Fully integrated single-chip silicon photonic processor for analog optical and microwave signals

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We propose a single-chip analog signal processor built in silicon photonics technology, capable of implementing programmable operations on both optical and RF signals, and converting between the two domains. This chip contains a configurable modulator capable of both phase modulation and amplitude modulation, transfer-printed tunable laser sources, and a programmable optical filter bank. This chip can be configured to implement a variety of functions on both microwave signals and optical signals, including electro-optical and opto-electric conversion, optical and RF signal generation (tunable laser sources and opto-electronic oscillators) and filtering, and RF signal multiplexing.

Key words: Integrated photonics, Microwave photonics, Hybrid integration

1. Introduction

Photonic integrated circuits (PICs) are widely used for optical signal transmission and the manipulation of light on a chip. Among the various PIC platforms, silicon photonics stands out by offering low-loss passive components, high-speed modulators, and germanium photodiodes, making it highly suitable for optical communications, signal processing, and photonic sensors. Moreover, silicon photonics is compatible with mature complementary metal-oxide-semiconductor (CMOS) fabrication technology, enabling scalability and low-cost mass production.

We demonstrate a sophisticated, self-contained silicon photonic processor that is programmable for processing both optical and microwave signals, with the ability to convert signals between the two domains. Built on the standard iSiPP50G silicon photonics platform from imec, the engine integrates nearly all key functionalities of silicon photonics. To incorporate an on-chip light source, we employed micro-transfer printing to integrate an indium phosphide (InP) optical amplifier.

This chip, which combines tunable lasers, high-speed electro-optic modulators, detectors, and a programmable optical filter, represents one of the first demonstrations of a fully "black-box" microwave photonics processing engine. For users processing analog RF signals, the internal optics of the chip are entirely abstracted. With highly programmable internal signal flow, this chip can accommodate any combination of optical and microwave input and output signals.

Equipped with optical connections and supporting devices, our photonic chip functions as a high-speed transmitter or receiver, a tunable optical or microwave filter, a frequency converter, or a tunable opto-electronic oscillator (OEO). Its robust performance is ensured using thermo-optic tuners, and the control and calibration of the entire chip can be carried out in the electrical domain using strategically placed optical monitor detectors throughout the chip.

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2. Chip Layout and Packaging

