A novel scheme of label abstraction and erasion based on Fabry-Perot semiconductor optical amplifier

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A novel label abstraction and erasion scheme based on a Fabry-Perot semiconductor optical amplifier (FP-SOA) is proposed for all-optical separation of the bit-serial label from payload and its performance is investigated by simulation. Important features of this scheme are that it does not make use of any high-speed electronics and only one device is needed. Using this scheme, label abstraction and erasion can be realized with the extinction ratio of 9.72 and 7.05 dB, respectively.

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Optical packet switching (OPS) network is a potential application to scale far beyond the speed, throughput, performance and packet forwarding rates of current internet networks. Optical label processing including label and payload separation, label renewal and label recognition is the basic technology for realizing OPS. Note that the label and payload separation is made up of label abstraction and label erasion and that it is one of the key functionalities required at the optical node. In order to transmit packets from source to destination all-optically, it is crucial to be able to generate local clock signals for processing, as well as to be able to separate and recognize the label information embedded in a packet. Several types of optical label technology such as bit-serial[1,2], code-division multiplexing[3,4], multi-wavelength[5], subcarrier multiplexing (SCM)[6] and orthogonal labelling[7] have been reported. In these methods, the bit-serial scheme has an advantage of enabling scalable labels with a small number of bits[8]. Several techniques have been proposed so far for the all-optical separation of the bit-serial label from payload[9−11]. In these methods, label and payload separation can be implemented with the circuits that consist of two subunits: an optical packet clock recovery circuit and an additional high-speed optical gate, while the optical gate can be made up of semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI), semiconductor optical amplifier delay interferometer (SOA-DI) or ultrafast nonlinear interferometer (UNI). Even though these methods have demonstrated the potential of all-optical processing, their circuits complexity increases with the number of header bits.

In this paper, a novel label abstraction and erasion scheme based on a Fabry-Perot semiconductor optical amplifier (FP-SOA) is proposed for all-optical separation of the bit-serial label from payload and its performance is investigated. FP-SOA is attractive not only due to simple fabrication without anti-reflection coating step but also due to its signal amplification capability and strong nonlinearity to perform all-optical separation of bit-serial label from payload. Important features of the scheme presented here are that it does not make use of any high-speed electronics and that only one device is needed. In our simulation, the payload is depressed and the label is amplified with 9.72-dB gain difference for label abstraction. Inversely, the payload is amplified and the label is depressed with 7.05-dB gain difference gain for label erasion. The simulation results indicate that this label abstraction and erasion scheme has the potential of being applied in the all-optical packet switching networks.

The optical processing in an optical label-swapping network is shown in Fig. 1. Note that the schematic diagram of the optical label abstraction and the optical label erasion are both included in the figure.

A FP-SOA is used to realize the abstraction and erasion of the bit-serial label due to the different gain that the label and payload achieve from the FP-SOA as shown in Fig. 1. The label will be abstracted when the gain for the label is much larger than that for the payload and will be erased when the gain for the payload is far larger than that for the label.

A simple way to realize the different gain for the label

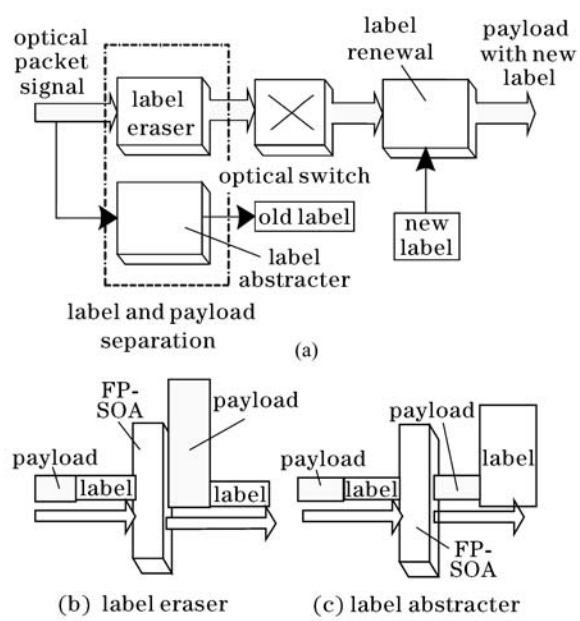

Fig. 1. Optical processing in optical node.

and payload is to adjust the different pulse width for them. The different pulse width naturely matches the relatively low bit-rate label and high bit-rate payload.

