A Research on Key Technologies in All-Optical Label Switching Networks

Yuchen Yan
Zhejiang University of Science and Technology,
No. 318, Hangzhou, Zhejiang, 310023
eihuiyik@163.com

Abstract. With the rapid development of Internet technology, the capacity of communication system is increasing rapidly and traditional switching technology based on optical-electrical-optical (O/E/O) conversion cannot satisfy requirements for information exchange. Construction of a high-speed, large-capacity, high-bandwidth all-optical switching network will be the future direction of communication systems. In this paper, the key technologies in all-optical label switching networks are investigated. First, five kinds of optical label technologies are studied. The principles and implementation methods of them are analyzed and compared. Then, optical switching fabrics based on different kinds of optical switches are discussed. Next, a 160Gb/s Optical Time Division Multiplexing (OTDM) signal 1 × 8 packet switching experiment is introduced. Finally, the research work is summarized, and the design of core nodes in optical packet switching network is prospected.

1. Introduction
With the emergence of hundreds of millions of users' requirements, the transmission capacity of optical backbone network is increasing rapidly. At the same time, the optical switching node should have the capacity of fast information exchange to meet the requirements of large capacity and fast speed optical switching. In past years, optical-electrical-optical (O/E/O) conversion is adopted at the switching node. However, the electrical bottleneck of the electrical components limits the switching capacity and speed. In order to realize high-speed information exchange, all-optical switching technology is proposed.

All-optical switching technology means the optical signal can be exchanged in optical domain without O/E/O conversion at the switching node, which can overcome the electronic bottleneck problem. The optical switching technologies can be divided into three categories: optical circuit switching (OCS), optical packet switching (OPS) and optical burst switching (OBS). The characteristics of the three optical switching technologies are compared in Table 1. It can be seen that OCS has large exchange granularity and low bandwidth utilization; OPS has the smallest exchange granularity and the highest bandwidth utilization; OBS does not require optical buffering, and it has relatively low exchange granularity and complexity. Optical label switching (OLS) is not a specific optical switching technology. It is not parallel with OCS, OPS and OBS. OLS is a technology for simplifying the processing of header processing units in OPS or OBS. It can be applied to various granular optical networks. Therefore, there is a combination of OLS and OPS or OBS technologies, named labeled OPS (LOPS) and labeled OBS (LOBS).
Table I. The characteristics of OCS, OBS, OPS and OLS

| Switching method    | OCS  | OPS  | OBS  | OLS  |
|---------------------|------|------|------|------|
| Switching granularity | Coarse | Fine | Fine | Fine |
| Bandwidth utilization | Low  | High | Medium | High |
| Delay               | High | Low  | Low  | Low  |
| Optical cache       | No   | Need | No   | Need |
| Overhead            | Small| Large | Small | Medium |
| Complexity          | Low  | High | Medium | Medium |
| applicability       | Week | Strong | Strong | Strong |

Compared with OPS, OLS is simpler. The generation and identification of optical labels are easier to implement, and the ways of carrying labels is more flexible and diverse. The advantages of OPS technology are inherited by OLS, such as large capacity, transparency to data format, high bandwidth utilization efficiency. Moreover, OLS could eliminate the complicated routing process, improve the data exchange rate greatly. Based on the above characteristics, OLS technology has become one of the most cutting-edge research topics in the field of optical communication [1]. In this paper, the key technologies in all-optical label switching networks are investigated, including optical label technologies, optical switching fabric and an all-optical optical packet switching experiment with in-band label.

2. Optical label switching technology

The structure of OLS switching node is shown in Fig.1. First, various methods are used to add routing control information to the optical packet to form a label. When the optical packets of different channels arrived at the switching node, the header processing unit first reads the label and synchronizes each packet. At this moment, the optical packet payload information is sent to the optical buffer unit for delay to wait for the core node to process the label. Then the label rewriting unit filters out the old label and inserts a new label for the optical packet. The switching control unit drives the optical switching array according to the label information, and forwards the new optical packet to the corresponding output port. The OLS lays the foundation for the realization of all-optical switching [2].

