GHz-rate positive conversion efficiency via FWM in multi-layer SiNx/a-Si:H waveguides

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Abstract: We demonstrate high-speed positive FWM conversion efficiency (CE) at 1-GHz repetition rate in a multi-layer platform of SiNx/a-Si:H waveguides. Positive CE is first measured at a peak pump power of 2-W, with up to 5-dB positive CE (corresponding to 6.2-dB of signal gain) at 3.35-W.

1. Introduction

The field of nonlinear silicon photonics has resulted in many exceptional demonstrations including broadband wavelength conversion [1], high speed signal measurement [2], the generation of heralded photons [3], high-speed all-optical demultiplexing [4], and countless others. Hydrogenated amorphous silicon (a-Si:H) has become an effective material for use in nonlinear silicon photonics due to having a Kerr coefficient that is an order of magnitude larger than crystalline silicon [5]. In general, there is a trade-off between high effective nonlinearity and low propagation losses in a-Si:H waveguides. Recent work in our group has been performed to greatly reduce the on-chip propagation losses associated with a-Si:H devices by combining low-loss silicon nitride (SiNx) waveguides with highly nonlinear a-Si:H waveguides in a multi-layer platform [6]. The fabrication of such devices is aided by the fact that a-Si:H films can be deposited at low temperatures (~300°C) using chemical vapor deposition, making it highly back-end compatible with CMOS electronics and ideal for 3-dimensional integrated photonic devices [6].

High-speed optical parametric amplification has typically been difficult to achieve in crystalline silicon waveguides due to the deleterious effects of two-photon absorption and free-carrier absorption at telecommunication wavelengths. Hydrogenated amorphous silicon has been shown to have a much higher nonlinear figure of merit, which is proportional to the ratio of the Kerr coefficient (n_2) to the two-photon absorption coefficient (β_{TPA}). As a result, parametric amplification has been demonstrated in a-Si:H waveguides at laser repetition rates as high as 1-GHz [7]. However, for applications such as on-chip GHz-rate optical parametric oscillators or photon-pair generation, it is essential to demonstrate optical parametric gain in a platform with extremely low propagation losses. Here we measure positive conversion efficiency (indicating optical parametric gain) via degenerate four-wave mixing (FWM) at 1-GHz repetition rate in a multi-layer platform consisting of low-loss SiNx waveguides and highly nonlinear a-Si:H waveguides.

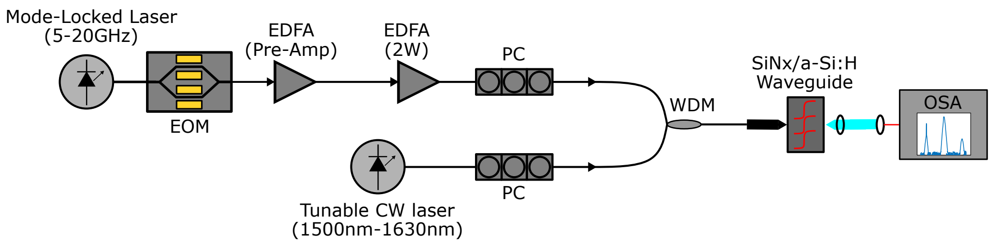

Fig. 1. Experimental setup for degenerate FWM at GHz repetition rate. (EOM: electro-optic modulator. WDM: wavelength division multiplexer. EDFA: erbium-doped fiber amplifier. PC: polarization controller. OSA: optical spectrum analyzer.)

2. Design/Experimental Results

The multi-layer platform consists of SiNx waveguides separated from a-Si:H waveguides by 650-nm of silicon dioxide (SiO_2) cladding. Light is coupled between layers using inverse nanotapers and is described in more depth in [6]. The devices are fabricated using standard CMOS fabrication processes including electron-beam lithography, reactive ion etching, and plasma enhanced chemical vapor deposition. The SiNx layer is patterned first and platinum alignment marks are used to align the two layers between e-beam steps. Chemical mechanical polishing is performed to planarize the SiO_2 separation layer before depositing the a-Si:H. The a-Si:H waveguides have a height of 235-nm and a width of 450-nm. With these dimensions, the waveguides are single-mode and are dispersion engineered to have efficient broadband four-wave mixing conversion. The SiNx waveguides have a height of 235-nm and width of 1000-nm. These dimensions are chosen to ensure single-mode operation. The a-Si:H (SiNx) waveguide linear propagation loss is extracted using the cutback method to be 5-dB/cm (0.5-dB/cm).

