All-Optical Variable Delay Buffer for Next Generation Optical Networks

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ABSTRACT

A novel all-optical delay buffer based on fiber Bragg gratings (FBGs) is proposed. This buffer has the ability to provide variable delay times and can store the contenting packets for a relatively long time.

Keywords: optical networks, fiber Bragg gratings, optical delay buffer.

1. INTRODUCTION

Although the all-optical networks provide a large capacity, they are not actually used in the current networks. In fact some technical problems limit its growth. One of the major problems is resolving packet contention which occurs when two or more incoming packets with the same wavelength compete for the same output at the same time. Previous studies have proved that asynchronous, variable-sized packet switching causes far more frequent packet contention than synchronous, fixed-sized packet switching [1]. Optical buffering using optical delay lines is a fundamental solution for resolving contention. These delay lines can be used to delay packets for a fixed amount of time. Much effort has been done to implement optical buffers, and several different architectures have been reported so far [2]-[4]. Though, these architectures have many advantages, most of them suffer from the following limitations. Firstly, their architectures are bulky, since the length of the fiber is directly proportional to the propagation time of light in the fiber. Secondly, each delay line requires one switch port, thereby increasing the overall switch cost with increased number of delay lines. Thirdly, the fixed delay times provided by the delay lines make it hard to extract the packet at any time instant.

In this paper, we propose a novel design to an all-optical variable delay buffer based on fiber Bragg gratings (FBGs). The main advantage of the proposed architecture over the conventional optical buffers is its ability to provide variable delay times using a very simple architecture. Therefore, the delayed packet can be extracted as soon as the control unit declares its decision. In addition, FBGs provide all-fiber geometry, low insertion loss, and potentially low cost. To evaluate whether this system can be useful in optical networking, we assess the analysis of four performance measures: Power loss, signal dispersion, signal to noise ratio, and achieved delay. We find that the maximum time of delaying is relatively high compared to other traditional architectures.

2. DESCRIPTION OF THE PROPOSED ALL-OPTICAL VARIABLE DELAY BUFFER

Figure 1 shows the schematic diagram of the proposed all-optical variable delay buffer for $M \times M$ switch fabric, where M is the dimension of the switch fabric. This architecture is composed of three-port optical circulators (OCs), switch control unit (SCU), switch fabric, and the basic building block S_{ij}, where $i = 1, 2, \ldots, M$ and $j = 1, 2, \ldots, p$ with p is maximum number of delay lines in the optical memory queue.

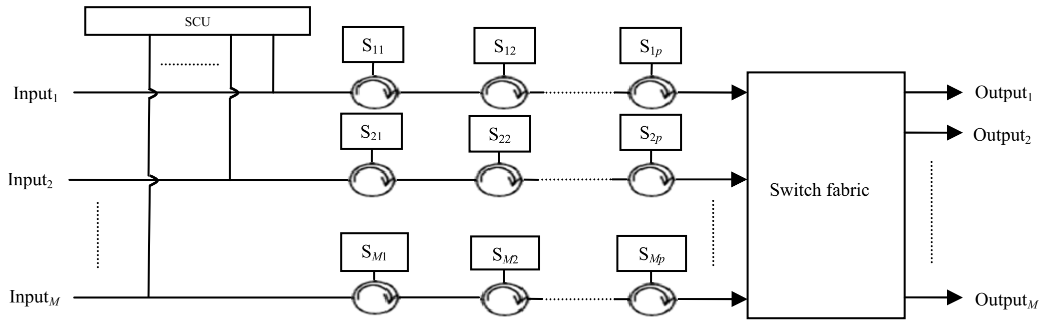

Figure 1. Schematic of the proposed architecture.

The basic building block S_{ij} is illustrated in Figure 2. It is consisting of two parts. The main one is used to confine the contenting packets. This part is a standard optical fiber (delay line) of length L_1 terminated by two identical groups of N cascaded FBGs with appropriate tuning control devices, where N is the number of wavelengths used in the network. All these FBGs are connected to the SCU which controls the tuning processes of the FBGs. The second part consists of erbium doped fiber amplifier (EDFA) and gain equalizer. This part is used to amplify the signal when needed.

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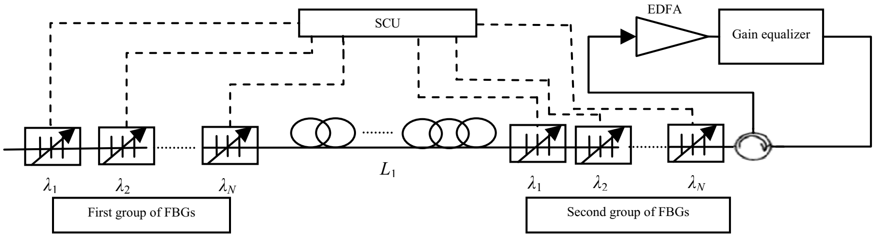

Figure 2. Schematic diagram of the basic building block S_{ij}.