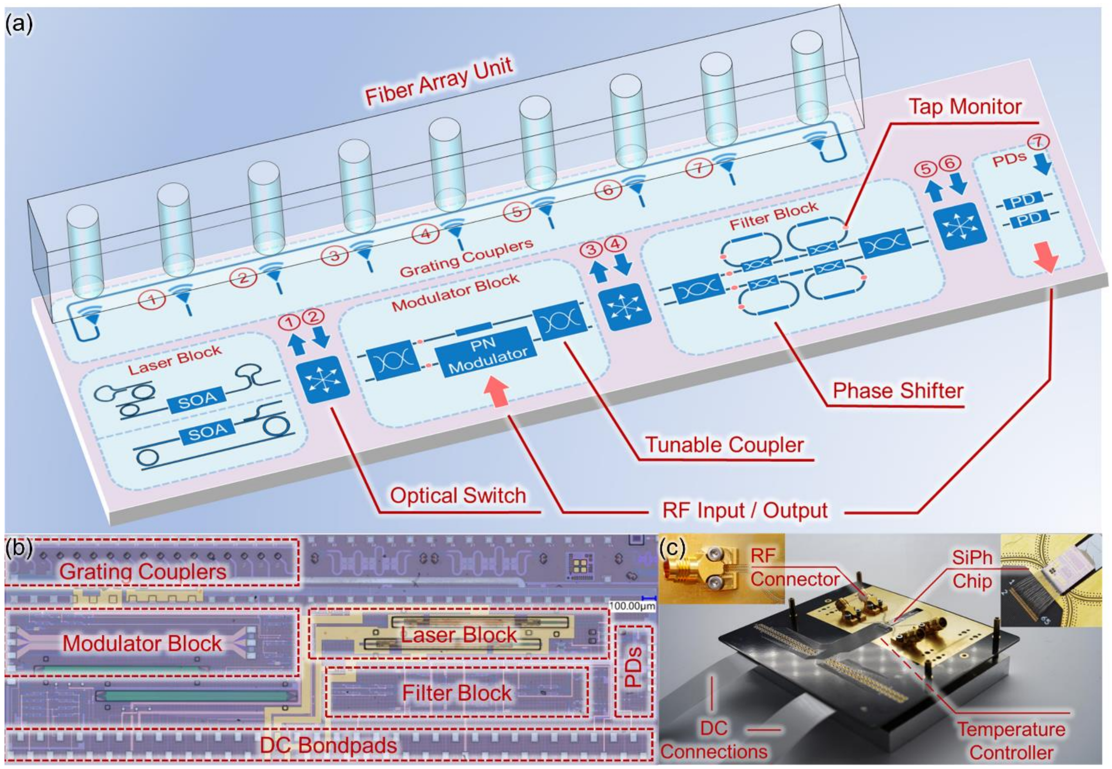

Fig. 1. (a) Schematic of the proposed signal processor. (b) Microscope image of the fabricated chip. (c) A packaged demonstrator with wirebonded controls and microwave connectors.

The schematic of our signal processor is shown in Fig. 1(a). It comprises four main functional blocks: a tunable laser block containing two lasers, a modulator block, an optical filter block, and a high-speed photodetector (PD) block. The longest optical path starts from the laser source, with the light guided into the modulator circuit. The modulator can be configured to implement either phase modulation or intensity modulation. The RF-modulated light is then directed into the optical filter block, which incorporates a four-ring-loaded Mach-Zehnder Interferometer (MZI) constructed with tunable couplers and tap monitors. Finally, the filtered optical signal is converted back to the microwave domain by the high-speed PDs.

All four functional blocks are interconnected via optical switches, allowing light signals to be routed in or out at each junction. This architecture provides the flexibility to configure the signal processor for both optical and RF signal processing. The optical switches are implemented using single-stage or double-stage MZIs, selected based on specific coupling ratio requirements.

The complete photonic circuit includes 15 optical input/output ports, 3 RF channels (1 input and 2 outputs), 52 heater-based optical phase shifters, and 8 tap monitors. A fabricated demonstrator of the processor is shown in Fig. 1(b). Due to the large number of optical and electrical connectors, a comprehensive packaging solution is essential to ensure system stability and robustness during operation. To address this, a custom-designed printed circuit board (PCB) made from high-speed materials minimizes RF propagation loss and is mounted on a temperature controller to stabilize the operating environment. A packaged sample, excluding the fiber array attachment, is shown in Fig. 1(c).

