Flexible Optical-Comb-Based Multi-Wavelength Conversion for Optical Switching and Multicast

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***Abstract*— Experimental results on multi-wavelength conversion based on optical comb generation for optical switching and multicast applications are presented. All the newly generated channels showed good performance with clear and open eye diagrams.**

***Keywords*- Optical switching; optical multicast; wavelength routing.**

I. INTRODUCTION

Optical multi-wavelength converter (MWC) is an attractive technology for WDM networks since it allows simultaneous conversion of incoming data without the necessity of multiple O-E-O transponders. It can be used to route and switch wavelengths, reduces the blocking probability of WDM networks, increases their transparency, and enables dynamic wavelength assignment and allocation capability [1]. Moreover, MWC facilitates new applications, such as optical multicast and optical switching. Several approaches for MWC have been reported in the literature as those based on four-wave mixing (FWM), cross-gain modulation (XGM), cross-absorption modulation (XAM), and cross-phase modulation (XPM). However, they present some disadvantages: FWM is limited by its low conversion efficiency, wavelength inflexibility and polarization dependence; XGM requires high input optical signal; XAM suffers from large insertion loss of electro-absorption modulators, and XPM-based MWC is strongly influenced by the in-band high-order FWM products [2]. In this paper, optical-comb-based MWC for optical switching and multicast is proposed and experimentally validated. Generating the multiple copies of the incoming signal via an optical comb has the following advantages: a) total transparency to the incoming wavelength, b) uniform optical power levels of all multicast channels, c) wide wavelength conversion range under some optical comb generation schemes, and d) low optical power requirements. The experimental results showed that the quality of newly generated signals was slightly degraded in comparison with back-to-back configuration.

II. OPERATING PRINCIPLE

The conventional technique for multi-wavelength generation based on an optical comb is achieved by using an electro-optic phase modulator (PM), whose operating principle is as follows. When a CW light of angular frequency w_0 is phase modulated by a sinusoidal signal of frequency f_m, the modulated light field, E_{out}, is given by:

$$\begin{aligned} E_{out} &= E_{in}\exp\left[jw_0 t - j\Delta\theta\sin\left(2\pi f_m t\right)\right] = \\ &= E_{in}\sum_{q=-\infty}^{+\infty} J_q\left(\Delta\theta\right)\exp\left\{j\left(w_0 - 2\pi q f_m\right)t\right\} \end{aligned} \quad (1)$$

where E_{in} is the input signal, $\Delta\theta$ is the modulation index and J_q *(.)* denotes the qth-order Bessel function. This phase modulation leads to a frequency modulation of the optical signal which results in the generation of new optical frequencies spaced symmetrically around w_0 with a separation equal to a multiple of f_m. Fig. 1 shows the response of the E/O phase modulator when introducing a CW light and a sinusoidal signal through the RF port of the PM. As it can be seen, an optical comb is generated.

Although electro-optic methods are a very promising solution for optical comb generation, they do not show flat spectral response as the intensity of each frequency component is governed by Bessel functions, as shown in Fig. 1 [3]. In the literature some techniques have solved this problem by using a two-stage modulator, where a phase modulator and a Mach-Zehnder modulator (MZM) are cascaded in tandem, or by using a conventional single-stage MZM [4-5]. By using these configurations an optical frequency comb with excellent spectral flatness can be generated.

To validate the capability of replicating the incoming data placed at a specific wavelength into multiple wavelengths, the experimental setup shown in Fig. 2 was used. The output signal from a laser was encoded with 2^{31}-1 pseudorandom binary sequence (PRBS) by an intensity modulator to form the 1.25 Gb/s nonreturn-to-zero (NRZ) data signal, and then was phase modulated by a sinusoidal signal of f_m= 10 GHz.

An optical spectrum analyzer (OSA) monitored the output spectrum. As illustrated in Fig. 2, the spectrum obtained at the output of the phase modulator is composed of new wavelengths transporting the input modulated data. It should be noted that the data bitrate can be increased as the new optical wavelengths generated by the optical comb are orthogonal so that they may overlap in a similar way to orthogonal frequency-division multiplexing (OFDM) systems [6].

