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Special Focus on Photonic Devices and Integration

Silicon-based on-chip hybrid (de)multiplexers

Chenlei LI, Hao WU, Ying TAN, Shipeng WANG & Daoxin DAI*

Centre for Optical and Electromagnetic Research, State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310058, China

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Abstract A review is given on the recent progress of silicon-based on-chip hybrid multiplexers, which are the key elements to enable more than one (de)multiplexing techniques simultaneously, including wavelength-division-multiplexing (WDM), polarization-division-multiplexing (PDM), and mode-division-multiplexing (MDM). This helps enhance the link capacity of optical interconnects multiplexed with many channels. The first part gives a review on the recent developed silicon-based hybrid WDM-PDM (de)multiplexers enabling WDM and PDM simultaneously, which helps achieve $2N$ channels by introducing N wavelengths and dual polarizations. The recent progress of silicon-based hybrid WDM-MDM (de)multiplexers developed is reviewed in the second part. With the hybrid WDM-MDM (de)multiplexers, one can achieve $N \times M$ channels by using N wavelengths and M guided-modes. Finally, the silicon-based hybrid MDM-PDM (de)multiplexers are presented as the key to enhance the link capacity for a single wavelength carrier.

Keywords silicon, photonics, (de)multiplexing, wavelength, mode, polarization, waveguide.

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1 Introduction

Recently, accompanied by the increasing demand for ultra-high link capacity of optical interconnects with different transmission distances, various multiplexing technologies have been demonstrated with great effort to enable many channels for huge-data transmissions [1–10]. Among these multiplexing technologies, wavelength-division-multiplexing (WDM) is one of the most successful technologies, utilizing a series of wavelength-channels carrying different signals to transmit in a single optical fiber/waveguide simultaneously. The WDM or dense WDM (DWDM) technology has been used very widely for fiber-optical communications and on-chip optical interconnects. In this case, each wavelength-channel requires a standalone laser source and a driver. As a result, the system cost and the complexity for the management increases greatly when increasing the wavelength-channel number. Furthermore, the wavelength-band available is usually several tens of nanometers, which is limited by e.g., the gain window of the amplifiers. Therefore, it is not easy to achieve hundreds of wavelength-channels when the channel-spacing is 0.8 nm or larger. A promising approach is introducing other techniques to increase the transmission capacity for a single wavelength carrier [1–10]. For example, it is possible to introduce dual polarization-channels as well as several mode-channels for any given wavelength [10].

Currently, the most popular technologies include space-division-multiplexing (SDM) with multiple cores [5–9], mode-division-multiplexing (MDM) with multiple guided-modes [10], and polarization-division

* Corresponding author (email: dxdai@zju.edu.cn)

multiplexing (PDM) with dual polarizations [11, 12]. These multiplexing technologies can help not only to save the physical space but also reduce the cost of the system. Furthermore, these multiplexing approaches based on the independent degrees of freedom and thus can be used simultaneously to form a hybrid multiplexing technology. In this way, it is possible to enhance the capacity of an optical interconnect even to Peta-bit/s [10]. In order to realizing hybrid (de)multiplexing systems, it is well known that the hybrid (de)multiplexers are always playing very important roles. Previously, people have developed some hybrid (de)multiplexers based on discrete elements, however, which are not compact and robust. Therefore, on-chip hybrid (de)multiplexers with compact footprints and high performances are desired [10]. One should realize that the situation becomes much more complicated when more channels from multiple wavelengths, dual polarizations as well as multiple modes are involved. As a result, it is very important to develop some key photonic integrated devices for wavelength-selective filtering, polarization-handling, and mode-manipulation.

Fortunately, in the past years great progress has been achieved by utilizing the platform of silicon photonics in terms of performance, uniformity, and reproducibility [13–23]. As it is well known, silicon photonics has been very attractive for realizing various passive photonic integrated devices due to its advantages of the compatibility with the fabrication process of CMOS (complementary metal-oxide-semiconductor). For example, various silicon-based multiple-channel wavelength-division-(de)multiplexers have been realized with ultra-compact arrayed-waveguide gratings (AWGs) [24–28] as well as microring resonators (MRRs) [29–39]. As demonstrated in [27], high-performance SOI (silicon-on-insulator)-nanowire AWG (de)multiplexers have been demonstrated with low excess losses of $\sim$1 dB and low channel-crosstalks of <-21 dB for the case with a channel-spacing of 3.2 nm, respectively. When using cascaded MRRs, one can achieve box-like responses with a very low excess loss and crosstalk, as demonstrated in [37–39], and thus it is possible to realize multi-channel wavelength-division-(de)multiplexers by introducing an array with many cascaded MRRs [40]. There have also been many silicon-based on-chip polarization-handling devices in the past years [41–53]. For example, a polarization-beam splitter (PBS) realized with bent directional couplers (DCs) works near-perfectly with a high extinction ratio of $>$30 dB and low excess loss ($<$0.5 dB) in an ultra-wide wavelength-band, as demonstrated recently [53]. On-chip mode (de)multiplexers have also been demonstrated by utilizing multi-mode interferometers [54], asymmetric Y-junctions [55–57], topology structures [58], adiabatic couplers [59, 60], asymmetric directional couplers (ADCs) [61–67], and grating-assistant couplers [68]. Some of them have very excellent performances owing to the smart structural designs as well as advanced fabrication techniques.

These high-performance key photonic integrated devices are very helpful for realizing on-chip hybrid (de)multiplexers. In this paper, we give a review on the recent progress on silicon-based on-chip hybrid multiplexers. First, we present the silicon-based hybrid WDM-PDM (de)multiplexers developed to utilizing multiple wavelength-channels and dual polarizations in Subsection 2.1. Subsection 2.2 gives a summary for hybrid WDM-MDM (de)multiplexers on silicon, which enables the WDM and the MDM simultaneously. Finally, we focus on hybrid PDM-MDM (de)multiplexers in Subsection 2.3.