The different gain induced by different pulse width can be explained as follows. The gain of FP-SOA is given by[12]

$$G(\nu) = \frac{(1-R_1)(1-R_2)G_s}{(1-\sqrt{R_1R_2}G_s)^2 + 4G_s\sqrt{R_1R_2}\sin^2\phi}, \quad (1)$$

where R_1 and R_2 are the facet reflectivities of FP-SOA and the single-pass gain G_s is

$$G_s = \exp[(\Gamma a(N - N_{tr}) - \alpha_L)L], \quad (2)$$

where a is the differential gain coefficient, Γ is the optical confinement factor, N_{tr} is the carrier density at transparency, α_L is the material loss coefficient given by

$$\alpha_L = K_0 + \Gamma K_1 N, \quad (3)$$

where K_0 is the carrier independent absorption loss coefficient, K_1 is the carrier dependent absorption loss coefficient. The single-pass phase shift ϕ is

$$\phi = \frac{2\pi\nu}{c}\int_0^L n_{eq}(z)\mathrm{d}z, \quad (4)$$

where ν is the frequency of the injected light, n_{eq} is the equivalent index of the amplifier waveguide given by

$$n_{eq} = n_{eq0} + \frac{\mathrm{d}n_{eq}}{\mathrm{d}n}N, \quad (5)$$

where n_{eq0} is the equivalent refractive index at zero carrier density and $\mathrm{d}n_{eq}/\mathrm{d}n$ is the differential of equivalent refractive index with respect to carrier density.

Equations (2) and (3) show that the single-pass gain G_s is only related to the carrier density N, since K_0, K_1, Γ, N_{tr}, a, L are all constants. Equations (4) and (5) indicate that the single-pass phase shift ϕ is related to the frequency of the light and the carrier density N, for n_{eq0}, $\mathrm{d}n_{eq}/\mathrm{d}n$, L are all constants. So according to Eq. (1), we can derive a conclusion that the gain G from the FP-SOA is only related to the wavelength of the optical signal and the carrier density N in the FP-SOA. Thus, for an optical signal with a fixed wavelength, there exists a relationship between the gain G and the carrier density N. Using the Matlab 7.1, the relationship curve is obtained from Eqs. (1)—(5), as shown in Fig. 2. In Fig. 2, there exists a gain peak in FP-SOA, which is different from travelling wave semiconductor optical amplifier (TW-SOA). At the right slope of the gain peak in Fig. 2, higher carrier density indicates lower gain, i.e. $G_B < G_A$ for $N_B > N_A$. On the other hand, higher carrier density relates to higher gain at the left slope, i.e. $G_C < G_D$ for $N_C < N_D$.

The gain characteristics shown in Fig. 2 can also be explained from the relationship between the gain and the wavelength of the signal as shown in Fig. 3, which is derived from Eqs. (1)—(5) using Matlab when we set the carrier density N to a fixed value. The FP-SOA has a characteristic that different wavelength is corresponding to different gain because of the Fabry-Perot cavity. For different light with different injected power corresponding to different carrier density, we obtain different gain-wavelength curve, such as the two curves for $N = 1.65 \times 10^{24}$ m^{-3} and $N = 1.6 \times 10^{24}$ m^{-3} in Fig. 3.

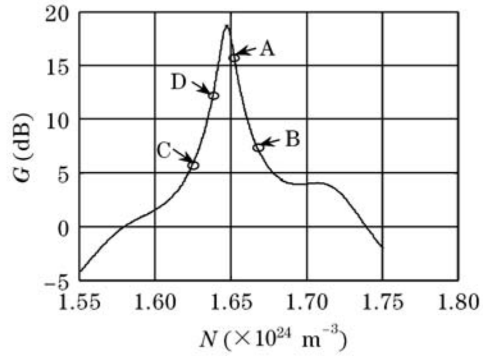

Fig. 2. Gain versus carrier density.

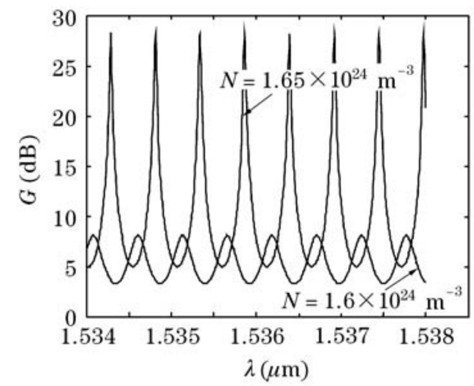

Fig. 3. Gain versus wavelength at carrier density $N = 1.65 \times 10^{24}$ m^{-3} and $N = 1.6 \times 10^{24}$ m^{-3}.