The full operation of the proposed design can be exhibited as follows: First, the input packets are detected by the SCU which specifies the contenting packets, the storing locations of the contenting packets in the optical buffer queue, and the packets which do not cause contention. Let's, for example, consider the operation in an optical network of four wavelengths. Assume that the used wavelengths meet the International Telecommunication Union (ITU) WDM standardization with 100 GHz (about 0.8 nm) channel spacing (λ_1 = 1548.5 nm, λ_2 = 1549.3 nm, λ_3 = 1550.1 nm, and λ_4 = 1550.9 nm). Assume, for instance, four packets of different wavelengths arrive at the input port 1 and the SCU decides that packets of wavelengths λ_1 and λ_2 should be stored in S_{11} and S_{12}, respectively. While the remaining two packets of wavelengths λ_3 and λ_4 should be directed to the switch fabric. To perform this decision, the FBGs of Bragg wavelengths λ_3 and λ_4 in the first group of all S_{1j}, j = 1, 2, ….., p, should not be tuned. This helps to direct the packets of wavelength λ_3 and λ_4 to the switch fabric. FBG of Bragg wavelength λ_1 in the first group of S_{11} should be tuned to have a Bragg wavelength of 1548.9 nm. This FGB should stay in this state till the packet of wavelength λ_1 pass through it, and then it is tuned again to its initial state to capture this packet. Similarly, the FBG of Bragg wavelength λ_2 in the first group of S_{12} should be tuned to have a Bragg wavelength of 1549.7 nm and by the same way it captures the second packet of wavelength λ_2.

The confined packets suffer from attenuation resulted from the propagation through the FBGs and the optical fiber of length $L_{1.}$ The SCU evaluates whether amplifications are needed according to the number of round trips through the optical fiber. When required, it tunes the FBG of Bragg wavelength λ_1 in the second group of S_{11} and the FBG of Bragg wavelength λ_2 in the second group of S_{12} to have Bragg wavelengths 1548.9 nm and 1549.7 nm, respectively. This will relay the packet to be amplified by the EDFA. When these packets come back to the optical fiber of length $L_{1,}$ both tuned FBGs should be converted again to their initial state to capture the packets again.

When the delay operation is elapsed, the SCU should tune the FBG of Bragg wavelengths λ_1 in the first group of S_{11} and the second FBG of Bragg wavelength λ_2 in the first group of S_{12} to have Bragg wavelengths 1548.9 nm and 1549.7 nm, respectively. This makes the two packets free and can be directed to the switch fabric.

The number of revolutions which the signal in the optical fiber of length L_1 can carry out depends obviously on the fiber length and the number of FBGs. This number cannot exceed a maximum value because of unacceptable signal loss. Each time the signal power reaches a predefined low value, amplification is performed. The amplification of the signal through EDFA cannot exceed a maximum number of times to preserve from unacceptable degradation of the signal to noise ratio (SNR).

3. THEORITICAL ANALYSIS

To discuss the limits and performances of the suggested system, we studied five performance measures: Delay line length, transit time, signal dispersion, power loss and signal to noise ratio. Assume that the operating bit rate in the optical network is B and the maximum packet size is X. To ensure that the packets can completely enter the delay line, L_1 is given as follows:

$$L_1 \geq \frac{cX}{2nB}, \tag{1}$$

where C is the speed of light and n is the core refractive index of the used optical fibers.

The maximum time of confining a packet, $T_{max,}$ depends on the maximum allowed round trips in the delay line, K, maximum number of amplifications, q, the delay line length, and the EDFA length, L_2. That is:

$$T_{\max} = \frac{2KqL_1n}{c} + \frac{qL_2n}{c} \ . \tag{2}$$

The maximum attenuation of a packet propagating directly from the input port to the switch fabric without delaying, A_1, is given by the following equation:

$$A_1 = 2pA_{OC} + 2(N-1)\,pA_{FBG}\,, \tag{3}$$

where, A_{OC}, and A_{FBG} are the attenuations induced by the OC and the FBG. A_{FBG} is the out of band transmission attenuation induced by the FBG. In our design we assume all FBGs have high reflectivity of 99.7%–99.9%; therefore, the attenuation through the reflection can be neglected.

The maximum attenuation of a packet before and during entering the delay line S_{ij}, A_2, is given by

$$A_2 = (2j-1)A_{OC} + (2Nj - N - 2j + 2)A_{FBG} \quad (4)$$

The maximum attenuation of a packet during and after leaving the delay line S_{ij}, A_3, is given by

$$A_3 = (2p-2j+1)A_{OC} + \left[N + 2(N-1)(p-j)\right]A_{FBG}\,. \quad (5)$$

After confining the packet in the delay line, the attenuation occurs in it should not exceed A_4 before amplification. A_4 can be given by the following equation:

$$A_4 = K\left[2L_1A_f + 2(N-1)A_{FBG}\right] + 2NA_{FBG} + 2A_{OC}\,, \quad (6)$$

where A_f is the attenuation per unit length of the delay line.

