SPECIFICATION

TITLE: ON-CHIP INTEGRATED WAVELENGTH DIVISION MULTIPLEXER AND PHOTONIC INTEGRATED CIRCUIT CHIP

[0001] This application claims priority to China Patent Application No. 202420440975.5, filed with the China National Intellectual Property Administration on March 7, 2024 and entitled "ON-CHIP INTEGRATED WAVELENGTH DIVISION MULTIPLEXER AND PHOTONIC INTEGRATED CIRCUIT CHIP", contents of the above identified application are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present disclosure relates to the technical field of optical communications, and more particularly, to an on-chip integrated wavelength division multiplexer and a photonic integrated circuit chip.

BACKGROUND

[0003] Wavelength division multiplexing carries a plurality of signals by means of different wavelengths, and the plurality of signals are transmitted and switched in a single optical fiber/waveguide, which is a key technology for achieving capacity expansion of information in optical communications. A device for achieving wavelength division multiplexing is referred to as a wavelength division multiplexing device (MUX), a device for achieving wavelength division demultiplexing is referred to as a wavelength division demultiplexing device (DEMUX), which are core devices of a wavelength division multiplexing system. However, in a practical application scenario of the

wavelength division multiplexing device, since a laser and the like are affected by various unstable factors such as ambient temperature and manufacturing error, an output wavelength is often caused to deviate from a target wavelength, thereby leading to problems of significant loss and crosstalk between channels. In such an application scenario, a wavelength division multiplexing device of a broad bandwidth and a flat type is required, so as to accommodate a wavelength drift of the laser and to ensure normal operation of the wavelength division multiplexing system.

[0004] A structure of an on-chip integrated wavelength division multiplexer as shown in FIG. 1 includes a first-stage multiplexing module 100' and a second-stage multiplexing module 200', and can significantly improve a channel bandwidth of a wavelength division multiplexing device. Two flat-type wavelength division multiplexing devices (flat-top wavelength division multiplexing devices 110') are utilized to perform first-stage multiplexing, and then second-stage multiplexing is performed by means of a polarization multiplexing module 230', so that a flat output within a larger wavelength range is achieved, and moreover, the structure includes only passive devices and requires no additional adjustment, and is thus suitable for a practical application scenario. However, such a wavelength division multiplexing device structure employs at least two flat-type wavelength division multiplexing devices to broaden a bandwidth, which results in a size of the entire wavelength division multiplexing system being doubled, and is thus unfavorable for implementation of a photonic chip of high density and high rate.

SUMMARY

[0005] An objective of the present disclosure is to provide an on-chip integrated wavelength division multiplexer and a photonic integrated circuit chip, so as to achieve a flat wavelength division multiplexing function having a larger bandwidth while simplifying the structural complexity and reducing the size of the wavelength division multiplexer.

[0006] According to one aspect of the present disclosure, an on-chip integrated wavelength division multiplexer is provided. The wavelength division multiplexer is integrated on a photonic integrated circuit chip, and includes a flat-top wavelength division multiplexing structure being polarization-insensitive. The flat-top wavelength division multiplexing structure has a first input waveguide group, a second input waveguide group and an output waveguide, the first input waveguide group includes a plurality of first input waveguides, the second input waveguide group includes a plurality of second input waveguides, and the second input waveguide group is located at one side of the first input waveguide group;

[0007] the plurality of first input waveguides are configured to respectively receive a plurality of incident lights of a predetermined first wavelength group and having a first polarization state, the plurality of second input waveguides are configured to respectively receive a plurality of incident lights of a predetermined second wavelength group and having a second polarization state, the output waveguide is a waveguide being polarization-insensitive, and the output waveguide is configured to output a multi-wavelength and polarization multiplexed light. The first polarization state and the second polarization state are perpendicular to each other;

[0008] the first wavelength group is one of an odd group and an even group

among wavelengths λ1, λ2, λ3... λn having a predetermined wavelength spacing, and the second wavelength group is another group of the odd group and the even group, in which $n \geq 4$ and n is a positive integer, and λ1, λ2, λ3... λn are sequentially arranged from smallest to largest or from largest to smallest according to the predetermined wavelength spacing; and

[0009] the flat-top wavelength division multiplexing structure is configured such that a predetermined difference exists between an effective refractive index of a transmission mode of the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state within the flat-top wavelength division multiplexing structure, causing the plurality of incident lights having the first polarization state received by the plurality of first input waveguides and the plurality of incident lights having the second polarization state received by the plurality of second input waveguides to be combined into one multi-wavelength and polarization multiplexed light within the flat-top wavelength division multiplexing structure and to be outputted from the output waveguide.

[0010] According to some embodiments of the present disclosure, a bandwidth of a channel corresponding to each of the plurality of first input waveguides or each of the plurality of second input waveguides in the flat-top wavelength division multiplexing structure covers a frequency band range corresponding to a central wavelength of the incident light configured for the corresponding first input waveguide or the corresponding second input waveguide plus a preset offset threshold.

[0011] According to some embodiments of the present disclosure, the preset

offset threshold is an offset specified by the ITU standard, the predetermined wavelength spacing is a wavelength spacing required by a communication system, the bandwidth is a 1 dB bandwidth of the corresponding channel, and the 1 dB bandwidth is greater than or equal to twice the preset offset threshold and is less than twice the predetermined wavelength spacing.

[0012] According to some embodiments of the present disclosure, the on-chip integrated wavelength division multiplexer further includes a plurality of polarization rotators, and a quantity of the plurality of polarization rotators is equal to a quantity of the plurality of first input waveguides or a quantity of the plurality of second input waveguides;

[0013] each input waveguide of one group of the first input waveguide group and the second input waveguide group is cascaded with one of the plurality of polarization rotators, and the one of the plurality of polarization rotators is configured to change a polarization state of each wavelength signal inputted into the one group, such that the polarization state of the plurality of incident lights incident on the first input waveguide group is perpendicular to the polarization state of the plurality of incident lights incident on the second input waveguide group.

[0014] According to some embodiments of the present disclosure, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and any one of an etched diffraction grating structure being polarization-insensitive, an arrayed waveguide grating structure being polarization-insensitive and an angled multi-mode interferometer structure being polarization-insensitive, and each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to the any

one of the etched diffraction grating structure, the arrayed waveguide grating structure and the angled multi-mode interferometer structure through a respective one of the plurality of multi-mode interferometers.

[0015] According to some embodiments of the present disclosure, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an etched diffraction grating structure being polarization-insensitive. The etched diffraction grating structure includes a plurality of first input channels, a plurality of second input channels, a free propagation region, an etched diffraction grating facet and an output channel. The plurality of first input channels, the plurality of second input channels and the output channel are respectively located at different positions on a circumference of a Rowland circle of the free propagation region, each of the plurality of first input channels is connected to a corresponding one of the plurality of first input waveguides through a respective one of the plurality of multi-mode interferometers, and each of the plurality of second input channels is connected to a corresponding one of the plurality of second input waveguides through a respective one of the plurality of multi-mode interferometers;

[0016] the free propagation region comprises a slab waveguide, and the slab waveguide is configured such that the predetermined difference exists, within the slab waveguide, between an effective refractive index of a transmission mode of the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state; the etched diffraction grating facet is configured to respectively diffract the plurality of incident lights having the first polarization state and the plurality of incident lights having the second

polarization state that have passed through the free propagation region, such that the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state are each focused at the output channel and are combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide.

[0017] According to some embodiments of the present disclosure, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an arrayed waveguide grating structure, and the arrayed waveguide grating structure includes an input slab waveguide, an output slab waveguide and a plurality of arrayed waveguides connected between the input slab waveguide and the output slab waveguide, each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to the input slab waveguide through a respective one of the plurality of multi-mode interferometers, and the output waveguide is connected to the output slab waveguide; each of the plurality of arrayed waveguides includes a tapered waveguide, a straight waveguide and a curved waveguide, a constant length difference exists between two adjacent arrayed waveguides of the plurality of arrayed waveguides, and the predetermined difference exists, within the input slab waveguide and the output slab waveguide, between an effective refractive index of the first polarization state and an effective refractive index of the second polarization state, such that the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state are combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide after being subjected to phase configuration by the plurality of arrayed waveguides in the

arrayed waveguide grating structure.

