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Improving the Steering Efficiency of 1x4096 Opto-VLSI Processor Using Direct Power Measurement Method

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Abstract

We report optimization of the steering efficiency of the 1-D Opto-VLSI processor using direct power measurement method for wavelengths in the near-IR and 632 nm. Highest improvement observed for the signal and interport isolation is 8 dB and 12 dB respectively. This improved performance of the processor is crucial to the realization of low crosstalk reconfigurable optical add/drop multiplexers (ROADM) using Opto-VLSI processors.

1. Introduction

Optical beam steering is commonly accomplished via mechanical systems like mirrors on gimbals. As such systems tend to be large, heavy and complex, a non-mechanical all-electronic beam steering component would often be preferred [1]. The use of very-large-scale integration (VLSI) technology in conjunction with new mixtures of Liquid Crystals (LC) has recently led to the construction of polarisation-insensitive Opto-VLSI processors capable of steering, splitting and reshaping optical beams [1]. Opto-VLSI processors have several properties that are attractive for laser beam steering including a small pixel size, low-switching voltage, low power consumption, and high optical efficiency [2]. From an application point of view non-mechanical beam steering and beam shaping are desired features for many applications including reconfigurable optical components, free-space optical communications, defence and security technology, 3D holographic memories, and laser-based imaging.

Our current research has been to harness the unique properties of Opto-VLSI processor to realise solid-state Reconfigurable Optical Add/Drop Multiplexer (ROADM) which involves switching various wavebands between a Thru-port and a Drop-port. In a ROADM, the steering efficiency of the processor is crucial as it affects the crosstalk level between the two ports. In this paper, we explore the use of a real-time power measurement method to improve the performance of Opto-VLSI processors. An algorithm is developed in LabVIEW to optimise the command voltage profile of the Opto-VLSI processor for maximum diffraction efficiency.

2. Opto-VLSI Processor

A reconfigurable Opto-VLSI processor comprises 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 [2,3], as illustrated in Fig. 1. Each pixel is assigned a few memory elements that store a digital value, and a multiplexer that selects one of the input voltages and applies it to the aluminium mirror plate. Opto-VLSI processors are electronically controlled, software-configured, polarization independent, cost effective because of the high-volume manufacturing capability of VLSI chips as well as the capability of controlling multiple fiber ports in one compact Opto-VLSI module, and very reliable since beam steering is achieved with no mechanically moving parts.

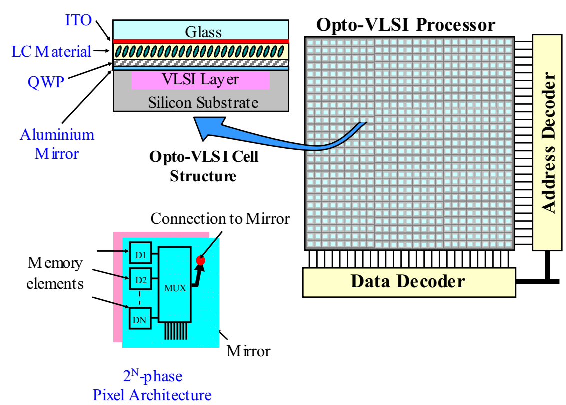

Fig. 1. Typical multi-phase Opto-VLSI processor and LC cell structure design.

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Fig. 1 also shows a typical layout and a cell design of a multi-phase Opto-VLSI processor. Indium-Tin Oxide (ITO) is used as the transparent electrode, and evaporated aluminium is used as the reflective electrode. The ITO layer is generally grounded and a voltage is applied at the reflective electrode by the VLSI circuit below the LC layer.

Fig. 2 illustrates the steering capability of Opto-VLSI processors. The way the processor steers an incident light beam is similar to the way a prism deflects an incident light beam via the prism action. In other words, we can think of the processor as a programmable prism as far as beam steering is concerned. The application of a periodic sequence of voltage ramps of period Λ across the Opto-VLSI array aperture steers the incident light beam to an angle θ (relative to the normal) given by the general grating equation [8,9]

$$\theta = \sin^{-1}\left[\frac{\lambda_o}{\Lambda} - \sin(\alpha)\right] \tag{1}$$

where λ_o is the incident wavelength in free space, α is the angle of incidence, Λ is the grating's period = $q \times d$, q is the number of pixels within the period of the programmable grating, and d is the interpixel distance.