![Figure 1. The schematic diagram of OLS switching node structure](image)

2.1. Optical label technology

2.1.1. Time Division Multiplexing (TDM) label. TDM labeling is the earliest optical labeling technology. As shown in Fig.2, the label and payload information are multiplexed in time domain. The label comes first, and the payload information follows it immediately. And the payload information is
separated by setting a certain protection time [3]. Due to the ease of label generation, extraction and identification, the technology of TDM optical labels is highly feasible in theory. However, in practical applications, this technology is only applicable to time-division synchronization networks. The packet synchronization requirements are too high, the node structure is complex, and the implementation cost is too high.

![Figure 2. TDM optical packet structure diagram](image)

2.1.2. Orthogonal modulation label. The basic principle of the orthogonal modulation optical label technology is to use two relatively independent modulation formats to carry the payload information and routing information on the same wavelength [4]. The payload and label arrive at the receiving end simultaneously, then they are independently detected. In ASK/FSK packet (shown in Fig.3), ASK is adopted to carry optical payload with a high rate (such as 10Gb/s), while FSK is adopted to carry label with a low rate (such as 155M/s). Because the amplitude and frequency dimensions are orthogonal, the payload and label can be simultaneously transmitted with very low interference.

The orthogonal modulation has several advantages. It can simplify the extraction of optical domain labels. The utilization efficiency of wavelength is very high, and the scalability is strong. However, there will be a certain degree interference between different modulation formats after transmission over optical fiber, which would distort signal performance.

![Figure 3. (a)ASK / FSK optical label signal structure diagram (b) system block diagram](image)

2.1.3. Wavelength label. Wavelength label is an optical labeling technology which uses specific wavelengths to carry the label. Wavelength labels can be divided into serial labels and parallel labels. The most common parallel method is multi-wavelength labels. As shown in Fig.4(a), multi-wavelength labels still follow the principle of label first and payload second in the time domain [5]. Optical label is composed of several light pulses with different frequencies. The label and payload occupy the same wavelength channel, and no extra wavelength channel is occupied. Fig.4(b) shows the principle of label separation and extraction by utilizing optical filters.

A specific implementation method of multi-wavelength labels is in-band label technology, that is, multi-wavelength parallel label signals are used as header signals [6]. In the time domain, label signals of various wavelengths are completely synchronized with data packets. Due to the spectrum of the high-speed RZ signal is relatively wide, the wavelength of the label signal can be arranged within the frequency band of the high-speed signal. The in-band label technology has many advantages. It doesn’t require additional wavelengths; The scalability is good and it can support large-scale packet switching nodes; The length of the packets is variable and the delay is small.
2.1.4. Subcarrier Multiplexing (SCM) label. SCM label is a widely used way of carrying labels. Fig.5(a) shows the principle of SCM label. The data signal is modulated with baseband. The low-speed label signal is modulated onto a subcarrier frequency, and then the label signal and payload signal at different frequencies are modulated on the same wavelength. In order to avoid crosstalk caused by the overlapping of the label and payload, the frequency interval between them should be large enough. The schematic diagram of label separation and extraction is shown in Fig.5(b). The SCM label can be separated using an optical filter.

The advantage of SCM is that it is easier to generate, extract and identify the label. It doesn’t need protection time between the label information and the payload data. The label and the payload are modulated on the same optical carrier, which saves spectrum resources [7]. The disadvantage is that the intermodulation introduced by SCM would cause great interference between label and payload. Moreover, multiple erasing and insertion of label signals would deteriorate the quality of the payload signal in a multi-node networks.

2.1.5. Optical code (OC) label. In OC label, different OCs are utilized to carry label information. Optical label is generated by an encoder, and then combined with optical payload. At the switching node, optical correlator is adopted to identify optical label, which is shown in Fig.6. When the label is transmitted to the core node, the 1×N splitter first divides it into N equal power signals. If the label is the same as the preset optical code, the output will be a high correlation peak. Otherwise, a low correlation peak is output. After passing through the arbiter, the low correlation peak is filtered out, and the high correlation peak signal is converted into a control signal, which is used to control the optical switch array.
In the spectral amplitude code (SAC) label switching system, the payload signal and the label signal occupy different wavelengths respectively. The labels are encoded in the wavelength domain, and different amplitudes are used to represent the "0" code and the "1" code. The schematic diagrams of the optical packet of the label switching system in frequency domain and time domain are shown in Fig.7. The OC label switching system has the advantages of large number of available labels, large network capacity, high network security and stability, etc., and can realize all-optical identification and exchange of optical labels theoretically [8]. The disadvantage is that due to the lack of high-speed optical control logic devices and optical control optical switches, the existing OC label processing and forwarding also need to be performed in the electrical domain [9].

