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A 1×4 Adaptive Optical Splitter Based on Opto-VLSI Processor

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Abstract— **We propose and experimentally demonstrate a novel high resolution 1×4 adaptive optical power splitter based on the use of an Opto-VLSI processor and a 4-f imaging system with an optimized optical beam waist profile. By uploading optimized multicasting phase holograms onto the software-driven Opto-VLSI processor, an input optical signal is dynamically split into different output fiber ports with user-defined splitting ratios. Experimental results showing dynamic optical splitting over a wavelength range exceeding 50 nm are presented.**

Index Terms— **adaptive optical splitter, beam splitter, liquid crystal devices, optical communication, opto-VLSI processor.**

I. INTRODUCTION

Recently, adaptive optical power splitters have attracted much attention due to the rapid deployment of passive optical networks (PON) for fiber-to-the-premises (FTTP), optical metropolitan area networks (MAN), and active optical cables for TV/video signal transport and distribution [1]. Currently, passive optical splitters are used in PONs where several hundred users share one optical line terminal (OLT) at the central office, distributing optical power to several tens of optical network units (ONUs) at the customer end of the network, each of which is shared by many users [2]. However, passive optical power splitters have limitations, not only in adding/dropping users to/from an ONU but also in changing services for each user.

An adaptive optical power splitter can dynamically distribute the optical power and services to users in the entire optical access network, thus providing numerous advantages such as improvement of optical network efficiency and network scalability, and high network reliability. An adaptive optical power splitter is also necessary for implementing a self-healing ring in a MAN [3], offering a popular protection mode that automatically recovers communication from failure. Furthermore, future optical line protection (OLP) systems will require adaptive optical splitters to transfer the optical power from the primary path to the secondary path dynamically, avoid the use of optical power attenuators and optical amplifiers, and monitor both paths instantaneously [4]. Another possible application of adaptive optical splitters is in the area of photonic signal processing [5], particularly, photonic RF transversal filters, where lightweight and broadband are of prime concern [6-8].

Very few dynamic optical splitter structures have recently been reported [9-14]. However, these structures have limitations such as noisy and uncontrollable output power level, poor reliability, and poor tolerance to environmental perturbations (temperature, vibrations, etc). In particular, the proof-of-principle 1×2 adaptive optical splitter based on Opto-VLSI processor reported by the authors [14], has low splitting resolution and output port counts due to the limitation in controlling the beam waist.

In this paper, we propose a novel adaptive optical splitter structure employing an Opto-VLSI processor and a 4-f imaging system with an optimized optical beam waist profile, enabling high-resolution optical power splitting to a larger number of output optical ports. The new adaptive optical splitter has additional advantages including, high diffraction efficiency (i.e. lower optical loss), low inter-port crosstalk, simple user interface, and compressed hardware and compact packaging. A software program was especially developed to generate the desired phase holograms that split an input signal arbitrarily and accurately to multiple output optical fiber ports.

II. OPTO-VLSI PROCESSORS AND OPTICAL BEAM MULTICASTING

The Opto-VLSI processor is an electronically-driven diffractive element capable of steering/shaping an incident optical beam without mechanically moving parts. As shown in Fig. 1, an Opto-VLSI processor comprises an array of liquid crystal (LC) cells driven by a Very-Large-Scale-Integrated (VLSI) circuit [13, 14], which generates digital holographic diffraction gratings that achieve arbitrary beam deflection/multicasting. A transparent Indium-Tin Oxide (ITO) layer is used as the ground electrode, and a quarter-wave-plate (QWP) layer is deposited between the LC and the aluminum mirror to accomplish polarization-insensitive operation. The voltage level of each pixel can individually be controlled by using a few memory elements that select a discrete voltage level and apply it, through the electrodes, across the LC cell.

A multicasting phase hologram can split an incident optical beam to N output beams with variable intensities in different directions, as illustrated in Fig. 2. A collimated beam incident onto the Opto-VLSI processor is diffracted along different directions, where the power of each diffracted beam depends on the multicasting phase hologram. The beam multicasting resolution, or minimum splitting angle relative to the zeroth order diffraction beam, is given by [15]

$$\alpha = \arcsin\left(\frac{\lambda}{N \times d}\right) \quad (1)$$

where λ is the optical wavelength, N denotes the number of pixels illuminated by the incident optical beam, and d is the pixel pitch.

