Flat-Spectral-Band Filter for Fabrication Tolerance and Wideband Spectral Range

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Abstract- Novel scheme for silicon-wire type flat-topped wavelength filter is proposed and theoretically verified. Multimode interference couplers with symmetric and asymmetric splitting ratios used in a delayed interference type filter made filtering spectra flat over wide wavelength range of >80nm with potentially better production yield.

I. Introduction

Recently, datacom interconnect bandwidth has been increased by utilizing wavelength division multiplexing (WDM) technology to facilitate ever-increasing communication needs [1]. Silicon based wavelength filters are prerequisite components for splitting and coupling WDM signals. To date, various silicon waveguide optical filters such as microring resonators (MRR), multiple delayed interferometers (MDI) and arrayed waveguide gratings (AWG) have been demonstrated. Among them, the MDI-type device [2,3] showed many operational advantages from the viewpoint of insertion loss, crosstalk and flat spectral band. Particularly, when it comes to considering inaccuracy of incoming signal wavelength or temperature fluctuation by external factors, spectral flatness is one of the most important requirements. In order to make the MDI-type filter spectra box-like in a wavelength domain, we need to accurately control several kinds of specific coupling coefficients κ (i.e. 0.33, 0.2, 0.08, 0.04 etc) together with κ=0.5, which makes the device design more complicated and also causes the degradation of productivity. In almost previously reported works, the above-mentioned asymmetric coupling ratios in the MDI-type filters were realized by using directional couplers (DCs) [2-5]. The κ of DCs $[\kappa_{DC}(\lambda)]$ normally changes as a wavelength deviates from the designated value. Thus, it has been difficult to achieve flat filtering response of >40-nm-wide spectral range [2,3]. These problems on $\kappa_{DC}(\lambda)$ have been fairly mitigated by using bent shaped DCs with narrow gap (125 nm) / polymer claddings [4], and adopting SiN material system with relatively lower dispersion property [5]. In Ref. 4, however, narrow DC gap and polymer cladding material requires technical complexity in a standard CMOS process, while in Ref. 5, SiN may have some difficulty in monolithically integrating with other functional devices such as silicon-based optical modulators or Ge-based photodetectors.

In this work, we propose and theoretically demonstrate all-silicon based MDI-type flatband wavelength filter using multimode interference (MMI) couplers and DCs that are compatible with CMOS process, better productivity, and Coarse WDM (CWDM) targeted wideband operability.

II. Theoretical Analysis

A. Proposed Device Scheme

Figure 1 shows the silicon-wire MDI-type 1×4 wavelength filter based on MMI couplers with $\kappa_{MMI} = 0.85, 0.72, 0.5$, and DCs with $\kappa_{DC} = 0.08, 0.04$. For 1×4 operation, the device uses two-stage DIs with appropriate optical delaylines and phase shifters to discriminate four kinds of wavelengths. As stated before, flat spectral response in previously reported MDI-type filter scheme was obtained by DCs with asymmetric coupling ratios $\kappa_{DC} = 0.33, 0.2, 0.08, 0.04$ [2]. Although the DC is flexible to adjust κ_{DC} by optimizing the coupling length, κ_{DC} is susceptible to the variation of a wavelength. Moreover, the closer the κ_{DC} is to 0.5, the more remarkable the rate of change of κ_{DC} becomes. Thus, the MDI-type filter based on DCs fundamentally has a narrower operating wavelength range.

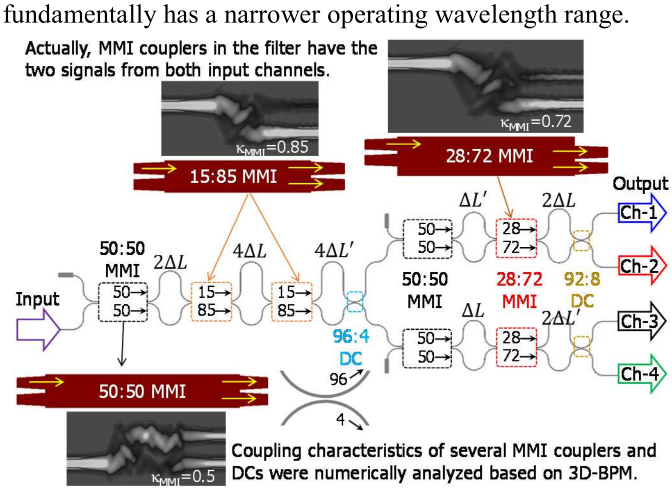

Fig. 1. Proposed MDI-type wavelength filters for Coarse WDM applications.

To solve this drawback, as shown in Fig. 1, the device employs three kinds of MMI couplers having less $\kappa(\lambda)$. It has been reported that asymmetric ratio of $\kappa_{MMI} = 0.85, 0.72$ can be realized without excess loss [6]. The available asymmetric values of κ_{MMI} are somewhat mismatched with the optimized condition [2], However, their values are close enough to make the spectral response box-like flat. Meanwhile, flat response also needs extremely asymmetric κ of 0.04 and 0.08, which is not easy to attain by MMI scheme. Fortunately, the closer the

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κ_{DC} is to 0, the significantly smaller the rate of change of κ_{DC} becomes. Consequently, since all the coupling components have higher tolerances to a wavelength, the proposed filter scheme shown in Fig. 1 can readily achieve wideband flat-topped response required for CWDM applications.

