A novel time-to-live countdown scheme based on asymmetric Mach-Zehnder interferometer and Fabry-Perot semiconductor optical amplifier

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We propose a novel optical time-to-live (TTL) processing scheme using asymmetric Mech-Zehnder interferometer (AMZI) and Fabry-Perot semiconductor optical amplifier (FP-SOA). AMZI transfers M TTL pulses into $M-1$ pulses and two residual pulses with 6-dB power difference. FP-SOA enhances the power difference between the $M-1$ pulses to the residual pulses to more than 10 dB. A numerical model is established for verifying the feasibility of this scheme.

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There has been increasing interest in the vision of an optical label switching recently[1]. Such IP-over-optical integration increases the flexibility and scalability of future optical data network. However, it also brings about some new challenges. One challenge is the problem of "routing loop" caused by the distributed nature of the IP control plane, where mislabeled packets are routed in circle, never reaching their destination and leading to severe network congestion[2]. Such loops are often prevented by a time-to-live (TTL) field within a packet header. The TTL field determines the maximum number of hops that a packet can take the network. A packet with zero TTL value will cease to propagate further. For a high-speed optical packet network, a similar TTL countdown approach can be adopted to facilitate loop mitigation. However, modifications are needed if this function is to be carried out in optical domain with the least amount of latency, which is something easy in electronics but often difficult in optical systems.

There has been minimal previous research on decrementing the TTL value in optical domain. Due to the lack of efficient optical logic processors, it is difficult to detect and decrement the TTL value inside the label directly. For simplifying the TTL processing, several types of TTL formats have been proposed, including binary-encoded pulses[3], phase-encoded pulses[4] and the number of ultrafast optical pulse[5]. Especially, using the number of return-to-zero (RZ) optical pulses to indicate TTL values is a flexible method to ease the TTL decrementing[5]. Although Hung *et al.* proposed to count down the number of optical ultrafast pulses by the change of polarization state induced by the semiconductor optical amplifier (SOA) saturation, there still exist following disadvantages. First, it is too difficult to maintain the orthogonal polarization between the first pulse and the subsequent pulses for different input optical power. Second, it needs a lot of apparatus such as polarization controller, polarization maintaining fiber and polarization beam splitter. Third, the optical extinction ratio is reduced in saturation state.

In this paper, we propose a new TTL processing scheme using asymmetric Mech-Zehnder interferometer (AMZI) and Fabry-Perot SOA (FP-SOA). AMZI changes M incoming pulses into $M-1$ pulses and two residual pulses with 6 dB lower than the $M-1$ pulses. FP-SOA enhances the power difference between the $M-1$ pulses to the residual pulses to more than 10 dB.

When an optical packet enters the ingress router of the optical packet network, its initial TTL value, which is indicated by the number of optical pulses, is appended in the front of the packets. In the core switching node, TTL domain will be extracted from the packet by the TTL extraction module and directed to TTL decrementing module. The schematic diagram of the TTL processing module is illustrated in Fig. 1(a). The research of the extraction of the TTL field is beyond the scope of this paper. The TTL decrementing module consists of AMZI and FP-SOA. The unbalanced delay between the two arms of AMZI equals to the period of TTL pulses. When two series of M pulses coupled again, they overlap with $M-1$ pulses and two non-overlapping pulses are left at the head and tail of the output pulse train as shown in

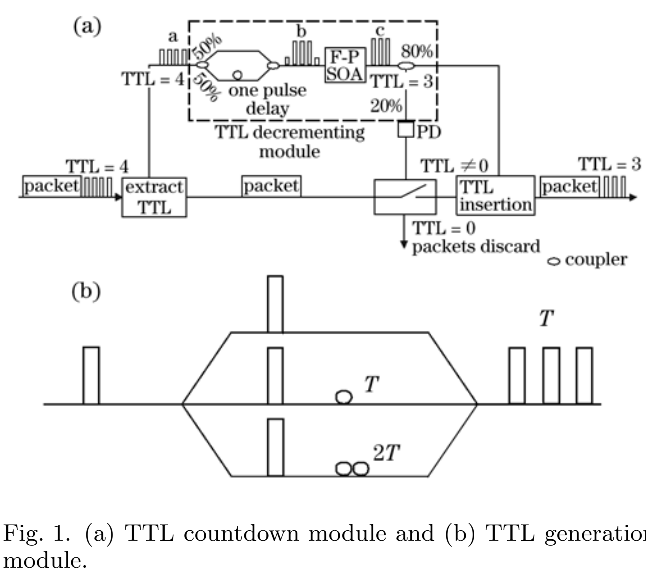

Fig. 1. (a) TTL countdown module and (b) TTL generation module.