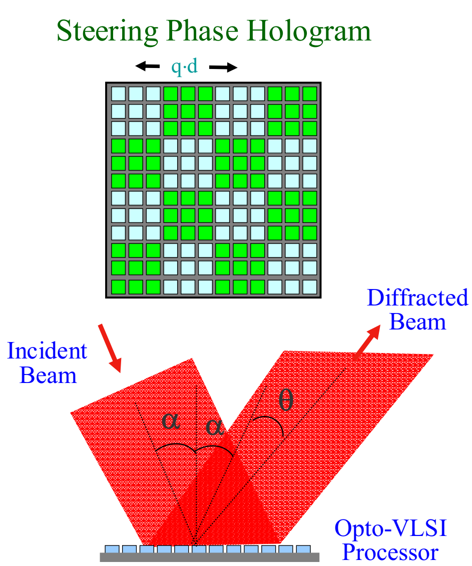


Fig. 2. Steering capability of an Opto-VLSI processor.

Liquid crystal is known to be birefringent and that the orientation of the molecules can be influenced by an applied external electric field. By changing the voltage across an LC cell, it is possible to rotate the orientation of these molecules and thus change the index of refraction for a given polarization.

The major challenge with LC is that switching is that the switching speed of a nematic liquid crystal phase shifter is generally inversely proportional to the square of the thickness of the nematic liquid crystal layer. Therefore, for fast response, it is desired to keep the liquid crystal layer thin. This can be achieved by driving the LC with modulo-2π sawtooth ramp [4]. This modulo-2π sawtooth ramp still steers an optical beam with unity efficiency (no sidelobes), but only for the designed wavelength for which the phase resets exactly equal 2π radians. Fig. 3 illustrates the equivalence of the phase retardation of a linear phase ramp and a blazed grating profile (both steer the light with unity efficiency).

Liquid crystals suffer from fringing fields and resistance to rapid change in orientation, which makes it difficult to electronically address a liquid crystal array at sub-wavelength spacing. This difficulty does not manifest during the uniform phase-ramp portion of the addressing process [5]. Instead, the difficulty comes at the reset point where abruptly drop in phase is desired.

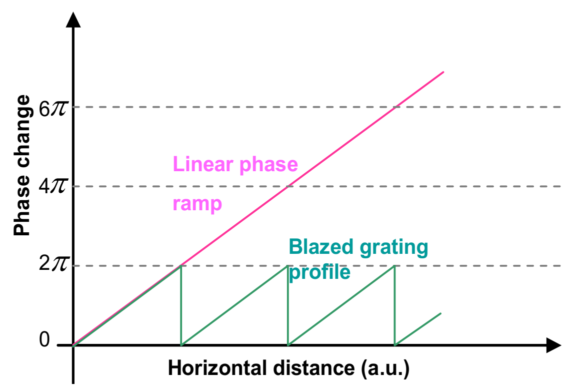


Fig. 3. Phase retardation of a prism. The linear phase ramp can be replaced by a blazed grating profile which still steers light with unity efficiency.

During the phase ramp, fringing field effects smooth the phase profile. At the reset point, the fringing field creates a spatial region with opposite phase profile as shown in Fig. 4. The flyback steers the portion of an incident optical beam to an opposite angular position thus reducing the diffraction efficiency. The length of the flyback region is approximately equal to the thickness of the LC layer [6]. For small steering angles (i.e. small ramp slope), the flyback region is a small percentage of the phase ramp and has a small impact on the diffraction efficiency. However, as the steering angle gets larger, a significant portion of the wavefront is coupled into higher diffraction orders, resulting in a significant reduction in diffraction efficiency and higher crosstalk.

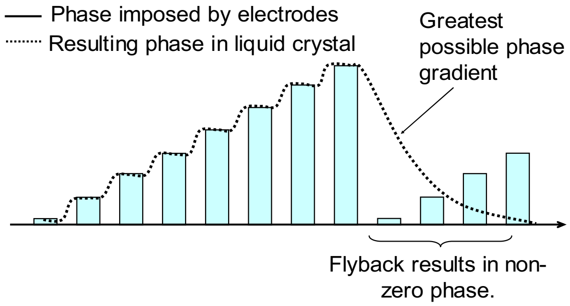


Fig. 4. Phase profile due to pixilation of electrodes and resistance of liquid crystal material to rapid change in orientation.

