Research article

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An optical parametric Bragg amplifier on a CMOS chip

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Abstract: We demonstrate a complementary metal–oxide–semiconductor (CMOS)-compatible optical parametric Bragg amplifier on an ultra-silicon-rich nitride chip. The amplifier design incorporates advantageous group index properties in a nonlinear Bragg grating to circumvent phase matching limitations arising from the bulk material and waveguide dispersion. The grating structure further augments the effective nonlinear parameter of $800 \text{ W}^{-1}/\text{m}$, considerably lowering the power required for the observation of strong parametric gain. On/off optical parametric gain of 20 dB is achieved using a low peak power of 1.6 W, in good agreement with numerical calculations. This represents a 7 dB improvement in the parametric gain compared to the absence of grating enhancement which is attributed to the Bragg grating induced superior phase matching.

Keywords: Bragg gratings; CMOS compatible devices; four-wave mixing; nonlinear optics; parametric amplification; silicon-rich-nitride.

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1 Introduction

Temporal pulse compression in Bragg gratings, first theoretically demonstrated by Winful in 1985 highlighted the potential for replacing bulk grating pairs in compression systems with waveguide (WG)-based Bragg gratings, thus cementing their applicability to fiber optic communications [1]. The use of fiber Bragg gratings (FBGs) in transmission for temporal compression was subsequently experimentally verified by Eggleton et al. [2]. These early works laid the groundwork for further studies of the nonlinear FBG phenomenon, including observations of pulse-train generation via high-order solitons, modulation instability, soliton fission, and gap solitons [3–8]. Ten years prior to the seminal work from Winful, innovations were brewing in a different domain. Foundational work in fiber-based optical parametric amplifiers was reported by Stolen [9]. Leveraging the dispersion of the WG modes to compensate for bulk dispersion, Stolen overcame the inherent limitations of silica's material dispersion to achieve phase matching and parametric gain, exceeding Raman gain in silica fibers by a factor of two. Advances made in these two divergent fields have heralded a new generation of devices, with trends toward chip-scale devices offering advantages in low power operation, compactness, and compatibility with complementary metal–oxide–semiconductor (CMOS) electronics.

While the field of FBG temporal compression and fiber-based parametric amplification appear mutually exclusive, properties of both phenomena may in fact be fortuitously combined: (i) The FBG property that enables temporal compression is the strong increase in group index and dispersion close to the grating stopband. (ii) Optical parametric amplification on the other hand is a phase-matched process relying on the dispersion of the guided mode in the fiber, its nonlinearity, and the power. While it has been shown that parametric amplification may indeed take place efficiently in various guided-wave media [10–16], limitations in phase-matching exist. Stolen's design acted to circumvent phase matching limitations stemming from the bulk material dispersion in silica, by cleverly leveraging the dispersion in the fiber's mode. Steel and de Sterke advanced this concept,

by theoretically studying the possibility of using FBGs to overcome limitations in phase matching that relied solely on the optical fiber mode [17–19]. Phase matching constraints however still exist from dispersion availed by guided wave structures, compelling designers to investigate alternative solutions.

Integrated photonic WGs offer ultrahigh optical nonlinearities and therefore the potential to miniaturize the footprint of optical parametric amplification (OPA)-based signal processing and pulse compression schemes. WG-based optical parametric amplifiers have thus far been designed by implementing dispersion engineering based on the cross-sectional modification of the WGs [10–14, 20]. However, the order of magnitude of group velocity dispersion (GVD) in CMOS compatible photonic WGs typically varies between 0.01 and 1 ps²/m [21–23] which significantly inhibits perfect phase matching and the maximum achievable parametric gain. To fully harness the strong nonlinear parameters available in integrated photonics, good phase matching conducive for maximum gain would likewise require higher magnitudes of dispersion not currently available in conventional WGs.

In this manuscript, we report the first demonstration of an optical parametric Bragg amplifier by exploiting the strong dispersion near the stopband to overcome phase matching limitations not just from material dispersion but also from WG dispersion. An on-chip Bragg grating with an effective nonlinear parameter of 800 W⁻¹/m is shown to possess an effective index profile and large band edge group index which significantly aids in the parametric amplification process. On/off signal and idler optical parametric gains of 20 dB are achieved in a 3 mm, CMOS-compatible nonlinear Bragg grating with a low peak power of 1.6 W. The experiments are in good agreement with the numerical calculations of the parametric gain. Our analysis and experiments verify that the larger parametric gain originates from the enhanced four-wave mixing (FWM) phase matching conferred by the nonlinear Bragg gratings, providing a 7 dB improvement in the gain over WG-based phase matching. The device design showcases a new paradigm of amplifiers based on optical parametric Bragg amplifier systems.

