Advances in High-speed and Adaptive Microwave Photonic Signal Processing

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Abstract

Photonic signal processing, using photonic approaches to condition wideband microwave signals, is attractive due to the inherent advantages of high time-bandwidth product and immunity to electromagnetic interference. In this keynote paper, we describe recent advances in wideband microwave photonic signal processing. This includes programmable microwave photonic phase shifters and true-time delay elements for phased array beamforming, and single bandpass tunable filtering approaches that overcome spectral periodicity. We also present optoelectronic oscillators with wideband frequency operating range, high-resolution multiple frequency microwave photonic measurement systems, and photonic RF memory structures that can realise a long reconfigurable storage time with wide instantaneous bandwidth.

1. Introduction

Photonic signal processing, using photonic approaches to condition microwave signals, offers the advantages of large time-bandwidth capabilities to overcome inherent electronic limitations, together with immunity to electromagnetic interference (EMI) [1-6]. It opens up new possibilities for overcoming the inherent bottlenecks

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caused by limited sampling speeds in conventional electrical signal processors [1]. In-fibre signal processors are directly compatible with fibre optic microwave systems, and can provide connectivity with in-built signal conditioning.

Microwave photonics is a unique technology that brings key benefits including the inherent speed, parallel signal processing capability, and very high sampling frequency ability [6]-[8]. These have led to diverse applications such as defence, fibre-radio, and radioastronomy areas, for tackling the problems of processing wideband fibre-fed distributed antenna signals, and for providing essential EMI immunity. These new techniques transcend the limitations of existing electronic methods, and enable new structures to be realised which not only can process high speed signals but which can also realise adaptive operation.

In this paper, we present recent new methods in wideband signal processors including ultra-wideband phase shifters and true time delays for phased array beamforming; single-passband programmable microwave photonic filters, optoelectronic oscillators, high-resolution multiple frequency microwave photonic measurement systems, and photonic RF memory structures.

2. Phase shifters and true time delays for beamforming networks

Optically controlled beamforming techniques for phased array antennas are of significant interest due to the advantages photonics can offer that include a wide operating bandwidth, remote antenna feeding, and EMI immunity [9]–[13]. Programmable phase shifters are required for adaptive beamforming. Thus, an optically controlled beam forming network that can operate over a wide frequency range, and which features the integration of the array phase taper and the array amplitude taper within a single unit, is highly attractive. A two-dimensional array of liquid crystal on silicon (LCoS) pixels that are configured with one input fiber and multiple output fibers, can be used to realise multiple wideband photonic microwave phase shifters [14]. The LCoS pixels enable dynamic wavelength routing to the output ports, and optical to radio frequency (RF) signal conversion with direct phase and amplitude translation control. This beamforming network is highly flexible and reconfigurable since it is software programmable, and since the microwave phase shifters in the array are independent and have quasi-continuous phase control from 0 to 2π, arbitrary scanning beam angles can be realized.

![Fig. 1. Measured phase shifts corresponding to the scanning angle of (a) 20°, (b) -20°, (c) 40°, (d) -40° (phase shifter 1 - - - - - - , 2 - - - - - - , 3 - - - - , 4 - - - - - - ).](image)
A set of four phase shifters to obtain a scanning angle of 20° (with half wavelength radiating element spacing) was realized for proof-of-concept demonstration. These corresponded to four RF phase shifts with values of 0°, -61.56°, -123.12° and 175.32° respectively. Each phase shifter was realized by applying specially calculated phase modulation patterns to impress optical phase differences between the respective optical carrier and the sideband for each WDM channel, which is directly translated to the microwave signal after detection. The ability to obtain a frequency-independent RF phase-shift over a range of RF frequencies from 10 GHz to 20 GHz was investigated for Ku-band antennas, and the measured phase responses via a vector network analyzer are shown in Fig. 1(a). Next, the flexibility of the structure was demonstrated by tuning the beam direction, which was achieved by programming the RF phase shifters. The phase shifter settings required for scanning angles of -20°, 40° and -40° can be calculated to be [0°, 61.56°, 123.12°, -175.32°], [0°, -115.7°, 128.6°, 12.9°] and [0°, 115.7°, -128.6°, -12.9°] respectively. The measured phase shifters responses are shown in Fig. 1(b)-(d).

