Proposal of All-optical Packet Header and Payload Separation Based on SOA-Assisted Mach-Zehnder Interferometer*

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Abstract A flexible scheme for all-optical packet header and payload separating using two SOA-based Mach-Zehnder interferometers (SOA-MZIs), one for header extraction and the other for payload extraction was proposed. In addition, the scheme, by changing configuration, was applicable for processing optical packets of different lengths and bit-rates. Through numerical simulations, an intensity contrast ratio of more than 16dB for both header and payload at 50Gb/s can be achieved.

Keywords SOA; MZI; XPM; Differential modulation
CLCN TN914.11 **Document Code** A

0 Introduction

As the packet data rates increase, all-optical techniques are expected to assist in releasing the network from undesirable latencies related to O/E/O conversions at the switching nodes, especially assuming that transmission line rates will continue to increase beyond 10 Gb/s. 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 recognize and extract the address information embedded in a packet. In the effort towards all-optical routing, several techniques have been proposed so far to enable all-optical header-payload separation[1~6]. In these methods, separation is achieved either with high speed electronics[1] or with optical switching, time multiplexing and self-synchronization schemes that generate the local clock signals powering the optical gates performing the address separation task[2~6]. Although these methods have demonstrated the potential of all-optical processing, their circuit complexity increases with the number of header bits.

Owing to the advantages of low power consumption, low latency, high stability and integration potential, SOA and MZI are frequently utilized for clock component extraction[7], electrooptical modulator[8], BOTDR system[9] and so on. In this paper, a novel serial optical header-payload extraction approach based on SOA-MZI is proposed and investigated. By the aid of this structure, optical headers are separated from payload for electronic detection or optical digital operation. Furthermore, headers of different lengths can be separated from the payload only by changing some parameters of the scheme. Numerical simulation results at 50Gb/s show that the architecture is suitable for all-optical header-payload separation, and the operating speed can be readily extended from 50Gb/s to 80Gb/s.

1 Operation principle

1.1 Configuration

As indicated in Fig. 1, the scheme consists of two SOA-MZIs, of which the asymmetric one serves as a header extraction component while the symmetric one, utilizing the original packet pulses and the extracted header, performs the function of payload extraction. In the scheme two pairs of SOAs, two multiplexers (W_1, W_2) and multiple couplers are employed. All couplers are 3 dB ones except C_1 and C_2.

When an optical packet with short and strong pulses enter the separation structure, it splits via a 99/1 coupler C_1 into two packet streams, of which the stronger one enters the 95/5 coupler C_2 and the weaker one exports from port2 for the purpose of payload extraction. Out of C_2, two streams are obtained which serve as probe signal (weak one) and control signal (stronger one) for SOA_1 and SOA_2. The probe signal, via coupler C_3, is divided into two parts, marked as the CW signal in the upper arm of the asymmetric SOA-MZI and the CCW signal in the lower arm. Meanwhile, the control signal is split via C_4 into signal B_1 and B_2, and introduced with a time delay of $\Delta\tau_1$ between

* Supported by National Natural Science Foundation Project of China (No. 60372100) and Doctoral Science and Research Foundation of Chinese Universities (No. 20030013004)
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Received date: 2005-04-13

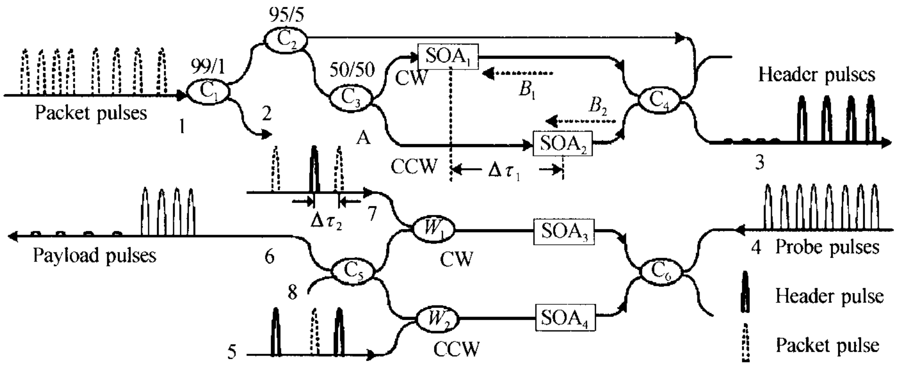

Fig. 1 Scheme of all optical packet header-payload separation

them into the SOAs of the SOA-MZI.