2 Results and discussion

2.1 Principles of the optical parametric Bragg amplifier

FWM is a nonlinear process that occurs in third-order nonlinear media, requiring both energy conservation and

phase matching. Nondegenerate FWM involves two different pump photons at different frequencies ($\omega_{p1,p2}$) generating a signal and idler photon at frequencies ω_s and ω_i , respectively. Degenerate FWM utilizes two pump photons at the same frequency ω_p being annihilated to generate a single signal and idler photon at frequencies ω_s and ω_i , respectively, according to the equation, $2\omega_p = \omega_s + \omega_i$. Pump and signal photons co-propagating in nonlinear media can lead to signal amplification and generation of idler photons (Figure 1a). The signal gain and idler conversion efficiency depend on the phase-mismatch, $\Delta k_t = 2\gamma_{\text{eff}}P_{\text{in}} + \Delta k_L$, where γ_{eff} and P_{in} are the effective nonlinear parameter and input peak power, respectively. $\Delta k_L = k_s + k_i - 2k_p$ is the linear phase mismatch, where k_p , k_s , and k_i are the pump, signal, and idler wavenumbers, respectively. The linear phase mismatch may alternately be described in terms of the effective index of the pump, signal, and idler (n_p , n_s , n_i), according to, $\Delta k_L = \frac{1}{c}(n_s \cdot \omega_s + n_i \cdot \omega_i - 2n_p \cdot \omega_p)$. High parametric gain is achieved if Δk_t is close to zero, indicating that $\Delta k_L \sim -2\gamma_{\text{eff}}P_{\text{in}}$.

In photonic WGs where the GVD, β_2 (and therefore n_{eff}) varies slowly with wavelength, Δk_L is approximately $\beta_2(\omega_p - \omega_s)^2$ for small pump-signal detuning [24]. The phase matching is therefore dependent on anomalous dispersion existing in the WG. In the regime of high peak power and large nonlinear parameter, small magnitudes of anomalous dispersion typically present in WGs are insufficient to cancel out the nonlinear contribution. In other words, achieving high parametric gain and strong idler conversion efficiencies requires anomalous dispersion magnitudes significantly larger than that available simply through geometry-based engineering of WG dispersion or that available through bulk material dispersion [21–23].

On-chip Bragg gratings possess strong band edge dispersion, useful for triggering soliton fission and the enhancement of supercontinuum generation [25–27]. As a result of the interaction between the forward and backward coupled waves located close to the grating stopband, the group index increases (decreases) rapidly as the wavelength is increased on the blue (red) side of the stopband. The GVD, $\beta_2 = \frac{\lambda^3}{2\pi c^2} \cdot \frac{d^2 n_{\text{eff}}}{d\lambda^2} = \frac{-\lambda^2}{2\pi c^2} \frac{dn_g}{d\lambda}$, where n_g is the group index of the propagating mode. Therefore, it may be seen that a rapid increase in the group index corresponds to a similar rapid increase in the effective index of the propagating mode, as well as a large β_2 . This large increase in the effective index may therefore be strategically leveraged for phase matching ($\Delta k_t = 0$) in the regime of large pump power and strong nonlinear parameter. In this paper, we shed light on nonlinear gratings for optical parametric Bragg amplification; this is achieved by applying the strong

Figure 1: (a) Energy conservation in degenerate FWM process. Two pump photons are converted into signal and idler photons. In a stimulated case, the signal wave is amplified while idler waves are generated. Momentum conservation (phase-matching) should be satisfied to fulfill amplification of signal waves and generation of idler waves. (b) Effective index near the band edges of photonic bandgap in the CMBGs structure. The slopes of red solid and black dashed lines depict effective indices in respective CMBGs and photonic nanowire waveguide (WG), where Λ is the period pitch of a grating.

effective index variation introduced in a nonlinear ultra-silicon-rich nitride (USRN) grating design toward enhanced phase matching.

Figure 1b illustrates how the phase-matching condition is satisfied in cladding modulated Bragg gratings (CMBGs), on which the optical parametric Bragg amplifier is based, compared to photonic nanowire WGs. Photonic bandgaps in CMBGs intrinsically possess two band edges where rapid, wavelength-dependent variations in the effective index and group index exist. Compared to photonic WGs where the effective index changes slowly, the variation of the effective index with the wavelength in CMBGs is larger close to the stopband: When the frequency approaches *Bandedge1* (blue edge), the wavenumber (k) in CMBGs is smaller than that in WG at the same frequency (ω). Equivalently, n_{eff} decreases as k decreases at *Bandedge1*. Therefore, n_{eff} in CMBGs is smaller than that in WGs close to *Bandedge1*. Conversely, when the frequency approaches *Bandedge2* (red edge), k is larger than that in a photonic WG at the same frequency. This implies that n_{eff} increases as k increases and n_{eff} in CMBGs is larger than that in WGs close to *Bandedge2*. Consequently, a wider range of effective indices is available in CMBGs for the purpose of phase matching, achieved through a judicious selection of the operating frequency close to the photonic band edges. Furthermore, this feature circumvents the typical requirement of operating in the anomalous dispersion region associated with FWM in photonic WGs.

