Dispersion Trimming in a Reconfigurable Wavelength Selective Switch

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Abstract—We experimentally demonstrate dispersion compensation in a wavelength selective switch, and characterize the bandwidth-dispersion product. At a channel bit-rate of 80 Gbit/s, we compensate for various amounts of dispersion (up to +60 ps/nm), tunable for each wavelength division multiplexed channel, solely by adjusting the phase front of the optical signal inside the wavelength selective switch. Error-free operation is obtained for all of the channels, and for each output port after propagation over various lengths of dispersive fiber.

Index Terms—Optical fiber communication, optical fiber dispersion, optical switches.

I. INTRODUCTION

Reconfigurable optical add/drop multiplexers (ROADM) are key network elements that will enable more agile optical transmission systems. Demands for flexibility and bandwidth have led to complex network architectures, for which complete up-front planning is becoming increasingly difficult. Moving from fixed add/drop multiplexers to reconfigurable ones partially mitigates this increased complexity. However, discrete reconfigurable devices, ranging from tunable dispersion compensating gratings to dynamic channel equalizers, are required to make full use of the reconfigurability of theROADM. Many different technologies are now competing for their share in this growing market [1]. Research in optical microelectromechanical systems (MEMS) is making progress in many of these areas, though a different MEMS device is still required for each function [2]. For example, MEMS-based channelized dispersion compensators with flat passbands [3] or tunable bandwidths [4] have already been demonstrated. Although the dispersion in each channel is reconfigurable with these devices, they are not compatible with a change of wavelength channel plan, particularly if it would consist of nonuniform channel bandwidths and spacings.

Fig. 1. Schematic overview of the dynamic wavelength processor, based on a 2-D LCOS array. The inset shows how the incremental phase retardation on each pixel translates into beam steering.

An alternative solution is to integrate some of these functions onto the ROADM itself, to slow down the fast growth in inventory requirements for reconfigurable optical networks. Recently, a promising tunable dispersion compensator was demonstrated with a potential capability for wavelength division multiplexing (WDM) [5]. It is based on virtually imaged phased array (VIPA) technology combined with a spatial light modulator (SLM). Here, we are taking a different approach, where we start from a very flexible wavelength selective switch (WSS), based on liquid crystal on silicon (LCOS) technology. Several functions of this WSS have been reported, such as switching of individual wavelengths to one of a number of output fibers, with reconfiguration on time scales of less than 100 ms [6]. Arbitrary attenuation for each wavelength channel and to each output port, as well as selective power sharing between ports are also possible [7]. By changing the phase pattern on the LCOS, the functionality can be updated or reconfigured, to arbitrarily add, drop, share or attenuate specified channels. The LCOS acts in fact as a reconfigurable, 2-D optical phased array reflector (Fig. 1, inset).

In this paper, we report on extending the functionality of the wavelength selective switch to also permit reconfigurable per-channel dispersion trimming [8]. We make use of the spectral phase modulation capacity of the processor, effectively showing a novel method of dispersion trimming in combination with the other ROADM functions. The use of this function is demonstrated on a 4-channel WDM system, with a bit rate of 80 Gbit/s.
per channel, to compensate dispersions of up to ±60 ps/nm, and the bit-error rate (BER) of the resulting signal is evaluated. We also characterize the spectral intensity shaping related to the dispersion compensation with the current implementation of the switch.

II. PRINCIPLE OF OPERATION

The active element in our wavelength selective switch (see Fig. 1, [6] and [7]) is a 2-D array of LCOS pixels. Light is sent from a fiber array through polarization diversity optics, which physically separate and align orthogonal polarization states to the high efficiency s-polarization state of a diffraction grating. This diffraction grating angularly disperses the light, so that each wavelength is sent to a different portion of the LCOS across the horizontal axis. The reciprocal linear dispersion $D = d\lambda/dx$ along the wavelength axis of the LCOS was chosen to be 0.005 nm/μm. Arbitrary channel bandwidths can be set by choosing the spatial extent on this wavelength axis for each channel. Vertically, the light diverges so that the signal overlaps a large number of pixels (typically about 400). Calculated phase front images are applied to the spatially dispersed signal via the LCOS. By sloping the phase front along the vertical axis, the signal is deflected to a desired output port, after the optical path is retracl upon reflection from the LCOS. The LCOS modulates the phase front of the signal through the voltage dependent retardation of each pixel.

