Nonvolatile phase change material based multifunctional silicon waveguide mode converters

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Abstract

Multimode photonics as a new research field of integrated photonics is closely relying on the waveguide mode, particularly for the higher-order waveguide mode. To efficiently generate higher-order waveguide modes in a single device, here we propose multifunctional silicon waveguide mode converters based on the nonvolatile and low-loss phase change material antimony triselenide (Sb$_2$Se$_3$). Such device is formed by two cascaded conversion regions along the silicon waveguide, where the first conversion region is formed by embedding a tapered Sb$_2$Se$_3$ layer into the silicon waveguide asymmetrically and the second one is formed by embedding two Sb$_2$Se$_3$ layers into the silicon waveguide symmetrically. When the embedded Sb$_2$Se$_3$ layers in two conversion regions undergo the phase transition between amorphous state and crystalline state, such device will achieve the mode conversions from input TE$_0$ mode to output TE$_0$, TE$_1$, TE$_2$, and TE$_1$+TE$_3$ mode with mode conversion efficiency$>95\%$, mode crosstalk$<-17$ dB, and insertion loss$<0.4$ dB in a device length of only 10.3 $\mu$m, where this multifunctional mode conversion in a single device has not been reported previously. To eliminate the output hybrid mode, we further revise the design and finally achieve the mode conversion from input TE$_0$ mode to output TE$_0$, TE$_1$, TE$_2$, and TE$_3$ mode directly. We believe the proposed multifunctional mode converters could be used as higher-order mode sources for the multimode photonics applications.

Keywords: Mode converter, Phase change material, Photonic integrated device, Multimode photonics
Introduction

Silicon photonic integrated circuits (PICs) based on the high refractive index contrast and CMOS-compatible processing of the silicon-on-insulator (SOI) platform has greatly pushed the development of on-chip optical interconnects [1-3]. For these PICs, they are normally working at the single-mode state (fundamental mode) in order to avoid the unwanted mode crosstalk and simplify the photonic device or circuit design. But on the other hand, the single-mode operation will restrict the allowable working modes in the optical waveguide, where the multimode will be almost prohibited. Actually, the optical mode is an intrinsic mode degree of freedom of light and every eigenmode is unique and orthogonal with each other, which can be employed well [4-6]. Therefore, higher-order mode devices are needed to be developed not just the fundamental mode devices. Under such condition, multimode photonics based on the on-chip multimode optical waveguide was proposed and gradually became an emerging field in the silicon PICs [7,8]. For the multimode photonics, one of the most important issues is to generate the required higher-order modes efficiently on-chip. So, higher-order mode generators or converters are really required, which could offer efficient higher-order mode sources for the multimode photonics applications [9,10].

To achieve the on-chip mode conversion, different waveguide structures have been proposed such as asymmetrical directional couplers (ADCs) and Mach-Zehnder interferometer (MZI) waveguides [11-14]. However, these typical waveguide structures have some intrinsic shortages for the mode conversion. For example, ADC-based mode converters should satisfy the wavelength-dependent phase matching condition between the input and output waveguides, thus leading to narrow working bandwidths and tight fabrication tolerances [11,12]. MZI-based mode converters normally require mode splitting, interfering, and recombining components, thus resulting in relative long device lengths [13,14]. In order to address above issues, mode conversion based on a single strip waveguide became preferred, where the refractive index perturbation should be introduced to change the refractive index distribution of strip waveguide, satisfying the mode conversion requirements [15]. Accordingly, waveguide etching method was an effective and relatively easy way, where deeply and shallowly etched slots with designed shapes have been applied in the silicon waveguide to achieve the mode conversions in a length of less than 10 μm [16-19]. Metal materials with unique permittivity compared with dielectric materials can also be deposited atop the silicon waveguide to achieve the mode conversion in a shorter length of ~3 μm [20,21]. However, metal absorption loss is the most serious problem for such type of mode converter, e.g., device loss ~2.7 dB [20,21]. Other materials with higher refractive index than silicon can also be combined with silicon waveguide to achieve the mode conversion, while complex fabrication process and high coupling loss are still needed to be solved [22]. In addition, with the rapid
development of high-performance computing, some optimization methods (e.g., inverse design [23], deep learning [24]) have been employed to design the mode conversion pattern on silicon waveguide. However, the generated etching patterns based upon the optimization methods have two issues: time-consuming iterative calculations and hard to fabricate accurately due to lots of tiny structures in the etching patterns [23,24]. By analyzing these reported mode converters, they are normally working at the manner of one function for one device, which cannot achieve two or more mode conversion functions in a single device. The multifunctional mode conversion devices could well support more device functions and applications for the multimode photonics, promoting this field toward multifunctional, programmable, and intelligentized directions [25-27].

