

WAVELENGTH DIVISION MULTIPLEXER AND SILICON PHOTONIC INTEGRATED CHIP

FIELD OF THE DISCLOSURE

5 **[0001]** The present disclosure relates to a technology in the field of optical communications, and more particularly to a wavelength division multiplexer and a silicon photonic integrated chip.

BACKGROUND OF THE DISCLOSURE

10 **[0002]** An optical communication capacity can be effectively increased through wavelength division multiplexing technology, in which key devices are a wavelength division multiplexer (MUX) and a wavelength division demultiplexer (DEMUX). A main structure of a planar waveguide-type wavelength division multiplexer includes an array waveguide grating, an etched
15 diffraction grating, and a cascaded Mach-Zehnder interferometer (MZI).

[0003] Furthermore, a silicon photonic chip is a key device for realizing optical interconnection, which can effectively reduce module cost in optical communication. Referring to FIG. 1, a conventional silicon-photonic wavelength division multiplexer that has the cascaded Mach-Zehnder interferometer structure
20 is exemplified to perform four-channel wavelength division multiplexing, and three Mach-Zehnder interferometers 10' that are arranged in parallel and in cascade are included therein. Each of the Mach-Zehnder interferometers 10' includes two 2×2 3dB couplers 11', two connecting arms 12', and one monitor photodetector 13'. Here, one of the connecting arms 12' is a tunable phase shift
25 arm (as indicated by broken lines in the drawing).

SUMMARY OF THE DISCLOSURE

Technical Problems

[0004] In the conventional wavelength division multiplexer that comprises the cascaded Mach-Zehnder interferometer structure, it needs to incorporate the monitor photodetectors 13' when tuning the tunable phase shift arm of each of the cascaded Mach-Zehnder interferometers 10'. However, such a tuning process is inconvenient, and power consumption for the same is large. In addition, an optical bandwidth of the 3dB coupler 11' is limited, and when a number of the 3dB couplers 11' are provided on an optical path of the wavelength division multiplexer that includes the multiple cascaded Mach-Zehnder interferometers 10', performance of the wavelength division multiplexer can be significantly decreased.

Technical Solutions

[0005] Objects of the present disclosure are to provide a wavelength division multiplexer and a silicon photonic integrated chip for which a quantity of phase shift arms is reduced, so as to achieve effects of low power consumption, a large optical bandwidth, easy tuning, and good stability.

[0006] To achieve one of the above objects, the present disclosure provides a wavelength division multiplexer, which includes at least two polarization control structures and at least one polarization-independent Mach-Zehnder interferometer that are disposed on a silicon substrate.

[0007] Each of the at least two polarization control structures includes two input ports and one output port, the at least one Mach-Zehnder interferometer includes two input ports and one optical signal output port, the optical signal

output port is used for outputting a multiplexed optical signal, and the output ports of the at least two polarization control structures are connected to the input ports of the at least one Mach-Zehnder interferometer.

[0008] Each of the at least two polarization control structures receives two linearly-polarized light beams of linearly-polarized incident light beams, the two linearly-polarized light beams are combined and outputted as a sub-multiplexed optical signal in which linear polarization states of the two linearly-polarized light beams are rotated to be perpendicular to each other, and the sub-multiplexed optical signal is inputted through one of the input ports of the at least one Mach-Zehnder interferometer. The at least one polarization-independent Mach-Zehnder interferometer receives the sub-multiplexed optical signals outputted by the at least two polarization control structures, and the sub-multiplexed optical signals are combined and outputted as the multiplexed optical signal which includes two linear polarization states that are perpendicular to each other.

[0009] As a further improvement of an embodiment, the at least two polarization control structures included in the wavelength division multiplexer are n in number, the at least one polarization-independent Mach-Zehnder interferometer included in the wavelength division multiplexer is $n-1$ in number, and n is an integer that is greater than or equal to 2.

