Multi-Channel WDM (De)Multiplexer Based on Multimode Contra-Directional Coupling Using Dielectric Etches

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Abstract: we present a four-channel flat-top coarse wavelength-division multiplexing (CWDM) (de)multiplexer employing contra-directional coupling between multiple modes simultaneously with shallow-etched dielectric etches in a single multimode waveguide.

1. Introduction

Photonic filters play significant parts in many applications, such as optical communication and sensing [1]. The wavelength-division multiplexing (WDM) is one of the most practical technologies for multi-channel communication, specifically, coarse wavelength-division multiplexing (CWDM) is a popular standard with a large channel spacing of 20 nm to relax requirements for wavelength control. As silicon photonics has provided a very attractive approach with merits of high integrated intensity and low cost, various photonic wavelength (de)multiplexers have been proposed and demonstrated on silicon-on-insulator (SOI) platform [2,3]. Among them, grating-assisted contra-directional couplers (GACDC) have attracted lots of attention in recent years [4–8], these devices utilize the principle of contra-directional coupling, which could be largely divided into two categories: the reversely coupling between two different modes in a single waveguide [4–6] and that between modes in two different waveguides [7,8]. This kind of filters could meet the need of various kind of WDM channel filters, as the coupling coefficients could be flexibly adjusted by varying the grating depths or coupling gaps [5], and they have advantages of low insertion losses, large bandwidths as well as flat tops [4]. Recently, dielectric metamaterials have also emerged as a platform for spatial mode conversions [9,10]. Lots of works are reported to utilized dielectric metamaterials to realize intermode co-directional coupling for mode conversions in a multimode waveguide [9,10] however, few works utilized dielectric metamaterials to realize contra-directional coupling, which could be useful for wavelength-selective devices.

In this paper, we propose a novel concept utilizing dielectric etches to realize multimode contra-directional couplings for WDM (de)multiplexers. Since the dielectric metamaterials can strongly manipulate the coupling coefficients between different modes, the input fundamental modes could be coupled into several high-order modes at different wavelength simultaneously. In theory, the number of the multiple high order modes mapping multiple WDM channels is only limited by the design of the dielectric etches, but may at the cost of the sidelobes. Thus, as an example, two cascaded perturbed waveguides with parallel dielectric etches employing two backward modes (TE_1 and TE_2 modes) for a four-channel CWDM (de)multiplexers are demonstrated. Besides, sidewall-misalignment-modulation (SMM) is applied to achieve a high sidelobes suppression ratio (SLSR). In simulation, this CWDM (de) multiplexers have shown flat tops spectra response and less than 0.15 dB low insertion losses (not considering the coupling losses from mode (de)multiplexers), also with good SLSRs of 18 dB.

2. Design principle and simulation result

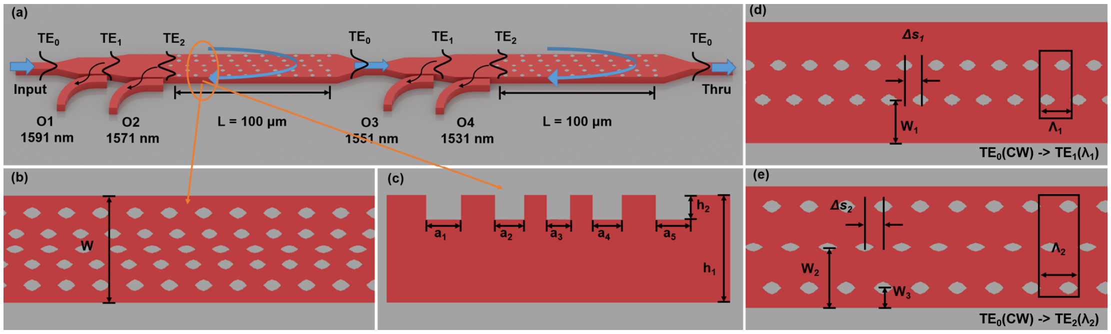

Fig. 1. Schematic configurations. (a) A 3D rendering of the proposed four-channel CWDM (de)multiplexers; (b) The zoomed in perturbed waveguide containing two kind of perturbations; (c) The cross-section of the perturbed waveguide; (d) The first kind of perturbation that reversely couple the input TE_0 mode into TE_1 mode; (e) The second kind of perturbation that reversely couple the input TE_0 mode into TE_2 mode.

