An investigation on data switching technology in mode division multiplexing networks

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Abstract. With the rapid growth of people's demand for communication speed and capacity, optical communication technology has developed vigorously with its advantages of high transmission rate, large capacity and low power consumption. In order to increase transmission capacity and bandwidth, multiple multiplexing technologies such as wavelength division multiplexing (WDM), time division multiplexing (TDM), polarization division multiplexing (PDM) have been widely studied. However, there is a capacity crisis in standard single-mode optical fibers. Mode division Multiplexing (MDM) technology is considered to be an effective way to solve the capacity crisis because it can keep the bandwidth of a single transceiver constant and effectively increase the total transmission capacity. Data exchange is an important function in optical communication system, which can effectively increase the flexibility of the network. However, the data exchange function in MDM system is rarely reported. In this paper, data exchange technologies in MDM networks are studied in detail, including OAM mode exchange based on optical devices and spatial light modulator (SLM), and TE mode exchange based on asymmetric directional coupler (ADC), micro-ring resonator (MRR) and Y-waveguides. The principles, advantages and disadvantages of each mode switching technology are analyzed and discussed in detail.

1. Introduction
Optical fiber communication system is widely used because of its small attenuation, strong anti-interference ability and large transmission capacity. In the past 30 years, thanks to the breakthroughs in some key technologies, optical fiber communication system has maintained high-speed development, such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM), high-order modulation format and orthogonal frequency division multiplexing (OFDM). More and more orthogonal degrees of freedom have been developed, which greatly improves the spectrum efficiency of optical fiber communication system. Among them, WDM is one of the most popular technologies. The continuous evolution of communication technology has triggered the emergence of a large number of new services, which puts higher requirements for data bandwidth. The existing technology will not be able to meet the requirements of human for faster data, and there is a "capacity crisis" in standard single-mode fiber [1]. Therefore, the further improvement of communication capacity is imminent. Mode division multiplexing (MDM) loads data on different orthogonal modes, which can keep the bandwidth of single transceiver unchanged and effectively improve the total transmission capacity. Therefore, MDM technology is considered to be an effective way to solve the capacity crisis[2].
At present, the mainstream MDM systems are divided into three types: MDM system based on LP mode, MDM system based on OAM mode and MDM system based on TE mode. The first two are traditional optical fiber communication MDM systems, and the third is on-chip MDM system. Although some multiplexing technologies are widely used in long-distance communication, they are too complex and expensive to be suitable for the cost-sensitive on-chip interconnection system. For on-chip optical interconnection system, WDM technology needs stable multiple light sources, which has high energy consumption and complex wavelength management and control. On the other hand, the polarization or mode of the on-chip planar waveguide is very stable, which makes it easier to be used as data channels. Moreover, MDM technology only needs a single wavelength light source, which greatly reduces the energy consumption, cost, and management complexity. Therefore, MDM has great potential in on-chip interconnection.

Data exchange or switching is one of the important functions in optical communication systems. At present, the main research focuses on the wavelength dimension [3-7]. In recent years, MDM is widely considered as an effective way to further expand the communication capacity. However, there are few reports on the data exchange function in MDM systems. Mode switching (switching data on different modes) can effectively improve the flexibility of the MDM network, especially the mode exchange function compatible with WDM technology, which will have important applications in the future multi-dimensional multiplexing systems. In this paper, the data exchange technology in MDM networks is investigated, including OAM mode switching based on optical fiber devices and spatial light modulator (SLM), and TE mode switching based on asymmetric directional coupler (ADC), micro ring resonator (MRR) and Y-waveguide. The principles, advantages, and disadvantages of each mode switching scheme are analyzed and discussed in detail.

2. Mode exchange schemes

2.1. Vortex mode exchange based on optical fiber device

OAM mode is a unique physical property of vortex beam with phase factor $e^{i	heta}$. The equal phase plane of the light field is a spiral surface, the point vector trajectory is a spiral line, and the intensity distribution presents a ring with Z axis as the symmetry axis. Topological charge $l$ is the only variable that distinguishes OAM eigenmodes and can be taken in any integer interval. The orthogonal OAM modes can be used as a new multiplexing dimension in optical fiber communication systems. It cannot only be used for data transmission, but also for information exchange. The principle of forward and backward all-fiber information exchange in MDM system is shown in Fig.1 [8]. In MDM network, the phase vortex modes carrying different data are multiplexed and transmitted together, and then distributed to different users. At the switching mode, there are a variety of information processing operations to achieve data management and switching. Information exchange is an important information processing function to realize two-way information transmission between two users. As shown in Fig.1, network nodes A and B are respectively in the front and back end of MDM network, which can perform information exchange function based on all-fiber information exchange control unit.
The phase vortex mode \( l = -1, 1 \) of circular polarization state is not the intrinsic mode of optical fiber, but can be superimposed by the intrinsic mode of optical fiber. By changing the weight coefficient in the optical fiber transmission matrix, i.e. using the polarization controller to introduce the phase difference of \( \pi \), the mutual conversion between the left circular polarization state phase vortex mode \( l = -1 \) and the right circular polarization state phase vortex mode \( l = 1 \) can be realized. The phase vortex mode of circularly polarized state \( l = -1, 1 \) is not the intrinsic mode of optical fiber and can be realized by the intrinsic mode of optical fiber \( HE_{21}^{\text{odd}} \) and \( HE_{21}^{\text{even}} \). The composition is as follows:

\[
OAM_{-1}^{R} = HE_{21}^{\text{even}} + HE_{21}^{\text{odd}} \\
OAM_{-1}^{L} = HE_{21}^{\text{even}} - HE_{21}^{\text{odd}}
\]

When the phase difference is \( \pi \), the above two formulas will be reversed, that is, information exchange is realized.

