# Optical Waveform Sampling of a 320 Gbit/s Serial Data Signal using a Hydrogenated Amorphous Silicon Waveguide

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**Abstract:** We propose using a hydrogenated amorphous silicon waveguide for ultra-high-speed serial data waveform sampling. 320 Gbit/s serial optical data sampling is experimentally demonstrated with +12 dB intrinsic four wave mixing conversion efficiency.
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## 1. Introduction

Silicon based optical signal processing has attracted considerable research interest in recent years, due to its complementary metal-oxide-semiconductor (CMOS) compatibility, low cost, ultra-compactness, broad working bandwidth and high-speed operation. Crystalline silicon (c-Si) waveguides have been studied extensively and various high speed optical signal processing have been realized by using c-Si waveguides, such as four wave mixing (FWM) based 10 Gbit/s signal regeneration [1], 160 Gbit/s demultiplexing and wavelength conversion [2,3], 1.28 Tbit/s waveform sampling and demultiplexing [4], and 640 Gbit/s wavelength conversion [5]. However, all these c-Si based signal processing suffer from the nonlinear two photon absorption (TPA) and slow dynamics of TPA induced free carrier absorption (FCA). The TPA in c-Si waveguides can not be avoided at the telecommunication wavelengths of 1550 nm. Therefore, the FWM conversion efficiency is heavily limited by the TPA and FCA. Several methods have been proposed to overcome this problem [6, 7]. However, these realizations suffer either from lower linear and nonlinear refractive indices or from incompatibility with CMOS fabrication. Silicon-on-insulator (SOI) waveguides with a hydrogenated amorphous silicon (a-Si:H) waveguide core are an alternative to the standard crystalline SOI high-index contrast waveguide platform. Because a-Si:H is a material with considerable freedom in chemical structure, different fabrication procedures can give rise to different material properties, including the bandgap. Therefore, it is possible to fabricate a-Si:H waveguides with low TPA at telecommunication wavelengths while maintaining the high nonlinearity. Recently a parametric on-off gain of + 26 dB was demonstrated in these waveguides [8].

In this paper, we will demonstrate an a-Si:H waveguide based 320 Gbit/s serial data signal waveform sampling system. In the demonstration, a +12 dB intrinsic conversion efficiency is achieved, which is 19.5 dB higher than previously obtained results in c-Si:H waveguides [4].

## 2. Characterization of the a-Si:H waveguide

The a-Si:H waveguide used in this experiment is 4 mm long and its cross-sectional dimensions are 220 nm × 500nm, as shown in Fig. 1 (Left). The propagation loss is about 3.6 dB/cm. Diffractive grating couplers are used to couple the light between fibers and the device. Fig. 1 (Right) shows the insertion loss of this waveguide, including coupling loss and propagation loss. The insertion loss ranges from 13 to 18 dB, depending on the wavelength used in the experiment.
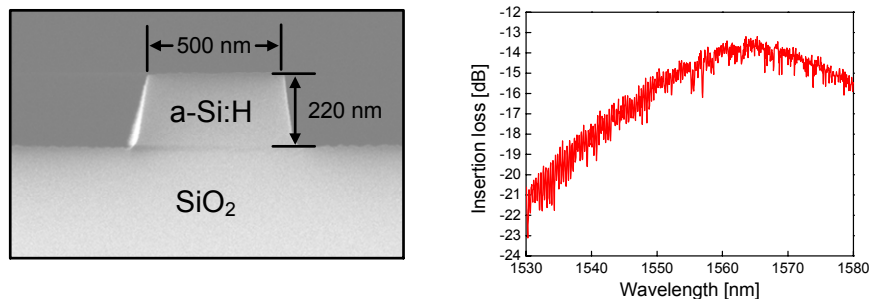


Fig. 1. (Left) The cross section of the a-Si:H waveguide, pictured using a scanning electron microscope, (Right) Measured insertion loss as function of wavelength.