In the scheme, the designed probe signal intensity is so not small as to modify the optical properties of the SOAs, which are just controlled by the control signal B_1 and B_2. When the control signal is injected into SOA, the gain of the SOA will be saturated during one pulsewidth by the first pulse, and then recovers slowly. Assuming that the bit interval is much shorter than the SOA recovery time, the gain will only partially recover and be saturated again for the arrival of the subsequent pulses. In SOA_1, CW signal and B_1 signal are assumed to be synchronized, thus SOA_1 will be saturated abruptly by B_1 signal when CW and B_1 signals encounter in SOA_1. Accordingly, CW signal will experience little gain and phase shift. While in SOA_2, B_2 signal will arrive $\Delta\tau_1$ (length of packet header) later than CCW signal does; header pulses will therefore undergo large gain and phase shift in SOA_2. Thus, the CW and CCW signals, having acquired different gains and experienced different nonlinear phase shifts in SOAs induced by the control signals, will interfere at coupler C_4, then header pulses can be acquired at port3.

Whereafter, the attenuated header (the attenuation ratio is set to 10 : 1) pulses and the signal from port 2, with differential modulation, are imported into the symmetric SOA-MZI-an optical logic XOR gate[10]. As control signals, the two optical pulse serials are combined before coupling into the arm of the MZI via W_1 and W_2. In port 7, packet pulses is $\Delta\tau_2$ ps ahead of header pulses, while in port 5, header pulses is $\Delta\tau_2$ ps ahead of packet pulses. Simultaneously, clock pulses, as probe pulses, are divided and introduced by C_6 into the MZI. In operation, the control signals impact phase-shifts of the probe pulses so as to influence the output of MZI. Ultimately, the payload pulses are obtained through the optical XOR operation between the packet pulses and the extracted header pulses.

1.2 Operation principle

Taking the symmetrical MZI as an example, $P_6(t)$, $P_8(t)$ is the output power at port6 and port8 respectively which can be determined mathematically by an amplitude transmission matrix[11]. Assuming the initial differential phase-shift of the probe light between the two arms of the MZI is 0, $P_6(t)$, $P_8(t)$ can be expressed as

$$P_6(t)=4^{-1}P_4(t)\{G_3(t)+G_4(t)-2\sqrt{G_3(t)G_4(t)}\cos[\Delta\phi_3(t)-\Delta\phi_4(t)]\} \quad (1)$$

$$P_8(t)=4^{-1}P_4(t)\{G_3(t)+G_4(t)-2\sqrt{G_3(t)G_4(t)}\cos[\Delta\phi_3(t)-\Delta\phi_4(t)]\} \quad (2)$$

$$\Delta\phi_i(t)=-\alpha\ln[G_i(t)] \quad (i=3,4) \quad (3)$$

where P_4 is the power of the probe signal from port 4; $G_3(t)$, $\Delta\phi_3(t)$ and $G_4(t)$, $\Delta\phi_4(t)$ are the power dynamic gain and nonlinear phase-shit experienced by the probe pulses in SOA_3 and SOA_4 respectively; and α is the linewidth enhancement factor of the two SOAs.

For simplicity, the loss and amplified spontaneous emission (ASE) noise are neglected[12,13]. Thereafter, the pulse transmission time is defined in SOA as $T_{TRAN}=Ln_{SOA}/c$, where n_{SOA} is the effective refractive index of the SOA. Using a theoretical model is as simple as possible and yet capable of capturing the main features of gain saturation and dynamics of the SOA. This model is well known and it had been used in Reference [14] to study the optical pulse propagation characteristics in SOA.

To model the characteristics of the SOA-MZI, the transparency assumption was taken similar to the approaches in Reference [14] and [15]. Namely, the SOA is quasi-transparent to both the pulse and the gain coefficient. The instant gain coefficients (h_i), the integral SOA gains (G_i) and the pulse phase-shifts (ϕ_i) are expressed as Equ. (4)~(6). To solve the equations, the form of a traveling wave is substituted for the instant SOA gain coefficient according to the transparency assumption, i. e. $g(z,t)=g(t-z/\nu_{SOA})$.

