The Research Progress in On-Chip Mode (De)multiplexer

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Abstract. With the increasing integration of communication devices and the demand for communication capacity, the methods to increase bandwidth and transmission capacity have attracted lots of attentions. As a new multiplexing dimension, mode division multiplexing (MDM) can effectively improve transmission capacity, in which different modes are utilized for data transmission. In this paper, we investigate the recent progress in on-chip mode (de)multiplexer, which is the key technology to realize mode (de)multiplexing. Firstly, several traditional on-chip mode (de)multiplexers are introduced, including mode (de)multiplexers based on Multi-Mode Interference (MMI), Adiabatic Coupler, Asymmetric Y-Junction, Asymmetry Directional Coupler (ADC) and Micro-ring Resonator (MMR), respectively. Secondly, hybrid (de)multiplexers combining MDM with Polarization Division Multiplexing (PDM) or Wavelength Division Multiplexing (WDM) are discussed. Finally, this paper looks forward to the development prospects of on-chip mode multiplexing technology.

1. Introduction
With the development of technology, electronic devices are already ubiquitous in people's daily lives. With the realization of the Internet of Things (IoT) and 5G, people's demand for information is becoming much higher. Traditional electronic communication technology can no longer meet the communication demand. At the same time, the shrinking of CMOS feature size highlights the shortcomings of the traditional electrical interconnection at the physical level[1], for example, the parasitic capacitance of the circuit causes the power consumption to increase exponentially; the time delay caused by the parasitic capacitance creates a tremendous obstacle to the increase of the transmission speed (single channel transmission rate < 25Gbit/s)[2]; the increased resistance generated by ultra-dense electronic circuits necessitates the heat dissipation and so on. However, simply using parallel computing and increasing the number of processor chips makes the system's data transfer speed and bandwidth requirements for inter-chip and on-chip interconnects reach a high level, which cannot be achieved through electrical interconnection.

Therefore, the researchers turn to optical communication technology and adopt multiple multiplexing technologies, such as WDM, TDM (Time Division Multiplexing) and PDM, which could improve the spectrum efficiency and transmission capacity. In recent years, MDM technology has been proposed, in which different modes in Few-mode Fiber (FMF) or Multi-mode Fiber (MMF) are utilized for data transmission. MDM technology introduces a new multiplexing dimension, enabling optical communication technologies to enhance data transmission speeds and bandwidths, which are not possible with electrical interconnections. Silicon photonic chips have many advantages, such as the compatibility with integrated electronic CMOS processes, low cost, high thermal conductivity, wide range of waveguide refractive index, and high integration, which make it the center of research in the last 10 years.

In this paper, we investigate on-chip mode multiplexing technology. Firstly, several traditional on-
chip mode (de)multiplexers are introduced. Then, hybrid (de)multiplexers combining MDM with PDM or WDM are discussed as well.

2. Implementation methods of on-chip mode (de)multiplexer

The mode (de)multiplexer is a key device for implementing on-chip mode multiplexing. In this part, we review the methods to realize on-chip mode (de)multiplexer, including MMI[3], Adiabatic Coupler[4], Asymmetric Y-Junction[5-6], ADC[7-10] and MMR [11].

2.1. MMI mode (de)multiplexer

The principle of MMI mode (de)multiplexer is mainly based on the Self-Imaging (SI) principle of light. When a small input light field is transmitted into a multimode waveguide region, all the supported waveguide modes in the multimode waveguide region are excited and interfere with each other. At this point, one or more self-images of the input light field may occur at the periodic spacing along the direction of transmission of the waveguide. Thus, mode (de)multiplexing can be realized by setting the appropriate device length. For example, there is a kind of N × N MMI splitter, whose structure is shown in figure 1, including N single mode waveguide inputs, multimode interference region and N single mode waveguide outputs. [12] It could support more channels without cascading.

