Performance analysis of all optical swapping networks with a label eraser made of a Gaussian filter

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In this paper, a simple label eraser employing Gaussian apodized fiber Bragg grating (FBG) for all optical label swapping (AOLS) networks is proposed. Relying on the analysis of the payload through multi-stage erasers, this kind of eraser significantly improves the cascadability in comparison with the traditional fiber-loop mirror (FLM) eraser. The influences of the residual labels on the intermediate swapping node labels through the eraser are also investigated. It is shown that the power penalty is only less 1 dB when the optical power ratio of residual label to the new label signal arrives at −8 dB. The influence is negligible due to the sharp notch filtering effect of the Gaussian apodized FBG.

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All optical label swapping (AOLS)[1] is one of potential solutions to improve the scalability and flexibility of the current optical networks. It implements the packet-by-packet routing and forwarding functions by multi-protocol label switching (MPLS) protocols directly into optical layer. In AOLS, the optical label process using subcarrier multiplexing (SCM) as optical labels including reading, writing and erasing is the basic elements for label assignment and swapping. Because the SCM label message needs repetitious erasing and rewriting by means of optical filtering when the optical payload is across several intermediate nodes, two key issues must be taken into account during the label erasing, one is cascadability of the eraser, the other is the influence on current labels by the pervious labels. Recently, several intricate optical label swapping techniques have been demonstrated using fiber-loop mirror (FLM)[2], but it has disadvantageous influence on payload frequency spectrum because of its cosine square transmission function. In this paper, a simple filter employing apodized fiber Bragg grating[3] as a label eraser is proposed. It has flat passband, high isolation degree and stable characteristics, which significantly suppress the distortion of the payload and label message through multi cascaded nodes. It also has narrow band and high coupling efficiency with fiber. In the second section, the performance analysis of the label eraser is presented. In third section, based on the analysis, the performance of the apodized FBG eraser is compared with that of the FLM eraser. The performance of optical eraser will have significant effects on both the payload and SCM labels. In this section, the general expression of the bit error rate (BER) for the payload through the cascaded erasers and the BER for the label are presented.

Because the payload will pass through several nodes from a source to a destination, good cascaded performance of the filter are required to keep the integrity of data transmission. Because of the frequency spectrum of the labels and the baseband signal are not overlapped, the optical packets with their SCM labels entering into the label eraser can be written by[4]

$$P_{\text{in}}(t) = P_0[1 + \sum_{n=1}^{N} d_n(t - nT_c) + S_1(t)\cos(\omega_{\text{sc}}t)], \quad (1)$$

where P_0 is the average transmitted optical power, $\{d_n: d_n = 0, 1\}$ is the data sequence, and T_c is the bit intervals. The code is pseudorandom binary sequence (PRBS) with the code length N. $S_1(t)$ is the optical label message and ω_{sc} is the subcarrier angle frequency. Then, the outputs of the eraser module can be expressed as

$$P_{\text{out}}(t) = P_{\text{in}}(t) \otimes T_1(t) \cdots T_{n-1}(t) \otimes T_n(t), \quad (2)$$

where $T_n(t)$ is the transfer function of the cascaded filters in time domain, n represents the cascaded filters number. The bit error rate (BER) of the output signal can be expressed as

$$\text{BER} = \frac{1}{N}\sum_{i=1}^{N} \text{ber}(i). \quad (3)$$

The ber(i) is the BER of the ith code, which is written by

$$\text{ber}(i) = \begin{cases} \frac{1}{4}\left[\text{erfc}\left(\frac{I_1 - I_D}{\sigma_1\sqrt{2}}\right)\right] & d_i = 1 \\ \frac{1}{4}\left[\text{erfc}\left(\frac{I_D - I_0}{\sigma_0\sqrt{2}}\right)\right] & d_i = 0 \end{cases}, \quad (4)$$

where I_1 and I_0 are the average optical current for the code "1" and code "0", respectively, which is direct ratio to the optical power P_{out} ($I = RP_{\text{out}}$, R is the photodetector responsibility), I_D is the decision threshold, σ_1 and σ_0 are the mean square root of the noise current of the code "1" and the code "0", respectively, which is contributed by the optical shot noise, optical beat noise, heat noise, and so on[5].

