1-1-2010

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This is an Author's Accepted Manuscript of: Juswardy, B., Xiao, F., & Alameh, K. (2010). Opto-VLSI-based RF Beamformer for Space Division Multiple Access Network. Proceedings of International Symposium on High Capacity Optical Networks & Enabling Technologies. (pp. 222-226). Cairo, Egypt. IEEE. Available [here](#)
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Opto-VLSI-based RF Beamformer for Space Division Multiple Access Network

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Abstract—In this paper, the architecture of a photonic-assisted smart antenna for Space-division Multiple Access (SDMA) is described. Antenna beam steering is achieved by generating independent true-time delay (TTD) for each element in the antenna arrays, through the use of an Opto-VLSI Processor in conjunction with a 10-km single mode optical fibre. Experimental results demonstrate RF beam steering in 4-element linear patch antenna array operating at 1.85GHz are presented.

Index Terms— Beam steering, Opto-VLSI, SDMA, smart antenna, phased-array antenna, microwave photonics, true-time RF delay.

I. INTRODUCTION

The tremendous growth of the broadband wireless communication applications, combined with the limited radio frequency (RF) spectrum availability, has driven the global demand for increased capacity and data rates of wireless networks to accommodate larger volumes of subscribers.

However, in current wireless network systems, the base station has no information on the position of each mobile user within a cell, and radiates the RF signal in all directions within the cell in order to provide radio coverage. This results in inefficient utilisation of the radiated power during the transmission and causing interference to adjacent cells (co-channel) that use the same frequency. In addition, the antenna receiver detects signals coming from all directions including noise and interference signals, making the processing of the desired signals more difficult, and as a result, limiting the transmission speed and number of users.

A Smart antenna is an attractive solution that can be used to improve spectrum usage and increase network capacity, together with a more efficient use of transmitted energy. Generally, smart antennas refer to antenna arrays with adaptive signal processing module,

so that the antennas can maximise the wanted signals and also minimise the interfering signals.

The RF radiation pattern of a smart antenna can be directed to each user to obtain the highest possible gain in the direction of that user, while rejecting the interfering signals from unwanted directions, enabling users residing in different beams but in the same wireless cell to use the same frequency (intra-cell frequency reuse) [1]. Therefore, spatially-separated users can be served in the same base-station sector. This concept is called Space Division Multiple Access (SDMA) system, where multiple users are separated spatially in the same cell while using the same frequency/time slot.

In ideal smart antennas, the beamformer can intelligently track and follow the desired signal as the intended user is moving, while adaptively sensing and nulling the interference signals from unwanted users. Hence, smart antennas allow for higher signal-to-noise ratio, lower transmission power, and permit greater frequency reuse and greater bandwidth within the same cell.

In summary, the benefits of using smart antennas for wireless communication system are as follow [2]:

- Improved system capacities
- Higher permissible signal bandwidths
- Spatial separation of the signal (using SDMA techniques)
- Higher signal-to-interference ratios
- Increased frequency reuse.

To obtain an optimal radiation pattern for broadband transmission, the signals received by or transmitted from the antenna array must be accurately time-compensated via true-time RF delay generation [3].

Electronic phase-shifting devices that are currently used to achieve beamforming are frequency dependent. Conventional RF transmission delay lines are limited by the loss of their metallic media. A smart antenna system based on the use of digital signal processor

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(DSP) is currently thwarted either by the limited resolution and the narrow bandwidth of analogue-to-digital converter, or by high power consumption of broadband analogue-to-digital converter.

The processing of RF signals for smart antenna using optics is more advantageous as compared to fully electronic circuit implementation or digital signal processor (DSP) used to control the antenna array beamforming. Optical signal processing offers attractive features such as small size, low weight, immunity to electromagnetic interference (EMI), compatibility with optical fibre network and, especially, the capability to generate true-time delay (TTD) for broadband beamforming, with minimal beam squint.

