

A MULTI-STAGE LATTICE FILTER

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to Singapore patent application no. 10202400344V which was filed on 7 February 2024, the contents of which are hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to a polarization insensitive multi-stage lattice filter for receiving O-band signals for coarse wavelength division multiplexing (CWDM).

BACKGROUND

[0003] Optical interconnects are commonly used to meet the growing demands of data centers, long-haul communications, and peta/exa-scale high-performance computing systems. These interconnects provide an efficient means to scale data transmission capabilities compared to electronic solutions. Among optical technologies, coarse wavelength division multiplexing (CWDM) has emerged as a cost-effective approach for increasing network capacity. As a result, CWDM components are required to have a broadband response so that such components may process multiple wavelength channels with low insertion loss and crosstalk, while also being robust against temperature variations up to 80°C. This effectively eliminates the need for active tuning or post-fabrication trimming. To this end, Silicon Photonic (SiPh) devices were found to be an ideal platform as it leverages mature CMOS technology making it particularly suitable for manufacturing CWDM components due to its scalability and cost-effectiveness.

[0004] Silicon Photonics utilizes high-refractive-index contrast materials such as silicon-on-insulator (SOI) and silicon nitride (SiN) for dense integration of photonic devices on-chip. Among these, SiN is preferred for CWDM devices as it provides better temperature stability and lower dispersion compared to SOI. CWDM devices function by creating interference between light signals propagating through waveguides of specific path lengths, which are combined and split by optical couplers. This design makes CWDM systems highly sensitive to the phase response of their components, particularly in multi-stage lattice filters that use cascaded Mach-Zehnder Interferometers (MZIs) with precise coupling ratios.

[0005] Polarization sensitivity is another significant challenge faced by CWDM devices, as the polarization of light changes as the light propagates through optical fibers. Most photonic integrated circuits (PICs) operate on a single polarization, resulting in up to 50% power loss during polarization conversion. To address this, those skilled in the art have proposed the use of polarization diverse designs whereby polarization splitters and rotators are used to preprocess optical signals to a single polarization, albeit at the expense of increased device footprint. An alternative approach proposed by those skilled in the art is to design polarization-insensitive components which minimize polarization dependence.

[0006] Polarization dependence in photonic components arises from several factors, with the most fundamental being the mode guiding properties determined by the waveguide's geometrical cross-section. The mode index (or effective index) and the resulting mode confinement are influenced by dimensions parallel to the polarization of the guided mode. For transverse electric (TE) modes polarized along the x-direction, the mode index largely depends on the width of the waveguide. Similarly, for transverse magnetic (TM) modes polarized along the y-direction, the mode index is primarily affected by the height of the waveguide. This polarization dependence can be mitigated using symmetrical waveguides with square-shaped cross-sections and uniform cladding materials.

[0007] Another source of polarization dependence stems from differential interactions of polarizations with the same physical medium, as can be exemplified in directional couplers (DCs). In DCs, the stronger spatial mode overlap of TM modes compared to TE modes results in higher coupling strength for TM modes, complicating the design of CWDM devices that rely on precise coupling ratios. While the use of devices such as splitters and rotators may address these issues, the use of such devices greatly increases the device's footprint. Hence, if polarization insensitive devices may be employed in CWDM devices, this greatly simplifies the design of the PIC in the transceiver circuit as it would be able to handle incoming optical signals of any polarization.

[0008] In addition to polarization dependence, photonic components are also bandwidth-limited by wavelength-dependent dispersive effects. Dispersion occurs because the interaction of geometrical structures with propagating light normalizes dimensions according to the wavelength, leading to performance variations across different wavelengths. While square-

shaped waveguides with uniform cladding materials were found to minimize some dispersive effects in optical waveguides, such waveguides do not fully address wavelength dependence in components such as directional couplers. These wavelength-dependent behaviours remain a significant challenge in CWDM device designs, as they impact the precision and efficiency of photonic components.

[0009] The performance of CWDM devices relies heavily on the design architecture and the performance of their constituent optical components. In order to improve the performance of the constituent optical components, those skilled in the art have proposed the use of broadband couplers in lattice filter architectures. However, while broadband coupling improves the response of lattice filters, it often introduces phase distortions that result in spectral distortion within the CWDM devices. Furthermore, most of these designs (particularly those based on subwavelength grating and continuously changing width/gap spacing) have stringent dimensional requirements, making them highly susceptible to fabrication imperfections.