In [6] and [7] all functions implemented on this dynamic wavelength processor (DWP) have been devoted to adjusting the power of the optical signal on a wavelength selective basis and switching to specified ports. For example, attenuation control for a channel is achieved by setting the phase pattern on the LCOS such that the light is split into two components. One is directed to the desired output port while the other is directed to a dump location within the device. By varying the relative powers in each of these two paths, the attenuation is precisely controlled.

However, the phase of the image on the LCOS can also be varied along the spectral (horizontal in Fig. 1) axis. A linear phase in the spectrum corresponds to an offset in the time domain. A parabolically varying spectral phase corresponds to a linearly varying group delay, which means that dispersion generation or compensation is also possible. Thus, both the phase and amplitude of an optical signal can be controlled in a precise way. Here we demonstrate how this can be advantageous for dispersion trimming, which can be integrated with the reconfigurable wavelength-selective switching function in the DWP. The group delay $\tau = d\phi/d\omega$ generated $\omega$ is related to the spatial phase change along the wavelength axis on the LCOS in the following way:

$$
\tau = \frac{d\phi}{d\omega} = \frac{d\phi}{d\lambda} \cdot \frac{d\lambda}{d\omega} = -\frac{\lambda^2}{2\pi c} \cdot \frac{d\phi}{d\lambda} = -\frac{\lambda^2}{2\pi c} \cdot \frac{d\phi}{dx} \cdot \frac{dx}{d\lambda} = -\frac{\lambda^2}{2\pi c} \cdot \frac{d\phi}{dx} \cdot \frac{1}{D}
$$

with $\omega$ as the angular frequency, $\lambda$ represents the wavelength, $x$ is the distance along the wavelength axis of the LCOS, $\phi$ is the phase, and $c$ is the speed of light.

III. DELAY GENERATION

When the spectrally dispersed signal is linearly phase modulated along the spectral axis, the beam is steered to an offset position on the grating. This causes a difference in total optical path length, thus explaining the temporal delay generation. As described by Neilson et al. [3], this system, with two passes on the grating, uses the second pass to both generate the delay and recombine the wavelengths. The beam displacement on the grating ultimately also leads to a horizontally displaced signal on the output fiber, as the beams do not come from the same pupil position. This is a fundamental limit, causing a tradeoff between the maximum achievable delay and the increased insertion loss of the optical signal. Because the signal is steered horizontally away from the output fiber, depending on the slope of the spectral phase modulation, the overlap integral between the optical signal and the aperture of the fiber decreases. For a linearly varying group delay, and, thus, a linearly varying offset from the output fiber, this translates into a Gaussian amplitude transfer profile across the spectrum of the signal.

To quantify the maximum delay available with the current design, the magnitude and arrival time of the optical signal is measured on a fast oscilloscope, after linear phase modulation in the DWP. The result is shown in Fig. 2, together with a simultaneous average power measurement. From this, one can derive the bandwidth-dispersion product for the DWP: $BW_{3\,\text{dB}} \times D = 40$ ps. Over a 3–dB spectral bandwidth of 1 nm, it is, thus, possible to reconfigure the DWP to compensate for ±40 ps/nm. For a bandwidth of only 0.5 nm this would increase to ±80 ps/nm.