[0010] As a further improvement of an embodiment, each of the at least two polarization control structures is an integrated polarization rotator-combiner.

[0011] As a further improvement of an embodiment, the integrated polarization rotator-combiner includes a straight-through waveguide, a cross waveguide, a straight-through port and a cross port that are respectively connected to the straight-through waveguide and the cross waveguide, and a mode conversion

structure that is connected to the straight-through waveguide. The straight-through waveguide and the cross waveguide are combined into a mode multiplexing structure, the straight-through port and the cross port each include a strip-to-ridge waveguide wedge structure, and the mode conversion structure
 5 has a bi-level taper.

[0012] As a further improvement of an embodiment, each of the at least two polarization control structures includes a polarization rotator and a polarization beam combiner.

[0013] As a further improvement of an embodiment, the polarization beam
 10 combiner includes three mode conversion couplers that are the same, and each of the mode conversion couplers includes a single-mode access waveguide and a multi-mode bus waveguide.

[0014] A first mode conversion coupler and a second mode conversion coupler of the three mode conversion couplers are arranged side by side, the multi-mode
 15 bus waveguide of a third mode conversion coupler is connected to the multi-mode bus waveguide of the first mode conversion coupler, and the single-mode access waveguide of the third mode conversion coupler is connected to an output end of the single-mode access waveguide of the second mode conversion coupler.

[0015] As a further improvement of an embodiment, the at least one Mach-
 20 Zehnder interferometer includes a 2×2 input 3dB coupler, two phase shift arms, and a 2×2 output 3dB coupler that are sequentially connected to each other, and at least one of the two phase shift arms is a tunable phase shift arm.

[0016] Each of the input 3dB coupler and the output 3dB coupler is a polarization-independent coupler, and a polarization rotator is disposed on each
 25 of the phase shift arms.

[0017] As a further improvement of an embodiment, the at least one Mach-Zehnder interferometer further includes a monitor photodetector, and the monitor photodetector is optically connected to an output port of the output 3dB coupler.

[0018] The present disclosure further provides a silicon photonic integrated chip, which includes the above-mentioned wavelength division multiplexer.

[0019] As a further improvement of an embodiment, the silicon photonic integrated chip further includes optical modulators, respectively. After multiple incident optical signals are modulated by the optical modulators, multiple modulated optical signals are outputted. The multiple modulated optical signals are respectively inputted through the input ports of the at least two polarization control structures of the wavelength division multiplexer, and are outputted as the multiplexed optical signal after passing through the at least two polarization control structures and the at least one Mach-Zehnder interferometer.

Beneficial Effects

[0020] Polarization control structures with designable bandwidths are adopted for increasing an optical bandwidth of the wavelength division multiplexer and reducing optical loss. The quantity of the phase shift arms that require tuning feedback is reduced to lower the overall power consumption of a device. Further, reliability and yields of the wavelength division multiplexer can be effectively enhanced due to a large manufacturing tolerance and good stability of the polarization control structures.

BRIEF DESCRIPTION OF THE DRAWINGS

Description of the Drawings

[0021] FIG. 1 is a schematic structural diagram of a conventional silicon-

photonic MZI-type wavelength division multiplexer.

[0022] FIG. 2 is a schematic structural diagram of a wavelength division multiplexer according to a first embodiment of the present disclosure.

5 [0023] FIG. 3 is a schematic structural diagram of an integrated silicon-substrate polarization rotator-combiner according to the first embodiment of the present disclosure.

[0024] FIG. 4 is a schematic structural diagram of a polarization-independent 2×2 input 3dB coupler.

10 [0025] FIG. 5 is a schematic structural diagram of a polarization-independent 2×2 output 3dB coupler.

[0026] FIG. 6 is a schematic structural diagram of a polarization rotator (PR).

[0027] FIG. 7 is a schematic structural diagram of the wavelength division multiplexer according to a second embodiment of the present disclosure.

15 [0028] FIG. 8 is a schematic structural diagram of a polarization beam combiner (PBC).