[0010] From a device design perspective, lattice filter architectures employing various combinations of coupling ratios have been extensively explored, with these coupling ratios typically realized using directional couplers. However, the inherent wavelength dependence of directional couplers leads to non-uniform transmission spectra and low extinction ratios in CWDM devices. While cascading the same lattice filter stages, in method known as "stage doubling," was found to achieve higher extinction ratios and to be polarization insensitive, this approach significantly increases the device footprint, posing a challenge for compact integration of such CWDM devices in photonic circuits

SUMMARY

[0011] In one aspect, the present application discloses a multi-stage lattice filter. The multi-stage lattice filter comprises a first lattice filter stage configured to receive wavelength channels within an O-band range, direct a cross transmission output to a second lattice filter stage, and direct a bar transmission output to a third lattice filter stage. In embodiments of the disclosure, the first, second and third lattice filter stages each comprise a first multimode interferometer (MMI), and a second MMI, wherein a first input of the second MMI is coupled to a first output of the first MMI via a first phase-shift mechanism, and a second input of the second MMI is coupled to a second output of the first MMI. The lattice filter stage also comprises a first

directional coupler (DC), wherein a first input of the first DC is coupled to a first output of the second MMI, and a second input of the first DC is coupled to a second output of the second MMI via a second phase-shift mechanism, and a second DC, wherein a first input of the second DC is coupled to a first output of the first DC via a third phase-shift mechanism, and a second input of the second DC is coupled to the second output of the first DC. It should be noted that a phase shift introduced by the second phase-shift mechanism is twice a phase shift introduced by the first phase-shift mechanism, and a phase shift introduced by the third phase-shift mechanism is four times the phase shift introduced by the first phase-shift mechanism with an additional phase offset of π .

[0012] In another aspect, the present application discloses a method for forming a multi-stage lattice filter. The method comprises the steps of forming a first lattice filter stage to receive wavelength channels within an O-band range, direct a cross transmission output to a second lattice filter stage, and direct a bar transmission output to a third lattice filter stage. It should be noted that the first, second and third lattice filter stages each are formed by the steps of forming a first multimode interferometer (MMI), forming a second MMI such that a first input of the second MMI is coupled to a first output of the first MMI via a first phase-shift mechanism, and a second input of the second MMI is coupled to a second output of the first MMI, forming a first directional coupler (DC) such that a first input of the first DC is coupled to a first output of the second MMI, and a second input of the first DC is coupled to a second output of the second MMI via a second phase-shift mechanism, forming a second DC such that a first input of the second DC is coupled to a first output of the first DC via a third phase-shift mechanism, and a second input of the second DC is coupled to the second output of the first DC, wherein a phase shift introduced by the second phase-shift mechanism is twice a phase shift introduced by the first phase-shift mechanism, and a phase shift introduced by the third phase-shift mechanism is four times the phase shift introduced by the first phase-shift mechanism with an additional phase offset of π .

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Various embodiments of the present disclosure are described below with reference to the following drawings:

Figure 1 illustrates a diagram showing the operation of a multi-stage lattice filter in accordance with embodiments of the present disclosure;

Figure 2 illustrates the routing of input wavelength channels through the stages of the multi-stage lattice filter in accordance with embodiments of the present disclosure;

Figure 3 illustrates a block diagram showing the optical components that are provided within each lattice filter stage in accordance with embodiments of the present disclosure;

Figure 4 illustrates a cross-sectional view of a waveguide in accordance with embodiments of the present disclosure;

Figure 5 illustrates a top view of a multi-mode interferometer and a directional coupler in accordance with embodiments of the disclosure;

Figure 6 illustrates a flowchart showing the process for determining the lengths of the waveguides in a first lattice filter stage in accordance with embodiments of the present disclosure;

Figure 7 illustrates a plot showing the dependence of mode index on the width and height of the waveguide for a TE mode with a wavelength of 1310nm;

Figure 8 illustrates a plot showing the simulated TE mode for a multi-mode lattice filter in accordance with embodiments of the disclosure;

Figure 9 illustrates a plot showing the simulated TM mode for a multi-mode lattice filter in accordance with embodiments of the disclosure; and

Figure 10 illustrates a flowchart showing the process for forming a multi-stage lattice filter in accordance with embodiments of the disclosure.

DETAILED DESCRIPTION

[0014] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0015] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0016] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0017] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0018] As used herein, “comprising” means including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0019] As used herein, “consisting of” means including, and limited to, whatever follows the phrase “consisting of”. Thus, use of the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0020] A “multi-stage lattice filter”, as used herein, refers to a lattice filter architecture having a plurality of stages where each stage comprises a plurality of optical components such as multi-mode interferometers (MMIs), phase-shift mechanisms and direction couplers (DC) that are arranged in a specific configuration.

[0021] In the context of various embodiments, the directional terms mentioned herein, such as “top” and “bottom” or “upper” and “lower” refer to directions as described with reference to the drawings. Therefore, the directional terms are only used for illustration and are not meant to limit the present disclosure.

[0022] It should be noted that although the terms first, second and third are used herein to describe various elements, these elements should not be limited by these terms as these terms are meant to only distinguish one element from another element. Thus, the first element described herein could be termed as a second element without departing from this disclosure.

[0023] As used herein, a “layer” refers to a material portion including a region having a particular thickness. The layer may extend over the entirety of the structure or may cover only part of the structure as defined in the description. For example, a layer may be located between

two horizontal planes; may be located between, or at, a top surface and a bottom surface of the structure. The layer may also extend horizontally, vertically, and/or along the surface of the structure.