Our experimental setup begins with a pico-second actively mode-locked laser with a repetition rate of 8-GHz. In order to decrease the laser-repetition rate to 1-GHz, pulses are sent through an electro-optic modulator driven by a pulse-generator. The signal is generated from a tunable continuous-wave (CW) laser. The pump and signal are

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combined using a wavelength division multiplexer (WDM) and are coupled into the multi-layer waveguides via a lensed fiber and on-chip inverse nanotapers in the SiNx layer. Once on-chip, light is coupled from the SiNx layer into a 5.5-mm long a-Si:H waveguide where optical parametric amplification occurs, and is then coupled back to the SiNx layer where it is output from the chip and sent to an optical spectrum analyzer (OSA). The setup is shown in figure 1. The pump wavelength is chosen to be 1550-nm and the signal is chosen to be 1525-nm. The pump pulse width is measured using an autocorrelator and is found to be 3.3-ps. We begin our four-wave mixing experiment using the lowest power pump in which we can still detect the idler. We then slowly increase the pump power to find the peak power at which there is positive conversion efficiency (CE) (defined as the ratio of output idler power with the pump on to output signal power with the pump off). We ensure that FWM is occurring in the a-Si:H layer by performing this same experiment in a single-layer SiNx waveguide and comparing the FWM results. Figure 2b shows the FWM spectrum for the multi-layer device, a single-layer SiNx device, and a single layer a-Si:H device. This figure clearly shows that the FWM in the multi-layer device is occurring in the a-Si:H layer as expected, as its FWM spectrum closely mirrors that of the a-Si:H single layer device while there is almost no idler visible for the SiNx device. As shown in figure 2a, we start to see positive conversion efficiency at peak pump power of 2-W in the multi-layer device, and with a peak of 5-dB that occurs at a peak pump power of 3.35-W. This amount of positive CE indicates 6.2-dB of optical parametric gain on the signal. Additionally, while positive conversion efficiency is achieved in the multi-layer device, it is not achieved in the single-layer a-Si:H waveguide. This is likely due to the superior input coupling to SiNx waveguides.

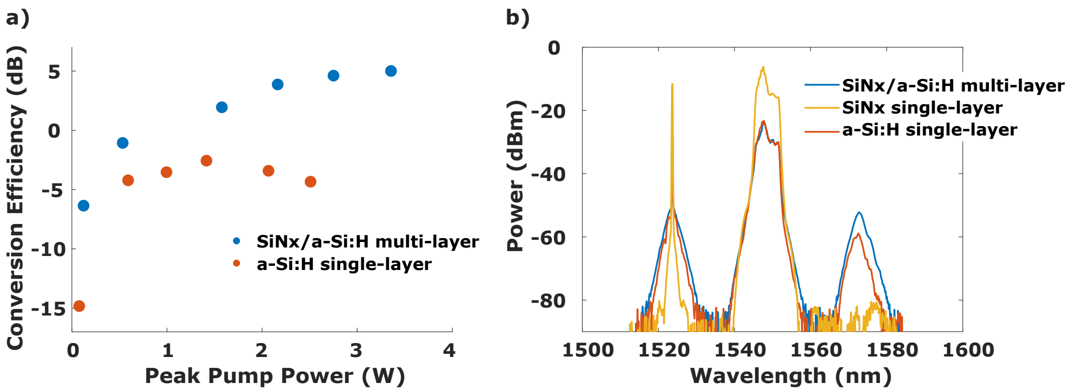

Fig. 2. a) Conversion efficiency as a function of peak pump power for multi-layer device and single-layer a-Si:H waveguide. b) FWM spectrum for multi-layer device, SiNx single-layer waveguide, and a-Si:H single-layer waveguide.

3. Conclusion

In this paper we demonstrate high speed positive conversion efficiency in a SiNx/a-Si:H multi-layer device. This demonstration allows for the possibility of designing an on-chip GHz-rate optical parametric oscillator and also represents a promising platform for achieving efficient GHz-rate photon-pair generation. For an on-chip OPO, at this laser repetition rate a cavity consisting mostly of SiNx propagation would need to have a length of ~20-cm. State-of-the-art demonstrations of ultra-low SiNx have shown losses below 0.01-dB/cm [8,9]. Using this type of platform and achieving losses close to the state-of-the-art in SiNx, the round-trip losses would be significantly reduced and the gain achieved in this demonstration would be enough to achieve optical parametric oscillation.

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