**Design of a dispersion-engineered broadband Ge11.5As24Se64.5-Si3N4 strip-slot hybrid waveguide with giant and flat dispersion over 350 nm for on-chip photonic networks**

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**Abstract**: We propose a new strip-slot hybrid waveguide with extreme large and flat dispersion over broad wavelength range. The strong resonance coupling between the strip and slot modes has been employed to obtain a high dispersion at desired wavelength. The properties of dispersion are analyzed using the finite-difference time-domain method. All numerical simulation results reveal that for the optimized waveguide structure, a maximum dispersion of −1.54×106 ps·nm-1·km-1 and dispersion full width at half−maximum of 2.5 nm at 1.55 μm are obtained. By cascading the strip-slot hybrid waveguides with varied width and height, a large and flattened dispersion of −9.8×105 ps·nm-1·km-1 covering 350 nm is achieved. Moreover, dispersion compensation of 100 Gbit/s return-to-zero on-off-keying optical-time-division-multiplexing signals after 50-km single mode fiber transmission, and after 7-km hollow-core photonic band-gap fiber transmission are demonstrated, separately. Such a waveguide will find widespread applications in on-chip all-optical signal processing.

**Keywords**: optical fiber communication, slot waveguide, dispersion compensation,

dispersion-engineered

1. **Introduction**

Over the past decade, there has been an increasing interest in slot waveguide because of its extraordinary characteristics of confining and guiding light in the thin slot region, which provides much design freedom to tailor the waveguide property [1–3]. Generally speaking, slot waveguides are formed by a sub-wavelength-scale low–refractive–index material embedded between two slabs of high– refractive–index materials. Owing to the discontinuity of the normal component of the electrical field *E* at the high-index-contrast interface, a slot waveguide can realize particular features, including high nonlinearity, large birefringence, controllable mode area, and flattened dispersion [4]. Many on-chip integrated photonic devices including supercontinuum (SC) sources [5], wavelength converters [6], polarization beam splitters [7], polarization rotators [8], mode converters [9] and integrated biochemical sensors [10] based on slot waveguides have been reported. On the other hand, dispersion induced pulse broadening and distortion is a serious problem in high-speed optical fiber communication systems, which will limit the bandwidth-distance product (BDP) and degrade the performance of high-bit-rate optical fiber communication systems. Therefore, dispersion compensators have been developed and have become indispensable, especially for long-haul backbone networks. To date, there have been mainly three kinds of dispersion compensators including dispersion compensation fibers (DCFs) [11], periodic fiber Bragg gratings [12], and all-pass filters [13], which all have been widely used to solve the dispersion issue in current commercial optical fiber communication systems. Among these, DCFs are the most popular, but they are usually quite long and have large bending radius. Meanwhile, they are not easy to realize on-chip photonic integration. In contrast, Bragg fiber gratings are much smaller, but there is a tradeoff between total dispersion and bandwidth. In addition, Bragg fiber gratings are very sensitive to environmental parameter perturbation/drift. And for etalon all-pass filters, a precise optical alignment process in fabrication is unavoidable. Recently, several kinds of on-chip dispersion elements including ring resonators [14], wideband silicon waveguides [15] and arrayed waveguide gratings (AWGs) [16] have been reported, but the obtained dispersion magnitude and operational wavelength region are still very limited. For example, in 2009, a horizontal strip/slot hybrid waveguide with a large dispersion of −181,520 ps·nm-1·km-1 was proposed. Dispersion compensation of 400 Gbit/s return-to-zero on-off-keying (RZ-OOK) signals after 10.87-km fiber transmission was demonstrated [17]. In 2015, a vertical strip-slot hybrid waveguide with a high dispersion of −4.8×105 ps·nm-1·km-1 was proposed [18]. In 2016, Nandam demonstrated a horizontal strip/slot hybrid waveguide and a reverse ridge waveguide with dispersions of −7.3×104 ps·nm-1·km-1 and −1.46×105 ps·nm-1·km-1, respectively [19-20]. In 2017, Kjellman suggested a broadband InP-based asymmetric dual width waveguide with a dispersion of either −23,200 or 8,200 ps·nm-1·km-1 [21]. Actually, in addition to achieving dispersion compensation, high dispersion devices have also been used for realizing various all-optical signal-processing functions, including time-stretched all-optical analog-to-digital conversion (ADC) [22], optical buffing [23], chirper pulse compression [24], and radio-beam steering [25]. This property makes on-chip highly dispersive elements candidates for potential applications in next-generation large-scale photonic integrated circuits.