[0018] According to some embodiments of the present disclosure, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an angled multi-mode interferometer structure, and the angled multi-mode interferometer structure includes the plurality of first input waveguides, the plurality of second input waveguides, a multi-mode interference region and the output waveguide. Each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to a same side of the multi-mode interference region through a respective one of the plurality of multi-mode interferometers, and a horizontal axial distance between a junction of each of the plurality of first input waveguides with the multi-mode interference region and a junction of the output waveguide with the multi-mode interference region and a horizontal axial distance between a junction of each of the plurality of second input waveguides with the multi-mode interference region and the junction of the output waveguide with the multi-mode interference region are configured to have a preset difference;

[0019] the multi-mode interference region is configured such that the predetermined difference exists, within the multi-mode interference region, between an effective refractive index of a transmission mode of the inputted plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the inputted plurality of incident lights having the second polarization state, so as to cause the inputted plurality of incident lights having the first polarization state and the inputted plurality of incident lights having the second polarization state to be focused at the output waveguide and to be combined into one multi-wavelength and polarization

multiplexed light to be outputted from the output waveguide.

[0020] According to some embodiments of the present disclosure, the on-chip integrated wavelength division multiplexer includes a substrate and a core layer located above the substrate, the flat-top wavelength division multiplexing structure is located in the core layer, and the core layer is any one of a silicon nitride layer, a silicon layer and a lithium niobate layer.

[0021] According to some embodiments of the present disclosure, the wavelength division multiplexer further includes a coupling structure, and the coupling structure is connected to the output waveguide of the flat-top wavelength division multiplexing structure, and the coupling structure is configured to couple the multi-wavelength and polarization multiplexed optical signal outputted from the output waveguide of the flat-top wavelength division multiplexing structure to an external optical fiber.

[0022] According to still another aspect of the present disclosure, a photonic integrated circuit chip is provided, and the photonic integrated circuit chip includes the on-chip integrated wavelength division multiplexer according to any one of the foregoing.

[0023] In the on-chip integrated wavelength division multiplexer and the photonic integrated circuit chip provided in the embodiments of the present disclosure, the wavelength division multiplexer includes a flat-top wavelength division multiplexing structure being polarization-insensitive, the flat-top wavelength division multiplexing structure has a first input waveguide group, a second input waveguide group and an output waveguide, and since the flat-top wavelength division multiplexing structure groups the central wavelengths configured for the first input waveguide group and the second input waveguide

group into even and odd groups, and optical signals of different groups are respectively inputted into the wavelength division multiplexer in different polarization states, and on the basis of the single flat-top wavelength division multiplexing structure being polarization-insensitive, by configuring corresponding parameters of the flat-top wavelength division multiplexing structure, for example, by configuring that a predetermined difference exists between effective refractive indices of transmission modes, within the flat-top wavelength division multiplexing structure, of a plurality of incident lights having different polarization states, two groups of a plurality of optical signals of different wavelengths with different polarization states are multiplexed into one multi-wavelength and polarization multiplexed light, whereby signal crosstalk between adjacent channels is reduced, the structural complexity of the wavelength division multiplexer is simplified and the size of the wavelength division multiplexer is reduced, and an integration level of the photonic integrated circuit chip is facilitated to be improved.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The technical solutions and other beneficial effects of the present disclosure will be made apparent by means of a detailed description of specific embodiments of the present disclosure in conjunction with the accompanying drawings hereinafter.

[0025] FIG. 1 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer in the related art;

[0026] FIG. 2 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer provided in one embodiment of the present

disclosure;

[0027] FIG. 3 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer provided in still another embodiment of the present disclosure;

[0028] FIG. 4 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer provided in another embodiment of the present disclosure;

[0029] FIG. 5 is a schematic structural diagram of a polarization rotator (PR) in the on-chip integrated wavelength division multiplexer shown in FIG. 4;

[0030] FIG. 6 is a schematic diagram of an etched diffraction grating structure being polarization-insensitive being employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure;

[0031] FIG. 7 is a schematic simulation diagram of wavelength division multiplexing performed by means of the etched diffraction grating structure in FIG. 6 in one embodiment of the present disclosure.

[0032] FIG. 8 is a schematic diagram of an arrayed waveguide grating structure being polarization-insensitive being employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure;

[0033] FIG. 9 is a schematic diagram of an angled multi-mode interferometer being polarization-insensitive being employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure.

[0034] Main reference numerals:

[0035] 1000, on-chip integrated wavelength division multiplexer; 110, flat-top wavelength division multiplexing structure; 501, first input waveguide; 502, second input waveguide; 503, output waveguide; 220, polarization rotator;

[0036] 221, ridge waveguide; 222, planar waveguide; 221a, first wedge-shaped structure; 221b, linear structure; 221c, second wedge-shaped structure; 222a, third wedge-shaped structure; 222b, fourth wedge-shaped structure;

[0037] 140, etched diffraction grating structure; 141, first input channel; 142, second input channel; 143, output channel; 144, free propagation region; 145, etched diffraction grating facet;

[0038] 150, arrayed waveguide grating structure; 151, input slab waveguide; 152, arrayed waveguide; 153, output slab waveguide;

[0039] 160, angled multi-mode interferometer; 161, first input waveguide; 162, second input waveguide; 163, multi-mode interference region; 164, output waveguide.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0040] The technical solutions in the embodiments of the present disclosure will be described clearly and completely hereinafter in conjunction with the accompanying drawings in the embodiments of the present disclosure. Apparently, the described embodiments are merely some of the embodiments of the present disclosure, rather than all of the embodiments. All other embodiments obtained by a person skilled in the art without involving any inventive effort on the basis of the embodiments in the present disclosure shall fall within the scope of protection of the present disclosure.

[0041] The terms "first" and "second" herein are merely used for descriptive purposes, and shall not be construed as indicating or implying relative importance or implicitly indicating a quantity of the indicated technical features. Thus, a feature defined with "first" or "second" may explicitly or implicitly

include one or more of the features. In the description of the present disclosure, "a plurality of" means two or more, unless otherwise expressly and specifically defined.

[0042] In the description of the present disclosure, it should be noted that, unless otherwise expressly specified and defined, the terms "mount", "connected" and "connection" shall be construed in a broad sense, and for example, may be a fixed connection, a detachable connection or an integral connection; may be a mechanical connection or an electrical connection, or may be mutually communicable; and may be a direct connection or an indirect connection by means of an intermediate medium, and may be internal communication between two elements or an interaction relationship between two elements. For a person of ordinary skill in the art, specific meanings of the above terms in the present disclosure may be understood according to specific situations.

[0043] The disclosure hereinafter provides many different implementations or examples for achieving different structures of the present disclosure. In order to simplify the disclosure of the present disclosure, components and arrangements of specific examples are described hereinafter. Of course, these are merely examples and are not intended to limit the present disclosure. In addition, reference numerals and/or reference letters may be repeated in different examples in the present disclosure, and such repetition is for purposes of simplification and clarity and does not in itself indicate a relationship between the various implementations and/or arrangements discussed.

[0044] One embodiment of the present disclosure provides an on-chip integrated wavelength division multiplexer, and the wavelength division

multiplexer is integrated on a photonic integrated circuit chip, and includes a flat-top wavelength division multiplexing structure being polarization-insensitive. The flat-top wavelength division multiplexing structure has a first input waveguide group, a second input waveguide group and an output waveguide, the first input waveguide group includes a plurality of first input waveguides, the second input waveguide group includes a plurality of second input waveguides, and the second input waveguide group is located at one side of the first input waveguide group.

[0045] The plurality of first input waveguides are configured to respectively receive a plurality of incident lights of a predetermined first wavelength group and having a first polarization state, the plurality of second input waveguides are configured to respectively receive a plurality of incident lights of a predetermined second wavelength group and having a second polarization state, the output waveguide is a waveguide being polarization-insensitive, and the output waveguide is configured to output a multi-wavelength and polarization multiplexed light, and the first polarization state and the second polarization state are perpendicular to each other.

[0046] The first wavelength group is one of an odd group and an even group among wavelengths $\lambda 1, \lambda 2, \lambda 3 \ldots \lambda n$ having a predetermined wavelength spacing, and the second wavelength group is another group of the odd group and the even group, $n \geq 4$ and n is a positive integer, and $\lambda 1, \lambda 2, \lambda 3 \ldots \lambda n$ are sequentially arranged from smallest to largest or from largest to smallest according to the predetermined wavelength spacing.

[0047] The flat-top wavelength division multiplexing structure is configured such that a predetermined difference exists between an effective refractive index

of a transmission mode of the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state within the flat-top wavelength division multiplexing structure, causing the plurality of incident lights having the first polarization state received by the plurality of first input waveguides and the plurality of incident lights having the second polarization state received by the plurality of second input waveguides to be combined into one multi-wavelength and polarization multiplexed light within the flat-top wavelength division multiplexing structure and to be outputted from the output waveguide.