In this paper, we propose and demonstrate Opto-VLSI RF beamformer capable of generating variable and frequency independent TTD. Our proposed TTD generation unit can be adaptively reconfigured to synthesize arbitrary true-time delays, and employs an Opto-VLSI processor, Erbium Doped Fibre Amplifier (EDFA) and a 10-km single mode optical fibre (Corning G.655 LEAF solution). The proposed true-time-delay unit has the capability to generate independent true-time delays for several antenna elements simultaneously, making it attractive for broadband beam-steering for SDMA applications.

II. OPTO-VLSI PROCESSOR

An Opto-VLSI processor is an array of reflective nematic liquid crystal (LC) pixels controlled by Very-Large-Scale-Integrated (VLSI) electronic circuits on the backplane of the LC, as shown in Fig. 1.

Fig. 1. Cross sectional view of the Opto-VLSI processor

The voltage level of every pixel can individually be controlled by applying a discrete voltage level on each pixel through the aluminum mirror electrode on the silicon substrate at the bottom of the LC. A transparent Indium-Tin Oxide (ITO) layer is used as the second electrode on top of the LC. A quarter-wave-plate (QWP) layer is deposited between the LC and the

aluminum mirror to accomplish polarization-insensitive operation [4].

An Opto-VLSI processor adaptively steers a light beam incident onto its active window by spatially modulating the phase of the incident light. Spatial light modulator is achieved using a nematic liquid crystal layer aligned such that the long axis of the liquid crystal molecules is oriented parallel to the polarization of the incident light. When voltage is applied across the electrodes, the LC molecules tilt causing the incident light to encounter a reduced refractive index. The change in refractive index translates directly to an optical phase shift for the incident light.

Fig. 2. Principle of optical beam steering through variable-pitch blazed grating generation [5].

By driving the Opto-VLSI with blazed-grating-like phase hologram, optical beam steering can be achieved as illustrated in Fig. 2. The blazed gratings result in a linear phase shift across the beam's wave front as it reflects off the Opto-VLSI processor, and the light propagating along the system's optical axis (β) is steered by an angle (α).

Generally, the diffraction (steering) angle of the Opto-VLSI processor, α_m , is given by [5]:

$$\alpha_m = \arcsin\left(\frac{m\lambda}{d}\right) \quad (1)$$

where m is the diffraction order, λ is the light wavelength in vacuum, and d is the grating period. By driving each pixel independently a phase hologram can be synthesized leading to optical beam steering, beam shaping or multicasting. This steered optical beam can be employed to generate TTD for RF signal, as will be explained in the following Section.

III. BROADBAND PHOTONIC RF BEAMFORMER STRUCTURE

An arrayed antenna front-end consists of several parallel signal paths; each channel is connected to an individual antenna element.

Fig. 3. The Principle RF beamsteering in antenna array.

The spatial directivity (radiation patterns) of the RF signals received or emitted can be steered by changing the phase of each antenna elements, as illustrated in Fig. 3.

In an antenna array receiver system, a plane wave signal arriving at each antenna element has a progressive time delay (τ) for each antenna receiver. The delay difference between two adjacent elements is related to their spacing distance (d) and the signal angle of incidence with respect to the normal of the antenna elements (θ) by this generalised equation:

$$c \cdot \tau = d \cdot \sin(\theta) \quad (2)$$

where c is the speed of light. In general, for a one-dimensional N -element linear array (Fig. 3), the signal arriving at the first antenna element is given by:

$$S_o(t) = A(t) \cos[\omega_c t + \varphi(t)] \quad (3)$$

where $A(t)$ and $\varphi(t)$ are the amplitude and phase of the incoming signal, and ω_c is the carrier frequency. The signal received by the m -th element can be expressed as:

$$S_m(t) = S_o(t - m\tau) \cdot \cos[\omega_c t - m\omega_c \tau + \varphi(t - m\tau)] \quad (4)$$

where ($m = 0, 1, 2, \dots, N - 1$), N is the number of antenna elements.