Recently, chalcogenide glasses have received considerable attention because they exhibit a broadband mid-infrared transmission window (the maximum operating wavelength is up to 25 μm) with high optical Kerr nonlinearity refractive index (approximately 100 ~ 1000 times that of silica) and negligible two-photon absorption [26-28]. This region contains the strong characteristic vibration transition of molecules and two atmospheric transmission windows, which makes it very important for applications in spectroscopy analysis, medical diagnostics, biological/chemical sensing, material characterization, food security and coherent optical communication [29]. Various on-chip integrated photonic devices including all-optical wavelength converter [30], optical time-division de-multiplexers [31] and SC sources [32] have been successfully demonstrated based on As2S3 waveguides. Nevertheless, emergent Ge-As-Se chalcogenide glass shows a superior combination of relatively high third-order nonlinearity, low optical loss, excellent film-forming properties, and requisite stability[33]. Thus, there has been a growing interest in designing planar optical waveguides by employing them for ultrafast all-optical signal processing. Several on-chip SC sources have been successfully demonstrated based on Ge11.5As24Se64.5 fibers/waveguides [34-37]. However, an on-chip dispersion compensator based on a chalcogenide waveguide has not been reported until now, to the best of our knowledge, and it is highly desirable for on-chip photonic signal processing.

In this paper, we propose an ultra-broadband strip-slot hybrid waveguide with high and flattened dispersion. By using the finite-difference time-domain (FDTD) method with perfectly-matched-layer (PML) boundary conditions, the effective indices and dispersion characteristics of strip-mode to slot-mode are investigated. Numerical simulation results reveal that by choosing appropriate strip-slot hybrid waveguide geometric parameters, a negative dispersion of -1.54×106 ps·nm-1·km-1 at 1550nm is attained. By cascading the strip-slot hybrid waveguide with different widths and heights, a large and flat dispersion of -9.8×105 ps·nm-1·km-1 over 350 nm (1630-1980nm) is achieved for the first time. Moreover, dispersion compensation of 100-Gbit/s RZ-OOK optical-time-division-multiplexing (OTDM) signals with a central wavelength of 1550 nm after 50-km single mode fiber transmission; and a central wavelength of 1650 nm after 7-km hollow-core photonic band-gap fiber (HC-PBF) fiber transmission are demonstrated, separately.

1. **Geometry of proposed strip-slot hybrid waveguide**

Figure 1(a) shows the cross-section of the proposed strip-slot hybrid waveguide. It consists of a strip waveguide of Ge11.5As24Se64.5 and a vertical Si3N4 slot waveguide separated by air with distance of *L*a. The strip waveguide and slot waveguide are horizontally coupled to each other. The substrate is SiO2. The width and height of the strip waveguide are *L*S1 and *H*. The slot waveguide is formed with Si3N4 of width *L*between two silicon layers. The width and height of the silicon slabs are *LS*2 and *H*, respectively. Due to the discontinuity of the electrical field at the interface between the slot and the slab, the electromagnetic field is enhanced and confined in the slot region of low-index material. Moreover, for the suitable waveguide structural parameters, the strong horizontal resonance coupling occurs between the strip- and slot-waveguide **quasi**-transverse-electric (***q***-*TE*) fundamental modes (horizontally polarized), which results in a large chromatic dispersion. Figure 1(b) shows the three-dimensional (3D ) topography of the proposed strip-slot hybrid waveguide.





Fig.1 Schematic of (a) 2D cross-section and (b) 3D topography for strip-slot hybrid waveguide.

1. **Simulation method**

The simulation is carried out based on the FDTD method from a software package of mode solution provided by Lumerical Solutions, Inc. In our simulation, a PML absorption boundary has been imposed on the cross section of the proposed strip-slot waveguide. By discretizing the Maxwell’s equations in time and space by Yee’s cell [38], a linear system of algebraic equations is formed. Next, an eigenvalue equation can be acquired from this linear equation. Then, by solving the eigenvalue equation, the effective refractive index and modal fields of the guided modes can be obtained. To make the solution of the discretized differential equations be convergent, the time step should meet the Courant condition ****[38]. The material linear refractive indices of Ge11.5As24Se64.5, silicon, silica and Si3N4 can be taken into consideration through the Sellmeier equations [39-40]:

 (1)

where *c* and λ are the speed of light and light's wavelength in vacuum, respectively. *n*(λ) describes the dependence of refractive index and wavelength. ε, c1, c2, c3, c4, c5, λ1, λ2, λ3 and λ4 are Sellmeier coefficients and resonant wavelengths, respectively (See Table1). Moreover, a summary of the key material parameters, including refractive index (RI) at 1550 nm, transparency window, Kerr nonlinear RI, two-photon absorption (βTPA) coefficient and energy gap of some materials is also given in Table 2 [41-42]. These are the most commonly used materials in the Silicon photonics community. We choose to use Si3N4 and Ge11.5As24Se64.5 as the core material because they comprise the best attributes of

silicon and SiO2 for Si-based integrated nonlinear photonics.

