A novel variable-length header extraction scheme based on ring laser for all-optical packet switching network

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Abstract
In this paper, a novel header extraction scheme based on a semiconductor ring laser is proposed and simulated for the proof of principle. This scheme is to be used in all-optical packet switching networks which can extract return-to-zero (RZ) modulation data packets with variable header/payload length and intensive spacing. Simulations and numerical analysis for a 3-byte header and 128-byte payload show that this structure can extract headers with more than a 20 dB contrast ratio. Additionally, the structure’s simplicity and its small size makes it a proper candidate for integration with other all-optical circuits.

Keywords Header extraction · Rate equations · Contrast ratio · All-optical devices

1 Introduction
Today’s optical technologies are developed in many aspects and branches (Zuo et al. 2013, 2015, 2017; Zhang et al. 2020; Hu et al. 2020 Jul; Li et al. 2019). The rapid growth of the internet, increasing data traffic and all-optical processing and storages in the modern societies force the communication networks to increase the bandwidth and capacity (Gervand et al. 2019; Danaee et al. 2019; Nurmohammadi et al. 2014). Hence, it is preferred to use optical communication networks that work based on optical packet switching (OPS) instead of current optical packet circuit (OPC) networks (Hailu 2018; Meyer et al. 2018). One of the main restrictions of the current networks is electronic-optical-electronic conversion (EOE), which is used for packet identification and processing in the electronic domain. Packets in optical communication networks consist of a header and payload (Lallas 2019a). One of the essential functions in the OPS switch is the separation of the packet header from the optical packet stream (Qin et al. 2017; Miao et al. 2016). Up to now, several different methods have been proposed in order to extract and process the packet header. These methods depend on labeling techniques. In the serial labeling techniques, the label is placed in the payload in the serial form and in parallel labeling techniques the label...
is processed parallel with the payload. There are some challenges in parallel labeling techniques such as label multiplexing on a separate wavelength or on a subcarrier frequency (Miao et al. 2016; Wu et al. 2017; Calabretta et al. 2009; Golmohammadi et al. 2013; Liu et al. 2011). In parallel labeling techniques the speed of extracting the label is high but the packet requires more bandwidth. As a result, in this method the bandwidth is more occupied (Lallas 2019b). Intensity modulated payloads as well as frequency shift keying (FSK) or Binary phase shift keying (BPSK) labels are serial labeling techniques (Hayashi et al. 2015; Changliu et al. 2009; Lu et al. 2021; Kakarla and Venkitesh 2016; Quang and Sóng 2017). These methods are amplitude or phase dependent and require synchronization pulse and need fixed packet data length. Hence, these methods are not suitable for flexible optical networks.

Since ring lasers can be used in the design of various optical gates as well as in data storage (Zimmermann et al. 1999) and processing (Quang and Sóng 2017), they are appropriate candidates to be used in the design of all-optical integrated circuits (Zimmermann et al. 1999; Hill et al. 2004). In this paper, a structure based on ring lasers is proposed which is capable of separating RZ coded headers from the packet with high speed and without delay.

The organization of this paper is as follow. The proposed structure is introduced in Sect. 2. Section 3 is devoted to calculations and analysis of the proposed structure. In Sect. 4, the simulation results will be discussed and finally, Sect. 5 concludes the paper.

2 Header extraction structure

Figure 1 shows a simple scheme of the proposed header extractor. In this structure, a continues wave (CW) laser beam and packet stream signals are applied into port A and B, respectively. Then the separated header signal and its inverse exit from port C and D respectively.

In the first case, assume that the packet signal does not exist, and the laser beam is applied. In this situation, the beam inside the ring propagates clockwise and results the signal at port D and the zero signal at port C.

In the second case, it is supposed that the header with a 15 Gb/s bit-rate is applied to port A. Assuming that the power of input header stream is higher than the laser beam, and

![Fig. 1 Schematic diagram of the optical header extraction method](image-url)
the length of header’s Gaussian pulse is long, these pulses saturate the ring laser and invert the beam propagation direction inside the ring and cause the packets to appear at port C.

Note that if the bit-rate of the packets that are applied into port B increases, the pulse length decreases, hence it cannot change the propagation direction inside the ring, and the packets will not appear at port C.