2 Silicon-based on-chip hybrid (de)multiplexers

As mentioned above, various (de)multiplexing techniques have been developed in the past decades and currently it is becoming more and more critical to develop hybrid (de)multiplexing techniques for enabling increased channel number. In recently years, people have demonstrated some silicon-based on-chip hybrid (de)multiplexers by combining more than one techniques, as shown in Figure 1. In the following parts, we give a review on the recent progress of on-chip hybrid (de)multiplexers for hybrid WDM-PDM, WDM-MDM and PDM-MDM systems.

2.1 On-chip hybrid PDM-WDM (de)multiplexers

As it is well known, it is possible to double the link capacity by introducing the PDM technology, which can be realized conveniently regarding the excellent silicon-based on-chip polarization-handling devices

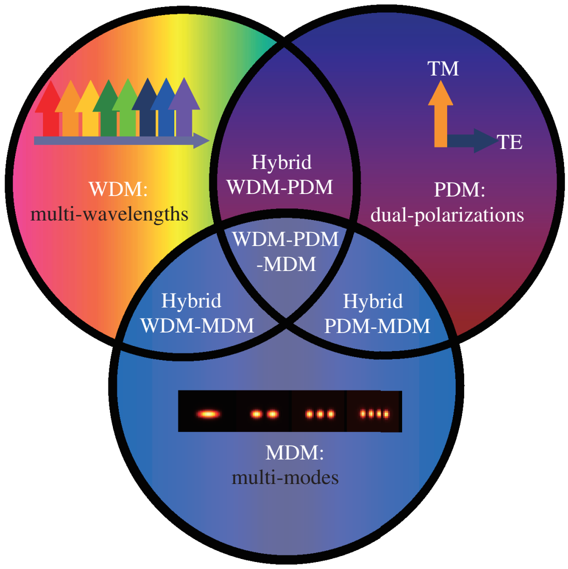

Figure 1 (Color online) Hybrid (de)multiplexing technologies combining more than one techniques.

developed in the past years. When it comes to combine the WDM and the PDM technologies, one of the most important key devices is on-chip hybrid PDM-WDM (de)multiplexers. It has been realized by combining WDM devices and polarization-handling devices on the same chip. AWGs are often used as one of the most popular multi-channel WDM devices. In recent years a silicon-based hybrid PDM-WDM (de)multiplexer was demonstrated by integrating a $(N + 1) \times (N + 1)$ bi-directional AWG with a polarization-diversity circuit, as shown in Figure 2(a) [69]. Here the polarization-diversity circuit consists of a PBS and a polarization rotator (PR). The PBS is realized by utilizing the polarization-selective evanescent coupling in a bent DC [46, 47] , while the PR is realized by utilizing the interference of two hybridized modes in a corner-cut SOI nanowire [43, 44]. Both the PBS and PR work well in a broad wavelength-band to be WDM-compatible. The launched $2N$ channels of optical signals carried by N wavelengths and dual polarizations are separated into two groups by the broadband PBS first and each group has N wavelength-channels $(\lambda_1, \lambda_2, \ldots, \lambda_N)$. With the broadband PR, the transverse magnetic (TM)-polarization group is converted to be transverse electric (TE) polarization. Then these two separated groups of signals are with the same polarization (i.e., TE) and demultiplexed by using the same AWG (de)multiplexer bi-directionally. In [69], an 18-channel hybrid WDM-PDM (de)multiplexer consisting of a 10×10 bi-directional AWG (de)multiplexer and a polarization-diversity circuit was demonstrated with a compact footprint of about 530 μm × 210 μm. Figure 2(b) shows the measured spectral responses for all the 18 channels. The solid and dashed curves are for the channels output from the ports at the left and right sides, respectively. These two groups of channels are aligned very well with nearly zero polarization dependent wavelength (PDλ), which is guaranteed intrinsically by the special design with a bi-directional AWG. For the bi-directional AWG, the channel crosstalk is about −13 dB, and the excess loss is estimated to be about 5∼6 dB. For practical applications, it is desired to reduce the crosstalk and the excess loss of the AWG, which can be achieved with smart structural designs and advanced fabrication processes. One might notice that the AWG performance strongly depends on the channel spacing. When the channel spacing decreases, the AWG size increases and more phase errors are introduced, which introduces higher crosstalk. As demonstrated in [26], the SOI-nanowire AWG (de)multiplexers have channel crosstalks of −17 – −23 dB, −15 – −20 dB, and −9 – −15 dB when the channel spacing is 3.2, 2, and 0.8 nm, respectively. One should realize that it is still very challengeable to achieve high-performance SOI-nanowire AWGs with a narrow channel-spacing.

As a popular alternative, MRRs have also been used frequently for realizing low-loss and low-crosstalk WDM filters. The MRRs is very compact when using SOI nanowires enabling micro-bends [29–37]. As a result, silicon-based MRRs usually have a free spectral range (FSR) as large as 20−30 nm, which