[0029] FIG. 9 is a schematic structural diagram illustrating one expansion of the wavelength division multiplexer according to the present disclosure.

[0030] FIG. 10 is a schematic structural diagram illustrating another expansion of the wavelength division multiplexer according to the present disclosure.

20 [0031] FIG. 11 is a schematic diagram of a silicon photonic integrated chip according to a third embodiment of the present disclosure.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Embodiments of the Disclosure

25 [0032] The disclosure will be described in detail below with reference to the

specific embodiments shown in the accompanying figures. However, these embodiments do not limit the disclosure, and the structural, method, or functional transformations made by a person having ordinary skill in the art according to these embodiments are all included in the protection scope of the disclosure.

5 **[0033]** In the drawings of the present disclosure, the sizes of certain structures or portions may be enlarged relative to other structures or portions for illustrative purposes, and thus are merely used for illustration of the basic structure of the subject matter of the present disclosure.

10 **[0034]** In addition, spatially relative terms (such as “over,” “above,” “under,” and “below”) in the present disclosure are used to conveniently describe a spatial relationship between one element/feature and another element/feature as shown in the drawings. These spatially relative terms are intended to include different orientations of a device in use or in operation other than the orientations illustrated in the drawings. For example, when the device in the drawing is turned
15 over, elements described as below and/or under other elements or features would then be oriented above the other elements or features. Therefore, the exemplary term “below” encompasses both orientations of “above” and “below”. The device may also be otherwise oriented (rotated 90 degrees or at other orientations), and the spatially relative terms used herein are to be interpreted accordingly. When
20 one element/layer is referred to as being disposed “above” or “connected to” another element/layer, said element/layer can be directly disposed above or connected to another element/layer, or a middle element/layer can be provided therebetween.

[0035] [First Embodiment]

25 **[0036]** A wavelength division multiplexer of the present disclosure includes a

silicon substrate, a buried oxide layer, a waveguide layer, and an upper cladding layer. As shown in FIG. 2, at least two polarization control structures 200 and at least one polarization-independent Mach-Zehnder interferometer 100 are disposed on the silicon substrate. Each of the polarization control structures 200 includes two input ports and one output port, the Mach-Zehnder interferometer 100 includes two input ports and one optical signal output port, and the optical signal output port is used for outputting a multiplexed optical signal. The output ports of the polarization control structures 200 are connected to the input ports of the Mach-Zehnder interferometer 100. Each of the polarization control structures 200 receives two linearly-polarized light beams of linearly-polarized incident light beams, the two linearly-polarized light beams are combined and outputted as a sub-multiplexed optical signal which includes two linear polarization states that are perpendicular to each other, and the sub-multiplexed optical signal is inputted through one of the input ports of the Mach-Zehnder interferometer 100. The above-mentioned at least one polarization-independent Mach-Zehnder interferometer 100 receives the sub-multiplexed optical signals outputted by the above-mentioned at least two polarization control structures 200, and the sub-multiplexed optical signals are combined and outputted as the multiplexed optical signal which includes two linear polarization states that are perpendicular to each other. The wavelength division multiplexer adopts polarization control structures that have designable bandwidths for increasing an optical bandwidth of the wavelength division multiplexer and reducing optical loss. A quantity of phase shift arms that require tuning feedback is reduced to lower the overall power consumption of a device. Further, reliability and yields of the wavelength division multiplexer can be effectively enhanced due to a large manufacturing tolerance

and good stability of the polarization control structures.

