Chip-scale dispersion engineering using chirped vertical gratings

D. T. H. Tan, K. Ikeda, R. E. Saperstein, B. Slutsky, and Y. Fainman

Department of Electrical and Computer Engineering, University of California San Diego, 9500 Gilman Drive, La Jolla, California 92093-0409 USA

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A strongly coupled, chirped Bragg grating made by sinusoidally modulating the sidewalls of a silicon waveguide is designed, fabricated, and experimentally characterized. By varying the device parameters, the operating wavelength, device bandwidth, sign (normal or anomalous), and magnitude of group-velocity dispersion may be engineered for specific photonic applications. Asymmetric Blackman apodization is best suited for maximizing the usable bandwidth while providing good ripple suppression. Dispersion values up to \(7.0 \times 10^4\) ps/nm/km are demonstrated at 1.55 \(\mu\)m.

Nanophotonics has the potential to enable integration of various information systems on a chip. The recent advances in silicon photonics compatible with cost-effective CMOS fabrication process have facilitated the realization of various devices and components using a silicon on insulator (SOI) material platform. However, owing to the high-index contrast of the silicon core with its oxide cladding, the advantage of high-mode confinement useful for miniaturization of various devices and components using a silicon on insulator (SOI) material platform has been realized in the fabrication of various devices and components using a silicon on insulator (SOI) material platform. However, owing to the high-index contrast of the silicon core with its oxide cladding, the advantage of high-mode confinement useful for miniaturization and optical nonlinearity enhancement [1,2] brings with it a concomitant increase in the effects of waveguide geometry on the group-velocity dispersion (GVD). As the speed, complexity, and size of the future integrated nanophotonic systems on a chip increases the issues of GVD will become even more pronounced. In addition, the ability to engineer GVD is essential for various linear [3–6] and nonlinear applications [7,8].

In this Letter, we present the design, fabrication, and experimental validation of a novel compact GVD device implemented with a sidewall-modulated chirped Bragg grating (CBG) in a silicon waveguide. We utilize concepts similar to those used in chirped fiber Bragg gratings (CBBGs) [5,6] but realized on a chip with a CMOS-compatible SOI material platform. Our GVD device implemented with the CBG extends the simple sidewall-modulation technique used in the past to construct lasers [9,10], resonant filters, and couplers [11–14]. We show numerically and experimentally that by controlling device parameters such as type of apodization and the magnitude and sign of the chirp, the GVD properties of our device such as bandwidth, wavelength of operation, sign, and magnitude of dispersion can be tailored to meet the needs of various chip-scale applications. Given that the CBG operates in reflection mode, we also discuss low-loss integration of the CBG into chip-scale photonic circuits.

Our GVD device uses the same SOI technology as prior research on resonant transmission filters [11–14]. A schematic of the device is shown in Fig. 1. The mean width, \(W = 500\) nm and height, \(H = 250\) nm of the waveguide result in an effective mode index, \(n_{\text{eff}} = 2.63\) and are chosen for single-mode operation at the chosen Bragg wavelength, \(\lambda_b = 1.55\) \(\mu\)m. The mean CBG period is \(L_o = \lambda_b / (2n_{\text{eff}}) = 295\) nm. Linear chirp is applied to the CBG to introduce quadratic phase and hence linear group delay within the reflection band. The CBG period at any point \(z\) is given by \(L(z) = L_o + \frac{F}{\pi} z^2 / L_o^2\), where \(F\) is the chirp parameter and \(L\) is the device length [15]. The total chirp in period for a fixed \(F\) is \(\Delta L = (F/\pi)(L_o^2 / L)\).

The large sidewall modulation of 50 nm on our CBG devices implies that in contrast to weakly coupled CBBGs in silica, they are operating in a strong coupling regime. Moreover, the relatively short length of strongly chirped device may not meet the slowly varying envelope approximation. Since the analytic expressions of coupled-mode theory derived for weak coupling regime are not valid for our device, we perform finite-difference time-domain (FDTD) simulations to study their characteristics. The effective index of a slab of height \(H\) infinite in the \(y\) direction was used in place of the material refractive index of silicon to reduce the problem to two dimensions. Although the reduction of the 3D to a 2D problem is approximate, this method retains the salient spectral characteristics [16] and has shown good experimental agreement for similar structures [13,17]. The effectiveness of different apodization filters [18] in achieving a flat-top response and in-band ripple suppression is first investigated. The reflection and group-delay spectra for \(L = 100\) \(\mu\)m, \(\Delta L = 7.5\) nm are shown in Fig. 2. While all apodization filters are

![Fig. 1. (Color online) CBG device geometry.](Image)
effective in suppressing group-delay ripple, asymmetric Blackman apodization [18] is most effective in maximizing the CBG bandwidth while maintaining a flat response. Therefore we adopt asymmetric Blackman apodization for our CBGs for further studies of the effect of $\Delta \Lambda$ on the CBG devices.

Figure 3(a) shows that increasing $\Delta \Lambda$ from 4 nm to 7.5 nm to 12 nm for a CBG with $L=100$ $\mu$m results in a wider reflection bandwidth, i.e., 38 nm, 60 nm and 88 nm, respectively; correspondingly, a smaller calculated GVD, i.e., $7.0 \times 10^5$ ps/nm/km, $3.3 \times 10^5$ ps/nm/km, and $2.1 \times 10^5$ ps/nm/km. This trend is found to be in agreement with observations in weakly coupled CFBGs [5].

