Variable Delay Optical Buffer Using Tunable Fiber Bragg Gratings

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Abstract

A novel all-optical variable delay buffer for next generation optical networks is reported. This buffer can store the contending packets for a relatively long time by using fiber Bragg gratings (FBGs). The proposed design is characterized by the ability to extract the delayed packets as soon as the contention is resolved.

Keywords

Contention resolution • Fiber Bragg grating • Optical buffer • Optical networks

Introduction

The all-optical networks have several advantages such as, high capacity, low insertion loss, and low price [1, 2]. However, they are not commercially used in the current networks. One of the main obstacles is packet contention which happens when two or more packets with the same wavelength are directed to the same destination at the same time. It was proven in the literature that the asynchronous (variable-sized) packet switching has a lower packet blocking probability than the synchronous (fixed-sized) packet switching [3].

Optical buffering is considered as one of the main solutions to resolve packets contention by using optical delay lines [4]. These buffers can delay the contending packets for fixed delay times by changing the lengths of the optical delay lines. Much effort has been done in the literature to design several successful architectures for the optical delay buffers [5, 6]. Though, these designs provide several advantages, most of them have several drawbacks. First, these architectures are bulky because they provide different delay lines and the delay is directly proportional to the length of each one. Second, it is hard to extract the contending packets at any time instant because the variable delay buffers have fixed delay times. Third, the overall design becomes more complicated and expensive as the number of delay lines increases because each delay line requires one switch port.

In this paper, we report a novel architecture to a variable delay optical buffer using tunable fiber Bragg gratings (FBGs). The main advantage of the proposed design over the traditional buffers is its ability to provide variable delay times. Therefore, the contending packets can be extracted at any time instant. Furthermore, using FBGs provide simplicity, low insertion loss, all-fiber geometry, and low cost [7]. To evaluate the efficiency of the reported design, we analyze four performance parameters: power loss, channel dispersion, signal-to-noise ratio (SNR), and delay times.

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Description of the Reported Buffer

Figure 1 is a schematic of the reported optical buffer designed for $N \times N$ optical switch fabric, where N represents the dimension of the fabric. This architecture consists of tunable FBGs, three-port optical circulators (OCs), control unit (CU), erbium-doped fiber amplifier (EDFA), gain equalizer, optical coupler, and switch fabric.

In front of each input port, there are two parts. The main part is a standard optical fiber (delay line) of length L_1 used to capture the contending packets. This fiber is terminated by two identical sets of M tunable cascaded FBGs, where M is the number of the channels used in the network. The tuning process of these FBGs is controlled by the CU. The second part is consisting of EDFA and gain equalizer which amplifies the confined packets when needed.

The operation of the designed buffer can be demonstrated as follows; first, the CU detects all of the input packets and specifies the contending packets, their delay lines, and the packets that can be directly served because they do not cause contention. For simplicity, let's assume the number of used wavelengths in the optical networks is four which meet the International Telecommunication Union (ITU) standardization of 100 GHz channel spacing (λ_1 = 1,548.5 nm, λ_2 = 1,549.3 nm, λ_3 = 1,550.1 nm, and λ_4 = 1,550.9 nm). In this case, four FBGs are required to be used in each set such that, their initial Bragg wavelengths are λ_1, λ_2, λ_3, and λ_4 as shown in Fig. 2.

Assume, for example, four packets of different wavelengths arrive simultaneously at the first input port and the CU decides to store the channels of wavelengths λ_1 and λ_2 because they are contending packets. While, its decision for the remaining two packets of wavelengths λ_3 and λ_4 is to serve them directly by the fabric. To perform these decisions, FBGs of Bragg wavelengths λ_3 and λ_4 in both the first and second groups should be tuned to have Bragg wavelengths of 1,550.5 and 1,551.3 nm, respectively, as shown in Fig. 3. This helps the packets of wavelengths λ_3 and λ_4 to be directed to the switch fabric. Additionally, FBGs in the first set of Bragg wavelengths λ_1 and λ_2 should be tuned respectively to have Bragg wavelengths of 1,548.9 and 1,549.7 nm, as shown in Fig. 3. These FBGs should remain in this state till the two packets of wavelengths λ_1 and λ_2 completely pass them, and then they are tuned again to their initial state to capture the contending packets in the delay line, as shown in Fig. 4.

The intensity of the confined packets attenuates due to the propagation through the FBGs and the delay line of length L_1. The CU decidestoamplifytheintensity ofthe confined packets based on the number of round trips through the delay line. When required, the FBGs in the first set of Bragg wavelengths λ_1 and λ_2 are tuned to have Bragg wavelengths of 1,548.9 and 1,549.7 nm, respectively. Consequently, the confined packets will be directed to the EDFA to be amplified. When the amplified packets come back to the delay line, the tuned FBGs should be returned back to their initial states to confine the packets again in the delay line.