2.2. Mode switching based on SLM

SLM is a kind of device which modulates the spatial distribution of light wave. It has the function of modulating beam in space in real time, which makes it become the key device of real-time optical information processing, optical computing. In MDM system, SLM can be used to realize mode conversion and mode switching. Fig.2 shows the schematic diagram of information switching based on SLM in MDM system [9]. There may be four types of switching in such a spatial switching network, including mode switching, spatial switching and the combination of them. The information switching can be realized by changing the phase distribution of SLM. Fig.3 (a) shows a typical spiral phase plate, which can change the topological charge number of the phase vortex mode to realize the phase vortex mode switching. Fig.3 (b) is a phase plate for spatial position switching. It can be a phase grating with different directions and periods to control the phase vortex mode from one spatial position to another. The superposition of the two phase plates is shown in Fig.3 (c), so that the joint switching of phase vortex mode and spatial position can be realized. Fig.3 (d) shows the phase plate for 4x4 phase vortex mode and spatial optical switching using a single SLM. The phase plate loaded on the SLM is divided into four parts, each of which has different phase distribution to achieve different switching functions, and the four parts do not interfere with each other.
2.3. Mode exchange based on ADC

In recent years, on-chip MDM technology is becoming a research hotspot. Combined with this trend, it is very valuable to explore data exchange in on-chip MDM system. Z. Zhang proposed a mode switching device based on ADC, as shown in Fig.4 [10]. In the mode multiplexing part, the three input signals with TE0 modes are converted into TE0, TE1 and TE2 by three different ADCs and multiplexed into a multi-mode waveguide. At the mode switching part, for different ADCs are adopted to perform mode exchange between TE1 and TE2 modes. TE1 mode is coupled into a thin waveguide at the lower end and converted into TE0 mode. Then it is coupled back into the bus waveguide and converted into TE2 Mode. On the other hand, TE2 mode is coupled to the upper thin waveguide and transformed into TE0 mode. Then it is coupled back into the bus waveguide and converted into TE1. So, TE1 and TE2 modes are exchanged, and the information loaded by the two modes is also exchanged. The mode coupling in the process of mode switching is also realized by asymmetric directional coupler with gradual width change.
2.4. Mode exchange based on MRR

MRR is also a common structure in integrated optical devices, which can be used to realize mode multiplexing and demultiplexing. The typical MRR structure is shown in the Fig. 5. The principle of MRR mode multiplexer/demultiplexer is similar to that of ADC, which is based on the directional coupling of asymmetric waveguide structure.

Figure 5. structure of all pass MRR. Where R and K represent the optical transmission coefficient and coupling coefficient of the coupling region, respectively

Fig. 6 shows the device to realize the mode exchange function, which is composed of two point symmetrical MRR type mode conversion/multiplexing devices [11]. The mode multiplexing signals of the two modes (TE0 and TE1) are input into MRR-1 to realize the coupling and conversion of TE1 mode into TE0. The specific structure and parameters are shown in Fig. 6 (b). The primary TE0 mode signal directly passes through the through port of MRR-1 due to phase mismatch. After passing through an adiabatic conical coupler, it enters the MRR-2 and converted into TE1 mode. The specific structure of MRR-2 is shown in Fig. 6 (c). The primary TE1 mode is dropped from the drop port in MRR-1 and converted into TE0 mode. Then it enters MRR-2. Due to the phase mismatch, the TE0 mode directly passes through MRR-2. At the drop port of MRR-2, the TE0 mode from drop port of MRR-1 and TE1 mode (primary TE0) are coupled together. In this way, the data exchange of mode multiplexing signals is realized. In order to reduce mode crosstalk, the adiabatic cone coupler needs to be designed long enough to realize the adiabatic coupling.
Based on the principle of MRR thermooptic effect, H. Xiao proposed a reconfigurable mode switch, and its structure diagram is shown in Fig. 7 [12]. It consists of n asymmetric MRRs, a multimode waveguide and a fundamental mode feedback waveguide (n is a positive integer). The MRR is the key to realize the mode switching function of the device. The input and output of the device is defined as I-O port. Each mode exchange area (MEA) is an asymmetric MRR with a hot electrode, which is also a key area for two mode switching. A MEA region corresponds to a mode switching region. Each MRR has different resonant wavelength. Therefore, when the MRR of other MEAs is controlled, the fundamental mode can also be exchanged with other modes. Because only one MRR is required in each MEA, the size of the device will be greatly reduced compared with the reported device [13-14]. In addition, due to the free spectrum range of MRR, when each MRR inputs several resonant wavelengths or cascades several MRRs in each mea, the device will be compatible with WDM devices.
2.5. Mode interchange scheme based on Y-branch