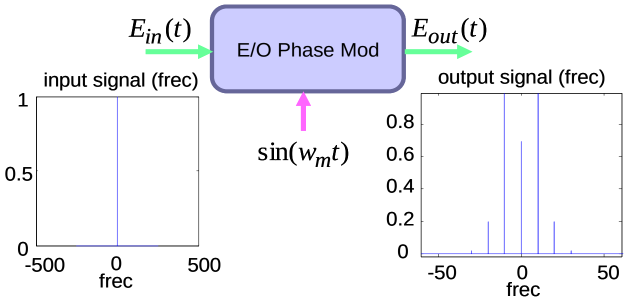

Figure 1. Generation of an optical comb using a phase modulator.

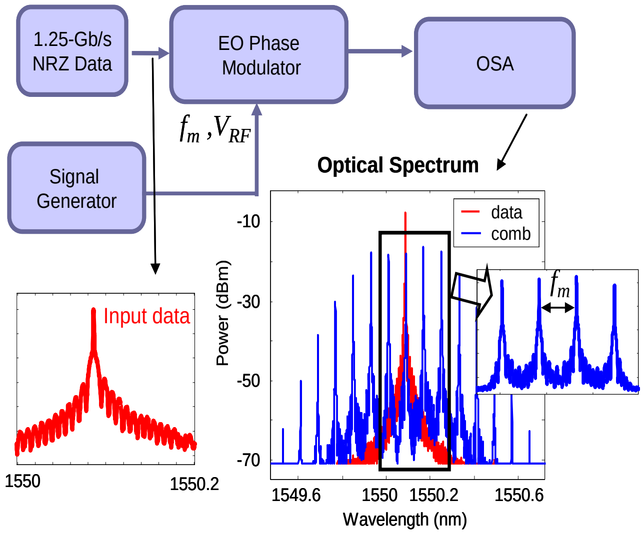

Figure 2. Experimental setup for validating multi-wavelength conversion of incoming data.

Moreover, higher frequency spacing can be achieved by increasing f_m.

The MWC operation was validated at 1.25 Gbit/s and 10-GHz spacing as a proof of concept. These values were imposed by the available experimental equipment.

A number of desirable optical network functionalities, such as transparent data multicast, can be enabled by using the optical-comb-based MWC. The implementation of multicast can be easily introduced into the optical switch using passive waveguides such as arrayed waveguide gratings (AWGs). To improve the flexibility of the system, we propose to perform the MWC based on optical comb followed by a select stage, where one or many wavelengths can be selected, as shown in Fig. 3.a. Concretely, this select block is implemented with FBG-based (Fiber Bragg Gratings) optical filters, as it will be explained in the next section. Additionally, MWC can also be used for optical switching in which only one wavelength is selected by a fast tunable filter (Fig. 3.b). In the literature there are some proposals for tunable optical filtering in the range of nanoseconds or even picoseconds [7-8].

Apart from the applications mentioned above, optical-comb-based MWC enables wavelength reuse in different lightpaths, eases wavelength contention and packet buffering issues, reduce node blocking probabilities, facilitates dynamic network wavelength assignments, and provides new ways for optical protection.

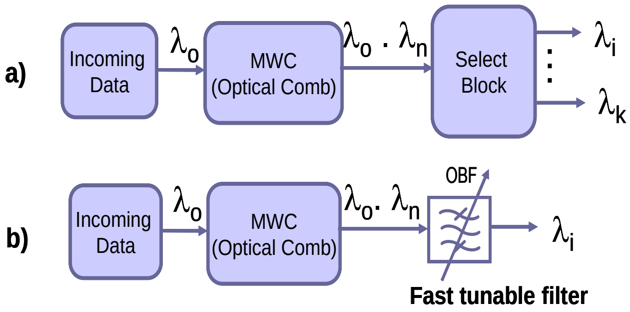

Figure 3. Main applications for the optical-comb-based flexible MWC: a) optical multicast; b) optical switching . *i*, *k*: integer [0 … *n*].