After finishing the delay operation, the CU should tune the FBGs of Bragg wavelengths λ_1 and λ_2 in the second set to have respectively Bragg wavelengths of 1,548.9 and 1,549.7 nm. This makes the confined packets free and can be served by the switch fabric.

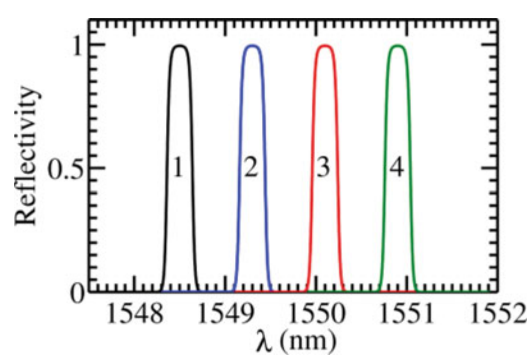

Fig. 2 Reflectivities of FBGs used in both sets 1 and 2 in the initial conditions when their Bragg wavelengths are λ_1 (*black*), λ_2 (*blue*), λ_3 (*red*), and λ_4 (*green*)

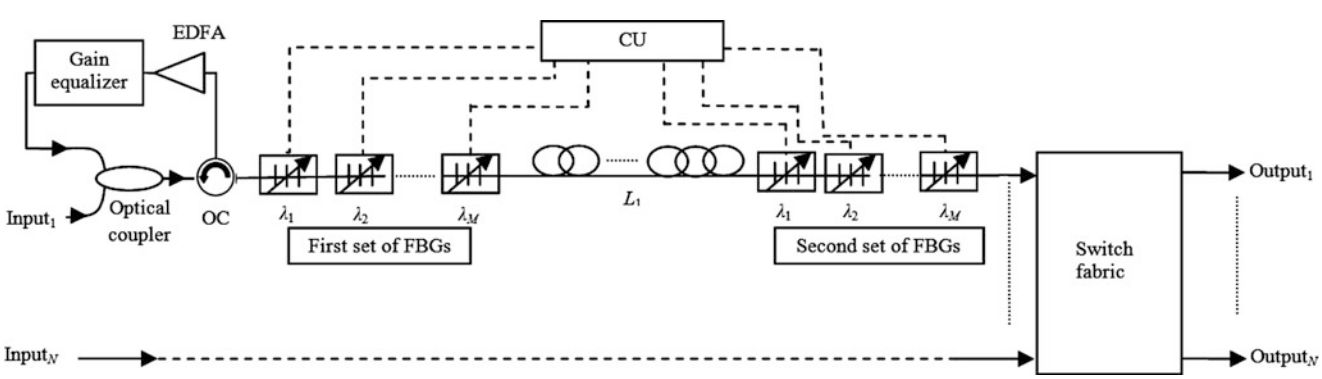

Fig. 1 Schematic of the reported architecture

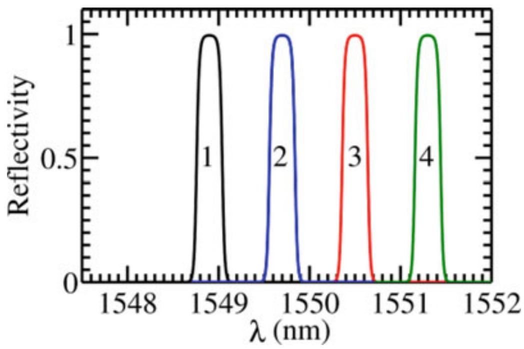

Fig. 3 Reflectivities of FBGs used in the first set when all of the packets enter the delay line

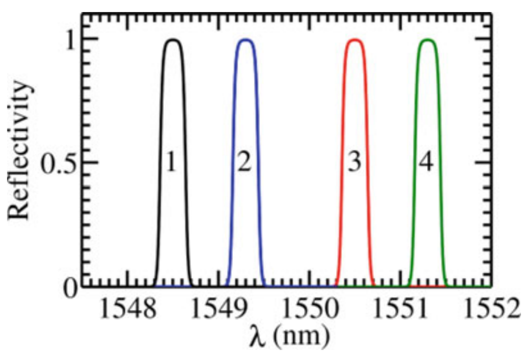

Fig. 4 Reflectivities of FBGs used in the first set when the packets of wavelengths λ_1 and λ_2 are captured by the delay line

The number of round trips that the contending packets can make in the delay line is basically depends on both the number of FBGs and the fiber length. This number is limited by the unacceptable signal attenuation threshold. When the intensity of the confined packet reaches a predefined low value, it is directed to be amplified by the EDFA. The maximum number of amplification by the EDFA is also limited by the unacceptable degradation of the signal to noise ratio (SNR).