The dependency of effective RIs and wavelengths (for symmetric and asymmetric modes) are numerically investigated. The total chromatic dispersion is a combination of waveguide dispersion and material dispersion. It can be obtained through  [43], where λ is the wavelength, *c* is the speed of light in vacuum, and *n*eff is the effective refractive index.

Table 1 Sellmeier coefficients and resonant wavelengths for different materials

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **material**  **coefficient** |  |  |  |  |  |  |  |  |  |  |
| Silicon | 11.68 | 0.939816 | 0.00810461 | 0 | 0 | 0 | 1.1071 | 0 | 0 | 0 |
| Silicon Nitride | 1 | 0 | 0 | 2.8939 | 0 | 0 | 0 | 0.13967 | 0 | 0 |
| Silica | 1 | 0 | 0 | 0.6961663 | 0.4079426 | 0.8974794 | 0 | 0.0684043 | 0.1162414 | 9.896161 |
| Ge11.5As24Se64.5 | 1 | 0 | 0 | 5.78525 | 0.39705 | 0 | 0 | 0.28795 | 30.39338 | 0 |

Table 2 Relevant optical parameters for different materials (RI denotes refractive index).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Parameter  material | RI  at 1550 nm | Transparency window (µm) | Loss (dB/cm) at 1550 nm | Nonlinear RI (m2/W) at 1550 nm | βTPA (cm/GW)  at 1550 nm | Eg (Energy band gap)  Eg (eV) |
| Silica | 1.46 | 0.13-3.5 | 0.2 | 2.6×10-20 | <<0.01 | 9 |
| Silicon | 3.45 | 1.1-9 | 0.4 | 4×10-18 | 0.79 | 1.12 |
| Si3N4 | 1.99 | 0.25-8 | 0.5 | 2.4×10-19 | ~0 | 5 |
| Ge11.5As24Se65 | 2.64 | 1-10 | 0.5 | 7.33×10-18 | 9.3×10-3 | 1.9 |

1. **Simulation results and discussions**

The effective refractive indices of *q*-*TE* fundamental modes at different wavelengths for the designed strip-slot hybrid waveguide are calculated for the following value of waveguide geometrical parameters. The width and height of the strip waveguide are *L*S1 =807 nm and *H=*400 nm. The width and height of the silicon slabs are *LS*2=170 nm and *H*=400 nm. The slot waveguide width *L* is 24 nm. The air distance *L*a=542 nm. Based on the above mentioned set of parameters, the effective RIs of the individual strip and slot modes, symmetric and asymmetric modes are all calculated and the results given in Fig.2(a). The dotted line and dashed line belong to the slot-waveguide mode and strip-waveguide mode, respectively. With increasing wavelength, the effective RIof the slot mode decreases faster than that of the strip mode. Thus, at a wavelength of λ=1.55μm, the effective RIs of the two modes exhibit a sharp bending and are very close to each other. Hence, composite modes are formed that consist of a symmetry mode and an asymmetry mode. Meanwhile, the resonance coupling occurs between the two modes. When the mode field energy transfers from the slot waveguide to the stripe waveguide, the dispersive symmetrical mode is generated. On the contrary, when the mode field energy transfers from the strip waveguide to the slot waveguide, the dispersion anti-symmetric mode is generated. Depending on which of the super-modes is excited in the waveguide, the dispersion can be normal or abnormal. The magnitude depends on the coupling strength between the strip and slot modes. The dispersion of the corresponding two super-modes (symmetric and asymmetric modes) are calculated and given in Fig.2(b). As can be seen in the figure, at the resonant wavelength of 1550 nm, a very high dispersion magnitude appears, which originates from the resonance coupling between the two modes and can be explained by the above mentioned dispersion equation. The dispersion values of the symmetric and asymmetric modes are almost the same but with opposite sign. It is -1.54×106 ps·nm-1·km-1 for the symmetric mode, while the asymmetric mode has positive dispersion. Moreover, the confinement loss is investigated to evaluate the performance of the proposed strip-slot waveguide. It can be calculated according to [44]. Here *n*eff is the effective refractive index, *Im* represents the imaginary part, and λ is the wavelength in vacuum. The dependence of confinement loss and wavelength is given in Fig. 2(c). It can be seen from the figure that the confinement loss increases with increasing wavelength for the symmetric mode, while it is opposite for the anti-symmetric mode. Fig.2 (d) illustrates the field distributions of the ***q***-*TE* fundamental mode at wavelengths of 1520 nm, 1550 nm, and 1580 nm, respectively. The optical power transfers from the slot to the strip region as the wavelength increases.





