PHOTONIC SIGNAL PROCESSING

Invited Paper

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ABSTRACT

Recent new methods in the processing of wideband signals using optical delay lines and Bragg gratings are described, including fast sampling and multiple-wavelength techniques. Photonic signal processing can realise multi-GHz sampling frequencies, overcoming inherent electronic limitations. These processors are directly compatible with fibre optic systems, and can provide connectivity with in-built signal conditioning. Processors for interference mitigation filters, signal correlators, high-resolution microwave filters, and true-time delay beamforming in phased array antennas, are discussed.

1. INTRODUCTION

Photonic processors for high-speed signal processing functions are attractive because of their very high time-bandwidth product capabilities. Such processors can remove the bottlenecks caused by limited sampling speeds in conventional electrical signal processors. Moreover, optical delay line structures allow direct processing of high frequency signals that are already in the optical domain. In-fibre signal processors are inherently compatible with fibre optic microwave systems, hence they can provide connectivity with in-built signal conditioning. These processors based on fibre Bragg gratings and multiple wavelength techniques open up new possibilities for the realisation of high resolution, wideband and adaptive processing of signals contained within the fibre.

The unique functional advantages of photonic signal processors, including its inherent speed, the ability to perform parallel signal processing, and the ability to generate true time delays, have led to a diverse range of operations [1],[2]. These include signal filtering with programmable capabilities [3], multi-Gbit/s A/D converters [4], frequency converters and mixers [5], signal correlators [6], and beamformers for phased arrays [7]. The processing of wideband signals directly within the fibre optic transmission link is attractive in applications such as signal distribution in fibre-radio mobile access systems and in radar phased array antennas. Since in such fibre optic systems the signal is already in the optical domain, it is desirable to incorporate photonic signal processing into the optical fibre network, as this can provide in-built signal conditioning that can be integrated with the fibre optic system. This paper describes recent new methods for wideband processing of signals using fibre delay lines and Bragg gratings. Structures for synthesising a large number of taps and sampling techniques are discussed. The use of wavelength multiplexing in conjunction with the spectral selectivity of gratings provides new processing functions. A range of signal processors, including interference mitigation filters, signal correlators, high resolution microwave filters, and true-time delay beamforming in phased array antennas, are discussed.

2. PHOTONIC SIGNAL PROCESSING WITH GRATING SAMPLING ELEMENTS

The fundamental discrete time signal processor has a structure in which successive samples of the signal are delayed, weighted and summed. For an input signal denoted by *x(t)* the output is given by

$$y(t) = \sum_{n=0}^{N-1} W_n x(t - n\tau) \qquad (1)$$

where W_n is the n^{th} tap weight, N is the number of taps and τ is the sampling period. This structure can generate a wide variety of signal processing functions. In addition, by programming either the tap weights or the unit delay time, adaptive processing can be obtained.

Techniques for obtaining the fundamental sampling, multiplication (amplitude weighting), time delay, and addition functions of a processor include high dispersion fibre [3], unbalanced Mach-Zehnder structures [8], and arrayed waveguides AWG [9]. Bragg gratings are particularly attractive as sampling elements, because they enable the tap weights, sampling time, and interaction wavelength to be controlled. The latter is particularly powerful, which together with WDM provides one of the most promising approaches for creating high capacity signal processors. Extremely high sampling frequencies can be realised using grating elements. Fig. 1 shows several fibre-based sampling techniques.

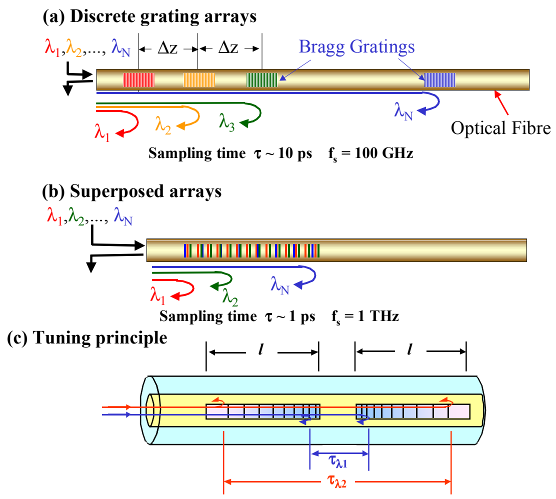

Fig. 1. High-speed sampling techniques using grating elements.