[0037] Reference is made to FIG. 2 to FIG. 6, in which a wavelength division multiplexer of four wavelengths is taken as an example. The wavelength division multiplexer of the four wavelengths includes two polarization control structures 200 that are arranged side by side and one Mach-Zehnder interferometer 100. In the present embodiment, each of the polarization control structures 200 is an integrated polarization rotator-combiner. As shown in FIG. 3, an integrated polarization rotator-combiner 210 includes a straight-through waveguide 211, a cross waveguide 212, a straight-through port 213 and a cross port 214 that are respectively connected to the straight-through waveguide 211 and the cross waveguide 212, and a mode conversion structure 215 that is connected to the straight-through waveguide 211. Here, the straight-through waveguide 211 and the cross waveguide 212 are combined into a mode multiplexing structure. The straight-through port 213 and the cross port 214 each include a strip-to-ridge waveguide wedge structure, and are input ports of the polarization control structures. The mode conversion structure 215 has a bi-level taper, and is used as an output port of the polarization control structures for outputting the multiplexed optical signal.

[0038] In the present embodiment, the polarization-independent Mach-Zehnder interferometer 100 includes a 2×2 input 3dB coupler 110, two phase shift arms 130, and a 2×2 output 3dB coupler 120 that are sequentially connected to each other. At least one of the two phase shift arms 130 is a tunable phase shift arm, and the tunable phase shift arm is indicated by broken lines in FIG. 2. Here, each of the input 3dB coupler 110 and the output 3dB coupler 120 is a polarization-independent (PI) 3dB coupler (i.e., PI 0.5). A polarization rotator 140 is also

disposed on the phase shift arm 130. Two ports at an input end of the input 3dB coupler 110 are used as the input ports of the Mach-Zehnder interferometer 100. The output 3dB coupler 120 has two ports at an output end thereof, in which one port is used as the optical signal output port of the Mach-Zehnder interferometer 100 for outputting a multiplexed optical beam, and another port is optically connected to a monitor photodetector (MPD) 150 for feeding back a tuning state of the tunable phase shift arm.

[0039] As shown in FIG. 6, the polarization rotator (PR) 140 includes a ridge waveguide 141 and a partial planar waveguide 142 located at a side of the ridge waveguide 141. The ridge waveguide 141 includes a first wedge structure 141a, a linear structure 141b, and a second wedge structure 141c that are sequentially connected to each other. The first wedge structure 141a is used as an input end of the polarization rotator 140, and a width thereof gradually narrows along an optical path until the first wedge structure 141a is connected to the linear structure 141b. A width of the second wedge structure 141c gradually widens along the optical path until the second wedge structure 141c is connected to an optical waveguide of the phase shift arm. The partial planar waveguide 142 has a height that is less than a height of the ridge waveguide 141, and includes a third wedge structure 142a and a fourth wedge structure 142b that are located at a same side of the ridge waveguide 141 and are connected to each other. The third wedge structure 142a is closely adjacent to a side surface of the first wedge structure 141a, the fourth wedge structure 142b is closely adjacent to a side surface of the linear structure 141b, a tip of the third wedge structure 142a is closely attached to a side surface at a wider end of the first wedge structure 141a, and a tip of the fourth wedge structure 142b is close to a narrower end of the second wedge

structure 141c. A linearly-polarized light beam is incident through the wider end of the first wedge structure 141a of the ridge waveguide 141. In the first wedge structure 141a and the linear structure 141b, the linearly-polarized light beam is distributed into the ridge waveguide 141 and the partial planar waveguide 142 in an optical mode, so that a polarization state thereof is continuously rotated with the light beam transmission. When the linearly-polarized light beam is incident to the second wedge structure 141c, a polarization direction is already rotated by 90 degrees, and then the linearly-polarized light beam is coupled into the optical waveguide of the phase shift arm through the second wedge structure 141c. In other embodiments, a polarization rotator-combiner as shown in FIG. 3 can also be used as a polarization rotator. The linearly-polarized light beam is incident from the cross port, and is coupled to the straight-through waveguide through the cross waveguide. Finally, the linearly-polarized light beam that is rotated by 90 degrees is outputted through the mode conversion structure.