In this paper, we propose multifunctional silicon waveguide mode converters based on the nonvolatile phase change material (PCM). Here, we choose antimony triselenide (Sb$_2$Se$_3$) as the PCM, the reason of which is that Sb$_2$Se$_3$ has a quite low optical loss (imaginary part<$10^{-5}$) in the optical communication bands [28,29] even at its crystalline state compared with other commonly used PCMs [30-32]. The proposed device consists of two conversion regions that are cascaded with each other along the silicon waveguide. For the first conversion region, a tapered Sb$_2$Se$_3$ layer is embedded in the silicon waveguide asymmetrically along the propagation direction. For the second conversion region, two identical tapered Sb$_2$Se$_3$ layers are embedded in the silicon waveguide symmetrically along the propagation direction. When these embedded Sb$_2$Se$_3$ layers in two regions of the device are working at the amorphous or crystalline state respectively, four combination phase states can be formed. From results, these four combination phase states can output four types of modes (TE$_0$, TE$_1$, TE$_2$, and TE$_1$+TE$_3$ mode) in a single device, where the total device length is 10.3 µm and the mode conversion efficiency (CE)>95%, mode crosstalk (CT)<-17 dB, and insertion loss (IL)<0.4 dB are obtained for the TE$_0$-to-TE$_0$/-TE$_1$/-TE$_2$ mode conversion, respectively. Moreover, we further improve the device to output four pure modes (TE$_0$, TE$_1$, TE$_2$, and TE$_3$ mode) only by setting the combination phase states of embedded Sb$_2$Se$_3$ layers for the proposed device. We hope the present scheme could offer a useful way to construct multifunctional multimode PICs [25,33].

**Device structure and principle**

Figure 1(a) illustrates the schematic of the proposed multifunctional silicon waveguide mode converter, where two cascaded mode conversion regions are employed along the propagation direction. The first conversion region (R$_1$) consists of one tapered Sb$_2$Se$_3$ layer embedded in the silicon waveguide with a taper length of $L_1$. The second one (R$_2$) consists of two identical tapered Sb$_2$Se$_3$ layers embedded in the silicon waveguide with the same taper length of $L_2$. The gap between these two regions along the propagation direction is $D_1$, which is used to tune the device performance and avoid the thermal interference during the phase transition.
process. After the tapered Sb$_2$Se$_3$ layers are embedded in the silicon waveguide, graphene and alumina (Al$_2$O$_3$) layers are further deposited on the top surface of two conversion regions, acting as the microheater in order to achieve the phase transition of the embedded Sb$_2$Se$_3$ layers. The enlarged cross-sections of the electrode component and the two conversion regions are shown in Figs. 1(b)-(d), where the thicknesses of Sb$_2$Se$_3$ layers in two conversion regions (R$_1$, R$_2$) are $T_1$ and $T_2$, respectively. Meanwhile, the thicknesses of the coated graphene, Al$_2$O$_3$, and metal electrode layers are $H_3$, $H_1$ (=20 nm), and $H_2$ (=100 nm), respectively. The width of Sb$_2$Se$_3$ layer is tapered from $W_{11}$ ($W_{21}$) to $W_{12}$ ($W_{22}$) in the region of R$_1$ (R$_2$) along the propagation direction as illustrated in Fig. 1(e). In addition, the input and output waveguide are the conventional silicon waveguide with a thickness of $H$=220 nm and a width of $W$=1.7 µm, respectively, where such waveguide width is chosen to well support the higher-order waveguide modes.

![Fig. 1](image)

Fig. 1. (a) Schematic of the proposed multifunctional silicon waveguide mode converter. (b) Cross-sectional view of the metal electrode component. (c) and (d) are the cross-sectional views of the waveguide structures in the first (R$_1$) and second (R$_2$) conversion region. (e) Structural parameters of the embedded Sb$_2$Se$_3$ layers in two conversion regions (R$_1$ and R$_2$). Table shows the device function and the output mode is dependent on the combination state of the two conversion regions. The structure and material parameters are also labelled.

Based on the aforementioned device structure, the device working principle is analyzed as follows, particularly for the higher-order mode generations through two conversion regions. To simplify the analysis process, we use the symbols of “0” and “1” to represent the amorphous and crystalline state of the embedded Sb$_2$Se$_3$ layer, respectively. When the embedded Sb$_2$Se$_3$ layer works at the amorphous state, its refractive index is ~3.28 at the wavelength of 1.55 µm. By contrast, the refractive index of Sb$_2$Se$_3$ layer increases to ~4.05 once its material state is switched to the crystalline state [28]. If such Sb$_2$Se$_3$ layer is further embedded in the silicon waveguide, we could create a changeable refractive index distribution region within the conventional silicon waveguide. For example, in the conversion region R$_1$, an Sb$_2$Se$_3$ layer with a taper shape is embedded in the
silicon waveguide asymmetrically along the propagation direction. At the crystalline state (“1”), the refractive index of Sb$_2$Se$_3$ layer is clearly higher than that of the adjacent silicon material. As the input TE$_0$ mode enters into such region, it will split into two beams where one beam propagates along the waveguide with Sb$_2$Se$_3$ layer and other one propagates along the waveguide without Sb$_2$Se$_3$ layer, corresponding to different propagation constants. When the phase difference between these two beams accumulates to $\pi$ through light propagation, the TE$_1$ mode can generate (two beams in opposite phase). At the amorphous state (“0”), the refractive index of Sb$_2$Se$_3$ layer is very close to that of silicon, where quite small refractive index difference can hardly change the mode propagation behavior in a short conversion length (<5 $\mu$m). So, the input TE$_0$ mode will pass through the conversion region nearly without influence and the output is still TE$_0$ mode. In the conversion region R$_2$, two identical tapered Sb$_2$Se$_3$ layers are embedded in the silicon waveguide symmetrically along the propagation direction. Such structure is designed to convert the TE$_0$ mode to TE$_2$ mode (“1”), where two Sb$_2$Se$_3$ layers are placed at inner sides of the silicon waveguide and the central position is no Sb$_2$Se$_3$ layer. Such design could create three propagation channels for three beams and the adjacent beam would propagate with different propagation constants. Once the accumulated phase difference between adjacent beams equals to $\pi$, the TE$_2$ mode can generate (three beams and adjacent beams in opposite phase). Similarly, if the Sb$_2$Se$_3$ layers work at the amorphous state (“0”), no mode conversion will happen and output TE$_0$ mode instead. Next, we cascade these two conversion regions and control them independently through microheaters. So, their combination states of these two conversion regions will become “00”, “10”, “01”, and “11”, respectively, where the corresponding output modes of the propose device can be TE$_0$, TE$_1$, TE$_2$, and TE$_1$+TE$_3$ mode (injecting TE$_0$ mode). Such multifunctional mode conversion feature has also been listed in the upper right corner of Fig. 1.

