Tunable optical buffer using a fiber bragg grating array and a widely tunable wavelength converter

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ABSTRACT

This paper demonstrates a tunable optical buffer with widely variable time delays using an array of fiber Bragg gratings (FBGs) filter and tunable wavelength converters (WCs). The flexibility of the proposed system gives an exact required delay and, consequently, better output port utilization. This system is designed to be compatible with 10 to 40 Gbps RZ communication systems.

Keywords: Tunable optical buffer, tunable wavelength converter and Fiber Bragg grating.

1. INTRODUCTION

Optical buffers are a group of delay lines or other optical signal storage media designed to provide either fixed or variable delays for light signals in the optical switch. Usually, the delay can be varied by the routing processor when performing packet synchronization, contention resolution and traffic shaping. Many optical buffering schemes have been developed that are based on slow-light, re-circulating and feed-forward buffers [1]. Among them, only fiber delay line-based buffers are practically feasible at the moment. However, the physical size of such buffers may become very large if long delay times are required [2]. In this paper, a novel optical buffer is used based on fiber Bragg gratings (FBGs) combined with a widely tunable wavelength converter (WCs).

Optical buffers that are designed for optical packet switching (OPS) applications have a set of performance requirements, which are [1]:
1. Nanoseconds delay reconfiguration time.
2. Dynamic configurable delay time.
3. Physical compactness.
4. Low insertion loss.
5. Low power consumption.

The most important attribute is the dynamic delay configuration time, and it is defined by the total time required by the buffer to store a value [1]. Since an OPS switch fabric usually reconfigures in several nanoseconds, the optical buffer should reconfigure its delay within the same amount of time. In addition, the delay should also be for an exact required period which differs based on many parameters as number of wavelengths per interface, number of WCs, packet size,…etc. This will be described in detail in next section. This means that even though, the packet can be stored in the buffer, the delay needs to be tunable for each input output pair. Such a feature is useful in a practical OPS router because resource contentions can sometimes end earlier or later for each wavelength per port.

In this paper, a method of all optical buffers can provide a large number of rapid selectable discrete delay values with low insertion loss and long available maximum delay is presented and demonstrated. This paper is organized as follows:
Section 1 is the introduction, while section 2 describes the different situations for using optical buffers and WCs in today's networks. Section 3 presents the benefits for using the proposed optical buffer variable delay system. Section 4 describes the FBG buffer characterization and section 5 describes a more precision delay system and its benefits. Finally, section 6 is a conclusion on of the present work.

2. USAGE OF OPTICAL BUFFER IN NETWORK DESIGN

Optical buffer is needed heavily in optical networks nowadays. There are many cases for using optical buffer and WC:

Case 1
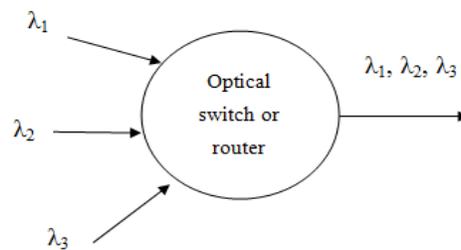Many input interfaces with different channels and one output interface.

Fig. 1. Optical switch of three input ports and one output port with no wavelength converter.

For example, if an optical router or switch has three input ports and one output port, all wavelengths will be relayed on the output interface with no interference problems. In this case, there is no need for optical buffer or WC.

Case 2
Many input interfaces with similar input wavelengths and one output interface with free wavelength at the output interface.
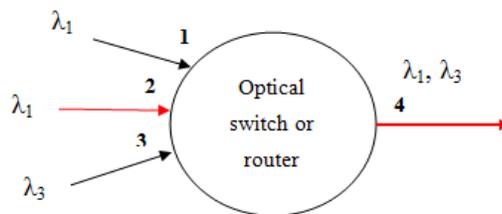

Fig. 2. Optical switch of three input ports and one output port, port 2 with WC.