[0048] In the on-chip integrated wavelength division multiplexer provided in the embodiment of the present disclosure, the wavelength division multiplexer includes a flat-top wavelength division multiplexing structure being polarization-insensitive, the flat-top wavelength division multiplexing structure has a first input waveguide group, a second input waveguide group and an output waveguide, and since odd-even grouping is performed by the flat-top wavelength division multiplexing structure on central wavelengths configured for the first input waveguide group and the second input waveguide group, and optical signals of different groups are respectively inputted into the wavelength division multiplexer in different polarization states, and on the basis of the single flat-top wavelength division multiplexing structure being polarization-insensitive, by configuring corresponding parameters of the flat-top wavelength division multiplexing structure, for example, by configuring that a predetermined difference exists between effective refractive indices of transmission modes, within the flat-top wavelength division multiplexing structure, of a plurality of

incident lights having different polarization states, two groups of a plurality of optical signals of different wavelengths with different polarization states are multiplexed into one multi-wavelength and polarization multiplexed light; on the one hand, the configuration of odd-even grouping of the central wavelengths doubles a spacing of the central wavelengths of adjacent channels in a same group, whereby signal crosstalk between adjacent channels is reduced; on the other hand, multi-wavelength and polarization multiplexing is achieved by means of the single flat-top wavelength division multiplexing structure being polarization-insensitive, whereby the structural complexity of the wavelength division multiplexer is simplified and the size of the wavelength division multiplexer is reduced, and an integration level of the photonic integrated circuit chip is facilitated to be improved.

[0049] Further, a bandwidth of a channel corresponding to each of the plurality of first input waveguides or each of the plurality of second input waveguides in the flat-top wavelength division multiplexing structure covers a frequency band range corresponding to a central wavelength of the incident light configured for the corresponding first input waveguide or the corresponding second input waveguide plus a preset offset threshold. That is, each channel in the flat-top wavelength division multiplexing structure has a relatively wide flat-top waveband bandwidth, and an actual operating wavelength is allowed to drift within a relatively large range, which is favorable for reducing sensitivity of the on-chip integrated wavelength division multiplexer to a waveguide width, a waveguide height, a waveguide inclination angle and a change of an ambient temperature. Moreover, no feedback adjustment is required during operation of the flat-top wavelength division multiplexing structure, whereby operating

efficiency is improved and energy consumption of the device is reduced.

[0050] FIG. 2 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer provided in one embodiment of the present disclosure.

[0051] A structure and an operating mechanism of the on-chip integrated wavelength division multiplexer 1000 will be described in further detail hereinafter in conjunction with FIG. 2.

[0052] Referring to FIG. 2, exemplarily, in the present embodiment, an on-chip integrated wavelength division multiplexer of four wavelengths is taken as an example, and is used for multiplexing four optical signals having a predetermined wavelength spacing and having wavelengths of λ1, λ2, λ3 and λ4 respectively into one multi-wavelength and polarization multiplexed light, and λ1, λ2, λ3 and λ4 are arranged in an order of wavelength magnitude, for example, arranged from smallest to largest. The on-chip integrated wavelength division multiplexer 1000 includes a flat-top wavelength division multiplexing structure 110 being polarization-insensitive, and the flat-top wavelength division multiplexing structure 110 has a first input waveguide group, a second input waveguide group and an output waveguide 503. The first input waveguide group includes two first input waveguides 501, the second input waveguide group includes two second input waveguides 502, and the second input waveguide group is located at one side of the first input waveguide group, that is to say, all of the second input waveguides are located at an outer side of an outermost one of the first input waveguides.

[0053] In this embodiment, an odd group λ1 and λ3 among the four wavelengths λ1, λ2, λ3 and λ4 is set as the predetermined first wavelength group,

and an even group λ2 and λ4 is set as the predetermined second wavelength group. The two first input waveguides 501 are respectively configured to receive the predetermined first wavelength group λ1 and λ3, and the two second input waveguides 502 are respectively configured to receive the predetermined second wavelength group λ2 and λ4. Two incident lights of the first wavelength group have a first polarization state, for example, a TE polarization mode, two incident lights of the second wavelength group have a second polarization state, for example, a TM polarization mode, and the first polarization state and the second polarization state are perpendicular to each other. The output waveguide 503 is configured to output one combined multi-wavelength and polarization multiplexed light of λ1, λ2, λ3 and λ4.

[0054] Specifically, two incident optical signals (λ1 and λ3) having the first polarization state (for example, a TE mode) are inputted by the two first input waveguides 501 of the flat-top wavelength division multiplexing structure 110, two incident optical signals (λ2 and λ4) having the second polarization state (for example, a TM mode) are inputted by the two second input waveguides 502 of the flat-top wavelength division multiplexing structure 110, and the flat-top wavelength division multiplexing structure 110 is configured such that a predetermined difference exists between an effective refractive index of a transmission mode of the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state within the flat-top wavelength division multiplexing structure, such that the two incident lights having the first polarization state received by the two first input waveguides 501 and the two incident lights having the second polarization state received by the

two second input waveguides 502 are combined into one multi-wavelength and polarization multiplexed light of λ1, λ2, λ3 and λ4 and outputted from the output waveguide 503. In this embodiment, two groups of a plurality of optical signals of different wavelengths with different polarization states are multiplexed into one multi-wavelength and polarization multiplexed light by means of the single flat-top wavelength division multiplexing structure being polarization-insensitive, whereby the structural complexity of the wavelength division multiplexing structure is simplified and the size of the wavelength division multiplexing structure is reduced, and an integration level of the photonic integrated circuit chip is facilitated to be improved.

[0055] In addition, a 1 dB flat-top waveband bandwidth of each channel in the flat-top wavelength division multiplexing structure 110 is capable of covering a frequency band range corresponding to a central wavelength of the incident light configured for the corresponding two first input waveguides 501 or the corresponding two second input waveguides 502 plus a preset offset threshold. That is, a bandwidth of each channel of the flat-top wavelength division multiplexing structure 110 is greater than a frequency band bandwidth corresponding to an offset wavelength range at two sides of a central wavelength, that is, a frequency band range between (λn+Δλ) and (λn−Δλ), where n = 1, 2, 3, 4… (where Δλ is a half of a passband width required by a system for the on-chip integrated wavelength division multiplexing device, that is, the above preset offset threshold). The ITU standard specifies that an operating bandwidth of each channel in the flat-top wavelength division multiplexing structure 110 having a wavelength spacing of generally 20 nm is a central wavelength ±6.5 nm, that is, the offset threshold Δλ specified by the standard is 6.5 nm. In this embodiment,

spectral flattening design is performed on the flat-top wavelength division multiplexing structure, such that the flat-top wavelength division multiplexing structure has a flat-top filtering spectrum, so that the bandwidth of each channel is greater than a frequency band range corresponding to an offset of 6.5 nm before and after a central wavelength corresponding to the channel, that is, greater than 13 nm, thereby ensuring that an actual incident central wavelength can still pass through with a low loss when fluctuating within a range of the offset threshold, and avoiding a problem of an excessive loss caused when an actual incident optical signal fluctuates and drift from a central wavelength.

[0056] It should be noted that the bandwidth of each channel described above refers to a 1 dB bandwidth of a filtering spectrum of each channel, that is, an optical loss within the bandwidth range is less than 1 dB as compared with a loss at a central wavelength. Bandwidths referred to in the following embodiments each likewise represent a 1 dB bandwidth.

[0057] In this embodiment, the above channel grouping manner of odd-even staggering is employed, which enables a spacing of central wavelengths of adjacent channels in a same group in the flat-top wavelength division multiplexing structure to be relatively large, for example, enables the spacing of the central wavelengths to be doubled, thereby avoiding a problem of crosstalk between channels caused when an actual incident optical signal fluctuates and deviates from a central wavelength.