$$h_i(t)=\int_{-\infty}^{\infty} d\tau \int_{-L/2}^{L/2} g_i(z,\tau)\delta(\tau-t-zn_{SOA}/c)dz \quad (4)$$

$$\frac{dh}{dt}=\frac{1}{1+\varepsilon\exp(h)P(0,t)}\{\frac{h_0-h}{\tau_c}-\varepsilon[\exp(h)-1]\cdot \frac{dP(0,t)}{dt}-[\exp(h)-1]P(0,t)(\frac{\varepsilon}{\tau_c}+\frac{1}{E_{sat}})\} \quad (5)$$

$$G_i(t)=\exp[h_i(t)] \quad (6)$$

The above theoretical analysis is also applicable to the asymmetrical SOA-MZI, and the relationship between $G_1(t)$ and $G_2(t)$ can be described as: $G_2(t)=G_1(t-\Delta\tau_1)$.

2 Numerical simulation results

The output contrast ratio (CR) is selected as a criteria to evaluate the performance of the separation scheme, which is formulated as Equ. (7), where for header, $P^{peak}_{extracted}$ denotes peak value of the N logical "1" extracted header pulses and $P^{peak}_{sup\,pressed}$ denotes the peak value of the M logical "1" suppressed payload pulses; while for extracted payload, things become reverse.

$$CR=10\log\frac{N^{-1}\sum_{i=1}^{N}P^{peak}_{extracted}}{M^{-1}\sum_{i=1}^{M}P^{peak}_{sup\,pressed}} \quad (7)$$

In this scheme, several configurations must be specified in order to obtain desirable performance of the header extraction: 1) The first bit of a packet has to be "1" as a marker pulse to indicate the exact beginning of the packet; 2) The pulse should be of short width and strong energy so as to induce fast and deep gain saturation in SOA; 3) To guarantee a full gain recovery of SOA, a guard-time between successive packets is needed.

In the numerical simulations, the optical packets are assumed to be 50 Gb/s pseudo-random bit sequence with the header length of 6 bits. Referring to the probe and control pulses energy configuration in[14,15], the input pulses energy energy of C_1 to 2 pJ and the probe pulses energy of port 4 to 20 fJ were designed. Other parameters in calculations are set as representative values[14,15] for InGaAsP semiconductor materials operating at a wavelength of approximately 1.55 μm, as listed in Table. 1.

Table. 1 Parameters used in the numerical simulations

Description	$SOA_{1\&2}$	$SOA_{3\&4}$
Small signal gain(g_0)	25 dB	25 dB
SOA length L	100 μm	100 μm
Carrier lifetime τ_c	400 ps	300 ps
Nonlinear gain compression factor ε	0.31 W^{-1}	0.2 W^{-1}
Effective refractive index n_{SOA}	3.62	3.62
Linewidth enhancement factor α	3.1	3.1
SOA saturation power E_{SAT}	5.37 pJ	3 pJ
Input pulse-width T_{FWHM}	1 ps	1 ps
Wavelength of incoming data λ	1.55 μm	1.55 μm

To investigate the function of the optical header payload separation scheme, the shape of input pulses and output pulses when $\Delta\tau_1$ = 116 ps, $\Delta\tau_2$ = 2 ps were compared. As is indicated in Fig. 2 CR of both header and payload are more than 16 dB; thus the validity of the optical packet header and payload separation structure can be adequately demonstrated. In addition, different length packet header can be extracted through altering the value of $\Delta\tau_1$, for example, when $\Delta\tau_1$ equals 135 ps, 7-bit-long header can be extracted.

