Wideband Spectral Enhancement through On-Chip Bragg-Soliton Dynamics

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Supercontinuum generation (SCG) through soliton fission provides high-brightness, spectrally-rich light needed for hyperspectral imaging, broadband spectroscopy, and fluorescence microscopy. The prospect of miniaturization has led to many demonstrations of this phenomenon in integrated platforms. However, due to the moderate dispersion and nonlinearity generally available in channel waveguides, femtosecond pulses have typically been required to date, as the use of picosecond pulses would require unpractically long devices to achieve soliton fission. Here, spectral bandwidth enhancement of the supercontinuum process through Bragg grating induced soliton-effect compression and soliton fission is demonstrated. This approach uses picosecond pulses on a complementary metal oxide semiconductor (CMOS)-compatible, millimeter-scale platform, consisting of a monolithically integrated cladding-modulated Bragg grating with a channel waveguide. The strong dispersion near the stopband of the grating enables compression and fission of picosecond higher-order solitons, which enhances the spectral broadening in the channel waveguide. A 4.3 spectral bandwidth enhancement is reported, with respect to a reference waveguide of the same length. The output spectra are further studied both through simulations and experiments and determined to possess high spectral coherence. These results highlight a simple route to significantly augment the bandwidth of nonlinear processes such as SCG while maintaining low power and compact footprint.

1. Introduction

Ultrabroadband spectra, necessary for a wide range of applications including hyperspectral imaging, broadband spectroscopy, and fluorescence microscopy, can be generated by injecting ultrashort pulses from a modelocked laser into a nonlinear waveguide. In this process termed supercontinuum generation (SCG), complex, interacting nonlinear effects harmonize to efficiently create broadband light. SCG has been attributed to phenomena such as Cherenkov radiation, cascaded four wave mixing, and soliton fission. In general, SCG leveraging soliton fission, which refers to breakdown and separation of a high-order soliton into its constituent fundamental solitons due to a large enough perturbation in the system, is preferred in applications such as spectroscopy, and optical frequency metrology, compared with SCG in the modulational instability (MI) regime, because of the improved coherence of the generated supercontinuum (SC).

SCG was extensively researched after the development of photonic crystal fibers (PCFs) which can be dispersion engineered at will and possess large effective nonlinearity. Other methods have been demonstrated in fiber platforms, including exploiting grating-induced phase shifts for local enhancement of SCG and cascading fibers with different dispersion profiles (high dispersion and low dispersion fibers, respectively) which has been shown theoretically to enhance SCG with a continuous wave (CW) input via MI.
Recently, SCG has made substantial progress in integrated waveguides for realizing compact broadband sources.\textsuperscript{15,12–19} A common approach here is to tailor the group velocity dispersion (GVD) of the channel waveguides optimizing the waveguide width and height parameters.\textsuperscript{[17,18]} Although promising, this approach offers limited flexibility for engineering the dispersion in conventional channel waveguides. Periodic structures such as Bragg gratings provide access to higher anomalous dispersion regimes compared with what is accessible in channel waveguides.

Orders of magnitude larger GVD in Bragg gratings, compared with the intrinsic dispersion, unlocks dispersion-induced pulse shaping at length scales of millimeters for picosecond pulses. Bragg solitons which propagate through a balance between the ultrastrong dispersion induced by the Bragg grating at frequencies close to the band-edge and the self-phase modulation (SPM), can facilitate soliton dynamics.\textsuperscript{[20,21]} These principles enabled the recent demonstration of Bragg-soliton-induced pulse compression and soliton fission in photonic integrated circuits.\textsuperscript{[22]} Here, pulse compression is associated with the narrowing of a high-order soliton as it undergoes initial contraction. When perturbed by higher-order dispersion, the soliton undergoes soliton fission; leading to shorter pulse widths than the original soliton where each derivative soliton propagates independently with its own group velocity and energy, increasing the subsequent self-phase modulation broadening and intrapulse Raman scattering frequency shift. The initiation of soliton-fission due to third-order dispersion (TOD) was previously observed under certain conditions, through spectral and time-resolved measurements.\textsuperscript{[22,23]}

In this article, we exploit the high-order soliton dynamics induced by an on-chip cladding-modulated Bragg grating (CMBG) concatenated with a channel waveguide to demonstrate enhancement of the SCG spectral width. We combine the dispersion properties of the two-stage device with the ultrasilicon nitride (USRN:Si$_3$N$_4$) platform, which possesses a large optical nonlinearity and no nonlinear absorption within the power regime explored in this work.\textsuperscript{[14,24]} In the first stage of the system, a Bragg grating, induces the soliton compression and soliton fission break-up on a millimeter length scale. The second stage is a channel waveguide, which harnesses the solitons induced in the first stage for enhanced spectral broadening. We demonstrate a 4.3$\times$ enhancement in the spectral width compared with a reference waveguide of the same length. We generate wideband spectra in a 7 mm long device, with picosecond pump pulses of 1.7 ps. Furthermore, the spectral coherence of the output spectra is experimentally characterized to be high, with an average spectral coherence exceeding 0.92 across the measured spectrum. Our results are promising for eliminating the need to use subpicosecond pulses for wideband spectral broadening and aims to accelerate the on-chip integration of SCG with current picosecond on-chip sources.\textsuperscript{[25,26]} We present a new avenue for the generation of wideband spectral broadening, using less expensive, picosecond pulse sources with lower peak powers in compact devices.

