Efficient mid-infrared dispersive wave generation in dispersion-engineered Si_3N_4 waveguides pumped at 2 µm

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Abstract: We demonstrate efficient generation of mid-infrared dispersive wave at 3.5 µm in a Si_3N_4 waveguide pumped by a 2090nm femtosecond mode-locked fiber laser. The 8% maximum efficiency allows for a milliwatt-level average power mid-infrared pulse.

OCIS codes: Nonlinear optics, integrated optics (190.4390), Nonlinear optics (190.0190)

1. Introduction

On-chip, multi-octave spanning supercontinuum sources based on dispersion engineered stoichiometric Si_3N_4 waveguides have been recently shown great potential for spectroscopy and frequency metrology applications in the near infrared (near-IR) [1-3]. Apart from the strong light confinement, transparency from visible to mid-infrared (mid-IR) and high nonlinearity, chip-integrated Si_3N_4 waveguides constitute a miniature-size photonic platform which exhibits remarkable flexibility in terms of dispersion engineering. However, there is a demanding need for pushing the limits of chip-based sources to the Mid-IR [4-6], where the strongest roto-vibrational molecular transitions lie. Dispersive wave generation (DWG) can coherently transfer energy from a near-IR mode-locked laser (MLL) pump to the mid-IR in very short waveguides, when the correct dispersion parameter is provided and phase matching condition is achieved. The ability to control the dispersion of Si_3N_4 waveguides with lithographic precision allowed to carefully set the frequency of the DWG in the mid-IR neighborhood when a telecom band MLL is employed [6]. However, limitation in the conversion efficiency, resulting in low power transfer to the dispersive wave (DW), still prevents the use of such techniques in applications.

In this work we demonstrate that such limitations in the DWG conversion efficiency can be overcome by red-shifting the pump while maintaining the desired phase-matching conditions. We use a 2090 nm femtosecond fiber MLL to pump a dispersion engineered Si_3N_4 waveguide with large cross-section optimized for mid-IR light guiding. This kind of approach, based on a turn-key fiber laser source, reaches a DWG efficiency of 8%. The resulting milliwatt-level average power mid-IR pulse appears to be an attractive integrated source for comb spectroscopy applications in the mid-IR region [7].

2. Experimental implementation

The experimental setup is presented in Fig. 1(a). The pump is a commercial soliton self-frequency shifted Thulium-doped fiber MLL (Brevity λ+, NOVAE) with pulse duration (FWHM) of ~90 fs and repetition rate 19 MHz. Light is coupled in and out of the inverse taper mode converters of the Si_3N_4 waveguide using two aspheric chalcogenide lenses. The total losses are estimated to be ~10.8 dB for the TM fundamental mode. The spectra are measured by a Fourier-transform infrared (FT-IR) spectrometer. The 5 mm long waveguide fabricated using the photonic Damascene process [8] features 0.2 dB/cm linear losses. The fabrication process allows for large core dimensions of 1.1 µm width and 2.15 µm height (Fig.1 (b)).

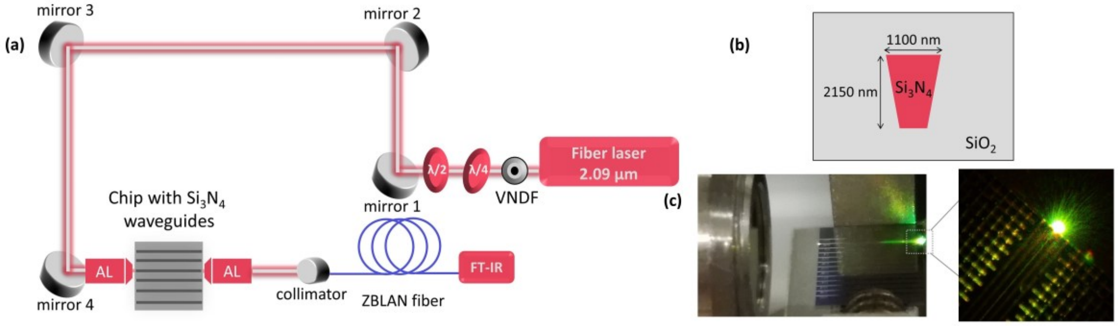

Fig.1(a). Schematic of the experimental setup where λ/2 (half waveplate), λ/4 (quarter waveplate) control the input light polarization and couple the pump onto the TM mode. VNDF: variable neutral density filter, AL: black diamond achromatic lens (b) Schematic cross section of large-core Si_3N_4 waveguides fabricated utilizing photonic Damascene process (c) Picture of the setup during operation at maximum coupled power with the soliton fission point clearly visible after ~3mm. Close up view of chip output facet (right).