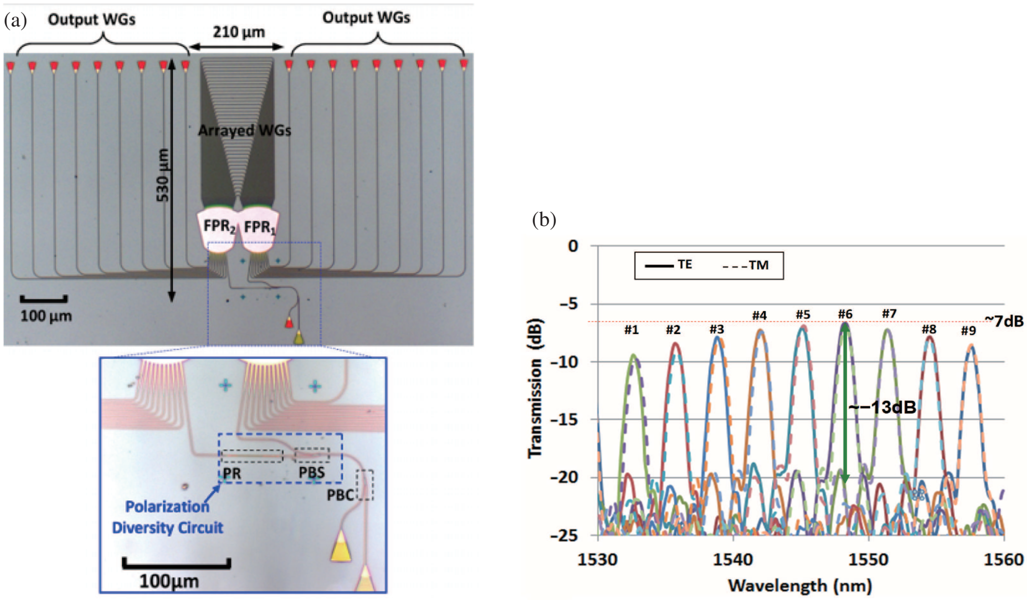

Figure 2 (Color online) The hybrid WDM-PDM (de)multiplexer consisting of a bi-directional AWG and a polarization diversity circuit. (a) Microscopic image of the fabricated device; (b) measured spectral responses [69] @Copyright 2015 OSA.

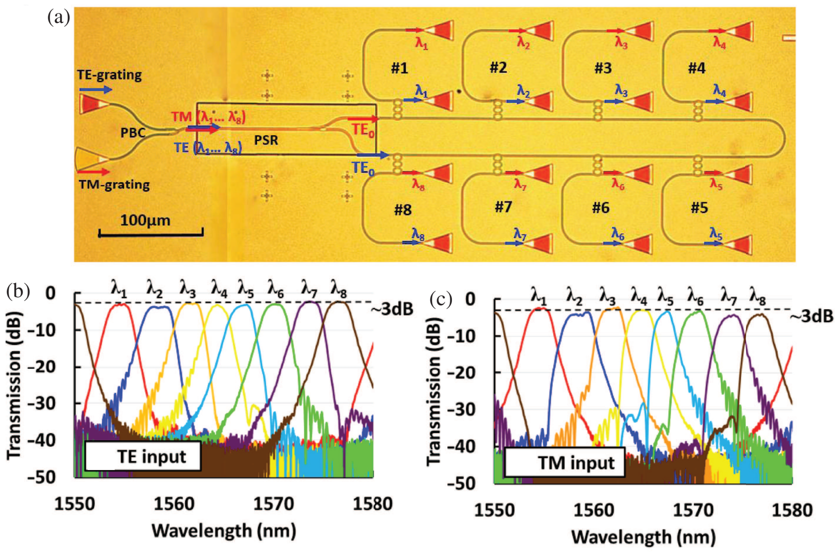

Figure 3 (Color online) A 16-channel hybrid PDM-WDM (de)multiplexer. (a) Microscopic image. Measured spectral responses for all the channels of (b) TE- and (c) TM-polarizations [70] @Copyright 2018 IEEE.

is enough to cover multiple wavelength-channels for DWDM systems. Furthermore, a box-like filtering response can be synthesized by introducing multiple cascaded microrings when the coupling coefficients are optimized [37–39]. Recently, we proposed and realized a novel hybrid PDM-WDM multiplexer by integrating an array of MRR-based optical-filters and a polarization-splitter-rotator (PSR), as shown in Figure 3(a) [70]. The PSR is designed with the structure consisting of an adiabatic taper, an ADC and an MMI mode filter. This PSR enables the polarization splitting and rotation simultaneously, and also has excellent performances in a broad wavelength-band as demonstrated previously [50]. In order to simplify the circuit configuration and the wavelength alignment of the MRRs, here the cross- and through-ports of the PSR are connected through the bus waveguide for all the MRR-based optical filters. In this way, each MRR-based optical filter works bi-directionally and provides two drop ports. The channels with the same wavelengths from dual polarizations are dropped separately. In order to reduce the cavity length and increase the FSR, which is important to cover all the wavelength channels, the MRRs are designed to be elliptical and the minimal bending radius is ∼2.65 μm. More importantly, these MRRs are designed to be wavelength-selective for TE polarization only with a very high polarization extinction ratio (ER) (>35 dB), which greatly reduces the polarization crosstalk due to the PSR. Figures 3(b) and (c) show the measured spectral responses at the drop ports of the 16-channel hybrid PDM-WDM multiplexer with eight MRR-based WDM filters when TE- and TM-polarized lights are launched from the TE- and TM-type grating couplers connected at the input ports of the polarization beam combiner, respectively. It can be seen that all the wavelength-channels for dual polarizations works very well with an excess loss (EL) of ∼3 dB. The crosstalk between the adjacent and non-adjacent channels are about −25 dB and <−35 dB. The channel spacing is 400 GHz (3.2 nm), and the 3 dB bandwidth is ∼250 GHz (2.0 nm), which makes the device tolerant to the wavelength variation.

It can be seen that the MRR-based hybrid WDM-PDM (de)multiplexer works pretty well in comparison with the AWG-based one reported in [69]. One should notice that there is usually some random variation of the resonance wavelengths for MRRs due to the ramdom fabrication errors. This wavelength variation is usually several nanometers or less [71], which depends on the uniformity of the fabrication process. For the present MRR-based optical filters, the resonant wavelengths are aligned well, which is attributed to the excellent fabrication process and the relatively large channel-spacing (e.g., 3.2 nm). On the other hand, it is still challengeable to achieve accurate the wavelength-alignment for an array of MRRs for DWDM with a channel-spacing less than 1.6 nm. As demonstrated previously, the approach of thermal-tuning is often introduced for the central wavelength alignment of an MRR array used for DWDM systems. Thermal-tuning for the MRRs on silicon is efficient because of the high thermo-optic coefficient of silicon. However, this not only makes the fabrication and management quite complicated, but also increases the structural size and the power consumption. In order to solve this problem, some post-fabrication processes have also been developed for permanent wavelength alignment in the past years, including E-beam compaction and laser trimming [71–73]. These techniques enable sufficient permanent wavelength shifts, which can be controlled finely to compensate the random wavelength variation caused by the random fabrication errors. This makes an MRR arrays useful potentially for DWDM systems.

