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Feng Xiao
Edith Cowan University

Budi Juswardy
Edith Cowan University

Kamal Alameh
Edith Cowan University

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Tunable true-time delay unit based on Opto-VLSI processing

Feng Xiao, Budi Juswardy, and Kamal Alameh
WA Centre of Excellence for MicroPhotonic Systems, Electron Science Research Institute,
Edith Cowan University, Joondalup, WA, 6027, Australia
Email: f.xiao@ecu.edu.au

***Abstract*—A novel tunable true-time delay unit is proposed and demonstrated. The unit is based on the use of an Opto-VLSI processor that dynamically selects a single waveband or multiple wavebands from an RF-modulated broadband optical signal and routes them to a high-dispersion fiber for arbitrary time delay synthesis. Experimental results demonstrate continuously tunable time delay of up to 4 ns.**

***Index Terms*— Microwave Photonics, Tunable True-Time Delay, Optical Signal Processing, Opto-VLSI.**

I. Introduction

The processing of microwave and millimeter-wave signals in the optical domain is a powerful technique that overcomes the bottlenecks encountered in all-electronic signal processors, such as electrical losses, electromagnetic interference (EMI) and bandwidth limitations [1]. A wide range of potential RF signal processing applications require high selectivity or resolution, wide tunability, and fast reconfigurability. In particular, the use of photonics-based true-time delay (TTD) units to realise adaptive wideband phased-array antenna (PAA) beamformers has extensively been investigated in the last decade for applications ranging from modern microwave radar to wireless communication systems [2-5]. Compared with all-electrical true time-delays, optical true time-delays have the advantages of broader bandwidth, lower insertion loss, higher phase stability, smaller size, lighter weight, and excellent immunity to electromagnetic interference and crosstalk.

Several approaches have been used to realise tunable true-time delay units, including the use of free-space [6], in-fiber bragg gratings (FBGs) [3], integrated optical waveguides [7], optical-switch-based n-bit TTD [8], dispersion-enhanced photonic-crystal fibers [9], and higher-order mode dispersion in multi-mode fibers [10].

In this paper we propose and demonstrate the principle of a novel tunable true-time delay unit that employs an Opto-VLSI processor, a broadband optical source, a semiconductor optical amplifier (SOA), and a high dispersion fiber. The true-time-delay unit can be reconfigured to synthesize arbitrary time delays of up to 4 ns and can also generate several delays simultaneously.

II. Opto-VLSI Processor

An Opto-VLSI processor is an array of liquid crystal (LC) cells driven by a Very-Large-Scale-Integrated (VLSI) circuit that generates digital holographic diffraction gratings to steer and/or shape optical beams [11]. A few memory elements are assigned to each pixel to selects a discrete voltage and apply it, through the aluminum mirror electrode, across the LC cells. Transparent Indium-Tin Oxide (ITO) is used as the second electrode. A quarter-wave-plate (QWP) layer between the LC and the aluminum mirror is used to accomplish polarization-insensitive operation [12]. This device is electronically controlled, software configurable, polarization independent, and very reliable since beam steering is achieved with no mechanically moving part. The deflection angle for the Opto-VLSI processor, α_m, is given by:

$$\alpha_m = \arcsin(\frac{m\lambda}{d}) \qquad (1)$$

where m is the diffracted order (here only first order is considered), λ is the vacuum wavelength, and d is the grating period.

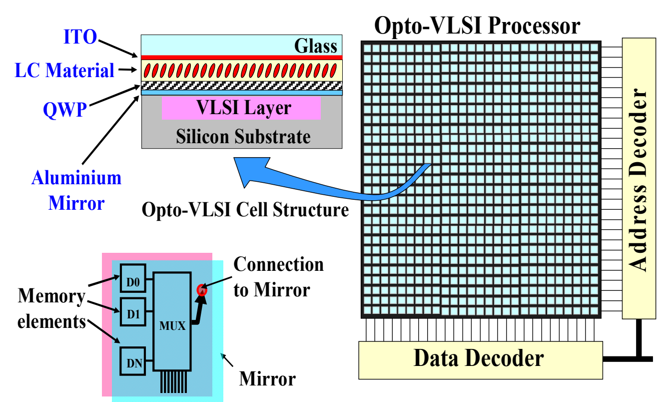

Fig. 1. Opto-VLSI processor structure. By addressing each pixel independently a phase hologram can be synthesized leading to optical beam steering and shaping.