2. Results

2.1. Two-Stage Device for Supercontinuum Enhancement

The operating principle of the two-stage device is shown in Figure 1a, where the numerically modeled temporal and spectral profiles of the pulse at 1) the input, 2) after the grating, and 3) at the device output are shown. Further details of the simulation methodology and results are provided in the Experimental Section and Results section respectively. We harness soliton-effect compression and fission at the initial grating stage caused by the TOD perturbation that arises from the strong variation of the GVD. The Bragg soliton dynamics facilitate considerably larger spectral broadening, compared with a reference nanowire with the same length. The addition of the grating stage just prior to the nonlinear waveguide eliminates the need for subpicosecond pumping to generate supercontinuum. The device shown in Figure 1a consists of two stages: 1) a CMBG with a length of 1 mm followed by 2) a 6 mm-long buried channel waveguide with a width of 600 nm.

The device is implemented on the USRN platform with a linear and nonlinear refractive index of 3.1 and 2.8$\times10^{-13}$ cm$^2$/W, respectively,\textsuperscript{[27]} and film thickness of 300 nm. CMBGs allow dispersion engineering by providing ample flexibility for achieving complex gratings via their tunable parameters such as gap (G), and grating pitch (\textit{A}).\textsuperscript{[28]} The CMBG consists of a channel waveguide with pillars placed next to it with a distance defined by $G$. The cladding modulated design allows ease of implementing flexible apodization schemes by varying the gap parameter. The upper and lower SiO$_2$ cladding ($n_{SiO2} = 1.46$) results in modal symmetry and a structurally robust device.\textsuperscript{[29]}

To preserve the dispersive properties of the first stage, minimize insertion losses, and out of band ripple, we apply apodization to the grating. The apodization scheme involves slowly decreasing the gap at the input of the waveguide according to a raised cosine function presented before.\textsuperscript{[22]} Adiabatically changing the distance between the pillars and the waveguide alters the effective refractive index ($n_{eff}$) perturbation, creating an apodization effect that suppresses the grating side lobes.

Figure 1b shows the transmission spectrum of the device where the photonic stopband induced by the grating periodicity results in a Bragg wavelength of $\lambda_B = 1567$ nm. A scanning electron micrograph of the grating prior to SiO$_2$ cladding deposition is shown in Figure 1c. We operate close to the band edge at the blue side of the stopband where the dispersion is large and anomalous, as shown with the gray shaded region in Figure 1b. In this region, the group index increases as the wavelength approaches the band edge. The dispersion parameters for the grating have previously been measured,\textsuperscript{[22]} and are as follows; $\beta_2 = -0.81$ ps$^2$/mm, $\beta_3 = 0.83$ ps$^3$/mm$^2$, $\beta_4 = -0.33$ ps$^4$/mm$^3$, $\beta_5 = -0.7$ ps$^5$/mm$^4$, and $\beta_6 = 0.01$ ps$^6$/mm$^5$ for the detuning between pulse wavelength and grating stopband used in this work. For the channel waveguide, the calculated dispersion parameters through mode analysis for the quasi-transverse electric (quasi-TE) mode are $\beta_2 = -1.2 \times 10^{-3}$ ps$^2$/mm$^2$, $\beta_3 = -5.3 \times 10^{-8}$ ps$^3$/mm$^3$, $\beta_4 = 2.4 \times 10^{-8}$ ps$^4$/mm$^4$, which are three, eight, and eight...
Figure 1. Schematic of the two-stage device design for enhanced spectral broadening. a) The device consists of two stages. The first stage is a grating, which triggers soliton fission, and the second stage is where wideband spectral broadening is generated. The various device parameters are shown in the figure, as well as the modeled temporal intensity (solid lines) and spectrum (dashed lines) showing the pulse evolution along two stages of the waveguide device for a soliton with order $N = 2.74$. $L_{\text{apod}} = 100 \mu\text{m}$ is the apodization length, $G_1$ and $G_2$ are 50 and 150 nm, respectively, and the grating pitch is $\Lambda = 339 \text{ nm}$. b) The measured transmission spectrum of the device and c) scanning electron micrograph taken before cladding deposition.
orders of magnitude smaller than that in the grating, respectively. The strong dispersion inherent in the CMBG band edge, strong nonlinearity, and absence of two-photon absorption are the enabling factors for the strong soliton dynamics to occur on very short, millimeter length scales toward the enhancement of supercontinuum.