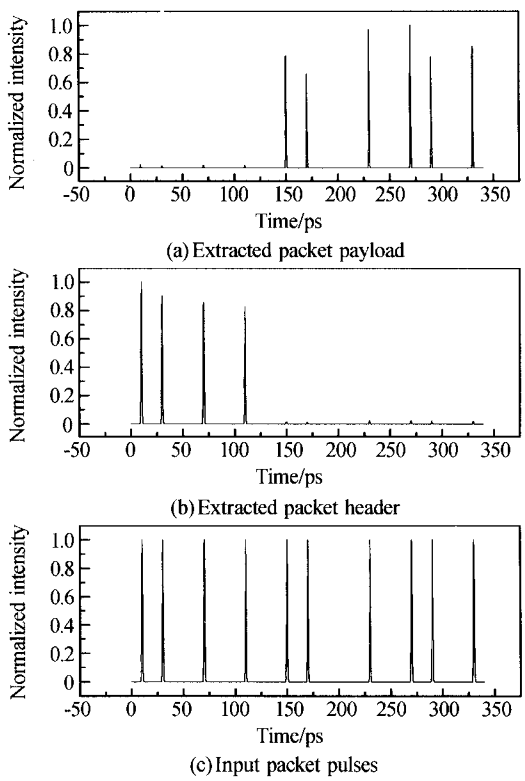

Fig. 2 Simulation of packet header payload separation

3 Parameter analysis

In order to choose optimal configuration for the scheme, the influence on the system performance exerted by the pulse energy and width is firstly investigated. Fig. 3 shows the CR as a function of the input pulse energy, with T_{FWHM} as a parameter. As expected, increasing the input pulse energy can improve the CR of extracted header; while for the payload, under the condition that $T_{FWHM}<3$ ps, which exists an optimal packet pulse energy that make CR of the extracted payload maximized. In addition, decreasing pulse width can improve the CR of the header and payload, and the output CR of extracted payload shows more sensibility for the variance of the pulse width than the header does. However, narrower pulse width will induce carrier heating, spectral hole burning and other intraband processes, which will increase the nonlinear gain compression effect. Consequently, appropriate pulse width should be selected.

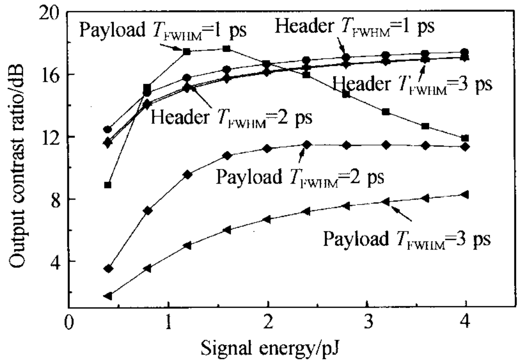

Fig. 3 Output CR vs. input packet pulse energy and width with fixed header attenuation ratio

Furthermore, it is found that when $T_{FWHM} > T_{TRAN}$, the extracted header pulses will become asymmetric apparently since different part of the pulse experiences different gain and phase-shift in SOA due to the long pulse duration. In addition, it is also found that the peak height of the transmission window of the SOA-MZI will turns lower when $T_{FWHM} > T_{TRAN}$.

Moreover, the dependence of the output CR on E_{SAT} and ε is plotted in Fig. 4. It reveals that low gain saturation energy is beneficial to yield a good output CR of header, while things become reverse for payload. In addition, increasing ε can improve the CR of both header and payload.

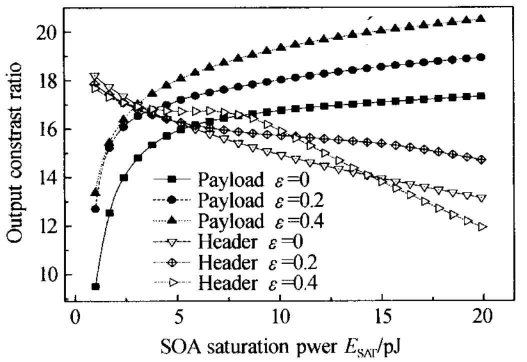

Fig. 4 Output CR vs. SOA saturation power E_{SAT} with different nonlinear compression factor

4 Conclusion

A novel all-optical packet header-payload separation scheme with SOA-MZI is proposed and analyzed. This scheme is simple, fast and integrable, with no special treatment of the packet pulses. Through numerical analysis and properly design of the parameters, an intensity contrast ratio of more than 16 dB of both header and payload extracted can be achieved at 50 Gb/s. In addition, parameter analysis is conducted and advice is given to optimize the system design.

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一种基于半导体光放大器马赫-曾德尔干涉仪的新型全光信头和净荷分离方案

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收稿日期：2005-01-20

摘 要 提出一种新型的光分组信头净荷分离方案. 利用一个非对称半导体光放大器马赫一曾德尔干涉仪提取出信头脉冲，然后再利用对称的 SOA-MZIs 构建异或门，完成信头脉冲和光分组脉冲在差分调制下的逻辑运算，提取出净荷脉冲. 在 50 Gb/s 速率下，数值仿真表明提取出的信头和净荷信号的开关比均超过 16 dB. 此外通过更改参数设置. 该方案还可以应用到不同速率，不同信头长度的信头净荷分离中.
关键词 半导体光放大器(SOA)；马赫-曾德尔干涉仪(MZI)；交叉相位调制(XPM)；差分调制

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