Nonlinear optical characterization of deuterated silicon-rich nitride waveguides

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Abstract: Nonlinear optical characterization of Silicon-Rich Nitride waveguides fabricated using deuterated silane are presented. Fourier Transform Infrared Spectroscopy reveals the absence of Si-H and N-H related bonds known to cause optical absorption close to a wavelength of 1550nm.

1. Introduction

Ultra-Silicon-Rich Nitride is a promising platform for optical devices operating axt the telecommunications wavelengths due to the absence of two-photon absorption above wavelengths of 1.2 µm and large nonlinear refractive index [1]. It is commonly known that Si-H and N-H bonds result in an absorbance peak around the telecommunications band at a wavelength close to 1.55 µm and are therefore sources of transmission losses [2, 3]. In this manuscript, we report the fabrication and experimental characterization of deuterated silicon-rich nitride (SRN-D) waveguides. The films are deposited using deuterated silane (SiD_4) instead of SiH_4 to eliminate Si-H bonds, and N_2 gas instead of NH_3 to eliminate N-H bonds. The replacement of Si-H bonds with Si-D bonds shifts the bond absorbance overtones to 2 µm, thus reducing the material absorption to 1.55 µm [4].

2. Experimental Characterisation

Fabrication of the SRN-D waveguide devices is performed by first depositing an SRN-D film of thickness 310 nm using plasma enhanced chemical vapor deposition on a silicon substrate with 3 µm SiO_2 thermal oxide layer. The waveguides are subsequently patterned using electron-beam lithography and reactive ion etching. Deposition of 2 µm of SiO_2 cladding is performed to form the upper cladding of the waveguides.

In order to characterize the deposited SRN-D films, Fourier-Transform Infrared Spectroscopy (FTIR) measurements were conducted to determine the presence of Si-H and Ni-H bonds from the fabrication process (fig 1a). Si-H and N-H bonds have an absorbance around 2082 cm^{-1} and 3390 cm^{-1} respectively, and the observed absence of an absorbance peak in this band within the results indicates the absence of Si-H and Ni-H bonds in the fabricated devices. FTIR measurements further reveal that the SRN-D films have a linear refractive index of 2.5. 1e shows the cutback measurement results for both TE and TM modes of the waveguide with a cross section of 800 nm by 310 nm. The propagation losses achieved for the TE and TM mode were 4.15dB/cm and 5.95dB/cm respectively.

Next, self-phase modulation (SPM) experiments were conducted to determine the nonlinear parameter and Kerr nonlinearity of the SRN-D material. 1.3 ps pulses at a wavelength of 1550 nm were launched into waveguides with a length of 6.9 mm and the degree of phase modulation due to SPM analyzed (fig 1c). 1c shows the output spectra of the 1.3 ps pulses as a function of input peak power, where the characteristic SPM-broadening is observed. The nonlinear parameter was then determined using the equation $\phi_{\mathrm{NL}} = \gamma P_0 L_{eff}$. Here, γ is the nonlinear parameter, P_0 is the peak power of the input pulse, and $L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$ (fig 1d). From the experiments, the extracted $\gamma = 95\ \mathrm{W^{-1}m^{-1}}$ and $n_2 = 9.8 \times 10^{-18}\ \mathrm{m^2W^{-1}}$ for a calculated effective modal area, A_{eff} of $4.2 \times 10^{-13}\ \mathrm{m^2}$.

Subsequently, a series of ring and racetrack resonators were fabricated with varying waveguide widths and gaps. The transmission spectrum of the resonators were obtained using an Optical Spectrum Analyzer and a wide-band continuous wave source at a spectrum of 1520 nm-1620 nm. Dips in the transmission spectrum of the resonators were fitted to a Lorentzian function (fig 1e) to obtain their Full-Width Half-Maximum (FWHM) values for determination of the quality factor. Of the devices, ring resonators of round-trip length 0.314 mm, waveguide width 0.85 µm, and gap 0.3 µm yielded the highest load quality factor at 62,000. The intrinsic quality factor Q_{int} can be calculated using $\frac{2Q_L}{1+\sqrt{T_0}}$ [5], where Q_L is the loaded quality factor and T_0 is the fractional transmission at the resonance, corresponding to an intrinsic quality factor of 64,700.