(d)

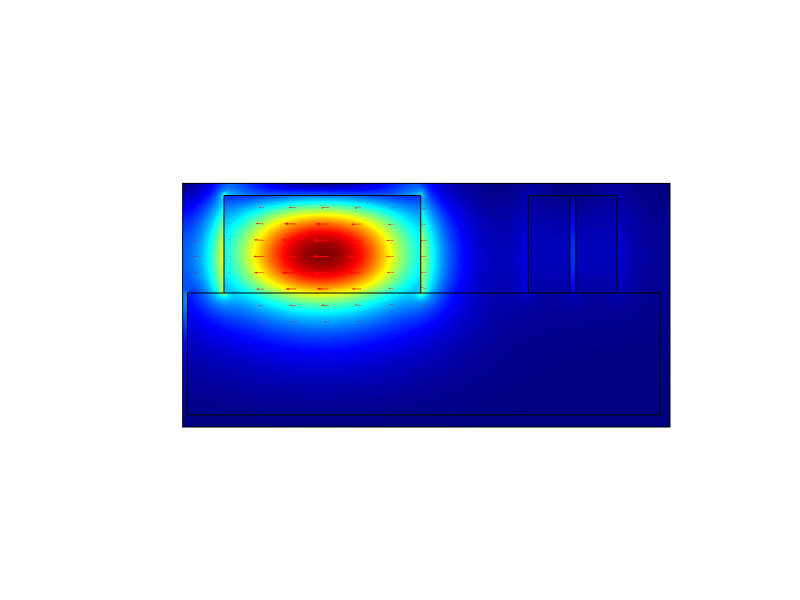
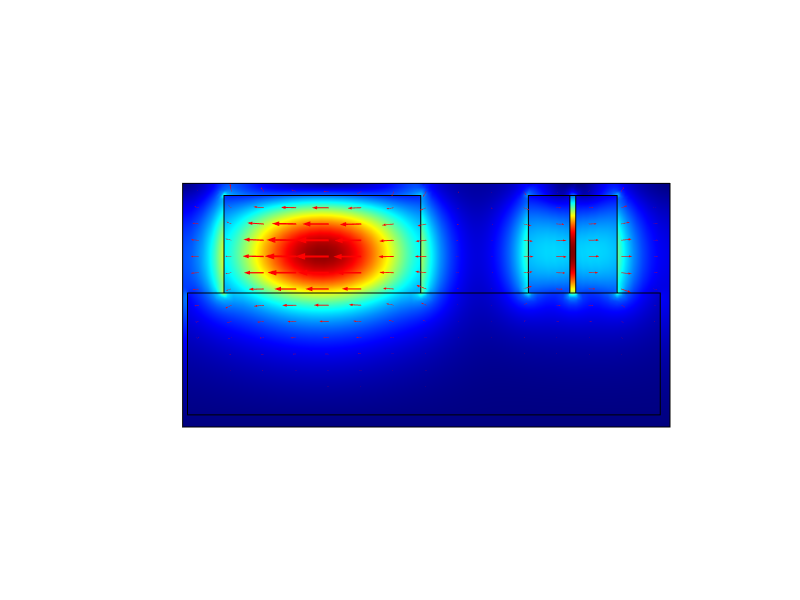
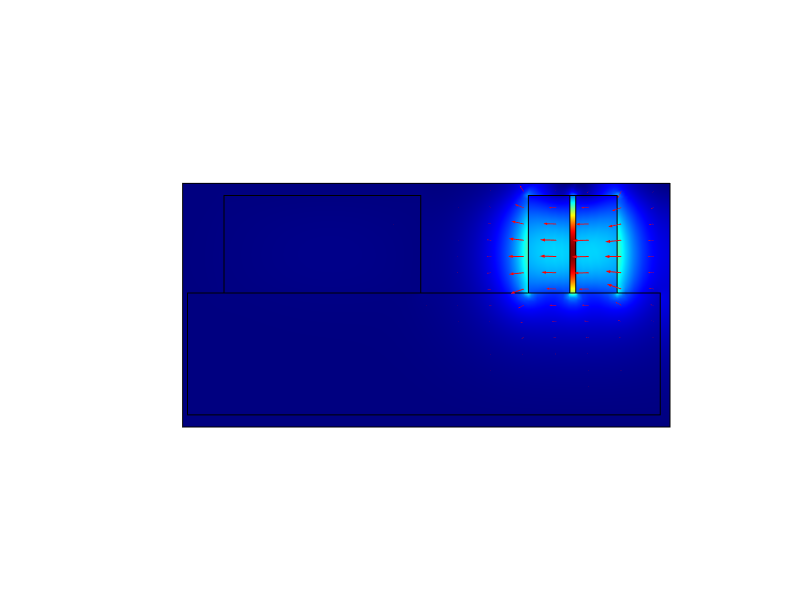


Fig.2 (a) Effective RI curves of individual strip mode, slot mode, symmetric mode, and asymmetric modes. (b) Dispersion curves of symmetric and anti-symmetric modes. (c) Dependence of confinement loss and wavelength. (d) Electrical field distributions of ***q***-*TE* fundamental mode at different wavelengths. From left to right: λ=1520 nm, λ=1550 nm and λ=1580 nm.