Assuming that, the dispersion parameter of the delay line is D_f, and the dispersion caused by the OC is D_{OC}. The maximum dispersion of a confined packet, D_{max}, is given by

$$D_{max} = 2qKL_1D_f\Delta\lambda + 2(q+p)D_{OC}\,. \quad (7)$$

To put more accuracy to the dimensioning problem, we select different components with the following specifications. The optical fiber of the delay lines introduces a loss of 0.2 dB/km and its dispersion parameter equals 0.1 ps/(nm·km) [2]. The OC has an insertion loss and dispersion either from port 1 to 2 or from port 2 to 3 of 0.5 dB and 0.1 ps, respectively [2, 5]. The bit rate of the optical network is 40 Gbps, the maximum packet size is 1500 byte, the used light source has 0.4 nm linewidth, and 16 wavelengths are used with 100 GHz channel spacing [1]. The used FBGs have a reflection bandwidth of 0.3 nm with a maximum reflectivity of about 99.9%. In addition, the apodization using Blackman profile can be used in fabrication to suppress sidelobes of the FBGs. FBGs are written on lithium niobate optical fiber which can be tuned by applying electric field parallel to the axis of the FBG. This technique can provide a very fast tuning speed of order nm/ns which is suitable for circuit or packet switching networks [6]. The out-of-band transmission loss introduced by each FBG is about 0.05 dB [5]. Assuming that the optical buffer maximum allowed attenuation is 30 dB (from the input port to the switch fabric) and the EDFA has a length of 30 m and offers a gain of 30 dB. The gain equalizer offers a nearly flat gain for the different WDM channels with peak to peak variations of 1 dB.

Using equation (1), the minimum value of L_1 is 30.4 m. As a result, we can choose L_1 equals 100 m in order to increase the delay time. To calculate the maximum number of delay lines, p, we have two restrictions: (1) the packets that propagate directly to the switch fabric without entering the delay lines should reach the switch fabric with maximum attenuation of 30 dB, (2) the maximum total power loss of any stored packet before and during entering the delay line, to reach the amplifier for the first time inside the delay line, after finishing the maximum number of round trips but before leaving the delay line, and after leaving the delay line should not exceed 30 dB. With the help of equations (3), (4), and (5), the maximum value of p which satisfies the two previous restrictions is 11 delay lines. Substituting in equation (6) with $A_4 = 30$ dB, we conclude that the value of K equals 17 round trips. Since the power equalizer has 1 dB peak to peak gain variations, hence the value of q which gives acceptable signal-to-noise ratio (SNR) is nearly 10 times [1]. Substituting with these values in equation (2), this gives T_{max} of around 169.2 μs. Finally the maximum dispersion of this system is 5.56 ps.

4. CONCLUSION

We proposed a novel optical buffer based on FBGs. The proposed architecture can be used to provide variable delay times for the contenting packets using a simple and small structure. Moreover, it can be used to delay a large number of packets, up to $M \times P \times N$, simultaneously. We have shown that for an optical network that use 16 wavelengths the contenting packets can be delayed up to 169.2 μs. Also, our design has the opportunity to extract the delayed packets as soon as the control unit declares its decision.

REFERENCES

[1] I. Kaminow, T. Li: *Optical fibEr Communucations*, Academic, 2002.

[2] S. Batti, M. Kachout, M. Zghal, N.Boudriga: A fiber Bragg grating based buffer: Architecture and performance evaluation, in *Proc. ICTON 2007*, Rome, Italy, July 2007, paper Fr2B.

[3] T. Zhang, K. Lu, J.P. Jue: Shared fiber delay line buffers in asynchronous optical packet switching, I*EEE J. on Selected Area in Commun*., vol. 24, pp. 118-127, Apr. 2006.

[4] W.A. Vanderbauwhede, H. Novella: A multiexit recirculating optical packet buffer, *Photonic Technology Letter*, vol. 17, pp. 1749-1751, Aug. 2005.

[5] Y-K.Chen, C-C. Lee: Fiber Bragg grating-based large nonblocking multiwavelength cross-connects, *J. Lightwave Technol.*, vol. 16, pp. 1746-1756, Oct. 1998.

[6] V.A. Pilipovich, A.K. Esman, I.A. Goncharenko, V.K. Kuleshov: High-speed continuous tunable fiber and waveguide lasers with controllable Bragg grating, *J. Opt. Commn*., vol. 203, pp. 289-294, March 2002.