To achieve such multifunctional mode conversion, efficient phase change between amorphous and crystalline state of the embedded Sb$_2$Se$_3$ layer is crucial. Here, we choose graphene as the heating material since graphene has ultra-high thermal conductivity and low heat capacity [34]. So, the microheater is formed by depositing graphene and Al$_2$O$_3$ layers atop the hybrid Sb$_2$Se$_3$-silicon waveguide, where the Al$_2$O$_3$ layer is employed to protect graphene from oxidation. Meanwhile, graphene is a monatomic layer with a thickness of ~0.35 nm and such ultra-thin film nearly does not affect the TE mode in the silicon waveguide [35]. For the Sb$_2$Se$_3$, it is a new type of PCM, which still owns the excellent features of PCM, such as nonvolatile property (zero static power consumption) and long-term stability [28-30]. These excellent material features will help the proposed device having the characteristics of nonvolatile phase transition, low power consumption, fast switch, and multifunctional mode conversion. In addition, three-dimensional finite-difference time-domain (3D-FDTD) method was used to study and optimize the structural parameters in the following sections [36,37].
Results and discussion

Before we perform the device design and analyses, the definitions of the key performance indicators (mode CE, CT, and IL) should be offered at first. Here, we employ TE₀-to-TE₁ mode conversion as an example and other mode conversions are similar. Mode CE is defined as [16,17]

\[
\text{CE} = \frac{P_{\text{TE}1}}{P_{\text{out}}} \times 100\% ,
\]

where \( P_{\text{TE}1} \) and \( P_{\text{out}} \) are the receiving power of the TE₁ mode and the total power at the device output port, respectively. Mode CT is defined as [16,17]

\[
\text{CT} = \max \left( 10\log_{10} \frac{P_{\text{OT}}}{P_{\text{TE}1}} \right) ,
\]

where \( P_{\text{OT}} \) is the receiving power of the other interfering modes relative to the TE₁ mode at the device output port, and the mode CT is chosen as the maximum value between different modes. Mode IL is defined as [16,17]

\[
\text{IL} = -10\log_{10} \frac{P_{\text{TE}1}}{P_{\text{in}}},
\]

where \( P_{\text{in}} \) is the input power of the TE₀ mode launching into the input part. For the mode converter, we hope to achieve high CE, low CT, and low IL based on the structural design and optimization. To achieve such target, we conduct the extensive numerical calculations based on the 3D-FDTD method to find the optimum device parameters. The optimized parameters are as follows: the embedded Sb₂Se₃ layer lengths and thicknesses \( L_1 = 4.1 \mu \text{m} \), \( L_2 = 2.2 \mu \text{m} \), and \( T_1 = 290 \text{ nm} \), \( T_2 = 350 \text{ nm} \), the taper end widths \( W_{11} = 220 \text{ nm} \), \( W_{21} = 340 \text{ nm} \), and the lateral shift relative to the waveguide center \( S_1 = 460 \text{ nm} \), \( S_2 = 590 \text{ nm} \) corresponding to the conversion regions of R₁, R₂, respectively. In addition, the gap \( D_1 \) between these two regions R₁ and R₂ is designed to be 4 \( \mu \text{m} \) and such value could well balance the conversion performance for different mode conversion functions. Meanwhile, considering the practical device fabrication requirement, we have fixed the terminal widths (\( W_{12} = W_{22} \)) of the embedded Sb₂Se₃ layer to be 100 nm, which could benefit the device fabrication [38,39].