The optical parametric gain of signal, G_s may be described according to the equation,

$$G_s = 1 + \left[\frac{\gamma_{\text{eff}} P_{\text{in}}}{g} \times \sinh(g L_{\text{eff}}) \right]^2 \quad (1)$$

where the parametric gain coefficient, $g = \sqrt{(\gamma_{\text{eff}} P_{\text{in}})^2 - \left(\frac{(2\gamma_{\text{eff}} P_{\text{in}} + \Delta k_L)}{2} \right)^2}$, and L_{eff} is the effective length. In the limit where Δk_L approaches zero, $\Delta k_L = -2\gamma_{\text{eff}} P_{\text{in}}$ resulting in the maximum value of G_s [10, 15]. The effective

nonlinear parameter, $\gamma_{\text{eff}} = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \cdot \left(\frac{n_g}{n_0} \right)^2$, where P_{in} is the input peak power, n_2 is the nonlinear refractive index of the material, A_{eff} is the effective area and n_0 is the material refractive index. In USRN, the linear and nonlinear refractive indices are 3.1 and $2.8 \times 10^{-13} \text{ cm}^2/\text{W}$, respectively. When $\lambda = 1526 \text{ nm}$, $n_g = 4.0$ and $P_{\text{in}} = 1.6 \text{ W}$, the quantities within Equation (1) equate to: $\gamma_{\text{eff}} = 800 \text{ W}^{-1}/\text{m}$ and $-2\gamma_{\text{eff}} P_{\text{in}} \sim -2560 \text{ m}^{-1}$. The contribution to Δk_L from the pump is $-2n_p \cdot \omega_p / c$ (negative sign). Conversely, contributions to Δk_L from the signal and idler frequency terms is $(n_s \cdot \omega_s + n_i \cdot \omega_i) / c$ (positive sign). In light of these quantities, phase matching within the grating may be further described according to the two regimes:

- (1) **Regime dominated by grating dispersion:** If pump wavelength is located at a position closer to *Bandedge2* relative to that of signal and idler wavelengths, we can achieve perfect phase matching.
- (2) **Regime dominated by WG dispersion:** If the pump, signal, and idler wavelengths are far from the grating band edge, phase matching approaches the case of a conventional photonic WG. In this case, perfect phase matching will be difficult to achieve (in the

limit where $2\gamma_{\text{eff}}P_{\text{in}}$ is large), due to the small magnitude of GVD (β_2) relative to a large pump peak power and nonlinear parameter. The linear phase mismatch in a photonic WG is defined as $\beta_2\Omega^2$, where Ω is the frequency detuning between pump and signal. The largest magnitude of anomalous GVD in high index contrast WGs is on the order of $-1 \text{ ps}^2/\text{m}$ [14]. Whereas $\beta_2\Omega^2$ is small, $2\gamma\cdot P_{\text{in}}$ possesses a large value due to large nonlinear parameter of $500 \text{ W}^{-1}/\text{m}$ of the USRN WG, where γ is the nonlinear parameter in WG. Perfect phase matching in the WG is, therefore, hard to achieve even if the pump-signal detuning is small.

It may further be inferred from Equation (1) that the achievable gain in the FWM process relies on γ_{eff} . Another intrinsic advantage of performing FWM in nonlinear Bragg gratings is the elevated group index (and therefore γ_{eff}) that resides close to the grating band edge. As the USRN platform possesses a strong nonlinear refractive index, the advantages conferred by appropriately designed nonlinear gratings may provide enhancements in FWM processes both from augmented nonlinear parameters and advantageous phase-matching.

2.2 Optical properties of USRN CMBGs

The USRN platform was engineered to possess a strong optical nonlinearity of $n_2 = 2.8 \times 10^{-13} \text{ cm}^2/\text{W}$ while simultaneously possessing negligible nonlinear loss near 1550 nm of wavelength [28–30]. CMBGs are periodic photonic structures that implement the periodic modulation of the effective index using cylinders placed at a fixed distance, G_2 , from a central WG as shown in the schematic of Figure 2a. Apodization may be achieved by adiabatically decreasing G from the ends of the grating toward the center. The CMBGs utilize a 600 nm (width, W) by 300 nm (height, H) USRN core with SiO_2 under- and over-cladding. The CMBGs parameters are pillar radius (r) of 100 nm, grating pitch (Λ_B) of 339 nm, and gap distance between the WG to pillar at the center (G_1) and ends (G_2) of the CMBGs are 50 and 150 nm, respectively. The 3 mm CMBG is designed with a 200 μm apodized section (L_A) on each end of the grating. Apodization is applied in order to minimize the transmission and group delay ripple, in particular, to ensure smooth transmission at the band edges of the photonic bandgap. The apodization profile is adopted by continuously increasing the gap distance from the center ($G_1 = 50 \text{ nm}$) to each end ($G_2 = 150 \text{ nm}$) over an