On the other hand, the residual labels due to incomplete rejection on a wider bandwidth of label eraser will influence upon the BER of the current label. At the label receiver, the label signal with the residual components of the pervious labels can be written by

$$S_c = S_2(t)\cos(\omega_{\text{sc}}t + \varepsilon S_{1r}(t - \tau)\cos(\omega_{\text{sc}}t + \varphi), \quad (5)$$

where $S_2(t)$ is the baseband signal of the current label, the second term in Eq. (5) represents the pervious power due to incomplete rejection, and τ is the binary bit sequence delay difference which is a random value distributed in one bit period. φ is the phase difference of the carrier frequency between the current label and the residual label, which is also a random value corresponding to the linewidth of the carrier. $\varepsilon = T(\omega_{\mathrm{sc}})$ is the optical power ratio of residual label to the current label signal. Three influences on the current label are needed to consider simultaneously, one is the delay time τ, the others are the phase difference φ and the code of the pervious label. We assume that the time decision point is at the midst of one bit periods, the electrical level of the receiver for the codes "1" and "0" can be given by

$$\begin{cases} I_i + I_1\varepsilon\cos\varphi = I_{c1}(\varphi) & \tau \le T/2 \\ I_i + I_0\varepsilon\cos\varphi = I_{c0}(\varphi) & \tau > T/2 \end{cases} \quad \text{for code "01"}, \tag{6}$$

$$\begin{cases} I_i + I_0\varepsilon\cos\varphi = I_{c1}(\varphi) & \tau \le T/2 \\ I_i + I_1\varepsilon\cos\varphi = I_{c0}(\varphi) & \tau > T/2 \end{cases} \quad \text{for code "10"}, \tag{7}$$

$$I_i + I_0\varepsilon\cos\varphi = I_{ci}(\varphi) \quad \tau = \text{any value} \quad \text{for code "00"}, \tag{8}$$

$$I_i + I_1\varepsilon\cos\varphi = I_{ci}(\varphi) \quad \tau = \text{any value} \quad \text{for code "11"}, \tag{9}$$

where $i = 1, 0$ represents the code "1" and "0", and I_1 and I_0 are the microwave receiver decision levels of the signal. Four cases are discussed according to the difference between τ and $T/2$, and the four kinds of two sequence bits of the pervious label. So the BER of the label is written by

$$\mathrm{BER} = \sum \frac{1}{4} \times \frac{1}{2\pi} \times \int_0^{2\pi} \frac{1}{4}\left[\mathrm{erfc}\left(\frac{I_{c1}(\tau,\varphi) - I_D}{\sigma_1\sqrt{2}}\right) + \mathrm{erfc}\left(\frac{I_D - I_{c0}(\tau,\varphi)}{\sigma_0\sqrt{2}}\right)\right]\mathrm{d}\varphi. \tag{10}$$

On account of the flat top and narrow band of Gaussian apodized Bragg grating, we use this kind of filter as the label eraser. In order to acquire the flat bandwidth and high isolation degree, which is the key influences for the eraser cascadability, the optical label filter is a 4-cm-long fiber Bragg grating with the Bragg wavelength at 1550.12 nm and the peak refractive index modulation 1×10^{-4}. The grating is Gaussian apodized to achieve a side mode suppression ratio of 40 dB, and the bandwidth at -1 dB and -25 dB are 0.16 nm and 0.165 nm, respectively. The passband is very flat and has steep edge, as shown in Fig. 1.

This simulation is conducted at 10 Gbit/s of the payload with an NRZ coded $2^7 - 1$ long PRBS, and 14 Gb/s subcarrier with 100 Mb/s ASK label message. The BER for payload is shown as a function of the optical power in Fig. 2. The sensitivity at 10^{-10} BER in back-to-back is -33.2 dBm. The 1-stage, 2-stage and 3-stage values of the BER are examined. The power penalty of 1-stage for the two kinds of filters is both less than 1 dB, but the power penalty of three cascaded FBG filters is 1.66 dB, obviously prior to that of cosine filters, 5.62 dB in comparison with the back-to-back signal. So the high cascadability for such label swapping nodes can be obtained in the photonic-switched networks.

Figures 3 and 6 are the result of the payload through different stage erasers. We can see the open eye deteriorates when the signal is across much more nodes. In addition, the eye diagrams indicate that FBG as label eraser is far better than FLM as label eraser especially through many cascaded nodes. Considered the delay time τ as an average distribution in Eq. (5), the power penalty of the label influenced by the residual components of the old label from Eq. (10) is shown in Fig. 7. It is seen from Fig. 7 that for $\varepsilon > -8$ dB, the power penalty of the label increases much more quickly.

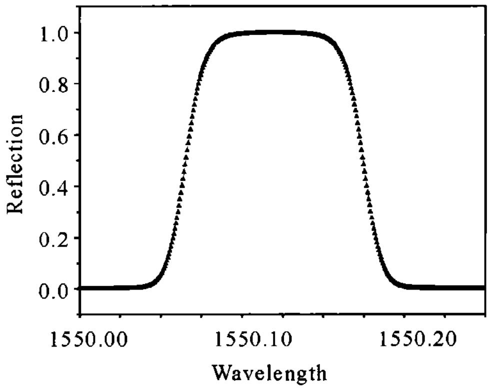

Fig. 1. Transfer function of the Gaussian apodized fiber Bragg grating.