3. Characterization

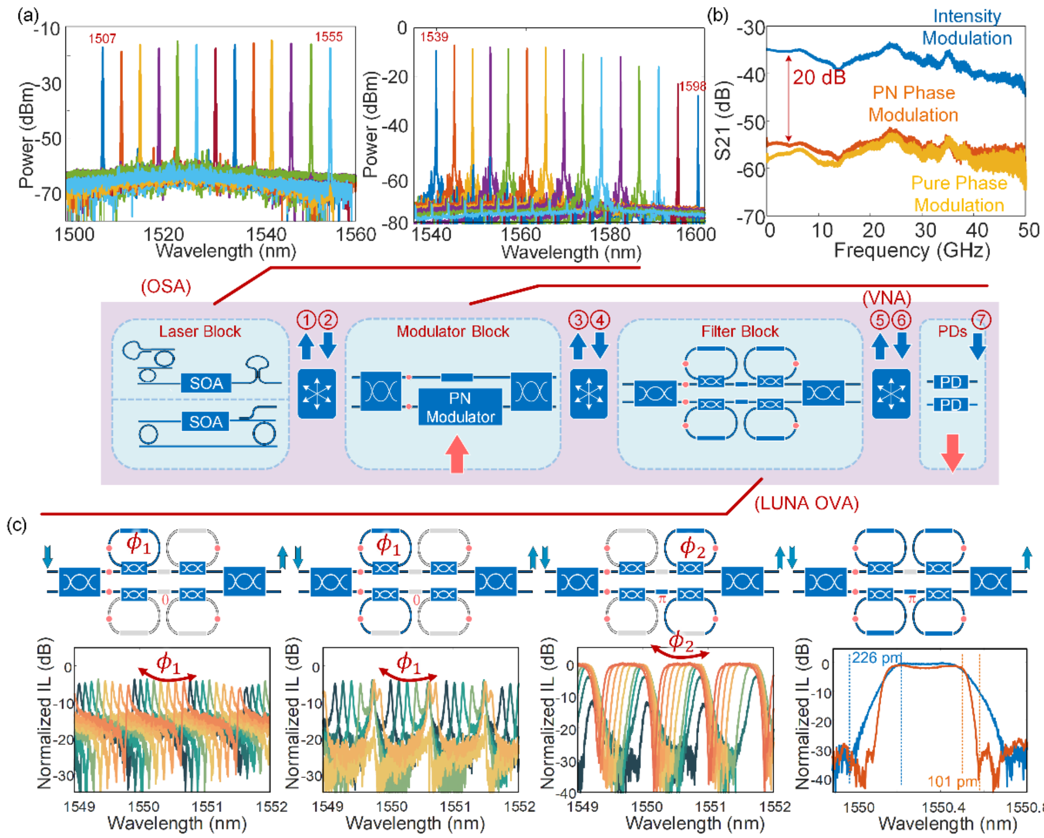

Fig. 2. Characterization of the blocks in the proposed signal processor. (a) Optical spectrum of the tunable lasers. (b) RF responses of the reconfigurable modulator. (c) Optical filtering responses of the tunable filter block. OSA: Optical spectrum analyzer. VNA: Vector network analyzer. OVA: Optical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

A characterization of the blocks in the signal processor is shown in Fig. 2. First, the laser block is measured using an optical spectrum analyzer (OSA). The laser block contains two laser designs: one based on a Fabry–Pérot (FP) cavity and the other on a ring cavity. Each laser cavity incorporates two ring filters, forming a Vernier bandpass filter to select the longitudinal modes. Two semiconductor optical amplifier (SOA) devices with different gain regions are transfer-printed into the cavities. By tuning the phase shifters in the ring filters and laser cavities, we can adjust the laser wavelength. The tuning results are shown in Fig. 2(a).

Fig. 2(b) displays the RF frequency responses of the reconfigurable modulator. This modulator is implemented by integrating a standard PN junction modulator into a tunable Mach-Zehnder Interferometer (MZI) that consists of two tunable couplers (TCs) 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, featuring a tunable phase relationship. This enables the RF signal generated from the modulated optical signal to match phase-modulated signals, intensity-modulated signals, or a combination of both. With this configurability, the modulator block can also be optimized for the desired modulation response.

The filter block in the signal processor consists of a ring-loaded MZI, which contains two tunable rings on each arm of the MZI. The responses of the filter block are shown in Fig. 2(c). The two cascaded rings on each arm function as a second-order all-pass filter. The splitter and combiner distribute light through the rings and mix the signals. The entire filter block can be programmed as a classical bandpass filter when the coupling ratio of the splitter and combiner is 0.5. By simultaneously tuning the coupling ratios, this block can serve as a universal optical filter, with performance limited by the filter orders.