[0058] Specifically, taking four ($\lambda1$, $\lambda2$, $\lambda3$ and $\lambda4$) wavelength-division optical signals as an example, a spacing of central wavelengths between adjacent channels of $\lambda1$, $\lambda2$, $\lambda3$ and $\lambda4$, that is, a difference between two adjacent central wavelengths, is set to 20 nm. Then, since odd-even grouping is performed on the

channels, a spacing of central wavelengths of channels corresponding to two adjacent first input waveguides 501 or two adjacent second input waveguides 502 in a same group is 40 nm, which is twice that before the grouping. The spacing of the central wavelengths between adjacent channels is increased, so that the bandwidth of each channel can be designed to be relatively wide, and the crosstalk between the channels will not be increased. For example, the bandwidth of each channel can be made to be greater than or equal to $2\Delta\lambda$ and less than 40 nm, that is, the 1 dB bandwidth of each channel is greater than or equal to twice the offset threshold and less than twice the predetermined wavelength spacing. Exemplarily, the above $\Delta\lambda$ is a central wavelength offset threshold required by a system, and for example, the ITU standard specifies that the offset threshold $\Delta\lambda$ is 6.5 nm, and then the 1 dB bandwidth of each channel of a filtering spectrum of the wavelength division multiplexing structure is within a range of 13 nm to 40 nm.

[0059] Since odd-even grouping is performed by the flat-top wavelength division multiplexing structure 110 on the central wavelengths configured for the first input waveguide group and the second input waveguide group, a spacing of central wavelengths of adjacent channels having a same polarization state in the flat-top wavelength division multiplexing structure is relatively large, whereby crosstalk between the channels is reduced. Meanwhile, the flat-top wavelength division multiplexing structure has a flat-top filtering spectrum, such that each channel thereof has a relatively wide bandwidth, and therefore the flat-top wavelength division multiplexing structure is capable of tolerating a problem of crosstalk between adjacent channels brought about by a central wavelength offset caused by an influence of a waveguide width, a waveguide inclination

angle, a waveguide height and a temperature change.

[0060] It should be understood that, as shown in FIG. 3, when λ1, λ2, λ3, λ4… λ7 and λ8 wavelength-division optical signals having a predetermined wavelength spacing and arranged from smallest to largest according to wavelength are inputted into the plurality of input waveguides of the flat-top wavelength division multiplexing structure 110, likewise, a multiplexing manner of staggered grouping is employed, incident optical signals of an odd group are inputted from a corresponding channel of each first input waveguide 501 of the flat-top wavelength division multiplexing structure 110, and incident optical signals of an even group are inputted from a corresponding channel of each second input waveguide 502 of the flat-top wavelength division multiplexing structure 110. For example, λ1, λ3, λ5 and λ7 of the odd group and having the first polarization state are inputted into the corresponding channel of each first input waveguide 501 of the flat-top wavelength division multiplexing structure 110 to be multiplexed, so as to obtain a combined light of λ1/λ3/λ5/λ7. λ2, λ4, λ6 and λ8 of the even group and having the second polarization state are inputted into the corresponding channel of each second input waveguide 502 of the flat-top wavelength division multiplexing structure 110 to be multiplexed, so as to obtain a combined light of λ2/λ4/λ6/λ8. It can be understood that, by configuring corresponding parameters of the flat-top wavelength division multiplexing structure 110, for example, by configuring that a predetermined difference exists between effective refractive indices of transmission modes, within the flat-top wavelength division multiplexing structure 110, of a plurality of incident lights having different polarization states, a plurality of incident lights having the first polarization state and a plurality of incident lights having the second polarization

state are each focused to one output waveguide for outputting, so that multi-wavelength and polarization wavelength division multiplexing is achieved. In addition, when more λ1, λ2, λ3, λ4… λn wavelength-division optical signals having a predetermined wavelength spacing are inputted into the plurality of first input waveguides 501 and the plurality of second input waveguides 502 of the flat-top wavelength division multiplexing structure 110, where $n > 8$, the same manner as described above may be employed for implementation, and details are not described herein again.

[0061] The above on-chip integrated wavelength division multiplexer includes a substrate and a core layer located above the substrate, and the flat-top wavelength division multiplexing structure is located in the core layer, and the core layer is any one of a silicon nitride layer, a silicon layer and a lithium niobate layer. Specifically, the on-chip integrated wavelength division multiplexer in the above embodiments is a silicon-based wavelength division multiplexer, the core layer is a silicon nitride layer, and the on-chip integrated wavelength division multiplexer includes a silicon-based substrate, a buried oxide layer and a silicon nitride layer, and the flat-top wavelength division multiplexing structure is provided on the silicon nitride layer. Of course, an on-chip integrated wavelength division multiplexer structure based on another semiconductor material may also be employed, for example, a wavelength division multiplexer based on a silicon material or a wavelength division multiplexer based on a lithium niobate material, such as providing the flat-top wavelength division multiplexing structure in a silicon layer of a silicon-on-insulator structure, or providing the flat-top wavelength division multiplexing structure in a lithium niobate layer (such as a thin-film lithium niobate), and the present disclosure is not limited

thereto.

[0062] The flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and any one of an etched diffraction grating structure being polarization-insensitive, an arrayed waveguide grating structure being polarization-insensitive and an angled multi-mode interferometer structure being polarization-insensitive, and each of the plurality of first input waveguides and each of the plurality of second input waveguides are each cascaded with one of the plurality of multi-mode interferometers, so as to achieve flattening of an output filtering spectrum, thereby increasing the 1 dB bandwidth of each channel.

[0063] FIG. 4 is a schematic structural diagram of an on-chip integrated wavelength division multiplexer provided in another embodiment of the present disclosure, and FIG. 5 is a schematic structural diagram of a polarization rotator (PR) in the on-chip integrated wavelength division multiplexer shown in FIG. 4.

[0064] Generally, in an optical communication system, a plurality of optical signals requiring wavelength division multiplexing generally have a same polarization state. As shown in FIG. 4 and FIG. 5, in the present embodiment, the on-chip integrated wavelength division multiplexer 1000 further includes a polarization rotator (PR) 220, which is used for changing the polarization state of one group of incident lights. For example, when λ1, λ2, λ3, λ4… λn wavelength-division optical signals having a predetermined wavelength spacing and being arranged from smallest to largest according to wavelength are inputted into the plurality of first input waveguides 501 and the plurality of second input waveguides 502 of the flat-top wavelength division multiplexing structure, only a plurality of input waveguides in one group thereof are respectively cascaded

with the polarization rotators 220, so as to change the polarization state of the received light beams, such that the polarization state of the incident lights incident on the first input waveguide group is perpendicular to the polarization state of the incident lights incident on the second input waveguide group. The polarization state of the incident lights in another group of the input waveguides remains unchanged.

[0065] Optionally, the above polarization rotator 220 may also be a silicon-based polarization rotator (PR), and in some embodiments, the silicon-based polarization rotator (PR) may be integrated with the flat-top wavelength division multiplexing structure in a same photonic integrated circuit chip. In some other embodiments, the polarization rotator (PR) may also be a discrete optical device, for example, a half-wave plate or a Faraday rotator.

[0066] As shown in FIG. 5, in the present embodiment, the polarization rotator 220 is used for changing the original polarization state of a received light beam into a polarization state perpendicular to the original polarization state. The polarization rotator 220 includes a ridge waveguide 221 and a partial planar waveguide 222 located at one side of the ridge waveguide 221. The ridge waveguide 221 includes a first wedge-shaped structure 221a, a linear structure 221b and a second wedge-shaped structure 221c which are connected in sequence. The first wedge-shaped structure 221a serves as an input end of the polarization rotator 220, and the width of the first wedge-shaped structure 221a gradually narrows along the direction of an optical path until the first wedge-shaped structure 221a is flush with and connected to the linear structure 221b. The width of the second wedge-shaped structure 221c gradually widens along the direction of the optical path until the second wedge-shaped structure 221c is

connected to an external optical waveguide. The height of the partial planar waveguide 222 is lower than the height of the ridge waveguide 221, and the partial planar waveguide 222 includes a third wedge-shaped structure 222a and a fourth wedge-shaped structure 222b which are located at a same side of the ridge waveguide 221 and are connected to each other. The third wedge-shaped structure 222a is immediately adjacent to a side face of the first wedge-shaped structure 221a, the fourth wedge-shaped structure 222b is immediately adjacent to a side face of the linear structure 221b, a tip of the third wedge-shaped structure 222a closely abuts a side face of a wider end of the first wedge-shaped structure 221a, and a tip of the fourth wedge-shaped structure 222b is adjacent to a narrower end of the second wedge-shaped structure 221c. Linearly polarized light is incident from the wider end of the first wedge-shaped structure 221a of the ridge waveguide 221, and at sections of the first wedge-shaped structure 221a and the linear structure 221b, the optical mode is distributed into the ridge waveguide 221 and the planar waveguide 222, such that the polarization state of the linearly polarized light will be rotated, and the polarization state has been rotated by 90 degrees when the linearly polarized light is incident on the second wedge-shaped structure 221c, and then the linearly polarized light is coupled into an external optical waveguide through the second wedge-shaped structure 221c.