Regarding the strip-slot waveguide, the dispersion value is dependent on the coupling coefficient, while the coupling coefficient strongly depends on the waveguide geometric parameters. Therefore, we optimized the geometric parameters of the strip-slot waveguides to realize a large negative dispersion magnitude simultaneous with large full-width half maximum (FWHM) bandwidth. To find suitable geometric parameters of *H*, *L*, *L*a, *L*S1and *L*S2 for high dispersion value at a desired wavelength, a series of numerical calculations were carried out. First, we investigated the impact of waveguide height *H* on the effective RIs. In our simulation, *L*a*=*542 nm, *L*S1*=*807 nm, *L=*24 nm*, L*S2*=*170 nm. *H* is increased from 350 nm to 600 nm in a step of 50 nm while all the other parameters remain constant. The results are described in Fig.3. Fig.3 (a) shows the relationship of dispersion and wavelength for different *H*. It can be found that the magnitude of dispersion increases with increasing *H*. For example, when the height *H* increases from 350 nm to 600 nm, the magnitude of dispersion increases from -1.43×106 ps·nm-1·km-1 to -1.7×106 ps·nm-1·km-1. Meanwhile, the central wavelength of the peak dispersion moves to longer wavelength. The reason is that the effective RI increases as the height *H* increases. This results in delays in the intersection point of the effective RI coefficients of the two modes. Therefore, it is an effective way to adjust *H* to realize dispersion compensation at the desired wavelength. On the other hand, the dispersion magnitude and FWHM are plotted as a function of *H*. We can see that the FWHM bandwidth decreases slightly with increasing *H*. For example, the bandwidth decreases from 2.2 nm to 1.7 nm when *H* increases from 350 nm to 600 nm.





Fig.3 (a) Dispersion profiles for different waveguide heights *H*. (b) Peak dispersion and bandwidth as a function of *H*.

Second, we investigate the influence of air distance *L*a on the effective RIs. In our simulation, *L*S1*=*807 nm, *L*=24 nm, *L*S2=170 nm, *H*=400 nm. *L*a increases from 182 nm to 482 nm while all the other parameters are fixed. The dependencies of dispersion and wavelength for different *L*a are calculated and the results are given in Fig.4(a).It can been seen from the figure that the peak dispersion magnitude increases dramatically with increasing *L*a. The obtained maximum dispersion is -9.67×105 ps•nm-1•km-1 for *L*a =482 nm, but the resonance wavelength is constant. The reason is that the slope of effective index increases with the increase of *L*a, but the intersection point of the effective RI remains constant. Moreover, the peak dispersion and FWHM are calculated as a function of wavelength for different *L*a ( Fig.4(b)). It is clear that the dispersion FWHM decreases with the increase of *L*a while the peak dispersion magnitude increases.





Fig.4 (a) Dispersion profiles for different air distances *L*a. (b) Peak dispersion and bandwidth as a function of *L*a.

Third, we investigate the relationship of the effective RIs and the waveguide slot width *L*. In our simulation, *L*a*=*512 nm, *H=*400 nm, *L*S1*=*807 nm, *L*S2*=*170 nm. *L* increases from 20 nm to 28 nm in a step of 2 nm while all the other parameters remain constant. The results are shown in Fig.5. It can be seen from the figure that the peak dispersion wavelength shifts towards the shorter wavelength, but the dispersion magnitude is not affected significantly by increasing *L*. When *L* increases by 2 nm, the drift of the dispersion peak wavelength is approximately equal to the interval of 12.5 nm. There is an approximately linear relationship between them. The reason is that increasing *L* has no significant effect on the slope difference of the effective index, but it changes the position of the intersection point, which results in the shift of the peak dispersion wavelength. When *L* varies from 20 nm to 28 nm, the peak dispersion wavelength shift is 50 nm. This characteristic provides a flexible design freedom for obtaining wide waveband dispersion compensation.





Fig.5 (a) Dispersion profiles for different left-slot waveguide heights *L*. (b) Peak dispersion and bandwidth as a function of *L*.