As illustrated in Fig. 2, the outputs from port 4 are λ_1, λ_3 but λ_1 from port 2 must be converted to λ_2 by a WC to be dispatched immediately or it can be delayed by an optical buffer. But, this will give an underutilized system of output channel.

Case 3
Many input interfaces with similar input wavelengths and one output interface with no free wavelength at the output interface.
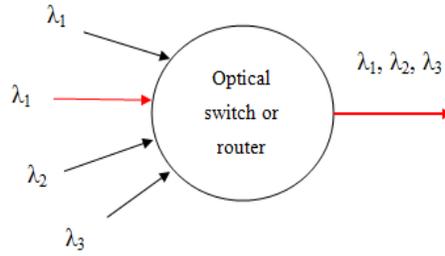
Fig. 3. Optical switch with four input ports and one output port.

As seen in Fig. 3, the output port has a contention for λ_1 so optical buffer is needed to delay λ_1 from the second port until any wavelengths in output port finish and λ_1 replace it using wavelength conversion. In this case, delay is a must in the system if one wants no drops. So, a rule buffer is needed if all wavelengths are used at the output port at the same time.

The novel system works in this case which is the worst case and is needed in big and heavy duty core networks. In this system, the utilization of channels is increased by using (Last Available Unused Channel) LAUC and if no channel are free on the output port, a processor can calculate the nearest (in time domain) expected channel to be free and the specific time needed for the delay. This system is to fulfill this exact delay requirement

3. TUNABLE OPTICAL BUFFER DESIGN USING FBG

The present discrete value delay system is designed to achieve two tasks. First, in this system, one can have a much better utilization as the output interface will be nearly totally utilized due to exact delay values calculated by the processor making the wasted free channel gaps on the output interface minimum.

Second, one of the most important parameters in practical implementation of fiber delay lines is the fiber length. Although in other systems a fiber cable with exact length is needed for each delay interval (for example, a 1000 m cable to get a delay of 5 μs delay and another 800 m cable to get a 4 μs delay and so on). So, for this system, one will have a total of 2000 m of fiber cables. Also, if one increase the precision to be for example 0.5 μs in between delays, this system will have a huge number of fiber cables and the total length of fiber cables will be gigantic. On the other side, the proposed system can have only one fiber cable of a specific length for example 500 m and use it to make all the previous delays even with better precision. This makes the system saves a lot of unneeded cables, their storage and maintenance making it very suitable in practical implementation.

3.1 Delay System Components and Their Interaction

The system consists of 5 sections, Fig.4. The first one is the decision signal which is responsible for mapping delay time to wavelength domain. This wavelength λ_{delay} is related to Bragg wavelength of cascaded FBG elements. Table 1 shows the mapped delay time, T_i, to a specific wavelength, λ_{delay}, the signal power, P_s, and exact fiber length, L_i, to FBG1. Lengths are calculated as seen in Eq. (1).

$$T_i= 2 \, (nL_i/c) \tag{1}$$

Where T_i is the wanted delay time, n is the core refractive index (=1.5), c is the free space speed of light and L_i is the fiber length to FBG1.