The equal spacing of the antenna elements can be seen from Eq. 4 as a progressive phase difference $\omega_c \tau$ and a progressive time delay τ . Adjustable time delay elements (τ'_m) can compensate the signal delay and phase difference simultaneously. The combined signal, $S_{sum}(t)$ can be expressed as:

$$S_{sum}(t) = \sum_{m=0}^{N-1} S_m(t - \tau'_m) \cdot \cos[\omega_c t - \omega_c \tau'_m - m\omega_c \tau + \varphi(t - m\tau - \tau'_m)] \quad (5)$$

Equations (5) shows that the signal received could be improved (the emitted wavefront could be directed), by adjusting the time-delay, τ'_m , of each antenna element.

When the time delay generator unit is capable of generating time delays that are independent from the frequency of operation ω_c , the system is said to be generating RF true-time delays (TTD) and is capable of beam steering broadband RF signals.

Figure 4 shows the proposed Opto-VLSI-based RF phase-array antennas architecture for broadband beam steering, based on multi-wavelength tunable fibre ring laser structures described in [6]. The structure consists of N tunable fibre lasers, all controlled by a single 2-D Opto-VLSI processor. Each tunable fibre laser employs an optical amplifier, an optical coupler, a polarisation controller, a circulator, and a collimator. The broadband amplified spontaneous emission (ASE) noise resulting from the ring loop is split by the optical coupler with a 5/95 power splitting ratio, where 5% of ASE power is used to extract the output of the tunable fibre laser while the remaining 95% is re-circulated in the fibre ring cavity. The polarisation controller (PC) is used to optimise the diffraction efficiency of the Opto-VLSI processor and to enforce single-polarisation lasing. All broadband ASE signals are directed to the corresponding collimator array ports, via optical circulators.

An optical lens (Lens 1) is used between the collimator array and a diffraction grating plate to focus the collimated ASE beams onto a small spot onto the grating plate. The grating plate spatially de-multiplexes the ASE beams, and spread them into broad wavebands. Another optical lens (Lens 2), located in the middle position between the grating plate and the Opto-VLSI processor, is used to collimate the dispersed optical beams and map them onto the surface of a 2-D Opto-VLSI processor, which is partitioned into N rectangular pixel blocks. Each pixel block is assigned to a tunable laser port and used to efficiently couple back any part of the ASE spectrum illuminating this pixel block along the incident path into the corresponding collimator port. The Opto-VLSI processor can arbitrarily select any wavebands that are

mapped onto its surface using the principle of beam steering described in Section 2. The selected wavebands are coupled back into the fibre collimator port, and then routed back to the gain medium via the corresponding circulator, thus forming an optical loop for single-mode laser generation.

N different wavelengths can independently be selected for lasing within the different fibre loops by uploading appropriate phase holograms (blazed grating) that drive all the pixel blocks of the Opto-VLSI processor. Therefore, this structure realises a multiport tunable fibre laser source that can simultaneously generate arbitrary wavelengths at its ports.

Fig. 4. Opto-VLSI-based phased array antenna architecture for broadband beam steering.

At the front-end of the phase-array antennas, the RF signal received by each antenna modulates the tunable laser sources generated by the Opto-VLSI. This is achieved by employing an Electro-Optic Modulator (EOM), whose RF port is connected to the antenna element through an RF amplifier employed to boost the power of the RF signals received by the antenna up to the level that is sufficient to drive the EOM. The optical input port of the EOM is connected to the 5% of the optical coupler output (laser source output). All RF-modulated optical signals are then multiplexed together into a single fibre optic and routed into an Erbium Doped Fibre Amplifier (EDFA) for amplification. Subsequently, the multiplexed RF-modulated optical signals are launched into an optical fibre cable, where they experienced true-time delays (TTD) that depend on their centre wavelengths. The delayed RF-modulated optical wavebands are finally detected by a photo-diode that produces the sum of the delayed RF signals.

One of the attractive features of the Opto-VLSI-based phased array antenna architecture shown in Fig. 4 is its ability to generate multiple RF delays without the need for RF splitters. Single or multiple arbitrary RF-modulated wavebands can be coupled back into the fibre collimators and the amplitude of each selected waveband can also be controlled simply by uploading the appropriate steering phase holograms that drive the various pixel-blocks of the Opto-VLSI processor. Each pixel blocks steers a waveband along its initial path or slightly off-track so that variable optical attenuation (and hence RF attenuation) is achieved for all delayed RF signal simultaneously.

