Armenian Journal of Physics, 2018, vol. 11, issue 4, pp.169-174

Advances in High-Speed Microwave Photonic Signal Processing

(Proceedings of the Int. Conference on " Microwave and THz Technologies and Wireless comm.")

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Received 15 November 2018

Abstract: Photonic signal processing offers a new powerful paradigm for processing high speed signals, due to its inherent advantages of wide bandwidth and immunity to electromagnetic interference. Recently there has been a strong drive to realise photonic integrated circuits using Silicon Photonics. This paper describes recent advances in integrated microwave photonic signal processing and sensing. These include optical single sideband modulators that can remove the effects of dispersion in wideband microwave photonic links, optical vector network analysers with high resolution, broadband tunable filters, multi-function processors, and integrated photonic sensors using optical micro-ring resonators that demonstrate extremely high sensitivity. These microwave photonic processors provide new capabilities for the realisation of high-performance signal processing and sensing.

Keywords: Photonic signal, photonic integrated circuits, single sideband modulator.

1. Introduction

Microwave photonics offers the prospect of overcoming a range of challenging problems in the processing of signals [1]. Its intrinsic advantages of high time-bandwidth product and immunity to electromagnetic interference (EMI) have led to diverse applications in the microwave and sensing fields [2]-[4]. Photonic signal processing leverages the advantages of the optical domain to benefit from the wide bandwidth, low loss, and natural EMI immunity that photonics offers. Recently there has been a strong drive to realise photonic integrated circuits using Silicon Photonics. This is particularly attractive because it enables a CMOS-compatible fabrication that enables the integration of combined photonic and electronic functions on one chip. It also makes possible a cost-effective implementation with reduced footprint, power and weight.

Recent advances in integrated microwave photonic signal processing and sensing are presented. These include optical single sideband modulators that can remove the effects of dispersion in wideband microwave photonic links, optical vector network analysers with high resolution, broadband tunable filters, multi-function processors, and integrated photonic sensors using optical micro-ring resonators that demonstrate extremely high sensitivity. These microwave photonic processors provide new capabilities for the realisation of high-performance signal processing and sensing.

2. Integrated Micro-Ring Single-Sideband Modulation

An important function that is required in many microwave photonic applications is the ability to generate optical single sideband (OSSB) modulation. OSSB is a technique that can overcome dispersion problems in radio-over-fibre systems that use simple antenna remote units, central office equipment sharing, and multiple wideband wireless services [5]. The OSSB scheme has also been widely used in optical vector network analyzers as it provides direct mapping between the optical and electrical domain [6]. Currently, there is a strong drive to realise silicon photonic

on-chip signal processors to provide a more cost effective, robust and compact solution for wide ranging applications. Ring resonator structures have been of great research interest in integrated photonics as they are not only compact but exhibit excellent performance.

A novel OSSB technique that has the capability to operate over a wideband range and at high RF frequencies to millimeter waves, is based on a simple silicon-on-insulator (SOI) dual-ring structure that exhibits weak electromagnetically induced transparency (EIT)-like behaviour [7]. The notch filter comprises a simple configuration of just two ring resonators with a ring circumference offset where the dual rings are separated by a bridging waveguide with a fixed length. It exhibits a weak EIT-like property at the through port and behaves like a notch filter with steep transition and high rejection ratio. Fig. 1(a) shows the scanning electron microscope (SEM) image of the double ring weak EIT notch filter fabricated on a silicon-on-insulator (SOI) wafer via ePIXfab**,** which comprises two micro-ring resonators having the design parameters that the length of the first and second rings are 57309 nm and 57313 nm respectively, and a waveguide length (L_d) having a value of 18327 nm in order to achieve the weak EIT effect. The height of the silicon core waveguide is 220 nm and the waveguide width is 450 nm for both the bus and racetracks. The filter features steep slope transitions and wide bandwidth in comparison with other double ring resonator structures of the same footprint size. The falling and rising edge slopes of the measured filter were calculated to be around 174.30 dB/nm and 171.07 dB/nm, respectively, showing excellent optical spectral component selection. Fig. 1(b) shows the optical sideband ratio of the generated OSSB signal at an RF frequency of 20 GHz measured using the high resolution optical spectrum analyzer.