apodization length (AL) according to the following relation [25],

$$G(z) = (G_2 - G_1) \times \cos^2(\pi x) + G_1,$$

where

$$x = \begin{cases} \frac{z}{2AL} & \text{if } z \leq AL \\ 0.5 & \text{if } AL < z < L - AL \\ \frac{z - L}{2AL} & \text{if } z \geq L - AL \end{cases}$$

The apodization profile impacts the modulation of the coupling coefficients, allowing a gradual transition from the effective index of the WG to the grating region. Consequently, appropriately implemented apodization will generate a smooth effective/group index profile, as well as smooth transmission at the band edges [25, 31, 32].

The CMBGs structure is adopted to allow greater control over the apodization since the coupling coefficient of the grating can be controlled by the distance of the cylinders to the central WG. The use of effective apodization is

Figure 2: (a) The schematic and scanning electron micrograph of a fabricated CMBGs. (b) Group (blue line) and effective (red line) indices on wavelength near the band edges of the photonic bandgap. Black dashed line depicts effective index in USRN WG. The light green line shows the linear transmission of the CMBGs with a 10 dB bandwidth of 12 nm.

important to minimize phase distortions in the grating band edge, enabling enhanced parametric amplification. Width or height modulated Bragg gratings are an important class of Bragg gratings in their own right. However, height corrugation is difficult to achieve in a single lithographic step, and WG width variation requires very small amplitude modulation at the apodized regions which could be difficult to accurately implement lithographically. For example, sidewall corrugated Bragg gratings have previously been reported to induce spectral distortion due to fluctuations in the WG dimension [33–37]. For these reasons, we had used the CMBGs to implement the optical parametric Bragg amplifier.

Fabrication of the USRN CMBGs was performed by first performing a 320 nm deposition of the USRN film using inductively coupled chemical vapor deposition at a temperature of 250 °C. Patterning of the structures was performed using electron-beam lithography, inductively coupled reactive ion etching, and plasma-enhanced chemical vapor deposition of the SiO₂ overcladding. A scanning electron micrograph is shown in Figure 2a. The CMBG stopband is centered at 1535 nm and possesses a 10 dB bandwidth of 12 nm as shown in the transmission spectrum (light green line) of Figure 2b. The total CMBG insertion loss outside of the stopband is –15 dB (fiber-WG coupling loss = 6.5 dB, propagation loss = 2 dB). The n_g of the CMBGs as a function of wavelength was measured with a dispersion analyzer as shown in Figure 2b (blue line). The effective index (n_{eff}) was derived from the relation, $n_g = n_{\text{eff}} - \lambda \cdot (dn_{\text{eff}}/d\lambda)$ (red line). It is further observed from Figure 2b that n_{eff} decreases at the blue side of the band edge and increases at the red side of the band edge, as compared to that in the USRN WG. When λ is far from the photonic band edges, n_{eff} and n_g are the same as that in the USRN photonic WG without the periodic pillars. n_g is symmetric about the center of the photonic bandgap, a characteristic that allows perfect phase matching to be implemented toward enhanced parametric gain.

2.3 Theoretical analysis of phase-mismatch and group velocity mismatch in USRN CMBGs

The optical parametric Bragg amplifier operates in transmission mode, specifically in the wavelength region of the grating where the transmissivity is high and the Bragg grating induced effective index varies rapidly (for phase matching). Operating in the transmission is essential as it allows us to take advantage of the high dispersion at the band edge induced by the Bragg grating structure.

Figure 3 shows the phase mismatch (Δk_t) and group velocity mismatch in the CMBGs. We utilize a 5 ps pulsed pump centered at 1550 nm with a peak power, $P_{\text{in}} = 1.6$ W. We used the CMBGs' dispersive behavior to counterbalance the large, positive nonlinear phase to achieve perfect phase matching. The total phase mismatch versus the signal wavelength is shown in Figure 3a, where the pump wavelength is fixed at 1550 nm and the continuous wave (CW) signal wavelength is varied. Vanishing phase mismatch is obtained at 1525 and 1574 nm. The dashed line denotes the phase mismatch for a WG where it is observed that conditions for vanishing phase mismatch do not exist. This phenomenon arises because the magnitude of anomalous dispersion is insufficient to cancel the nonlinear contribution.