3. Results and discussion

Wavelength conversion of the 2.09 µm pump is achieved through soliton-induced DWG within the supercontinuum process in the large cross-section Si_3N_4 waveguides. These waveguides are designed to feature anomalous dispersion at the pump wavelength and to satisfy the phase-matching condition between the 2.09 µm solitonic pump and two DWs located in the visible and the mid-IR [6]. The measured output spectra for different values of coupled input average power are shown in Fig.2(a). Above the threshold of 6.8 mW the DWG near 3.5 µm is observed. Fig. 2(b) shows the simulated spectrum for 10.7 mW injected power and the integrated dispersion with the DWG phase-matching points. Simulations are in good agreement with experiments, predicting accurately the position of the DWs. Below the threshold, the soliton number is small and the temporal pulse compression is insufficient for the soliton to spectrally cover the phase-matching region for DWG. Beyond this power level, the soliton sheds a part of its energy to the phase-matched DWs before the end of the waveguide (Fig.1(c) and 2(c)). Once again the simulations and experiments are in good agreement, with soliton fission near the 3mm mark of propagation and green light from the visible DW being observed. To quantify the conversion efficiency of the mid-IR DWG, a long pass filter with cut off at 2.5 µm is placed after the output lens. The power coupled into the DW is estimated as the ratio of mid-IR power over the total output power (soliton power and mid-IR DW power, as the black diamond lens absorbs visible radiation). For a coupled pump power of 17.4 mW, the DW reaches 8% of efficiency, meaning a DW average power of 1.4 mW inside the waveguide, corresponding to 0.41 mW in the Mid-IR out of the chip which is suitable for spectroscopic applications [7].

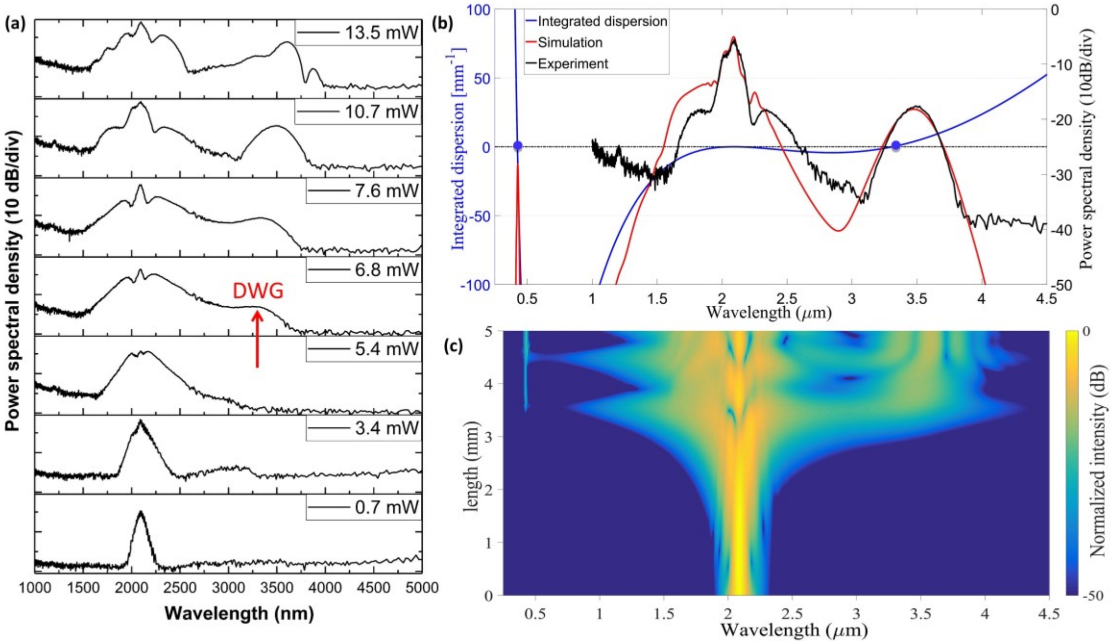

Fig. 2. (a) Dispersive wave evolution in the w=1.10 µm, h=2.15 µm Si_3N_4 waveguide for TM mode measured for different pump powers. (b) Simulated (red) and measured (black) supercontinuum spectrum for 10.7 mW coupled power, and simulated integrated dispersion (blue) with phase-matching points. (c) Evolution of the supercontinuum spectrum as a function of the propagation.

In summary, we experimentally showed that we can overcome the limitations of conversion efficiency affecting mid-IR DWG by red-shifting the pump. The efficiency is improved while still relying on a turn-key fiber source. This result, combined with the accurate control of the waveguide dispersion that can be achieved only in photonic integrated chips, makes Si_3N_4 waveguide platforms good candidates for compact spectroscopy devices.

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