Nonlinear optics in ultra-silicon-rich nitride devices

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ABSTRACT

Ultra-silicon-rich nitride (USRN) is a CMOS-compatible material grown at low temperatures. Due to their high silicon content and relatively large material band gap, USRN possesses a high Kerr nonlinearity, two orders of magnitude larger than in stoichiometric silicon nitride while possessing negligible two-photon absorption at telecommunications wavelengths. As such, USRN is highly suitable for nonlinear optics in silicon-based devices. In this paper, we report recent developments in the demonstration of nonlinear optical phenomena in USRN devices. We report Bragg soliton dynamics such as observations of gap solitons and optical parametric Bragg amplification, as well as high spectro-temporal compression implemented on USRN.

Keywords: Nonlinear integrated optics, ultra-silicon-rich nitride, Bragg solitons.

1. INTRODUCTION

Nonlinear optics in silicon-based devices is of particular significance due to their ability to be fabricated using complementary metal-oxide semiconductor processes prolific in electronics, enabling economic, wide scale manufacturability. While the silicon-on-insulator platform has seen significant success in the implementation of large scale photonic integrated circuits, their use for nonlinear optics at telecommunications wavelengths is encumbered by two-photon and free-carrier losses. Crystalline silicon has a material band gap of 1.1eV which implies a two-photon edge of 2.2μm. Conversely, stoichiometric silicon nitride has negligible nonlinear losses at telecommunications wavelengths but a considerably lower Kerr nonlinearity than crystalline silicon. Ultra-silicon-rich nitride is a low temperature, chemical vapor deposition grown CMOS-compatible material with an engineered material band gap of 2.1eV, circumventing nonlinear losses at the full telecommunications band. Its high silicon content enables it to maintain a Kerr nonlinearity which is two orders of magnitude larger than in stoichiometric silicon nitride. USRN has been used successfully in a variety of nonlinear optics applications, including high spectro-temporal compression, Bragg soliton phenomena and topological photonics. We report these experimental demonstrations in this paper.

2. NONLINEAR OPTICAL PHENOMENA IN ULTRA-SILICON-RICH NITRIDE DEVICES

Optical solitons form from the balance between optical nonlinearity and group velocity dispersion. In Bragg gratings, one dimensional periodic structures, the optical nonlinearity works in tandem with the grating induced dispersion on the stopband edge to give rise to Bragg solitons [1]. Cladding modulated Bragg gratings utilize pillars which are placed periodically along a central waveguide to give rise to the effective index modulation [2-6]. The gap between the pillars and the central waveguide may also be modulated in order to apodize the grating, eliminating transmission and phase ripple. Bragg soliton-effect compression and fission have previously been demonstrated using CMBGs. The modified dispersion and effective index profile on the grating stopband edge may be used advantageously for enhanced phase matching in parametric processes. An optical parametric Bragg amplifier was designed to leverage the elevated effective index induced by the red side of the grating stopband edge. The enhanced phase matching improved the parametric gain by 7dB over a waveguide [4].

The high Kerr nonlinearity in USRN may be advantageously combined with the grating's optical properties to give rise to gap solitons. Gap solitons refer to the class of Bragg solitons with solutions within the stopband. We have experimentally observed gap solitons on a chip and associated signatures such as slow light, temporal compression and intensity dependent transmission. Figure 1 (d) shows the experimentally measured temporal delay of optical pulses as the input peak power is increased. As the power increases, the Kerr effect results in a red shift in the grating stopband and induces light which is originally at the stopband edge where the group index is large, to shift into the region where the group index is smaller. This results in a difference in the velocity of light – We experimentally observed slow light that is 35% the speed of light in vacuum, equivalent to a one-fifth reduction in the group velocity compared to a USRN photonic waveguide [6].