Finally, we investigate the dependency of the effective RIs on the strip waveguide width *L*S1 and slab waveguide width *L*S2. In our simulation, *L*S1 increases from 822 nm to 942 nm in a step of 30 nm while *H=*400 nm, *L=*28 nm, *L*S2*=*170 nm, *L*a=332 nm. The results are described in Fig.6. As can be seen from Fig. 6(a), with the increase of *L*S1, the peak dispersion wavelength has a blue-shift (from 1610 nm to 1549 nm). The peak dispersion magnitude increases significantly. As illustrated in Fig.6(b), the peak dispersion magnitude increases from -2.1×105 ps·nm-1·km-1 (for *L*S1=822 nm) to -4.1×105 ps·nm-1·km-1 (for *L*S1=942 nm), and the corresponding dispersion FWHM decreases from 13.4 nm to 7.2 nm.

On the other hand, when *L*S2 increases from 169 nm to 173 nm in a step of 1 nm while *H=*400 nm, *L=*28 nm, *L*S1*=*807 nm, *L*a=394 nm. The results are shown in Fig.7. It can be seen in Fig. 7(a), with the increase of *L*S2, that the peak dispersion wavelength shifts from 1522 nm to 1571 nm. The reason is that with increasing *L*S2, that the effective RI of the slot waveguide increases, and the intersection point of the effective RIs shifts towards longer wavelength. Meanwhile, the peak dispersion magnitude decreases significantly. It can be seen from Fig.7(b), that the peak dispersion magnitude decreases from -4.9×105 ps·nm-1·km-1 to -3.9×105 ps·nm-1·km-1. In contrast, the FWHM bandwidth increase from 5.8 nm to 7.5 nm.





Fig.6 (a) Dispersion profiles for different left-slot waveguide heights *L*S1. (b) Peak dispersion and bandwidth as a function of *L*S1.





Fig.7 (a) Dispersion profiles for different left-slot waveguide height *L*S2. (b) Peak dispersion and bandwidth as a function of *L*S2.

From the above analysis, it can be seen that the increase of *H*, *L*a and *L*S1 can effectively increase the peak dispersion magnitude, but it will reduce the FWHM. On the contrary, the increase of *L*S2 can effectively increase the FWHM, but it will reduce the peak dispersion. In contrast, the increase of *L*can move the peak dispersion wavelength while having little influence on the dispersion magnitude and FWHM. This rule provides an useful guidance for designing the highly dispersive component that meets the dispersion requirement in practical engineering applications. Moreover, by optimizing the combination of different waveguide structural parameters, such as setting *L*a =400 nm, *L*S1 =822 nm, *L*S3 =177 nm, and decreasing *L* in a step of 2 nm respectively, meanwhile, changing the value of *H* appropriately, a high and flattened dispersion over a wide wavelength range can be obtained. The dispersion curves are shown in Fig.8. As can be seen from Fig.8 (a), the average dispersion magnitude of -3.6×105 ps·nm-1·km-1 from 1520 nm to 1620 nm (covering the *C+L* waveband) is obtained, and the dispersion magnitude fluctuation is less than 0.85%. In contrast, when we set *L*a =936 nm, *L*S1 =655 nm, *L*S3=189 nm, and decrease *H* from 89 nm to 28.7 nm in a step of 6.7 nm, at the same time, changing the value of *L* between 611.7 nm and 560 nm, as described in Fig.8 (b), a high and flattened dispersion of -9.8×105 ps·nm-1·km-1 over 350 nm (from 1620 to1970 nm) can be obtained.

From the viewpoint of engineering application, this strip-slot hybrid waveguide with flattened and high dispersion can be fabricated by cascading different waveguide sections with optimized geometric parameters. This is compatible with advanced CMOS technology. In addition, how to couple light from an optical fiber into such a hybrid a waveguide in a most efficient way is a problem that demands attention. In general, there are two main ways to couple light from an optical fiber into a waveguide. One is to use a grating, which is inherently bandwidth-limited. The other is to use a taper coupler, which requires one-die-at-a-time mechanical polishing to achieve smooth surfaces for high coupling efficiency. Until now, many methods for tapered waveguide coupling structures have been reported in past few years. For example, Cardenas et al. achieved low loss waveguide-lensed fiber coupling based on etched facet silicon inverse tapers [45]. Shiraishi et al. demonstrated a spot-size converter that consists of a horizontal linear up-taper, a vertical down-taper, and a thin slab-waveguide in cascade for coupling between a single-mode fiber and a silicon-wire waveguide [46]. Wang et al. reported a cantilever inverse taper coupler with a SiO2 gap for coupling an optical beam between an optical fiber and a silicon waveguide [47]. Based on previous design experience, it is feasible to couple light into such hybrid waveguide efficiently. The detailed structural design scheme, coupling efficiency and tolerance are beyond the scope of this paper, and thus will be discussed in the future. Therefore, it is promising to develop the strip-slot hybrid waveguide designed in this work, which can find potential applications for integrated multi-channel dispersion compensation and on-chip all-optical signal processing.