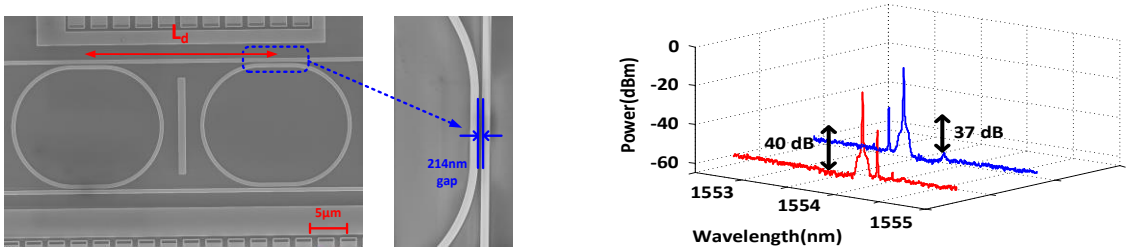

Fig. 1: Fabricated EIT notch filter and measured OSBB: (a) top-view SEM image of the fabricated SOI double ring weak EIT notch filter, (b) measured OSSB at 20 GHz where the blue line represents the upper sideband suppression of the left edge while the red line represents the lower sideband suppression of the right edge of the fabricated double ring weak EIT notch filter.

Fig. 2 experimentally demonstrates how the described OSSB modulator eliminates dispersion degradations in a microwave optical transmission link. It can be seen that the deep 30 dB dispersion-induced power fading generated with optical double sideband (ODSB) modulation is nearly eliminated, enabling a nearly constant RF response with just ±1.25 dB ripple over a 30 GHz range when using the weak EIT-like notch filter optical single sideband (OSSB).

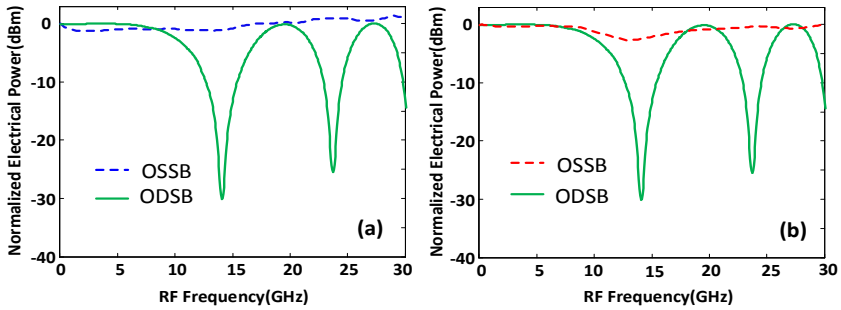

Fig. 2: Elimination of dispersion degradations in transmission: comparison between OSSB system with (a) upper sideband suppression (blue dashed line) (b) lower sideband suppression (red dashed line), and ODSB.

3. Tunable Single-Passband Microwave Photonic Filter

The ability of microwave photonic signal processing to realize filters that exhibit an extremely wide tunable RF range is a particular advantage that transcends the abilities of electronic RF filters. A particularly effective technique to realize single passband microwave photonic filters (SPMPF) is based on the concept of optical-to-RF mapping using phase-modulation to intensity-modulation conversion to translate the spectral response of an optical filter to the bandpass response of the microwave filter. The structure of a novel photonic integrated structure that can realize a widely tunable SPMPF which has a very good filter shape factor and which achieves shape-invariance during tuning is shown in Fig. 3(a) [8]. It is based on an integrated optical double notch filter using a cascaded pair of microring resonators, which produce two notches having slightly different stopband widths and centre frequencies.