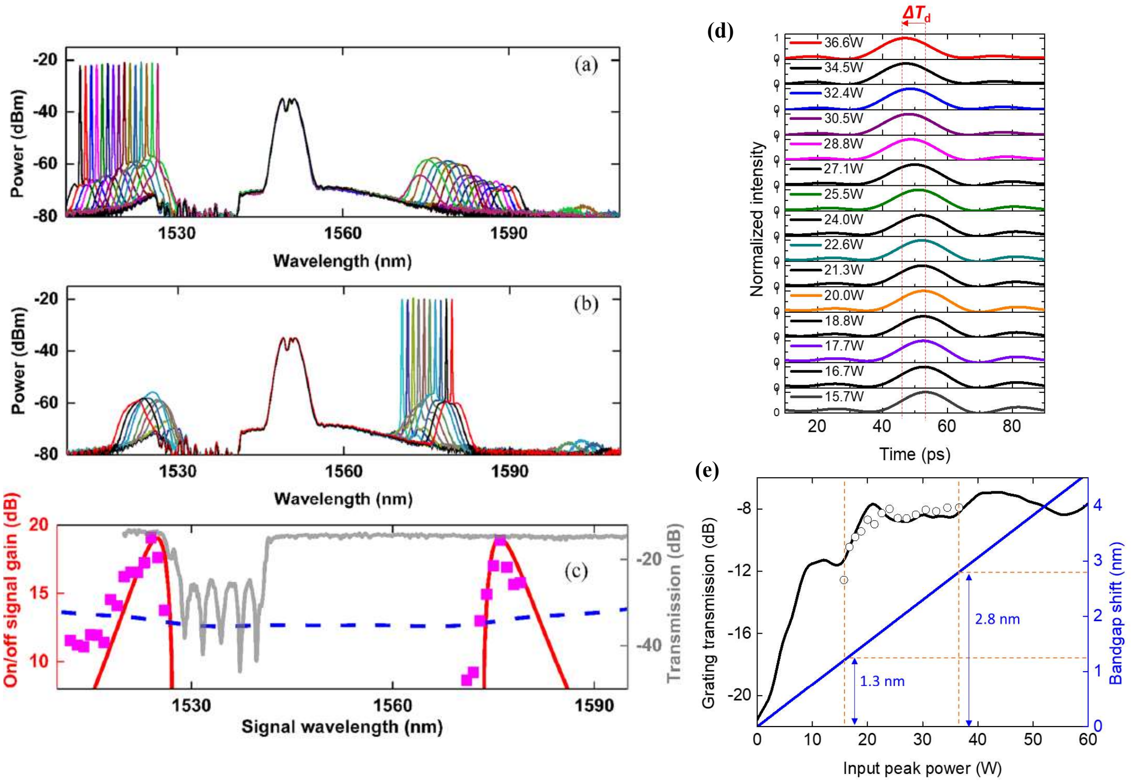

Fig. 1 (a) OPBA FWM spectra for a signal wavelength of (a) 1512–1526 nm and (b) 1570–1579 nm. (c) Signal gain (on/off) (pink dots) are compared with theoretical curves in the CMBGs (red line) and WG (blue dashed). (d) Temporal delay of optical pulses as a function of input peak power. (e) Measured output power vs. input pulse power (empty circle dots). This is compared with the CMBG transmission. The blue line denotes the bandgap shift.

Bragg solitons are one approach for achieving the temporal compression of optical pulses. In this approach, the dispersion and nonlinearity are distributed over the propagation medium. Another approach for the compression of optical pulses involves decoupling the optical nonlinearity and dispersion [7]. Figure 2a shows the schematic of a two-stage device which may be used for temporal and spectral compression. For temporal compression, pulses enter the nonlinear stage first where they undergo self-phase modulation. Subsequently, the chirped pulses are rephased in the dispersive stage. We have demonstrated a maximum compression factor of 11x is achieved for 5.8 ps pulses at a low power of 13.3W, accompanied by an increase in the pulse peak power by 9.4x (Fig. 2b – d). To achieve spectral compression, pulses first enter the dispersive stage where spectral phase is introduced to the pulses. The pulses then propagate through the nonlinear stage, where self-phase modulation causes the temporally faster (slower) frequencies to experience a downshift (upshift) in frequency, resulting in spectral compression. We experimentally demonstrate 3.0x spectral compression of 480fs pulses (Fig. 2e – g).