![Figure 1. The sketch of MMI couplers [12]](image1)

Takui et al. [13] proposed a two-mode mode (de)multiplexer using the SI principle, as shown in figure 2. This device consists of a Mode Converter-Splitter (MCS) region, a Phase Shift (PS) region, and a 3-dB Coupler region. In the MCS region, two optical signals in different modes are converted and separated. When the length of this region is 3Lπ/4, the first-order mode light is converted into two fundamental modes with equal energy and a π difference in phase, which output on both sides. While the fundamental mode light is input and output from the center position. In the PS region, the fundamental mode light on one side is delayed by π, so that the phases of the outputs from both sides are the same. Finally, after passing through the 3-dB coupling region whose length is 3Lπ/2, the fundamental mode lights on both sides are coupled and output from the upper side, while the fundamental mode light at the center position is still output from the center position, which realizes mode (de)multiplexing of two modes.

The MMI mode (de)multiplexer has the advantages of large bandwidth and good processing error tolerance. However, its structure is too complex and it can only support two modes.

2.2. Adiabatic coupler mode (de)multiplexer

When the two waveguides are closed to each other, it facilitates the coupling of the evanescent field, and energy coupling can be achieved between different modes, which have the same transmission constant. [14] Based on this principle, Xing et al. [15] proposed an Adiabatic Coupler mode (de)multiplexer, the schematic diagram of which is shown in figure 3.

![Figure 2. The MMI mode (de)multiplexer [13]](image2)

![Figure 3. The Adiabatic Coupler mode (de)multiplexer[15]](image3)
When the two waveguides are closed together, there are two mode patterns: odd mode and even mode. The working principle is that the even mode (odd mode) transmitted in the waveguide 1 (2) will gradually transform into a field pattern uniformly distributed in the two waveguides. It has simple structure, but can only support two modes of transmission. In order to increase the amount of modes, Chen et al. [15] proposed an adiabatic coupling super-symmetric optical waveguide structure, and successfully realized three-channel MDM. However, the problem that the adiabatic coupling multiplexer supports fewer modes still exists.

2.3. Asymmetric Y-Junction mode (de)multiplexer
The Y-Junction waveguide is one of the most important unit devices in integrated photonic device. According to its geometric structure, it can be divided into two types: symmetric and asymmetric. Among them, the symmetric Y-Junction waveguide can equally divide the optical power and is always applied in waveguide interferometers, modulators, light switches, digital-to-analog converters and optical power splitters. [16] The asymmetric Y-Junction waveguide is at a relatively preliminary stage due to its relatively difficult design and fabrication. An asymmetric Y-Junction waveguide is a kind of devices that actualizes a light output with specific splitting ratio, which has many applications, such as being used to implement a compact 1×N splitter [17], being utilized in photon RF phase shift arrays to increase the linear dynamic range of the device and reduce its RF power fluctuations [18] and being applied in on-line detection of waveguide input optical power.

The asymmetrical Y-Junction structure can also realize mode (de)multiplexing. When the Mode Conversion Factor (MCF) is less than 0.43, it can be used for a power splitter; while the MCF is greater than 0.43, it can be used as a mode (de)multiplexer. Accordingly, Jeffrey et al. [19] proposed an asymmetric Y-junction mode demultiplexer, as shown in figure 4.

![Figure 4](image)

**Figure 4.** (a) The structure of asymmetric Y-Junction mode (de)multiplexer  
(b) Even mode field  
(c) Odd mode field  
(d) The scanner electron microscopy of asymmetric Y-Junction mode (de)multiplexer [19]

It can be found that Y-Junction is similar to the adiabatic coupling structure, but there are several differences in the multimode region. In the asymmetric Y-Junction structure, it is a single multimode waveguide. While in the adiabatic coupling type, there are two single mode waveguides. At the same time, the mode field pattern excited by the even mode is also different.