The four-channel CWDM (de)multiplexer is schematically illustrated in figures 1(a)-(e), which consists of two cascaded perturbed waveguides, four asymmetric directional couplers (ADCs) and several taper waveguides. The designed perturbed waveguide with dielectric metamaterials is zoomed in as presented in figure 1(b), and its cross-section is shown in figure 1(c). Each perturbed waveguide contains two kinds of perturbations as shown in figures 1(d) and 1(e) that reversely couple the input fundamental mode into the TE_1 or TE_2 modes respectively. The work flow of the device is as follows [see figure 1(a)]: Firstly, the TE_0 mode launches into the perturbed waveguide through a taper waveguide directly as a result of the significant effective index difference between TE_0 modes in the different waveguides. Then the input TE_0 mode is reversely coupled into the TE_1 or TE_2 modes by the dielectric perturbations when the wavelength satisfies phase-matching conditions. Here, ADCs structures could serve as mode (de)multiplexers, the backward TE_1 and TE_2 modes would be coupled into the TE_0 mode in two different asymmetric waveguides as two channels, and the part of the mode (de)multiplexers could be designed with the same parameters demonstrated in our previous work [10]. Afterwards, two perturbed waveguides are cascaded to realize a four-channel CWDM demultiplexer. On the other hand, this device could also serve as a CWDM multiplexer to multiplex four optical carrier signals onto a single optical waveguide by using different wavelengths. When modulated TE_0 modes are added from the O_1, O_2, O_3 and O_4 ports, they will be coupled into TE_1 or TE_2 modes in the perturbed waveguides by the mode (de)multiplexers, and then reversely coupled into TE_0 modes at different wavelengths by the dielectric perturbations, and finally output from a common port. Therefore, both the functions of wavelength multiplexing and demultiplexing are achieved. In addition, a taper waveguide is introduced between two perturbed waveguides to filter out high-order modes, so that the crosstalk and the undesired Fabry-Perot resonance could be mitigated [4].

Here, we present the detailed parameters of our proposed device. The waveguide width W is set as 1.2 μm to support the TE_0, TE_1 and TE_2 modes. The thickness h_1 is set as 220 nm for a typical SOI technology. The parameters a_1, a_2, a_3, a_4, a_5 and h_2 are set as 120, 125, 80, 125, 120 and 40 nm respectively to achieve suitable coupling coefficients. The dielectric materials are positioned at $W_1 = 430$ nm, $W_2 = 600$ nm and $W_3 = 200$ nm respectively as shown in figures 1(d) and 1(e). Besides, the top and bottom arcs of the shape of each single perturbation is defined as half-sine functions. As has been pointed out in [4], the relationship between the period of the dielectric perturbations and the operation wavelength for contra-directional coupling could be expressed as: $\Lambda = \lambda / (n_m + n_n)$, where Λ is the period of the perturbation, λ is the center of operation wavelength, n_m and n_n are effective refractive index of mth and nth mode respectively. This equation could decide the period of the perturbations, which indicates that the TE_0 mode could be coupled into any modes when the target wavelength satisfy the phase-matching condition. Consequently, for the first perturbed waveguide, the perturbation periods Λ_1 and Λ_2 are set as 305 nm and 325 nm for the operation wavelength of 1591 nm and 1571 nm. For the second cascaded perturbed waveguide, the perturbation periods Λ_1 and Λ_2 are set as 293 nm and 311 nm for the operation wavelength of 1551 nm and 1531 nm. To have a tradeoff between the coupling length and the reversely coupling efficiency, the length of each perturbed waveguide L is set to be 100 μm. Moreover, it is well-known that the filters based on contra-directional coupling suffer from strong sidelobes [4], leading to a high isolation between adjacent channels. To suppress the sidelobes, SMM has been proved to be an effective apodization method [6]. In SMM apodization, longitudinal-apodized has been introduced for the perturbations, and the superposition of the dielectric perturbations is modulated as a Gaussian function of the propagation distance z, thus the longitudinal shift Δs_1 and Δs_2 [see figures 1(d) and 1(e)] could be expressed as [6]:

$$\Delta s_1 = \Lambda_1 \exp\left(-c_1 (z-0.5L)^2 / L^2\right)/2,\quad \Delta s_2 = \Lambda_2 \exp\left(-c_2 (z-0.5L)^2 / L^2\right)/2$$

where c is the apodization strength and L is the length of the perturbed waveguide. Here, the constants c_1 and c_2 are set as 8 and 10 respectively to improve the SLSR and reduce channel crosstalk. Note that the SMM apodization could lead to some undesired backward reflections, which could limit the usable spectral ranges [6].

