Integrated Quarter-Wave Shifted Bragg Grating Array with Equalized Channel Spacing

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Abstract: A 4-channel integrated quarter-wave shifted Bragg grating array with precisely equalized channel spacing was demonstrated in a CMOS-compatible process using sidewall Bragg gratings and the equivalent phase shift method.

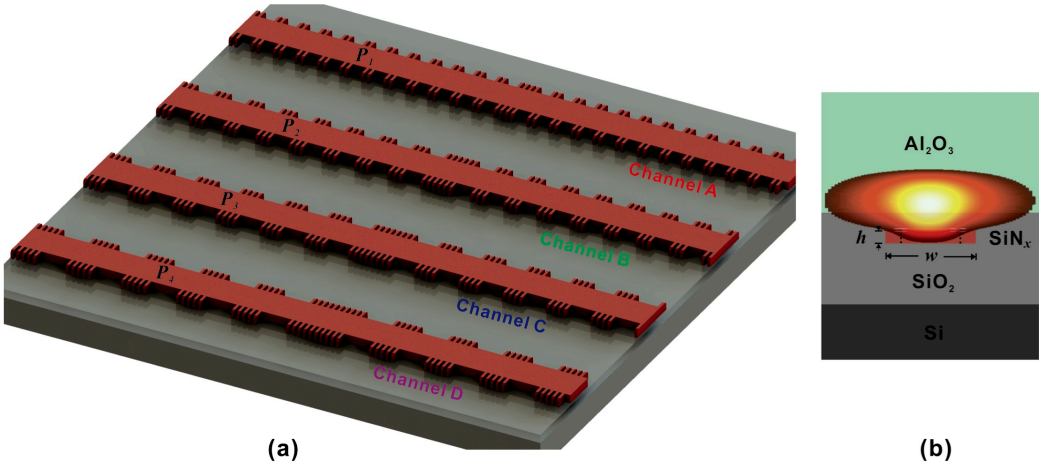
OCIS codes: (130.3120) Integrated optical devices; (050.5080) Phase shift.

1. Introduction

Integrated quarter-wave shifted Bragg gratings are essential for distributed feedback (DFB) laser diodes since they ensure single wavelength lasing [1], which is pivotal for both long-haul fiber-optic telecommunications and short-reach on-chip data communications. Furthermore, in wavelength division multiplexed (WDM) communications, an array of quarter-wave shifted Bragg gratings enables multiple channels with equally-spaced wavelengths aligned with the WDM grid. However, with traditional designs, it is challenging to accurately fabricate quarter-wave shifted Bragg grating arrays with equalized channel spacings, considering the small channel spacing requires picometer-scale changes in the grating period.

In this work, we present an experimental demonstration of a 4-channel integrated quarter-wave shifted Bragg grating array with equalized channel spacing. Sidewall Bragg gratings are used to make the waveguide and grating in one lithography and etch step, and an equivalent phase shift (EPS) method is implemented to create the quarter-wave phase shift. The grating array is fabricated in a complementary metal-oxide-semiconductor (CMOS) compatible silicon nitride (SiN_x) process with an equalized channel spacing of 4.38nm and a measured channel spacing variation of less than 30pm, which holds promise for on-chip DFB WDM laser arrays when combined with our recently developed erbium-doped waveguide laser process [2] as an alternative integrated light source for silicon photonics.

2. Side-coupled Bragg Grating



(a) (b)

Fig. 1. (a) A schematic of the proposed 4-channel integrated quarter-wave phase-shifted Bragg grating array using equivalent phase shift structure with sampled Bragg grating. (b) A schematic of the cross section of the designed waveguide with sidewall gratings. The fundamental optical mode is also shown.

Integrated waveguide-based Bragg gratings take many forms such as the commonly-used surface grating where two lithography and etch steps are required to form the waveguide and the Bragg grating on the top surface of the waveguide separately [3]. In order to simplify the fabrication process, sidewall gratings [4] are used here so that the waveguide and gratings can be fabricated in one lithography and etch step, as shown in Fig. 1. Figure 1(b) shows a cross section of the device. A 100-nm thick SiN_x layer on top of thermally grown silicon dioxide (SiO_2) forms an inverted ridge waveguide with width w=4µm and a layer of aluminum oxide (Al_2O_3) forms the waveguide core. The layer stack and waveguide dimensions are designed to permit the development of an erbium waveguide laser with maximum gain in the optical mode [2]. The Bragg grating is formed in the sidewalls of the SiN_x ridge by etching to a depth of 500nm that provides a grating coupling coefficient κ=11cm^{-1}. The grating period Λ is 480nm at 50% duty cycle.

