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# Octave-spanning Supercontinuum Generation in a Silicon-rich Nitride Waveguide

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**Abstract:** We generate supercontinuum (817 – 2250 nm at -30dB) in a dispersion-engineered silicon-rich nitride waveguide by pumping fs pulses with 82 pJ from an erbium-fiber oscillator. Spectral broadening mechanisms include soliton fission and dispersive wave generation.

**OCIS codes:** (130.2790) Integrated optics: nonlinear; (130.2755) Glass waveguides; (190.7110) Ultrafast nonlinear optics

## 1. Introduction

Silicon nitride is a material platform highly suitable for nonlinear optics applications. The nonlinear coefficient in bulk is ten times larger than silica glass and its transparency window covers from the UV to  $> 6 \mu\text{m}$ . This material does not display two-photon absorption in the telecommunications wavelength band and waveguides can be manufactured with very low propagation losses. Nonlinear applications demonstrated so far include microresonator comb generation [1], supercontinuum generation [2-4], continuous-wave pumped wavelength conversion [5] and other high-speed optical signal processing (reviewed in [6]).

Critical to the above applications is the ability to tailor the dispersion in waveguides. This is usually realized by manipulating the cross-section geometry. However, in order to overcome the inherent strong normal dispersion of silicon nitride at wavelengths below  $2 \mu\text{m}$ , the waveguide must be thick ( $> 500 \text{ nm}$ ). This introduces challenges in the fabrication owing to high tensile stress in the films. Advanced processing solutions include the patterning of barriers [7] and horizontal layer growth in trenches [8] to avoid crack formation in the waveguide's core material. Supercontinuum generation with femtosecond pulses [2,9] has been recently reported using these novel fabrication methods. The broadband light is sufficiently coherent to measure the carrier-envelope-offset frequency [10], an important goal for frequency comb metrology.

A different path for dispersion engineering in silicon nitride waveguides was recently adopted, namely by varying the stoichiometry of the film [11]. In particular, with a relatively higher proportion of silicon with respect to nitride, we found a higher refractive index, nonlinear Kerr coefficient and lower stress than with stoichiometric silicon nitride films, resulting in strong light confinement and high nonlinearity. Here, we show supercontinuum generation in a silicon-rich nitride waveguide pumped by femtosecond pulses. The supercontinuum spans more than 1.5 octaves and it uses pulses with very little energy ( $< 100 \text{ pJ}$ ), similar to state of the art experiments [10]. This is possible in part due to the low linear propagation loss and in part due to the high nonlinear coefficient. An important difference of our work with respect to other results [2,3,9,10] is that the pump pulses are at  $1.5 \mu\text{m}$ , which allows for extending the supercontinuum deeply into the short-wave infrared. These results offer the prospect of using silicon-rich nitride waveguides for generating short- and mid-infrared radiation using erbium-doped fiber technology.

## 2. Experimental results

### 2.1. Dispersion engineering in silicon-rich nitride waveguides

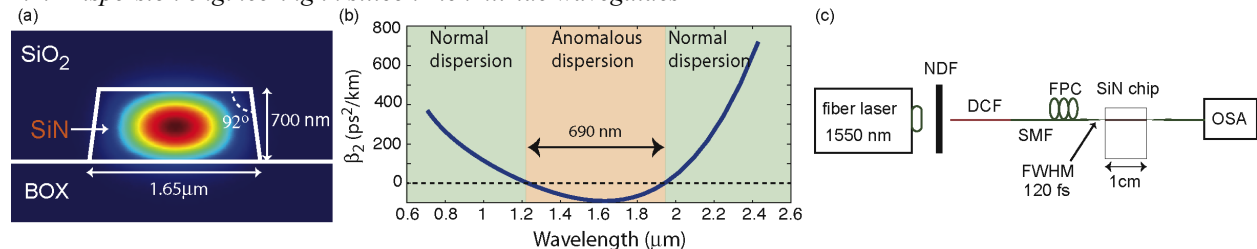


Figure 1. (a) Sketch of cross-section geometry and modal confinement of power for fundamental quasi-TE mode; (b) numerical calculation of group velocity dispersion for the waveguide structure shown in (a); (c) sketch of experimental setup for supercontinuum generation. NDF: neutral density filter; DCF: dispersion compensating fiber; SMF: single-mode fiber; FPC: fiber polarization controller; OSA: optical spectrum analyzer.