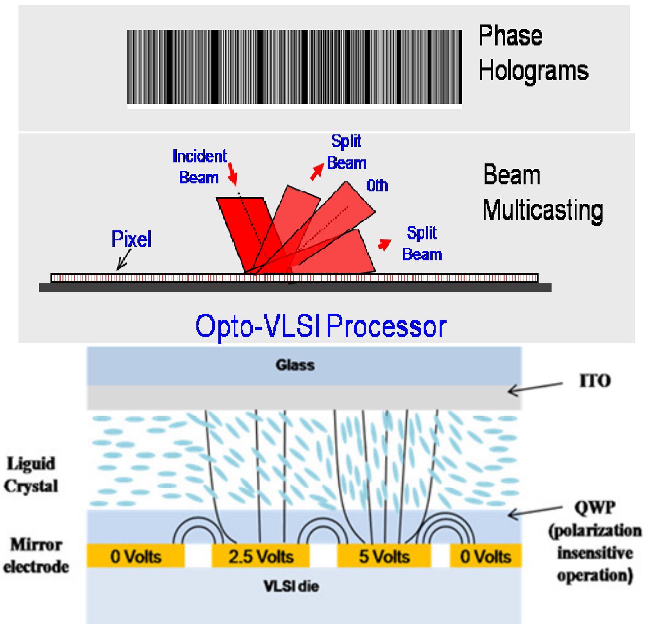

Fig. 1. Opto-VLSI processor layout, Opto-VLSI cell structure and pixel architecture. Opto-VLSI capability of optical beam multicasting by uploading phased holograms.

Several computer algorithms, such as the genetic, simulated annealing, phase encoding, and projection algorithms [16], have been used for generating optimized multicasting phase holograms that produce a target far-field distribution, defined by the replay beam positions and the corresponding power splitting ratios. For a target splitting ratio profile, an optimised phase hologram can always be generated, which minimizes the zeroth order diffraction and maximizes the signal-to-crosstalk ratio at every output port.

III. EXPERIMENTS

A. System description

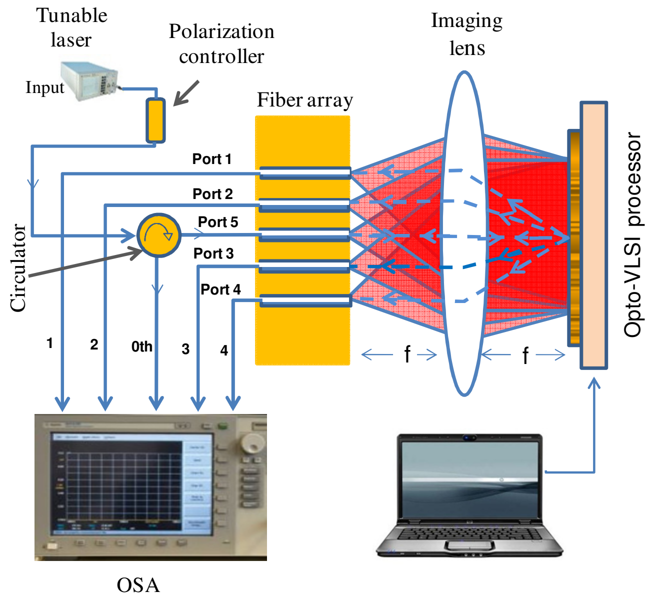

Fig. 2. Schematic diagram of the adaptive optical splitter using an Opto-VLSI processor and a 4-*f* imaging systems.

The structure of the proposed reconfigurable optical power splitter is shown, through an experimental setup, in Fig. 2. It consists of an Opto-VLSI processor, a lens, and an optical fiber array, aligned to form a 4-f imaging system. The Opto-VLSI processor has 1×4096 pixels with pixel size of 1.0 µm wide and 6.0 mm length, and 1.8µm pixel pitch (i.e. 0.8 µm of dead space between pixels). To demonstrate the principle of the 1×4 adaptive optical splitter, a custom-made fiber array with spacing 127 µm was used. The spacing between the output ports was 254 µm (twice of the fiber array spacing), thus the split beam angles were θ= ±0.58, ±1.16 with respect to 0^{th} order beam direction, as illustrated in Fig. 2. The power of the 0^{th} order beam was coupled to a fiber port for monitoring the diffraction efficiency of the Opto-VLSI processor.