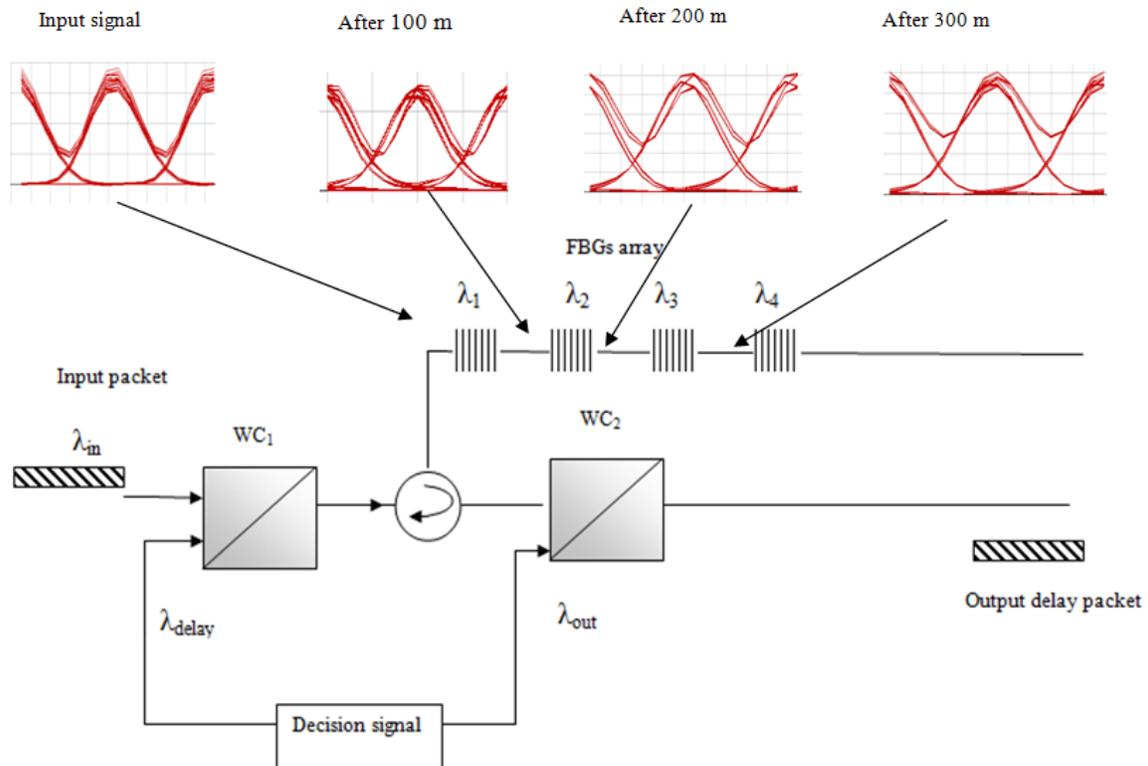| $T_i(\mu s)$	Order of FBG		P_s (mW)	L_i (m)
0	FBG1	λ_1	0.2302647	0.0
1	FBG2	λ_2	0.2137465	100
2	FBG3	λ_3	0.2112680	200
3	FBG4	λ_4	0.2093483	300
4	FBG5	λ_5	0.1901005	400
5	FBG6	λ_6	0.1797361	500

Table 1 Measurements summary.

Fig. 4. Optical buffering system implemented by FBGs and WCs with the eye diagram at each step.

The second section is WC$_1$. The incoming packet is converted by a rapid tunable WC$_1$ to a specific wavelength, λ_{delay}, which is controlled by an external decision signal. The third section is the ideal circulator which transmits the optical signals in the clockwise sense. For example, the wave arriving at port 1 is transmitted to port 2 and the wave arriving at the port 2 is transmitted to port 3 and so on. The fourth section is an array of FBGs. The FBG is designed as narrow band stop filter. The resonant wavelengths are reflected back toward port 2 in the circulator and the non-resonant wavelength is transmitted through the fiber without loss.

The last section is WC$_2$ which is responsible for converting output wavelength from port 3 in circulator (λ_{delay}) to λ_{out} the first free wavelength on output interface as decided by the processor. This is due to the delayed wavelength which is not equal to the wavelength desired on the output interface.

The system setup and results are shown in Fig.4, in which FBGs and WCs are used to implement wavelength-dependent delay lines. In the proposed method, an incoming packet is converted by a rapid-tunable WC to a specific wavelength which is controlled by an external decision signal, and the desired delay value is mapped to the wavelength domain by cascaded FBG elements. Figure 4 also shows the eye diagrams; FBG4 is a little bit noisier than other channels.

