 ring resonators, and two high speed PDs. The silicon photonic chip is fabricated in imec's iSiPP50G process, and the tunable lasers are enabled by III-V semiconductor optical amplifiers (SOAs) with micro-transfer-printing technology.

Chip Layout and Packaging

The schematic of our signal processor is depicted in Fig. 1(a). It comprises four main blocks: a tunable laser block containing two lasers, a modulator block, an optical filter

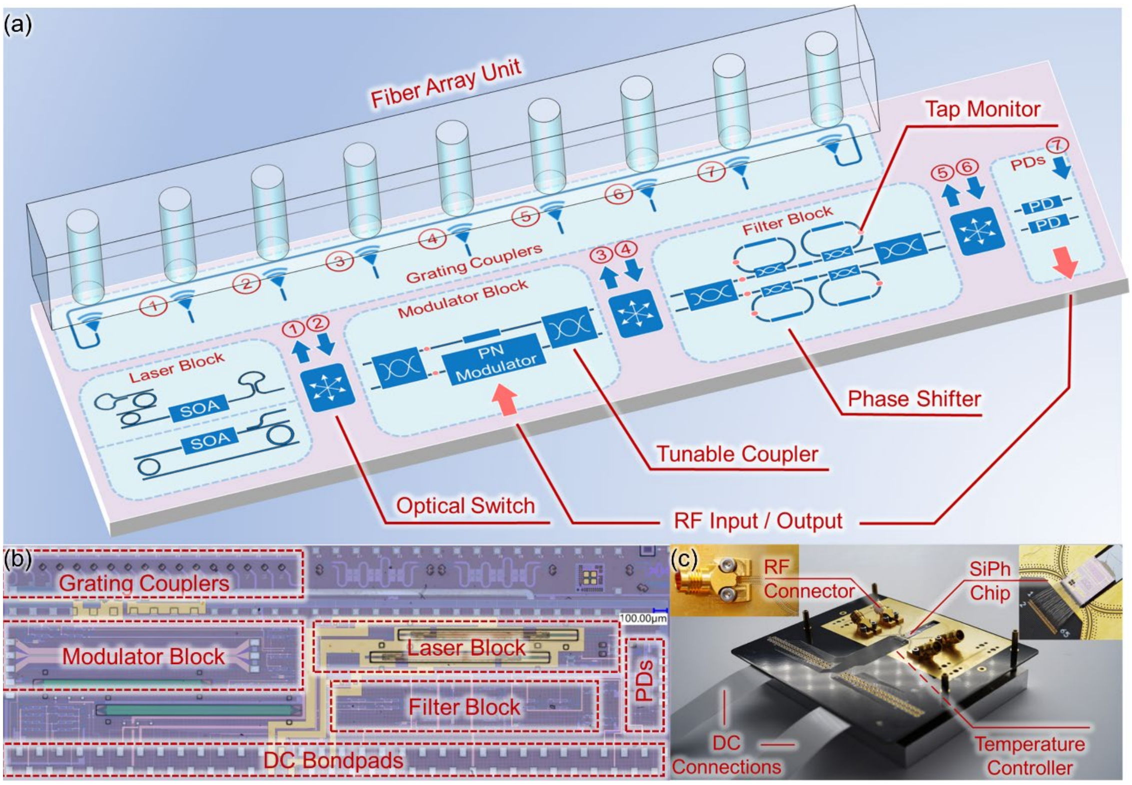

Fig. 1. (a) Schematic of the proposed signal processor. (b) Microscope image of the fabricated chip. (c) A packaged demonstrator with wirebonded controls and microwave connectors.

block, and a high-speed PD block. The longest optical path starts from the laser source, then the light is guided into the modulator circuit. The modulator can be configured to implement either phase modulation or intensity modulation. The RF signal modulated light is then directed into the optical filter block, which involves a four-ring-loaded MZI built with tunable couplers and tap monitors. Subsequently, the high-speed PDs can convert the filtered light signal into the microwave domain.

All four functional blocks are interconnected using optical switches, allowing the light signal to be routed in or out at each joint point. This architecture enables the signal processor to be configured for both optical and RF signal processing. The optical switches are implemented with single-stage MZIs or double-stage MZIs, depending on the specific coupling ratio requirements.

The complete photonic circuit consists of a total of 15 optical input/output ports, 3 RF channels (1 input and 2 outputs), 52 heater-based optical phase shifters, and 8 tap monitors. A processed demonstrator is shown in Fig. 1(b). With the significant number of optical and electrical connectors involved, a comprehensive packaging approach is required, to ensure the system's stability and robustness throughout its operation. A printed circuit board (PCB) is specifically designed and fabricated with high-speed materials, to ensure a low RF propagation loss, and the PCB is mounted on a temperature controller to stabilize the ambient temperature. Eventually, a packaged sample (without fiber array attachment) is shown in Fig. 1(c).