2.2 On-chip hybrid MDM-WDM (de)multiplexers

In order to further increasing the link capacity of an optical interconnect when there are N wavelengths available, another effective approach is to develop a hybrid (de)multiplexing technology enabling MDM and WDM simultaneously. When using a multimode optical fiber/waveguides supporting multiple guided-modes [74–78], it is possible to obtain a high-capacity data transmission with $M \times N$ channels in total when M modes and N wavelengths. In [79], a hybrid MDM-WDM data transmission was realized with the combination of an off-chip three-channel WDM device and an on-chip two-channel mode (de)multiplexer based on an asymmetric Y-junction. Such a $2 \times 3 \times 10$ Gb/s MDM-WDM link was demonstrated with a 60 Gb/s aggregate bandwidth. In this experiment, the used off-chip WDM device has three wavelength-channels with a channel-spacing of $\Delta\lambda_{\rm ch} = 8$ nm. As it can be seen, for hybrid WDM-MDM multiplexing systems, one of the most important key devices is on-chip hybrid MDM-WDM (de)multiplexers, which have been realized by integrating WDM devices and mode (de)multiplexers on the same chip. In [80], a hybrid WDM-MDM (de)multiplexer was designed by using two-channel mode (de)multiplexers based on multimode interference (MMI) couplers with a tilt joint as a phase shifter. There are three wavelengths-channels with a channel-spacing of 3 nm involved. The numerical simulation result show that the excess losses of the channels are ∼6 dB in theory. In [81], a hybrid MDM-WDM (de)multiplexer based on photonic crystals (PhCs) is proposed theoretically to manipulate the TE_0 and TE_1 modes at wavelengths of 1550 and 1570 nm. The simulation result shows that this device has low excess losses and low crosstalk. Unfortunately, PhC waveguides usually have very high loss in the practical case and usually one has to control the structural dimensions very carefully due to the small fabrication tolerance. Furthermore, there is no demonstration to show the potential for DWDM applications with a narrow channel spacing.

As demonstrated before, the mode (de)multiplexer based on cascaded ADCs could work very well

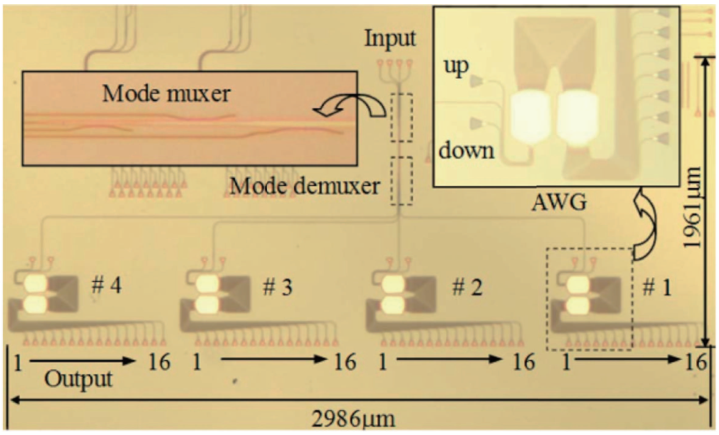

Figure 4 (Color online) Fabricated 64-channel hybrid MDM-WDM (de)multiplexer consisting of a four-channel mode (de)multiplexer and four 16-channel AWG (de)multiplexers [83] @Copyright 2014 OSA.

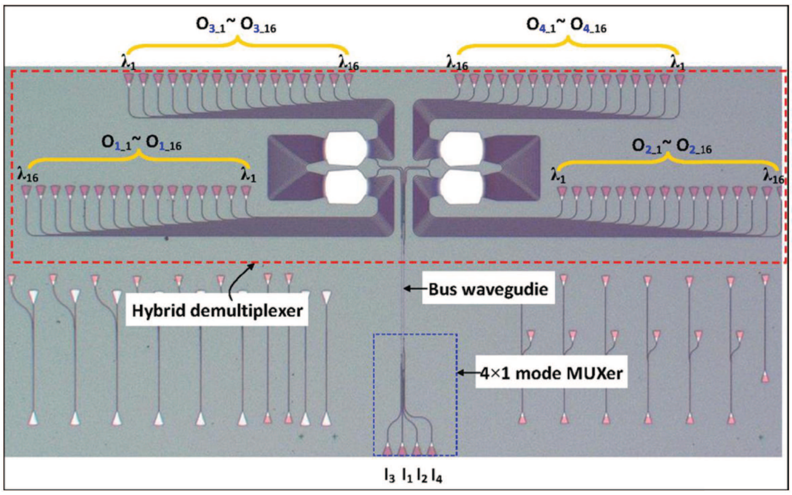

Figure 5 (Color online) Fabricated 64-channel hybrid MDM-WDM (de)multiplexer consisting of a four-channel mode (de)multiplexer and two bi-directional AWG (de)multiplexers with 16 wavelength-channels [84] @Copyright 2015 Wiley.