4. FBG BUFFER CHARACTERIZATION

To demonstrate the functional feasibility, for example, a system of four FBGs connected to a three-port circulator was established for the initial demonstration. The four FBGs arranged in the order of 1550 nm (FBG1), 1551.9 nm (FBG2), 1553.59 nm (FBG3) and 1551.1nm (FBG4). The fiber lengths among FBGs were designed to have equal increments by 100 m. The time delay differences between the FBG1 and others are 1, 2 and 3μs, respectively. The insertion loss can ultimately be reduced to the limit of the fiber transmission loss (< 0.2 dB/km), which enables realization of very large buffer depths. As shown, Fig. 5 is the combined reflection spectrum from the four FBGs. No grating crosstalk was evident in the frequency domain data. Figure 6 illustrates the relation between bit error rate and optical received power.
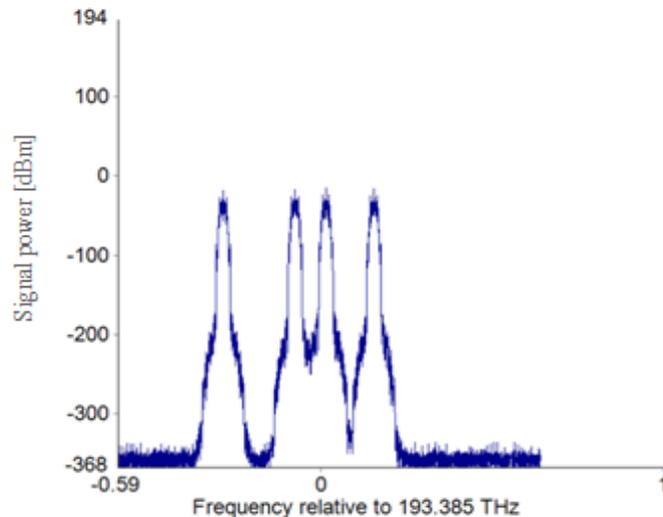

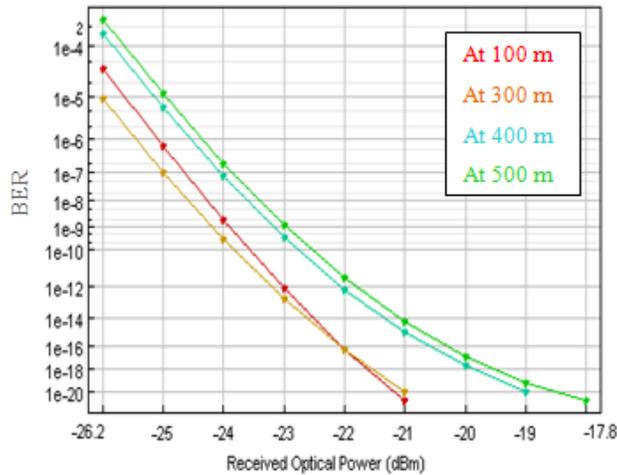Fig. 5. Reflection spectrum from the four FBGs.

Fig. 6. Bit error rate versus the received optical power.