As a result of the strong second-order dispersion, three orders of magnitude larger than in photonic waveguides, we are able to achieve a soliton order, \( N = 2.74 \) using pulses possessing a full-width half maximum (FWHM) of 1.7 ps. Soliton order is calculated by:

\[
N^2 = L_D = \frac{T_0^2 P_0}{|\beta_2|}, \quad L_{NL} = (\gamma P_0)^{-1}
\]

where \( T_0 \) refers to the temporal pulse width, and \( P_0 \) denotes the coupled input peak power. From Figure 1a, we observe that the grating stage initiates the soliton fission, and the majority of the spectral width is generated in the second stage of the waveguide where the nonlinear effects dominate. At the output of the first stage, the pulse is compressed to 0.55 ps, which leads to a \( 2.3 \times \) enhancement in the peak power with respect to the input peak power of 5.5 W, despite the propagation losses of 1.3 dB mm\(^{-1}\).

### 2.2. Experimental Characterization of Wideband Spectral Enhancement

Experimental characterization was carried out using pulses with an FWHM of 1.7 ps, with a coupled peak power fixed at 5.5 W. Full details of the experimental setup are provided in Experimental Section. In the first set of experiments, we utilize two devices with different Bragg wavelengths, both of which consist of a 1 mm CMBG and 6 mm channel waveguide. The first device has a Bragg wavelength, \( \lambda_B = 1567 \) nm, whereas the second device has \( \lambda_B = 1588 \) nm. Figure 2a shows the output spectrum of the two devices when the 1.7 ps pulses centered at \( \lambda_B = 1567 \) nm are injected. The pulses are located relatively close to the band edge of the first device (\( \lambda_B = 1567 \) nm). In this situation, it is observed that the broadening of the input pulses is extensive, spanning from 1340 to 1680 nm (340 nm) at the \( -30 \) dB level. The output spectrum for the device with \( \lambda_B = 1588 \) nm exhibits comparatively less broadening (BW\(_{30\text{dB}} = 86 \) nm). As a further reference, the output spectrum of a 7 mm channel waveguide is also shown in Figure 2 and shown to have a similar extent of broadening as the device with

![Figure 2](image-url)

**Figure 2.** Experimental characterization of supercontinuum enhancement in the grating + waveguide device. a) Source spectrum (solid black line), output spectral response for the reference waveguide (solid red line), and gratings with \( \lambda_B = 1588 \) nm and \( \lambda_B = 1567 \) nm (green and solid blue lines, respectively). b) Output spectrum for 3 mm grating and 7 mm waveguide, with \( \lambda_B = 1575 \) nm (solid blue line), reference waveguide (solid red line), and source (solid black line).
λ_B = 1588 nm. This confirms that far from the band edge of the device, there is no enhancement in the output spectral width from the presence of Bragg soliton behavior. Conversely, for the grating with Bragg wavelength of λ_B = 1567 nm, the input pulses are located close to the CMBG band edge, where rich soliton dynamics become accessible, including TOD-induced initiation of soliton fission. These constituent solitons are instrumental in enhancing the spectral richness of the output pulses. The results confirm that in the absence of the grating, the extent of broadening is small.

We define here the enhancement factor, \( E_F = \frac{\text{BW}_{\text{sol}}/\text{BW}_{\text{Ref}}}{\text{BW}_{\text{Ref}}/\text{BW}_{\text{WG}}} \)

where the numerator and denominator refer to the output –30 dB spectral width of the CMBG + waveguide device, and the output –30 dB spectral width of a reference waveguide of the same total length, respectively. For the device with λ_B = 1567 nm, there is a 4.3 × enhancement in the output spectral width compared with the reference waveguide. The spectral response of the structure having λ_B = 1588 nm is similar to that of the reference waveguide; evidence of the Bragg nature of solitons contributing to the enhancement for λ_B = 1567 nm. There are negligible grating effects when we operate far away from the band edge for the grating with λ_B = 1588 nm; whereas close to the band edge (λ_B = 1567 nm), we have a large enhancement in the spectral broadening due to the TOD-induced soliton fission. We would also like to note that the lengths of two stages make an impact on the enhancement factor. According to the definition of \( E_F \), this is expected, as a longer total device length would result in a larger spectral broadening in the reference waveguide, meaning that a longer total device length might lead to a smaller enhancement factor.

The prerequisites to initiating the soliton compression and fission in a 1 mm-long CMBG are also considered in our design: 1) The uniform, nonapodized grating length of \( L_g = L - L_{\text{apod}} = 0.8 \text{ mm} \) exceeds the fission length for the power levels used in this experiment, \( L_{\text{fiss}} \sim L_D/N = 0.41 \text{ mm} \); 2) \( \beta \) parameter which is a metric used to gauge the onset of soliton fission, defined as \( \beta = \beta_0/N \), \( \beta_0 = 0.18 \) is larger than the threshold \( \beta_0 \) given in the literature. After the soliton is initiated at \( L_{\text{fiss}} \), the constituent solitons need to travel further inside the waveguide for the distinct peaks in the time domain to separate sufficiently and become visible. The location where the maximum soliton pulse compression occurs, and where the soliton fission occurs, are inherently related, and the fission length was initially examined in the soliton self-compression context, where the self-compression distance (\( z_{SD} \)) was obtained as \( z_{SD} = 0.71 \times L_D/N \).