The measured group delay curves and associated passbands are shown in Figs. 3 and 4, for a range of negative and positive dispersions, respectively. The group delay ripple is very small (< 0.5 ps) over the central wavelengths of the channel. Any deviation from a linear curve towards the edges of the usable passband can be mitigated by fine-tuning the exact phase for these wavelengths on the LCOS. It is also possible attenuate the central wavelengths of the channel accordingly, in order to create a flat passband.

To increase the dispersion-bandwidth product, one could incorporate a more dispersive grating. The same delay can then be
the central wavelength of the channel. This can be reduced further through more advanced pixel control. No polarization dependent dispersion variation was observed for the levels of dispersion tested.

IV. SYSTEM EXPERIMENT SETUP

To further validate the tunable dispersion functionality, we conducted multichannel high speed systems experiments. A schematic overview of our system experiment is shown in Fig. 5. Four distributed feedback laser diode outputs with a frequency spacing of 400 GHz are multiplexed using an arrayed waveguide grating (AWG). The multiplexed signal is sent to an electroabsorption modulator (EAM) which carves 40–GHz pulses simultaneously out of all of the channels. The pulses are data modulated with a pseudorandom bit sequence (PRBS), with a pattern length of $2^{31} - 1$. This data modulated WDM signal is then interleaved to reach an aggregate bit rate of 80 Gbit/s per channel at four simultaneous wavelengths.

To emulate an agile network, the signal is split into four branches, each holding a different stretch of fiber, with a $1 \times 4$ optical coupler. Branch 1 contains 25 km of dispersion shifted fiber, giving a total dispersion of $-60$ ps/nm. Branches 2 and 3 contain 1.2 and 3 km of standard single mode fiber, respectively (total dispersions of 20 and 50 ps/nm). For back-to-back comparison, branch 4 is connected directly to the DWP. By remotely updating the phase front modulation on the LCOS, we select both a specific port and a specific wavelength channel to switch to what is defined as the output port. In addition to the wavelength selection, we also implement parabolic spectral phase modulation, leading to a linear group delay. Finally, a second EAM is used to demultiplex the signal back to 40 Gbit/s for BER testing. In our simple system, the demultiplexing EAM is driven from the same electrical clock as the transmitter EAM and no clock recovery is implemented.

V. RESULTS

Fig. 6 shows a series of eye diagrams, measured with a high-speed sampling oscilloscope (65–GHz optical bandwidth). The eye diagram of the transmitted 80 Gbit/s signal without propagation in any significant amount of fiber (branch 4) is shown as a reference in Fig. 6(g). Fig. 6(h) shows the demultiplexed eye diagram of one of the channels after transmission and matched dispersion compensation.

Without dispersion compensation in the DWP, the 80 Gbit/s eye diagram is almost completely closed, as seen in Fig. 6(c). When transmitted over either of the longer fibers, in branches 1 or 3 [Fig. 6(a) and (e)], no open eye can be observed. Thus without dispersion trimming no pattern synchronization on the BER is possible after transmission over any of the fibers. However, as can be seen from the compensated 80 Gbit/s signals in traces Fig. 6(b), (d), and (f), with the appropriate dispersion compensating image uploaded onto the DWP, the eye is fully restored, and error-free ($<10^{-12}$) operation is obtained for all channels in each branch.

Fig. 7 shows the measured Q-factors versus input power on the receiver, for a single wavelength channel after each of the four branches. These Q-factors are calculated from a series of bit error rate measurements with variable decision thresholds.

Fig. 6. Eye diagrams measured after the DWP [except (h), which is measured after time-demultiplexing], for one filtered wavelength channel. In (a), (c), and (e), no spectral phase modulation is applied, while in (b), (d), and (f), the phase profile is matched to compensate the respective dispersion in each branch. (5 ps/div horizontally.)