Next, we will conduct the device design and optimization in order to find the optimum structural parameters. Along with the light propagation, we first determine the structural parameters in the conversion region R₁ which could achieve the mode conversion from input TE₀ to output TE₁ mode (crystalline state, “1”) and without mode conversion (amorphous state, “0”). Then, in the conversion region R₂, its structural parameters should also be determined in order to achieve the mode conversion from input TE₀ to output TE₂ mode (crystalline state, “1”) and without mode conversion (amorphous state, “0”). Note that the conversion regions R₁ and R₂ are cascaded and the output mode in R₁ is used as the input mode in R₂. Also, the structural parameter optimizations in R₂ are based on the TE₀ mode, which means the conversion region R₁ should be worked at the amorphous state.
Fig. 2. Mode CE, CT, and IL of the proposed mode converter as functions of (a) the tapered Sb$_2$Se$_3$ layer length $L_1$, taper end width $W_{11}$, Sb$_2$Se$_3$ layer thickness $T_1$, and lateral shift $S_1$ in the conversion region $R_1$, and (b) the tapered Sb$_2$Se$_3$ layer length $L_2$, taper end width $W_{21}$, Sb$_2$Se$_3$ layer thickness $T_2$, and lateral shift $S_2$ in the conversion region $R_2$, respectively. Insets illustrate the schematics of the calculated structural parameters and the light blue shadow regions show the allowable variation ranges under the criteria of CE>95% and CT<−16 dB. (“0”). If the conversion region $R_1$ works at the crystalline state (“1”), the output mode of the conversion region $R_2$ will become a hybrid mode. More details will be offered in the following part and we will further design the device to make such hybrid mode into a pure TE$_3$ mode, which would be required for the practical device application [6]. Figure 2(a) shows the mode CE, CT, and IL of the proposed device as functions of the tapered Sb$_2$Se$_3$ layer length $L_1$, taper end width $W_{11}$, Sb$_2$Se$_3$ layer thickness $T_1$, and lateral shift $S_1$, where the calculations are around their optimized values in the conversion region $R_1$. According to the results, we find that the variation of IL is relatively small compared with those of mode CE and CT. So, if we set the mode CE>95% and CT<−16 dB as the criteria, the allowable variation ranges of $L_1$, $W_{11}$, $T_1$, and $S_1$ are [3.9 µm, 4.4 µm], [220 nm, 230 nm], [290 nm, 300 nm], [450 nm, 460 nm] (or [490 nm, 500 nm]), respectively, which have also been marked as the light blue shadow region in Fig. 2(a). By contrast, we should well control the taper end width, Sb$_2$Se$_3$ layer thickness, and lateral shift relative to the waveguide center during the practical device fabrication since their tolerance ranges are relatively smaller. To achieve high performance, we set $L_1$=4.1 µm, $W_{11}$=220 nm, $T_1$=290 nm, and $S_1$=460 nm as the optimum values in the following analyses, corresponding to the mode CE=96.9% (99.7%), CT=−18.4 dB (−28 dB), and IL=0.18 dB (0.02dB) for the TE$_0$-to-TE$_1$ (TE$_0$-to-TE$_0$) mode conversion, respectively. Next, we further analyze the conversion region $R_2$, which is employed to output higher-order TE$_2$ mode. Figure 2(b) shows the mode CE, CT, and IL of the proposed device as functions of the tapered Sb$_2$Se$_3$ layer length $L_2$, taper end width $W_{21}$, Sb$_2$Se$_3$ layer thickness $T_2$, and lateral shift $S_2$ in the conversion region $R_2$. By setting the combination phase states of aforementioned conversion regions $R_1$ and $R_2$, we can achieve the mode conversions of TE$_0$-to-TE$_0$ (“00”), TE$_0$-to-TE$_1$ (“10”), and TE$_0$-to-TE$_2$ (“01”) based on the excellent phase
transition properties of embedded Sb_{2}Se_{3} layers [28], where their performance indices have been illustrated in Fig. 2(b). Note that the TE_{0}-to-TE_{0} mode conversion has quite low influence since in such case the phase states of Sb_{2}Se_{3} layers in both regions are amorphous states, whose refractive indices are close to that of silicon. So, the structural parameter variations of Sb_{2}Se_{3} layers will not introduce obvious impact on the conversion performance. While for the TE_{0}-to-TE_{1} and TE_{0}-to-TE_{2} mode conversions, the device performances reveal some fluctuations due to the structural parameter variations. If we set the same criteria (mode CE>95% and CT<-16 dB) with that of region R_{1}, the allowable variation ranges of L_{2}, W_{21}, T_{2}, and S_{2} are [2.1 \mu m, 2.4 \mu m], [300 nm, 360 nm], [340 nm, 360 nm], [560 nm, 630 nm], respectively, which have also been marked as the light blue shadow region in Fig. 2(b). These tolerance ranges are almost larger than those in the conversion region R_{1}, which will be friendly for the device fabrication. The optimum parameters are set as L_{2}=2.2 \mu m, W_{21}=340 nm, T_{2}=350 nm, and S_{2}=590 nm, respectively, corresponding to the mode CE=97.8 \% (95.4\%, 99.1\%), CT=-18.9 dB (-17.4 dB, -26.4 dB), IL=0.17 dB (0.35 dB, 0.06 dB) for the TE_{0}-to-TE_{2} (TE_{0}-to-TE_{1}, TE_{0}-to-TE_{0}) mode conversion, respectively. So, the conversion performances of three modes are all relatively well through the proposed device scheme, which could well support the on-chip multimode propagation and processing.

Fig. 3. (a) Mode CE, CT, and IL of the proposed mode converter as a function of the gap D_{1} between two conversion regions (R_{1}, R_{2}). The vertical dotted line shows the chosen optimum value D_{1}=4 \mu m. (b) Wavelength spectra of the device performance (mode CE, CT, and IL) for the mode conversions from input TE_{0} mode to output TE_{0}/TE_{1}/TE_{2} mode. Three mode conversions have been considered and the wavelength range is calculated from 1.4 to 1.7 \mu m.

