Octave-Spanning Supercontinuum Generation in a Nonlinear Ultra-Silicon-Rich Nitride Waveguide

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Abstract: A 1.2-octave-spanning supercontinuum generation is demonstrated in a 3-mm-long ultra-silicon-rich-nitride waveguide using 17 pJ, 500 fs pulses. The generated supercontinuum possesses a spectral coherence ($|g_{12}|$) exceeding 0.94 on average across the measured wavelength range. © 2022 The Author(s)

1. Introduction
Supercontinuum generation (SCG) has been extensively investigated in many on-chip platforms, including silica [1], silicon [2] and silicon nitride [3]. Ultra-silicon-rich-nitride (USRN) possesses a large linear refractive index (3.1), high Kerr nonlinearity ($2.8 \times 10^{-13} \text{ cm}^2 \text{ W}^{-1}$) and large bandgap (2.1 eV), making it an ideal platform for nonlinear photonics [4, 5]. In this paper we demonstrate octave-spanning supercontinuum, extending from 1006 nm to 2240 nm in a 3-mm-long USRN waveguide using 500 fs pulses with a low pulse energy of 17 pJ. Experimental spectra show good agreement with simulations. The spectral coherence of generated supercontinuum was further experimentally characterized to have an average $|g_{12}|$ exceeding 0.94.

2. Numerical calculations and experimental characterization
The schematic of experimental setup for supercontinuum generation in the USRN waveguide is shown in Fig. 1(a). In the experiment, a mode-locked femtosecond fiber laser is utilized to launch 500 fs pulses with a repetition rate of 20 MHz centred at 1555 nm, followed by an erbium-doped fiber amplifier (EDFA). The pulses are then adjusted for quasi-TE polarization before coupling into the waveguide using tapered lensed fibers. The coupling losses are ~6 dB per facet. Two different optical spectrum analyzers (OSAs) are used to monitor the output spectra, one for the range from 800 to 1750 nm, and the other for the range from 1600 to 2400 nm.

Fig. 1(b) shows the measured supercontinuum at different pulse energies coupled into the USRN waveguide. From Fig. 1(b), the spectral broadening increases with pulse energies and dispersion waves can be clearly seen at both the short wavelength side (~1000 nm) and long wavelength side (~2200 nm) at higher pulse energies. At 17 pJ, a 1.2-octave-spanning supercontinuum, from 1006 to 2240 nm at 40 dB below the peak of the spectrum, is obtained.

Fig. 1. (a) Schematic of the experimental setup for supercontinuum generation in the USRN waveguide, where blue lines denote the polarization maintaining fibers, where FFL: femtosecond fiber laser, EDFA: erbium-doped fiber amplifier, DUT: device under test, OSA: optical spectrum analyzer. (b) Measured and (c) Simulated supercontinuum at different pulse energies coupled into the USRN waveguide.
The pulse propagation dynamics in the USRN waveguide were simulated by solving the generalized nonlinear Schrödinger equation (GNLSE) with split-step Fourier method, as shown in Eq. (1),

$$\frac{\partial A}{\partial z} = \sum_{k=2}^{7} \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A}{\partial t^k} - \frac{\alpha}{2} A + i\gamma(1 + i\tau_{\text{shock}}) \frac{\partial}{\partial t} \left( |A|^2 A \right)$$

(1)

where $A(z, t)$ is the slowly varying pulse envelope, a good approximation in this regime. Same input pulse parameters were used in the simulation as the experiment. In the experiment, we considered dispersion, linear self-phase modulation and self-steepening effects, where $\beta_k$ is the $k$th order dispersion coefficient, $\alpha$ is the linear loss, a value obtained experimentally, $\tau_{\text{shock}} = 1/\omega_0$ is the shock coefficient and $\gamma$ is the nonlinear parameter. Simulated output spectra at the same coupled pulse energies are plotted in Fig. 1(c). The simulated spectra in Fig. 1(c) show similar broadening trends and dispersive wave positions with the experimental results in Fig. 1(b).

Next, we characterized the coherence of generated supercontinuum in the 3-mm-long USRN waveguide, using a Michelson interferometer. The setup used is shown in Fig. 2 (a). Fig. 2 (b) shows the experimentally measured spectral coherence (red circles) and fringes (blue line). In Fig. 2 (b), the clear fringes with good fringe visibility demonstrate the spectral coherence of the generated supercontinuum. The degree of coherence can be quantified with a parameter $|g_{12}(\lambda)|$, calculated using $|g_{12}(\lambda)| = \left| (I_1(\lambda) + I_2(\lambda)) V(\lambda) / (2\sqrt{I_1(\lambda) I_2(\lambda)}) \right|$, where $I_1(\lambda)$ and $I_2(\lambda)$ are the optical intensities in the two arms of the interferometer, and $V(\lambda)$ is the fringe visibility obtained through the equation $V(\lambda) = (I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}})$. Due to the low pump power, the high coupling losses from free space to fiber, and the bandwidth limitations of components used in the Michelson interferometer, the coherence fringes that could be observed using the OSA is limited to the wavelength range shown in Fig. 2 (b). Nevertheless, the average spectral coherence $|g_{12}|$ is characterized to be $> 0.94$ across the measured spectrum.

Fig. 2. (a) Setup used for the coherence measurements. (b) Experimentally measured spectral coherence (red circles) and fringes (blue line).

3. Conclusions
In conclusion, we demonstrated an octave-spanning supercontinuum generation extending from 1006 to 2240 nm at the –40 dB level in a 3-mm-long USRN waveguide. The broadening is achieved using 500 fs pulses centred at 1555 nm with a low pulse energy of 17 pJ. The spectral broadening is caused by self-phase modulation, soliton fission and dispersive wave generation. Good agreement is obtained between the experimental and simulation results based on the generalized nonlinear Schrödinger equation. We also experimentally characterized the spectral coherence of the generated supercontinuum, and an average coherence exceeding 0.94 is obtained across the measured spectrum. The generated broadband spectra using 500 fs pulses possessing high spectral coherence provides a promising route for CMOS-compatible light sources for self-referencing applications, metrology and imaging.

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