Theoretical Performance Analysis

In order to evaluate the advantages and limits of the reported architecture, we measure the different performance parameters such as, delay line length, maximum delay time, signal dispersion, attenuation, and SNR. Assume that the maximum packet size in the optical network is Y and the used bit rate is B. The condition on the length of the delay line to make sure that the packets can completely enter the delay line is:

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

where c denotes the speed of light and n is the core refractive index of optical fiber used as a delay line.

The maximum delay time $T_{\max}$ can be represented as follows:

$$T_{\max} = \frac{2nKQL_1}{c} + \frac{nQL_2}{c}, \tag{2}$$

where K is the maximum allowed number of round trips in the buffer before the intensity of a delayed packets falls by attenuation to unaccepted threshold. Q denotes the maximum allowed number of amplifications, and L_2 is the EDFA length.

The packets directed to the switch fabric without delay suffer from maximum attenuation A_1 of:

$$A_1 = A_{OC} + 2MA_{FBG} + \alpha L_1, \tag{3}$$

where A_{OC} and A_{FBG} are the attenuation induced by the OC and FBG, respectively. In this design, it is assumed that the attenuation of FBGs is due to the out of band transmission only. This is because the maximum reflectivity at the Bragg wavelength is high enough to neglect the losses during reflection. Also, it is assumed that the optical coupler has negligible losses. The attenuation per unit length in the delay line is denoted by α.

The maximum allowed attenuation A_2 of a delayed packet before the decision of amplifying it by the EDFA is:

$$A_2 = 2A_{OC} + 2K\alpha L_1 + (M + KM - K + 1)A_{FBG}. \tag{4}$$

Assume that the dispersion parameter of the delay line is D_f and the dispersion resulted from using OC is D_{OC}, the maximum allowed dispersion $D_{\max}$ for a confined packet is:

$$D_{\max} = 2KQL_1D_f\Delta\lambda + (2Q + 1)D_{OC}, \tag{5}$$

where $\Delta\lambda$ is the spectral width of the light source used in the network.

To accurately evaluate the performance of the reported design, we select some commercial optical components with the following characteristics. The bit rate, maximum packet size, light source spectral width, and number of wavelengths used in the optical network are 40 Gbps, 1,500 byte, 0.4 nm, and 16, respectively [1]. The used OCs are symmetric between their ports and have respectively 0.5 dB and 0.1 ps insertion loss and dispersion [8]. FBGs have 0.3 nm reflection bandwidth, 99.5 % maximum reflectivity, and apodized using Blackman profile to suppress their side lobes [9]. FBG can be written on lithium niobate optical fiber so that, it can be tuned by applying electric field parallel to its axis [10]. This tuning method has a fast tuning speed in order of nm/ns which fits the requirements of the optical networks. The loss of FBG resulted from out of band transmission is 0.05 dB [11]. Furthermore, assume that the maximum allowed attenuation before EDFA amplification is 30 dB, in other words, the EDFA gain in 30 dB, the EDFA length is 30 m, and the gain equalizer offers flattening with peak-to-peak variation of 1 dB [3]. Finally, the optical fiber of the delay line has 0.2 dB/km attenuation loss and 0.1 ps/(nm.km) dispersion parameter [3].

Using Eq. (1), the minimum allowed delay line length is 30.4 m. Its maximum value can be calculated by using Eq. (3) such that, A_1 should not exceed 30 dB. The maximum delay length is found to be 139.5 km. Therefore, let's choose $L_1 = 31$ m to get the packet out of the delay line as soon as the CU declares this. The maximum allowed number of round trips can be obtained by substituting with $A_2 = 30$ dB in Eq. (4) to find K equals 36 round trips. Since the EDFA gain equalizer provides 1 dB peak-to-peak variation, the maximum number of EDFA amplifications that gives acceptable level of SNR is around ten times [3]. Substituting of these values in Eq. (2), the maximum delay time is found to be 116 μs. Finally, Eq. (5) shows the maximum, dispersion of this architecture is 3 ps.

Conclusion

We reported a novel all-optical variable delay buffer based on tunable FBGs. This architecture can be used to delay a large number of contending packets, up to $N \times M$, simultaneously. For an optical network of 16 channels, the reported buffer can store the contending packets up to 116 μs with relatively low dispersion. Finally, this architecture is characterized by its simplicity, low price, and the opportunity to extract the contending packets whenever the CU declares this decision.

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