5. ENHANCEMENT TUNABLE OPTICAL BUFFER

The previous optical buffer system solves the delay time for whole values [1 μs, 2 μs,..]. But, if one needs a time delay of 1.4 μs, this system will not give us the required delay. The enhancement system will solve this problem. One can see, in Fig. 7, the enhanced fraction section of the tunable optical buffer system.
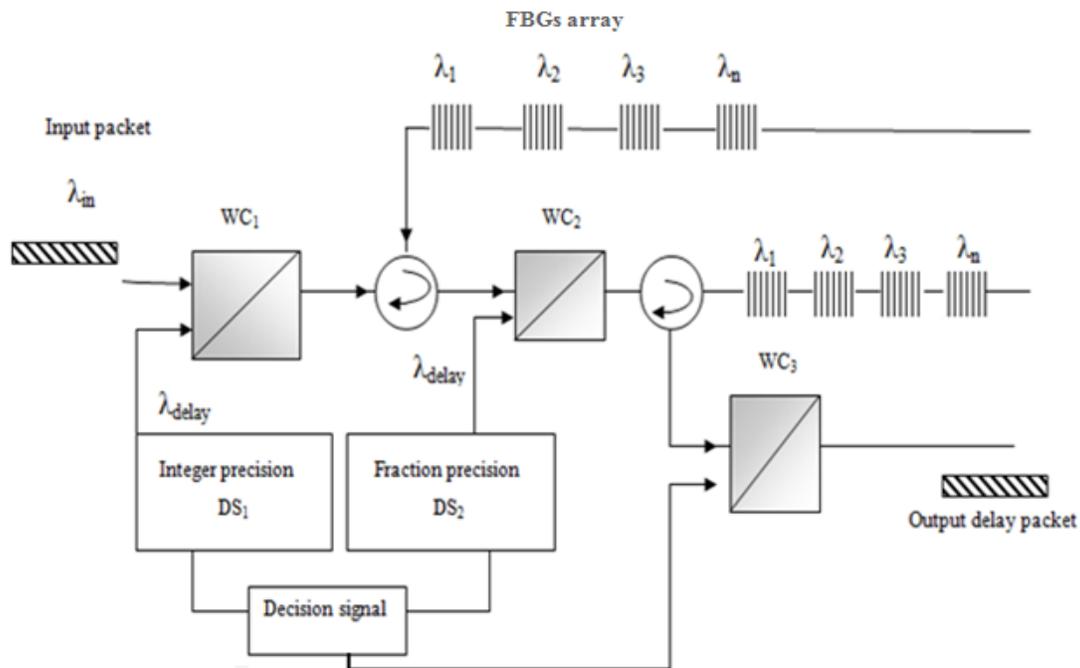

Fig. 7. Optical buffering system implemented by FBGs and WCs.