One of the signatures of Bragg solitons is their wavelength sensitivity relative to the band edge of the Bragg grating [20,30,31]. As the wavelength approaches the stopband, the grating induced dispersion increases and therefore to support soliton fission due to the decrease in the fission length, \( L_{\text{fiss}} \). We conducted further experiments which investigated the degree of spectral enhancement as a function of pulse wavelength. Figure 3a shows the output spectrum from a device consisting of a 1 mm CMBG (\( \lambda_B = 1567 \text{ nm} \)) followed by a USRN waveguide with a length of 1 cm, as the source pulse wavelength is increased from 1543.9 to 1556.8 nm. The output spectrum of a reference waveguide of the same total length (1.1 cm) is used to establish the enhancement factor. Figure 3a shows that far from the band edge (source pulses at 1543.9 nm), no enhancement in the output spectrum is observed. This observation is consistent with the pulse being in a regime of minimal Bragg-induced dispersion. As the wavelength of the pulse approaches the band edge, the first stage of the device becomes more efficient at generating soliton compression and fission, and finally arrives at a wavelength where the CMBG length exceeds \( L_{\text{fiss}} \). In this regime, considerable spectral enhancement is observed.

However, beyond 1551 nm, the enhancement factor starts to decrease. Note that the stopband of this CMBG is centered at 1567 nm, with the blue band edge located at 1561 nm. Therefore, the spectrum of the source pulse is sufficiently far from the band edge to preclude spectral truncation, even when tuned to 1556.8 nm. We draw insight from Figure 4, which shows the pulse evolution along two dispersion lengths for a soliton with order, \( N = 2.74 \) by solving the generalized nonlinear Schrödinger equation (GNLSE) shown in Equation (1), thoroughly explained in the next section. It is observed that in the presence of higher-order dispersion terms (third and higher), soliton fission occurs. More importantly, Figure 4d shows that some spectral elements emerge at longer wavelengths, beyond 1560 nm as a result of the fission process. These wavelength elements could encroach into the stopband and reduce the overall enhancement. Due to the solitons’ behavior where it spectrally expands and compresses cyclically over the CMBG length, as well as the fairly weak CMBG coupling coefficient (\( \kappa = 68 \text{ mm}^{-1} \)), only partial attenuation of the longer wavelengths occur. Though in a sufficiently large extent to reduce the enhancement for overly red-shifted wavelengths in Figure 3, when the operation wave-length is not optimized, notably leading to greater attenuation as the source pulse wavelength becomes too red-shifted.

In addition, there is some insight to be derived by experimentally comparing the spectral width enhancement for 1 and 3 mm CMBGs. Figure 2b shows that the 1 mm CMBG length gives superior spectral enhancement than the 3 mm CMBG. This observation stems from a similar effect as that attributed to the decrease in the spectral enhancement when the source pulse wavelength is too close to the band edge. To shed light on the origin of this phenomenon, we refer to simulations of the spectral and temporal pulse evolution of a soliton with \( N = 2.74 \). Figure 4a,b shows the case where only GVD and SPM is included in the simulation, and third- and higher-order dispersion are not accounted for. In this scenario, no fission is observed. Figure 4c,d shows the pulse evolution where the third- and higher-order dispersion effects are included. We infer, from the simulations results in Figure 4d that for \( L_{\text{CMBG}} = 1 \text{ mm} \), the soliton goes through only one cycle of soliton period (at \( z/L_D = 0.4 \)). The broadening in spectrum coincides with observations of the pulse narrowing in time (Figure 4b). For \( L_{\text{CMBG}} = 3 \text{ mm} \), the pulse cycles through spectral broadening and narrowing multiple times (at \( z/L_D = 0.4 \), and again at \( z/L_D = 1.5 \)), generating longer wavelengths that encroach into the stopband of the CMBG. Consequently, \( L_{\text{CMBG}} = 3 \text{ mm} \) experiences a greater extent of attenuation compared to \( L_{\text{CMBG}} = 1 \text{ mm} \). The different extents of spectral broadening between 1 and 3 mm gratings can also be partially attributed to higher propagation losses in the grating compared to the channel waveguide. In particular, Figure 2b shows that the blue side of the spectrum develops far less extensively for
$L_{\text{CMBG}} = 3 \text{ mm}$ compared with $L_{\text{CMBG}} = 1 \text{ mm}$. It may be inferred that the impact of soliton fission for spectral enhancement is greater for $L_{\text{CMBG}} = 1 \text{ mm}$ for the 1.7 ps input pulses used. An astute choice of source pulse wavelength relative to the band edge, grating length, and their interaction should, therefore, be carefully considered in the overall design.