[0040] During operation, optical signals of the four wavelengths (i.e., λ_1 , λ_2 , λ_3 , and λ_4) are all in a linearly-polarized TE₀ mode, and the optical signals of λ_1 and λ_3 are inputted through the straight-through port 213 and the cross port 214 of one integrated polarization rotator-combiner 210, respectively. Accordingly, the optical signal of λ_1 enters into the straight-through waveguide 211, and the optical signal of λ_3 enters into the cross waveguide 212. The mode of the optical signal of λ_1 within the straight-through waveguide 211 remains unchanged, and the optical signal of λ_1 outputted through the mode conversion structure 215 is still in the TE₀ mode. The optical signal of λ_3 within the cross waveguide 212 is coupled into the straight-through waveguide 211, so that the mode of the optical signal of λ_3 is changed into TE₁ and mode-multiplexed with the optical signal

within the straight-through waveguide 211. Then, the optical signal of λ_3 is converted to a TM0 mode through the mode conversion structure 215, and is combined with the optical signal of λ_1 in the TE0 mode (originally within the straight-through waveguide 211) mentioned above, such that one sub-
 5 multiplexed optical signal that includes λ_1 in the TE0 mode and λ_3 in the TM0 mode (TE0 + TM0) is formed. Similarly, the optical signals of λ_2 and λ_4 are inputted into the straight-through port 213 and the cross port 214 of another integrated polarization rotator-combiner 210, respectively. Accordingly, the optical signal of λ_2 enters into the straight-through waveguide 211, and the
 10 optical signal of λ_4 enters into the cross waveguide 212. Eventually, one sub-multiplexed optical signal that includes λ_2 in the TE0 mode and λ_4 in the TM0 mode is outputted through the mode conversion structure 215. These two sub-multiplexed optical signals (i.e., λ_1 (TE0) + λ_3 (TM0) and λ_2 (TE0) + λ_4 (TM0)) are inputted through the two input ports of the polarization-independent 2×2 input
 15 3dB coupler 110 of the Mach-Zehnder interferometer 100, respectively. λ_1 (TE0), λ_2 (TE0), λ_3 (TM0), and λ_4 (TM0) are each transmitted through the two phase shift arms 130 at half optical power. The polarization direction of light of each wavelength is rotated by 90 degrees through the polarization rotator 140 in the phase shift arm 130. Then, a polarization state of the light of each wavelength is
 20 changed into: λ_1 (TM0), λ_2 (TM0), λ_3 (TE0), and λ_4 (TE0). Through tuning the tunable phase shift arm, and through cooperation of the two polarization rotators 140 in the two phase shift arms 130 (for controlling a phase difference between the optical signals in the TE mode and a phase difference between the optical signals in the TM mode), the optical signals in the two phase shift arms 130 can
 25 be outputted through a same one of the two ports of the polarization-independent

output 3dB coupler 120, and the optical power detected by the monitor photodetector 150 disposed at another one of the two ports approaches zero. That is, one port of the 2×2 output 3dB coupler 120 of the Mach-Zehnder interferometer 100 outputs the multiplexed optical signal of λ_1 (TM0), λ_2 (TM0), λ_3 (TE0), and λ_4 (TE0). When the tunable phase shift arm is being tuned, the monitor photodetector 150 can be used to monitor the optical power at another output port of the output 3dB coupler 120 until the optical power at said output port is zero (or approaches zero) or a minimum value. When an output light beam cannot be completely combined and outputted with another light beam due to a change in a phase of the output light beam being affected by the surroundings or other factors, a monitor photodetector may detect an increase of the optical power and feed this information back to a controller. Then the controller will tune the phase of the tunable phase shift arm until the optical power detected by the monitor photodetector approaches zero or the minimum value again.

[0041] The wavelength division multiplexer of the four wavelengths adopts two passive polarization control structures that are configured with designable bandwidths. Accordingly, a bandwidth limitation of the 3dB couplers can be reduced, the optical bandwidth of the wavelength division multiplexer can be increased, and the optical loss can be reduced. During the operation process, the four-wavelength wavelength division multiplexing can be realized by only tuning one phase shift arm. Since there are fewer phase shift arms that require tuning feedback, the overall power consumption of the device is reduced. Further, the reliability and the yields of the wavelength division multiplexer can be effectively enhanced due to the large manufacturing tolerance and the good stability of the polarization control structures.