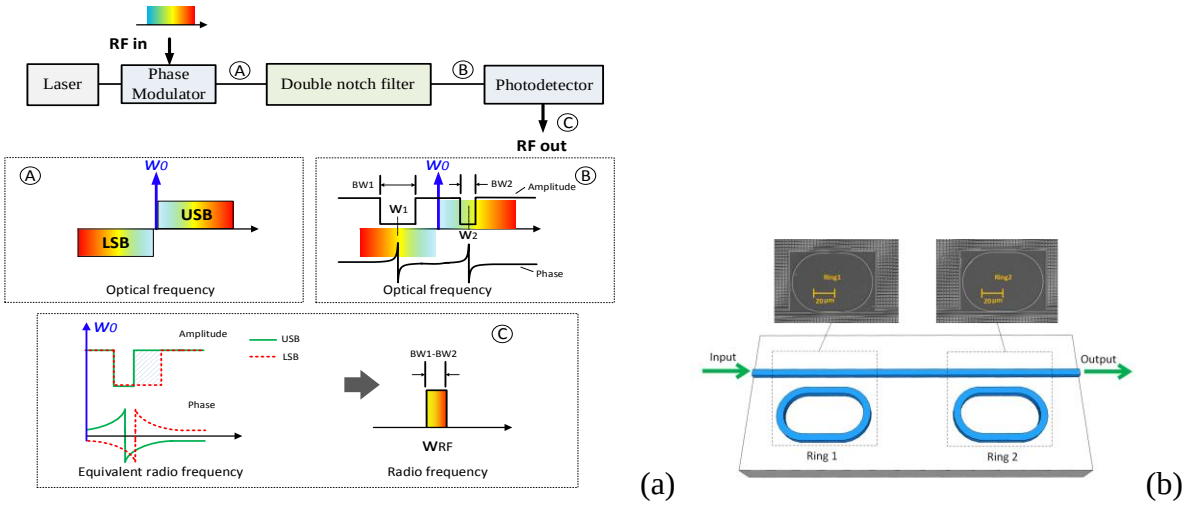

Fig. 3: (a) Schematic and operating principle of the single passband microwave photonic filter based on optical double notch filter. (b) Schematic diagram of the optical double notch filter.

The operating principle is based on phase to intensity modulation conversion, wherein the optical notch filters break the anti-phase symmetry of the modulation sidebands. The RF filter bandwidth is determined by the bandwidth difference of the two optical notch filters, not by their absolute individual bandwidths. This eliminates the need for narrow-band notch filters. The integrated optical double notch filter using a cascaded pair of non-identical microring resonators having slightly different stopband widths and centre frequencies is shown in Fig. 3(b).

The filter can be tuned by tuning the centre the frequencies of micro-resonators, while centred on the optical carrier, which can be done using integrated microheaters may be used. Fig. 4 shows the measured tuning response of the filter. The filter response is single-passband and it demonstrates 6-17 GHz tuning with shape-invariance.

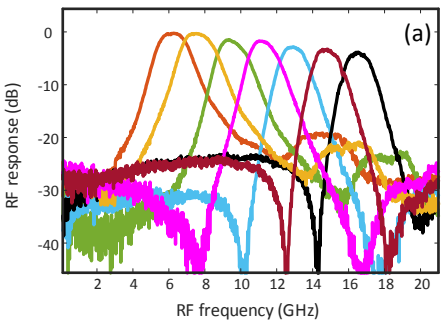

Fig. 4: Measured tuning response of the filter.

4. Multi-Function Signal Processing

There is a strong drive to realize compound signal processing functions that can be implemented together, and also to realize integrated silicon photonics. Silicon photonics is particularly attractive as it has the important advantage of integration compatibility with electronics for the drive interfaces on the same chip. For example general purpose and programmable signal processors capable of synthesizing a multitude of on-demand signal processing tasks have been reported for compact programmable RF-photonic filters using silicon photonics integrated waveguide mesh processors that enable multiple functionalities to be selected [9]. In addition, new system configurations have been realized that are capable of performing a distributed variety of compound functionalities such as individually controlled, cascaded microwave photonic bandpass filter and phase shifter functions within one subsystem. This utilizes a silicon photonics on-chip phase shifter based on single all-pass microring resonator [10], enabling the execution of multiple cascaded signal processing functions, while providing a separate control for each function.