[0024] As used herein, "cross transmission" refers to an optical signal that is output from a specific port of a device, such that the signal remains aligned with the same side of the optical coupler as it was input. For example, when an optical signal enters an input port of a directional coupler, it exits through the corresponding output port on the same side of the coupler, maintaining its original path alignment. Cross transmission typically occurs when the signal undergoes constructive interference as it propagates through the device, ensuring efficient routing of the optical signal to its intended path.

[0025] As used herein, "bar transmission" refers to an optical signal that is output from a specific port of a device, such that the signal crosses over to the opposite side of the optical coupler relative to where it was input. For example, when an optical signal enters an input port of a directional coupler, it exits through an output port on the opposite side of the coupler, effectively switching its path alignment. Bar transmission typically occurs when the signal undergoes destructive interference or a designed phase shift as it propagates through the device, allowing for selective redirection of the optical signal to its intended output.

[0026] Additionally, for the sake of brevity, extensive explanations of conventional techniques of fabricating semiconductor devices and integrated circuits are not described in detail herein. The tasks and processes described herein may also be integrated into a more comprehensive procedure with extra steps of features that are not elaborated upon in this document. Specifically, certain processes of fabricating semiconductor devices are well known to one skilled in the art hence, such processes will be omitted entirely.

[0027] Directional Coupler (DC)

[0028] A directional coupler (DC) consists of two single-mode waveguides separated by a narrow gap. These waveguides are positioned close enough that evanescent power coupling occurs between them, allowing light to transfer from one waveguide to the other. The coupling ratio κ of a DC is primarily determined by the gap spacing and the length of the coupler L_c .

Mathematically, the coupling ratio can be expressed as $\kappa = \sin^2(\gamma L_c)$, where γ is defined as a coupling coefficient that is a function of the spatial mode overlap between the two waveguides, which in turn depends on the gap spacing and the polarization of the light.

[0029] Thus, the coupling ratio in a DC can be continuously adjusted by modifying the couplers' lengths and gap spacing. However, it should be noted that the DC also exhibits polarization dependence and wavelength sensitivity. The wavelength sensitivity of a DC arises from the relationship between the wavelength of the optical signal and the geometrical dimensions of the coupler. This sensitivity is closely related to the slope of the coupling ratio with respect to the coupler length L_c . Specifically, the wavelength sensitivity is highest when the coupling ratio $\kappa = 0.5$ as this corresponds to the steepest slope. Conversely, directional couplers with coupling ratios of $\kappa \sim 0$ and $\kappa \sim 1$ have the smallest slope and, therefore, exhibit minimal wavelength dependence.

[0030] Multi-mode interferometer (MMI)

[0031] A multi-mode interferometer (MMI) comprises of a wide multimode waveguide typically connected to single-mode waveguides serving as input and output ports. An MMI operates based on a self-imaging mechanism, where a mode from a carefully positioned input port excites multiple modes within the multimode waveguide. These excited modes interfere with one another and re-image into specific mode patterns at the output ports after propagating a certain distance. The imaging distance L_{MMI} depends on the MMI width W_{MMI} , refractive index n_{MMI} , and wavelength λ of the optical signal, with the relationship being mathematically expressed as $L_{MMI} = 2n_{MMI}W_{MMI}^2$.

[0032] Due to its multimode nature, an MMI exhibits weak polarization and wavelength dependences, making it relatively robust compared to a directional coupler (DC). However, unlike a DC, the coupling ratio of an MMI cannot be continuously tuned. MMIs are typically designed to achieve fixed coupling ratios such as 50:50 ($\kappa = 0.5$) and 85:15 ($\kappa = 0.85$). These fixed coupling ratios correspond to specific peak locations along the MMI length, where $\kappa = 0.5$ or $\kappa = 0.85$ minimizes wavelength sensitivity.

[0033] Figure 1 illustrates a multi-stage lattice filter 100 in accordance with embodiments of the disclosure. Multi-stage lattice filter 100 is configured to separate and route optical wavelength channels CH1, CH2, CH3, CH4 through three lattice filter stages S1, S2, S3 based on their transmission paths. In embodiments of the disclosure, each stage is configured to process the incoming signals using a combination of cross transmission and bar transmission routing paths to direct specific channels toward their respective outputs.

[0034] As illustrated in Figure 1, it can be seen that lattice filter stage S1 routes wavelength channels CH1 and CH3 through cross transmission, while wavelength channels CH2 and CH4 are routed through bar transmission. This ensures initial separation of the wavelength channels and it can be seen from output 102 that the wavelength channels remain relatively uniform as these wavelength channels are routed out through stage S1.

[0035] As the wavelength channels propagate through lattice filter stage S2, i.e., output 104, and lattice filter stage S3, i.e., output 106, it can be seen that the bandwidth and spacings of the passband increases by two times, i.e., 2x, compared to the output at lattice filter stage S1, i.e., output 102. Outputs 104 and 106 are designed such that the cross and bar outputs from lattice filter stage S1 can be specifically directed to the cross and bar output ports of lattice filter stages S2 and S3.