3. Equivalent Phase Shift Method

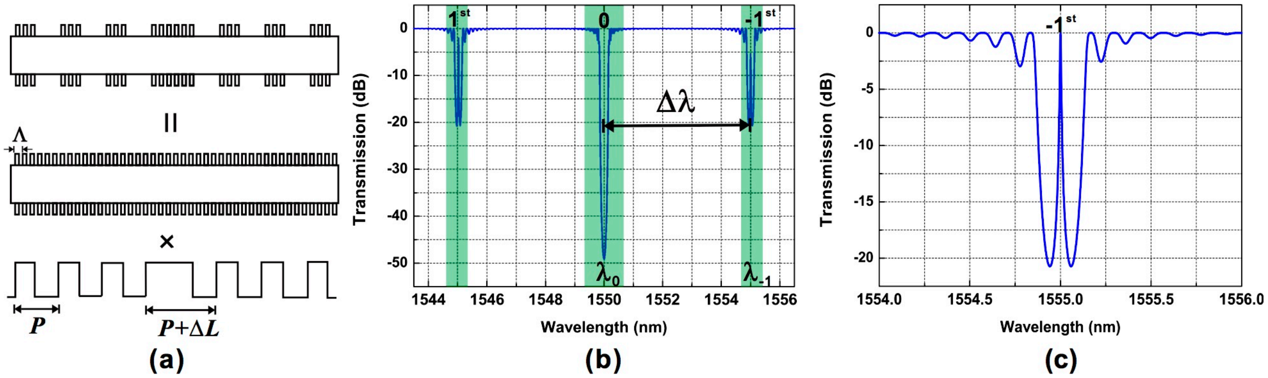


Fig. 2. (a) A schematic of the equivalent phase shift method. (b) Simulated transmission spectrum of the grating where multiple resonant orders are observed. (c) A close-up view of the -1st order where a quarter-wave phase shift response is seen in the center.

In ordinary quarter-wave phase-shifted gratings where the phase shift is directly applied to the grating period [1], the resonant wavelength of the phase shift is altered by shifting the grating period; however, when the wavelength spacing is dense, doing so can require a sub-nanometer change in grating period making it difficult to fabricate using optical lithography. Here, instead, we use the equivalent phase shift (EPS) method [5] to make the quarter-wave shifted Bragg grating array with a better control over the resonant wavelength of the phase shift, the structure of which is schematically shown in Fig. 1(a). As illustrated in Fig. 2(a), the EPS Bragg grating consists of a uniform grating with period Λ modulated by a quasi-periodic sampling function with period P ($P>>\Lambda$). This generates multiple resonant orders in the transmission spectrum of the grating, as shown in Fig. 2(b). The wavelength spacing $\Delta\lambda$ between adjacent resonant orders is given by

$$\Delta\lambda = \frac{2n_{eff}\Lambda^2}{P} \qquad (1)$$

where n_{eff} is the effective refractive index of the waveguide with the sidewall grating. The wavelength of the 0th order is given by the Bragg condition $\lambda_0=2n_{eff}\Lambda$. Phase shifting the sampling function by ΔL introduces an equivalent phase shift $\Delta\varphi$ in the center of the -1st order, where

$$\Delta\varphi = \frac{2\pi\Delta L}{P} \qquad (2)$$

Therefore, an equivalent quarter-wave phase shift ($\Delta\varphi=\pi$) occurs in the -1st order when $\Delta L=P/2$, as shown in Fig. 2(b) and Fig. 2(c). Since ΔL is usually much larger than the grating period (as $P>>\Lambda$), the phase shift can thus be accurately controlled with EPS method. Moreover, the resonant wavelength of the equivalent phase shift in the -1st order is $\lambda_{-1}=\lambda_0+\Delta\lambda$. As a result, the resonant wavelength can be stepped by changing the sampling period P while keeping the grating period Λ constant to create a multi-channel quarter-wavelength phase-shift Bragg grating array. The wavelength spacing of the resulting the multi-channel array is given by

$$\Delta\lambda_{CH} = 2n_{eff}(\frac{\Lambda}{P})^2\Delta P \qquad (3)$$

where ΔP is the stepsize of the sampling period. In optical lithography, the grating period Λ can readily be kept constant provided that the channels are spatially close to each other on the mask. And since $\Lambda<<P$, the wavelength

spacing $\Delta\lambda_{CH}$ can be accurately controlled by ΔP to make a quarter-wave phase-shift Bragg grating array with equalized wavelength spacing.