B. Analytic and Numerical Calculations

First, the wavelength sensitivities of each DC and MMI coupler used in the MDI-type filter were implemented by numerical simulation based on 3-dimensional beam propagation method (3D-BPM). We assumed 350-nm-wide and 220-nm-thick silicon-wire waveguides operating at O-band regime. The gap for DCs and MMI access waveguides was commonly set to be 0.2 μm, which is readily available value in standard fabrication process. Other factors related to splitting ratios such as the width and length of MMI regions and the position of input/output access waveguides were properly determined based on MMI self-imaging principle [6]. Figure 2 shows the simulated coupling ratios for several kinds of (a)DCs and (b)MMI couplers. In Fig. 2(a), DCs show sinusoidally-varying κ_{Cross} and κ_{Bar} whose sensitivity tends to be more noticeable as κ_{Cross} approaches to 0.5. This result means that the specific coupling condition for attaining flat-topped response is satisfied only at around $\lambda = 1.31\ \mu m$.

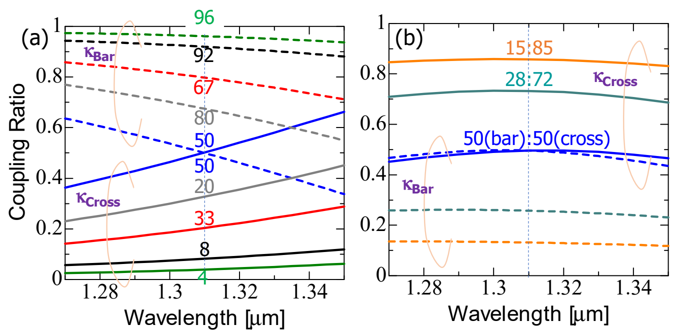

Fig. 2. Calculated κ for (a)DCs and (b)MMI couplers for flat filter spectra.

Meanwhile, as seen in Fig. 2(b), each designed κ_{MMI} keeps nearly constant over 100-nm-wide spectral range. It is noted that the rate of change of κ_{DC} (=0.04, 0.08) used in the proposed MDI-type filter shows much less sensitive to a wavelength, which means that the proposed filter response is not degraded mainly by these DC coupling responses.

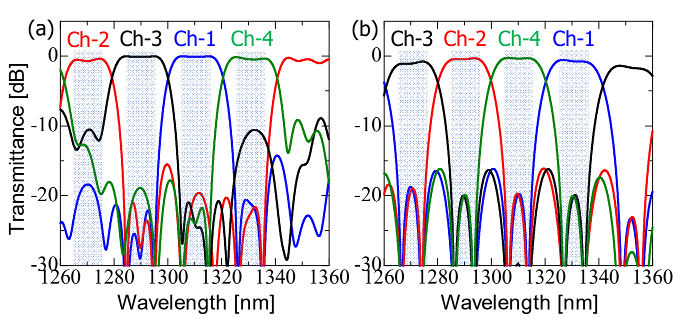

Fig. 3. Calculated CWDM spectra based on (a)DCs and (b)proposed scheme.

In order to analytically calculate filter spectral response of the conventional and proposed MDI-type wavelength filter, we used transfer matrix method based on coupled mode theory [2,3]. It is noted that the optical coupling characteristics of $\kappa_{Cross}(\lambda)$ and $\kappa_{Bar}(\lambda)$ for all DCs and MMI couplers numerically simulated by the 3D-BPM were applied to the main loop of the transfer matrix for the proposed MDI-type filter.

Figure 3 shows the calculated spectral characteristics of the MDI-type filter based on (a)conventional (all DCs) and (b)proposed scheme (MMI couplers and DCs). The single mode Si-wire waveguide delayline (ΔL) in the MDI was set to have the channel spacing of 20-nm at λ =1.31 μm. In Fig. 3(a), conventional scheme exhibits extremely better performance at around $\lambda = 1.31\ \mu m$. However, considering CWDM targeted span, some channels such as Ch-2 and Ch-4 inherently suffer from markedly higher spectral crosstalk. On the other hand, as can be seen in Fig. 3(b), since the symmetric and asymmetric ratios of the MMI couplers have robustness to a wavelength change, the proposed device can stably be operated without degrading spectral crosstalk over 80-nm-wide spectral range.

The reason why the sequence of output channels of the two devices shown in Fig. 2 is different is the asymmetric ratios of the MMIs in Fig. 2(b) are opposite to those of the DCs in Fig. 2(a). Thus, to obtain phase matching for the specific wavelengths shaded in each CWDM grid, some notation of optical delaylines and phase shifters were modified in the proposed scheme. Overall, the proposed filter has good productivity because less sensitive $\kappa_{MMI}(\lambda)$ indicates a broader margin for parameter deviations from ideal specifications.

III. Summary

We proposed and theoretically analyzed CWDM targeted flat-topped wavelength filter consisting of asymmetrically splitting MMI couplers and DCs. Robustness of coupling ratios of MMIs made spectral response flat over 80-nm-wide span and spectral crosstalk far less than conventional schemes, which could also contribute better production yield in standard CMOS process.

Acknowledgment

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