[0036] Specifically, in lattice filter stage S2, wavelength channel CH1 is routed through cross transmission, while wavelength channel CH3 transitions to bar transmission. Simultaneously, in lattice filter stage S3, wavelength channel CH2 is routed via cross transmission and wavelength channel CH4 via bar transmission. Outputs 104 and 106 show that these wavelength channels are now completely isolated with wavelength channels CH1 and CH2 being routed through cross transmission and wavelength channels CH3 and CH4 being routed through bar transmission of the respective lattice filter stages.

[0037] The routing of a plurality of wavelength channels through a multi-stage lattice filter is illustrated in Figure 2. Multi-stage lattice filter 200 is designed to separate and route four input wavelength channels λ_1 , λ_2 , λ_3 , λ_4 , which correspond to channels CH1, CH2, CH3, and CH4 respectively, into distinct outputs. The input signal, comprising the combined wavelengths, is provided to the lattice filter stage S1 of multi-stage lattice filter 200. In lattice

filter stage S1, based on the free-spectral-range (FSR) of stage S1, the input signal is processed and separated into two groups. The first group comprising wavelength channels CH1 and CH3 are routed through output 202 using a cross transmission mechanism, while the second group comprising wavelength channels CH2 and CH4 are routed through output 204 using a bar transmission mechanism.

[0038] Wavelength channels CH1 and CH2 are then provided to lattice filter stage S2 where they are further processed in lattice filter stage S2 to be completely isolated from one another, with wavelength channel CH1 (having wavelength λ_1) exiting through output 206 and wavelength channel CH3 (having wavelength λ_3) exiting through output 207.

[0039] Similarly, wavelength channels CH2 and CH4 are provided from output 204 to lattice filter stage S3 where they are completely isolated from each other, with wavelength channel CH2 (having wavelength λ_2) exiting through output 208 and wavelength channel CH4 (having wavelength λ_4) exiting through output 209. Through this arrangement of the lattice filter stages S1, S2 and S3, multi-stage lattice filter 200 is able to achieve precise wavelength separation of the input wavelength channels into discrete outputs while maintaining low crosstalk and high extinction ratios thereby making multi-stage lattice filter ideal for CWDM applications.

[0040] Figure 3 illustrates a block diagram showing the optical components that are provided within each lattice filter stage in accordance with embodiments of the present disclosure. As shown, lattice filter stage 300 comprises a combination of MMIs (i.e., MMIs 302 and 306), DCs (i.e., DCs 310 and 314), and phase-shift mechanisms (i.e., mechanisms 304, 308, 312) for processing optical signals. Specifically, two input optical signals, which may comprise any of the four input wavelength channels λ_1 , λ_2 , λ_3 , λ_4 , which correspond to channels CH1, CH2, CH3, and CH4, are first provided to the input ports of MMI 302. MMI 302 then splits the optical signals into two paths, paths 320 and 321. The optical signal propagating along path 320 is then provided to phase-shift mechanism 304 which causes this optical signal to be phase shifted by phase ϕ_1 . The phase shifted optical signal is then provided to an input port of MMI 306. The optical signal propagating along path 321 is then provided to another input port of MMI 306.

[0041] Upon receiving both input optical signals, MMI 306 then splits the optical signal into two paths, paths 322 and 323. The optical signal propagating along path 322 is provided to an input port of DC 310. Another optical signal that is propagating along path 323 is then provided to phase-shift mechanism 308 which causes this optical signal to be phase shifted by phase ϕ_2 . The phase shifted optical signal is then provided to another input port of DC 310.

[0042] DC 310 then splits the optical signal into two paths, paths 324 and 325. The optical signal propagating along path 324 is then provided to phase-shift mechanism 312 which causes this optical signal to be phase shifted by phase ϕ_3 . The phase shifted optical signal is then provided to an input port of DC 314. The optical signal propagating along path 325 is then provided to another input port of DC 314. The outputs from DC 314 are then directed to output ports 316 and 318, ensuring wavelength-dependent separation and routing with minimized crosstalk.

[0043] In summary, it can be said that input signals are first provided to the input ports of MMI 302, which splits the optical signals into two paths. These paths are then modified by a phase-shift mechanism 304 in one branch before being recombined in MMI 306. From MMI 306, the optical signals are routed to a pair of DCs 310, 314, with additional phase-shift mechanisms 308, 312 applied along the paths to introduce the necessary phase shifts for proper channel routing. The DCs 310, 314 provide the coupling and splitting required for wavelength separation and routing before providing the isolated output signals at the output ports of DC 314.

[0044] In embodiments of the disclosure, the coupling ratios of MMIs 302 and 306 are each set to 0.5, i.e., $\kappa = 0.5$, thereby achieving a 50% coupling ratio where the slope of the spectral response is smallest for MMI devices. When the coupling ratios of DCs 310 and 314 are each set to 0.04, i.e., $\kappa = 0.04$, this allows the coupling ratio of the DC device to exhibit low wavelength sensitivity due to the small slope near the spectral valley of the coupling response. In terms of polarization dependence, the multimode nature of the MMI device inherently reduces the polarization sensitivity of each lattice filter stage. For the DC sections of each lattice filter stage, the very small coupling ratios further minimize polarization dependencies, enhancing the robustness of the design.