Figure 3(a) plots the mode CE, CT, and IL of the proposed mode converter as a function of the gap D_{1} between two conversion regions (R_{1}, R_{2}). From results, the device performance is relatively stable and only mode CT and CE reveal slight fluctuations. The reason is that for the mode conversions from input TE_{0} mode to output TE_{0}/TE_{1}/TE_{2} mode in here, no more than one conversion region (R_{1} or R_{2}) is kept in the crystalline state, so these two conversion regions almost do not interfere with each other. The obtained slight fluctuations might come from the structural reflection at the interface between the embedded Sb_{2}Se_{3} layer and silicon waveguide since their refractive indices are different. By considering the device performance, we set the gap D_{1} as 4 \mu m, which could help achieve higher CE and lower CT. Such value has also been used in the conversion region R_{2}.
to find its optimum structural parameters. Figure 3(b) shows the wavelength dependence of mode CE, CT, and IL of the proposed multifunctional mode converter, where the TE0-to-TE0/-TE1/-TE2 mode conversions have been considered including the material dispersions [40]. From results, the TE0-to-TE0 mode conversion reveals quite low wavelength dependence within the calculation range from 1.4 to 1.7 µm compared with other mode conversions. For the device bandwidth, the allowable working wavelength can be changed from 1522 to 1622 nm (bandwidth: 100 nm) for the TE0-to-TE1 and TE0-to-TE2 mode conversions by keeping mode CE>90%, CT<-15 dB, and IL<0.5 dB. Within the whole calculation wavelength range, the obtained mode CE, CT, and IL are higher than 98%, less than −22 dB, and less than 0.2 dB, respectively, for the TE0-to-TE0 mode conversion. Therefore, within a 100 nm working bandwidth, we can achieve the mode conversions from input TE0 mode to output TE0/TE1/TE2 mode in a single device only relying on the combination phase states of embedded Sb2Se3 layers in two conversion regions for the proposed device. Such multifunctional mode converter could further support the development of on-chip programmable photonics, where every outputting state can be easily programmed to realize a designated function [26,27].

Figure 4 illustrates the electric field evolutions of the proposed multifunctional mode converter working at different combination phase states, where all four combination states of “00”, “10”, “01”, and “11” for the embedded Sb2Se3 layers have been considered and the working wavelength is 1.55 µm. We can clearly observe that the input TE0 mode passes through the two conversion regions nearly without any disturbance and directly output TE0 mode at the combination phase state of “00” shown in Fig. 4(a). The total conversion length is only 10.3 µm for the proposed multifunctional device.

Figure 4 illustrates the electric field evolutions of the proposed mode converter working at different combination phase states, where all four combination states of “00”, “10”, “01”, and “11” for the embedded Sb2Se3 layers have been considered and the working wavelength is 1.55 µm. We can clearly observe that the input TE0 mode passes through the two conversion regions nearly without any disturbance and directly output TE0 mode at the combination phase state of “00” shown in Fig. 4(a). The total conversion length is only 10.3 µm for the proposed multifunctional mode converter. In Fig. 4(b), the input TE0 mode is firstly converted to the...
higher-order TE_1 mode through the first conversion region and then this generated TE_1 mode passes through the second conversion region and output TE_1 mode at the combination phase state of “10”. In Fig. 4(c), the input TE_0 mode directly passes through the first conversion region and then this TE_0 mode is converted to the higher-order TE_2 mode in the second conversion region and output TE_2 mode at the combination phase state of “01”. In Fig. 4(d), the input TE_0 mode is firstly converted to the higher-order TE_1 mode through the first conversion region, which is similar with the electric field evolution shown in Fig. 4(b), and then the converted TE_1 mode is further converted to a hybrid mode with TE_1 and TE_3 mode through the second conversion region and output such hybrid mode at the combination phase state of “11”. We should note that the generated hybrid mode is not beneficial for the mode recognition and we still hope to generate the higher-order TE_3 mode in a single device instead.

![Fig. 5. Electric-thermal simulation for the proposed multifunctional mode converter.](image)

For the proposed device, its multifunctional mode conversion is closely related to the phase transition of embedded Sb_2Se_3 layers between the amorphous state and crystalline state. To verify the feasibility of the phase transition process, electric-thermal phase transition method is used based upon the proposed microheater formed by depositing graphene and Al_2O_3 layers atop the hybrid Sb_2Se_3-silicon waveguide, and the electric-thermal simulation is performed using COMSOL Multiphysics [41]. Figure 5 illustrates the result of electric-thermal simulation and every combination phase state of two conversion regions corresponds to a kind of mode conversion function. The phase transition temperature and melting temperature of embedded Sb_2Se_3 material are 473 K and 893 K [28]. When the two conversion regions are in the amorphous states at room temperature, the input TE_0 mode will transmit and directly output TE_0 mode without mode conversion phenomenon. Next, if the conversion region R_1 (or R_2) generates the phase transition from amorphous state to crystalline state, the input TE_0 mode will be converted to the output TE_1 mode (TE_2 mode). According to the electric-thermal
simulation, the conversion region R1 and R2 are almost no thermal interference under the gap $D_1=4 \ \mu m$, so we can control these two conversion regions independently. For the device reconfigurability, we only need to make the phase transition from crystalline state to amorphous state of the embedded Sb$_2$Se$_3$ layers, which could recover the device function from input TE$_0$ mode to output TE$_0$ mode. The required amorphization temperature is higher than crystallization temperature but below the melting temperatures of silicon, silica, graphene, and Al$_2$O$_3$. So, such phase transition process will not damage the proposed multifunctional mode converter and the reconfigurable device function can also be obtained.