5. Microwave Photonics Based Sensor

Optical sensors for monitoring the physical environment have important advantages including immunity to electromagnetic interference, inertness in chemical and biological applications, compactness, light-weight, and ability to operate in harsh environments. Techniques based on microwave photonics, in which the wavelength shift of the optical sensor is converted directly into the variation of an RF frequency signal are particularly attractive [11]. This is based on using an optoelectronic oscillator (OEO) [12] whose microwave oscillation frequency is determined by the resonant wavelength of the optical device that is employed for sensing. This method effectively translates the optical domain measurement into an electrical spectrum measurement, thus enabling a significantly higher frequency resolution that makes possible the achievement of a very high measurement resolution. Moreover, a much faster interrogation speed is also enabled since the microwave frequency can readily be measured by a digital signal processor (DSP) with high speed and high resolution.

An OEO-based optical sensor that is based on an integrated microwave photonic filter comprising a photonic micro-ring resonator is shown in Fig. 5 [13], where the integrated micro-ring resonator functions as a sensing probe element.

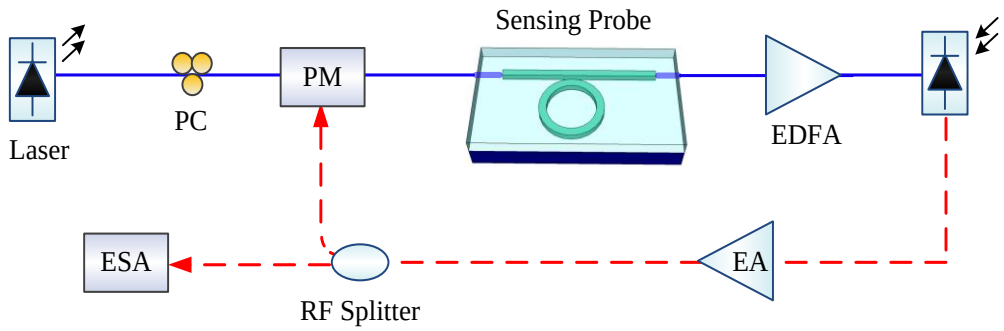

Fig. 5: Structure of the integrated OEO based temperature sensor. PM: phase modulator; EDFA: Erbium doped fiber amplifier; EA: electronic amplifier; PC: polarization controller; ESA: electrical spectrum analyser.

The micro-ring resonator essentially generates a microwave photonic filter whose center frequency corresponds to the location of the optical notch filter relative to the carrier. As an application, the target measurand was chosen to be temperature, where an easily integrated optical notch filter is employed as a sensor probe whose resonant wavelength is sensitive to temperature variations owing to the thermo-optic effect that changes the refractive index [14], thus resulting in a filtered RF signal output of the OEO whose frequency has a one-to-one correspondence to the temperature. Fig. 6 shows the experimental results.

Fig. 6(a) shows the OEO output is an almost pure electrical signal at 14.3 GHz at a temperature of 24.78 °C. The inset of Fig. 6(a) shows the zoomed in response which illustrates a narrowband signal with a linewidth of just 0.1 MHz. The next most dominant mode is located at around 4.9 MHz away from the peak oscillation mode and shows a mode suppression of around 30.6 dB. The temperature sensing performance was measured by changing the temperature of the nano-chip sensor from 24.27 °C to 25.29 °C. Fig. 6(b) shows the superimposed spectra of the generated microwave frequencies at different temperature points. As the temperature increases, the signal is shifted to a higher frequency. A linear relationship is seen between the temperature change and RF frequency shift, as shown in the linear fit in Fig. 6(c). The results demonstrate the ability to obtain extremely sensitive performance to small temperature variations with an achieved ultra-high sensitivity of 7.7GHz/°C.