[0045] The combined effect of three key features described in the sections above ensure the polarization-insensitive and broadband operation of the multi-stage lattice filter. The first feature is the design of the square-shaped waveguide cross-section, which minimizes polarization dependence, the second feature is the polarization-insensitive and broadband coupling ratio of $\kappa=0.5$ which is achieved using the MMIs; and the third feature is the wavelength- and polarization-insensitive coupling ratio of $\kappa=0.04$ which is achieved using the DCs.

[0046] In embodiments of the disclosure, phase-shift mechanisms 304, 308 and 312 may comprise a square-shaped optical waveguide. The cross sectional view of such a square-shaped optical waveguide is illustrated in Figure 4. Waveguide 400 comprises a silicon nitride (SiN) core 406 that is encapsulated by silicon dioxide (SiO₂) cladding layers 408, whereby SiN core 406 is formed on a SiO₂ layer 404 which in turn is formed on silicon substrate 402. SiN core 406, which is designed to propagate optical signals along its length, comprises a rectangular cross-section defined by its width w , and height h . SiO₂ cladding layer 408 provides optical confinement by creating a high refractive index contrast between SiN core 406 and the surrounding material, enabling efficient light propagation within the waveguide.

[0047] The high refractive index contrast between SiN and SiO₂ allows for strong mode confinement in SiN core 406, making waveguide 400 suitable for dense integration of photonic components. The symmetrical cladding material and square-like cross-section also contributes to the reduction of polarization dependence which in turn ensures consistent performance for TE and TM modes.

[0048] Figure 5 illustrates a top view of MMI device 502 and DC device 504 in accordance with embodiments of the disclosure. One skilled in the art will recognize that other MMI and/or DC designs and configurations such as the inverse designs of these MMI and/or DC designs may be used without departing from this disclosure.

[0049] A differential optical path for the i -th segment of the multi-stage lattice filter may be defined in terms of its phase shift as:

$$\phi_i = \frac{2\pi n_{eff}(\lambda)L_i}{\lambda} \quad \dots \text{equation (1)}$$

where $n_{eff}(\lambda)$ is defined as the mode index of a guided mode λ that is propagating through a lattice filter stage. This mode index $n_{eff} = n_{eff}(\lambda, w, h)$ is dependent on the wavelength of the guided mode λ , the waveguide's width w , and the waveguide's height h .

[0050] For polarization-independent operation, the waveguide cross-section should be square-shaped ($w = h$) with a uniform cladding, such as SiO_2 , as shown in Figure 4. The phase relationships between each of the phase-shift mechanisms in each of the lattice filter stages may be expressed as $\phi_2 = 2\phi_1$ and $\phi_3 = 4\phi_1 + \pi$. Based on these relationships, the waveguide lengths of each of the phase-shift mechanisms may be defined as $L_1 = \frac{m\lambda_1}{n_{eff}\lambda_1}$, $L_1 = 2L_2$, and $L_3 = 4L_1 + \frac{\lambda_2}{2n_g L_1}$ where m is defined as a mode number which comprises an integer (i.e., $m = 1, 2, 3$, etc.)

[0051] The group mode index n_g is defined as $n_g = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$ and is related to the free spectral range (FSR) of the multi-stage lattice filter by $FSR = \frac{\lambda_1^2}{n_g L_1}$. In lattice filter stage S1 (with reference to Figure 2), the length L_1 is adjusted to achieve an FSR of 40 nm, which corresponds to approximately twice the CWDM channel spacing ($FSR_{S1} \sim 2 \times 20 \text{ nm} = 40 \text{ nm}$). Additionally, L_1 is configured such that its optical path length aligns with integer multiples of the wavelength of Channel 1 ($\lambda_1 = 1.271 \mu\text{m}$), ensuring that the mode number m remains an integer (i.e., $m = 1, 2, 3$, etc.).

[0052] In lattice filter stage S2, the lengths of the phase-shift mechanisms are adjusted such that its free spectral range (FSR) is approximately twice that of lattice stage filter S1, i.e., $FSR_{S2} \approx 2 \times FSR_{S1} = 80 \text{ nm}$. This adjustment results in $L_1(S2) = 0.5 \times L_1(S1)$. The remaining lengths, $L_2(S2)$ and $L_3(S2)$ may then be determined based on the same phase relationships as that of lattice filter stage S1, such that $\phi_2(S2) = 2\phi_1(S2)$ and $\phi_3(S2) = 4\phi_1(S2) + \pi$.

[0053] In lattice filter stage S3, the optical length $L_1(S3)$ is adjusted to introduce a phase shift of $\pi/4$ relative to lattice filter stage S2. This adjustment in the length corresponds to $L_1(S3) = 0.5 \times [L_1(S1) + \lambda_1/(2n_{eff} \lambda_1)]$. Similarly, the lengths $L_2(S3)$ and $L_3(S3)$ are both

determined based on the same phase relationships as that of lattice filter stage S1, $\phi_2(S3) = 2\phi_1(S3)$ and $\phi_3(S3) = 4\phi_1(S3) + \pi$.