III. TUNABLE TIME DELAY STRUCTURE AND PRINCIPLE

Figure 2 shows the experimental setup used to demonstrate the principle of the proposed tunable true-time delay structure. A broadband light source of amplified spontaneous emission (ASE) is externally modulated by the RF signal through an electro-optic modulator (EOM). The RF modulated light is routed via a circulator into a Semiconductor Optical Amplifier (SOA), and then collimated and launched into a diffractive grating plate that demultiplexes the wavebands of the collimated ASE along different directions and maps them onto the Opto-VLSI processor. By partitioning the active window of the Opto-VLSI processor into pixel blocks and driving them with optimized steering phase holograms, some wavebands can appropriately be steered and coupled back into the fiber collimator, while all the other wavebands are steered off-track and hence dramatically attenuated. The coupled wavebands are injected back into the SOA and amplified thus generating high amplitude output optical signals. The selected wavebands can be arbitrarily tuned by changing the phase holograms uploaded onto the pixel blocks of the Opto-VLSI processor. The amplified optical signals are then fed, through a circulator, to a high dispersion optical fiber, where the different RF-modulated wavebands experience different optical path difference, and hence different time delays. The delayed RF-modulated wavebands are finally photodetected by a photo-receiver (which is built into the Network Analyzer). In the experimental setup, an optical spectrum analyzer (OSA) is used to monitor a small portion of the light detected by the photodiode of the Network Analyzer.

In order to measure the tunable time delay, two wavelengths were generated by the Opto-VLSI processor. One was fixed, and the other was tuned, so that a variable time delay between the two wavebands was generated via the high dispersion fiber. The Network Analyzer was set to measure the RF notch response that results from the photodetection of the two RF-modulated wavebands. The time delay between the two wavebands was then calculated by measuring the notch frequencies of the RF response. The transfer function for two wavelengths can be described as

$$H(\omega) = RM^2 \,|\exp[-j(T_0 + T)\omega] + \exp[-jT_0\omega]| \quad (2)$$

where M is the modulated amplitude of the waveband, R is the responsivity of the photodiode, T_0 is the time delay due to the optical path, and T is time delay between the two wavelengths introduced by the high dispersion fiber characteristics. Furthermore, the notch frequencies of the transfer function are given by:

$$f_{notch} = (k + 1/2)\frac{1}{T}, k = 0,1,2,... \quad (3)$$

When the center wavelength of the waveband changes, the time delay T varies (since the other waveband is fixed), and consequently, the free spectral range of the filter response (FSR = $1/T$) varies accordingly. The time delay, T, can be expressed as:

$$T = \alpha \cdot \Delta\lambda \quad (4)$$

where α denotes the dispersion coefficient of the high-dispersion fiber, and $\Delta\lambda$ is the wavelength span between the centers of the two wavebands.

IV. EXPERIMENTAL RESULTS

In the experiments, the RF signal generated by the Network Analyzer was used to intensity modulate a broadband ASE source using a 4-GHz JDS Uniphase electro-optical modulator (EOM). The light amplified by the SOA (made by Q-Photonics, Inc.) was collimated at about 1 mm diameter, and was then launched onto the active window of a 256-phase-level one-dimensional Opto-VLSI processor having 1×4096 pixels with 1 µm pixel size and 0.8 µm dead spacing between adjacent pixels. A Labview software was developed to generate the optimized digital phase holograms that steer the specific wavelengths back into the fiber collimator and simultaneously equalise their intensities. The selected RF-modulated wavebands were routed, via the circulator, into a high dispersion fiber (HDF) of dispersion coefficient 382.5ps/nm and insertion loss 4.6 dB.

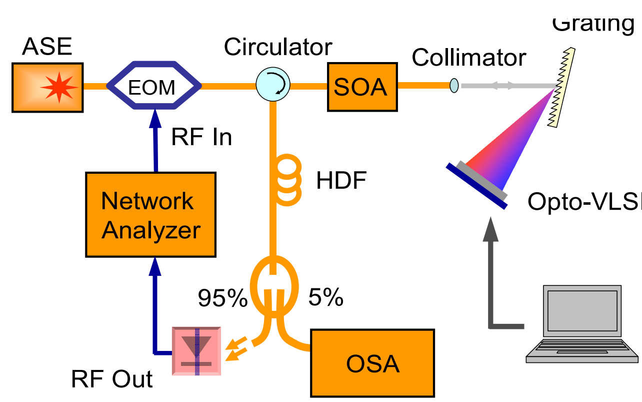

Fig. 2. Tunable time delay structure and Experimental setup

By employing an appropriate phase hologram onto the Opto-VLSI processor, one waveband was fixed at centre wavelength of 1544.9nm, while the other waveband was tuned from 1534.0nm to 1544.9nm, thus realizing a time delay difference from 0 to about 4 ns between the two wavebands. Fig. 3 shows the optical signals monitored by the OSA for three true-time delay scenarios, corresponding to wavebands centered at 1540.2nm, 1543.0nm, 1543.9nm, respectively. The inset for each figure shows the corresponding phase hologram. The RF spectral responses for the three scenarios are shown in Fig. 4. The measured notch frequencies of the RF responses were about 0.28GHz, 0.68GHz, and 1.3GHz, corresponding to time delays of about 1.79ns, 0.72ns, and 0.38ns (using Eq. 3), respectively. The experimental results are in excellent agreement with the theoretical calculation from Equation 4.