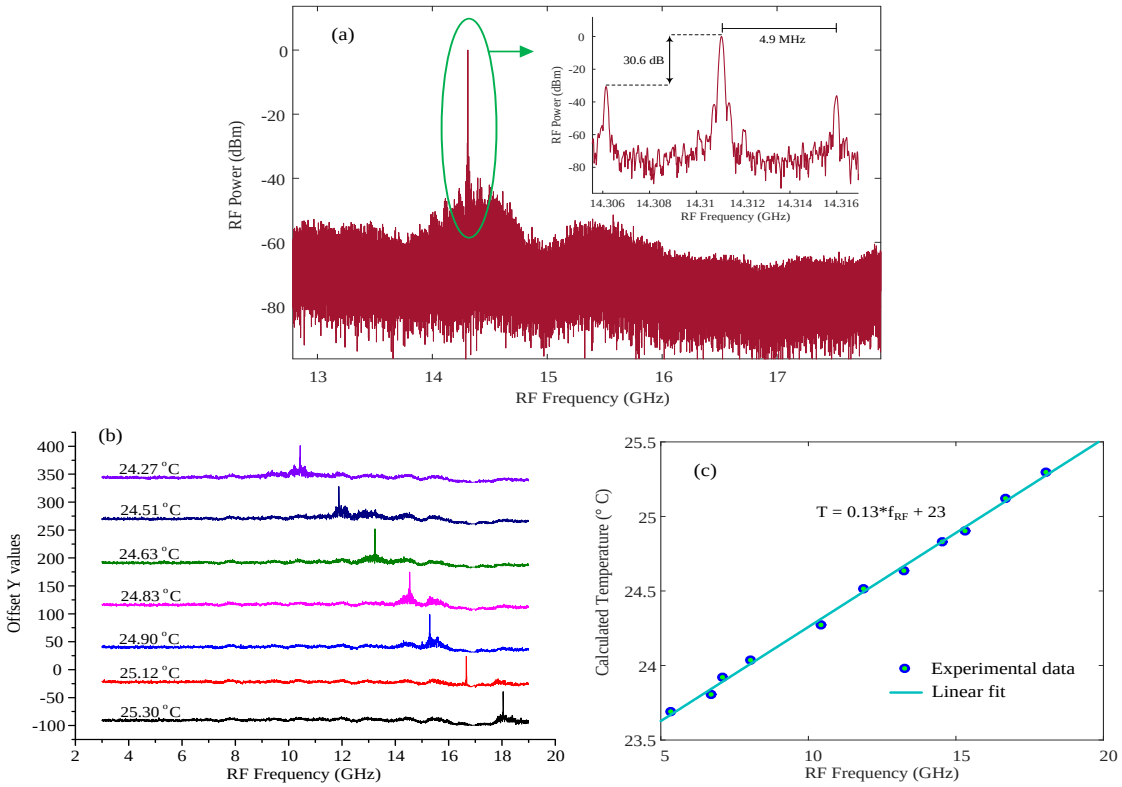

Fig. 6: Experimental results (a) Measured RF response at 24.78°C. Inset: Zoomed-in response of the RF oscillation mode. (b) Measured OEO RF oscillation frequency shift with temperature variations (c) Measured oscillation frequency shift as a function of the temperature.

6. Conclusion

Photonic signal processing offers the advantages of high time-bandwidth product capabilities to overcome inherent electronic limitations. A key benefit for wideband systems is that the entire RF/mm-wave spectrum constitutes only a small fraction of the carrier optical frequency. This opens the way to realize tunability over extremely wide microwave frequency ranges, and the ability to achieve ultra-wideband operation with wide instantaneous bandwidth and EMI immunity to provide connectivity with in-built signal conditioning.

Recent new methods in wideband signal processing have been presented. These include optical single sideband modulators that can remove the effects of dispersion in wideband microwave photonic links, optical vector network analysers with high resolution, broadband tunable filters, multi-function processors, and integrated photonic sensors using optical micro-ring resonators that demonstrate extremely high sensitivity. These processors provide new capabilities for realizing high-performance and high-resolution signal processing.

7. Acknowledgments

This work was supported by the Australian Research Council. Thanks are extended to X. Yi, L. Li, S. Song, S. Chew, P. Bian and L. Nguyen for their valuable contributions to this work.

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