The radiation patterns of a four-element phased array antenna were investigated based on the measured phases of the respective four microwave phase shifters. The beam steering was obtained by appropriately programming the respective optical phase shifts in the structure while keeping the amplitude constant across the elements for simplicity. The simulated results shown in Fig. 2 that based on the phase measured in Fig. 1, show beam directions of -40°, -20°, 20° and 40°, which demonstrates beam steering of the phased array antenna. The structure can be scaled to over 100 phase shifters for the operation of 10 GHz–20 GHz beamforming under SSB+C modulation, and for C-band optical bandwidth.

True-time-delay elements are also instrumental in photonic beamforming techniques that offer the prospect of the realization of phased array antennas which can operate with wide instantaneous bandwidth. An array of multiple true-time-delay elements, which can be independently and continuously tuned, based on a WDM parallel signal processing approach in conjunction with a diffraction-based Fourier-domain optical processor (FD-OP), can be obtained [15]. This technique features the ability to scale to realize a large number of true-time-delay lines while sharing a single optical processing device, while also enabling control of the signal amplitude at the same time as controlling the true-time-delays.
The measured RF phase versus RF frequency for different phase slopes as shown in Fig. 3, which was achieved by programming the linear phase slope continuously from -11.5°/GHz to +11.5°/GHz by means of the LCoS system. Excellent high-linearity phase responses can be observed from the measurement results. The corresponding time delays are shown in Fig. 3(b). The tuning range is from -32ps to +32ps. The standard deviation of the delay is less than 0.7ps. The flat response in Fig. 3(b) indicates a true RF time delay. The measurement range spans from 4GHz to 20GHz. The lowest measurement frequency (4GHz) was determined by the minimum operating frequency of the 90 degree coupler used for the SSB+C modulation, and the highest frequency was limited by the bandwidth of the vector network analyser used in the experiment.

3. Widely tunable single bandpass filters

The use of stimulated Brillouin Scattering (SBS) in optical fibre is an attractive approach for implementing high-resolution microwave photonic filters. The application of SBS in microwave photonics provides high-Q filtering capability, thanks to the narrowband MHz spectrum selectivity of the SBS effect.

A novel widely tunable single bandpass filter based on processing the carrier-suppressed sidebands and SBS is reported in [16]. The RF filter utilizes the frequency selectivity of the SBS gain spectrum to realize single bandpass response, and employs the carrier suppressed modulation to achieve Brillouin pump and optical carrier for phase modulation. The single bandpass filter can be tuned via adjusting RF oscillation frequency applied to the modulator to alter the frequency difference between the upper and lower optical sidebands. Therefore the frequency change of RF oscillation is doubly mapped on to the central frequency shifting of the single bandpass filter, which enables wideband and continuous tuning capability. A microwave photonic filter with a single bandpass that has a narrow bandwidth of about 20.6 MHz and a tuning range of 20 GHz, is shown in Fig. 4. The filter shows highly selective RF responses. Less than ±1.2 dB amplitude fluctuation and over 30 dB out-of-band rejection ratio are observed within the whole tuning range.
The SBS principle can also be applied to realize a widely tunable narrow notch filter [17]. A continuous measured notch filter tuning range from 2 GHz to 20 GHz has been obtained with very high resolution, having a -3dB bandwidth of 82 MHz, and with a deep notch having >40 dB suppression over the tuning range. The SBS concept can be extended to enable the realization of a switchable microwave photonic filter that can be switched between a bandpass filter and a stopband notch filter response, using simple and rapid control [18]. It is based on a SBS technique in conjunction with a dual drive Mach-Zehnder modulator (DDMZM) that processes the sidebands of the RF modulated signal. Switching of the filter function is simply and conveniently obtained by changing the DC bias to the DDMZM, and in addition the centre frequency can also be tuned.

Another technique for realizing single bandpass filters is based on the principle of shifted dispersion-induced RF fading by using a dual-input Mach–Zehnder electro-optic modulator (EOM) that is fed from a broadband optical source with unbalanced input fiber lengths into the upper and lower arms of the EOM, in combination with a dispersive medium [19]. This topology consequently produces a spectral response equivalent to the curve of the dispersion-induced RF fading that is shifted from the conventional baseband location to high frequencies. Therefore, an equivalent single passband is formed without the requirement of the conventional tap coefficients. Moreover, the filter response sidelobe suppression can be significantly improved by applying a Gaussian windowed profile to the broadband optical source. By compensating the fundamental limitation in the dispersion induced RF fading, i.e. RF distortion due to non-constant group delay slope, high resolution microwave photonic signal processors can be achieved [20]. Fig. 5 shows a shape-invariant tunable filter with a single passband of a 3 dB bandwidth of 157 MHz over the 0–20 GHz tuning range achieved by using a rectangular spectrum source of 2300GHz and a compensated
chirped fiber Bragg grating having a constant group delay slope of -330ps/nm.