[0042] [Second Embodiment]

[0043] In contrast to the first embodiment, the polarization control structures 200 of the present embodiment (as shown in FIG. 7 and FIG. 8) include a polarization rotator (PR) 220 and a polarization beam combiner (PBC) 230. In this embodiment, the polarization rotator 220 adopts the structure as shown in FIG. 6 (which is similar to that of the polarization rotator of the first embodiment), and includes the ridge waveguide and the partial planar waveguide located at a side of the ridge waveguide, details of which will not be reiterated herein. In other embodiments, the polarization rotator-combiner as shown in FIG. 3 can also be used as the polarization rotator. The linearly-polarized light beam is incident from the cross port, and is coupled to the straight-through waveguide through the cross waveguide. Finally, the linearly-polarized light beam that is rotated by 90 degrees is outputted through the mode conversion structure.

[0044] As shown in FIG. 8, the above-mentioned polarization beam combiner 230 includes three mode conversion couplers (i.e., a first mode conversion coupler 231, a second mode conversion coupler 232, and a third mode conversion coupler 233) that are the same, and each of the mode conversion couplers includes a single-mode access waveguide and a multi-mode bus waveguide. The first mode conversion coupler 231 and the second mode conversion coupler 232 are arranged side by side, and are disposed at an input end of the polarization beam combiner 230. Single-mode access waveguides 231a and 232a of the two mode conversion coupler 232 and 232 are connected to an output port of the polarization rotator and an input port of the wavelength division multiplexer, respectively. The third mode conversion coupler 233 is connected in cascade with the above-mentioned first mode conversion coupler 231 and second mode

conversion coupler 232. A multi-mode bus waveguide 233b of the third mode conversion coupler 233 is connected to an output end of a multi-mode bus waveguide 231b of the first mode conversion coupler 231, and a single-mode access waveguide 233a of the third mode conversion coupler 233 is connected to
 5 an output end of the single-mode access waveguide 232a of the second mode conversion coupler 232.

[0045] The wavelength division multiplexer of the four wavelengths is taken as an example. During operation, the optical signals of the four wavelengths (i.e., λ_1 , λ_2 , λ_3 and λ_4) are all in the linearly-polarized TE mode, and the optical
 10 signals of λ_1 and λ_3 are respectively inputted into the two input ports of one of the polarization control structures 200. While the optical signal of λ_1 is directly incident into the polarization beam combiner 230, the optical signal of λ_3 is incident into the polarization beam combiner 230 after being rotated by 90 degrees through the polarization rotator 220 and converted into the linearly-
 15 polarized light beam that is in the TM mode. Through the polarization beam combiner 230, λ_1 in the TE mode and λ_3 in the TM mode are combined and outputted as the sub-multiplexed optical signal of λ_1 (TE) and λ_3 (TM). Similarly, the optical signals of λ_2 and λ_4 are respectively inputted into the two input ports of another one of the polarization control structures 200. While the optical signal
 20 of λ_2 is directly incident into the polarization beam combiner 230, the optical signal of λ_4 is incident into the polarization beam combiner 230 after being rotated by 90 degrees through the polarization rotator 220 and converted into the linearly-polarized light beam that is in the TM mode. Through the polarization beam combiner 230, λ_2 in the TE mode and λ_4 in the TM mode are combined
 25 and outputted as the sub-multiplexed optical signal of λ_2 (TE) and λ_4 (TM).