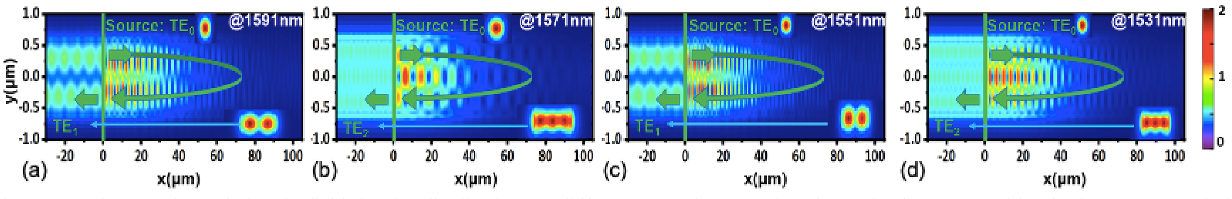

Fig. 2. The top view of electric field density distributions at different operation wavelength. In the first waveguide, the input TE_0 mode is reversely coupled into (a) the TE_1 mode at 1591 nm (b) the TE_2 mode at 1571 nm. In the second cascaded perturbed waveguide, the input TE_0 mode is reversely coupled into (c) the TE_1 mode at 1551 nm (d) the TE_2 mode at 1531 nm.

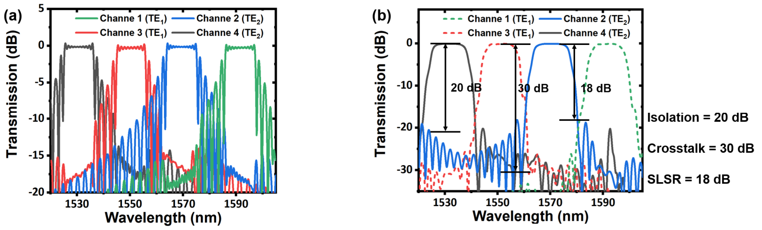

Fig. 3. The simulated reflection response of each perturbed waveguide. (a)without apodization (b)with apodization index c_1=8 and c_2=10.

The three-dimensional finite-difference time-domain (3D-FDTD) method is implemented to verify the performance of the device. Figures 2(a)-(d) show the top view of electric field density distributions as light travels in the perturbed waveguides, and these figures are for the TE_0-to-TE_1 or TE_0-to-TE_2 modes conversions happened at the wavelength of 1591, 1571, 1551 and 1531 nm, respectively. Figures 3(a) and 3(b) show the simulated reflection spectra of our proposed device without mode (de)multiplexers. As shown in figure 3(b), the SMM apodization could suppress the sidelobes well without compromising performances, thereby leading to a good SLSR of 18 dB, and the insertion losses of the four channels are 0.15, 0. 11, 0.12 and 0.10 dB respectively. The response spectra also have flat tops, the 1 dB bandwidths are 10.3,12.0,10.0 and 11.8 nm, and 20 dB bandwidth are 22.27, 27.02, 19.94 and 19.88 nm, thus the BW_{1dB} / BW_{20dB} is around 50%.

3. Conclusion

Table 1. Comparison of several different CWDM (de)multiplexers and our device

Ref.	Structure	Size (μm^2)	Flat-top	Loss (dB)	Isolation (dB)	BW_{1dB} (nm)	BW_{1dB}/BW_{20dB}
[2]	AWG	550×3900	—	~5	~–25	~5	26%
[3]	MZI	300×100	√	~1	~–20	16	53%
[4]	GACDC	600×40	√	~1	~–20	~16	75%
[8]	GACDC	600×2	√	~1	~–12	~12	54%
This work(Sim.)	Etches assisted CDC	300×3	√	<0.15	~–20	~10	50%

Table 1 compares the performance of our proposed CWDM (de)multiplexers with several other reported work. It indicates that our proposed device are competitive candidates in WDM systems. In summary, we have proposed an original multi-channel wavelength-selective operation employing all-dielectric metasurface structures to realize contra-directional coupling between multiple modes. A four-channel CWDM (de)multiplexer is proposed for an SOI platform with flat-tops, compact footprint, low insertion losses (<0.15 dB), suitable bandwidth (1 dB bandwidth of ~10 nm), low crosstalk (<–30 dB), good channel isolation (>20 dB) and high sidelobes suppression ratio (~18 dB) in simulation. Our proposed concept is promising for on-chip applications that require compact size with multi-channel wavelength and mode division multiplexing.

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