As the amount of modes increases, the size of the device often reaches hundreds to thousands of micrometers, which cannot meet the demand for ultra-high integration photonic chips. In order to solve this problem, Chang et al. [20] proposed a new mode multiplexer based on the sub-wavelength structure of asymmetric Y-branch (as shown in figure 5). By utilizing the capacity of the sub-wavelength structure, its flexibility in refractive index and the ability to adjust the phase of the light field in the sub-wavelength size, this scheme adopts reverse design to break through the constraints of the conventional basic mechanism of the Y-Junction waveguide’s adiabatic evolution, as a consequence, realize the effect of low radiation loss. This new sub-wavelength Y-Junction of the oversized branch angle reduces the size of the mode multiplexer by two orders of magnitude, and multiplexes two and three modes in 2.4 × 3 μm2 and 3.6 × 4.8 μm2, respectively. This is also the smallest size currently reported internationally,
which has broad application prospects in ultra-large-scale integrated silicon-based optical interconnects.

![Figure 5](image)

Figure 5. (a) Schematic of the two-mode MUX based on SW structure asymmetric Y-junction. (b) The optimized pattern for the manually-set initial pattern as shown in Figure 5(a). (c)- (e) Simulated magnetic field distributions of Hz for TE0, TE1 and TE2, respectively. [20]

2.4. ADC mode (de)multiplexer

Asymmetry Directional Coupler (ADC) is a kind of structure that is currently utilized, in which mode conversion is realized based on phase matching. When the effective refractive index of fundamental mode in the multimode waveguide and the high-order mode in the single-mode waveguide is equal, the phase matching condition is satisfied, and the mode conversion between the fundamental mode and the high-order mode is realized.

Based on this, Dai et al. proposed a curved waveguide directional coupling PBS [21], which has the characteristics of simple structure and compact size, and can effectively separate the TE0 mode and the TM0 mode within a small coupling length. In recent years, PBS and PR based on such structural principle have been fully researched and reported. Zhou et al. [22] designed and fabricated two types of directional coupled PBS separately based on the bridge waveguide structure and the curved asymmetric slot waveguide structure. The simulation results of the coupler of the bridge waveguide structure show that the device has a better beam splitting effect at a wavelength of 1550 nm, and the coupling length of the device is only 7.2 μm. However, due to process error, the actual performance is poor, but it can still test the obvious splitting effect for different polarization states. The directional coupler based on the silicon-based curved slot waveguide adopts an asymmetric slot waveguide structure, which uses different polarization modes to transmit the difference of the effective refractive index in the waveguide to realize mode phase matching, and can realize an extremely high polarization extinction ratio.

Dai et al. [23] designed a 4-mode mode (de)multiplexer based on the ADC structure, as shown in figure 6(a). The fundamental modes are respectively converted to first-order mode, second-order mode and third-order mode. Their mode field distributions are as shown in figure 6(b) to figure 6(d), respectively.

![Figure 6](image)

Figure 6. (a) ADC mode (de)multiplexer (b) 0th order to 1st order mode conversion (c) 0th order to 2nd order mode conversion (d) 0th order to 3rd order mode conversion [23]
The advantage of the ADC mode coupling structure is that it is simple in structure and easy to integrate. However, it is necessary to precisely control the coupling length of the mode conversion area, otherwise it is easy to generate energy loss and mode crosstalk. In addition, the structure has a high process sensitivity problem and puts high demands on the process manufacturing. Therefore, in order to solve the problem of error sensitivity, Ding et al. [24] proposed a tapered progressive ADC structure, as shown in figure 7. By adopting this configuration, the different modes of the two waveguides can be kept equal over a range of widths, thereby reducing the error sensitivity. Based on this work, Wang et al. [25] further proposed a reverse bi-conic gradient ADC mode (de)multiplexer (as shown in figure 8), which achieves a larger application bandwidth by sacrificing device size.

![Figure 7. The mode multiplexer based on tapered progressive ADC structure [24]](image)

**Figure 7. The mode multiplexer based on tapered progressive ADC structure [24]**

**2.5. MMR mode (de)multiplexer**

Micro-ring resonator (MMR) is commonly utilized in integrated optical devices. It can be used in filters, optical switches, wavelength division multiplexers, etc., and is also widely used at the system level.