These two sub-multiplexed optical signals (i.e., λ_1 (TE0) + λ_3 (TM0) and λ_2 (TE0) + λ_4 (TM0)) are inputted through the two input ports of the polarization-independent 2×2 input 3dB coupler 110 of the Mach-Zehnder interferometer 100, respectively. λ_1 (TE0), λ_2 (TE0), λ_3 (TM0), and λ_4 (TM0) are each transmitted
 5 through the two phase shift arms 130 at half the optical power. The polarization direction of the light of each wavelength is rotated by 90 degrees through the polarization rotator 140 in the phase shift arm 130. Then, the polarization state of the light of each wavelength is changed into: λ_1 (TM0), λ_2 (TM0), λ_3 (TE0), and λ_4 (TE0). Through tuning the tunable phase shift arm, and through cooperation
 10 of the two polarization rotators 140 in the two phase shift arms 130 (for controlling the phase difference between the optical signals in the TE mode and the phase difference between the optical signals in the TM mode), the optical signals in the two phase shift arms 130 can be outputted through the same one of the two ports of the polarization-independent output 3dB coupler 120, and the
 15 optical power detected by the monitor photodetector 150 disposed at another one of the two ports approaches zero or the minimum value. That is, one port of the 2×2 output 3dB coupler 120 of the Mach-Zehnder interferometer 110 outputs the multiplexed optical signal of λ_1 (TM0), λ_2 (TM0), λ_3 (TE0), and λ_4 (TE0).

[0046] In the present embodiment, the polarization beam combiner that
 20 includes the three mode conversion couplers is combined with the polarization rotator for performing polarization beam combining on two incident optical signals that have a same linear polarization state. In this way, crosstalk can be reduced. In addition, since the mode conversion coupler has characteristics of low loss and a large bandwidth, the optical loss can be further reduced, and the
 25 optical bandwidth of the device can be increased.

[0047] The four-wavelength wavelength division multiplexing is exemplified in the above-mentioned first and second embodiments for illustrative purposes. In other embodiments, the wavelength division multiplexer can also be used for wavelength division multiplexing of other multiple wavelengths. To this end, the polarization control structures are arranged to correspond in quantity to multiplexed wavelength channels for connecting in parallel and in cascade with the Mach-Zehnder interferometers. That is, the polarization control structures included in the wavelength division multiplexer are n in number, the polarization-independent Mach-Zehnder interferometers included in the wavelength division multiplexer are $n-1$ in number, and n is an integer that is greater than or equal to 2. When n is 2, the wavelength division multiplexer is the above-mentioned wavelength division multiplexer of the four wavelengths. When n is 3, the wavelength division multiplexer is expanded into a wavelength division multiplexer of six wavelength channels (as shown in FIG. 9). When n is 4, the wavelength division multiplexer is expanded into a wavelength division multiplexer of eight wavelength channels (as shown in FIG. 10). Naturally, more expansions can also be produced in a similar manner.

[0048] [Third Embodiment]

[0049] Referring to FIG. 11, the present embodiment provides a silicon photonic integrated chip, which includes optical modulators 300 and the wavelength division multiplexer mentioned in any of the previous embodiments. After multiple incident optical signals are modulated by the optical modulators 300, multiple modulated optical signals are outputted. The multiple modulated optical signals are respectively inputted through the input ports of the wavelength division multiplexer, and are multiplexed by the polarization control structures

200 and the Mach-Zehnder interferometer 100, so as to output the multiplexed optical signal. The silicon photonic integrated chip is integrated with the wavelength division multiplexer mentioned in any of the previous embodiments to perform the wavelength division multiplexing. Accordingly, the power
5 consumption of the device can be effectively reduced, the optical bandwidth can be increased, and reliability and yields of a product can be enhanced.

[0050] The series of detailed descriptions listed above are only specific descriptions of feasible implementations of the disclosure, and they are not intended to limit the protection scope of the disclosure. All equivalent
10 embodiments or modifications made without departing from the technical spirit of the disclosure shall be included within the protection scope of the disclosure.