A tunable laser source with an output optical power of +1.5 dBm and a wavelength of 1550 nm was used as the input signal, and launched through the input port of the splitter. A lens of focal length f = 25 mm was placed between and at an equal distance, f, from both the fiber array and the Opto-VLSI processor. With no phase hologram uploaded onto the Opto-VLSI processor, only the 0^{th} order diffraction beam was reflected back and focused through the imaging system into same fiber input port 5 centered the four output fiber ports, resulting in minimum crosstalk into ports 2, and 3, as illustrated in Fig. 2. The 0^{th} order signal was directed to optical spectrum analyzers (OSA), via a circulator, in order to monitor the diffraction efficiency. The input signal from the input port at the fiber array was collimated through a lens, to an optical beam diameter of 5.48 mm, which illuminated around 3046 pixels of the Opto-VLSI processor, leading to a high diffraction efficiency and high optical splitting resolution of 0.01 degree (around 10 times better than the resolution reported in [14]).

By driving the Opto-VLSI processor with an optimized multicasting phase hologram, the optical beam illuminating the Opto-VLSI processor was split into four different optical beams (in addition to the 0^{th} order beam) which propagated along the optimized directions so that they were coupled back into the fiber output ports through the 4-f imaging system. The split optical beams coupled into the output ports propagated along angles equal to $\theta_{2,3} = \pm 0.58°$, and $\theta_{1,4} = \pm 1.16°$ with respect to the 0^{th} order beam direction. Optical spectrum analyzers (OSA) were used to monitor the power levels of the split optical signals coupled into the output ports 1, 2, 3 and 4.

B. Experimental Results and Discussion

Several optical splitting scenarios were attempted in the experiments to demonstrate the adaptive optical power splitting capability of the proposed optical splitter. Figs 3 shows the measured output power levels coupled into Port 1, Port 2, Port 3 and Port 4, corresponding to different splitting ratios.

Fig. 3(a) demonstrates a scenario where the input optical power is split equally into the four output ports by uploading phase hologram corresponding to splitting profile 1.0:1.0:1.0:1.0, resulting in uniform optical power distribution at all the four output ports. Fig. 3(b) shows the measured output optical signals when the output fiber Port 4 was switched off using a phase hologram corresponding to a splitting profile of 1.0:1.0:1.0:0.0. Fig. 3(c) shows the measured output optical signal when two ports 'Port 2 and 4' were dropped down by 4 dB and 7 dB, respectively, by uploading a phase hologram corresponding to a splitting profile of 1.0:0.5:1.0:0.2. Note that the crosstalk level in Fig. 3(b) was less than -25 dB.

The measured maximum output power fluctuation for the fixed-weight output ports was less than 1dB. The experimental results shown in Fig. 3 demonstrate the ability of the adaptive optical splitter structure to realize arbitrary optical splitting ratios through the use of optimized multicasting phase holograms.