In general, there must be a ring waveguide and a coupling mechanism with the ring waveguide in the MRR. When the light in the ring is transmitted in the ring for a round, the phase is exactly an integer multiple of $2\pi$, and the light wave will constructively interfere to achieve polarization. According to the difference in the structure of the MRR, it is divided into an all-pass MRR and an upload-download MRR.

The all-pass MRR is that the MRR has only one segment of the waveguide coupled thereto, and the structure is as shown in figure 9. As to the upload-download MRR structure, it adds a segment of the coupled waveguide for uploading and downloading based on the all-pass MRR, as shown in figure 10.

![Figure 9. The structure of an all-pass MRR [26]](image)

**Figure 9. The structure of an all-pass MRR [26]**

![Figure 10. The structure of an upload-download MRR [26]](image)

**Figure 10. The structure of an upload-download MRR [26]**
The principle of this type of MRR mode (de)multiplexer is similar to that of the ADC mode (de)multiplexer, which is based on directional coupling of asymmetric waveguide structures. However, the MRR-type structure incorporates a micro-ring structure, which adds the polarization mechanism, so that it is not necessary to design an accurate coupling length and improve the process tolerance. At the same time, the flexibility of the device is increased, and the application scenario of the device is greatly expanded. Moreover, MRR can also be used as a WDM upload/download filter to perform the required signal processing on WDM multiplexed signals.

However, there are some problems with the MRR type mode (de)multiplexer. Compared to ADC, the MRR introduces an additional resonant micro-ring, resulting in a weak coupling between the curved waveguide and the straight waveguide, making the mode conversion efficiency low. In order to solve this problem, Ye et al. [26] proposed a waveguide structure using a ridge waveguide instead of the conventional strip waveguide structure, thereby greatly improving the coupling strength without adding additional loss.

### 3. Combination of mode multiplexing and other multiplexing technologies

Nowadays, various types of multiplexing technologies have been developed intensively to improve communication capacity and enhance device performance. In order to further improve the communication capacity, hybrid multiplexing technologies have been gradually developed. This part focuses on hybrid polarization-mode multiplexing and wavelength-mode multiplexing.

#### 3.1. Polarization-mode multiplexer

For hybrid MDM and PDM, Wang et al. [27] proposed a cascading ADC polarization-mode hybrid multiplexer (as shown in figure 11). The device consists of a PBS (for TE mode and TM mode), three ADCs for high-order TE polarization modes and three ADCs for high-order TM polarization modes, thus achieving four (de)multiplexing of TE polarization modes and four (de)multiplexing of TM polarization modes. However, such a device is prone to cause crosstalk of polarization modes. Thus, Wang et al. [31] introduced a waveguide grating polarizer (shown in figure 12) to eliminate this effect.

![Figure 11](image1.png)

**Figure 11.** (a) The 8-channel polarization-mode hybrid multiplexer [27]  
(b) The 8-channel polarization-mode hybrid demultiplexer [31]

![Figure 12](image2.png)

**Figure 12.** The improved 8-channel polarization-mode hybrid multiplexer with grating polarizer [31]
After introducing a grating polarizer, the waveguide grating is not only used as a polarizer with a high extinction ratio, but also as a fiber-chip coupler. Finally, the polarization-mode hybrid multiplexer performance is significantly improved by the addition of a grating polarizer.

3.2. Wavelength-mode multiplexer
The hybrid multiplexing technology of optical communication also has a combination of WDM and MDM. In 2014, Bryce et al. designed and fabricated silicon-on-insulator (SOI) ring resonator hybrid multiplexers. [32] The device has small crosstalk and can achieve mixed multiplexing of wavelengths and modes. However, its insertion loss is large. Since then, such hybrid multiplexers have also been designed. Muluceta et al. proposed a novel two-wavelength and dual-mode multiplexers [33]; by Tan et al. proposed a 32-channel wavelength-mode multiplexer based on a silicon-based waveguide [34].