The waveguide is built in 220-nm-thick hydrogenated amorphous silicon deposited on top of a 1950-nm-thick polished high-density silicon dioxide layer. The 220-nm thick a-Si:H film is deposited by plasma-enhanced chemical vapor deposition (PECVD). The film was formed using silane (SiH4) as a precursor gas along with helium (He) dilution. Low losses can be achieved by optimizing several parameters, such as the gas ratio (He/SiH4) and the plasma power [9]. After forming the waveguide core layer, 500-nm-wide photonic wires were patterned using CMOS fabrication technology. The bandgap of a-Si:H films is measured to be 1.61 eV, by using spectroscopic ellipsometry (in the 300–1600nm range) [8], while c-Si has a bandgap of 1.12 eV. Therefore, the half-bandgap of a-Si:H is approximately 0.805 eV, corresponding to $\lambda = 1540$ nm. This half-bandgap will dramatically decrease the TPA in the a-Si:H waveguide when the wavelength is longer than 1540 nm, and thus improve the FWM conversion efficiency.

## 3. Experimental setup

The experimental scheme of a-Si:H based optical sampling is shown in Fig. 2. A fiber ring mode-locked laser is used as the sampling source, which uses a 30 cm erbium-doped fiber as gain medium and carbon nanotubes (CNT) as the mode-locker [10].The generated sampling pulses have a repetition rate of  16.3 MHz and a squared hyperbolic secant shape with ~ 710 fs FWHM, measured using an autocorrelator directly at the laser output. The central wavelength of the pulses is at 1558 nm and has a 4 nm 3-dB spectral bandwidth. To avoid serious spectral broadening due to self-phase modulation (SPM) in the highly nonlinear a-Si:H waveguide, the sampling pulse is broadened to 1.4 ps by adding 10 m single mode fiber (SMF). The 320 Gbit/s serial data signal is generated using the Optical Time Division Multiplexing (OTDM) technique. An erbium glass oscillator (ERGO) optical pulse source generates a 10 GHz pulse train at 1550 nm with 2 ps FWHM. After amplification in an EDFA, the 10 GHz data pulses are sent into a dispersion flattened highly nonlinear fiber (DF-HNLF) to broaden the spectrum. Then a 5 nm bandpass filter is used to filter out part of the spectrum. The pulse width of the 10 GHz pulses is compressed to 1 ps in this way. A Mach-Zender modulator encodes a 10 Gbit/s on-off keying (OOK) data sequence (PRBS $2^7$-1) on the pulse train and the 10 Gbit/s data signal is multiplexed to 320 Gbit/s by a passive fiber delay PRBS and polarization maintaining multiplexer (MUX). The 320 Gbit/s OTDM OOK data signal is coupled into the a-Si:H waveguide together with the sampling pulse train. The polarization states into the a-Si:H waveguide of the data signal and the sampling pulse are aligned to the TE mode by polarization controllers. The data signal power and sampling pulses power before coupling into the a-Si:H waveguide is 5 dBm and -5 dBm respectively. In the a-Si:H waveguide, FWM will take place when the sampling pulses (pump) overlap with the data pulses (signal) and generate a new FWM product (idler). After the a-Si:H waveguide, the FWM product is selected by L-band filters and directly detected using a high sensitivity photo-detector (with 200 MHz bandwidth). To observe the waveform on the 1 Gsample/s oscilloscope (with 350 MHz bandwidth), the sampling pulse itself is used as a gate trigger for the oscilloscope and the sampling frequency is fine-tuned to ensure the correct temporal order of the samples.
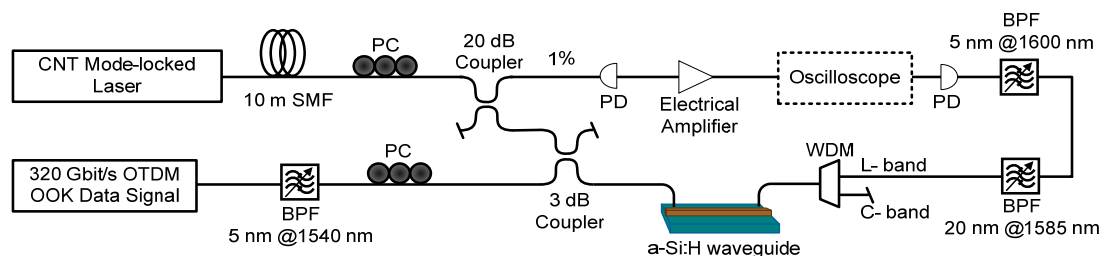


Fig. 2. The experimental setup of the a-Si:H waveguide based optical sampling system