[0067] FIG. 6 is a schematic diagram of an etched diffraction grating structure being polarization-insensitive employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure.

[0068] As shown in FIG. 6, in the present embodiment, an etched diffraction grating structure being polarization-insensitive is employed as the flat-top wavelength division multiplexing structure, and exemplarily, the flat-top

wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an etched diffraction grating structure. The etched diffraction grating structure 140 includes a plurality of first input channels 141, a plurality of second input channels 142, a free propagation region 144, an etched diffraction grating facet 145 and an output channel 143. The plurality of first input channels 141, the plurality of second input channels 142 and the output channel 143 are respectively located at different positions on a circumference of a Rowland circle of the free propagation region 144, each of the plurality of first input channels 141 is connected to a corresponding one of the plurality of first input waveguides through a respective one of the plurality of multi-mode interferometers, each of the plurality of second input channels 142 is connected to a corresponding one of the plurality of second input waveguides through a respective one of the plurality of multi-mode interferometers, the output channel is connected to the output waveguide, and the output waveguide is a waveguide being polarization-insensitive. The free propagation region 144 includes a slab waveguide, and the free propagation region 144 is configured, on the basis of a relationship between an effective refractive index of a fundamental mode in the slab waveguide base on a core layer material and a thickness of the slab waveguide base on the core layer material, such that a predetermined difference exists between an effective refractive index of a transmission mode of an inputted plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of an inputted plurality of incident lights having the second polarization state in the etched diffraction grating structure. The etched diffraction grating facet 145 is configured to respectively diffract the plurality of incident lights having the first polarization state and the plurality of

incident lights having the second polarization state that have passed through the free propagation region, according to a correspondence relationship among a wavelength, an effective refractive index of a fundamental mode of the slab waveguide base on the core layer material and a diffraction angle, such that the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state that have passed through the free propagation region are combined into one multi-wavelength and polarization multiplexed light, and the output channel 143 is configured to output the multi-wavelength and polarization multiplexed light.

[0069] Exemplarily, in the present embodiment, the etched diffraction grating structure includes two first input channels, two second input channels and one output channel in total. Incident optical signals ($\lambda 1$ and $\lambda 3$) of an odd group and having the first polarization state (for example, a TE mode) received by the first input waveguide group are respectively inputted into the free propagation region from the plurality of first input channels (for example, TE input channels) through the multi-mode interferometers. Incident optical signals ($\lambda 2$ and $\lambda 4$) of an even group and having the second polarization state (for example, a TM mode) received by the second input waveguide group are respectively inputted from the plurality of second input channels (for example, TM input channels) through the multi-mode interferometers. When initial polarization states of the plurality of incident lights of the odd group and the even group are the same, for example, are both a TE mode, each of the second input waveguides may be cascaded with a polarization rotator, so as to rotate the incident optical signals originally having the first polarization state (such as a TE mode) into incident optical signals having the second polarization state (such as a TM mode), and

subsequently the incident optical signals having the second polarization state are inputted into the etched diffraction grating structure via the second input waveguides. The etched diffraction grating structure achieves focusing of light beams of different wavelengths on the Rowland circle by means of an arrangement of etched diffraction grating teeth satisfying an optical path difference relationship. By respectively inputting the plurality of incident optical signals having the first polarization state and the plurality of incident optical signals having the second polarization state at different input positions and at different input angles, and calculating a position of the output channel on the corresponding Rowland circle, and the inputted plurality of incident lights of the odd group and having the first polarization state and the inputted plurality of incident lights of the even group and having the second polarization state can all be focused at the output channel located on the Rowland circle, so that a multi-wavelength and polarization multiplexed optical signal is outputted via the output waveguide. During operation, two incident optical signals λ1 and λ3 of the odd group and having the first polarization state are inputted from preset positions and, after passing through an interior of the Rowland circle, generate two input mode spots, and subsequently the two input mode spots enter the free propagation region 144 of the Rowland circle to propagate, are incident on corresponding reflecting surfaces of the etched diffraction grating facet 145, and are focused at the output channel located on the Rowland circle after being reflected by the etched diffraction grating facet 145. Likewise, two incident optical signals λ2 and λ4 of the even group and having the second polarization state are inputted from preset positions and, after passing through the interior of the Rowland circle, generate two input mode spots, and subsequently the two

input mode spots enter the free propagation region 144 of the Rowland circle to propagate, are incident on corresponding reflecting surfaces of the etched diffraction grating facet 145, and are likewise focused at the output channel located on the Rowland circle after being reflected by the etched diffraction grating facet 145, so that one multi-wavelength and polarization multiplexed optical signal (λ2/λ4) is outputted from the output channel 143.

[0070] It should be understood that, since odd-even grouping is performed on the wavelengths of the incident lights configured for the first input waveguide group and the second input waveguide group of the etched diffraction grating structure being polarization-insensitive, a spacing between central wavelengths of adjacent channels in the flat-top wavelength division multiplexing structure is relatively large, and a predetermined wavelength spacing of the adjacent channels can be doubled. Meanwhile, in the flat-top wavelength division multiplexing structure, by connecting a multi-mode interferometer (MMI) between the first input waveguide and the first input channel and connecting an MMI between the second input waveguide and the second input channel, flattening of an output frequency spectrum is achieved, such that each channel thereof has a relatively wide flat-top waveband bandwidth, so that when an actual incident central wavelength fluctuates, the actual incident central wavelength can still pass through with a low loss, and a problem of an excessive loss caused when an actual incident optical signal fluctuates and deviates from the central wavelength is avoided.

[0071] In the present embodiment, an expression formula of a radius of the Rowland circle is derived according to a grating equation of the etched diffraction grating EDG, and the expression formula of the radius of the Rowland

circle is represented by the following formula:

[0072] $$L_f = \frac{D\lambda}{d\lambda}\frac{n_{eff}}{n_g}\frac{1}{\sin(\theta_{in}) + \sin(\theta_{out})}$$;

[0073] Wherein, Lf is a diameter of the Rowland circle, D is a waveguide spacing, λ is a central wavelength, dλ is a wavelength spacing of the input channels, neff is an effective refractive index of a fundamental mode of the free propagation region of the slab waveguide, ng is a group refractive index, θin is an incident angle, and θout is an output angle in a mode of the first polarization state or the second polarization state.

[0074] Inside the slab waveguide, since the slab waveguide is of a thin-film slab structure, and light of a TE polarization mode and light of a TM polarization mode differ in boundary conditions, there is a difference between neff of a transmission mode of the light of the TE polarization mode in the slab waveguide and neff of a transmission mode of the light of the TM polarization mode in the slab waveguide, and thus the predetermined difference between the two can be designed by utilizing this difference, such that incident lights of different polarization states that are inputted from different positions on the Rowland circle and at different input angles are all focused at a same output channel on the Rowland circle and are thus outputted from a same output waveguide. For example, the difference between neff of the transmission mode of the light of the TE polarization mode in the slab waveguide and neff of the transmission mode of the light of the TM polarization mode in the slab waveguide can be configured by changing a material type of the slab waveguide or a thickness of the slab waveguide. A difference between an effective refractive index of the TE polarization mode and an effective refractive index of the TM polarization mode is greater than a maximum value of effective refractive index differences of

different wavelengths in a same polarization mode, for example, greater than an effective refractive index difference between a first wavelength and a last wavelength in the same mode. In this embodiment, according to the above formula, a difference between an effective refractive index of the TM polarization mode and an effective refractive index of the TE polarization mode is required to satisfy the following condition. At a central wavelength, a difference between a product of a ratio of the effective refractive index of the TE polarization mode to a group refractive index and the wavelength, and a product of a ratio of the effective refractive index of the TM polarization mode to a group refractive index and the wavelength, is greater than a maximum value of differences between products of ratios of effective refractive indices to group refractive indices and corresponding wavelengths for different wavelengths in a same polarization mode. For example, the difference is greater than a difference between products of ratios of effective refractive indices to group refractive indices and corresponding wavelengths for a first wavelength and a last wavelength in the same mode.