On one hand, we leverage the grating-induced dispersion toward improved phase matching. On the other hand, the grating-induced modification in the group index profile could impede the temporal overlap of pump, signal, and idler pulses. Therefore, the effect of the altered group index (or equivalently, the group velocity) profile is another

Figure 3: (a) Phase mismatch (Δk_t) in the CMBGs (red solid line) and WG (blue dashed line) as a function of signal wavelength. The pump wavelength is 1550 nm and the signal wavelengths are varied between 1510–1528 and 1573–1595 nm. For the Δk_t curve at a shorter signal wavelength of 1510–1528 nm, the signal wavelength is located close to *Bandedge1* to optimize the phase mismatch. For the Δk_t curve at a longer signal wavelength of 1573–1595 nm, generated idler wavelengths are tuned close to *Bandedge1* to optimize the phase mismatch. The pump is located near *Bandedge2* to minimize Δk_t . The 5 ps pump peak power is 1.6 W. (b) The group velocity matching length (L_{gvm}) is defined as $\tau/[1/v_p - 1/v_{s,i}]$, where τ is pulse width and $v_p, v_{s,i}$ are velocities for pump, signal, and idler beam. L_{gvm} is larger than the device length of 3 mm (green dashed). Gray lines depict linear transmission in the dB scale as a function of wavelength.

important element to analyze. The input CW beam serves only as a stimulating source. The generated signal, idler, and input pump assume a pulsed form, particularly since the amplified signal and idler are generated only at temporal instances when the pump pulses co-propagate with the signal. We may derive further insight from the nonlinear Schrödinger equation for FWM. Equations (2) and (3) are coupled equations describing the generated idler amplitude A_4 [24]:

$$\frac{\partial A_4}{\partial z} + \frac{1}{v_g} \frac{\partial A_4}{\partial t} = i\gamma \left(|A_4|^2 A_4 + 2 \sum_{k \neq 4} |A_k|^2 A_4 + 2A_1 A_2 A_3^* e^{-i\Delta k_L z} \right) \quad (2)$$

$$\begin{aligned} \frac{\partial A_4}{\partial z} = i\gamma \left(|A_4|^2 A_4 + 2 \sum_{k \neq 4} |A_k|^2 A_4 + 2A_1 (\sigma - (\nu_k - \nu_4)t)^2 A_4 + 2A_1 (\sigma - (\nu_1 - \nu_4)t) A_2 (\sigma - (\nu_2 - \nu_4)t) A_3^* (\sigma - (\nu_3 - \nu_4)t) e^{-i\Delta k_L z} \right), \end{aligned} \quad (3)$$

where A_i , v_i are the field amplitude and group velocity of fields, and subscript 1, 2 refer to the degenerate pump photons. Subscript 3 and 4 are for signal and idler photons, respectively. The source term is a direct product of three photons, namely two pump photons and one signal photon. It follows from Equations (2) and (3) that the temporally nonoverlapped source term will be zero. In the absence of the source term, the idler cannot increase in amplitude. The group velocity matching length (L_{gvm}) is defined as $\tau/|1/\nu_1 - 1/\nu_{3,4}|$, where τ is the temporal pulse width. For FWM to take place efficiently through the entire device length, the group velocity matching length should exceed the device length. In our USRN CMBGs, our analysis shows that this condition is indeed satisfied: The L_{gvm} is larger than the device length of 3 mm as shown in Figure 3b [24].

2.4 Experimental results of gain in the optical parametric Bragg amplifier

Experiments are performed using a 5 ps pulsed pump with a repetition rate of 20 MHz centered at 1550 nm. A tunable CW laser is used as a signal source. The input peak power of the pump is fixed at 1.6 W. Both pump and signal lasers are combined using a 3 dB coupler and coupled into the USRN CMBGs via a tapered fiber. The output spectra coupled out from a tapered fiber are measured by an optical spectrum analyzer (OSA). In our experiments, the experimentally measured FWM spectra are shown in Figure 4a and b as the signal wavelengths tuned from 1512–1526 and 1570–1579 nm, respectively, where the pump, amplified signal, generated 1st and 2nd idlers at each signal wavelength are observed. The signal wavelength is tuned from 1512 to 1526 nm at the blue side of the grating stopband