### 2.3. Pulse Propagation Dynamics and Spectral Coherence

The wideband spectral broadening experienced by pulses propagating through the two-stage device is further studied by solving the generalized nonlinear Schrödinger equation (GNLSE) which is a good approximation in this regime,\(^{[30,31]}\) assuming a slowly varying pulse envelope, $A(z,t)$

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A + i \sum_{k=2}^{6} \frac{\beta_k}{k!} \frac{\partial^k A}{\partial T^k} + i \gamma (|A|^2 A)$$

(1)

where $\beta_k$ represent the higher-order dispersion coefficients, $\alpha$ is the linear attenuation coefficient, $\gamma$ is the nonlinear coefficient, and $|A|^2 A$ is the intensity-dependent term.

Full details of the numerical simulations are provided in the Experimental Section. The presence of anomalous dispersion is essential for observing soliton dynamics, and the high-order soliton regime in the CMBG corresponds to where the nonlinearity dominates the dispersive effects ($L_{\text{NL}} \ll L_D$). Our experimental conditions, $L_D = 1.1 \text{ mm}$ and $L_{\text{NL}} = 0.15 \text{ mm}$, imply a soliton order of $N = 2.74$.

**Figure 5a** shows the numerically calculated output spectrum (blue dashed line) corresponding to the experimental result of Figure 2a. We further investigate the coherence of the generated spectrum, which is crucial for several applications including spectroscopy and as a source for wavelength division multiplexing. In this numerical study, we incorporate one photon per mode (OPN) quantum noise into the input pulse,\(^{[8,33,34]}\) and perform 100 individual simulations using Equation (1). The 100 individual outputs are plotted as the gray envelope in Figure 5a. The spectral coherence of the generated spectrum may be evaluated using

$$|g_{12}(\lambda)| = \left| \frac{E_1(\lambda) E_2(\lambda)}{\sqrt{|E_1(\lambda)|^2 |E_2(\lambda)|^2}} \right|$$

(2)

where $E_{1,2}$ represent individually calculated spectra, calculated as an ensemble average of the 50 total simulated pairs. Figure 5a further plots the calculated coherence of the generated spectrum.

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**Figure 3.** Experimental characterization of wavelength sensitivity of the device. a) Spectrum measured of the source (black), reference waveguide output (red) and 1 mm CMBG ($\lambda_B = 1567 \text{ nm}$) + 1 cm waveguide output (blue) as a function of source pulse wavelength. b) Enhancement factor as a function of wavelength.
Figure 4. Modeled temporal intensity and spectral plots showing the pulse evolution along two dispersion lengths for a soliton with order, $N = 2.74$. a) Temporal and b) spectral pulse evolution where only GVD and SPM effects are present. c) Temporal and d) spectral pulse evolution when higher-order dispersive effects are included. It is observed that soliton fission after initial pulse compression occurs, implying that higher-order dispersion, predominantly TOD triggers soliton fission. The white horizontal dashed line marks $L_{\text{fiss}}$. 

(red line), showing an average calculated coherence $>0.99$. Furthermore, it was previously reported that a smaller soliton order ($N < 10$), as is the case in our experiments where $N = 2.74$, is favorable for achieving an average supercontinuum coherence close to 1.$^{[8]}$

The spectral coherence of the generated spectrum was further characterized using a Michelson interferometer. A collimated beam was split by a beam splitter with both paths incorporating a delay to overlap two different pulses in time. The interfered beams are subsequently coupled back into fiber and measured using an optical spectrum analyzer (OSA). A schematic of the setup used for the coherence measurements is provided in Supporting Information (Figure S2, Supporting Information).

The measured fringes are shown in Figure 5b, where clear fringes with good fringe visibility are observed (blue solid line). This good fringe visibility demonstrates the spectral coherence of the generated supercontinuum. To quantify the degree of coherence, we utilize the expression, $|g_{12}(\lambda)| = \frac{I_1(\lambda)I_2(\lambda)}{\sqrt{I_1(\lambda)I_2(\lambda)}} V(\lambda)$, where $I_1$ and $I_2$ are the optical intensities in the two arms.$^{[16,35,36]}$ and the fringe visibility, $V(\lambda) = \frac{I_{\text{max}}}{I_{\text{min}}}$. Because of the low pump power, coupling losses, and bandwidth limitations of the components used in the Michelson setup, the coherence fringes that could be measured using the OSA are limited to the wavelength range shown in Figure 5b, a phenomenon which has also been reported in other on-chip coherence measurements.$^{[35,36]}$ Nevertheless, the average spectral coherence is experimentally characterized (magenta circles in Figure 5b) to be $>0.92$ across the measured spectrum.