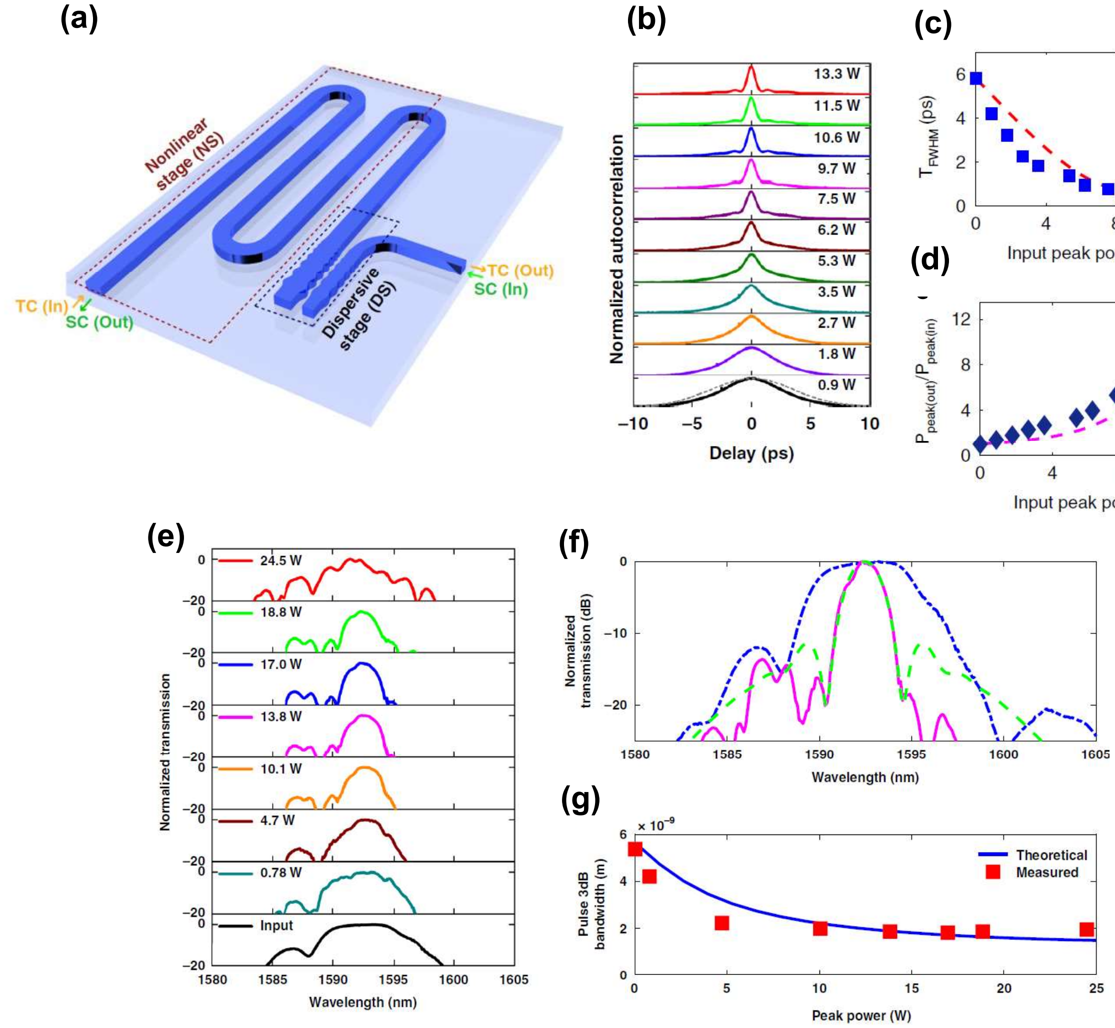

Figure 2. (a) Schematic of the high spectro-temporal compression system. (b) Measured autocorrelation traces, (c) compressed pulse width (TFWHM) and (d) increase in output pulse peak power $\left(\frac{P_{peak(out)}}{P_{peak(in)}}\right)$ for 5.8 ps pulses as a function of input peak power. (e) Measured spectrum as a function of input peak power for 480 fs input pulses. (f) Measured spectrally compressed pulse (fuchsia line) and input pulse (blue line) spectrum, and numerically calculated spectrally compressed pulse spectrum (green). (g) The experimentally measured and theoretical pulse bandwidth as a function of input peak power.

3. CONCLUSIONS

We have reported recent progress made using USRN devices for nonlinear optics. As a result of the large Kerr nonlinearity and negligible nonlinear losses at telecommunications wavelengths, a variety of nonlinear phenomena may be observed and implemented. The application of USRN in nonlinear topological photonics is an area of active research, yielding insights into how the Kerr effect may be used to control optical effects implemented in topological structures [8-11]. Future work which harnesses the advantageous properties of USRN may lead to new types of nonlinear optical devices and low power observations of novel nonlinear optical phenomena.

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