IV. EXPERIMENTAL RESULTS

Experiments were conducted using the setup illustrated in Fig. 4 to evaluate the performance of a 4-element ($N=4$) rectangular patch type photonic-based smart antenna system for broadband beam steering in a phased-array antenna. The antenna elements were separated at a distance of $\lambda/2$. A 2-D Opto-VLSI processor was used mainly to provide the tunable fibre laser sources. Each tunable laser source had a dedicated EDFA operating in the C-band, a 1×2 optical coupler with 5/95 power splitting ratio, and a fibre collimator array. The Opto-VLSI processor enabled us to independently and simultaneously select any part of the gain spectrum of the EDFA and inject it back into the corresponding fibre ring laser cavity for lasing. The 8-bit, 512×512 pixels Opto-VLSI had a pixel size of $15\mu\text{m}$. Two lenses with 10 cm focal length were placed at 10 cm from both sides of the grating plate. The polarisation of the ASE signal (95% power) was directed by a polarisation controller (PC) and collimated at about 0.5 mm diameter. A blazed grating plate, having 1200 lines/mm and a blazed angle of 70° at 1530 nm with respect to the normal of Lens 1, was used to de-multiplex the EDFA gain spectra, which were mapped onto the active window of the Opto-VLSI processor by Lens 2. Labview software was developed to generate the optimised digital holograms that steer the desired waveband and couple back into the corresponding collimator for subsequent recirculation in the fibre loop.

The active window of the Opto-VLSI processor was divided into four pixel blocks corresponding to the positions of the four de-multiplexed ASE signals, each block dedicated to one antenna array element. Optimised digital phase holograms were applied to the four pixel blocks, so that desired wavebands from the ASE spectra illuminating the Opto-VLSI processor could be selected and coupled back into their fibre

rings, leading to simultaneous lasing at specific wavelengths. By using appropriate phase hologram, the selected wavebands can be tuned in terms of their wavelength separations and amplitudes. 5% of the selected optical wavebands were then routed via a coupler to the optical input of electro-optics modulators (EOM), each EOM is dedicated to one antenna element. To generate the true time delay (TTD) required for RF beam steering, each RF-modulated optical waveband was routed to a 10-km Corning LEAF non-zero dispersion shifted fibre optic cable with dispersion coefficient of between 2.8-9.3 ps/nm/km and insertion loss of 0.2 dB/km at 1550 nm.

Fig. 5. Opto-VLSI-based tunable optical waveband generations (left), and the corresponding RF beam steering profile measured during the experiments (right).

The RF signal produced after the photodetection of the delayed RF-modulated wavebands was monitored by an RF power meter. Figure 5 (a-d) shows example of measured antenna radiation pattern (right) corresponding to different equi-spaced wavebands (left) generated by the Opto-VLSI processor. As the spacing between the optical waveband is increased from 1nm to 4nm, the measured main lobe of the RF radiation pattern was steered from 10° to 25° , as illustrated in Figure 5 (right). These experimental results demonstrate the capability of the Opto-VLSI based smart antenna beamformer, and has the potential application in spatial division multiple access (SDMA) network. The null steering capability of the beamformer is being investigated, and will be reported elsewhere.

V. CONCLUSION

We have proposed and evaluated an Opto-VLSI-based tunable true-time (TTD) delay generation unit for adaptively steering the radiation pattern of RF phased array antennas. We demonstrated that by using a single Opto-VLSI processor 4 independent optical wavebands can be generated and their spectral tuned. The RF-modulated wavebands are used to generate TTD in 4-element rectangular patch arrayed antennas. Experimental results show the capability of the proposed structure to perform RF beam steering between 0° - 25° for SDMA applications.

ACKNOWLEDGMENT

This research is supported by Office of Research and Innovation (ORI), Edith Cowan University, Australia; and the Department of Nanobio Materials and Electronics, Gwangju Institute of Science and Technology (GIST), Republic of Korea.

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