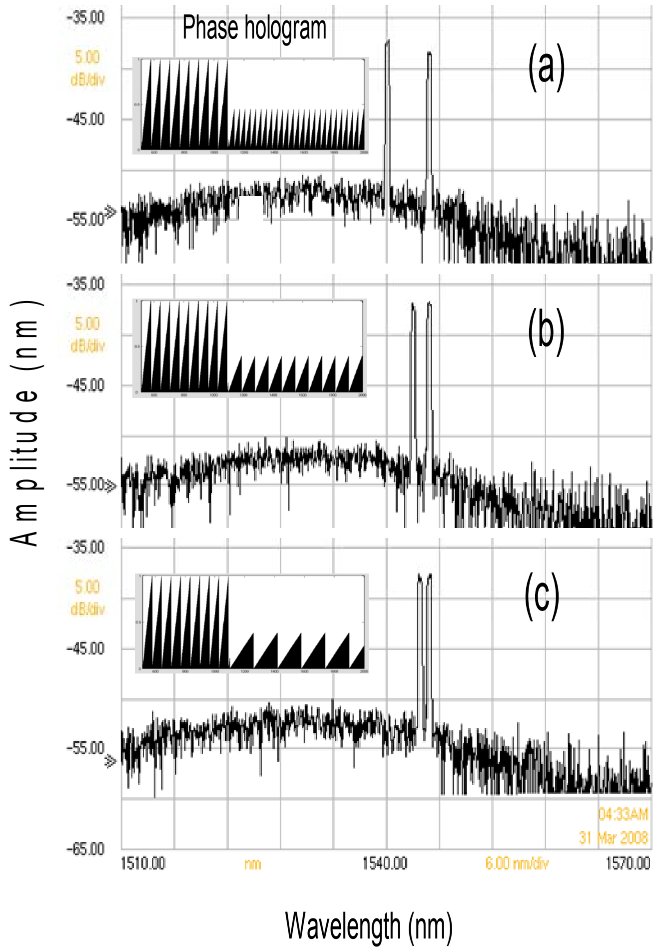

Fig. 3. Optical spectrum detected by the OSA. One waveband was fixed at 1544.9nm while the center of the other waveband was tuned to (a) 1540.2nm, (b) 1543.0nm, and (c) 1543.9nm, by changing the phase holograms uploaded onto the Opto-VLSI processor.

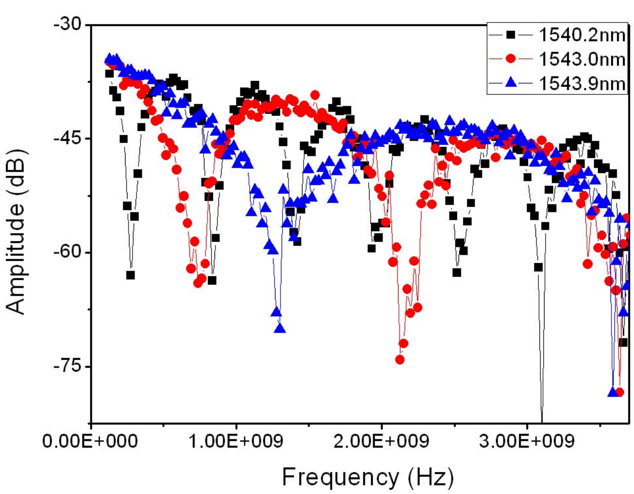

Fig. 4. Measured RF spectral responses that resulted from the photodetection of a RF-modulated waveband centered at 1544.9nm and another RF-modulated waveband centered at (-■-)1540.2nm, (-●-) 1543.0nm, and (-▲-) 1543.9nm.

By reconfiguring the Opto-VLSI processor, optimised digital phase hologram can be uploaded to tune the time delay continuously. Note that, from Eq. 4, the delay time T depends on the dispersion coefficient of the dispersion medium, and therefore, a higher dispersion medium can result in a larger maximum attainable time delay.

It is important to note that, by simultaneously driving the pixel blocks of the Opto-VLSI processor with appropriate phase holograms, multiple wavebands can simultaneously be reflected and routed to the high-dispersion fiber, leading to the synthesis of several arbitrary time delays. This latter feature is crucial for null steering in broadband smart antenna applications.

Note also that the ability of the proposed true-time delay unit structure to generate variable multiple true-time delays makes it attractive for a broad range of photonics-based RF signal processing applications.

V. Conclusion

We have proposed and demonstrated the principle of a tunable time delay structure employing an Opto-VLSI processor, a broadband amplified spontaneous emission source (ASE), a diffractive grating plate, and a high-dispersion fiber. The RF-modulated ASE source has dynamically been sliced into narrow RF-modulated wavebands using phase hologram uploaded onto the Opto-VLSI processor. By delaying the RF-modulated wavebands via a high dispersion fiber, a tunable true-time delay structure has been realized. A true-time delay tunable from 0 to 4 ns has experimentally been measured demonstrating an excellent agreement with the theoretical results. This structure can synthesise multiple true-time delay simultaneously, and has applications in RF phased-array antennas and photonic RF signal processing.

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