Tunable All-Optical Time-Slot-Interchange and Wavelength Conversion Using Difference-Frequency-Generation and Optical Buffers

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***Abstract*—In this letter, we demonstrate a module that simultaneously performs optical time-slot interchange and wavelength conversion of the bits in a 2.5-Gb/s data stream to achieve a reconfigurable time/wavelength switch. Our switch uses difference-frequency-generation (DFG) for wavelength conversion and fiber Bragg gratings as wavelength-dependent optical time buffers. This tunable technique employs high-extinction-ratio and low-additive-noise DFG.**

***Index Terms*—Difference frequency generation, fiber Bragg gratings, optical buffer, time-slot interchange, time-to-wavelength mapping, wavelength conversion.**

I. INTRODUCTION

IT MAY BE CRITICAL for future networks to provide additional switching functionality in the optical physical layer to ensure high-speed and high-throughput performance. Typically, switching is performed in one of the following domains: time, wavelength, or space. As traffic grows, the network may require the use of more than one of these switching domains concurrently in order to meet the increasing demand. Improved flexibility, throughput, and robustness would, thus, be achieved in future heterogeneous networks that combine wavelength-, time-, and space-division switching for data traffic.

In a network that includes elements of time-division multiplexing (TDM), the time slot of each bit defines its output port at each switching node. This makes time-slot interchange (TSI) the most commonly used method of switching in the time domain [1]. Time-slot-interchange is achieved by shifting a given bit from one time slot into a different one, thereby changing its destination. This can be readily accomplished in the electronic domain by shift registers. However, accomplishing TSI in the optical domain may be highly desirable to avoid optoelectronic data conversion, as well as the potentially limited switching speed of electronic circuits. Similarly, all-optical wavelength conversion would enable a highly efficient reconfigurable network switching architecture with wavelength reuse and contention resolution.

Two reported techniques for implementing all-optical TSI include the following: 1) using fixed delay lines as optical-time buffers and semiconductor optical amplifiers (SOA) as gates to perform TSI with a 1.6-ns guard time at 125 MHz [2], and 2) using lithium-niobate space switches followed by fixed delay lines to perform TSI on a 29-Mb/s signal [3]. The SOA used in the first method has limited switching speed, generates crosstalk due to a limited extinction ratio, and adds noise to the signal through amplified spontaneous emission. The space switches used in the second method generate signal crosstalk and have scalability problems. Crosstalk is a particularly serious problem in time switching because coherent effects are generated, which may induce large power penalties and bit-error-rate floors [4].

All-optical wavelength conversion has been accomplished by several methods, including the following: cross-gain modulation [5], cross-phase modulation [6], and four-wave mixing [7]. However, these methods generally use an SOA as their wavelength-shifting medium, which typically gives rise to at least one of the following disadvantages: 1) limited conversion speed; 2) limited wavelength range; 3) additive noise; 4) limited output extinction ratio; 5) induced chirp; and 6) narrow dynamic range of input power.

We demonstrate the combination of all-optical TSI and wavelength conversion of a 2.5-Gb/s data signal to achieve a reconfigurable time/wavelength switch. We use the combination of difference frequency generation (DFG) as a wavelength converter and tunable fiber Bragg gratings (FBG) as optical time buffers to generate switch elements. The swapping of adjacent time slots is achieved by using three such switch elements, in which 1) the first wavelength converter places the odd-numbered bits at a new wavelength; 2) FBGs introduce a two-bit delay between wavelengths; and 3) the second wavelength converter places the nondelayed even-numbered bits to the new wavelength. We achieve DFG wavelength conversion in an annealed proton exchanged waveguide in periodically poled lithium niobate, which

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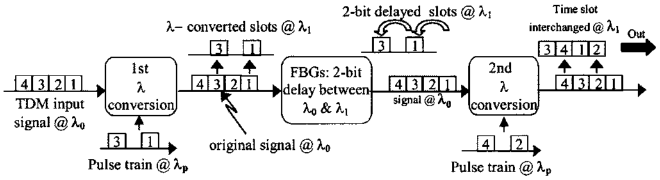

Fig. 1. Conceptual diagram of our time slot interchange and wavelength conversion experiment.

has the following advantageous properties: 1) negligible additive spontaneous emission noise; 2) negligible chirp; 3) similar up- and down-conversion efficiency; 4) limited crosstalk and high extinction ratio at the output; and 5) large > terahertz bandwidth [8]. Furthermore, tunable FBG optical buffers provide better scalability and are more reconfigurable than conventional buffers based on fiber delay lines.

II. EXPERIMENTAL SETUP

Fig. 1 shows the conceptual diagram of the swapping of adjacent time slots. In the first wavelength/time switch, odd numbered time slots are selected and copied from λ_0 to λ_1 by means of DFG. A wavelength-dependent matrix of discretely tunable time-slot delays, as defined by the tunable set of FBGs, introduces a two-bit delay between λ_0 and λ_1. By applying stress on FBGs, it is possible to tune their reflecting wavelengths. Using this technique, relative timing of the bit streams can be changed, creating a tunable optical time buffer. In progression, the second wavelength/time switch selects and copies the even numbered time slots to the already delayed λ_1 bit stream, resulting in all-optical TSI and wavelength conversion.