[0075] In this embodiment, all of the incident lights are required to be focused at a same output channel, and therefore, on the above-mentioned Rowland circle, all of the wavelengths have a same output angle θout. By substituting parameters such as an equivalent refractive index neff-TE of the TE polarization mode, the wavelengths of a corresponding group, a group refractive index and an output angle into the above Rowland circle formula, an input angle θin required to be satisfied by the incident light of each wavelength can be inversely derived. Likewise, by substituting parameters such as an equivalent refractive index neff-TM of the TM polarization mode, the wavelengths of a corresponding group, a

group refractive index and an output angle into the above Rowland circle formula, an input angle θin required to be satisfied by the incident light of each corresponding wavelength is inversely derived. The equivalent refractive indices of the two polarization modes are required to satisfy that the input angles of the incident lights of the respective wavelengths of the TE polarization mode and the input angles of the incident lights of the respective wavelengths of the TM polarization mode do not overlap at all, that is, positions, on the Rowland circle, of the input channels of the respective wavelength channels corresponding to the TE polarization mode and positions, on the Rowland circle, of the input channels of the respective wavelength channels corresponding to the TM polarization mode are completely separated from each other and are distributed in two regions that are completely staggered from each other. By determining the positions of the respective first input channels and the respective second input channels on the Rowland circle in the above manner, the incident lights of the first polarization state inputted from the respective first input channels and the incident lights of the second polarization state inputted from the respective second input channels can all be focused at a same output channel, so as to output one multi-wavelength and polarization multiplexed light, thereby achieving multi-wavelength and polarization multiplexing of a single wavelength division multiplexer.

[0076] FIG. 7 is a schematic simulation diagram of wavelength division multiplexing performed by means of the etched diffraction grating structure in FIG. 6 in one embodiment of the present disclosure. The simulation is performed on the basis of an etched diffraction grating structure on a silicon-based silicon nitride platform, which includes a silicon substrate, a silicon dioxide buried oxide

layer and a silicon nitride layer, and here the silicon nitride layer is the above slab waveguide, that is, the aforesaid core layer material is silicon nitride. In this embodiment, a thickness of the silicon nitride layer is 350 nm, a refractive index of silicon nitride is 2.15, and an equivalent refractive index difference of transmission modes (fundamental modes) of the TE polarization mode and the TM polarization mode in the silicon nitride layer is approximately 0.115, or is greater than 0.115, either of which enables the respective first input channels and the respective second input channels to be completely separated.

[0077] The simulation results are shown in FIG. 7, in which λ1, λ2, λ3 and λ4 are respectively 1271 nm, 1291 nm, 1311 nm and 1331 nm as specified in the ITU-T G.694.2 protocol, and the respective central wavelengths are spaced apart by 20 nm. In the left figure, solid lines represent filtering spectra of odd wavelength channels (which are inputted into the EDG as TE polarization signals), and 1 dB flat-top waveband bandwidths of the two channels with central wavelengths of 1271 nm and 1311 nm each reach approximately 20 nm, which is greater than 13 nm, and it can thereby be ensured that flat regions throughout the ranges of the central wavelengths of 1271 nm ±6.5 nm and 1311 nm ±6.5 nm required by the standard, with an optical loss lower than 1 dB. In the right figure, dashed lines represent filtering spectra of even wavelength channels (which are inputted into the EDG as TM polarization signals), and 1 dB flat-top waveband bandwidths of the two channels having central wavelengths of 1291 nm and 1331 nm also each reach approximately 20 nm, which is greater than 13 nm, and it can thereby be ensured that flat regions throughout the ranges of the central wavelengths of 1291 nm ±6.5 nm and 1331 nm ±6.5 nm, with an optical loss lower than 1 dB. Moreover, in the above two groups, the central wavelengths of

the adjacent channels are spaced apart by 40 nm, and this spacing is sufficiently large, whereby signal crosstalk between the channels is avoided. Therefore, even if the waveband of the central wavelength is shifted toward a longer waveband (red shift) or toward a shorter waveband (blue shift) due to factors such as an influence of a waveguide width, a waveguide height, a waveguide inclination angle and a temperature change, the flat-top wavelength division multiplexing structure can still ensure that flat regions throughout an offset range of the central wavelength ±6.5 nm required by the standard. A 1 dB bandwidth of a broadband wavelength division multiplexing device obtained by means of this design reaches 20 nm, which is significantly increased as compared with a bandwidth of a wavelength division multiplexing device not employing this design structure, and a broadband output response of the wavelength division multiplexing device being polarization-insensitive is successfully achieved, whereby feasibility of the present solution is verified.

[0078] FIG. 8 is a schematic diagram of an arrayed waveguide grating structure being polarization-insensitive employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure.

[0079] As shown in FIG. 8, in the present embodiment, an arrayed waveguide grating (AWG) structure being polarization-insensitive is employed as the flat-top wavelength division multiplexing structure, and exemplarily, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an arrayed waveguide grating structure being polarization-insensitive. The arrayed waveguide grating structure 150 includes an input slab waveguide 151, an output slab waveguide 153, and a plurality of arrayed waveguides 152 (also referred to as waveguide channels) connected between the

input slab waveguide and the output slab waveguide, and each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to the input slab waveguide 151 through a respective one of the plurality of multi-mode interferometers. Each of the plurality of arrayed waveguides includes a tapered waveguide, a straight waveguide and a curved waveguide, and a constant length difference exists between two adjacent arrayed waveguides. On the basis of a difference existing between effective refractive indices of transmission modes of incident lights of different polarizations in the input slab waveguide, the waveguide array and the output slab waveguide, and on the basis of the length differences of the respective arrayed waveguides, a polarization-wavelength dependent phase difference relationship is constructed, such that a plurality of incident lights having the first polarization state and a plurality of incident lights having the second polarization state are combined into one multi-wavelength and polarization multiplexed light after being subjected to phase configuration by the input slab waveguide 151, the plurality of arrayed waveguides 152 and the output slab waveguide 153, so as to achieve hybrid multiplexing of multi-wavelength and polarization by means of a single arrayed waveguide grating AWG. Specifically, in the arrayed waveguide grating structure being polarization-insensitive, a predetermined difference between an effective refractive index of the TE polarization mode and an effective refractive index of the TM polarization mode is greater than a maximum value of effective refractive index differences of different wavelengths in a same polarization mode, for example, greater than an effective refractive index difference between a first wavelength and a last wavelength in the same mode.

[0080] Exemplarily, a quantity of channels of the plurality of arrayed

waveguides 152 is 15, and of course may also be another quantity, which is not limited in the present disclosure. Specifically, the arrayed waveguide grating structure 150 is fabricated on a silicon on insulator (SOI) material by employing an etching process, the SOI material includes a top silicon layer, a silicon dioxide buried oxide layer and a silicon substrate, and a thickness of the top silicon layer is 220 nm, whereby structures such as the arrayed waveguides can be formed on the top silicon layer by etching, and an etching depth is, for example, 220 nm, that is, the core layer is a silicon layer. During operation, two incident optical signals λ1 and λ3 are focused, after being subjected to phase configuration by the input slab waveguide, the plurality of arrayed waveguides and the output slab waveguide in the arrayed waveguide grating structure, at a position where the output waveguide connected to the output slab waveguide, and are combined into one combined optical signal (λ1/λ3) to be outputted from the output waveguide. Likewise, two incident optical signals λ2 and λ4 are focused, after being subjected to phase configuration by the input slab waveguide, the plurality of arrayed waveguides and the output slab waveguide in the arrayed waveguide grating structure, at the position where the output waveguide connected to the output slab waveguide, and are combined into one combined optical signal (λ2/λ4) to be outputted from the output waveguide, and finally one multi-wavelength and polarization multiplexed optical signal containing λ1/λ2/λ3/λ4 is outputted via a same output waveguide. The flat-top wavelength division multiplexing structure formed by employing the above arrayed waveguide grating structure being polarization-insensitive can also widen the flat-top waveband bandwidth of the flat-top wavelength division multiplexing structure, and on the basis of the arrayed waveguide grating structure, two groups of a

plurality of optical signals of different wavelengths with different polarization states are multiplexed into one multi-wavelength and polarization multiplexed light, whereby the structural complexity of the wavelength division multiplexer is simplified and the size of the wavelength division multiplexer is reduced, thereby facilitating an improvement in the integration level of the photonic integrated circuit chip. Moreover, as compared with a flat-top wavelength division multiplexing structure formed by a plurality of cascaded Mach-Zehnder interferometer structures, the above arrayed grating structure has advantages such as a compact structure, a small size, a low insertion loss, a narrow wavelength division multiplexing spacing and a relatively low process difficulty.

[0081] FIG. 9 is a schematic diagram of an angled multi-mode interferometer being polarization-insensitive employed as a flat-top wavelength division multiplexing structure in one embodiment of the present disclosure.