Discrete high-reflectivity fibre Bragg grating arrays, Fig 1(a), can produce a minimum delay step size of 10 ps [10], which corresponds to a sampling frequency of 100 GHz. Superposed fibre gratings, Fig 1(b), based on multiple overwritten gratings with different Bragg wavelengths and coupling coefficients in the same length of fibre, can realise even smaller delay increments [11]. Recently, superposed grating designs have been shown to be capable of realising 32 time delay steps at 1 nm wavelength spacing with a 1 ps delay increment. In addition the time delay step has high linearity with a standard deviation below 1.7%. This delay step corresponds to a sampling frequency of 1 THz. The tuning principle for the processor function, Fig. 1(c), is based on controlling the basic unit time delay by changing the wavelength and shifting the point of reflection along a chirped grating. Wavelength tuning can be fast, enabling agile programming capability with continuous tuning.

3. PHOTONIC INTERFERENCE MITIGATION FILTERS

The antenna, in fibre radio or radar systems, typically receives unwanted high-amplitude interfering signals in addition to the wanted signal. The former must be rejected to avoid undue demands on the dynamic range requirements of the fibre optic link. A photonic signal processor can excise the interference in the fibre signal by providing a narrow stopband, and at the same time to transmit the wanted signal over a flat wide passband. A new topology for a fibre-based interference mitigation filter that can realise this function is shown in Fig. 2.

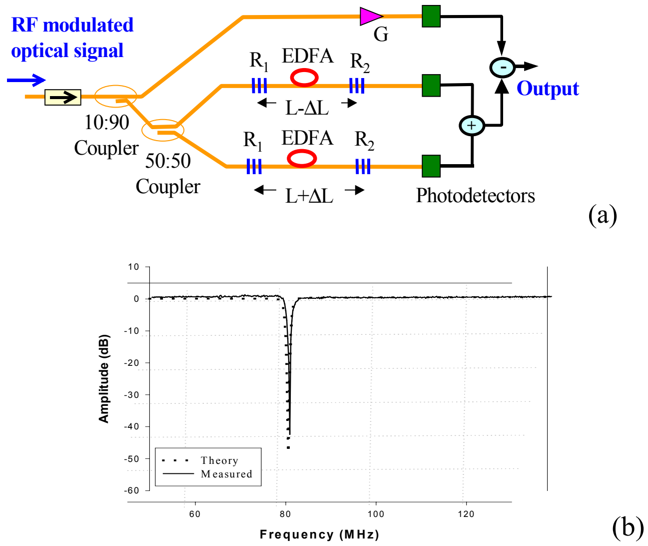

Fig 2 Fibre-based filter for interference mitigation (a) Topology (b) Frequency response.

In this structure, the signal is routed via a direct fibre path and dual parallel paths, which contain high-Q optical bandpass filters. These two photonic filters are designed to be slightly detuned from the centre frequency corresponding to the required notch frequency f_o, and operate at frequencies f_o-Δf and at f_o+Δf. This is shown by the different cavity lengths between the Bragg gratings of L+ΔL and L-ΔL in Fig. 2 (a). These optical bandpass filters are operated in the transmission mode, so their outputs can be directly summed via the photodetectors. This combined response is subtracted from the all-pass direct path response, to yield a narrow-stopband filter response, with very flat and wide passbands. The frequency response of this fibre-based interference rejection filter is shown in Fig. 2(b). The narrow notch and flat, lossless passbands demonstrate the high-resolution filtering capabilities of the photonic signal processor.

4. MULTIPLE WAVELENGTH WDM SIGNAL PROCESSORS

The use of multiple wavelengths is a powerful technique for realising parallel signal processing. Structures comprising wavelength multiplexed Bragg grating arrays enable tailoring of arbitrary profiles to obtain windowing in the design of the filter response, for to obtain side-lobe suppression in band pass filters. Structures based on multiple wavelength sources and chirped fibre gratings also have versatile possibilities [9],[12],[13] for realising reconfigurable filter operation. By changing the wavelength separation between the multiple wavelength sources, the basic delay time of the signal processor can be reconfigured and the filter centre frequency can be programmed. Secondly, by changing the power of each wavelength source component, the time response of the filter can be apodised and hence the filter transfer function shape can be reconfigured.

WDM processors can also eliminate phase noise, which occurs in single wavelength incoherent optical processors. Because the noise due to laser phase noise appears at the beat frequency corresponding to the wavelength separation, which is very high and falls outside the photodetector bandwidth, the laser phase noise is automatically filtered out.