## 4. Experimental results

The 320 Gbit/s OTDM OOK data is successfully sampled using this a-Si:H based sampling system. Fig. 3 (Left) shows a clear open eye-diagram measured with the constructed system. Furthermore, the pulse width of the sampled data pulse is measured to be 1.3 ps. Compared to the pulse width of 1 ps measured using an autocorrelator, the sampled pulses are wider than the real pulse width when using the a-Si:H based optical sampling process. This broadening is caused by the sampling time resolution, which is limited by the sampling pulse width and the walk-off between the sampling and sampled pulses. The time resolution of this a-Si:H based sampling system is estimated, by deconvolving from the actual pulse width (measured with autocorrelator) [11], to $\Delta\tau=((1.3\ \text{ps})^2-(1\ \text{ps})^2)^{1/2}\approx0.830$ ps. This time resolution could be further improved by using narrower sampling pulses.
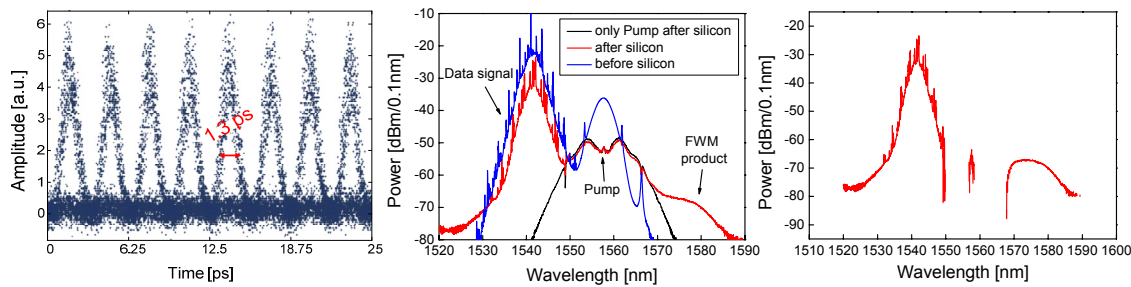
Fig. 3. (Left) Sampled eye-diagram of the 320 Gbit/s serial data signal using the a-Si:H based optical sampling system, (Middle) Measured optical spectra before and after the a-Si:H waveguide, (Right) Spectrum of data signal and FWM product at output of waveguide when subtracting the pump.

Fig. 3 (Middle) is the measured spectra during the sampling process. Comparing to the input pump spectrum, the output is broadened, as shown in curve 'only Pump after silicon'. This broadening is caused by SPM in the a-Si:H waveguide. Fig. 3 (Right) shows the spectra of the data signal and FWM product at the output of the waveguide. Here, the pump only spectrum is subtracted. To calculate the FWM conversion efficiency in the a-Si:H waveguid, the output power of the data signal and FWM product are measured to $P_{data\_out}$ = - 14.5 dBm and $P_{FWM\_out}$ = - 44 dBm, respectively, by integrating the spectrum shown in Fig. 3 (Right). Here we define the intrinsic conversion efficiency as the ratio between the FWM product power just before it is coupled out from the a-Si:H waveguide and the data signal power coupled into the a-Si:H waveguide. Therefore the intrinsic conversion efficiency is expressed as

$$\eta_{Intrinsic} = (P_{FWM\_out}+l_{coupling}) - (P_{data\_out}+l_{coupling}+l)$$

Where $l_{coupling}$ is the coupling loss between fiber and waveguide, and $l$ is the propagation loss of the waveguide which is 1.5 dB for this a-Si:H waveguide. Moreover, considering the duty cycle between sampling pulses and the data signal (43 dB here), the intrinsic conversion efficiency amounts to +12 dB. In a similar optical sampling system based on c-Si [4], the intrinsic conversion efficiency is -7.5 dB. This 19.5 dB improvement on intrinsic conversion efficiency is believed a benefit from the much lower TPA in the a-Si:H waveguide compared to the c-Si waveguide at the wavelengths longer than 1540 nm.

## 5. Conclusion

We have successfully demonstrated a 320 Gbit/s serial data signal waveform sampling using an a-Si:H waveguide. The sampling system has a temporal resolution of 830 fs and intrinsic conversion efficiency of +12 dB. This result shows that the a-Si:H waveguide has a promising potential for ultra-high-speed nonlinear optical signal processing.

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