Wang et al. [35] proposed a 64-channel WDM-mode demultiplexer based on a cascaded ADC structure, as shown in figure 13. The four AWGs in the device are identical in design and have a wavelength channel spacing of 3.2 nm. When four modes (TM0, TM1, TM2, TM3) and 64 channels of optical signals carried by 16 wavelengths are incident, they pass through a 4-channel mode demultiplexer, a single-mode output waveguide, and an AWG wave demultiplexer. At last they output from the output ports.

![Figure 13. The 64-channel wavelength-mode hybrid multiplexer. [36]](Image)

Dai et al. [36] also proposed a new design based on N×N bi-directional AWG, as shown in figure 14. Through this multi-mode and multi-wavelength form, the number of available channels can be significantly increased, which provides a practical development prospect for obtaining ultra-large capacity optical communication and optical interconnection links.

![Figure 14. Wavelength-mode hybrid multiplexing link [36]](Image)

4. Conclusion
As a new kind of multiplexing technology, MDM technology has received extensive attention and considerable development in recent years. Mode (de)multiplexer are the key components to realized mode (de)multiplexing. In this paper, we discuss the various structures of on-chip mode (de)multiplexer. We also investigate the comprehensive application technology of mode multiplexing and other multiplexing technologies. These studies have laid a solid foundation for the widespread application of mode multiplexing technology. With the development of MMF and FMF technology, the problem of high attenuation rate and crosstalk effect is overcome, and on-chip mode (de)multiplexers, which is
equipped with high integration, large channel capacity, and wide communication bandwidth, in the future, will be used in a wider range of applications.