So for a fixed wavelength, the gain G for different carrier density N is different. In this sense, Fig. 3 is in accordance with Fig. 2.

Because the pulse with large energy depletes more carriers than the one with small energy, the wide pulse leads to lower carrier density than the narrow one for the same peak power. By setting the working points to the right slope of the gain peak such as "A" and "B" in Fig. 2, and adjusting the bias current, the label (wide pulses) can achieve higher gain than the payload (narrow pulses). After experiencing a certain loss in the attenuator, the payload can be depressed and the label can be abstracted to label recognition. When we set the bias current to a relatively large value, the label and the payload will deplete much carriers and the carrier density will recover to a low value such as "C" and "D", the label will obtain lower gain than the payload. After an attenuator, the label can be depressed for further inserting the new label.

To verify the feasibility of the scheme, a numerical model of FP-SOA is established in Matlab 7.1. For deriving a large extinction ratio, all the SOA parameters especially the facet reflectivities, the length and the bias current need to be optimized. In this model, the input and output facet reflectivities $R_1 = R_2 = 0.019$, the length $L = 0.7$ mm, the bias current $I = 40.2$ mA, and other parameters adopt the typical values presented in Ref. [12].

Two Gaussian pulse trains with different pulse widths are used to represent the label and payload. The pulse train with larger pulse width w_1 refers to the label, while the one with smaller width w_2 is corresponding to the payload. The pulse width ratio is $W = w_1/w_2$.

In the simulation, the results are contrary for the wavelengths of 1536.95 and 1537.02 nm when the other conditions are the same. For the case of 1536.95 nm, the label obtains more gain than the payload while for the case of 1537.02 nm, the payload achieves more gain than the label. This can be explained from the gain-wavelength characteristics for the FP-SOA as shown in Fig. 3, that is, for a fixed carrier density, the gain is different at different wavelength. So for the label with the fixed pulse width corresponding to a fixed carrier density, the gain that the label achieves is different at different wavelength. At one wavelength, the label can obtain larger gain than the payload while for another wavelength, the label can achieve lower gain than the payload. Thus, the wavelength that the label and payload have should be optimized to realize the two different effects for the label and payload processing.

To realize the different effect for different wavelength in actual OPS network, the wavelength stability and linewidth should be considered, the resolved scheme is shown in Fig. 4. When the optical packet signal with the wavelength of 1536.95 nm is sent to the optical packet node, it can be divided into two parts by optical coupler. One is directly sent to the FP-SOA and then the label is abstracted. The other is first sent to the tunable erbium-doped fiber laser to change the wavelenth into 1537.02 nm, then the optical signal with the wavelength of 1537.02 nm is sent to the following FP-SOA. The label is erased after the optical signal passes the FP-SOA. In Fig. 4, the fiber laser can output optical signal with the linewidth less than 0.07 nm according to Refs. [13,14].

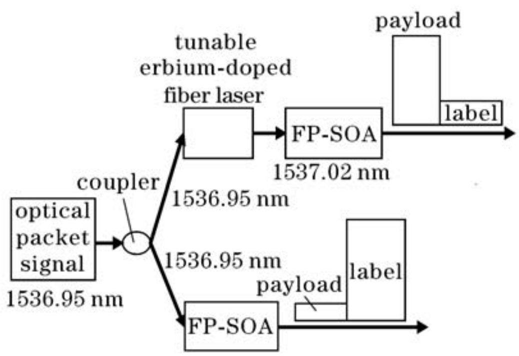

Fig. 4. Scheme to resolve the wavelength problem.

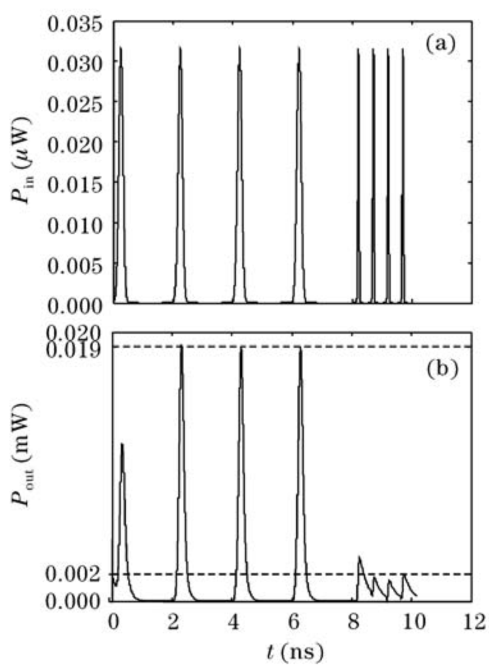

Fig. 5. Input (a) and output (b) pulses waveforms presenting label abstraction.