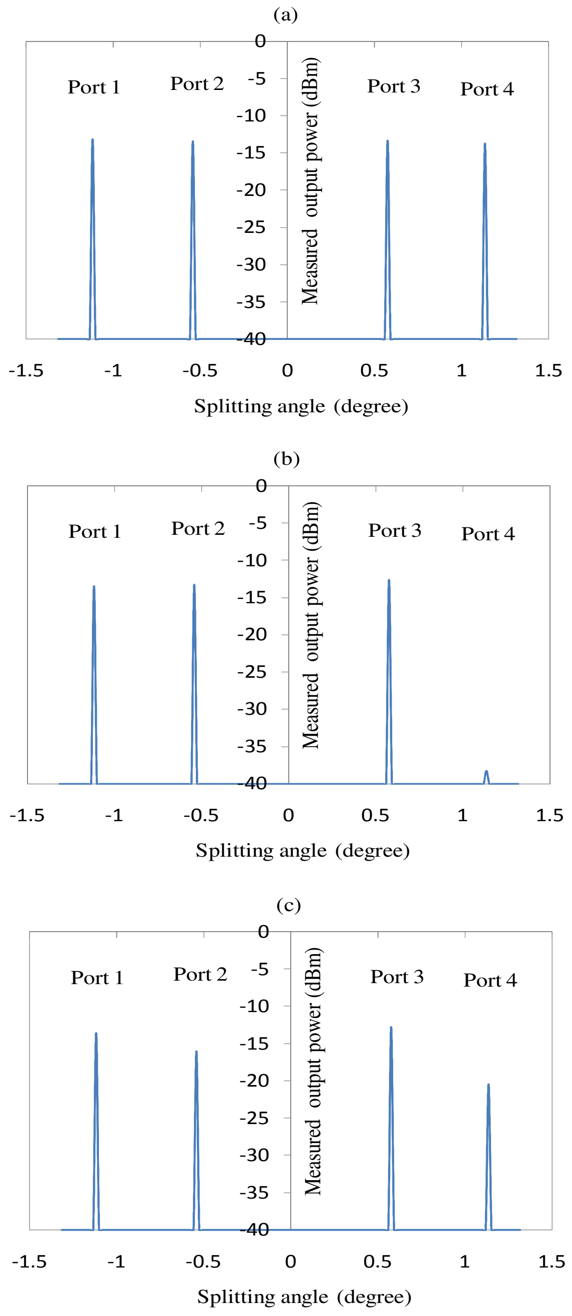

Fig.3. Measured output power coupled into Ports 1, 2, 3, and 4 when phase holograms corresponding to a splitting ratio, (a) 1.0:1.0:1.0:1.0 (b) 1.0:1.0:1.0:0.0 and (c) 1.0:0.5:1.0:0.2 were uploaded onto the Opto-VLSI processor.

To investigate the bandwidth of the proposed adaptive optical splitter, the wavelength of the tunable laser source was varied from 1525 nm to 1575 nm. The measured optical power versus wavelength at the output ports are shown in Fig. 4, for a splitting profile equal to 0.4:1:1:0.4. The measured maximum output power fluctuation at the four output ports was around 1.0 dB over a wavelength span from 1525 nm to 1575 nm, demonstrating a splitter bandwidth in excess of 50 nm.

The total insertion loss of the optical power splitter was 4.8 dB, resulting mainly from the low fill factor of the Opto-VLSI processor, 4-f imaging system alignment, and imperfect optical components used in the experiments. This insertion loss can further be reduced through an improved Opto-VLSI chip design, and the use of broadband AR coatings for the various optical components. Note that by using a 2-dimensional Opto-VLSI processor and a 2-dimenssional fiber array, a high-resolution dynamic optical splitter with up to 16 output ports can potentially be realized with negligible insertion loss penalty. This feature makes the adaptive optical splitter attractive for many emerging optical network and photonic signal processing applications.

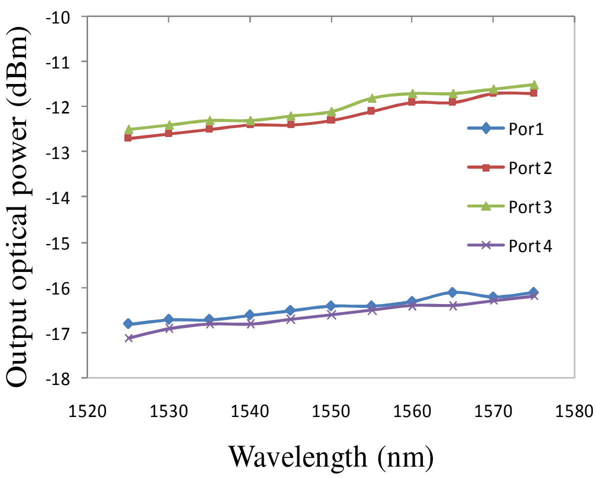

Fig. 1. Measured wavelength response of the proposed adaptive optical splitter for splitting profile of 0.4:1:1:0.4.