[9]. Allowing for the fact that there is no clock recovery in the demultiplexing EAM, the curves for the different branches are close together, showing very little BER penalty in the transmitted wavelength channels after the dispersion has been compensated in the DWP. Q-factor curves for a similar experiment performed at 40 Gbit/s (with intrinsic clock recovery on the BERT system) show virtually no power penalty for different settings of the dispersion (Fig. 8). Therefore, we are confident that the discrepancies between the slopes of the 80 Gbit/s curves are due to lack of optimization of clock settings in the demultiplexing stage, due to rapidly varying path lengths in the fibers induced by temperature fluctuations.

VI. COMBINED FUNCTIONALITY

To demonstrate that the new dispersion compensation functionality is compatible with previously demonstrated functions, we programmed the LCOS in such a way that 50% of a certain channel is sent to one port, without any spectral phase modulation, the other half is sent to another port, with phase modulation to precompensate for the following 3 km of SMF. This is done by applying different phase slopes to the top and bottom 50% of the pixels vertically (to steer the signal to two different output ports), whilst only applying quadratic phase modulation to the top 50% of the pixels. The eye diagrams for this single channel 40 Gbit/s experiment are shown in Fig. 9. Without proper precompensation in the DWP, the eye is almost completely closed [Fig. 9(c)], however, open eye diagrams are obtained for each arm when appropriate dispersion compensation is applied. Apart from demonstrating that the dispersion
compensation is compatible with the splitting function, it also shows that it is compatible with arbitrary attenuation in each channel. In the latter case, part of the signal would simply be steered to a dump location within the device rather than to a specific output port.

**VII. CONCLUSION**

The high level of reconfigurability expected in future optical networks will bring along new requirements in flexible, per channel dispersion compensation. We have shown dispersion compensating functions (up to ±60 ps/nm for 80 Gbit/s channels) in a flexible wavelength selective switch, and verified the operation in a high speed WDM system experiment. The dispersion can be reconfigured for each wavelength channel and each output port. These functions are fully compatible with previously reported functions such as drop-and-continue and per wavelength attenuation control. It is for example possible to drop part of the optical signal in a number of specified channels and (partially) compensate for dispersion, whilst sending the rest of the signal in these channels to an express port without dispersion compensation. This phase and magnitude control on a per-wavelength and per-port basis further enhances the applicability of this technology as a key component in modern optical networks.

**REFERENCES**


**Michael A. F. Roelens** (M’06) received the civil engineering degree in micro- and optoelectronics from Ghent University, Ghent, Belgium, in 2002, and the Ph.D. degree from the Optoelectronics Research Centre (ORC), University of Southampton, Southampton, England, in 2006.

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From 1993 to 1995, he was with the University of Iowa, Iowa City, investigating ultrafast coherent dephasing nonlinearities in GaAs multiple-quantum wells (MQWs) at cryogenic temperatures. After this time, he moved into industrial research in laboratories in the defense and mining industries. In 2000, he took positions working for Nortel Networks (Photonic) and then JDS Uniphase, where he designed and prototyped components used in ultra-high-speed long-haul transmission networks, including microoptic circulators and dispersion compensating fiber Bragg gratings. In 2003, he became a Research Fellow and Laboratory Manager with the University of Sydney, Sydney, Australia, funded by the Australian Research Council under the Centres for Excellence program (CUDOS). His research interests are in the areas of ultrafast optical processes, novel optoelectronic devices, and nonlinear optical properties of solid-state materials.

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**Dmitri Abakoumov** received the Master’s degree in physics and engineering from the Moscow Institute of Physics and Technology, Moscow, Russia, in 1988.

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Dr. Eggleton is a Fellow of the Optical Society of America (OSA). He was the recipient of the Distinguished Lecturer Award from the IEEE Lasers and Electro-Optics Society, the 1998 Adolph Lomb Medal from the OSA, the 2003 ICO prize from the International Commission on Optics, the 2004 Malcolm McIntosh Prize for Physical Scientist of the Year, an R&D100 Award, and the Pawsey Medal from the Australian Academy of Sciences.