![Schematic diagram of OC label structure](image)

**Figure 6. Schematic diagram of OC label structure**

![Frequency and time domain diagrams of SAC optical packets](image)

**Figure 7. Frequency and time domain diagrams of SAC optical packets**

2.2. Design of optical switching fabric

The optical switching fabric is the core part of the entire optical network, which directly determines whether the optical switching can be performed normally. Several common optical switches are discussed in this part.

2.2.1. MEMS. Micro-Electron-Mechanical-Systems (MEMS) optical switch is a micro-mechanical structure composed of semiconductor materials. It integrates electricity, light and micro-electronic machinery into a chip, which can transparently transmit services with different rates and protocols. The MEMS device is composed of movable micro-mirrors, driving actuators, and input/output optical fibers. The basic principle of the system is shown in Fig.8, the movable micro-mirror surface is rotated by the action of static electricity, thereby changing the propagation direction of input light [10]. Switch response time is in the order of milliseconds. MEMS integrates the advantages of mechanical optical switches such as low loss, low cross-talk, low polarization sensitivity, high extinction ratio and wave-guide switch switching speed, small size, and easy large-scale integration. However, the switching speed is slow and only suitable for OCS networks.

2.2.2. SOA. Semiconductor optical amplifier (SOA) is currently a relatively mature optical switch array control element. When there is a bias voltage, the SOA amplifies the input signal to be the switch-on state, and when the bias voltage decreases, the switch is off. SOA is generally combined with other technologies or materials to form an optical switch matrix. There are two main ways to implement an SOA-based optical switch matrix. One is broadcast-and-select structure [11], as shown in Fig.9. At the input end, the input light is divided into N channels by fiber waveguides. In each channel, if the light passes through the SOA that does not inject current, it is absorbed and the optical path is cut off. If the light passes through the SOA injecting current, the optical path is opened. The
other one is to cascade SOAs to achieve a larger-scale optical matrix. SOA-based optical switches can inherently be used to amplify attenuated optical signals to compensate for optical losses. Simultaneously, it has the advantages of low cross-talk, low operating current, wide bandwidth and high-speed switching capability.

![Figure 8. Two-dimensional MEMS structure diagram](image)

**Figure 8. Two-dimensional MEMS structure diagram**

![Figure 9. Broadcast-and-select optical switch fabric based on SOA](image)

**Figure 9. Broadcast-and-select optical switch fabric based on SOA**

### 2.2.3. Crosspoint
Crosspoint is a type of directional coupling switch in electro-optical switches. As shown in Fig.10, the optical Crosspoint matrix switch includes 16 interconnected sub-switches, each of which includes two passive waveguides that intersect each other perpendicularly. At the output port, two sections of active vertical coupler waveguides Active Vertical Coupler (AVC) are placed on the intersection of the input and output passive waveguides. AVC uses the structure of SOA and has the function of optical amplification [12]. The size of Crosspoint is very small. The working mode is to make the device have the function of optical switch through the change of refractive index and gain or absorption effect inside AVC. Crosspoint optical switching devices have excellent switching performance. As can be seen from the experimental and simulation results [13], Crosspoint has extremely wide wavelength response characteristics, which is very suitable for use in high-speed networks, such as OPS networks.

![Figure 10. Schematic diagram of the working principle of Crosspoint](image)

**Figure 10. Schematic diagram of the working principle of Crosspoint**

### 2.2.4. Mach-Zehnder Interferometer (MZI) optical switch
With the rapid development of dense wavelength division multiplexing (DWDM) technology, electro-optical devices, which are designed with micro-ring resonators, have received widespread attentions from researchers at home and abroad [14]. MZI is the basic unit of the optical exchange array, as shown in Fig.11. The working principle is to generate phase difference caused by the change of the refractive index of the two interference arm waveguides. Controlling the phase difference can realize interference cancellation or phase expansion at the beam combining position, which can realize the switching function. The switching time of
thermos-optic switches is generally in the order of ms, and the switching time of electro-optical switches is in the order of ns.