3 Modeling and numerical analysis

Ring laser is an active device consisting of one ring and two waveguides. Applying current to the active region causes the lasing operation. In the initial state, when the current amplitude is low, the linear characteristic is dominant and both clockwise (CW) and counter-clockwise (CCW) modes can propagate inside the ring. Increasing the applied current causes the domination of the nonlinear characteristics which leads the ring laser to operate in the unidirectional mode, and only one mode can propagate inside the ring (Sorel et al. 2003; Yuan et al. 2008a; Born et al. 2005).

The longitudinal electric fields inside the ring cavity are expressed as:

\[ E(x, t) = E_1(t) \exp \left[ -i(\omega_0 t - kx) \right] + E_2(t) \exp \left[ -i(\omega_0 t - kx) \right] \]  

(1)

\[ E_{\text{ext}}(x, t) = E_{\text{ext}}(t) \exp \left[ -i((\omega_0 t + \Delta \omega_{\text{ext}} t + \Delta \Phi_{\text{ext}}) + kx) \right] \]  

(2)

where \( E_1(t), E_2(t), \) and \( E_{\text{ext}}(t) \) are mean complex electrical fields corresponding to CW, CCW, and external injection amplitude modes, respectively. \( \omega_0 \) and \( \omega_2 \) are optical frequencies of the ring cavity modes in clockwise and counter-clockwise directions respectively, and \( x \) represents the longitudinal spacing. \( \Delta \omega_{\text{ext}} \) is the detuning of angular frequency of external injection and free running mode, and \( \Delta \Phi \) is their phase difference. The time evolution of the fields inside the cavity can be described by the following rate equations (Sorel et al. 2002; Yuan and Yu 2008):

\[
\frac{dE_1}{dt} = \frac{1}{2} (1 - i\alpha) \left( \Gamma \nu g g_s (N - N_{tr}) \times (1 - \varepsilon_s |E_1|^2 - \varepsilon_c |E_2|^2) - \frac{1}{\tau_{p1}} \right) 
\]

\[ E + i(\omega_0 - \omega_{\text{in}})E_1 + K_{\text{ext}}E_{\text{ccw}} \exp \left[ -i(\Delta \omega_{\text{ext}} t + \Delta \Phi_{\text{ext}}) \right] \]  

(3)

\[
\frac{dE_2}{dt} = \frac{1}{2} (1 - i\alpha) \left( \Gamma \nu g g_s (N - N_{tr}) \times (1 - \varepsilon_s |E_1|^2 - \varepsilon_c |E_2|^2) - \frac{1}{\tau_{p1}} \right) 
\]

\[ E_2 + i(\omega_0 - \omega_{\text{in}})E_2 + K_{\text{ext}}E_{\text{ccw}} \exp \left[ -i(\Delta \omega_{\text{ext}} t + \Delta \Phi_{\text{ext}}) \right] \]  

(4)

where the spatial overlap between the optical mode and active layer gain is represented by optical confinement factor \( \Gamma \). \( g_s \) and \( \nu g \) are differential gain and group velocity in the active layer, respectively. \( \alpha \) is the linewidth enhancement factor in the semiconductor medium which is related to phase-amplitude coupling. \( N \) is the carrier density, while \( N_{tr} \) and \( \omega_{\text{in}} \) are the carrier density and the longitudinal resonant frequency at transparency, respectively. \( \tau_2 \) and \( \tau_2 \) are photon lifetimes in the ring cavity of the two modes. \( K_{\text{ext}} = \sqrt{(T_{\text{p}}/f_{\text{b}})} \) is the coupling coefficient in which \( T_{\text{p}} \) is the power coupling rate and \( f_{\text{b}} \) is feedback power rate. \( \varepsilon_s \) and \( \varepsilon_c \) are self-saturation and cross gain saturation coefficients, respectively. In these equations, the carrier density in the active region is defined as (Chrostowski and Shi 2008):
\[
d\frac{dN}{dt} = \frac{j}{eV} - \frac{N}{\tau_e} - \left( v_g g_n (N - N_{tr}) \times (1 - \varepsilon_s |E_1|^2 - \varepsilon_c |E_2|^2) \right) \cdot |E_1|^2 \\
- \left( v_g g_n (N - N_{tr}) \times (1 - \varepsilon_s |E_2|^2 - \varepsilon_c |E_1|^2) \right) \cdot |E_2|^2
\]

(5)

where \( V \) is the volume of the quantum well active region, \( j \) is the injection current density, \( e \) is the electron charge, and finally, \( \tau_e \) is the carrier lifetime.