It can also be used for microwave optical filter implementations or optical frequency division multiplexing techniques. Moreover, in [9] a novel spectrum-efficient elastic path network based on the concept of optical-comb-based MWC has been proposed.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 4 shows the experimental setup for the data multicast demonstration, where flexible multi-wavelength conversion was achieved by using an optical comb. The non return to zero (NRZ) data signal was generated by externally modulating a tunable CW laser source tuned to 1550.17 nm and sent to a 10-GHz PM. The sinusoidal modulation frequency was set to 10 GHz obtaining new wavelengths placed symmetrically around 1550.17 nm with 10-GHz spacing. It should be noted that with a single-stage MZM and increasing f_m an optical comb with higher frequency spacing can be easily created [5]. After MWC, the generated channels were then filtered to prove the multicast operation for 4 channels. These 4 channels (λ_0, λ_1, λ_2, λ_3) were routed to the select block after being amplified. The select block was comprised of two FBG-based optical filters and two optical switches to allow total flexibility in the choice of the output wavelength and port. Fast switching speed can be achieved by using electro-optic switches [10]. The FBG-A grating performed a coarse filtering to split up λ_0 and λ_1 from λ_2 and λ_3 (IN 1, IN 2: insets of Fig. 4), obtaining a ~30-dB rejection ratio. After the first filtering stage, an optical switch was used to select either IN 1 or IN 2 (Out 1). This signal was then sent to another grating, FBG-B, which performed a fine filtering to select only one output wavelength (Fig. 5). To this end, the FBG-B was composed of two cascaded gratings with 10-GHz bandwidth and centred at λ_0 and λ_3, respectively. Finally, the signals coming from the FBG-B were sent to a second optical switch for flexible routing to the desired output port. An example of operation is as follows. If the reflected signal of the FBG-A (IN 1) is routed to Out 1 and sent to the FBG-B, λ_0 is obtained at IN 3 and λ_1 at IN 4 ports (Fig. 5.a, Fig. 5.b). Otherwise, if the signal passing through the FBG-A (IN 2) is routed to Out 1, λ_2 is obtained at IN 3 and λ_3 at IN 4 ports (Fig. 5.c, Fig. 5.d).

To check the quality of these multicast signals, we measured the bit-error-rate (BER). Every channel was extracted and sent to a photoreceiver. The obtained BER curves are reported in Fig. 6. As it can be seen, all channels exhibited a limited penalty (2.5 dB in the worst case at BER= 10^{-9}). This penalty was mostly caused by the characteristics of the fabricated filters used since the measured channel was not perfectly filtered and thus a slight interference from adjacent channels appeared. Indeed the channels that suffered most from this effect were those ones having lowest difference between the pass and rejected bands (Channels placed at λ_0 and λ_3). All the channels showed clear and open eye diagrams for BER values lower than 10^{-9}, as shown in the inset of Fig. 6 (Lambda 0).