[0054] Simulation

[0055] Waveguide dimensions from a multi project wafer fabrication (MPW) from Advanced Micro Foundry (AMF) were utilized to carry out a simulation of a multi-stage lattice filter in accordance with embodiments of the disclosure. Specifically, the multi-stage lattice filter design focused on a SiN material system consisting of 400 nm thick SiN waveguide cladded with SiO₂, that is formed on a silicon substrate. The intended wavelength range of the multi-stage lattice filter was set to be in the O-band, ranging from $\lambda = 1.25 \mu\text{m}$ to $\lambda = 1.35 \mu\text{m}$, specifically for the known O-band wavelength channels at 1271nm, 1291nm, 1311nm, and 1331nm. In terms of dispersive properties, it should be noted that SiN exhibits much less dispersion than silicon, while still having a refractive index that is sufficiently high enough to enable high device integration. The other reason for choosing SiN is its larger critical dimensions than those based on silicon, making the filter design more tolerant to fabrication imperfections.

[0056] A process for designing a multi-stage lattice filter in accordance with embodiments of the disclosure is illustrated in Figure 6. Process 600 begins at step 602 by obtaining the empirical refractive index data (n, k) of the core and cladding waveguide materials from existing known databases. At step 604, process 600 then proceeds to obtain the waveguide dispersion by tabulating the mode index as a function of wavelength across the O-band (i.e., in this process, the range 1.25 μm to 1.35 μm was utilized), from which a linear fitting was extracted. Such an exemplary table is shown below as Table 1.

$\lambda(\mu\text{m})$	TE		TM	
	n_{eff}	n_g	n_{eff}	n_g
1.25	1.54297	1.92970	1.54297	1.92975
1.27	1.53691	1.91316	1.53691	1.91323
1.29	1.53112	1.89655	1.53111	1.89665
1.31	1.52558	1.87993	1.52557	1.88007
1.33	1.52030	1.86335	1.52029	1.86353

1.35	1.51526	1.84686	1.51525	1.84711
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TABLE 1

[0057] In order to obtain the dimensional tolerances, additional tabulations for different waveguide widths and heights may be performed by process 600. The mapping of the mode index as a function of width and height is shown in Figure 7 for a TE mode having a wavelength of 1310 nm. The mode index dependence on waveguide geometries may be defined as:

$$n_{eff}(w, h, \lambda) = m_1(w, h)\lambda + m_2(w, h) \quad \dots \text{equation (2)}$$

where,

$$\begin{aligned} m_1(w, h) &= m_1(w_0, h_0) \times (m_{w,11}w + m_{w,12}) \times (m_{h,11}h + m_{h,12}) \\ m_2(w, h) &= m_2(w_0, h_0) \times (m_{w,21}w + m_{w,22}) \times (m_{h,21}h + m_{h,22}) \end{aligned}$$

comprise the slopes obtained from the linear fitting, which for TE and TM modes are defined as follows:

[0058] **TE Coefficients**

$$\begin{aligned} m_1 &= -0.27704, m_2 = 1.888842, m_{w,11} = 3.00782, m_{w,12} = -0.2375 \\ m_{w,21} &= 0.837502, m_{w,22} = 0.658489, m_{h,11} = 1.851486 \\ m_{h,12} &= 0.230283, m_{h,21} = 0.526902, m_{h,22} = 0.783563 \end{aligned}$$

[0059] **TM Coefficients**

$$\begin{aligned} m_1 &= -0.27714, m_2 = 1.888964, m_{w,11} = 1.843016, m_{w,12} = -0.233776 \\ m_{w,21} &= 0.525432, m_{w,22} = 0.78417, m_{h,11} = 2.992885 \\ m_{h,12} &= -0.23131, m_{h,21} = 0.834905, m_{h,22} = 0.659566 \end{aligned}$$

[0060] Process 600 then proceeds to step 606 where temperature dependences are acquired and incorporated. Empirical thermo-optical effects, i.e., $\partial n/dT$, may be incorporated after all the waveguide's dispersion properties have been acquired. The incorporation of the temperature dependences may be defined as follows:

$$n_{eff}(w, h, \lambda, T) = n_{eff}(w, h, \lambda, T_0) + \left(\frac{\partial n}{\partial T}\right)(T - T_0) \quad \dots \text{equation (3)}$$

[0061] At step 608, process 600 then uses the obtained waveguide dispersion to obtain the optical lengths for the first phase-shift mechanism, i.e., the waveguide, in each stage in the multi-stage lattice filter. At step 610, process 600 then obtains the differential optical lengths for the second and third phase-shift mechanisms, i.e., the waveguide, in each stage in the multi-stage lattice filter.

[0062] Once process 600 has been completed, the wavelength-dependent response of the MMIs and directional couplers in each of the stages of the multi-stage lattice filter is simulated based on the empirical refractive index data of the core and cladding waveguide materials. The complex amplitudes (which consists of both amplitude and phase error from the MMI and DC designs) are extracted and incorporated into the simulation that is set up to integrate optical dispersion within the differential optical length, MMI, and DC optical couplers.