[0082] As shown in FIG. 9, in the present embodiment, an angled multi-mode interferometer being polarization-insensitive is employed as the flat-top wavelength division multiplexing structure, and exemplarily, the flat-top wavelength division multiplexing structure includes a plurality of multi-mode interferometers and an angled multi-mode interferometer being polarization-insensitive. The angled multi-mode interferometer (MMI) 160 includes a plurality of the first input waveguides 161, a plurality of the second input waveguides 162, a multi-mode interference region 163 and one of the output waveguides 164, and each of the plurality of first input waveguides is connected to the multi-mode interference region through a respective one of the plurality of multi-mode interferometers, and each of the plurality of second input waveguides is connected to the multi-mode interference region through a

respective one of the plurality of multi-mode interferometers. A horizontal axial distance between each of the plurality of first input waveguides and the output waveguide and a horizontal axial distance between each of the plurality of second input waveguides and the output waveguide are all unequal, and connection positions of the respective first input waveguides at the multi-mode interference region and connection positions of the respective second input waveguides at the multi-mode interference region are completely separated. In FIG. 9, L1 represents a horizontal axial distance between a first one of the first input waveguides (λ1) and the output waveguide, L3 represents a horizontal axial distance between a second one of the first input waveguides (λ3) and the output waveguide, L2 represents a horizontal axial distance between a first one of the second input waveguides (λ2) and the output waveguide, and L4 represents a horizontal axial distance between a second one of the second input waveguides (λ4) and the output waveguide.

[0083] In the present embodiment, the horizontal axial distance between the input waveguide and the output waveguide in the above multi-mode interference region can be represented by the following expression formula:

[0084] $$L = \frac{4mn_{eff}w^2{}_{mmi}}{\lambda_n}$$;

[0085] where m is an imaging order, and m = 1 in the present embodiment, neff is an effective refractive index of a fundamental mode in the multi-mode interference region, Wmmi is a width of the multi-mode interference region, λn is a fundamental mode wavelength corresponding to an n-th channel, and L represents a distance between a center of each input waveguide and a center of the output waveguide along a length direction of the multi-mode interference region.

[0086] The multi-mode interference region 163 is configured, on the basis of a relationship between horizontal axial distances from input to output of incident lights having different polarization states and different wavelengths and effective refractive indices of fundamental modes transmitted in the multi-mode interference region for the different polarization states, such that an inputted plurality of incident lights having the first polarization state and an inputted plurality of incident lights having the second polarization state are all focused at the output waveguide and are combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide.

[0087] Exemplarily, taking wavelength division multiplexing of four channels as an example, the angled multi-mode interferometer 160 includes two first input waveguides, two second input waveguides and one output waveguide, and ends of the above first input waveguides, second input waveguides and output waveguide that are connected to the multi-mode interference region may each employ a tapered waveguide to perform mode field broadening.

[0088] A conventional angled multi-mode interferometer (MMI) achieves multiplexing and demultiplexing of wavelengths on the basis of different periodic lengths of different wavelengths in the multi-mode interference region 163. In the embodiment of the present disclosure, by utilizing that equivalent refractive indices of different polarization modes transmitted in the multi-mode interference region are different, a predetermined difference is made to exist, by means of design, between an equivalent refractive index of a fundamental mode of an incident optical signal having the first polarization state transmitted in the multi-mode interference region and an equivalent refractive index of a fundamental mode of an incident optical signal having the second polarization

state transmitted in the multi-mode interference region, and thus, after a plurality of incident lights having the first polarization state and a plurality of incident lights having the second polarization state are respectively incident into the multi-mode interference region from the first input waveguides and the second input waveguides that are located at different positions in a length direction of the multi-mode interference region, the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state can all be focused at a same output waveguide and be combined into one multi-wavelength and polarization multiplexed light to be outputted. Specifically, in the angled multi-mode interferometer, a predetermined difference between an effective refractive index of the TE polarization mode and an effective refractive index of the TM polarization mode is greater than a maximum value of effective refractive index differences of different wavelengths in a same polarization mode, for example, greater than an effective refractive index difference between a first wavelength and a last wavelength in the same mode.

[0089] Exemplarily, inputted wavelength signals λ1, λ2, λ3 and λ4 are firstly divided into two polarization states in an odd-even staggered manner through polarization rotators, that is, λ1 (TE), λ2 (TM), λ3 (TE) and λ4 (TM), wherein, λ1 (TE) and λ3 (TE) are respectively inputted from the two first input waveguides, and λ2 (TM) and λ4 (TM) are respectively inputted from the two second input waveguides. Subsequently, the four wavelength signals enter the multi-mode interference region 163 to form four input mode spots. Since the effective refractive indices of transmission modes of the four wavelength signals are different, and transmission of a fundamental mode is involved in the present

embodiment, and the effective refractive indices of the transmission modes of the TE and TM polarization states have a predetermined difference, an influence of the predetermined difference on an interference period is significantly greater than an influence of a difference between effective refractive indices of different wavelengths on the interference period, and for a fixed input position, output positions of input mode spots of the TE and TM polarization states are different, and meanwhile, output positions of different wavelengths are also different. Conversely, by respectively inputting incident lights of the TE polarization state and incident lights of the TM polarization state from a plurality of different input positions, outputting from a same output position can be achieved. That is, the four input mode spots formed by the aforesaid four wavelength signals in the multi-mode interference region are focused at a same output position by the multi-mode interference region, and are combined into one multi-wavelength and polarization multiplexed light to be outputted from a same output waveguide, so that the function shown in FIG. 9 is achieved. Moreover, a spacing of adjacent wavelengths in a same group is doubled by utilizing odd-even grouping, which is favorable for achieving an increase in bandwidth, and meanwhile reduces crosstalk between channels, so as to satisfy a requirement for a wavelength offset range in practical applications.

[0090] Further, as shown in FIG. 2, the on-chip integrated wavelength division multiplexer 1000 further includes a coupling structure 310, and the coupling structure 310 is connected to the output waveguide of the flat-top wavelength division multiplexing structure 110, and is used for coupling a combined optical signal outputted from the output waveguide of the flat-top wavelength division multiplexing structure 110 to an external optical fiber, so as to output an optical

signal for which combining has been completed, and the coupling structure 310 has a relatively high coupling efficiency and is capable of reducing a coupling optical path loss. Specifically, the coupling structure 310 may be a low polarization dependent loss edge coupler (low PDL edge coupler).

[0091] The present disclosure further provides a photonic integrated circuit chip, and the photonic integrated circuit chip includes the on-chip integrated wavelength division multiplexer according to any one of the foregoing embodiments.

[0092] In the on-chip integrated wavelength division multiplexer and the photonic integrated circuit chip provided in the embodiments of the present disclosure, the wavelength division multiplexer includes a flat-top wavelength division multiplexing structure being polarization-insensitive, the flat-top wavelength division multiplexing structure has a first input waveguide group, a second input waveguide group and an output waveguide, and since odd-even grouping is performed by the flat-top wavelength division multiplexing structure on central wavelengths configured for the first input waveguide group and the second input waveguide group, and optical signals of different groups are respectively inputted into the wavelength division multiplexer in different polarization states, and on the basis of the single flat-top wavelength division multiplexing structure being polarization-insensitive, by configuring corresponding parameters of the flat-top wavelength division multiplexing structure, for example, by configuring that a predetermined difference exists between effective refractive indices of transmission modes, within the flat-top wavelength division multiplexing structure, of a plurality of incident lights having different polarization states, two groups of a plurality of optical signals

of different wavelengths with different polarization states are multiplexed into one multi-wavelength and polarization multiplexed light, whereby the structural complexity of the wavelength division multiplexer is simplified and the size of the wavelength division multiplexer is reduced, thereby facilitating an improvement in the integration level of the photonic integrated circuit chip.

[0093] In the above embodiments, the description of each embodiment has its own emphasis, and for a part not described in detail in a certain embodiment, reference may be made to related descriptions of other embodiments.

[0094] The on-chip integrated wavelength division multiplexer and the photonic integrated circuit chip provided in the present disclosure have been described in detail above in conjunction with the embodiments, and specific examples have been applied herein to set forth principles and implementations of the present disclosure, and the description of the above embodiments is merely used for facilitating understanding of the technical solutions of the present disclosure and core ideas thereof. It should be understood by a person of ordinary skill in the art that modifications may still be made to the technical solutions described in the foregoing embodiments, or equivalent replacements may be made to some of the technical features therein, and such modifications or replacements do not cause the essence of the corresponding technical solutions to depart from the scope of the technical solutions of the embodiments of the present disclosure.