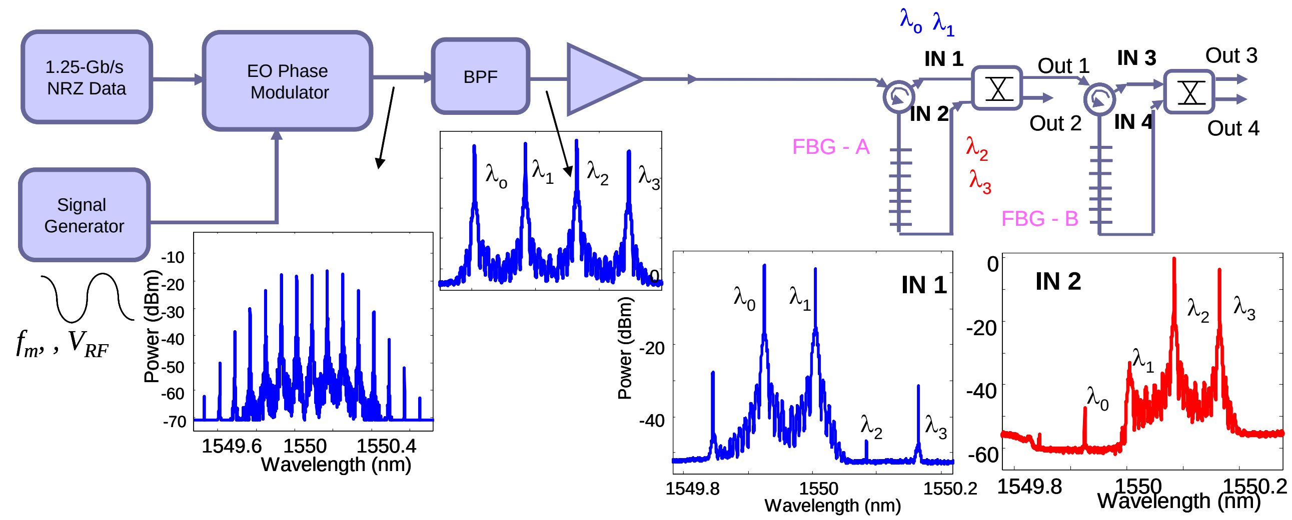

Figure 4.Experimental setup of MWC based on optical comb for performing data multicast.

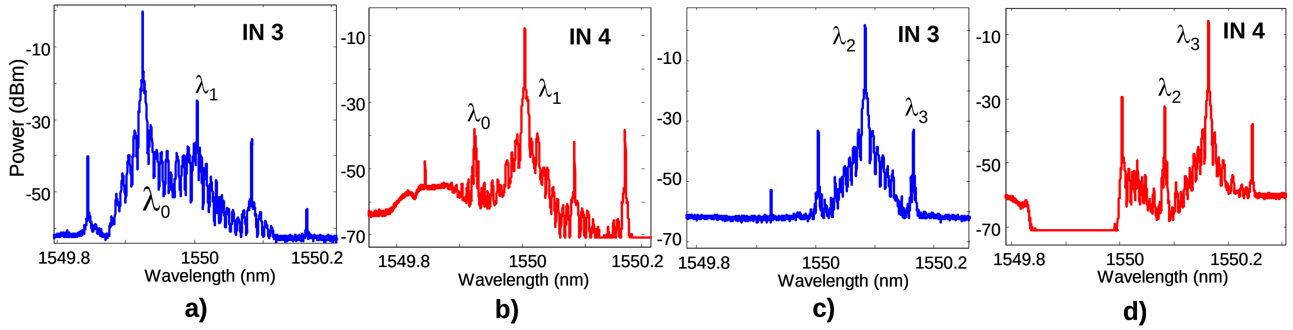

Figure 5. Optical spectrum at the system output: a) and b) when IN 1 is redirected to the Out 1; c) and d) when IN 2 is sent to Out 1.

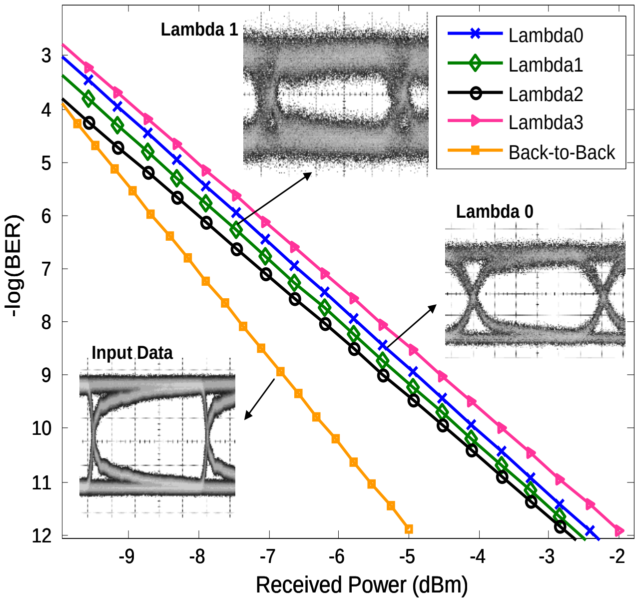

Figure 6. BER performance of one-to-four multi-wavelength conversion compared with the back-to-back configuration.

IV. CONCLUSIONS

Optical-comb-based MWC can be suitable for several applications in next generation networks, such as optical multicast. In this paper, optical multicast of an NRZ signal at 1.25 Gbit/s was experimentally demonstrated. By using an optical comb, the input signal was transferred into multiple wavelengths transparently. To increase the flexibility of the system the generated signals were sent to a select block responsible of selecting one or many output wavelengths and of routing them to a specific output port. All the multicast channels showed good performance and clear eye diagrams.

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