(*Bandedge1*), in order to experimentally determine the maximum gain as shown in Figure 4a. The generated idlers wavelengths are tuned closing to *Bandedge1* to optimize phase mismatch, thus obtain maximum gain by tuning from 1570 to 1579 nm of signal wavelength as shown in Figure 4b. Figure 4c shows the measured and theoretical on/off signal gains as a function of signal wavelength. On/off signal gain is defined as $P_{sig,peak}/P_{signal,out}$, where $P_{sig,peak}$ is calculated using $P_{sig,peak} = \frac{1}{RT} \left(\int P_{sig,avg}(\lambda) d\lambda \right)$, and R and τ are the repetition rate of the pulse and the pulse width, respectively. $P_{sig,avg}(\lambda)$ represents the average output power spectrum of the signal measured using the OSA. The power of the CW signal line is subtracted from $P_{sig,avg}(\lambda)$ to obtain $P_{sig,peak}$. $P_{signal,out}$ is the CW signal power at the output of the device with the pump off [11–15]. By tuning the signal wavelength to the blue side of the band edge, the maximum signal gains of 20 dB are obtained at a signal wavelength of 1524 nm. The maximum on/off signal gain is obtained to be 20 dB at a signal wavelength of 1576 nm where the phase-matching condition is optimally satisfied.

Theoretical on/off signal gain is defined as $P_{sig,peak}/P_{signal,out}$, where $P_{sig,peak}$ and $P_{signal,out}$ are the amplified signal peak power and CW signal power at the device output, respectively. G_s is defined as the amplified signal power at the device output divided by input signal power. Consequently, the on/off signal gain is given by, $G_s \cdot e^{\alpha \cdot L_{eff}}$, where $L_{eff} = \frac{1}{\alpha} [1 - e^{-\alpha L}]$ and α is the loss coefficient. The figure shows the trend of measured on/off signal gains (pink dots) agrees well with the theoretical calculations (red solid line).

The comparison of the on/off signal gain between the CMBGs and WG is also presented in Figure 4c. The maximum gain achieved in the CMBGs is around 20 dB, occurring at a signal wavelength of around 1524 and 1576 nm where the phase-matching condition is satisfied. We may observe from Figure 3 that as the signal wavelength closes to *Bandedge1* increasing beyond 1524 nm and approaches *Bandedge2* decreasing below 1576 nm, phase matching and group velocity matching become worse. Thus as expected, it is observed from Figure 4c that the gains drop sharply. A decrease in gain is observed as the signal wavelength shifts away from the stopband as a result of the worsening phase matching. The slow decreases in gains decreasing below 1524 nm and increasing beyond 1574 nm are also to be expected since variations in both group index and dispersion vary much less rapidly in regions far from the grating stopband. Conversely, in the WG case, it is observed that the gain remains fairly constant at around 13 dB in the wavelength of interest wavelength even if perfect phase matching is not satisfied (blue

Figure 4: Experimentally measured FWM spectra for the optical parametric Bragg amplifier at the signal wavelength of (a) 1512–1526 nm and (b) 1570–1579 nm. (c) On/off signal gains (pink dots) are compared with theoretical curves in the CMBGs (red line) and WG (blue dashed). The grating transmission is presented as the grayline. 1st/2nd idler gains corresponding to the FWM spectra in (a) and (b) are shown in (d) and (e), respectively.

dashed). Consequently, it is theoretically and experimentally predicted that the enhanced phase matching conferred by CMBGs allows a significant increase in the achievable parametric gain compared to WGs. We note further that far from the grating stopband, the parametric gain approaches that achievable in a USRN WG without the grating structure. In our experiment, 12 nm of working bandwidth with on/off parametric gain exceeding 8 dB is achieved at each band edge and the parametric gain exceeds that achieved in the WG across an 8 nm bandwidth. Summarily, the optical parametric Bragg amplifier provides augmented parametric gain from enhanced phase matching close to the grating stopband, and similar gain as a USRN WG when operating far from the grating stopband.

The FWM spectrum in Figure 4a and b both show evidence of cascaded FWM, where a 1st and 2nd idler is

generated during the parametric process. The on/off n th idler gain is calculated as $P_{\text{idler}(n),\text{peak}}/P_{\text{signal,out}}$, where n represents the idler number. The power within the n th idler is calculated using the expression, $P_{\text{idler}(n),\text{peak}} = \frac{1}{R\tau} \left(\int P_{\text{idler}(n),\text{avg}}(\lambda) d\lambda \right)$, where $P_{\text{idler}(n),\text{avg}}(\lambda)$ is the average output power spectrum of the n th idler measured using the OSA [11–15]. As the signal wavelength is tuned closer to the blue side of the band edge, the effective index decreases at a faster rate compared to the WG. Therefore, the total phase matching eventually goes to zero. We can further observe a 2nd idler gain of close to 1 dB at a signal wavelength of 1525 nm, corresponding to when the signal gain exceeds 16 dB as shown in Figure 4d. The 1st and 2nd idlers are generated at two wavelength regions: from 1570–1594 nm, and close to 1600 nm as shown in Figure 4a. The generated 1st idler is tuned near the blue side of the band edge, the 1st

and 2nd idlers are generated from 1520–1530 nm, and 1600–1610 nm, respectively, as shown in Figure 4b. Second idlers are observed with conversion efficiencies varying between –4 and 1 dB, corresponding to when the signal gain exceeds 12 dB as shown in Figure 4e. We observe similar parametric gain values in both Figure 4c–e because the signal (idler) wavelengths are tuned at the blue (red) side of the band edge by switching the location of the signal/idler wavelengths with each other. The output pump shows self-phase-modulation-induced broadening due to the large nonlinear parameter in the CMBGs.