We achieve DFG wavelength conversion with an annealed proton exchanged waveguide in periodically poled lithium-niobate. The device employs a cascaded second-order nonlinear optical process $\chi^{(2)}$:$\chi^{(2)}$, where a pump and signal wave (both in the 1550–nm band) are mixed to create an output, whose wavelength is $\lambda_{\text{converted}} \approx 2\lambda_{\text{pump}} - \lambda_{\text{signal}}$. Second harmonic generation (SHG) results in conversion of the pump to the second harmonic $2\lambda_{\text{pump}}$. This SHG wave simultaneously mixes with the signal through DFG to generate the output at $\lambda_{\text{converted}}$. The nearly instantaneous nature of the parametric processes result in a signal bandwidth of several terahertz. The conversion efficiency is proportional to the square of the pump power. It should be emphasized, therefore, that any increase in the pump power translates into twice as much improvement in conversion efficiency, i.e. 1 dB into 2 dB.

Our experimental setup is shown in Fig. 2. A 2.5-Gb/s bit stream at 1555 nm is input to the TSI/wavelength conversion module. Inside the module, the +19-dBm DFG pump is generated using an external cavity laser at 1550 nm that is modulated by a 2.5-Gb/s rectangular pulse train. A wavelength-division-multiplexing (WDM) coupler is used to combine the pump signal and the incoming bit stream. It also filters out the ASE noise of the high-power erbium-doped fiber amplifier (EDFA). The "ON" bits of the rectangular pulse train (i.e., the high levels) are time synchronized with the odd numbered data-bit time slots at the input to the first wavelength converter. When the pump power is high, a duplicate of the 1555-nm signal is produced at 1545 nm, effectively selecting and copying the bits in the odd numbered time slots to a new wavelength. Our wavelength conversion efficiency is -16 dB, however this can be increased by reducing the fiber pigtailing loss and increasing the pump power [9]. Recent advances in waveguide technology have resulted in much higher normalized conversion efficiencies [10], such that 0-dB conversion should be obtained with only 16-dBm pump power. Present at the output of the first wavelength converter are the original signal at 1555 nm, the pump at 1550 nm, and the newly created odd-numbered time slots at 1545 nm.

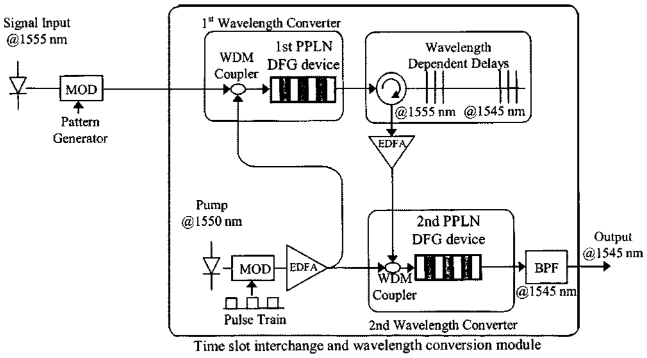

Fig. 2. Experimental setup.

The FBGs provide a delay of two bit times (800 ps) for the 1545-nm signal with respect to the 1555-nm signal, and filter out the pump at 1550 nm. The wavelength-dependent delays provided by the FBGs form our optical time buffers. By tuning the gratings, wavelengths can be reflected from different gratings, resulting in discrete time delays from the FBG array structure.

In the second wavelength converter, the high level of the rectangular pulse train is time synchronized to the even numbered time slots. The second device works under the same operating conditions as the first, in that it copies only the even numbered time slots to 1545 nm. After the second device, a bandpass filter at 1545 nm is used to filter out the pump (1550 nm) and the original signal (1555 nm), leaving only the wavelength-converted TSI signal. We note that the $\chi^{(2)}$:$\chi^{(2)}$ process of our wavelength converters results in a very high extinction ratio for our time/wavelength switch. Thus, the crosstalk between the non-selected even-numbered time slots from the first DFG and the selected even-numbered time slots from the second DFG is minimal.

III. RESULTS AND DISCUSSION

Fig. 3 shows the waveforms at the various stages of time switching and buffering in our system. Odd numbered time slots are selected and copied at the first wavelength converter/time switch, and are delayed by the optical-buffer FBG array. Fig. 3(a) shows the incoming bit stream (1555 nm) with odd and even numbered time slots. The rectangular pulse train at 1550 nm [see Fig. 3(b)] is the pump input to the first wavelength converter. The high levels are time synchronized to the odd numbered time slots, selecting and copying them to 1545 nm. Fig. 3(c) shows the newly created 1545-nm bit stream with odd numbered time slots only. The even numbered time slots are not selected for wavelength conversion because they are aligned with the low "OFF" level of the 1550-nm pump. Fig. 3(d) shows the 1545-nm signal after the FBG grating array, delayed by two bit times with respect to the 1555-nm original signal.