Fig. 8 shows the schematic diagram of the mode exchanger proposed by C. Sun [15]. It is composed of two symmetrical y branches and a phase shifter, which forms a MZI structure. A heater is placed on one arm to introduce the phase difference between the two arms. The symmetrical Y-branch backbone waveguide supports two modes, while the branch width only supports the fundamental mode. The working principle of symmetric Y-branch can be described as even supermode $S_0$ and odd supermode $S_1$, as shown in Fig.9 (a). When the fundamental mode is input from the Y-branch main waveguide, it first becomes $S_0$, then it is split into two parts with the same strength, and both are fundamental modes. When $TE_1$ mode is input from the Y-branch main waveguide, it first evolved into $S_1$ and split into two fundamental modes with the opposite strength. Fig.9 (b) shows the mode field propagation diagram of symmetric Y-branch, and the illustration shows the mode field of cross section at key position.

![Figure 8. Schematic diagram of mode exchanger based Y-branch](image)

![Figure 9. (a) mode evolution principle of symmetric Y-branch; (b) mode field propagation diagram of symmetric Y-branch](image)

After passing through the first Y branch, the two separated beams are combined through the second Y branch. The output mode is determined by the phase difference between the two arms introduced by the phase shifter. Fig.10 (a) shows the operation principle of mode switching. By controlling the phase shifter, the mode switch has two states of on and off. In the on state, the phase difference is introduced $TE_0$ and $TE_1$, and the modes can be exchanged with each other. While in the off state, no phase difference is introduced $TE_0$ and $TE_1$. The pattern remains unchanged. Therefore, by controlling the phase difference introduced by the phase shifter, the mode switching can be decided. Fig.10 (b) shows the mode field propagation diagram of the mode exchanger, and the illustration shows the mode
field of input and output. We can clearly see that the two input modes remain unchanged in the off state, while they are exchanged in the on state.

Figure 10. (a) operation principle of mode exchange; (b) mode field propagation diagram of mode exchanger

3. Conclusion

In order to meet the increasing demand of optical communication system for transmission rate and communication capacity, various multiplexing technologies and advanced modulation formats have been widely studied and used in optical networks. The multiplexing dimension is increased from the basic wavelength and time domain to the space and polarization domain. As a new type of multiplexing technology, MDM technology has been widely concerned in recent years because it can be compatible with other dimensions of multiplexing technology. It is generally considered as the key technology for the next generation to meet the demand of communication capacity growth.

In this paper, some representative mode switching technologies are discussed. The vortex mode exchange based on optical fiber device can realize information exchange, and it does not need to convert the signal carrier in the transmission process, which effectively ensures the accuracy of the signal. However, it is difficult to control the phase difference introduced by the polarization controller and the accuracy of the phase difference cannot be guaranteed to be $\pi$. SLM has the advantages of good flexibility, repeatable programming and system reconfiguration without changing the optical path. However, it has large volume, high price and poor compatibility with optical fiber system. ADCs can realize on-chip mode switching. Once the device is designed and manufactured, it can not be rebuilt. In recent years, MRR has attracted great attention and interest, and has become a hot research topic. MRR has the advantages of low cost, compact structure, high integration, low insertion loss and low crosstalk. Because the resonance of MRR does not need cavity surface or grating to provide optical feedback, it is very convenient to integrate with other optoelectronic devices. The free spectral region (FSR) can be effectively increased by connecting the MRRs with different radii in series, thus the number of channels can be effectively increased. Multiple MRRs in series or in parallel can form a nearly square resonance spectrum, which makes the spectral response very flat. For the mode interchange scheme based on Y-Waveguide, it can only support data switching between two modes. So it is necessary to study how to increase the supported mode numbers. It should be pointed out that the reconfigurable characters in the data exchange schemes based on MRR and Y-waveguide are realized by heating MRR or the phase shifter. The heating time and heating method would be affected by the environment and are not easy to control.

Although people have made great progress in the field of on-chip MDM, there are still many challenges. Especially for the mode multiplexer, the number of mode channels operated by the current
The mode multiplexer scheme is less than 11, which is far less than the number of wavelength channels in WDM domain. In principle, the scheme based on asymmetric directional coupler can reuse more mode channels. However, due to the sensitivity of process, the practical fabrication of the device faces great challenges. The mode switching scheme based on MRR and Y-Waveguide can't realize real-time control. Mode multiplexer is the cornerstone of MDM technology. Mode multiplexers supporting more mode channels can realize higher bandwidth density optical interconnection. Therefore, reconfigurable and scalable mode multiplexers are the future direction. In addition, the miniaturization of communication system is a trend in the development of optical communication system.

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