![Fig. 6.](image)

**Fig. 6.** (a) Schematic of the improved multifunctional silicon waveguide mode converter. (b) and (d) are the cross-sectional views of the mode conversion region R1 and R2, respectively. (c) Structural parameters of the embedded Sb$_2$Se$_3$ layers in two conversion regions (R1 and R2). Table shows the device function and the proposed device can achieve the mode conversion from input TE$_0$ mode to output TE$_0$, TE$_1$, TE$_2$, and TE$_3$ mode. The structural and material parameters are also labelled.

For the above device, we can easily achieve the TE$_0$-to-TE$_0$, TE$_0$-to-TE$_1$, TE$_0$-to-TE$_2$, and TE$_0$-to-TE$_1$+TE$_3$ mode conversions, but the last output mode of these mode conversions is a hybrid mode rather than a pure mode. So, we will further conduct the device design to achieve the mode conversion from input TE$_0$ mode to output TE$_0$, TE$_1$, TE$_2$, and TE$_3$ mode in a single device. To realize this target, we have changed the structural design in the conversion region R2 to make the mode conversion from input TE$_0$ to output TE$_3$ mode feasibly. The schematic of the improved device design is shown in Fig. 6, where the top and cross-sectional views of the device have been offered including a device function table. In order to well support the TE$_3$ mode, the silicon waveguide width is further increased to 2.3 $\mu m$. Compared with the device structure illustrated in Fig. 1, we have changed the original two identical tapered Sb$_2$Se$_3$ layers in the conversion region R$_2$ (Fig. 1) into one tapered Sb$_2$Se$_3$ layer in here (Fig. 6), where the device structures in R$_2$ are always kept symmetry relative to the...
waveguide center. Such improved structural design in the conversion region R2 (crystalline state) is employed to achieve the mode conversions from TE0 to TE2 mode and from TE1 to TE3 mode. The definitions of structural parameters are similar with those of Fig. 1, where the taper lengths of region R1 and R2 are $L_3$ and $L_4$ with a gap of $D_2$. The thicknesses of region R1 and R2 are $T_3$ and $T_4$, and the width of embedded Sb$_2$Se$_3$ layer is tapered from $W_{31}$ ($W_{41}$) to $W_{32}$ ($W_{42}$) in the region of R1 (R2) along the propagation direction shown in Fig. 6. For the device working principle, it is similar with that of device shown in Fig. 1. When the conversion region R2 is in the amorphous state (“0”), the device can achieve the TE$_0$-to-TE$_0$ and TE$_0$-to-TE$_1$ mode conversion relying on the amorphous state (“0”) and crystalline state (“1”) of the conversion region R1, where these functions are similar with those of device in Fig. 1. When the conversion region R2 is in the crystalline state (“1”), the device can achieve the TE$_0$-to-TE$_2$ and TE$_0$-to-TE$_3$ mode conversion. For the TE$_0$-to-TE$_2$ mode conversion, the input TE$_0$ mode firstly passes through the region R1 nearly without disturbance since region R1 is in the amorphous state (“0”) and then enters into the region R2, where the TE$_0$ mode is splitted into three beams. The central beam propagates along the waveguide with embedded Sb$_2$Se$_3$ layer and the other two beams propagate along the waveguide without embedded Sb$_2$Se$_3$ layer in both sides, where the conversion structure is symmetry about the waveguide center. As the phase difference between adjacent beams accumulates to $\pi$ through light propagation, the TE$_2$ mode will be generated (three beams and adjacent beams in opposite phase). For the TE$_0$-to-TE$_3$ mode conversion, the input TE$_0$ mode is firstly converted to the TE$_1$ mode since region R1 is in the crystalline state (“1”) and the converted TE$_1$ mode is further splitted into four beams in region R2, where such phenomenon can be viewed as the combination of two mode conversions in region R1. After light propagation, as the phase difference between adjacent beams accumulates to $\pi$, the TE$_3$ mode will be generated (four beams and adjacent beams in opposite phase). Therefore, four pure modes (TE$_0$, TE$_1$, TE$_2$, and TE$_3$ mode) can be easily generated in a single device only by setting the combination phase state of the proposed device as “00”, “10”, “01”, and “11”, respectively.