In this system, one can have one precision as x.y µs. The delay value is converted to two design signals: one for the whole number design signal (DS_1) and the other for the fraction design signal (DS_2). The DS_1 is inserted to WC_1 which gives the whole number delay as discussed in the previous system. The DS_2 is inserted to WC_2 which gives the fraction number delay. For example, if the required delay 1.5 µs the design signal is divided to DS_1 and DS_2. DS_1=1 µs will be converted to a wavelength λ_2, equal to one of the FBG center wavelengths. λ_2 was sent into the input port of the circulator, and the reflected delay signal was output from port 3. The second WC_2 has two inputs. The first one is the reflected delay signal and the other is the DS_2 =0.5 µs which will be converted to λ_6' (FBG6 in the second array) and the reflected delay signal was output from port 3 (second circulator) then the total delay = 1.5 µs. Table 2 shows the mapped delay time to a specific wavelength λ_{delay}' and the exact fiber length to $FBG'1$ (In the second section). By enhanced tunable optical buffer, one can achieve any delay value starting from nanosecond to microsecond and it gives an exact delay leading to a better output port utilization. Figure 8 shows how one can delay an input packet by 7.54 µs.
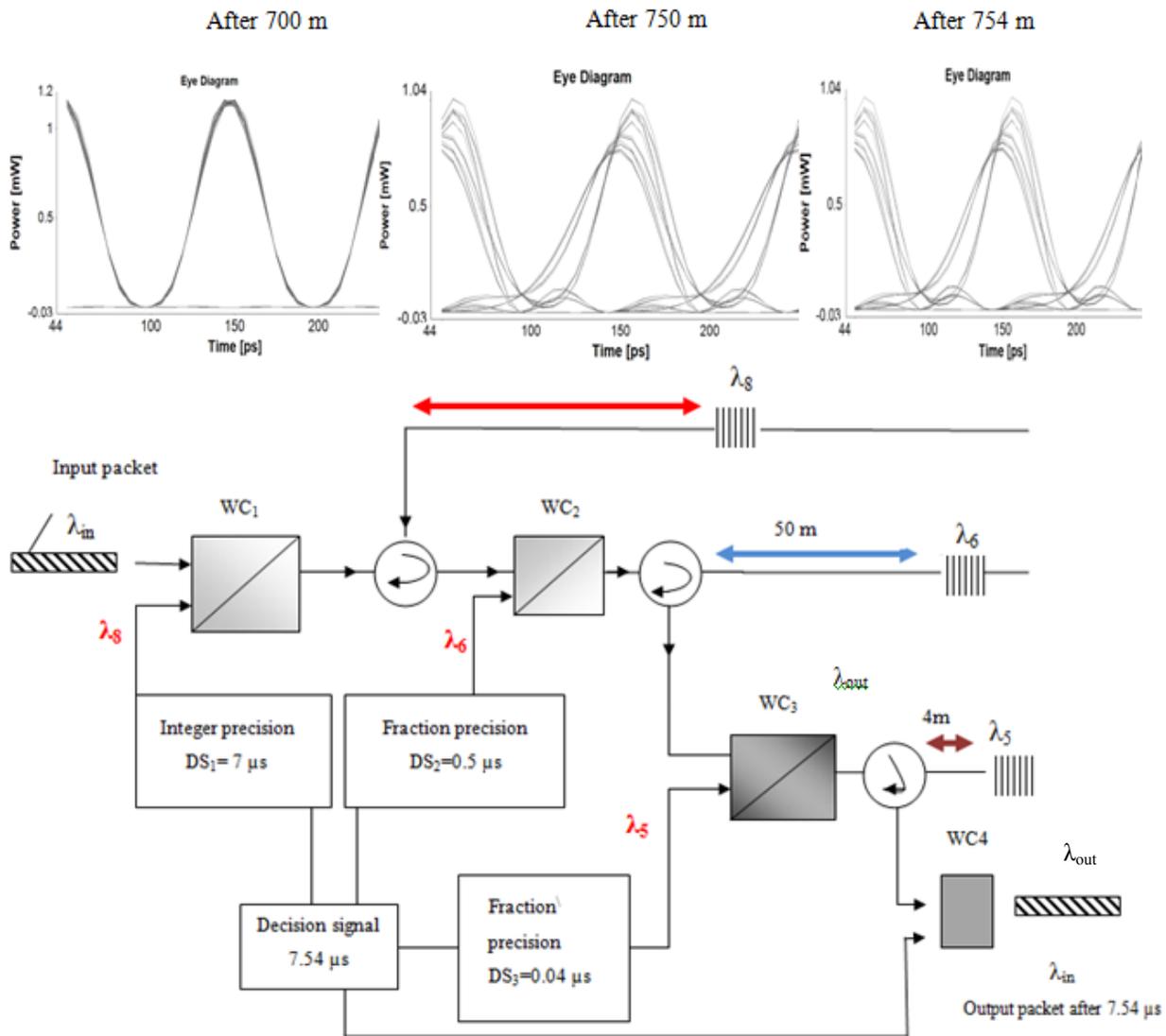

Fig. 8. Enhanced optical buffering system to delay input packet by 7.54µs and eye diagrams.

$T_i(\mu s)$	Order of 2nd array of FBG		L_i (m)
0	FBG1	λ_1	Zero
0.1	FBG2	λ_2	10
0.2	FBG3	λ_3	20
:	:	:	:
0.9	FBG10	λ_{10}	90

Table 2 Length of fiber to FBG1 in enhancement section.

6. CONCLUSION

A large number of rapidly selectable discrete delay values with long available maximum delay can be achieved by the proposed method of all-optical buffering using FBGs and rapidly-tunable WCs. A very good utilization and a shorter fiber delay line (FDL) are seen in the proposed design. An FBG buffer working at 10 Gbps for an RZ system has been designed and programmable time delays from tens of nanoseconds to microseconds are obtained. A preliminary 10 Gbps four element FBG system has been built to demonstrate its functionality. According to these initial measurements and demonstrations, it is believed that the proposed method has a great possibility to work at 40 Gbps. One also reduced the fiber length used in the delay system by half. In traditional optical delay line, one uses 200 m to get 1μs delay, but in the proposed system this length is reduced to 100 m.

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