Fig.8 Flat dispersion of (a) -3.6×105 ps·nm-1·km-1 over 160 nm and (b) -9.8×105 ps·nm-1·km-1 over 350 nm

To meet the requirement of the ever-increasing communication bandwidth of Internet traffic, great efforts have been made to find new optical fiber transmission windows. In addition to the conventional telecom wavelengths of the ***C*** waveband (1.55 μm range), recently, optical fiber communication at the ***U*** waveband (from1625 nm to 1675 nm), and even in the 2-µm region has aroused great concern due to the emergence of various mature optical fiber components (for example, a specially designed low-loss hollow-core photonic band-gap fiber (HC-PBF) and the commercially available thulium-doped fiber amplifier covering approximately 22-THz amplification bandwidth from 1830 nm to 2050 nm) [48]. Several optical fiber transmission links in the 2-μm wavelength region have been experimentally demonstrated [49-50]. Because the designed strip-slot waveguide has a high and flattened negative dispersion in a wide wavelength range. This feature becomes of great interest due to the feasibility of performing dispersion compensation in the ***U*** waveband and even in the 2-µm region. Next, the dispersion compensation effect of the designed strip-slot hybrid waveguide at 1.55μm(***C*** waveband) and 1.65μm(***U*** waveband) are investigated, separately. The rule of dispersion compensation is *D*S·*L*S+*D*C·*L*C=0, here, *D*S and *D*C are chromatic dispersion of the transmission medium (standard single mode optical fiber or HC-PBF) and dispersion compensation medium (dispersion compensation fiber/waveguide), respectively [51]. *L*S and *L*C are the length of transmission medium and dispersion compensation medium, respectively. According to this rule, we can calculate the length of the dispersion compensation medium (dispersion compensation fiber/waveguide). Thus, the length of the dispersion compensation medium is related with the accumulated dispersion during optical signal transmission.

In our simulation, we considered the rapid development of optical fiber communication systems. On one hand, to support cloud computing, Big Data, 5G and other technologies, 100 Gbit/s is a popular bit rate and has become the leading technology in current backbone networks. On the other hand, on-chip ultrafast all-optical signal processing has been experimentally demonstrated in recent years. For example, C. Koos et al. fabricated a 4-mm-long silicon-organic hybrid waveguide with a high nonlinearity coefficient of γ=1×105 W-1 km-1 and performed all-optical de-multiplexing of 170.8 Gbit/s to 42.7 Gbit/s [52]. Therefore, an ultra-high speed RZ-OOK optical time division multiplexing (OTDM) signal with a bit rate of 100 Gbit/s is used. For 1.55μm, the accumulated dispersion of after 50-km standard single mode fiber transmission is compensated. Commercially available G.652 fiber serves as the transmission medium. The loss and dispersion are 0.2 dB/km and 16 ps/nm-km, respectively, for G.652 optical fiber at 1.55 μm [51]. After dispersion compensation by the designed strip-slot hybrid waveguide, the Q factor and bit error ratio (BER) are measured and plotted in Fig.9 (a). An eye diagram after disperson compensation has been inserted into Fig.9, in which it can be seen, that with increasing received **optical** power, the Q factor increases and the BER decreases. For 1.65 μm, the HC-PBF is used as the transmission medium because of its minimum loss and low latency at the ***U*** waveband. The loss and dispersion are 3 dB/km and 65 ps/nm-km, respectively, for the HC-PBF at 1.65 μm [53]. After 7-km HC-PBF transmission, the accumulated dispersion of the 100 Gbit/s RZ-OOK OTDM signal is also compensated by the designed strip-slot hybrid waveguide. The Q factor and BER are measured and plotted in Fig.9 (b), in which it can be seen that the Q factor increases with increasing received power while the BER decreases. Error free transmission is achieved when received optical power is higher than -21 dBm and -16 dBm for G.652 and HC-PBF transmission systems, respectively. The eye diagram for both Fig.9 (a) and Fig.9 (b) are all fully-open. It shows that the designed strip-slot hybrid waveguide can achieve dispersion compensation over a wide wavelength range from the **C** waveband to the ***U*** waveband.