The overall diffraction efficiency due to quantization as well as the flyback effects can be approximated by [4]

$$\eta_{total} = \left[\frac{\sin(\pi/q)}{\pi/q}\right]^2 \cdot \left(1 - \frac{\Lambda_F}{q \cdot d}\right)^2 \qquad (2)$$

where

Λ_F = width of the flyback region

Λ = length of the grating period = $q \cdot d$

Another contribution of loss comes from the nonlinear phase response of the LC as a function of the applied voltage. This effect happens in the linear ramp region that contributes to the steering of the light beam. Therefore, the amount of loss due to non-linear effect becomes significant when the number of pixels per grating period is large (small steering angle). In short, at large steering angle, the loss is primarily due to pixilation and flyback, while at small steering angle, the majority of the loss is due to nonlinear phase change. Note that the 'nonlinear loss' is not fundamental and it could be removed significantly by taking the phase—voltage into account. Fig. 5 shows the steering efficiency versus the number of pixels for an Opto-VLSI processor with and without the effects of flyback. It is obvious that the flyback significantly reduces the steering efficiency when the number of pixels is low.

Spacing at the half-wavelength level would allow large-angle beam steering without creating the detrimental flyback effect [7]. For optimal performance, the beam-steering capabilities of liquid crystal devices are currently limited to about 4° in either direction in order to maintain high efficiency beam steering.

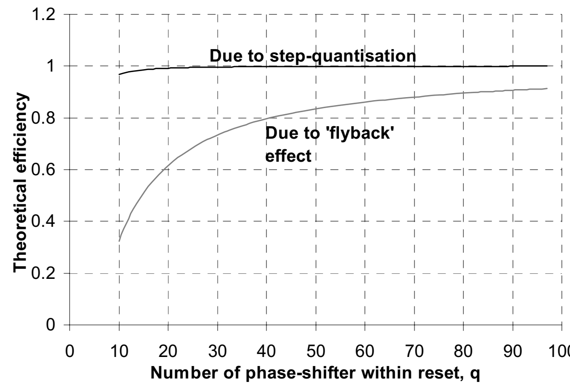


Fig. 5. Steering efficiency of the first order beam versus number of pixels due to step-quantization of Opto-VLSI processor and flyback effect.

3. Opto-VLSI based ROADM architecture

A schematic setup to realize ROADM using Opto-VLSI processor is as shown in Fig. 6. The input wavelengths launched at the Input-port are routed, through a circulator, to a fiber collimator that converts the WDM signal into a collimated optical beam, which is demultiplexed by a dispersive grating along different directions. This causes different wavelengths to be mapped onto different regions on the Opto-VLSI active window. Depending on the hologram loaded into the Opto-VLSI processor, each wavelength can either be steered to the Thru-port, or directed to the Drop-port for Drop-operation. As an illustrative example shown in Fig. 6, where only the wavelength λ_1 is steered to the Drop-port while the other channels are steered to the Thru-port. If the same wavelength λ_1* (carrying different data) is launched into the Add-port, it follows the same optical path of the dropped wavelength but in opposite direction, and hence it is coupled into the Thru-port and multiplexed with the WDM channels. Note that because each wavelength resides on a unique position on the active window, there is one appropriate steering angle that couples that wavelength into the desired port with the highest possible power.

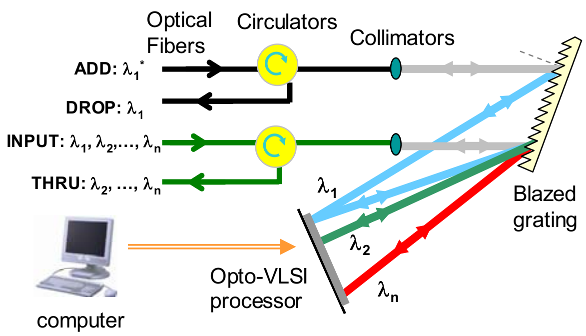


Fig. 6. Experimental setup for the reconfigurable optical add/drop multiplexer (ROADM).