IV. Conclusion

An adaptive optical splitter structure employing Opto-VLSI processor and an optical fiber array in conjunction with a 4-f imaging system has been demonstrated. Experimental results have shown that an input optical signal can arbitrarily be split and coupled into four output optical fiber ports by simply uploading optimized multicasting phase holograms onto the Opto-VLSI processor. A crosstalk level below -25 dB and a wavelength range exceeding 50 nm have been attained, making the adaptive optical splitter attractive for access optical networks and optical signal processing.

References

[1] A. Queller, "Dynamic power distribution in PON/FTTP networks", Lightwave **21**(7), (2004) http://www.lightwaveonline.com/about-us/lightwave-issue-archives/issue/dynamic-power-distribution-in-ponfttp-networks-53906787.html

[2] M. D. Vaughn, D. Kozischek, D. Meis, A. Boskovic, and R. E.Wagner, "Value of reach-and-split ratio increase in FTTH access networks," J. Lightw. Technol. **22**(11), 2617–2622 (2004).

[3] J. Shi and J. P. Fonseka, "Hierarchical self-healing rings," IEEE/ACM Trans. Netw. **3**(6)**,** 690–697 (1995).

[4] D. Griffith and S. Lee, "A 1 + 1 protection architecture for optical burst switched networks," IEEE J. Sel. Areas Commun. **21**(9), pp. 1384–1398 (2003).

[5] J. Capmany, B. Ortega, D. Pastor, and S. Sales, "Discrete-Time Optical Processing of Microwave signals", J. lightw. Technol. **23**(2), pp. 702-723 (2005).

[6] R. A. Minasian, K. E. Alameh, and E. H. W. Chan, "photonic based interference mitigation filters", IEEE Trans. Microwave Theory Tech.**49**(10), pp. 1894-1899 (2001).

[7] F. Xiao, B. Juswardy, and K Alameh, "Tunable photonic microwave filters based on Opto-VLSI processors", IEEE Photon. Technol. Lett. **21**(11), pp. 751-753 (2009).

[8] T. Sugiyama, M. Suzuki, and S. Kubota, "An Integrated Interference Suppression Scheme with an Adaptive Equalizer for Digital Satellite Communication Systems", *IEICE Trans. Commun*., vol. E79-B, pp. 191-196 (1996).

[9] Z. Yun, L. Wen, C. Long, L. Yong, and X. Qingming, "A 1×2 Variable Optical Splitter development", J. of Lightw Technol. **24**(3)**,** 1566-1570 (2006).

[10] F. Ratovelomanana, N. Vodjdani, A. Enard, G. Glasere, D. Rondi, and R. Blondeau, "Active Lossless Monolithic One-by-Four Splitters/Combiners Using Optical Gates on InP", IEEE Photon. Technol. Lett. **7**(5)**,** 511-513 (1995).

[11] S. S. Choi, J. P. Donnelly, S. H. Groves, R. E. reeder, R. J. Bailey, P. J. Taylor, A. Napoleone, and W. D. Goodhue, " All-Active InGaAsP-InP Optical Tapered-Amplifier 1×N Power splitters", IEEE Photon. Technol. Lett. **12**(8)**,** 974-976 (2000).

[12] X. Zhao, and S. Jose, "Dynamic power optical splitter", Patent No US 7 068 939 B2, June 2006.

[13] R. Zheng, Z. Wang, K. E. Alameh, and W. A. Crossland, "An Opto-VLSI Reconfigurable Broad-Band Optical Splitter", IEEE Photon. Technol. Lett. **17**(2)**,** 339-341 (2005).

[14] H. A. B. Mustafa, F. Xiao, and K. Alameh, "Adaptive Optical Splitter employing an Opto-VLSI processors and 4-f Imaging System", J. Lightw. Technol. **28**(19), 2761-2765 (2010).

[15] F. Xiao, K. Alameh, and T. T. Lee, "Opto-VLSI-based tunable single-mode fiber", Opt. Express **17**(21), 18676-18680 (2009).

[16] S. T. Ahderom, M. Raisi, K. Alameh, and K. Eshraghian, "Testing and Analysis of Computer Generated Holograms for MicroPhotonics Devices", In Proceeding of the second IEEE international Workshop on Electronic design, Test and applications (DELTA'04), Australia, pp. 47-52(2004).