Claims

[Claim 1] An on-chip integrated wavelength division multiplexer, wherein the wavelength division multiplexer is integrated on a photonic integrated circuit chip, and the wavelength division multiplexer comprises a flat-top wavelength division multiplexing structure being polarization-insensitive, the flat-top wavelength division multiplexing structure having a first input waveguide group, a second input waveguide group and an output waveguide,

wherein the first input waveguide group comprises a plurality of first input waveguides, the second input waveguide group comprises a plurality of second input waveguides, and the second input waveguide group is located at one side of the first input waveguide group;

wherein the plurality of first input waveguides are configured to respectively receive a plurality of incident lights of a predetermined first wavelength group and having a first polarization state, the plurality of second input waveguides are configured to respectively receive a plurality of incident lights of a predetermined second wavelength group and having a second polarization state, the output waveguide is a polarization-insensitive waveguide, and the output waveguide is configured to output a multi-wavelength and polarization multiplexed light, wherein the first polarization state and the second polarization state are perpendicular to each other;

wherein the first wavelength group is one of an odd group and an even group among wavelengths λ1, λ2, λ3... λn having a predetermined wavelength spacing, and the second wavelength group is another group of the odd group and the even group,

wherein $n \geq 4$ and n is a positive integer, and $\lambda 1$, $\lambda 2$, $\lambda 3$... λn are sequentially arranged from smallest to largest or from largest to smallest according to the predetermined wavelength spacing; and

wherein the flat-top wavelength division multiplexing structure is configured such that a predetermined difference exists between an effective refractive index of a transmission mode of the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state within the flat-top wavelength division multiplexing structure, causing the plurality of incident lights having the first polarization state received by the plurality of first input waveguides and the plurality of incident lights having the second polarization state received by the plurality of second input waveguides to be combined into one multi-wavelength and polarization multiplexed light within the flat-top wavelength division multiplexing structure and to be outputted from the output waveguide.

[Claim 2] The on-chip integrated wavelength division multiplexer according to claim 1, wherein a bandwidth of a channel corresponding to each of the plurality of first input waveguides or each of the plurality of second input waveguides in the flat-top wavelength division multiplexing structure covers a frequency band range corresponding to a central wavelength of the incident light configured for the corresponding first input waveguide or the corresponding second input waveguide plus a preset offset threshold.

[Claim 3] The on-chip integrated wavelength division multiplexer

according to claim 2, wherein

the preset offset threshold is an offset specified by the ITU standard, the predetermined wavelength spacing is a wavelength spacing required by a communication system, the bandwidth is a 1 dB bandwidth of the corresponding channel, and the 1 dB bandwidth is greater than or equal to twice the preset offset threshold and is less than twice the predetermined wavelength spacing.

[Claim 4] The on-chip integrated wavelength division multiplexer according to claim 1, further comprising a plurality of polarization rotators, wherein a quantity of the plurality of polarization rotators is equal to a quantity of the plurality of first input waveguides or a quantity of the plurality of second input waveguides; and

wherein each input waveguide of one group of the first input waveguide group and the second input waveguide group is cascaded with one of the plurality of polarization rotators, and the one of the plurality of polarization rotators is configured to change a polarization state of each wavelength signal inputted into the one group, such that the polarization state of the plurality of incident lights incident on the first input waveguide group is perpendicular to the polarization state of the plurality of incident lights incident on the second input waveguide group.

[Claim 5] The on-chip integrated wavelength division multiplexer according to claim 1, wherein the flat-top wavelength division multiplexing structure comprises a plurality of multi-mode interferometers and any one of an etched diffraction grating structure, an arrayed waveguide grating structure and an angled multi-mode interferometer structure, all of which are

polarization-insensitive, and each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to the any one of the etched diffraction grating structure, the arrayed waveguide grating structure and the angled multi-mode interferometer structure through a respective one of the plurality of multi-mode interferometers.

[Claim 6] The on-chip integrated wavelength division multiplexer according to claim 1, wherein

the flat-top wavelength division multiplexing structure comprises a plurality of multi-mode interferometers and an etched diffraction grating structure being polarization-insensitive, the etched diffraction grating structure comprises a plurality of first input channels, a plurality of second input channels, a free propagation region, an etched diffraction grating facet and an output channel, wherein the plurality of first input channels, the plurality of second input channels and the output channel are respectively located at different positions on a circumference of a Rowland circle of the free propagation region, each of the plurality of first input channels is connected to a corresponding one of the plurality of first input waveguides through a respective one of the plurality of multi-mode interferometers, and each of the plurality of second input channels is connected to a corresponding one of the plurality of second input waveguides through a respective one of the plurality of multi-mode interferometers; and

wherein the free propagation region comprises a slab waveguide, and the slab waveguide is configured such that the predetermined difference exists, within the slab waveguide, between an effective refractive index of a transmission mode of

the plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the plurality of incident lights having the second polarization state; the etched diffraction grating facet is configured to respectively diffract the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state that have passed through the free propagation region, such that the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state are each focused at the output channel and are combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide.

[Claim 7] The on-chip integrated wavelength division multiplexer according to claim 1, wherein

the flat-top wavelength division multiplexing structure comprises a plurality of multi-mode interferometers and an arrayed waveguide grating structure, the arrayed waveguide grating structure comprises an input slab waveguide, an output slab waveguide and a plurality of arrayed waveguides connected between the input slab waveguide and the output slab waveguide, each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to the input slab waveguide through a respective one of the plurality of multi-mode interferometers, and the output waveguide is connected to the output slab waveguide; and

wherein each of the plurality of arrayed waveguides comprises a tapered waveguide, a straight waveguide and a curved waveguide, a constant length difference exists between two

adjacent arrayed waveguides of the plurality of arrayed waveguides, and the predetermined difference exists, within the input slab waveguide and the output slab waveguide, between an effective refractive index of the first polarization state and an effective refractive index of the second polarization state, such that the plurality of incident lights having the first polarization state and the plurality of incident lights having the second polarization state are combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide after being subjected to phase configuration by the plurality of arrayed waveguides in the arrayed waveguide grating structure.

[Claim 8] The on-chip integrated wavelength division multiplexer according to claim 1, wherein

the flat-top wavelength division multiplexing structure comprises a plurality of multi-mode interferometers and an angled multi-mode interferometer structure, the angled multi-mode interferometer structure comprises the plurality of first input waveguides, the plurality of second input waveguides, a multi-mode interference region and the output waveguide, wherein each of the plurality of first input waveguides and each of the plurality of second input waveguides are each connected to a same side of the multi-mode interference region through a respective one of the plurality of multi-mode interferometers, and a horizontal axial distance between a junction of each of the plurality of first input waveguides with the multi-mode interference region and a junction of the output waveguide with the multi-mode interference region and a horizontal axial distance between a junction of each of the plurality of second

input waveguides with the multi-mode interference region and the junction of the output waveguide with the multi-mode interference region are configured to have a preset difference; and

wherein the multi-mode interference region is configured such that the predetermined difference exists, within the multi-mode interference region, between an effective refractive index of a transmission mode of the inputted plurality of incident lights having the first polarization state and an effective refractive index of a transmission mode of the inputted plurality of incident lights having the second polarization state, so as to cause the inputted plurality of incident lights having the first polarization state and the inputted plurality of incident lights having the second polarization state to be focused at the output waveguide and to be combined into one multi-wavelength and polarization multiplexed light to be outputted from the output waveguide.

[Claim 9] The on-chip integrated wavelength division multiplexer according to claim 1, wherein the on-chip integrated wavelength division multiplexer comprises a substrate and a core layer located above the substrate, the flat-top wavelength division multiplexing structure is located in the core layer, and the core layer is any one of a silicon nitride layer, a silicon layer and a lithium niobate layer.

[Claim 10] The on-chip integrated wavelength division multiplexer according to claim 1, wherein the on-chip integrated wavelength division multiplexer further comprises a coupling structure, the coupling structure is connected to the output waveguide of the flat-top wavelength division multiplexing structure, and the coupling structure is configured to couple the multi-wavelength

and polarization multiplexed optical signal outputted from the output waveguide of the flat-top wavelength division multiplexing structure to an external optical fiber.

[Claim 11] A photonic integrated circuit chip, comprising the on-chip integrated wavelength division multiplexer according to any one of claims 1 to 10.