The designed CBG device was fabricated on a SOI wafer with a 250 nm layer of silicon on top of a 3 $\mu$m oxide layer using electron-beam (e-beam) lithography followed by reactive ion etching. SiO$_2$ cladding was deposited over the fabricated Si structure using plasma-enhanced chemical vapor deposition (PECVD). Scanning electron microscopy (SEM) micrographs of fabricated structures before PECVD deposition of SiO$_2$ are shown in Fig. 4. It should be noted that the fabrication process of the CBG is more challenging compared to that used in the past [11–13], since the implementation of apodization (i.e., tapering of sidewall modulation amplitude from 0 to 50 nm) and chirp (i.e., rapid change in the period of the sidewall modulation) is more demanding in terms of the resolution and the linearity of the lithographic process required to achieve the desired filter function.

The characterization of the fabricated CBG devices was performed using TE-polarized light from a broadband source (1.52 to 1.62 $\mu$m) connected to a circulator. Light reflected from the CBG device is routed through the circulator and enters the input port of an optical spectrum analyzer, where the reflection spectrum is obtained. We fabricated test samples with an access waveguide around 200 $\mu$m in length in front of the CBG structure. For the dispersion characterization, we used Fabry–Perot (FP) resonance oscillations in the measured reflection spectrum of the device. The resonator is defined by two reflectors, the cleaved input facet of the Si waveguide and the CBG. We use a method similar to that reported in [19]: the length traversed by each wavelength component from the cleaved input facet to the point of reflection in the CBG may be experimentally determined using the relation $l_c = (\lambda^2/2n_g(\Delta \Lambda))$, where $\Delta \Lambda$ is the free spectral range of the FP resonator and the value of $n_g$ is fixed at 4.2. The total group delay is subsequently found using $2(l_c \times n_g/c) = (\lambda^2/c(\Delta \Lambda))$, which is independent of the value of $n_g$. Finally, the GVD is obtained using the derivative of the group delay with respect to wavelength. Since the GVD of the access waveguide is 2 orders of magnitude lower than that of the device [20], the measured dispersion is dominated by that of the CBG. Typical experimental data of the reflection spectrum is shown in Fig. 5(a) for a fabricated CBG with $\Delta \Lambda = -7.5$ $\mu$m and $L = 100$ $\mu$m. The reflectivity data is compared with the numeric modeling result obtained for the same CBG geometry but with the average waveguide width adjusted to $W = 520$ nm to account for fabrication inaccuracies causing a 20 nm shift of the center wavelength of operation determined experimentally. The modeled result shows good agreement with the envelope and bandwidth of the measured spectrum.
Within the device bandwidth in Fig. 5(a), the period of the FP oscillations increases as wavelength increases, implying negative (i.e., normal) dispersion. Three fabricated CBG devices with \( L = 100 \, \mu m \) and \( \Delta \Lambda = -4, -7.5, \) and 12 nm were characterized in terms of their group delay [Fig. 5(b)]. The GVD is extracted from the slope of a linear fit applied to the experimental data. The expected GVD values for \( L = 100 \, \mu m, \Delta \Lambda = -4, -7.5, \) and 12 nm from the simulations are \(-0.070, -0.033, \) and \(0.021 \, ps/nm,\) respectively; the measured GVD values are \(-0.067, -0.032,\) and \(0.020 \, ps/nm,\) respectively, showing good agreement between the numeric and experimental results. Note that as expected, changing the sign of the chirp changes the sign of the dispersion [Fig. 5(b)].

In this work we investigate CBGs limited in length to 100 \( \mu m, \) because the high-resolution writing window of our e-beam system is 100 \( \mu m. \) However, it should be noted that longer CBGs are highly desirable for several reasons. First, with longer CBGs we can achieve close to 100% reflectivity, even for large \( \Delta \Lambda \) [Fig. 3(a)]. Second, the ripple in both the reflection and group delay spectra can be significantly reduced for longer asymmetrically apodized CBGs [18] [see Figs. 3(a) and 3(b) comparing \( L = 100 \, \mu m \) and \( L = 200 \, \mu m \) for fixed \( \Delta \Lambda \)].

By introducing the sidewall modulation to waveguides of arbitrary dimensions, a CBG may be integrated with the waveguide for dispersion compensation. As an example, a 300 nm by 500 nm silicon waveguide exhibits GVD of 1100 \( ps/nm/km \) [20], GVD experienced by a 200 fs pulse that has propagated over a length of 3 cm in the waveguide may be compensated for using a CBG with \( L = 100 \, \mu m \) and \( \Delta \Lambda = -7.5 \, nm \). It should be noted that efficient chip-scale integration of reflective devices such as our CBG will commonly require a circulator [5], which remains a challenge for the Si photonics material platform. At present however, we can explore two alternative integration approaches, using (1) a directional coupler at the cost of a 6 dB power penalty or (2) a pair of coupled waveguide grating structures similar to those described in [13], which may be designed as coupled CBGs to simultaneously compensate for GVD and reroute the compensated data without the power penalty.

In summary, the CBG device proposed here provides a platform to engineer normal or anomalous dispersion for photonic systems applications, including GVD compensation in silicon waveguides. The experimental tests of the designed and fabricated devices validate the 2D FDTD method used for modeling of the CBG structures. Asymmetric Blackman apodization was found to be most effective in suppressing group-delay ripple while maximizing the useable bandwidth. The experiments demonstrated a dispersion value of \( 7.0 \times 10^5 \, ps/nm/km \) in a wide spectral range of about 40 nm in the near-IR spectral range of 1.55 \( \mu m. \) Both normal and anomalous dispersion has been demonstrated. The operating bandwidth may be adjusted and arbitrary amounts of dispersion achieved by adjusting the sign and magnitude of the chirp. The tunability of the CBG bandwidth makes it highly suitable for accommodating ultrashort pulses with high spectral content.

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