4. Experiment

The proposed quarter-wave shifted Bragg grating array utilizing an EPS structure was fabricated in a 300-mm CMOS foundry using 193-nm optical immersion lithography at the 65-nm technology node. Four wavelength channels were made with sampling-period stepsize ΔP=12.25μm. The transmission spectra of all four channels were measured at transvers-electric (TE) mode using a tunable laser with a wavelength accuracy of 10pm. As predicted by the simulation in Fig. 2(b), several resonant orders are seen in each channel. Figure 3(b) shows a close-up view of the 0th order and the -1st order. An equivalent quarter-wave phase shift is generated in the -1st order in each channel. The measured resonant wavelength from Channel A to Channel D is 1493.48nm, 1497.880nm, 1502.25nm, and 1506.65nm, respectively. The resulting channel spacing between adjacent channels is 4.40nm, 4.37nm, and 4.40nm, equalized to within 30pm. These precisely equalized channels highlight the benefits of the EPS technique where the channel spacing difference is largely immune to fabrication variations, according to Equation (3). It is also noted that the 0th order (or Bragg wavelength) of all four channels are aligned, as the baseline grating period Λ of all of the channels are statistically equal since they are spatially close (75μm apart) on the mask.

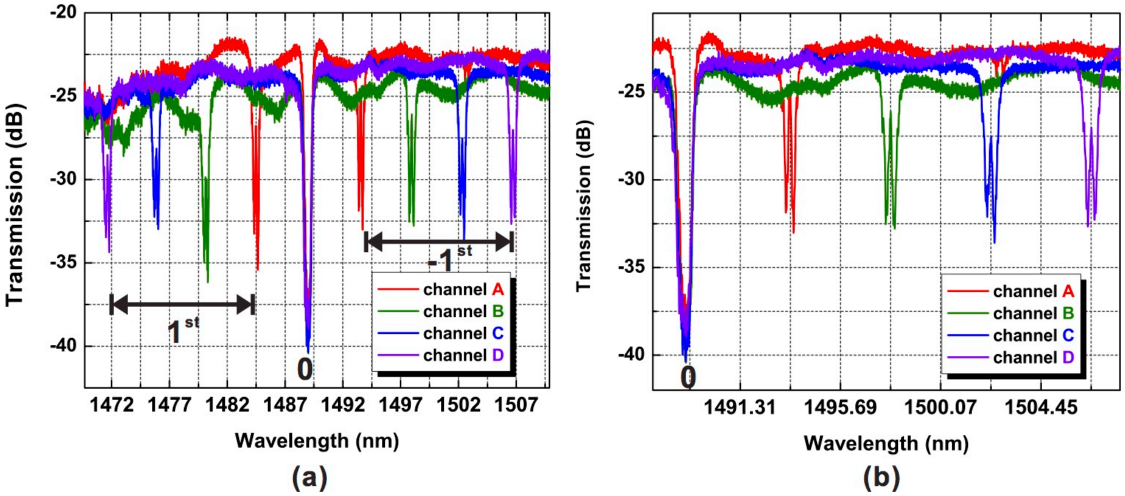


Fig. 3. (a) Measured transmission spectra of all of the channels of the 4-channel quarter-wave phase-shifted Bragg grating array. Multiple resonant orders are shown in each channel. (b) A close-up view of the 0th and -1st order.

5. Conclusions

We demonstrated a 4-channel quarter-wave shifted Bragg grating array fabricated with a CMOS-compatible SiN_x process. Sidewall gratings were employed to simplify the grating fabricated and equivalent phase shift method was utilized to better control the channel spacing. A precisely equalized channel spacing was achieved with a channel spacing difference less than 30pm. The CMOS-compatibility of the process and highly equalized channel spacing is promising for future development of multi-wavelength on-chip DFB arrays serving as high-quality WDM light sources for telecommunication and data communications, as well as other integrated devices such as grating-based electro-optic resonant modulator arrays. This work was supported by DARPA under the E-PHI project, grant no. HR0011-12-2-0007.

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