A new topology for a photonic signal processor, based on a WDM mapping concept with grating arrays to realise a highly parallel delay-processing function is shown in Fig. 3. This exploits the regularity a characteristic of the sampling process to give a significant increase in the number of taps with a given number of interconnects.

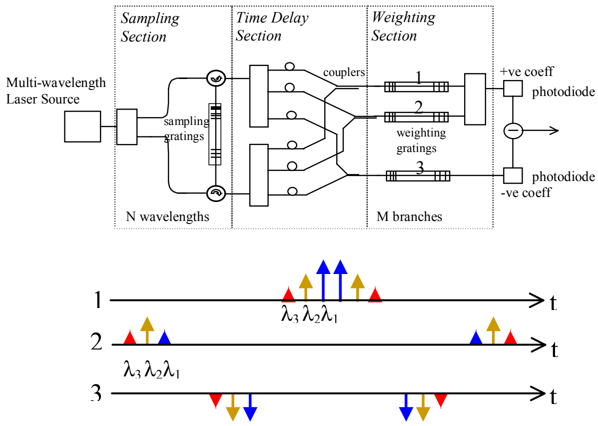

Fig 3 (a) WDM processor topology (b) .
Symmetric taps generated in branches 1 to 3.

In this structure, sampling is realised by a grating array with 100% reflectivity, and two streams of output are tapped from the two sides of the grating array simultaneously. Hence the taps in the upper and lower streams have a reversed sequence of wavelengths, which enables a symmetric wavelength-coding scheme to be realised for symmetrical impulse response filters. Because all taps share the same sampling unit and the symmetric wavelength sequence of this topology, the number of gratings required is reduced to at least half of an ordinary M-wavelength signal processor [14].

5. SIGNAL CORRELATORS

Grating based processors can perform high-speed correlation of optical signals. The output is given by

$$R(\tau) = \int_{-\infty}^{\infty} s(t) f(t-\tau) dt \qquad (2)$$

where *s(t)* represents the incoming code sequence, and *f(t)* represents the stored impulse response. Autocorrelation output is obtained only if the two bit sequences *f(t)* and *s(t)* are identical. This correlator has ability to decode ultra fast sequences at multi-Gbit/s rates, and can be programmed to recognise different high bit-rate codes by tuning the gratings.

6. GRATING BEAMFORMERS IN PHASED ARRAYS

In multi-beam phased array antennas, optical true-time-delay beamforming has unique potential to synthesise a large number of high-resolution beams (500-1000), and operate squint-free over a wide range of microwave frequencies. WDM techniques have received particular attention for increasing the beamforming capabilities of phased array antennas [7],[15], by significantly reducing the number of required interconnects for multibeam operation. However fundamental beat noise interference sets restrictions on the frequency of operation that limit the ultimate beamforming capacities of optically controlled phased arrays. A novel WDM grating based beamformer that removes the beat noise limitation, and achieves minimum interconnect number, uses a simple frequency down-conversion technique prior to performing the true-time delay equalisation in the optical domain [16]. The true-time delay equalisation is now performed at the IF, rather than at the RF, resulting in reduced wavelength. Thus, for a given wavelength span, a larger number of wavelengths can be used, resulting in an increased beam capacity. While doing equalisation at IF, this topology still retains the important advantage of optical beamforming, namely the ability to do parallel signal processing by means of WDM techniques. Hence in addition to increasing the beam capacity, it also gives a minimum interconnect beamformer solution. This architecture uses only a single fibre optic link for each beam direction, whereas conventional single-wavelength beamformers require M fibre optic links for each beam direction. Hence significant reductions in interconnect hardware can be obtained. For example, for a 512 beam array, more than 99% reduction in optical interconnects is possible using the WDM beamformer. The fibre grating based beamformer approach enables the synthesis of large multi-beam phased arrays with true-time delay capability.

7. CONCLUSION

Photonic signal processing can realise multi-GHz sampling frequencies, overcoming inherent electronic limitations. These processors are directly compatible with fibre optic systems, and can provide connectivity with in-built signal conditioning. The ability to realise dense parallel signal processing and adaptive operation is important for high capacity signal processing functions. The structures can also be implemented in planar integrated form, which gives high functionality. A range of signal processors, including interference mitigation filters, signal correlators, high-resolution microwave filters, and true-time delay beamforming in phased array antennas, have been described. Grating based processors offer wideband and programmable processing functions, and the ability to solve the connectivity problem in large multi-function phased arrays.

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