The small soliton order in the first stage is enabled by the large dispersion induced by the Bragg grating, which is more than three orders of magnitude larger than in photonic waveguides. The design of the device can be altered for the best performance for specific starting pulse conditions. For a given pulse width and power, the design principles of the two-stage system involve the following: 1) designing the grating length required for optimum Bragg soliton-effect compression and fission, and 2) designing the waveguide length to be sufficiently long for the spectrum to broaden. Because of the large dispersion in the CMBG, soliton evolution in the CMBG stage varies rapidly.
with propagation length. Therefore, optimal design of the grating length is a critical parameter for the best enhancement. A further study about the effects of input power and pulse width through simulations can be found in the Supporting Information.

In addition, the impact of different waveguide designs may also be inferred from the device performance when different waveguides are used in the second stage. Two-stage devices incorporating the same 1 mm CMBG length and 6 mm waveguide length but different waveguide widths (550 and 650 nm) are fabricated and their spectral enhancement properties are experimentally studied. Note that these devices are identical to that used in Figure 2a, with only the width of the USRN waveguide in the second stage changed. The calculated waveguide dispersion for $W = 550$ nm and $W = 650$ nm is $\beta_2 = -1.5 \times 10^{-3}$ and $-1.0 \times 10^{-3}$ ps$^2$ mm$^{-1}$, respectively. Note that the center wavelength of the gratings for each of these

![Figure 5. Simulated pulse propagation dynamics. a) Numerically calculated spectra for the source pulse (fuchsia dotted), reference waveguide (green dotted). The 100 individual simulations for the 1 mm CMBG + 6 mm USRN waveguide (as used in the experimental results of Figure 2) output is shown as the gray envelope. The simulated output without noise is shown as the blue dashed curve. The calculated coherence as a function of wavelength is shown as the red dotted curve. b) Experimentally measured spectral coherence (magenta circles) and fringes (blue solid line) obtained from interfering two different pulses exiting the device at different times. c) Evolution of 1.7 ps pulses as they propagate through the two-stage device. In this case, the pulse spectrum broadens considerably after the CMBG. d) Evolution of 1.7 ps pulses as they propagate through a 7 mm long CMBG. In this case, negligible spectral broadening is observed.](image-url)
two devices are slightly different, 1566 and 1571 nm for Figure 6a,b, respectively, as a result of the fabrication tolerances involved in the lithographic process. However, the operating wavelengths of the pulses used in each device have the same relative detuning from the center of the grating stopband, consistent with that used in Figure 2a; Consequently, the CMBG dispersion experienced by the pulses is similar. Pulses with a FWHM of 1.7 ps and peak power of 5.5 W are launched into each of these devices. Figure 6a,b shows the spectral broadening experimentally measured for a two-stage device incorporating a waveguide with a width of 650 and 550 nm, respectively. The measured output spectra as the detuning between input pulse wavelength and grating stopband is varied are shown in each figure. The 30 dB bandwidth achieved in the two-stage devices with a W = 650 and 550 nm was 270 and 200 nm (plotted as the magenta curves in Figure 6a,b, respectively). Comparing the spectra measured in Figure 2a and 6, it is observed that W = 600 nm results in the widest spectral enhancement. We note further that the effective area of the mode for both W = 600 nm is similar to that for W = 650 nm and 7% smaller than for W = 550 nm; The smallest nonlinear parameter for W = 550 nm, in turn, contributes to the smaller observed 30 dB bandwidth.

Although the extent of spectral broadening is observed in the experiments to vary somewhat with the waveguide design, our study reveals that the most important determinant of the spectral enhancement lies in ensuring that the grating design is optimum for the pulse conditions. Indeed, from Figure S3, Supporting Information, it can be observed that the 30 dB bandwidth of the output spectrum can increase by as much as threefold when the input peak power increases from 90% to 100% of the optimum value. Conversely, an increase in the waveguide width from 550 nm (Figure 2a) to 650 nm (Figure 6a) results in only a variation of 35% in the 30 dB bandwidth.

Even though the CMBG stage is the critical factor in the performance in the two-stage device, the USRN waveguide stage also plays a role in harnessing the soliton-effects derived from the nonlinear grating. Dispersive wave generation has been shown to considerably extend the bandwidth of supercontinuum generated using ≈100 fs pulses in silicon on insulator waveguides.[16,37] Acquiring increasing amplitude as they propagate through the waveguide, dispersive waves transfer energy from the pulse which propagates as a soliton(s), with their effects strengthening as peak power increases and pulse widths decrease.[38] Consequently, we may infer that future improvements in the generated spectrum may be achieved by two-stage system designs which leverage the CMBG for stronger temporal compression, to attain even shorter pulse widths and higher peak power increase prior to entering the waveguide. These conditions, as well as possible waveguide engineering to generate one or more zero dispersion wavelengths, would be more conducive to generating strong dispersive waves, thereby extending the spectrum. In our experiments, 1.7 ps pulses were used, and these are temporally compressed by the CMBG to a temporal width of 0.55 ps and accompanied by a 2.3× peak power enhancement at the output of the CMBG. With stronger temporal compression in the CMBG stage, dispersive waves could play a more central role in the generated spectrum. We note further that a balance between the compression and losses in the CMBG needs to be carefully considered, to maximize the peak power propagating in the USRN waveguide.