Figure 7 shows the calculated mode CE, CT, and IL of the improved mode converter as functions of its taper length $L_3$ ($L_4$), taper end width $W_{31}$ ($W_{41}$), lateral shift $S_3$, and embedded Sb$_2$Se$_3$ layer thickness $T_3$ ($T_4$) in the conversion region R1 (R2). To find the optimum device parameters, we firstly optimize the conversion region R1 to achieve the TE$_0$-to-TE$_0$ and TE$_0$-to-TE$_1$ mode conversion and then optimize the conversion region R2 cascaded with R1 to further achieve the TE$_0$-to-TE$_2$ and TE$_0$-to-TE$_3$ mode conversion, where this optimization process is similar with that of device shown in Fig. 1. The terminal widths ($W_{32}=W_{42}$) of the embedded Sb$_2$Se$_3$ layers are also fixed to be 100 nm by considering the device fabrication [38,39]. For the taper length $L_3$, two types of mode conversions (TE$_0$-to-TE$_0$ and TE$_0$-to-TE$_1$) reveal different performance trends and we set the optimum value as $L_3=3.1$ $\mu$m by balancing these two cases. Meanwhile, the variation curves of taper end width...
$W_3$ and lateral shift $S_3$ show similar trend and their optimum performances are within the ranges of [340 nm, 400 nm] and [400 nm, 460 nm], respectively, where we choose $W_3=350$ nm and $S_3=430$ nm under the following analyses. When the embedded Sb$_2$Se$_3$ layer thickness $T_3$ increases from 220 nm to 300 nm, the TE$_0$-to-TE$_0$ mode conversion performance becomes better gradually while the TE$_0$-to-TE$_1$ mode conversion performance deteriorates on the contrary, as shown in Fig. 7(a). So, we set $T_3$ as 220 nm with good device performance, corresponding to the mode CE=93.6% (93.4%), CT=$-12.8$ ($-16.2$) dB and IL=$0.29$ ($0.32$) dB for the TE$_0$-to-TE$_0$ (TE$_0$-to-TE$_1$) mode conversion. Next, in the conversion region R$_2$, we embed the second tapering Sb$_2$Se$_3$ layer in the silicon waveguide with a symmetric manner relative to the waveguide center (zero lateral shift), where its structural parameters are determined based on the all four mode conversion cases shown in Fig. 7(b). According to the calculation results, we can easily find the optimum structural parameters since there are obvious performance extreme points for the TE$_0$-to-TE$_2$ and TE$_0$-to-TE$_3$ mode conversions and the TE$_0$-to-TE$_0$ and TE$_0$-to-TE$_1$ ones are nearly unsensitive to the variations of taper length $L_4$ and taper end width $W_4$. Under these conditions, we set the optimal structural parameters as $L_4=3.9$ $\mu$m, $W_4=640$ nm, and $T_4=360$ nm, where the mode CE>85%, CT<$-11$ dB, and IL<$1$ dB are achieved for all four mode conversions in a single device. Such multifunctional mode converter together with relatively well device performance for all mode conversion cases has not been reported previously and the proposed device scheme could offer an useful way to construct multifunctional multimode PICs, also supporting the on-chip programmable PICs [25]. Figure 8(a) describes the mode CE, CT, and IL of the improved mode converter versus the gap $D_2$ between two conversion regions (R$_1$, R$_2$). From Fig. 8(a), we can clearly observe that the device performance reveals relatively stable against the gap $D_2$ since the waveguide structure in the gap region is same for all mode propagation. Through comprehensive considering the mode conversions from input TE$_0$ mode to output TE$_0$/TE$_1$/TE$_2$/TE$_3$ mode, we have set the gap $D_2$ as 2.5 $\mu$m, where longer gap length corresponds to lower mode CE and higher mode CT for the TE$_0$-to-TE$_2$ and TE$_0$-to-TE$_3$ mode conversions and shorter gap length corresponds to lower mode CE for the TE$_0$-to-TE$_2$ mode conversion and higher mode CT for the TE$_0$-to-TE$_3$ mode conversion, respectively. Moreover, the wavelength dependence of the device performance is plotted in Fig. 8(b), where all four mode conversions have been considered together with the material dispersions [40]. If we should keep the mode CE>80% for all four mode conversions, the allowable working bandwidth can be extended from 1458 to 1587 nm (bandwidth: 129 nm), which could well satisfy the requirements of optical communications.
Fig. 7. Mode CE, CT, and IL of the improved mode converter as functions of its (a) taper length $L_3$, taper end width $W_{31}$, lateral shift $S_3$, embedded Sb$_2$Se$_3$ layer thickness $T_3$ in the conversion region $R_1$, and (b) taper length $L_4$, taper end width $W_{41}$, embedded Sb$_2$Se$_3$ layer thickness $T_4$ in the conversion region $R_1$, respectively. Insets illustrate the schematics of the calculated structural parameters.

Fig. 8. (a) Mode CE, CT, and IL of the improved mode converter as a function of the gap $D_2$ between two conversion regions ($R_1$, $R_2$). The vertical dotted line shows the chosen optimum value $D_2=2.5$ $\mu$m. (b) Wavelength spectra of the device performance (mode CE, CT, and IL) for the mode conversions from input TE$_0$ mode to output TE$_0$/TE$_1$/TE$_2$/TE$_3$ mode. Four mode conversions have been considered and the wavelength range is calculated from 1.4 to 1.7 $\mu$m.