4. Optoelectronic oscillators

Optoelectronic oscillators enable the generation of high frequency and stable microwave signals by combining the unique advantages of electronic and photonic component [21]. The OEO has diverse applications in optical communication links, precision testing and measurement equipment, high frequency wireless communication technologies, radar systems and microwave spectroscopy [22], where it has the potential to enhance the information capacity, speed and accuracy of signal processing functions in these systems.

A continuously tunable OEO, realised using the shifted dispersion induced RF fading techniques based on an unbalanced Mach-Zehnder structure is proposed in [23] as shown in Fig. 6. The OEO oscillation frequency is determined by the shifted frequency of the RF fading, which can be simply tuned by adjusting the difference between the multi-path waveguides. The generation of a continuously frequency tunable microwave signal was demonstrated in the range of 2.7 GHz to 9.8 GHz, limited only by the operating bandwidth of the loop components. This design provides a simple mechanism for signal tuning and has significant potential to provide high frequency oscillators.

5. Microwave frequency measurement

The ability to perform frequency measurement (FM) on an unknown microwave signal over several decades of RF bandwidth with high resolution is an important requirement for defence and radar warning system applications [24]. A frequency measurement structure that can realise multiple-frequency measurement, while simultaneously achieving a high resolution and a wide measurement range is based on the concept of successively frequency-shifting (using a recirculating loop) a modulation sideband of the optical signal until it is brought close to the reference carrier frequency, and then combining and detecting them through a narrowband filter [25]. This approach requires only simple pulse detection and simple counting of the number of recirculations until an output signal is detected, from which the frequencies inherent in the unknown input microwave signal can be measured over a wide frequency range and with high resolution.

Fig. 7 shows the measured output results for a single input microwave signal as its frequency was changed between 10 MHz to 20 GHz. The time position of the observed RF pulse changes as the frequency of the microwave signal changed. It can be seen that the estimation error stayed within 250 MHz, which was the frequency shift amount. Fig. 7(a) summarises the signal frequency to time mapping from inputs ranging from 0.1 to 20 GHz. Excellent agreement between the measurement and the simulation result can be seen. The measurement error as a function of the input frequency is shown in Fig. 7(b). It can be noted that the errors stayed within ± 125 MHz, and did not change when the RF frequency was increased, i.e. the frequency measurement resolution was the same for the whole measurement range.
6. Photonic RF memory

Many applications in radar and defence require reconfigurable high-fidelity storage of received radar pulses. Photonic approaches can provide a solution. A structure that can realise a long storage time, wide IBW and high dynamic range is based on the use of an optical frequency shifter inside a recirculating delay line loop to overcome the lasing problem and to enable multiple recirculations and long storage time to be realized [26]. Optical switches at the input switch the pulse into the loop, and at the output switch out the selected RF pulse after the desired storage time for subsequent detection by a photodetector. Fig. 8 shows the measured waveform of the RF pulse measured after storage of 150 μs, which was equivalent to 100 circulations. The stored RF signal waveform was very similar to the one that was injected into the FS-RDL loop, which shows high signal fidelity even after 100 circulations.

Measurements have also demonstrated that the structure can store an RF microwave pulse with only small changes in the pulse amplitude for 280 μs, which is one of the longest storage times reported.

7. Conclusion

Photonic signal processing offers the possibility of realizing high multi-GHz sampling frequencies, overcoming inherent limitations with electronic approaches. Recent new developments in wideband signal processors including ultra-wideband phase shifters and true time delays for phased array beamforming; widely tunable single passband and switchable filters; optoelectronic oscillators; high-resolution multiple frequency measurement systems; and
photonic RF memory structures with a long reconfigurable storage time, have been presented. These processors provide new capabilities for the realisation of high-performance signal processing based on microwave photonics.

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References