However, the output spectrum of the conventional MZI filter is a "cosine" comb spectrum, and the peak performance and top flatness of the filter output spectrum cannot meet the actual filtering requirements. Some researchers have used a 2×2 coupler to connect the micro-ring resonator to the MZI, and designed an improved micro-ring-assisted MZI filter. The output spectrum of the filter has been greatly improved on the waveform [15].

![Figure 11. Schematic diagram of MZI switch structure](image)

3. 160Gb/s OTDM signal 1×8 packet switching experiment

In this section, 160Gb/s OTDM signal 1×8 packet switching experiment is discussed, in which a narrow-band fiber Bragg grating (FBG) is adopted as a filter to extract label and optical LiNbO3 is adopted to construct optical switch matrix [16].

The experimental setup of 160Gb/s OTDM signal 1×8 packet switching node is shown in Fig.12. First, a 40GHz passive fiber-mode laser generates a narrow pulse sequence with a center wavelength of 1546nm and a pulse width of 1.2ps. The optical narrow pulse sequence is then modulated by 40Gb/s LiNbO3 and then multiplexed to 160Gb/s by OTDM.

The repetition period of the multiplexed payload data packet is 12.8ns, which includes a random packet data signal of 8.8ns and a guard time of 4ns. The label generates a square wave signal with a period of 12.8ns and a pulse width of 8.8ns through another pattern generator, and the intensity of the CW light obtained by coupling three tunable lasers is modulated. The wavelength of the labels fixed at 1544.36nm, 1545.16nm, 1547.72nm. The data and label are coupled by the coupler. The coupled spectrum is shown in Fig. 13(a) and the waveform is shown in Fig.14(a). The 1×8 packet switching node is composed of three parts: label extraction, label processing and optical switch matrix. The payload data and the label are separated by the label extraction unit, and then the payload data is sent to the optical switch matrix. The spectrum of the data signal after label separation is shown in Fig.13(b). The 3 label signals are reflected by the FBG of the corresponding wavelength and detected by photodetectors (PD), Fig. 14(b), (c) and (d) are the electrical signals output by the three PDs respectively. Fig.14(e) is the output waveform of the decoding circuit 1 port. Fig.14(f) shows the role of the control signal Next, the waveform of the 160Gb/s data packet output by the optical switch. It can be seen that the 160Gb/s signal is output from port 1 only when the label signal is "001". Due to the limitation of device, not all 8 switches are added in the experiment and only one switch is utilized to test performance. The switching penalty of a 1×8 packet switching node is 0.8dB.
Figure 12. Experimental setup of 160Gb/s OTDM signal 1×8 packet switching node

(a) before the label extraction (b) after the label extraction

Figure 13. The spectrum of optical signal

Figure 14. Switching node dynamic switching waveform

4. Summary

In this paper, the key technologies of all-optical label switching are investigated. First several existing optical switching technologies are analyzed and compared, including OCS, OBS, OPS, OLS. Next, the detailed optical label technologies are discussed, including TDM technology, orthogonal modulation technology, wavelength label technology, SCM label, OC label. For the optical switch matrix at the core node of the optical switch, several common optical switches based on MEMS, SOA, Crosspoint, and MZI are also investigated. In terms of 1×N switching nodes, a 1×8 160Gb/s OTDM signal packet switching experiment is discussed, in which FBG is adopted for label extraction and LiNbO3 optical switch is used for payload routing.

The future all-optical switching network must have the characteristics of high speed, large capacity, data modulation format and rate transparency, scalability, low latency, and low power consumption. For optical label technology, multi-wavelength labels may be a development direction in the future in the case of abundant wavelength resources. The production of multi-wavelength labels and signals is very simple, easy to separate, and has good scalability. It may be realized on a large scale. For the design of the core node of the optical packet switching network, there are still many problems. In this paper, only a basic optical switching node is discussed. However, there are still many issues to consider for the construction of a huge and complex all-optical switching network in the future, especially the design of the logic of optical packet forwarding and the scalability of the optical switching node. The logic design of the gate is far from enough. Although the optical logic can be implemented in the laboratory, it is not
simple enough to meet the conditions for large-scale implementation. In short, there is still a long way to build a mature all-optical switching network.

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