Fig. 1(a). For simplicity, the two non-overlapping pulses are called the first residual pulse and the last residual pulse according to their positions. Under the condition of complete coherent interference, the electrical field of the coupling output in AMZI is the sum of the electrical fields from the two arms. The amplitude of electrical field of $M-1$ pulses is double that of each residual pulse and the optical power will become four times. So the $M-1$ pulses have optical power 6 dB higher than each of the residual pulse. For maintaining the coherence of TTL pulses, a method of TTL pulses generation is proposed as shown in Fig. 1(b). Since each of TTL pulses is duplicated from the same pulse, the coherence of them can be reserved. The FP-SOA will be used to suppress the residual pulses and amplify the $M-1$ pulses. The working principle can be explained with the gain characteristic of FP-SOA which can be expressed as

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

where R_1 and R_2 are the facet reflectivity. The single pass gain G_s and phase ϕ under the assumption of uniform carrier distribution can be expressed as

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

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

$$\phi=\frac{2\pi}{\lambda}nL, \quad (4)$$

where Γ is optical confinement factor, N_{tr} net gain coefficient, α loss coefficient, L the cavity length, λ is the wavelength, n the equivalent refractive index, K_0 the carrier independent absorption loss coefficient, and K_1 the carrier dependent absorption loss coefficient. The equivalent refractive index n is relative to the carrier density N. In general, n is modeled as

$$n=n_0+\frac{dn}{dN}N, \quad (5)$$

where n_0 is the equivalent refractive index at zero carrier density, dn/dN is the differential ratio of the equivalent refractive index with respect to the carrier density. From Eqs. (2) and (3), it is easy to be found that the single pass gain G_s is only related to carrier density N, since Γ, N_{tr}, K_0, K_1, L are all constants. Equations (4) and (5) show that the phase ϕ is related to the wavelength λ and carrier density N, since n_0, L, dn/dN are constants. From Eq. (1), it can be said that the gain of FP-SOA is not only sensitive to frequency but also fluctuated with carrier density. The gain of FP-SOA fluctuating with carrier density can be seen in Fig. 2.

The principle of using FP-SOA to suppress the two residual pulses can be explained as follows. Due to the reflectivity of the two facets in FP-SOA, the variation of carrier density in FP-SOA will cause the change of the refractive index which will change the gain of FP-SOA directly. For a certain wavelength, the gain of FP-SOA only fluctuates with the carrier density. For suppressing the low-power pulses and amplifying the high-power pulses, FP-SOA is required to work in the region I. In this region, the gain increases with the depletion of the carrier. So the pulse extinction ratio between the $M-1$ pulses and the residual pulses is easy to be improved by using this characteristic in FP-SOA. For optimizing FP-SOA parameters, M pulses will be decreased to $M-1$ pulses after passing through TTL processing module.

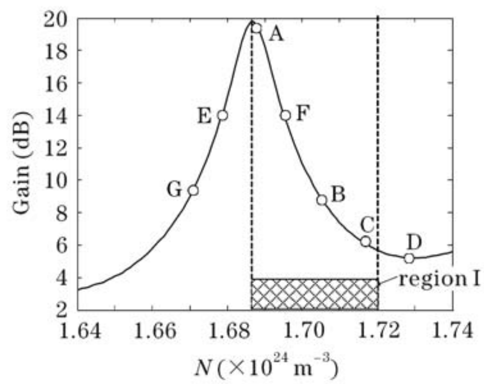

Fig. 2. Gain versus carrier density.

After TTL processing module, 20% power of TTL pulses will be tapped to a photo-detector (PD) to judge TTL value. If no pulse signal is detected, it means that TTL value has been decreased to 0 and the optical packet has expired its living time. In this case, the optical packet will be discarded by an optical switch. On the contrary, TTL value is larger than 0 and the optical packet will be allowed to enter the following processing modules including optical switch matrix, wavelength conversion, fiber delay lines, optical regeneration and so on. Before the optical packet enters into the next processing module, the new TTL value, $M-1$ optical pulses, will be inserted into the TTL domain of the optical packet by a coupler.

For verifying the feasibility of the proposed scheme, a numerical model of FP-SOA is established in Matlab7.0. For the FP-SOA, two facet reflectivity $R_1=R_2=0.016$, the length $L=0.7$ mm, the bias current $I=42.67$ mA, the wavelength $\lambda=1533.01$ nm, other parameters are adopted as the typical values presented in Ref. [6].

Figure 3 shows the optical pulses waveform at the positions "a", "b" and "c" in Fig. 1. Due to the slow carrier recovery time of FP-SOA, the pulse interval is set to 2.5 ns and the pulse width is 170 ps. We denote the pulse power ratio between $M-1$ pulses and the two residual pulses as OER. OER is 6 dB at "b" after AMZI

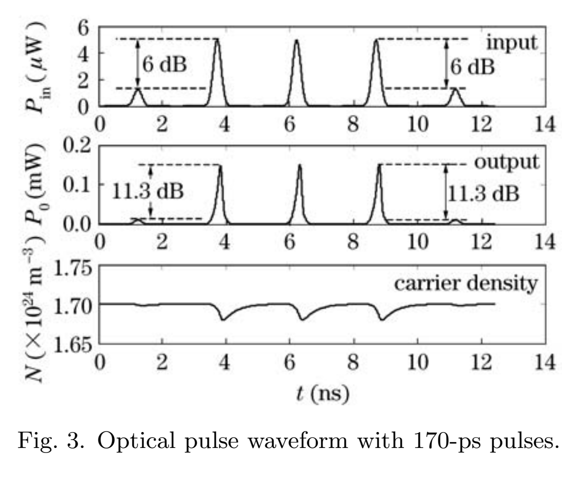

Fig. 3. Optical pulse waveform with 170-ps pulses.