CLAIMS

What is claimed is:

1. A wavelength division multiplexer, comprising:

5 at least two polarization control structures and at least one polarization-independent Mach-Zehnder interferometer that are disposed on a silicon substrate;

 wherein each of the at least two polarization control structures includes two input ports and one output port, the at least one Mach-Zehnder interferometer includes two input ports and one optical signal output port,
10 the optical signal output port is used for outputting a multiplexed optical signal, and the output ports of the at least two polarization control structures are connected to the input ports of the at least one Mach-Zehnder interferometer;

 wherein each of the at least two polarization control structures receives
15 two linearly-polarized light beams of linearly-polarized incident light beams, the two linearly-polarized light beams are combined and outputted as a sub-multiplexed optical signal which includes two linear polarization states that are perpendicular to each other, and the sub-multiplexed optical signal is inputted through one of the input ports of the at least one Mach-Zehnder
20 interferometer; wherein the at least one polarization-independent Mach-Zehnder interferometer receives the sub-multiplexed optical signals outputted by the at least two polarization control structures, and the sub-multiplexed optical signals are combined and outputted as the multiplexed optical signal which includes two linear polarization states that are
25 perpendicular to each other.

2. The wavelength division multiplexer according to claim 1, wherein the wavelength division multiplexer comprises n of the at least two polarization control structures and $n-1$ of the at least one polarization-independent Mach-Zehnder interferometer, and n is an integer that is greater than or equal to 2.
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3. The wavelength division multiplexer according to claim 1, wherein each of the at least two polarization control structures is an integrated polarization rotator-combiner.
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4. The wavelength division multiplexer according to claim 3, wherein the integrated polarization rotator-combiner includes a straight-through waveguide, a cross waveguide, a straight-through port and a cross port that are respectively connected to the straight-through waveguide and the cross waveguide, and a mode conversion structure that is connected to the straight-through waveguide; wherein the straight-through waveguide and the cross waveguide are combined into a mode multiplexing structure, the straight-through port and the cross port each include a strip-to-ridge waveguide wedge structure, and the mode conversion structure has a bi-level taper.
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5. The wavelength division multiplexer according to claim 1, wherein each of the at least two polarization control structures includes a polarization rotator and a polarization beam combiner.
- 25 6. The wavelength division multiplexer according to claim 5, wherein the

polarization beam combiner includes three mode conversion couplers that are the same, and each of the mode conversion couplers includes a single-mode access waveguide and a multi-mode bus waveguide; wherein a first mode conversion coupler and a second mode conversion coupler of the three mode conversion couplers are arranged side by side, the multi-mode bus waveguide of a third mode conversion coupler is connected to the multi-mode bus waveguide of the first mode conversion coupler, and the single-mode access waveguide of the third mode conversion coupler is connected to an output end of the single-mode access waveguide of the second mode conversion coupler.

7. The wavelength division multiplexer according to any one of claims 1-6, wherein the at least one Mach-Zehnder interferometer includes a 2×2 input 3dB coupler, two phase shift arms, and a 2×2 output 3dB coupler that are sequentially connected to each other, and at least one of the two phase shift arms is a tunable phase shift arm; wherein each of the input 3dB coupler and the output 3dB coupler is a polarization-independent coupler, and the polarization rotator is disposed on each of the phase shift arms.

8. The wavelength division multiplexer according to claim 7, wherein the at least one Mach-Zehnder interferometer further includes a monitor photodetector, and the monitor photodetector is optically connected to an output port of the output 3dB coupler.

9. A silicon photonic integrated chip, comprising the wavelength division

multiplexer as claimed in any one of claims 1 -8.

10. The silicon photonic integrated chip according to claim 9, further comprising optical modulators; wherein, after multiple incident optical signals are modulated by the optical modulators, multiple modulated optical signals are outputted; wherein the multiple modulated optical signals are respectively inputted through the input ports of the at least two polarization control structures of the wavelength division multiplexer, and are outputted as the multiplexed optical signal after passing through the at least two polarization control structures and the at least one Mach-Zehnder interferometer.