### 4 Results and discussions

One of the most important parameters to define the header extractor performance is the contrast ratio (CR), which is defined by Eq. 6 in which \( N \) and \( M \) are the number of payload and header pulses, respectively. Also, \( P_H \) and \( P_P \) represent header and payload power, respectively (Liu et al. 2011).

\[
CR = 10 \log \frac{\sum_{j=1}^{N} P_H}{\sum_{j=1}^{M} P_L} (dB)
\]

(6)

For simulating the proposed structure, a Gaussian pulse is applied to the ring laser. In order to create the packet sequence, a 2-bit header random data was combined with a 20-bit payload stream. Also, based on experimental parameters in Sorel et al. (2003); Yuan et al. 2008a; Born et al. 2005; Sorel et al. 2002; Yuan and Yu 2008), the active region of the ring laser is InGaAs and its radius is assumed 6 µm. The simulation parameters are listed in Table 1.

Figure 2 shows the output power of the proposed scheme where the packet stream contains a 2-byte header and a 128-byte payload random data stream input. As can be seen, the header stream has been amplified while the payload bits have been attenuated.

#### Table 1 Ring laser simulation parameters

| Symbol | Description                  | Value          |
|--------|------------------------------|----------------|
| R      | Ring radius                  | 6 µm           |
| \( \Gamma \) | Confinement factor        | 0.226          |
| \( \alpha \) | Linewidth enhancement factor | 4              |
| \( g_n \) | Group velocity               | 0.857e\(^{-8}\) m s\(^{-1}\) |
| \( \tau_{pl} \) | Photon lifetime for mode 1  | 4.85e\(^{-12}\) s |
| \( \tau_{p2} \) | Photon lifetime for mode 2  | 4.85e\(^{-12}\) s |
| \( \tau_p \) | Photon lifetime              | 4.85e\(^{-12}\) s |
| \( \tau_e \) | Electron lifetime            | 3.14e\(^{-9}\) m\(^2\) s |
| \( T \) | Coupler transmission         | 0.3            |
| \( f_b \) | Power coupling back ratio    | 0.5            |
| \( \varepsilon_s \) | Self-nonlinear coefficient  | 3.16e\(^{-23}\) m\(^3\) |
| \( \varepsilon_c \) | Cross-nonlinear coefficient | 6.32e\(^{-23}\) m\(^3\) |
| \( I \) | Bias current                 | 3 mA           |
| \( \lambda \) | Lasing wavelength           | 1.55 \( \mu \) m |
| \( N_{th} \) | Carrier density at transparency | 0.788e\(^{-23}\) m\(^{-3}\) |
| \( P_{cw} \) | Input laser (CW) power      | 1 mW           |
Additionally, the CR of the output header is greater than 18 dB. Also, Fig. 3 represents the output of header extractor with a 3-byte header and a 128-byte random data stream input. It is clear that the size of data packet and space between header and payload do not affect the output results of the proposed scheme.

Figure 4 demonstrates the output power of the port C with respect to the input data packet frequency. It can be seen that by increasing the bit rate, the output power decreases rapidly.
As mentioned before, if a packet with a header bit rate of less than 20 Gb/s and payload of more than 70 Gb/s is applied to the proposed structure, a high-contrast header signal will appear at the output port.

Figure 5 demonstrates the variation of CR versus the input power. As can be seen by increasing the input power the CR decrease very fast.

Figure 6 shows the CR versus header extractor versus packet input frequency detuning. As can be seen by changing the input frequency detuning the CR doesn’t change meaningfully. Hence, the proposed structure can extract headers with deferent frequencies.
5 Conclusion

In this paper, a novel structure based on a ring laser was proposed to separate the header data stream. The proposed structure does not require synchronization and does not depend on the length of the header. Simulation results showed that the output header CR can be larger than 20 dB when the input signal power is as low as 0.2 mW. On the other hand, CR increases as the current increases, while the required input power decreases. Also, by varying the input frequency detuning, the CR doesn’t change meaningfully. The structure is simple and optically integrable and can be used for OPS networks.

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Availability of data and material All the results are clearly mentioned in the article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This material is the authors’ own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. The paper reflects the authors’ own research and analysis in a truthful and complete manner. This research does NOT involve human participants or Animal.

Consent to participate All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Consent to publish All authors have been personally and actively involved in substantial work leading to the paper, and consent to publish of submitted paper.
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