To further analyze how parametric gain is facilitated with the enhanced phase matching conferred by the grating, we investigate the FWM process when the pump is located at the blue side of the band edge. In other words, this particular placement of the pump and signal does not lead to ideal phase matching. In this case, situating the pump wavelength at the red side of the band edge is ideal for achieving a negative Δk_L value. However, the smaller effective index when the pump is at the blue side of the band edge makes it difficult to obtain negative Δk_L and results in significantly less effective phase matching. In the

next set of experiments, a USRN CMBGs with the stopband centered at 1575 nm is used (gray line in Figure 5a). The signal wavelength is varied from 1556 to 1563 nm, on the blue side of the band edge. We note here that the effective index is smallest at 1563 nm. As the pump wavelength is also located at the blue side, the on/off signal and idler gains are measured to be around 10 dB at a signal wavelength of 1563 nm (Figure 5b), which is smaller than that achieved in Figure 4 where the pump wavelength is located at the red side. No visible 2nd idler is observed due to the smaller overall parametric conversion efficiency in this configuration.

Next, the parametric gain is measured in the CMBGs far from the band edge. When the pump wavelength is far from the band edge in the CMBGs, pump, signal, and idler waves evolve similarly to the WG case. The gray line in Figure 5c represents the transmission vs. wavelength for a CMBG that does not have a photonic bandgap in the wavelength range of interest between 1520 and 1610 nm. We use a pump wavelength of 1547 nm and tune the signal wavelength between 1520 and 1529 nm. The measured on/off signal and 1st idler gains are 12 dB at a signal wavelength of 1525 nm

Figure 5: FWM spectra (a) and their on/off signal and 1st idler gains (b) at signal wavelength of 1556–1563 nm. FWM spectra (c) and their on/off signal and 1st idler gains (d) at signal wavelength of 1520–1529 nm. Black dashed lines in (b) and (d) show the theoretical on/off signal gains which agree well with the experiments. Gray lines depict linear transmission in the dB scale as a function of wavelength. Input peak power is 1.6 W.

Figure 6: FWM spectra at a signal wavelength of (a) 1540–1545 nm using the CMBGs as that used in Figure 4a and b signal wavelength of 1583–1589 nm using the CMBGs as that used in Figure 5a. No idlers are observed in either case due to poor phase matching.

(Figure 5d). The measured on/off signal gains agree well with the values in the theoretical simulation (black dashed lines).

A further set of experiments is conducted to confirm the role of the CMBGs-induced phase matching. Poor phase matching is observed when the pump is located at the red side of *Bandedge2* and the signal wavelength is tuned to close to the *Bandedge2* as shown in Figure 6a. As the signal frequency term, $n_s\omega_s$ in Δk_L has the largest magnitude with positive sign close to the band edge, the discrepancy between Δk_L and the quantity, $-2\gamma_{\text{eff}}P_{\text{in}}$ is large and poor phase matching is expected. When the pump wavelength is located at the blue side of *Bandedge1*, the pump frequency term, $-2n_p\omega_p/c$ from Δk_L possesses a smaller magnitude with a negative sign, again resulting in poor phase-matching (Figure 6b). Therefore, idlers are not observed in Figure 6a and b.

We reconsider the pump-probe setup used in Figure 4a and investigate the impact of changing the pump wavelength. When the pump wavelength is changed from 1550 to 1554 nm while utilizing the same experimental condition of Figure 4a, the maximum signal gain is blue-shifted from 1524 to 1522 nm as shown in Figure 7. This phenomenon arises from the smaller resultant effective index associated with the blue-shifted pump. In order to fulfill the phase-matching condition, $\Delta k_L \sim -2\gamma_{\text{eff}}P_{\text{in}}$, $n_s\omega_s$ is decreased as $-2n_p\omega_p/c$ is decreased in $\Delta k_L = (n_s\omega_s + n_i\omega_i - 2n_p\omega_p)/c$. Therefore, the impact of the signal wavelength on the trend observed in the on/off signal gain in Figure 7 further confirms the effectiveness of the optical parametric Bragg amplifier in conferring improved phase matching.