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

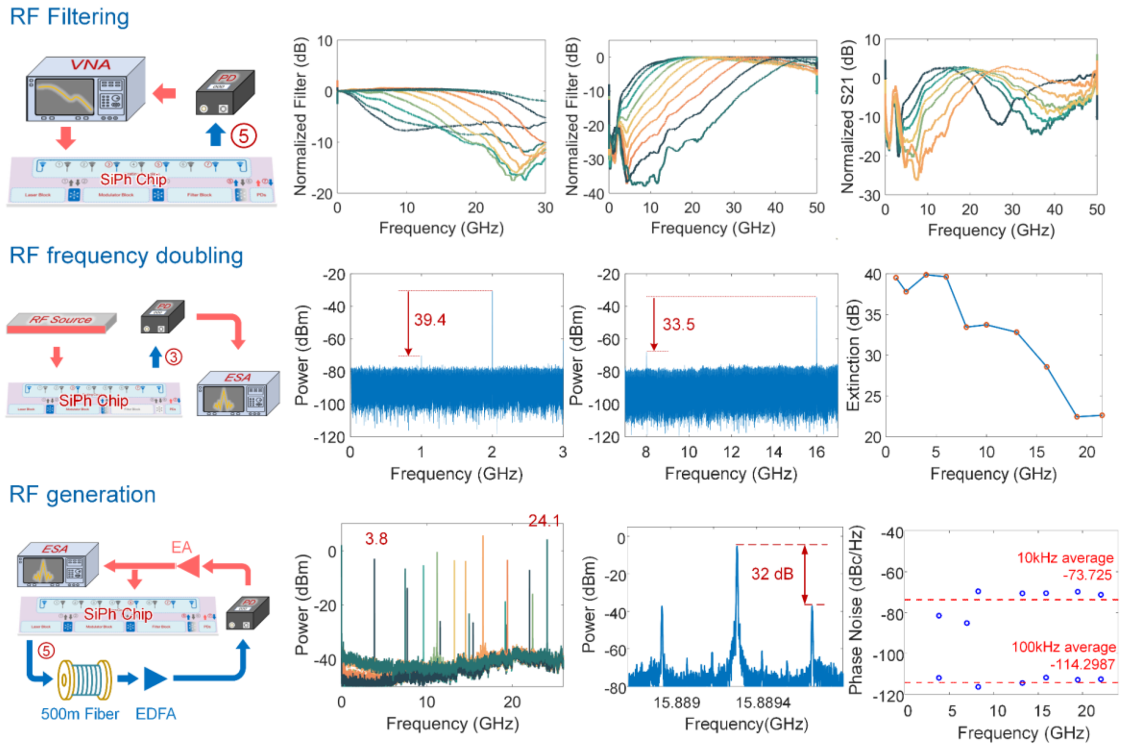

Fig. 3. Experimental setup and results for RF signals filtering, frequency doubling and generation.

4. RF Signal Processing

As shown in Fig. 3, the signal processor can be utilized for filtering, frequency multiplexing, and RF signal generation through the collaboration of its multiple blocks. When a modulated light signal is directed into the filter block, the optical spectrum of the signal is shaped by the optical filter. This process results in the recovered RF signal being filtered, effectively turning the entire link into a microwave photonic filter. By employing cascaded ring filters, the system can achieve all classical bandpass RF filter configurations. Tuning results, with the filter block configured as two cascaded ring filters, are presented in Fig. 3.

The reconfigurable modulator block enables high-extinction-ratio carrier suppression modulation by directing additional light into the PN modulator to compensate for extra losses [2]. Using this approach, the recovered RF signal is observed to have doubled its frequency, as demonstrated in Fig. 3.

Additionally, the system can establish an RF oscillation cavity with a tunable RF filter, functioning as an OEO. Similar to a laser cavity, an OEO oscillates and generates an RF signal when the RF gain surpasses the loss in the cavity. By tuning the central frequency of the RF filters, the oscillation frequency of the OEO can be adjusted. The corresponding tuning results are also illustrated in Fig. 3.

5. 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.

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