Figures 5(a) and (b) show the input and output pulse waveforms when the input pulse peak power is −45 dBm, the wavelength is 1536.95 nm, $w_1 = 400$ ps and $w_2 = 100$ ps. As shown in Fig. 5(b), the label obtains more 9.72 dB gain than the payload.

Figure 6 shows the output pulse waveform of the input as Fig. 5(a). But the wavelength is changed to 1537.02 nm. As shown in Fig. 6, the payload achieves more 7.05 dB gain than the label.

Figures 5 and 6 show the feasibility of the scheme. But due to the carrier recovery time, the first pulse of the pulse train is not fully amplified.

We also measure the extinction ratio at different pulse width ratio W using Matlab 7.1. Figure 7(a) shows the relationship between the extinction ratio and the pulse width ratio W for label abstraction while Fig. 7(b) corresponding to that for label erasion. It can be seen from Fig. 7(a) that the extinction ratio is increasing while $W < 5$ and falling down when $W > 5$ with the increase of W. It is in accordance with the transition of the working points A and B in the gain curve. The point A will shift to left slope of the gain peak when W is increasing for the fixed pulse width w_2. So at the beginning, the extinction ratio is increasing while W is increasing. When the point A shifts to the left slope of the gain peak, the extinction ratio will start to fall down. In Fig. 7(b), with the increasing of pulse width ratio W, the extinction ratio is shifting to a higher one. This can be explained from the transition of points C and D in the gain curve. When W is increasing, point C will shift to lower gain, consequently the extinction ratio becomes larger and larger. From the above analysis, we find that for a given case, there must be an optimized W to make the extinction ratio largest. It depends on working points of the label pulses and payload pulses in the gain curve.

In OPS systems, the extinction ratio is one of the key parameters of system performance. The extinction ratio is the difference value of power between the label and payload. In Fig. 5, label obtains more 9.72 dB gain

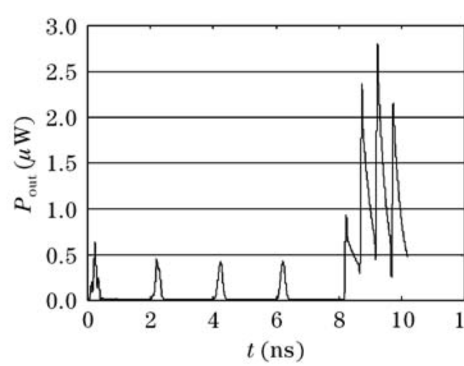

Fig. 6. Output pulses waveform presenting label erasion.

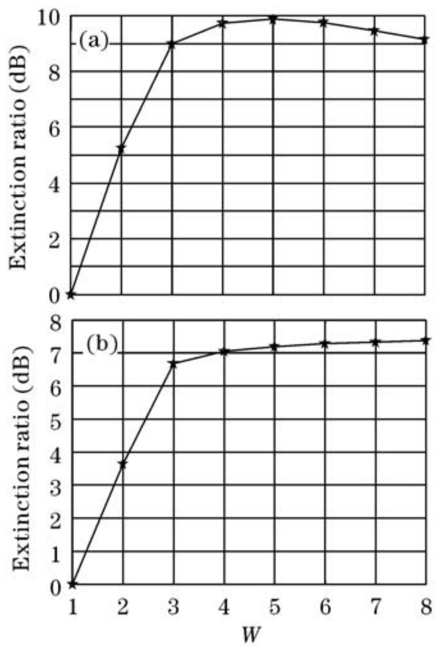

Fig. 7. Extinction ratio versus pulse width ratio W in the cases of (a) label abstraction and (b) and label erasion.

than the payload, which means the power of label is 9.72 dB higher than that of payload. In actual system, 9.72 dB is enough to detect the label and not detect the payload when we set a threshold power at the output of the FP-SOA, accordingly to realize the label abstraction. The higher the extinction ratio is, the better that the detection system distinguishs the label and payload. So, it is better to make the extinction ratio large to realize the label abstraction and erasion well.

In conclusion, a novel scheme of bit-serial label abstraction and erasion based on FP-SOA is presented. And the influence of pulse width ratio between the label and payload pulse on the extinction ratio is also investigated. The simulation shows that this scheme is feasible and promising. By adjusting the parameters of FP-SOA and injected optical packet signal, the label abstraction and erasion can be realized with extinction ratio of 9.72 and 7.05 dB, respectively. In addition, the carrier recovery time is the main confinement for improving the pulse rate.

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