The fabrication and analysis of the silicon-rich nitride waveguides is reported in [11]. Briefly, the non-stoichiometric silicon nitride (SiN) film is fabricated in a low-pressure chemical vapor deposition process on top of a buried oxide layer (BOX). Standard deep UV lithography and dry etching are used to pattern the waveguide. The silica cladding

(SiO<sub>2</sub>) is manufactured in a plasma-enhanced chemical vapor deposition process step. The waveguides feature losses  $\sim 1$  dB/cm and a Ker parameter  $\gamma \sim 7$  (Wm)<sup>-1</sup> around 1.5  $\mu$ m. The waveguide dimensions are displayed in Fig. 1(a). The slight tilt in the sidewalls is a consequence of the etching process. The effect is included in the numerical simulations of dispersion shown in Fig. 1(b). A broad region with flat and moderate anomalous dispersion spanning 690 nm is obtained, as desired for efficient supercontinuum generation.

## 2.2. Supercontinuum generation

The setup for supercontinuum generation is displayed in Fig. 1(c). A commercial femtosecond fiber laser produces  $\sim 100$  fs pulses at 1550 nm with  $\sim 90$  MHz repetition rate, which are free-space coupled into the DCF by using an objective lens. The DCF compensates for the chirp accumulated in the remaining chain before the waveguide. Neutral density filters are used to control the pulse energy, and the polarization is set to the quasi-TE with an FPC. This is followed by a piece of SMF spliced to a tapered lensed fiber, which focuses to a spot size of around 2  $\mu$ m FWHM. The pulse duration was here measured with an intensity autocorrelator to around 140 fs, revealing some remaining chirp in the pulse. The coupling loss is estimated at  $-6$  dB per facet, leading to an estimated maximum total power inside the waveguide of 7.4 mW. The output from the waveguide is collected with a lensed fiber and sent to an optical spectrum analyzer (OSA). To record the entire supercontinuum spectrum, we utilized two OSAs with spectral ranges 600–1700 nm and 1200–2400 nm. These spectra are overlapped to get the final spectrum.

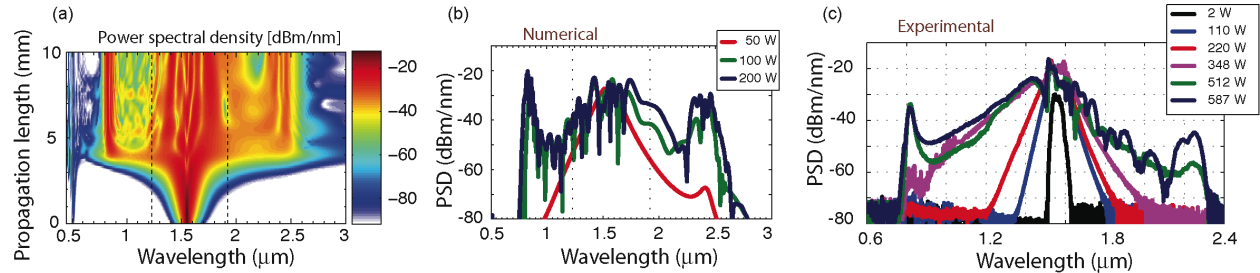


Figure 2. (a) Numerical analysis of a 100 fs pulse propagation inside silicon-rich nitride waveguides. The two white dashed lines indicate the zero-dispersion wavelengths. (b) Expected supercontinuum output at different coupled peak powers; (c) measured optical spectra at corresponding coupled peak powers.

The numerical simulation in Fig. 2(a) is based on a generalized nonlinear Schrödinger equation for the fundamental mode and includes the waveguide's dispersion, nonlinear Kerr response, propagation loss, self-steepening and third-harmonic generation. Raman scattering is not considered since it is weak in silicon nitride. The expected output spectra after 1 cm of propagation in the silicon-rich nitride waveguide for different powers are displayed in Fig. 2(b). The time-frequency dynamics indicates soliton fission and the generation of two dispersive waves located in the 750 and 2400 nm, where the waveguide displays normal dispersion. These spectral signatures can be recognized in the measured supercontinuum for a coupled peak power of 587 W (or 82 pJ).

## 3. Conclusions

We have generated supercontinuum spanning  $> 1.5$  octaves (from 817 – 2250 nm at  $-30$  dB) by pumping a dispersion engineered silicon-rich nitride waveguide. The dispersion is controlled by varying the stoichiometry of the film and the cross-section geometry of the waveguide. The pulses have relatively low energy (up to 82 pJ) and are obtained from a commercially available erbium-fiber oscillator. These results open the prospect to generate short and mid-IR in a CMOS-compatible waveguide by exploiting the mature erbium-fiber technology.

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