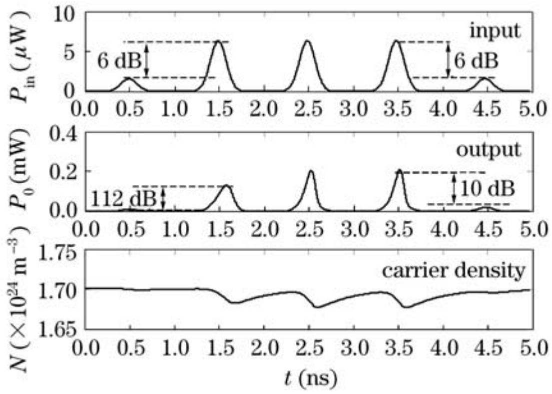

Fig. 4. Optical pulse waveform with 120-ps pulses.

and is enhanced to 11.3 dB at "c" after FP-SOA.

Figure 4 shows the 1-Gb/s optical pulses waveform with 120-ps pulse width at the same positions "a", "b" and "c" in Fig. 1. The main parameters are: $R_1 = R_2 = 0.016$, $L = 0.7$ mm, $I = 42.71$ mA, and $\lambda = 1533.01$ nm. After TTL processing module, OER is still enhanced to more than 10 dB. But due to the carrier recovery time, the first pulse of $M-1$ pulses is not fully amplified and the tailing residual pulse is not depressed completely. This phenomenon is easy to be found in higher pulse rates also. In the future work, our main task is to reduce the carrier recovery time, so the TTL processing can be realized at a much higher rate.

Figures 5 and 6 show the relationship between OER and the peak power of input optical pulses when the pulse width is 170 and 120 ps respectively. It can be seen that the system has about 5 dB dynamic range of the input optical power for above 10 dB pulse power ratio. There exists a peak in the relationship curve of OER and $P_{\rm in}$ that can be explained through the working point shift with the change of $P_{\rm in}$. With low optical input power, the FP-SOA works at "B—D" segment in Fig. 2, and the power ratio OER is below 10 dB. Along with the increase of the peak power of the input pulse the FP-SOA works at "A—B" segment in Fig. 2, OER will be increased to about 10 dB. With high input power, the FP-SOA works at "A—G" segment in Fig. 2, the power ratio OER will be less than 6 dB. For a special condition, supposing the $M-1$ pulses work at position "F" in Fig. 2 and the residual pulses work at position "E", OER will be 6 dB. From the above analysis, we find that the peak power of the input pulse is required to work on "A—B" segment.

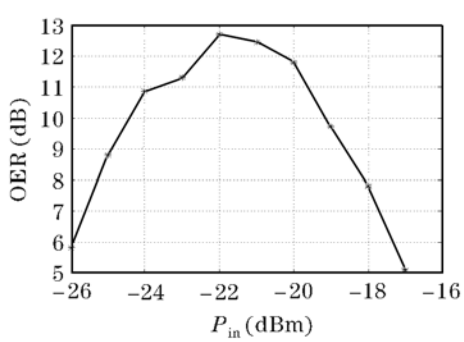

Fig. 5. Ratio between the $M-1$ pulses and the two residual pulses (OER) versus the input power when the pulse width is 170 ps.

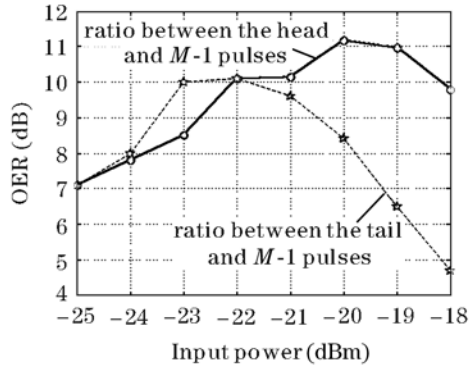

Fig. 6. OER versus the input power when the pulse width is 120 ps.

Figure 6 also shows that there is a small difference between the first residual pulse and the last pulse. The relationship between carrier density and time in Fig. 4 shows that at the beginning, the carrier density of the first residual pulse maintains a high level. The succeeding $M-1$ pulses begin to lead the carrier density into the high-gain region (segment A—B in Fig. 2). But the pulse interval must be large enough so that the carrier density recovers to the low-gain area (segment C—D in Fig. 2) before the next pulse comes. For suppressing the last residual pulse the carrier density must recover back into the low-gain area when the last residual pulse is coming. But the suppression of the last residual pulse is not identical with that of the first one since the carrier density at the beginning of the two residual pulses is different from each other. So the contrast ratio in the first residual pulse is different from that in the last one.

In this paper, a TTL processing scheme based on AMZI and FP-SOA realizes the TTL decrement for avoiding the optical network congestion. By adjusting the working point of FP-SOA, M pulse train is reduced to $M-1$ pulse train with more than 10 dB pulse power ratio. The enhancement of carrier recovery time is the main subject of improving the pulse rate.

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