4. Experimental results

Two experiments were performed to validate the steering efficiency improvement. The primary experiment involved the above reconfigurable optical add/drop multiplexer (ROADM) setup and the use of a near-infra-red (NIR) tunable laser source. In the second experiment, we focused on the optimization of the steering efficiency of the Opto-VLSI processor illuminated using a He-Ne laser source (632 nm) in free-space.

A. Optimization results for NIR (ROADM setup)

In this setup, the waveband 1545 nm was launched into the input port of the ROADM, and the appropriate phase hologram with *linear* blazed grating profile was uploaded into the processor so as to couple the waveband into the Thru-port with highest coupling efficiency and the optical power on the spectrum analyzer was recorded. Next, the grating profile was allowed to evolve to maximize the power of the first order beam. This approach (i) minimized the flyback effect and (ii) helped to linearise the LC phase-voltage relationship taking into account the fringing field due to the pixilated electrode array and the LC viscosity. The same procedure was repeated for other wavebands namely 1550, 1555, 1560, 1565, and 1570 nm which required different grating periods ranging from 36 to 166 μm respectively, for optimum coupling. The output power levels for these wavebands are plotted in Fig. 7 for the linear as well as the optimized voltage profiles.

Fig. 7 shows that the power output of the linear series begins to drop off as the steering angle becomes smaller (larger grating period). This is in agreement with the hypothesis put forward in the introduction (Section 1). That is, the non-linear LC phase-voltage effect becomes more pronounced as the period becomes larger and more optical power is distributed to other higher diffraction orders when linear voltage ramp is applied. On the other hand, in the short period region the non-linear LC phase–voltage becomes negligible while the flyback effect begins to dominate.

In the ROADM setup, light from higher diffraction orders can potentially couple into undesired port leading to poor inter-port isolation. Optimization can increase the power of the first order (the steered order) while reduce powers of the higher orders. Table 1 shows measurements of two optimised Opto-VLSI voltage profiles for steering angles of 0.27° and 2.7°. It was noticed that for a steering angle of 0.27° the optimized nonlinear voltage profile exhibits 8dB improvement in coupling efficiency and 12dB enhancement in port isolation. For a steering angle of 2.7°, the fly-back effect dominates over the nonlinear effect, leading to limited improvements in diffraction efficiency and port isolation of 2dB and 3dB, respectively. Note that, despite the fact that these improvements at high steering angles are limited to a few dB, the signal and inter-port isolation levels are adequate for practical ROADMs.

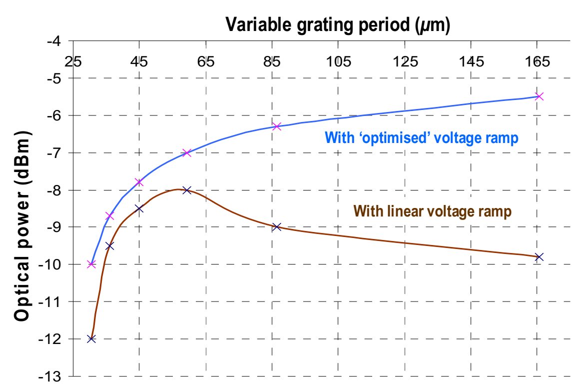
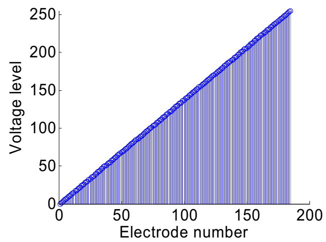
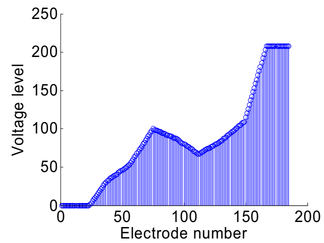
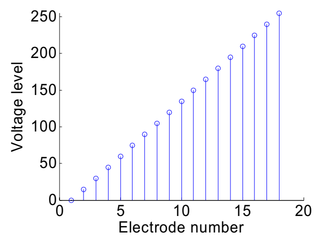
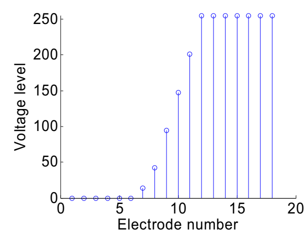


Fig. 7. Optimisation results using the near-IR source for linear voltage ramp input and 'optimised' (nonlinear) voltage ramp input.