3. Discussion

The efficient generation of supercontinuum in the soliton-fission regime is typically associated with femtosecond pulses. In this work, we demonstrate a considerable enhancement of the spectral bandwidth through the use of Bragg solitons in picosecond regime. SCG in CMOS-compatible waveguides pumped at the 1550 nm region have been demonstrated using silica waveguides, crystalline, and amorphous silicon waveguides and silicon nitride waveguides.[5,12,14–17,39,40] These demonstrations generally require high peak powers, and pulses on the femtosecond scale.

Our work serves as an important step toward taking these sophisticated nonlinear optical effects from benchtop to compact, monolithically integrated devices. To the best of our knowledge, this represents the first demonstration of a fully chip-scale two-stage system where soliton-compression and fission with picosecond pulses are intentionally triggered to enhance the generation of supercontinuum. The CMBG design, including its length, operating regime and apodization profile is specifically tailored to optimize the pulse profile at the output of the CMBG, to maximize the peak pulse power prior to spectral broadening in the nonlinear waveguide. This demonstration is greatly facilitated by the high nonlinear figure of merit in USRN and the strong dispersion in our CMBG (three orders of magnitude larger β2 than in photonic waveguides). Consequently, high soliton-effect compression using picosecond...
pulses can take place over very short lengths (<1 mm) and significantly longer pulses to generate SCG, compared with other SCG demonstrations using soliton effects in conjunction with multistage operation involving fibers\textsuperscript{[31,45]} or conventional single-stage photonic waveguides.\textsuperscript{[15,12,14–17,39,40]} These demonstrations in 1550 nm pumped waveguides generally require high peak powers, and pulses on the femtosecond scale. The noteworthy achievement in this article is the demonstrated use of low-power picosecond pulses for SCG via soliton compression and fission on a fully chip-scale, CMOS-compatible platform; The spectrum is further observed through experiments and simulations to exhibit high coherence. This introduces an important new paradigm for wideband, coherent spectral generation that may leverage significantly longer pulses, than typically used in waveguides for SCG. Through careful choice of the Bragg grating and waveguide lengths and further optimization of the waveguide in the second stage, the ability to use longer pulse widths, and lower powers to generate similar extents of supercontinuum is possible.

With regards to the dispersion design of the CMBG, the coupling coefficient is one of the primary parameters impacting the dispersion properties. A stronger coupling coefficient generates a larger $\left| \frac{\beta}{\beta_0} \right|$\textsuperscript{[46]} In other words, a stronger coupling coefficient results in a smaller magnitude of $\beta_1$ for a given value of $\beta_2$. This quality is important for pulses to access a strong $\beta_2$ without being overwhelmed by distortions from an inordinately large $\beta_1$. The relative strength of $\beta_1$ could be reduced by increasing the coupling coefficient. However, the coupling coefficient of the CMBGs are currently limited by the resolution of the lithographic process. To increase the coupling coefficient further to access a $\left| \frac{\beta}{\beta_0} \right|$ that is even larger would require the gap, $G$ in the CMBGs to be reduced beyond the current value of 50 nm, which is difficult to resolve lithographically. In contrast, the current value of $\beta_1$ is ideal from the standpoint of still allowing both fission and temporal compression to proceed efficiently. Certainly in the current grating design, the TOD is already large enough to trigger soliton fission ($L_{\text{fiss}} < L_{\text{grat}}$ and $\beta_1$ parameter $>\beta_0$), and therefore does not need to be any stronger. If $\left| \frac{\beta}{\beta_0} \right|$ decreases further, more severe pulse distortions from $\beta_1$ can arise, encumbering the efficacy of the spectral enhancement process. Consequently, the current grating dispersion performance is optimal in that the magnitude of $\left| \frac{\beta}{\beta_0} \right|$ governed through the coupling coefficient is large enough for temporal compression to occur efficiently without excessive distortions while still enabling soliton fission to occur.

Finally, we note the qualitative differences between soliton compression/fission occurring in the CMBG and waveguides. First, soliton compression and fission occur on very short length scales in the CMBG (<1 mm) due to the strong Bragg grating-induced dispersion; this facilitates compression and soliton fission for longer pulses on the order of picoseconds. Conversely, soliton compression and soliton fission in conventional single waveguide configurations occur over longer lengths, requiring much shorter initial pulse widths (routinely <100 fs).\textsuperscript{[8]} The strong dispersion induced by the CMBG at the band edge allows us to operate in a regime where the soliton order $N$ is smaller ($N < 10$) even when using picosecond pulses, which ensures that the average coherence of the supercontinuum will be close to 1.\textsuperscript{[8]} Ciret et al. previously reported that substantially different phenomena trigger soliton fission that occurs in the conventional single waveguide configuration with ultrashort pulses.\textsuperscript{[47]} In particular, nonlinear loss was reported to be the dominant perturbation in semiconductor waveguides. Because our platform does not possess nonlinear losses—a quality that preserves the pulse energy, the large TOD induced by the Bragg grating, is the basis of the soliton fission.