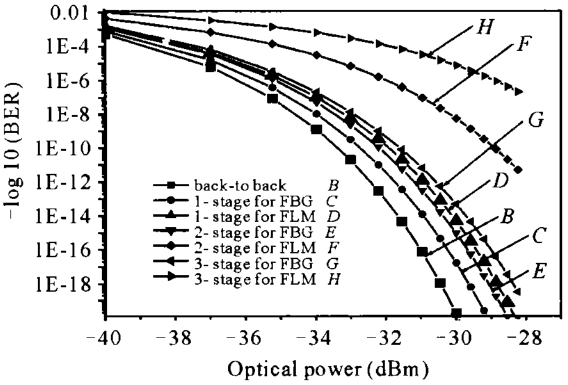

Fig. 2. Bit error rate vs optical power.

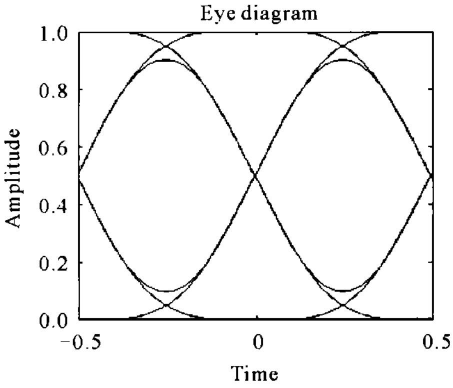

Fig. 3. The eye diagram of 1-stage for FLM.

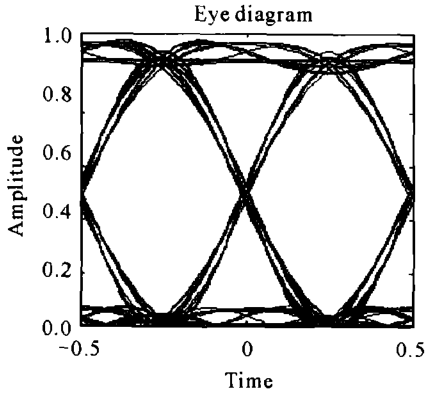

Fig. 4. The eye diagram of 1-stage for FBG.

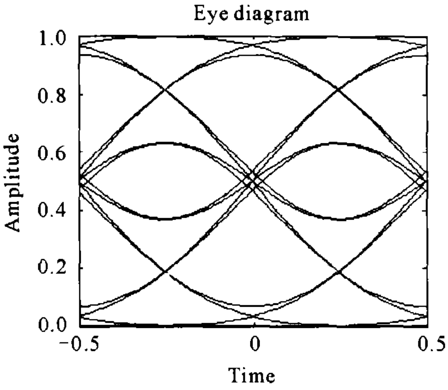

Fig. 5. The eye diagram of 3-stage for FLM.

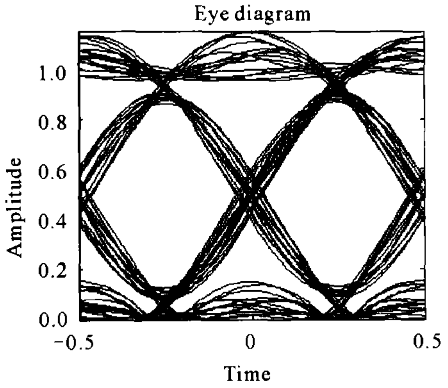

Fig. 6. The eye diagram of 3-stage for FBG.

The power penalty is only less than 1 dB when the label power ratio < −8 dB that is easy condition to satisfy due to the sharp filtering effect for the Gaussian apodized FBG eraser. The use of the sharper notch eraser greatly reduces the power penalty for the SCM label signals, so it can reduce the request on the label receiver.

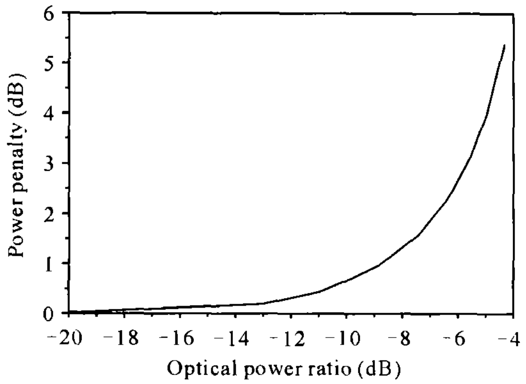

Fig. 7. Power penalty of the label message.

In summary, a simple optical label eraser that has the flat passband and sharp notch characteristics based on Gaussian apodized FBG eraser filter is proposed. A numerical model is set up to analyse the influence on payload through the cascaded filter and a comparison between the FBG filter and the FLM filter is made. The high transmittance and excellent cascadability can be obtained by means of Gaussian apodized FBG as the label eraser. The effect of residual label on the new label is negligible because of the sharp notch filtering effect of the FBG filter. Due to the simplicity and easy fabrication of the filter, our analysis clearly demonstrates the feasibility of all-optical label swapping in future networks.

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