TABLE 1: COMMAND VOLTAGE PROFILES FOR STEERING ANGLE OF 0.27 DEGREE AND 2.7 DEGREES.

Steering angle [degree]		Measured optical power [dBm]		Improvement
		Linear	**Non-linear (Optimized)**	
0.27	**Command voltage profile**			
	Signal	-18	-10	+8 dB
	Inter-port isolation	**13**	**25**	+12dB
2.7	**Command voltage profile**			
	Signal	-13	-11	+2 dB
	Inter-port isolation	**34**	**37**	+3dB

B. Optimization results for He-Ne laser (632nm) in free-space

A linear voltage ramp of period 128 electrodes per grating period was uploaded into the Opto-VLSI processor to generate a diffraction pattern in which the first order corresponds to the steered beam. The diffraction pattern was intercepted by a screen placed 3 m away from the Opto-VLSI processor. The optical power of the first order beam was measured using a power meter (Newport 1830-C). The diffraction pattern generated by both the linear and 'optimized' voltage ramps are as shown in Fig. 8. Optimization of the voltage ramp yielded a power improvement of 7.5 dB.

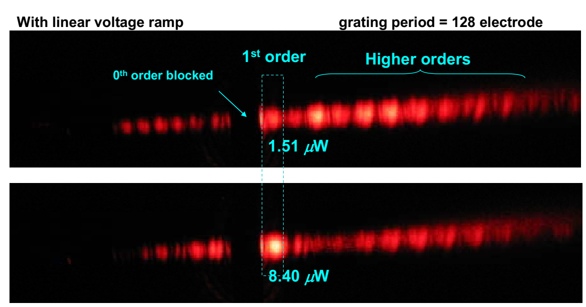


Fig. 8. Optimization result for the He-Ne laser in free space using a steering grating period of 128 electrodes per period (128 μm).

From Fig. 8, we can also observe that (i) the position of the first and other higher orders remain at the same position for a given grating period, and (ii) the shape of the voltage profile ramp affects the exact distribution of optical power among the diffraction orders. The optimized voltage ramp shifted the power

distribution from the higher orders into the first order (the steered beam). This increases the signal while reduces the 'noise'. In other words, it improves the signal-to-noise ratio significantly, and this significant improvement is consistent with the near-IR results tabulated in table 1 whereby the improvement in signal and inter-port isolation is 8 dB and 12 dB respectively.
The general optimized voltage profile is largely in agreement with the LC phase-voltage plot if not for the 'hump' that seems to prevail for both the near-IR and 632 nm.

5. Conclusion

The impact of non-linearity of LC materials and the flyback-effect on the steering efficiency and inter-port isolation has been investigated in this paper. A computer algorithm has been developed and experimentally demonstrated, which optimizes the voltage profile to maximize the steering efficiency and the inter-port isolation. Improvements in signal and inter-port isolation of 8 dB and 12 dB respectively, have been demonstrated.

6. References

[1] Emil Hällstig, "Nematic Liquid Crystal Spatial Light Modulators for Laser Beam Steering", Dissertations, Acta Universitas Upsaliensis, 2004.
[2] Xinghua Wang, "Liquid Crystal on Silicon (LCOS) Wavefront Corrector and Beam Steerer", SPIE Proc., Vol. 5162, pp. 139-146, Dec 2003.
[3] Mehrdad Raisi, Selam Ahderom, Kamal Alameh, Kamran Eshraghian, "Dynamic MicroPhotonic WDM Equalizer", Second IEEE International Workshop on Electronic Design, Test and Applications, IEEE, 2004.
[4] Xinghua Wang, "Performance evaluation of liquid crystal on silicon spatial light Modulator", Optical Engineering, Vol. 43(11), pp. 2769-2774, November 2004.
[5] D. Dayton, S. Restaino, J.Gonglewski, "Novel Spatial Light Modulators for Active and Adaptive Optics", SPIE Proc., Vol. 4124, November 2000.
[6] Paul McManamon, "Optical Phased Array", IEEE, Vol. 84, No. 2, pp. 268-298, February 1996.
[7] Paul McManamon, "Putting on the Shift", SPIE's oemagazine, pp. 15-17, April 2003.