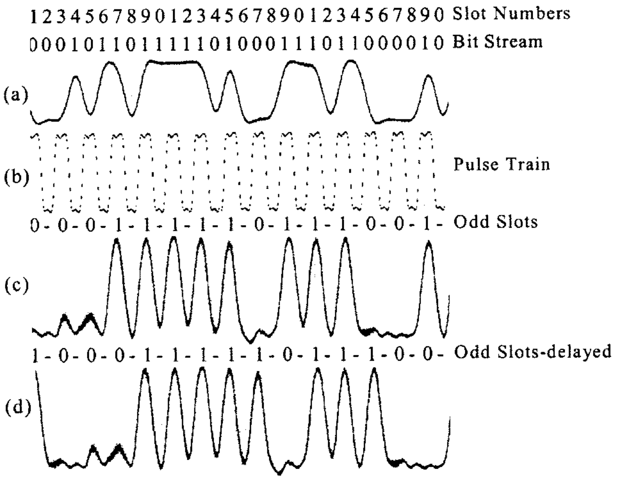

Fig. 3. (a) Incoming bit stream at 1555 nm., (b) Rectangular pulse train (pump) at 1550 nm, copying odd numbered time slots to 1545 nm. (c) 1545-nm DFG signal after first PPLN device. (d) 1545-nm signal after the FBG array, two bit time delayed with respect to 1555-nm signal.

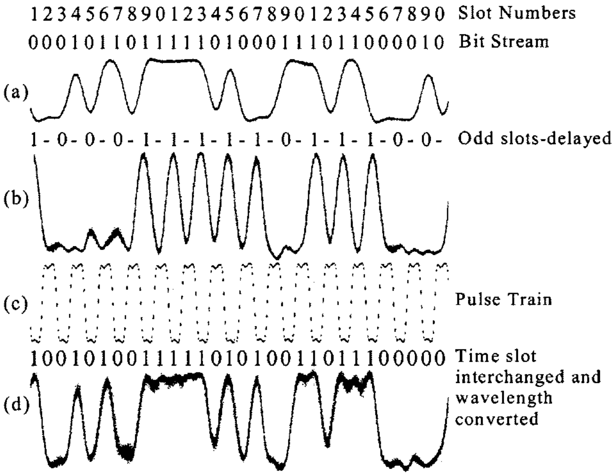

Fig. 4. (a) 1555-nm input signal to second PPLN. (b) 1545-nm input signal to second PPLN. (c) rectangular pulse train (pump) at 1550 nm, copying even numbered time slots to 1545 nm. (d) 1545-nm signal output from second PPLN device, time slots interchanged and wavelength converted.

The input and output waveforms of the second wavelength converter are shown in Fig. 4. Only the even numbered time slots are selected and copied in this stage. Fig. 4(a) shows the original 1555-nm bit stream as the input to the second wavelength converter. Fig. 4(b) shows the 1545-nm signal input to the second wavelength converter with no even numbered time slots present. The rectangular pulse train at 1550 nm [seeFig. 4(c)] is now time aligned to the even numbered slots so that only these slots are selected and copied to 1545 nm. Fig. 4(d) shows the 1545-nm output signal after the converter and bandpass filter. The empty, even-numbered slots of the 1545-nm signal are now filled in with the even-numbered slots from the original 1555-nm signal. Since the odd numbered time slots were buffered by two bit times before entering the second converter, the time slots of the original signal are interchanged and wavelength converted at the output of our module.

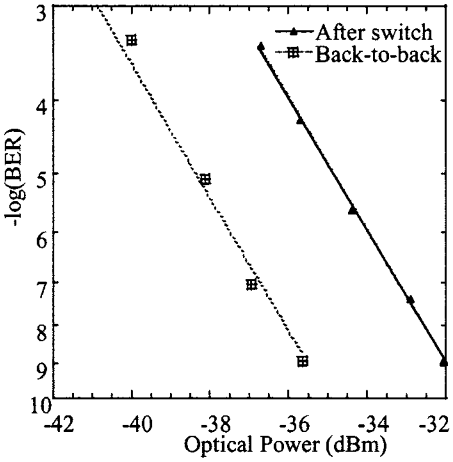

Fig. 5. BER curves for back-to-back and after our TSI and wavelength-conversion module.

Fig. 5 shows the BER curves for the signals before and after the time/wavelength switch. Our technique induced <4-dB power penalty. This penalty is primarily due to coherent crosstalk from poor extinction ratio of our external modulator driving the pump laser, and low wavelength-conversion efficiency and various insertion losses. The first problem can be mitigated by increasing the extinction ratio of the selecting pulse by >30 dB. This will result in time-switching extinction ratios in excess of 50 dB, effectively eliminating crosstalk interference. As discussed above, the problem of low conversion efficiency can be eliminated through the use of advnaced waveguide designs.

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