over a broad bandwidth [82]. Therefore, it is promising to develop hybrid MDM-WDM (de)multiplexers by integrating an ADC-based mode (de)multiplexer [28] and AWG-based WDM devices. As shown in Figure 4 [83], such a hybrid MDM-WDM (de)multiplexer was realized with a four-channel mode (de)multiplexer and four identical AWG (de)multiplexers integrated on the same chip. These four AWGs have a channel spacing of 3.2 nm and have the same central wavelengths $(\lambda_1, \lambda_2, \ldots, \lambda_N)$ for the N wavelength-channels. As an example, the demonstrated hybrid MDM-WDM (de)multiplexer has 64 channels in total by utilizing four mode-channels and 16 wavelength-channels. It is also possible to achieve a hybrid MDM-WDM (de)multiplexer with a simplified configuration when using bi-directional AWGs, as shown in Figure 5 [84]. In this example, the hybrid MDM-WDM (de)multiplexer consists of a four-channel mode (de)multiplexer based on ADCs and two bi-directional 17×17 AWG (de)multiplexers. The crosstalk from the other mode-channels is about $-16 - -25$ dB in a broad wavelength band, while the spectral responses of the wavelength-channels for any one of mode-channels are similar to those of discrete AWG (de)multiplexers on the same chip. The crosstalk between the (non)adjacent wavelength-channels is ~ -14 dB [84], which is the typical number for SOI-nanowire AWGs without any special structural designs or special fabrication processes. These experimental results have well proved the compatibility of the ADC-based mode (de)multiplexer working with WDM filters. It is still expecting to develop high-performance on-chip hybrid MDM-WDM (de)multiplexer enabling many mode-/wavelength-channels in the near future.

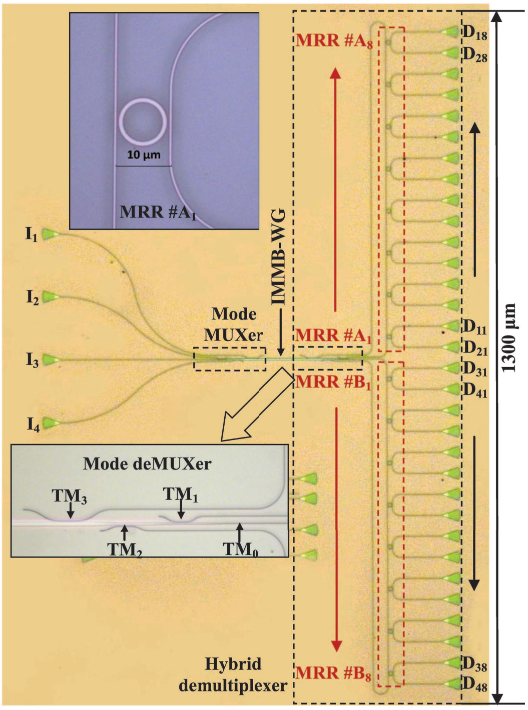

Figure 6 (Color online) Fabricated hybrid MDM-WDM (de)multiplexer for TM polarization [89] @Copyright 2018 IEEE.

As an alternative, the combination of MRRs and mode (de)multipelxers also provides another promising option for realizing the hybrid WDM-MDM technology [85–88]. In 2014, a hybrid MDM-WDM (de)multiplexer based on ADC-assisted MRRs was demonstrated to enable an hybrid MDM-WDM link with two mode-channels and three wavelength-channels with a channel-spacing of $\Delta\lambda_{\rm ch} = 8$ nm [85]. In this design, each MRR has an ADC for the coupling between the microring and the multimode bus waveguide, in which way the desired higher-order mode-channel can be dropped wavelength-selectively. Later a hybrid MDM-WDM multiplexer based on ADC-assisted MRRs was also demonstrated with Si_3N_4 optical waveguides, and a MDM-WDM link for data transmission was demonstrated [86]. It is can be seen that the MRRs are widely used because of the compactness and the potential to be low loss and low crosstalk.

More recently, we proposed and demonstrated a silicon-based on-chip hybrid MDM-WDM (de)multiplexer with 32 channels by including four mode-channels and eight wavelength-channels [89], as shown in Figure 6. This hybrid MDM-WDM (de)multiplexer consists of a mode (de)multiplexer based on cascaded ADCs and a WDM (de)multiplexer based on an MRR array. Each MRR-based WDM filter for this hybrid MDM-WDM (de)multiplexer works bi-directionally to be shared by two mode channels, which is realized by connecting two output ports of the mode-(de)multiplexer through the bus waveguide of MRR arrays. This helps reduce the device footprint greatly and also simplifies the configuration significantly. As the four-channel mode (de)multiplexer has been developed very well for TM polarization [82], this hybrid MDM-WDM (de)multiplexer was also designed for TM polarization as an example. It is important to achieve an MRR with a large FSR, which is determined by the cavity length given by $L_{\rm cav} = 2\pi R$. In order to obtain a sharp bending, which is needed for achieving a large FSR, a multimode microring waveguide was introduced for these MRRs. For a multimode microring waveguide with a core width $w_{\rm co} = 850$ nm, the bending loss is still acceptably low (i.e., ∼30 dB/cm) even when the bending radius is as small as $R = 4$ μm, which is much smaller than that for a regular singlemode microring waveguide. In this way, one has an FSR as large as 24 nm for TM polarization, which can cover more than 8 channels when the channel spacing is less than 3 nm. Meanwhile, the resonance of the higher-order mode can be suppressed very well due to weak coupling and high bending loss. The fabricated hybrid MDM-WDM (de)multiplexer has an excess loss of <4.5 dB and a crosstalk lower than 18 dB. The realized channel-

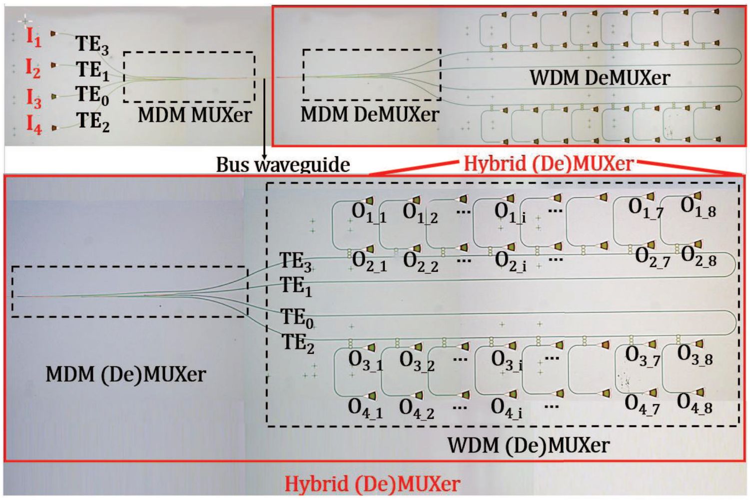

Figure 7 (Color online) Fabricated hybrid MDM-WDM (de)multiplexer for TE polarization [82] @Copyright 2018 OSA.

spacing is about 2 nm as designed. It is possible to achieve more wavelength-channels by reducing the wavelength channel-spacing.