4. Conclusion

In summary, we experimentally demonstrated 4.3× spectral-width enhancement using a two-stage device consisting of a 6 mm USRN waveguide preceded by a 1 mm CMBG. By triggering Bragg soliton-effect compression and fission of high-order Bragg solitons prior to propagating in a nonlinear waveguide, the spectral content developed is considerably enhanced. Through wavelength-dependent experiments, the Bragg nature of the soliton dynamics is shown to be the origin of the observed spectral enhancement. Experimental characterization of the spectral coherence reveals an average coherence exceeding 0.92 across the measured output spectrum. This new technique is a promising path toward significantly enhancing wideband spectral broadening, facilitating the use of nonfemtosecond pulses and low peak powers toward SCG, reducing the cost and complexity associated with deploying supercontinuum sources used for imaging, microscopy, and broadband spectroscopy.

5. Experimental Section

Fabrication: The material platform used was back-end CMOS-compatible USRN, which had a material composition of Si$_2$N$_2$. USRN was bandgap engineered ($E_g = 2.1$ eV) to avoid two-photon absorption (TPA), while still having a high Kerr nonlinear index ($n_2 = 2.8 \times 10^{-13}$ cm$^2$/W$^{-1}$) at 1530 nm. The linear refractive index of USRN was 3.1. Fabrication of the CMBGs was performed on a silicon substrate with 10 μm SiO$_2$ thermal oxide layer. First, USRN films with a thickness of 300 nm were deposited using inductively coupled chemical vapor deposition at a low temperature of 250°C. Thereafter, the gratings were defined on the USRN film using electron-beam lithography, inductively coupled plasma etching, followed by 2 μm SiO$_2$ cladding deposition using atomic layer deposition and plasma-enhanced chemical vapor deposition.

Numerical Simulation Details: The generated supercontinuum was further studied by solving the generalized nonlinear Schrödinger equation (GNLSE) which is a good approximation in this regime\textsuperscript{[50–51]} assuming a slowly varying pulse envelope, $A(z,t)$

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A + i \sum_{k=1}^{6} \frac{\beta_k}{k!} \int_{-\infty}^{+\infty} \frac{\partial^6 A}{\partial t^6} + i \gamma |A|^2 A \tag{3}$$

We include dispersion up to the sixth order. The loss parameter, $\alpha = 3.0$ cm$^{-1}$ (13 dB cm$^{-1}$) and 0.80 cm$^{-1}$ (3.5 dB cm$^{-1}$) for the first and second stages, respectively, as characterized using the cut-back method. The nonlinear parameter of the waveguide stage, may be calculated using $\gamma = \frac{\beta_2}{2\pi}$, where $\beta_2 = 2.8 \times 10^{-13}$ cm$^2$/W$^{-1}$ is the nonlinear refractive index of USRN, $\lambda$ is the input pulse wavelength and $A_{in}$ is the effective area of the waveguide mode, calculated using a fully vectorial
The nonlinear parameter of the CMBG is enhanced due to the scaling from the slow-down factor $S = \left( \frac{\alpha}{n_0} \right)^2 = 2.8$. Effects of chromatic dispersion are included through the second term at the right-hand side. The calculated waveguide dispersion further utilizes the USRN material refractive index data measured using Fourier transform infrared spectroscopy. Nonlinear effects such as self-steepening, intrapulse stimulated Raman scattering, and optical shock formation were not included in the simulation, as for relatively wide pulse widths (>1 ps) these effects were negligible.\textsuperscript{[48,49]} In addition, we omitted the TPA and free-carrier (FC) effects due to the absence of the nonlinear losses in USRN films. Nonlinear losses were negligible in USRN at optical intensities up to 50 CW cm\textsuperscript{-2};\textsuperscript{[14]} significantly larger than the power levels used here. Therefore, we only considered the linear propagation losses, $\alpha$.

Experimental Characterization Details: The linear transmission of the device was measured using an amplified spontaneous emission (ASE) source and OSA with a wavelength range from 600 to 1700 nm. The pulses used in the experiment originate from a fiber laser emitting hyperbolic-secant picosecond pulses with a repetition rate of 20 MHz repetition rate. The temporal pulse width of the input pulses is measured using an auto-correlator to be 1.7 ps. The optical pulses were adjusted for quasi-TE polarization before coupling into the CMBG-waveguide structure using tapered polarization-maintaining (PM) fibers. The coupling losses between tapered lensed fiber and the device was 8.5 dB. The output spectra were measured using an optical spectrum analyzer. The schematic of the setup is given in the Figure S1, Supporting Information.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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Research data are not shared.

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