Characterization

A characterization of the blocks in the signal processor is shown in Fig. 2. Firstly, the laser block is measured by an optical spectrum analyzer (OSA). There are two laser designs in the laser block, which are based on a Fabry–Pérot (FP) cavity and a ring cavity,

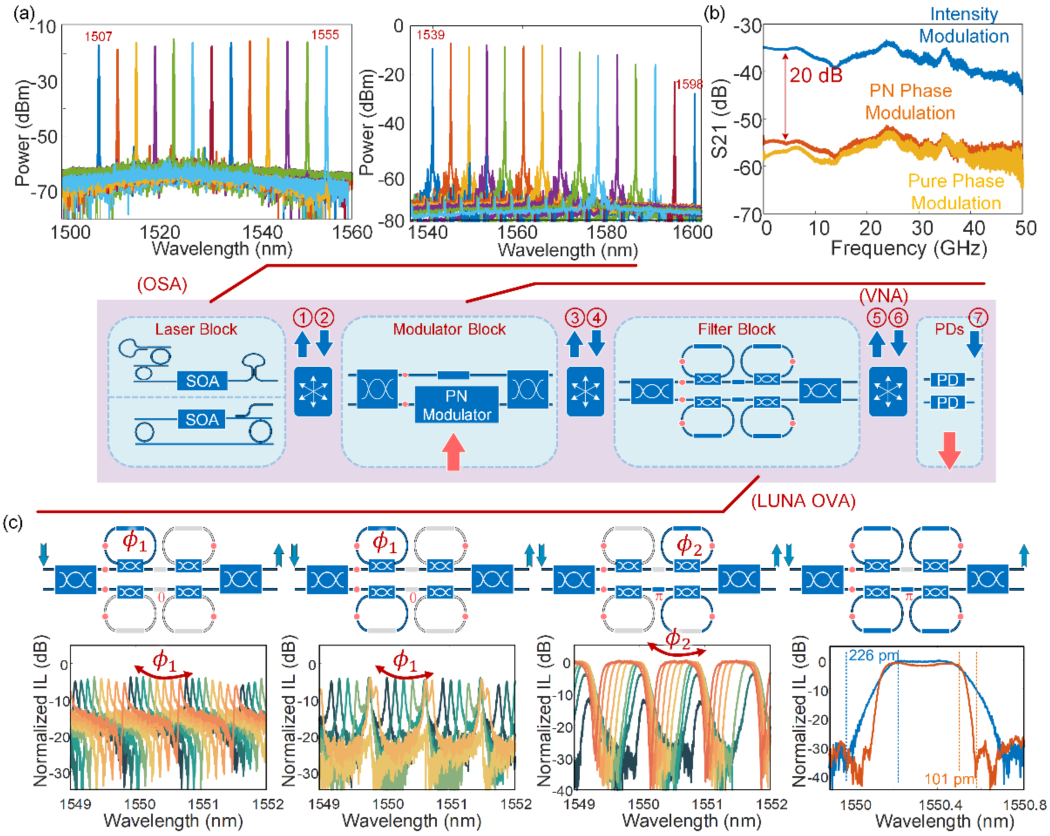

Fig. 2. Characterization of the blocks in the proposed signal processor. (a) Optical spectrum of the tunable lasers. (b) RF responses of the reconfigurable modulator. (c) Optical filtering responses of the tunable filter block. OSA: Optical spectrum analyzer. VNA: Vector network analyzer. OVA: Optical vector analyzer.

respectively. Two ring filters are used in each laser cavity to form a Vernier bandpass filter to select the longitudinal modes. Two SOA devices with different gain regions are transfer-printed in the cavities. By tuning the phase shifters in the ring filters and the laser cavities, we can alter the lasers wavelength. The tuning results are shown in Fig. 2(a).

Fig. 2(b) shows the RF frequency responses of the reconfigurable modulator. It is implemented by integrating a standard PN junction modulator into a tunable MZI comprising two tunable couplers (TC) and a phase shifter [1]. By manipulating the coupling ratios of the TCs and the phase shifter, a double-sideband modulated signal with two RF sidebands can be generated with a tunable phase relationship. This means that the RF signal generated from the modulated optical signal can match a phase-modulated signal, an intensity-modulated signal, or their combination. With this configurability, the modulator block can also be configured to optimize the modulation response.