[0063] Figure 8 illustrates the simulated results of the proposed design for the TE mode and Figure 9 illustrates the simulated results of the proposed design for the TM mode. Based on the specifications obtained from realistic industrial demand of such lattice filters, such as having an extinction ratio (ER) of $ER \geq 20\text{dB}$, insertion loss (IL) of $IL \leq 2\text{dB}$, and channel bandwidth (BW) of $BW = 12\text{nm}$, it can be seen from Figures 8 and 9 that the proposed multi-stage lattice filter designed in accordance with embodiments of this disclosure is able to satisfy the requirements set out above for both TE and TM modes.

[0064] A flowchart showing a process for forming a multi-stage lattice filter in accordance with embodiments of this disclosure is illustrated in Figure 10. Process 1000 begins at step 1002 by forming a first lattice filter stage, where the first lattice filter stage is configured to receive wavelength channels within an O-band range, direct a cross transmission output to a second lattice filter stage, and direct a bar transmission output to a third lattice filter stage. Once this is done, process 1000 then proceeds to form the optical components for each of the first, second and third lattice filter stages. Process 1000 does so by first forming a first MMI at step 1004. At step 1006, process 1000 then proceeds to form a second MMI such that a first input of the second MMI is coupled to a first output of the first MMI via a first phase-shift

mechanism, and a second input of the second MMI is coupled to a second output of the first MMI. At step 1008, process 1000 then forms a first DC such that a first input of the first DC is coupled to a first output of the second MMI, and a second input of the first DC is coupled to a second output of the second MMI via a second phase-shift mechanism. At step 1010, process 1000 then forms a second DC such that a first input of the second DC is coupled to a first output of the first DC via a third phase-shift mechanism, and a second input of the second DC is coupled to the second output of the first DC. In this embodiment, a phase shift introduced by the second phase-shift mechanism is twice a phase shift introduced by the first phase-shift mechanism, and a phase shift introduced by the third phase-shift mechanism is four times the phase shift introduced by the first phase-shift mechanism with an additional phase offset of π .

[0065] In further embodiments of the disclosure, process 1000 forms the first and second MMIs with each of them having a coupling ratio of 0.5 and forms the first and second DCs with each of them having a coupling ratio of 0.04.

[0066] In further embodiments of the disclosure, the phase shift introduced by the first phase-shift mechanism is determined based on a mode index and a wavelength of a channel propagating through the waveguide of the first phase-shift mechanism, and a length of the waveguide. The length of a waveguide of the first phase-shift mechanism of the first stage lattice filter is formed such that the length of the waveguide of the first phase-shift mechanism corresponds to an integer multiple of an effective wavelength of a first channel propagating through the waveguide, the effective wavelength being determined based on a wavelength of the first channel and an effective refractive index of the wavelength of the first channel.

[0067] In further embodiments of the disclosure, the wavelength channels received by the first stage lattice filter comprises a first channel, a second channel, a third channel and a fourth channel for coarse wavelength division multiplexing (CWDM), wherein the cross transmission output comprises the first and the third channels, and the bar transmission output comprises the second and the fourth channels. The second lattice filter stage is configured to output a cross transmission output comprising the first channel and output a bar transmission output comprising the third channel, and whereby the third lattice filter stage is configured to output a cross transmission output comprising the second channel and output a bar transmission output comprising the fourth channel

[0068] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations, and modifications as falling within the scope of the appended claims.

CLAIMS:

1. A multi-stage lattice filter comprising:
 - a first lattice filter stage configured to:
 - receive wavelength channels within an O-band range;
 - direct a cross transmission output to a second lattice filter stage, and
 - direct a bar transmission output to a third lattice filter stage;
 - wherein the first, second and third lattice filter stages each comprise:
 - a first multimode interferometer (MMI);
 - a second MMI, wherein a first input of the second MMI is coupled to a first output of the first MMI via a first phase-shift mechanism, and a second input of the second MMI is coupled to a second output of the first MMI;
 - a first directional coupler (DC), wherein a first input of the first DC is coupled to a first output of the second MMI, and a second input of the first DC is coupled to a second output of the second MMI via a second phase-shift mechanism;
 - a second DC, wherein a first input of the second DC is coupled to a first output of the first DC via a third phase-shift mechanism, and a second input of the second DC is coupled to the second output of the first DC,
 - wherein a phase shift introduced by the second phase-shift mechanism is twice a phase shift introduced by the first phase-shift mechanism, and a phase shift introduced by the third phase-shift mechanism is four times the phase shift introduced by the first phase-shift mechanism with an additional phase offset of π .
2. The multi-stage lattice filter according to claim 1, wherein the first and the second MMIs each have a coupling ratio of 0.5 and the first and the second DCs each have a coupling ratio of 0.04.
3. The multi-stage lattice filter according to claims 1 or 2, wherein the first, the second and the third phase-shift mechanisms each comprise a square-shaped waveguide.
4. The multi-stage lattice filter according to claim 3, wherein the phase shift introduced by the first phase-shift mechanism is determined based on a mode index and a wavelength of a channel propagating through the waveguide of the first phase-shift mechanism, and a length of the waveguide.