An MRR-based hybrid MDM-WDM (de)multiplexer for TE polarization has also been demonstrated recently. This hybrid MDM-WDM (de)multiplexer consists of an M-channel mode (de)multiplexer based on dual-core adiabatic tapers and an N-channel MRR-based WDM filter with box-like responses [82], as shown in Figure 7. The mode (de)multiplexer has four mode-channels of TE polarization and is realized by using the design with dual-core adiabatic tapers. In this way, it has a large fabrication tolerance and the WDM-compatibility to work well in a broad wavelength-band. For WDM filters, the box-like response was obtained by using cascaded MRRs with bent DCs. As a result, the WDM filters becomes less sensitive to environmental variations. For TE polarization, the microring waveguide can be bent very sharply even when it works under the singlemode condition. For the part of bent DCs, the bending radius is chosen as $R_1 = 5$ μm in order not to introduce high bending loss for the narrow bent access waveguide. For the other part of the microring waveguide, the bending radius is chosen as $R_2 = 3$ μm in order to minimize the cavity length and maximize the FSR. For such a micro-resonators designed in an elliptical shape with bending radii $R_1 = 5$ μm and $R_2 = 3$ μm [37], the FSR is as large as 27 nm, which is enough to cover eight wavelength-channels when $\Delta\lambda_{\text{ch}} = 3.2$ nm. Similarly to the configuration shown in Figure 6, each MRR-based WDM filter of this hybrid MDM-WDM (de)multiplexer also works bi-directionally. As an example, a 32-channel hybrid MDM-WDM (de)multiplexer for TE polarization was demonstrated by integrating a four-channel mode-(de)multiplexer and 8-channel MRR-based WDM filters. This 32-channel hybrid MDM-WDM multiplexer has excess losses of 2 – 5 dB and inter-mode crosstalks of ~ -20 dB. For the wavelength-channels, the crosstalk between adjacent and non-adjacent channels ($\Delta\lambda_{\text{ch}} = 3.2$ nm) is ~ -25 and ~ -35 dB, which is much better than the regular AWG (de)multiplexers on silicon. This hybrid MDM-WDM (de)multiplexer can be improved further by increasing numbers of the mode-channels as well as the wavelength-channels. It is expecting to develop high-performance hybrid WDM-MDM (de)multiplexer enabling more mode-/wavelength-channels in the near future.

2.3 On-chip hybrid PDM-MDM (de)multiplexer

In order to achieve ultra-high-capacity optical interconnects, it is still a challenge to develop novel devices enabling more channels for a single wavelength [90]. As discussed previously, the channel number is increased greatly by introducing dual polarizations or multiple guided modes. Definitely, it is possible to combine the multiple guided-modes and dual polarizations, in which way one can obtain more channels for a single wavelength-carrier. The key elements are on-chip hybrid PDM-MDM (de)multiplexer, which can work with dual polarizations and multiple guided-modes [91–95]. Intrinsically speaking, an on-chip hybrid PDM-MDM (de)multiplexer is a mode (de)multiplexer with dual polarizations.

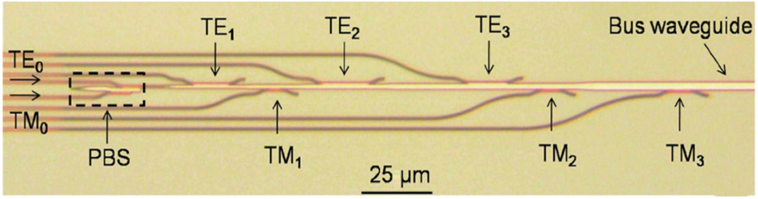

Figure 8 (Color online) 8-channel hybrid PDM-MDM (de)multiplexer [91] @Copyright 2014 Wiley.

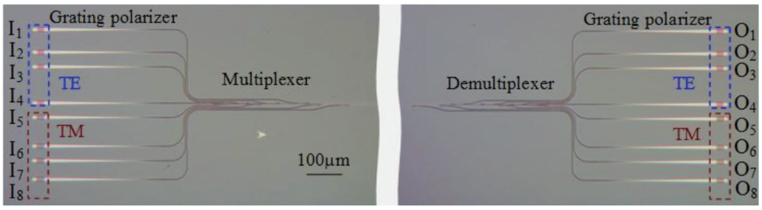

Figure 9 (Color online) Fabricated PIC consisting of an improved 8-channel hybrid PDM-MDM (de)multiplexer [92] @Copyright 2014 OSA.

One might notice that there have been many impressive results reported for a single-polarization on-chip mode (de)multiplexers [56–68]. Among various structures for mode (de)multiplexers, ADCs have been very popular due to is simplicity of design and fabrication. Previously most ADC-based mode (de)multiplexers were developed only for TM polarization. Theoretically speaking, an ADC can be designed for not only TM-polarization modes but also TE-polarization modes. Therefore, the design with cascaded ADCs can be extended possibly for realizing a hybrid (de)multiplexer enabling MDM and PDM simultaneously. As demonstrated in [91], a 8-channel hybrid MDM-PDM (de)multiplexer consisting of six cascaded ADCs and a PBS was realized (see Figure 8). This hybrid MDM-PDM (de)multiplexer works with four channels for TE-polarization modes and four channels for TM-polarization modes. For this hybrid MDM-PDM (de)multiplexer, these six cascaded ADCs were designed according to the phase-matching condition to extract the TE_1, TE_2, TE_3, TM_1, TM_2, and TM_3 modes from the bus waveguide. The PBS based on a three-waveguide coupler [48] was used to separate/combine the TE_0 and TM_0 modes at the input/output of the (de)multiplexer. The demonstrated experimental results show that there is some undesired crosstalk due to some inevitable coupling from different polarization modes. In order to filter out the polarization crosstalk to improve the performance of the hybrid MDM-PDM (de)multiplexer, a regular polarizer can be introduced at the output ends. For example, an 8-channel hybrid MDM-PDM (de)multiplexer with improved performances was realized by introducing grating-type polarizers at the output ends as shown in Figure 9 [92].