The filter block in the signal processor is a ring loaded MZI, which contains two tunable rings on each arm of a tunable MZI, and its responses are shown in Fig. 2(c). The cascaded two rings on each arm work as a second-order all-pass filter, and the splitter and the combiner distribute lights through the rings and mix them up. The whole filter block can be programmed to be all classical bandpass filters if the coupling ratio of the splitter and the combiner is 0.5. And by tuning the coupling ratios simultaneously, this block can be a universal optical filter (limited by the filter orders).

In the PD block, two vertical germanium PIN photodiodes from imec library are used. They are designed to have a bandwidth of 50 GHz and an efficiency of 0.8 A/W.

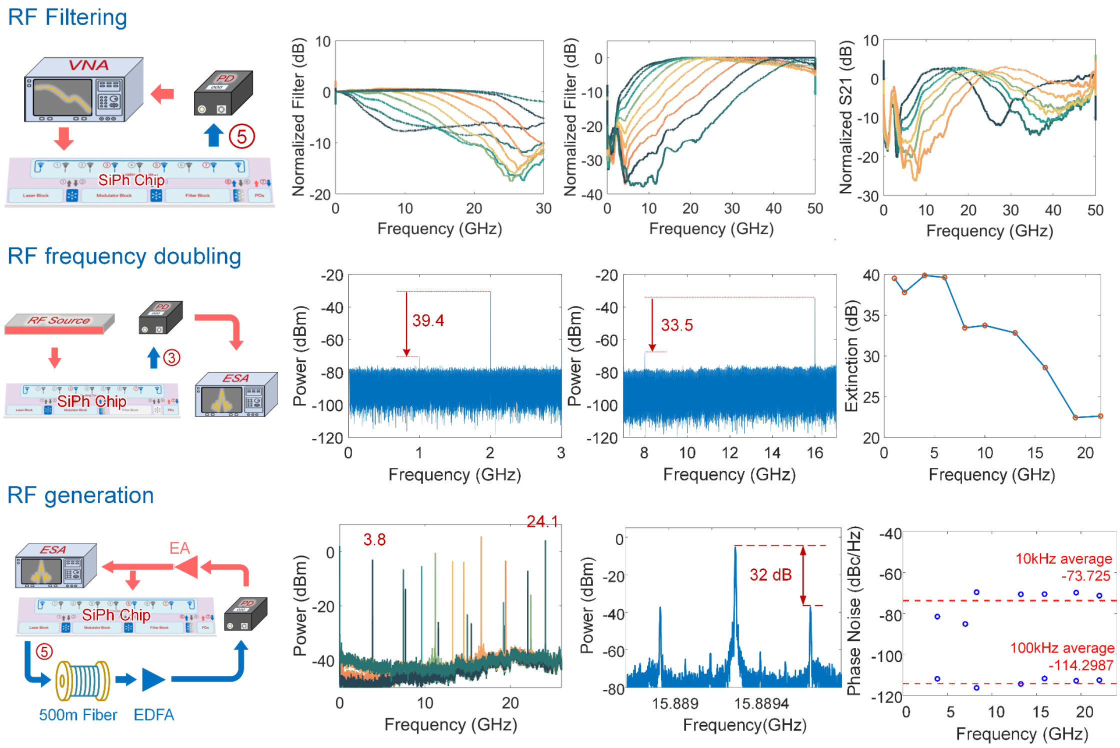

Fig. 3. Experimental setup and results for RF signals filtering, frequency doubling and generation.

RF Signal Processing

As shown in Fig. 3, the signal processor can also be used for the filtering, frequency multiplexing, and generation of the RF signals, using a combination of different blocks.

If a modulated light signal is guided into the filter block, the optical spectrum will be manipulated by the optical filter, thus the recovered RF signal will be filtered as well, making the full link as a microwave photonic filter. We just need cascaded ring filters to reach all classical bandpass RF filters in our system. Some tuning results are shown in Fig. 3, where the filter block is configured as two cascaded ring filters.

The reconfigurable modulator block can be used to achieve a carrier suppression modulation with a high extinction ratio, with feeding more lights into the PN modulator to compensate the extra loss [2]. With this scheme, the recovered RF signal will have a doubled frequency, and the results are shown in Fig. 3.

We can achieve an RF oscillation cavity with a tunable RF filter by feeding the outputs into the inputs, which named as an opto-electronic oscillator (OEO). Like a laser cavity, if the RF gain in an OEO is higher than the loss, the cavity will oscillate and generate an RF signal. By tuning the RF filters central frequency, we can tune the oscillation frequency. The tuning results are also shown in Fig. 3.

Conclusion

We proposed a single-chip signal processor, which can be used for the generation and filtering of both optical and RF signals, and the conversion between these two domains.

References

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