The performance of the optical parametric Bragg amplifier may be evaluated with respect to the gain, device length (L), and input peak power (P_{in}) used. We utilize the

Figure 7: Comparison of on/off signal gains between pump wavelength (λ_{pump}) of 1550 and 1554 nm. The blue triangular line is the same as the pink dots at the shorter wavelength region in Figure 4c.

figure of merit $G_{PL} = 10 \times \log_{10} \left(\frac{G_{\text{sig}}}{P_{\text{in}}^2 \cdot L^2} \right)$, where $G_{\text{sig}} = \frac{P_{\text{sig, peak}}}{P_{\text{signal, out}}}$, is the on/off parametric gain, to compare the performance of various on-chip parametric amplifiers. G_{PL} accounts for the fact that the FWM process increases with the square of input peak power $\times$ device length [38]. This comparison plot is included in the revised manuscript as Figure 8 [11–14, 39]. G_{PL} for our device is 26, which is the largest among other on-chip parametric amplifiers including silicon and amorphous silicon photonic WGs. It indicates that parametric amplification in USRN CMBGs benefits from enhanced phase-matching and the augmented group index at the grating band edge.

Brillouin scattering has been used to generate large amplification of >20 dB [40, 41]. However, the bandwidth of Brillouin amplification is inherently limited by the phonon

Figure 8: Comparison of on/off parametric gains among on-chip parametric amplifiers of Ref. [11–14, 39], and our work.

lifetime which is typically tens of Megahertz [24]. Wider gain bandwidth has been demonstrated by broadening the stimulated Brillouin scattering pump but is still limited to gigahertz bandwidth, considerably smaller than the parametric amplification bandwidth achieved in our work which approximates terahertz bandwidth.

Efficient, on-chip FWM processes have also been implemented with much success using high-Q silicon nitride and Hydex micro-ring resonators, enabling wide-band frequency comb generation [22, 42, 43]. Noting that optical parametric amplification in silicon nitride ring resonators has not been demonstrated, as far as we are aware, the fundamental difference with the approach demonstrated in our work is the bandwidth constraint imposed by the resonant response of the rings. Another possible reason is the weaker Kerr nonlinearity in Silicon nitride ($100\times$ smaller than in USRN).

In the optical parametric Bragg amplifier, aside from the high parametric amplification, the gain may be conferred to signals over a continuous wavelength range, albeit within the operating bandwidth of the band edge. Indeed, there is a bandwidth over which perfect phase matching may be achieved, which perhaps can be extended in the future through further design optimizations. In addition, the footprint of a typical silicon nitride ring resonator (100 μm radius) is about $3.1 \times 10^{-8} \text{ m}^2$, larger compared to the footprint of the optical parametric Bragg amplifier ($5 \times 10^{-9} \text{ m}^2$).

We note that this amplification strategy may be implemented for any wavelength region and is especially useful for achieving phase matching when the background WG dispersion is normal. When a strong nonlinear phase is expected either from a high-powered pump or strong device nonlinearity, the Bragg-induced improvement in phase matching would most certainly facilitate more

efficient parametric processes. High pump powers reduce the coherent length for FWM in the presence of nonperfect phase matching. Because the device length should be less than the coherence length, strong pump powers place a limit on the usable device length. Therefore, perfect phase matching induced by the CMBG structure enables a longer coherence length and therefore, a longer device length can potentially be used for optical parametric amplification once group velocity matching is satisfied.

3 Conclusion

We have demonstrated a CMOS-compatible optical parametric Bragg amplifier on a chip, which strongly leverages the advantageous group index (or effective index) properties to achieve perfect phase matching and enhanced parametric gain. These results further show that limitations from bulk material or WG dispersion may be efficiently circumvented through the judicious design of the optical parametric Bragg amplifier. An on-chip parametric gain of 20 dB is achieved using a low peak power of 1.6 W. Regardless of the sign and magnitude of high-order dispersion inherent in the bulk material or WG dispersion, perfect FWM phase matching can be satisfied by utilizing the strong distortion in the effective refractive index present at both band edges of the photonic bandgap in the CMBG structures. The optical parametric gain is further enhanced by the augmented effective nonlinear parameter availed in the CMBG structures. In the absence of proper phase matching in the CMBG structures, poor parametric conversion is observed, corroborating the salience of design in achieving a grating-enhanced parametric gain. We further observe cascaded FWM, with conversion efficiencies exceeding 0 dB for the 2nd idler. A 7 dB increase in the on/off parametric gain compared to photonic nanowire WGs is experimentally observed. The demonstrated work introduces a new paradigm for the realization of CMOS-compatible, high gain amplifiers, and could benefit the design approaches undertaken in a wide plethora of nonlinear optics devices that rely on phase matching.

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