One should realize that it is still not easy to realize a low-loss and low-crosstalk hybrid MDM-PDM (de)multiplexer with many channels (e.g., $M \geqslant 10$). Recently, we proposed and demonstrated a novel 10-channel hybrid MDM-PDM (de)multiplexer by using dual-core adiabatic tapers waveguides with dual polarizations [95], as shown in Figure 10. This novel architecture consists of several stages of cascaded dual-core adiabatic tapers waveguides integrated with PBSs. As an example, the hybrid MDM-PDM (de)multiplexer was designed with a 2.3 μm-wide bus waveguide, supporting six mode-channels of TE polarization and four mode-channels of TM polarizations. These ten mode-channels are (de)multiplexed with five cascaded dual-core adiabatic tapers and six PBSs integrated on the same chip. These PBSs are realized with the design of cascaded bent DCs and work very well over a broad bandwidth [53]. By using any adiabatic dual-core taper, one can simultaneously extract a TE mode-channel and a TM mode-channel from the multimode bus waveguide. As a result, the high-order supermodes localized in the bus waveguide can be converted to the fundamental mode localized in the narrow waveguide. The extracted TE- and TM mode-channels are then separated by the integrated PBS. As shown by the measured results given in Figure 11, this 10-channel hybrid MDM-PDM (de)multiplexer works very well with low crosstalks (~ -20 dB) and low excess losses (<1 dB) over a large wavelength range from 1525 to 1610 nm. It allows to cover more than 100 wavelength-channels when choosing a channel-spacing of $\Delta\lambda_{ch} = 0.8$ nm. This

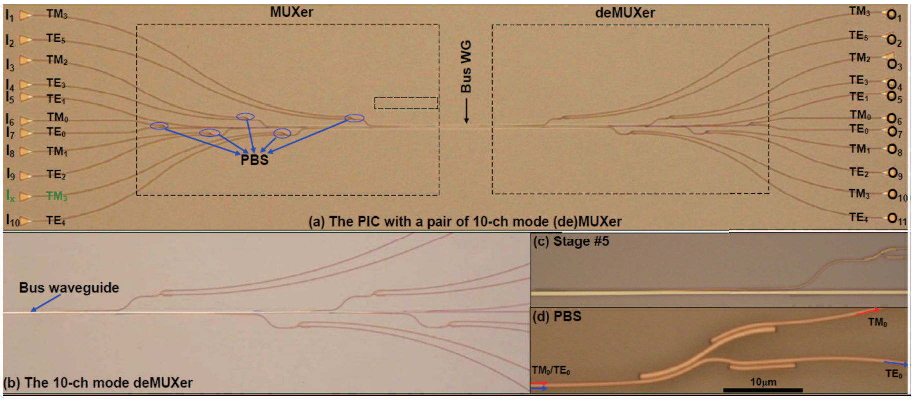

Figure 10 (Color online) A 10-channel hybrid MDM-PDM (de)multiplexer based on dual-core adiabatic tapers waveguides with dual polarizations [95] @Copyright 2017 Wiley.