References

[1] Miller, D. A. B. (2009) Device requirements for optical interconnects to silicon chips. Proceedings of IEEE., 97(7):1166-1185.
[2] Vlasov, Y. (2012) A silicon CMOS-integrated nano-photonics for computer and data communications beyond 100 Gbit/s. Communications Magazine, IEEE., 50(2):S67-S72.
[3] Uematsu, T, et al. (2012) Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission. Journal of Lightwave Technology.30(15),2421-2426.
[4] J, Xing., et al. (2013) Two-mode multiplexer and demultiplexer based on adiabatic couplers. Optics Letters., 38(17):3468-3470.
[5] Riesen, N., Love J.D. (2012) Design of mode-sorting asymmetric Y-junctions. Appl Opt., 51(15):2778-2783.
[6] W, Chen., et al. (2013) Mode multi/demultiplexer based on cascaded asymmetric Y-junctions. Opt Ex. Press.,21(21):25113-25119.
[7] L, Luo., et al. (2014) WDM-Compatible mode-division multiplexing on a silicon chip. Nature Communications., 5(2):3069.
[8] H, Qiu., et al. (2013) Silicon mode multi/demultiplexer based on multimode grating-assisted couplers. Optics Express., 21(15):17904-17911.
[9] D, Dai., et al. (2013) Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light. Optics Letters.,38(9):1422-1424.
[10] J, Wang., et al. (2014) On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode and polarization-division multiplexing. Laser & Photonics Reviews., 8(2):L18-L22.
[11] Dorin, B.A., et al. (2014) Two-mode division multiplexing in a silicon-on-insulator ring resonator. Optics Express., 22(4):4547-4558.
[12] Y, Shi. (2008) Design, simulation and fabrication of some photonic integrated devices based on planar waveguide. Zhejiang University.
[13] Uematsu, T., et al. (2012) Design of a compact two-mode multi/demultiplexer consisting of multi-mode interference waveguides and a wavelength insensitive phase shifter for mode-division multiplexing transmission. J Lightwave Technol., 30(15):2421-2426.
[14] X, Chen., et al. (2019) Structure of adiabatic coupled supersymmetric waveguides. Acta Optica Sinica., 39(2):0223001.
[15] J, Xing., et al. (2013) Two-mode multiplexer and demultiplexer based on adiabatic couplers. Opt Lett., 38(17):3468-3470.
[16] X, Tang., et al. (2009) Design and analysis for novel asymmetric Y-branch waveguides. Acta Optica Sinica.,29(8):2077-2081.
[17] H, Lin., et al. (1999) Novel optical single-mode asymmetric Y-branches for variable power splitting. IEEE J. Quant. Electron.,35(7):1092-1096.
[18] J, Han., et al. (2003) Single-chip integrated electro-optic polymer photonic RF phase shifter array. J. Lightwave Technol., 21(12):3257-3261.
[19] Riesen, N., et al. (2012) Design of mode-sorting asymmetric Y-junctions. Appl Opt., 51(15):2778-2783.
[20] W, Chang., et al. (2018) Ultra-compact mode (de) multiplexer based on subwavelength asymmetric Y-junction. Opt Express., 26(7):8162-8170.
[21] D, Dai., et al. (2011) Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler. Optics express., 19(19):18614-18620.
[22] Z, Zhou. (2018) Silicon-based integrated polarization beam splitter with asymmetrical directional coupler. Huazhong University of Science & Technology.
[23] Y, Ding., et a1. (2013) On chip two-mode division multiplexing using tapered directional coupler-based mode multiplexer and demultiplexer. Opt Express., 21(8):10376-10382.
[24] L, Luo., et al. (2014) WDM-compatible mode-division multiplexing on a silicon chip. Nat Commun., 5:3069.
[25] A, Wu., et al. (2015) Broadband and fabrication-tolerant on-chip scalable mode-division multiplexing based on mode-evolution counter-tapered couplers. Optics Letters., 40(9):1956.
[26] M, Ye. (2016) Silicon mode-related devices and their applications in multi-dimensional multiplexing systems. Huazhong University of Science & Technology.
[27] J, Wang., et al. (2014) On-chip silicon 8-channel hybrid (de)multiplexer enabling simultaneous mode and polarization-division-multiplexing. Laser & Photonics Rev., 8(2):L18-L22.
[28] S, Chen., et al. (2015) Compact monolithically-integrated hybrid (de)multiplexer based on silicon-on-insulator nanowires for PDM-WDM systems. Optics Express., 23(10):12840-12849.
[29] J, Wang., et al. (2014) Silicon hybrid demultiplexer with 64 channels for wavelength/mode-division multiplexed on-chip optical interconnects. Opt Lett., (39):6993-6996.
[30] D, Dai., et al. (2015) Monolithically integrated 64-channel silicon hybrid demultiplexer enabling simultaneous wavelength and mode-division-multiplexing. Laser & Photonics Reviews., 9(3):339-344.
[31] J, Wang., et al. (2014) Improved 8-channel silicon mode demultiplexer with grating polarizers. Opt Express., (22):12799-12807.
[32] Dorin, B.A., et al. (2014) Two-mode division multiplexing in a silicon-on-insulator ring resonator. Optics Express., 22(4):4547-58.
[33] Mulugeta, T., et al. (2015) Silicon hybrid (de)multiplexer enabling simultaneous mode and wavelength-division multiplexing. Optics Express., 23(2):943-9.
[34] Y, Tan., et al. (2017) Microring-based 32-channel hybrid multiplexer for mode-/wavelength-division-multiplexing. Asia Communications and Photonics Conference., Su3L.4.
[35] J, Wang., et al. (2014) Silicon hybrid demultiplexer with 64 channels for wavelength/mode-division multiplexed on-chip optical interconnects. Opt Lett., (39):6993-6996.
[36] D, Dai., et al. (2015) Monolithically integrated 64-channel silicon hybrid demultiplexer enabling simultaneous wavelength and mode-division-multiplexing. Laser & Photonics Reviews., 9(3):339-344.