5. The multi-stage lattice filter according to claim 3, wherein a length of a waveguide of the first phase-shift mechanism of the first stage lattice filter is selected such that the length of the waveguide of the first phase-shift mechanism corresponds to an integer multiple of an effective wavelength of a first channel propagating through the waveguide, the effective wavelength being determined based on a wavelength of the first channel and an effective refractive index of the wavelength of the first channel.
6. The multi-stage lattice filter according to claim 5, wherein a length of a waveguide of the first phase-shift mechanism of the second stage lattice filter is twice the length of the waveguide of the first phase-shift mechanism of the first stage lattice filter.
7. The multi-stage lattice filter according to claim 6, wherein a length of a waveguide of the first phase-shift mechanism of the third stage lattice filter is selected such that the waveguide of the first phase-shift mechanism of the third stage lattice filter introduces a phase shift of $\pi/4$ relative to a phase shift introduced by the first phase-shift mechanism of the second stage lattice filter.
8. The multi-stage filter according to claim 5, wherein the first channel comprises an O-band signal for coarse wavelength division multiplexing (CWDM).
9. The multi-stage filter according to claim 1, wherein the wavelength channels received by the first stage lattice filter comprises a first channel, a second channel, a third channel and a fourth channel for coarse wavelength division multiplexing (CWDM), wherein the cross transmission output comprises the first and the third channels, and the bar transmission output comprises the second and the fourth channels.
10. The multi-stage filter according to claim 9, whereby the second lattice filter stage is configured to output a cross transmission output comprising the first channel and output a bar transmission output comprising the third channel, and whereby the third lattice filter stage is configured to output a cross transmission output comprising the second channel and output a bar transmission output comprising the fourth channel.
11. A method for forming a multi-stage lattice filter, the method comprising:
forming a first lattice filter stage to:

receive wavelength channels within an O-band range, direct a cross transmission output to a second lattice filter stage, and direct a bar transmission output to a third lattice filter stage,

wherein the first, second and third lattice filter stages each are formed by the steps of:

forming a first multimode interferometer (MMI);

forming a second MMI such that a first input of the second MMI is coupled to a first output of the first MMI via a first phase-shift mechanism, and a second input of the second MMI is coupled to a second output of the first MMI;

forming a first directional coupler (DC) such that a first input of the first DC is coupled to a first output of the second MMI, and a second input of the first DC is coupled to a second output of the second MMI via a second phase-shift mechanism;

forming a second DC such that a first input of the second DC is coupled to a first output of the first DC via a third phase-shift mechanism, and a second input of the second DC is coupled to the second output of the first DC,

wherein a phase shift introduced by the second phase-shift mechanism is twice a phase shift introduced by the first phase-shift mechanism, and a phase shift introduced by the third phase-shift mechanism is four times the phase shift introduced by the first phase-shift mechanism with an additional phase offset of π .

12. The method according to claim 11, wherein the first and the second MMIs each are formed with a coupling ratio of 0.5 and the first and the second DCs each are formed with a coupling ratio of 0.04.
13. The method according to claims 11 or 12, wherein the first, the second and the third phase-shift mechanisms each comprise a square-shaped waveguide.
14. The method according to claim 13, wherein the phase shift introduced by the first phase-shift mechanism is determined based on a mode index and a wavelength of a channel propagating through the waveguide of the first phase-shift mechanism, and a length of the waveguide.
15. The method according to claim 13, wherein a length of a waveguide of the first phase-shift mechanism of the first stage lattice filter is formed such that the length of the waveguide of the first phase-shift mechanism corresponds to an integer multiple of an effective

wavelength of a first channel propagating through the waveguide, the effective wavelength being determined based on a wavelength of the first channel and an effective refractive index of the wavelength of the first channel.

16. The method according to claim 15, wherein a length of a waveguide of the first phase-shift mechanism of the second stage lattice filter is formed to be twice the length of the waveguide of the first phase-shift mechanism of the first stage lattice filter.
17. The method according to claim 16, wherein a length of a waveguide of the first phase-shift mechanism of the third stage lattice filter is formed such that the waveguide of the first phase-shift mechanism of the third stage lattice filter introduces a phase shift of $\pi/4$ relative to a phase shift introduced by the first phase-shift mechanism of the second stage lattice filter.
18. The method according to claim 15, wherein the first channel comprises an O-band signal for coarse wavelength division multiplexing (CWDM).
19. The method according to claim 11, wherein the wavelength channels received by the first stage lattice filter comprises a first channel, a second channel, a third channel and a fourth channel for coarse wavelength division multiplexing (CWDM), wherein the cross transmission output comprises the first and the third channels, and the bar transmission output comprises the second and the fourth channels.
20. The method according to claim 19, whereby the second lattice filter stage is configured to output a cross transmission output comprising the first channel and output a bar transmission output comprising the third channel, and whereby the third lattice filter stage is configured to output a cross transmission output comprising the second channel and output a bar transmission output comprising the fourth channel.