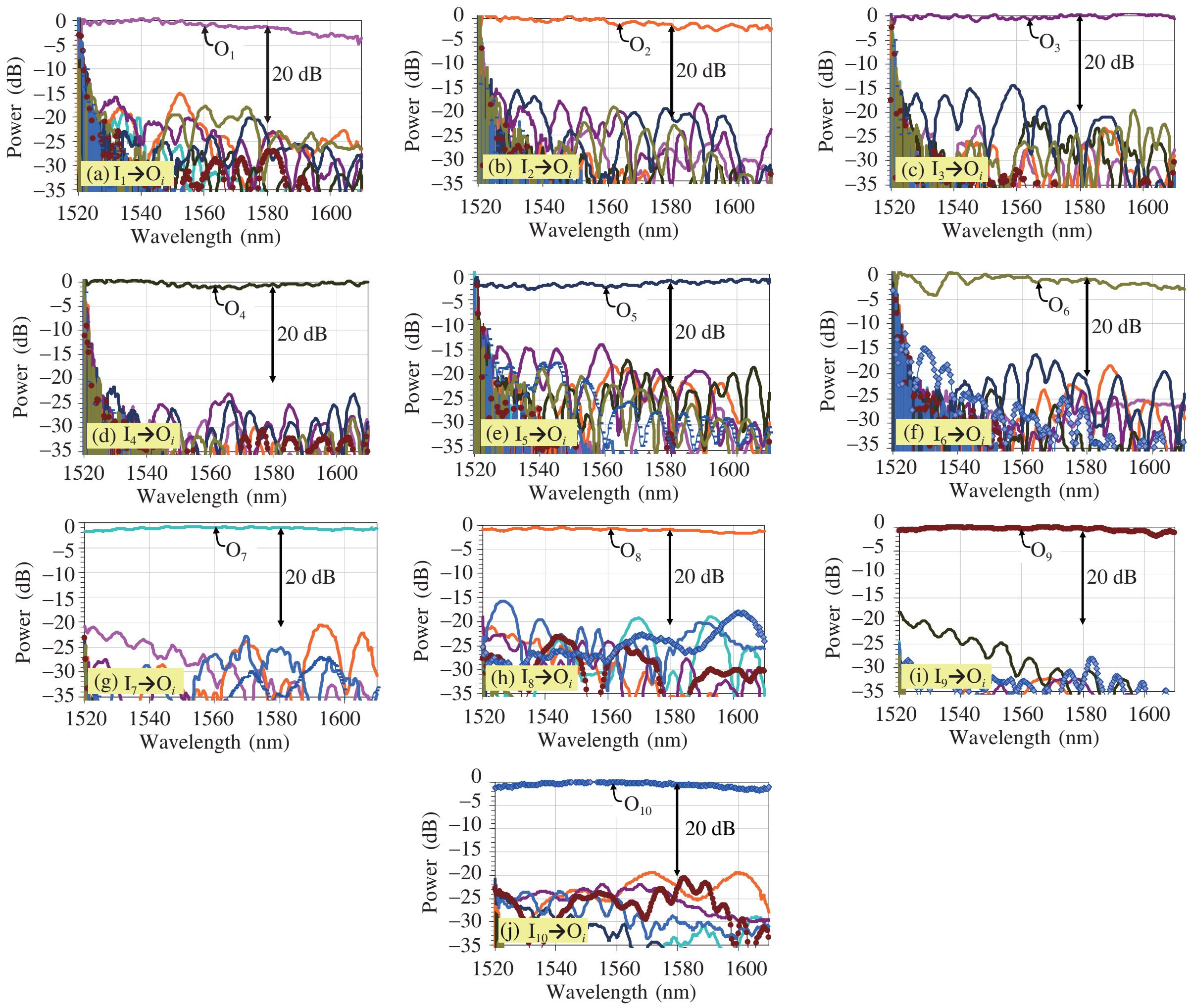

Figure 11 (Color online) Measured transmissions at the then output ports ($O_1 \sim O_{10}$) of the 10-channel hybrid MDM-PDM (de)multiplexer when light is launched from port (a) I_1, (b) I_2, (c) I_3, (d) I_4, (e) I_5, (f) I_6, (g) I_7, (h) I_8, (i) I_9, (j) I_{10} of the mode multiplexer, respectively [95] @Copyright 2017 Wiley.

makes it possible to develop a multi-dimensional hybrid (de)multiplexing technology with >1000 channels by combining WDM, MDM as well as PDM simultaneously in the future.

Table 1 Summary of the reported on-chip (de)multiplexers

Types	Ref.	Year	N_{TE} a)	N_{TM} b)	N_w c) $\times \Delta\lambda_{\mathrm{ch}}$ (nm)	N_{all}	Loss (dB)	CT (dB)	Structure
WDM+PDM	[69]	2015	1	1	9×3.2	18	7	-13	PSR+AWG
WDM+PDM	[70]	2018	1	1	8×3.2	16	3	< -25	PSR+MRRs
WDM+MDM	[79]	2014	2	0	3×8	6	2.4	-19.7	ADCs+MRRs
WDM+MDM	[80]	2016	2	0	3×3	6	1	< -22	MMI
WDM+MDM	[84]	2015	4	0	16×3.2	64	5	-14	ADCs+AWG
WDM+MDM	[85]	2014	2	0	3×8	6	< 10	< -18	ADCs+MRRs
WDM+MDM	[89]	2018	0	4	8×8	32	< 4.5	-18	ADCs+MRRs
WDM+MDM	[82]	2018	4	0	8×3.2	32	0.5 – 5	-16.5	Dual-core Tapers+MRRs
MDM+PDM	[91]	2014	4	4	–	8	< 3	< -17.7	ADCs+PBS
MDM+PDM	[95]	2018	6	4	–	10	0.2 – 1.8	5 – -25	Dual-core Tapers+PBS

a) N_{TE}: number of TE polarization; b) N_{TM}: number of TM polarization; c) N_w: number of wavelength.

3 Conclusion

As a summary, this paper gives a review for recent progresses on silicon-based on-chip hybrid (de)multiplexers (as shown in Table 1), which work as the key elements to combine more than one (de)multiplexing techniques simultaneously, e.g., WDM, PDM, and MDM. Here three types of on-chip hybrid (de)multiplexers are considered to enable the combinations of PDM-WDM, MDM-WDM and MDM-PDM. From Table 1, it can be seen that hybrid (de)multiplexers have been realized with the integration of various WDM, PDM, and MDM structures, including AWGs, MRRs, PSRs, as well as couplers. These functional devices for WDM, MDM, and PDM are very important for the realization of on-chip hybrid (de)multiplexers. For WDM, there are two popular WDM devices available, i.e., AWGs and MRRs, which have been realized successfully when the channel spacing is relatively large (e.g., 3.2 nm). On the other hand, it is still not easy to achieve low-loss and low-crosstalk AWGs or MRRs with dense channel spacing (e.g., 0.8 nm). Fortunately, this can be solved by improve the design and the fabrication techniques. The PDM devices include PSBs, PRs, and PSRs, which have been developed very well with very high performances in the past years. The MDM devices have also been developed with various structures as a new-rising functional element. By utilizing these fundamental devices, various silicon-based on-chip hybrid (de)multiplexers have been realized. It can be seen that the channel number is increased very significantly, which helps enhance the link capacity of optical interconnects. This also helps reduce the cost because less lasers are needed. And great effort is still needed to improve the performance of the on-chip hybrid (de)multiplexers by introduce smart structural designs and advanced fabrication techniques. One should also notice that low-loss and low-crosstalk multimode manipulation is very desired for any hybrid (de)multiplexing systems with MDM. For example, it will be very helpful to develop low-loss and low-crosstalk data transmission in a multimode waveguide bend as well as a waveguide coupler between a few-mode fiber and a multimode waveguide. It is still very challengeable to develop on-chip hybrid WDM-MDM-PDM (de)multiplexers with 10^3 channels by combining multiple wavelengths, multiple modes as well as dual polarization. Such a hybrid (de)multiplexing systems is very complicated and more efforts should be given to develop high-performance on-chip hybrid (de)multiplexers and other functional devices in the future.

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