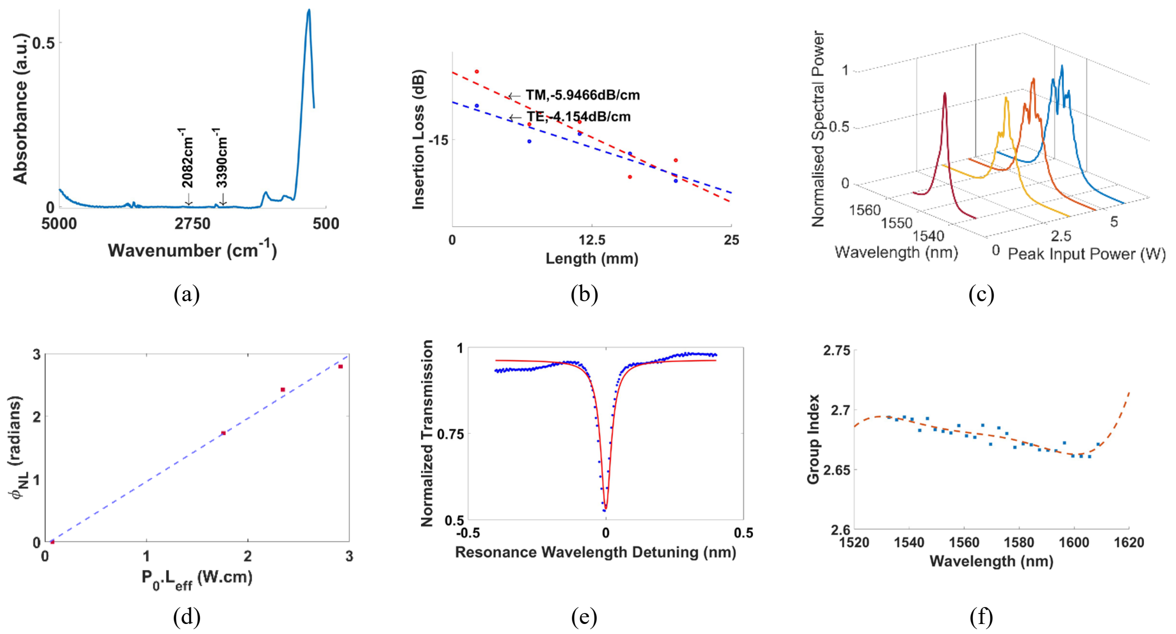

Fig. 1: (a) Absorbance Spectrum (b) Insertion Loss from Cutback Measurements. TM Mode(–) and TE Mode(–) (c) SPM Spectrum plots for peak input powers 5.9 W (–), 4.7 W (–), 3.6 W (–), and source (–) (d) Nonlinear Parameter fit for experimental data (■) and fitted line (–) (e) Sample Lorentzian fit for experimental data (■) and fitted curve (–) (f) Group Index of ring resonators of radius 50 µm. Exp data (■) and fitted curve (–).

To determine waveguide dispersion, the group index of the resonators was determined using $n_g = \frac{\lambda^2}{FSR \times L}$ (fig 1f), following which the β_2 dispersion parameter was calculated using $\beta_2 = -\frac{\lambda^2}{2\pi c^2}\left(\frac{dn_g}{d\lambda}\right)$. Experimental results and subsequent simulation results suggest that the waveguides with this thickness are unlikely to achieve anomalous dispersion exclusively using a variation of waveguide widths.

3. Conclusions

We have introduced a deuterated silicon-rich nitride platform which has been confirmed using FTIR measurements to not contain Si-H or N-H bonds in the deposited film. The film is deposited using a backend CMOS-compatible process at a low temperature of 350 °C using plasma enhanced chemical vapor deposition using SiD_4 gas and N_2 gas. Nonlinear characterization reveals a nonlinear parameter and nonlinear refractive index of 95 $W^{-1}m^{-1}$ and 9.8×10^{-18} m^2W^{-1} respectively. The absence of Si-H bond related absorption in the SRN-D films could enable lower overall propagation losses to be achieved compared to films deposited with regular silane gas while retaining the large optical nonlinearities that have come to be associated with silicon-rich nitride devices.

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