To better present the chosen device parameters, we have made a Table 1 to list the structural parameters of the proposed multifunctional mode converter and its improved design, where type I and type II stand for the devices shown in Figs. 1 and 6, respectively. From Table 1, we can find that the minimum structural size of the proposed device is obviously larger than 200 nm, which could be realized using the current E-beam lithography and reactive ion etching system [38,39]. For the device fabrication, its main process includes three key parts: fabricating silicon waveguide as the basic conversion waveguide, embedding Sb$_2$Se$_3$ layers in the silicon waveguide as the key multifunctional tunable elements, and depositing graphene and Al$_2$O$_3$ layers atop the hybrid Sb$_2$Se$_3$-silicon waveguide as the microheater. First, the silicon waveguide and the required taper slots in
Two conversion regions are fabricated on the SOI wafer using E-beam lithography and reactive ion etching processes [38,39]. Second, Sb2Se3 layers with designated thicknesses are deposited in two conversion regions to fill the etched slots using magnetron sputtering [31], where other part except for the slot range should be removed. Third, graphene layers grown by chemical vapor deposition are transferred to the surfaces of two conversion regions [42], where the metal electrodes are added on both sides of two conversion regions in order to allow the electric-thermal phase transition which is required for achieving the multifunctional mode conversions. Finally, 20-nm-thick Al2O3 layers are deposited atop the graphene layers in two conversion regions for protecting the graphene from oxidation [35]. Through these fabrication steps, we can realize the proposed multifunctional mode converter and its improved version.

Table 1 Structural Parameters of Proposed Multifunctional Mode Converter and Its Improved Design

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameters</th>
<th>L1 (µm)</th>
<th>L2 (µm)</th>
<th>W11 (µm)</th>
<th>W21 (µm)</th>
<th>T1 (µm)</th>
<th>T2 (µm)</th>
<th>D1 (µm)</th>
<th>S1 (µm)</th>
<th>S2 (µm)</th>
</tr>
</thead>
<tbody>
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<td>Values</td>
<td>4.1</td>
<td>2.2</td>
<td>0.22</td>
<td>0.34</td>
<td>0.29</td>
<td>0.35</td>
<td>4</td>
<td>0.46</td>
<td>0.59</td>
</tr>
<tr>
<td>II</td>
<td>Values</td>
<td>3.1</td>
<td>3.9</td>
<td>0.35</td>
<td>0.64</td>
<td>0.22</td>
<td>0.36</td>
<td>2.5</td>
<td>0.43</td>
<td>0</td>
</tr>
</tbody>
</table>

At last, we study and plot and electric field evolutions of the improved mode converter under four combination phase states, as shown in Fig. 9. For the same input TE0 mode, we can clearly find that the output mode can be TE0, TE1, TE2, and TE3 mode in a single device with a length of only 9.5 µm as long as the combination phase states of embedded Sb2Se3 layers in two conversion regions are set as “00”, “10”, “01”, and “11”, respectively. Using this device, we can easily obtain four modes (TE0~TE3) in a single device as the input TE0 mode launches into this device and every output mode can be well controlled through the phase transition mechanism, where all the obtained mode purities are also relatively well with high CE and low CT. Such multifunctional mode converter completely breaks the conventional mode converter with one function for one device [11-24], which could greatly improve the device function and support new applications. For example, these generated waveguide modes can be employed as the higher-order mode sources for the on-chip multimode applications and be further built the on-chip multimode PICs, supporting multimode light transmission and processing on-chip together with programmable functions.
Fig. 9. Electric field evolutions (dominant component: \(E_y\)) of the improved multifunctional mode converter working at different combination phase states. The input TE\(_0\) mode can be converted to the output TE\(_0\), TE\(_1\), TE\(_2\), and TE\(_3\) mode through the proposed device corresponding to the combination phase states of “00”, “10”, “01”, and “11”, respectively. The total conversion length is reduced to only 9.5 \(\mu\)m for the improved multifunctional mode converter.

**Conclusion**

In summary, we proposed multifunctional silicon waveguide mode converters, where the multifunctional mode conversion is achieved by embedding nonvolatile and low-loss Sb\(_2\)Se\(_3\) layers into the silicon waveguide. To satisfy the requirements of more mode conversions, we have designed two cascaded conversion regions along the silicon waveguide, where the first conversion region is formed by embedding a tapered Sb\(_2\)Se\(_3\) layer into the silicon waveguide on its one side and the second one is formed by embedding two identical tapered Sb\(_2\)Se\(_3\) layers into the silicon waveguide symmetrically. Based on the excellent phase transition feature of the embedded Sb\(_2\)Se\(_3\) layers, the input TE\(_0\) mode can be efficiently converted to the output TE\(_0\), TE\(_1\), TE\(_2\), and TE\(_1+TE_3\) mode in a device length of 10.3 \(\mu\)m when the combination phase states of two conversion regions are set as “00”, “10”, “01”, and “11”. The obtained mode CE, CT, and IL are >95%, <−17 dB, and <0.4 dB for the TE\(_0\)-to-TE\(_0/TE_1/TE_2\) mode conversion, respectively, the performance of which is well for three mode conversions simultaneously in a single device. Further, we redesign the device to achieve the mode conversion from input TE\(_0\) mode to output TE\(_0\), TE\(_1\), TE\(_2\), and TE\(_3\) mode, no longer existing the output hybrid mode. These four pure waveguide modes outputting from a single device can be appointed as the key mode sources for the on-chip multimode PICs. We also hope the proposed device scheme could offer a new way to construct multifunctional and programmable photonic devices or PICs.
CRediT authorship contribution statement

Yedeng Fei: Conceptualization, Visualization, Software, Writing – original draft. Yin Xu: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing. Yue Dong: Investigation, Software, Formal analysis. Bo Zhang: Investigation, Software, Data curation. Yi Ni: Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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