Fig.9 Dispersion compensation of 100 Gbit/s optical transmission systems for (a) 1.55μm and (b) 1.65μm

**The proposed strip-slot waveguide devices can be manufactured by filling two predefined trenches with Si3N4 using low pressure chemical vapor deposition (LPCVD) and with Ge11.5As24Se64.5 using thermal evaporation, respectively. The individual fabrication steps are shown in Fig.10. First, a SOI wafer with thick top silicon layer on 2-μm-thick Buried Oxide (BOx) is used. Reactive ion etching (RIE) is used to etch one trenches with depth *H* and width *L* into the top silicon surface of a wafer as illustrated in Fig. 10(b). Second, a Si3N4 film layer is deposited at 800°C from NH3 and SiH2Cl2 precursors. To release the internal stress of the material, the deposition process is performed through two steps and wafers are allowed to cool down to room temperature. Then, the slot waveguide core is obtained by removing the remaining Si3N4 from the top of the wafer using chemical-assisted mechanical polishing and dry etching as illustrated in Fig. 10(d). Third, RIE is used to etch another trenches into the top silicon surface of a wafer with depth *H* and width *L*S1 as illustrated in Fig. 10(e). Fourth, a Ge11.5As24Se64.5 film layer is deposited by thermal evaporation from a baffled box at a deposition rate of 1Å/s. The deposited films are annealed in a vacuum oven at 150℃. In the next step, the remaining Ge11.5As24Se64.5 is removed from the top of the wafer by mechanical polishing and dry etching as illustrated in Fig. 10(e). Finally, RIE is used to eliminate the remaining silicon. So the strip-slot hybrid waveguide is**

**fabricated successfully.”**



Fig.10. Steps of waveguide manufacturing: (a) SOI wafer with thick top silicon layer on 2-μm-thick BOx. (b) A trench is created in the top silicon layer using a RIE process. (c) A Si3N4 film layer is deposited. (d) The slot waveguide core is obtained by removing the remaining Si3N4 from the top of the wafer. (e) Another trenches is created in the top silicon layer using a RIE process. (f) A Ge11.5As24Se64.5 film layer is deposited by thermal evaporation. (g) The residual Ge11.5As24Se64.5 on the top surface of the wafer is removed from the wafer. (h) The strip-slot hybrid waveguide is fabricated by eliminate the remaining silicon using RIE.

1. **Fabrication tolerance**

From the viewpoint of waveguide fabrication, the deviation of structural parameters from standard values cannot be avoided completely. Therefore, it is necessary to perform tolerance analysis for the proposed strip-slot waveguide. The simulation was carried out from two aspects. First, all five structural parameters (namely *H*, *L*S1, *L*S2, *L*, and *L*a in Fig.1) have been modified by ±0.5% independently with respect to the optimal values, while keeping the other parameters constant. The results are shown in Fig.11(a)-11(e). Fig.11(a) shows that the dispersion property of the strip-slot waveguide is almost unchanged when the waveguide height *H* is changed by ±0.5%. Similarly, when the air width *L*a changes by ±5%, the dispersion characteristics vary slightly (see Fig.11(e)). In contrast, when changing the width of the strip waveguide *L*S1, the width of silicon slabs *L*S2, and the slot width *L* by ±5%, separately, the peak dispersion wavelengths shift obviously. The wavelength drift values are 5 nm, 20 nm and 4 nm, respectively. It can be seen from Fig.11(b), (c) and (d), respectively. Second, all five structural parameters have been modified by ±0.5% simultaneously, the dispersion properties are shown in Fig.11(f). Note that the peak dispersion wavelength shifts obviously. Therefore, the peak dispersion wavelength of the waveguide is nearly insensitive to changes in *H* and *L*a, while the sensitivity to the tolerances in *L*S1, *L*S2, and *L* is slightly high. In addition, the change of the peak dispersion values of the waveguide are sufficiently low for all technological tolerances separately and even jointly.













Fig.11 Fabrication tolerance analysis of the designed strip-slot waveguide. Relationship of dispersion and wavelength for (a) (1±0.5%)*H*,(b) (1±0.5%)*L*S1, (c)(1±0.5%)*L*S2, (d)(1±0.5%)*L*,(e) (1±0.5%)*L*a and (f) (1±0.5%) ( *H*, *L*S1, *L*S2, *L*, and *L*a).

1. **Conclusions**

A dispersion-engineered broadband strip-slot hybrid waveguide is proposed in this paper. The influence of waveguide geometric parameters on the dispersion magnitude and FWHM are investigated using the FDTD method. The results reveal that, for the optimized geometric parameters, a negative dispersion of -1.54×105 ps·nm-1·km-1 and a dispersion FWHM of 2.5 nm at 1.55 μm induced by the coupling between the strip and slot modes is realized. Moreover, a high and flat dispersion over 350 nm from 1630 to 1980 nm is achieved by cascading different waveguide sections with varied waveguide geometric parameters. In addition, dispersion compensation of 100 Gbit/s RZ-OOK OTDM signals with a central wavelength of 1550 nm after 50-km G.652 single mode fiber transmission, and central wavelength of 1650 nm after 7-km HC-PBF fiber transmission are demonstrated. The proposed strip-slot hybrid waveguide exhibits excellent dispersion performance and can be efficiently applied to on-chip ultrafast photonic networks (including multi-channel WDM dispersion compensation, tunable delay, ADC, and time lens.)

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