Pattern-Effect-Free Wavelength Conversion based on FWM in Hydrogenated Amorphous Silicon Waveguide

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Abstract: We investigate wavelength conversion performance of a hydrogenated-amorphous-silicon waveguide with fast free-carrier decay time. No noticeable penalty between BER curves for 2.5-ps RZ-OOK 10-Gb/s signals of PRBS 2^7-1 and 2^{31}-1 was observed.

OCIS codes: (230.7405) Wavelength conversion devices; (190.4380) Nonlinear optics, four-wave mixing

1. Introduction

Silicon waveguides have attracted much attention because their strong optical confinement enhances the third-order nonlinearity enough for their application to nonlinear signal processing such as wavelength converter [1] and optical gating [2]. However, the nonlinear index change in crystalline silicon (c-Si) is often limited by two-photon absorption (TPA) and TPA-induced free-carrier absorption (FCA). The carrier decay time in c-Si waveguides has already been reported to have about 1 ns, which leads to serious pattern effects in high-speed signal processing [3, 4]. On the other hand, the author's group has discovered that hydrogenated amorphous silicon (a-Si:H) waveguide has an ultra-fast carrier decay time of 100 fs at telecommunication wavelengths, although TPA is present [5]. This feature can potentially eliminate the above mentioned pattern effects commonly observed in c-Si waveguides. Amorphous silicon is widely used for solar cells and thin film transistor liquid crystal display (TFT-LCD) with high quality and reliability. Recently there have been several studies on the fabrications of low-loss (< 3 dB/cm) a-Si:H waveguides [6, 7]. Also the optical nonlinearities in a-Si:H waveguides by four-wave mixing (FWM) have been reported [8]. In this paper, we report on the pattern dependence of FWM-based wavelength conversion using a-Si:H waveguides in which input data signals serve as pump light of the FWM process.

2. Measurement

An a-Si:H waveguides was fabricated from a 250-nm-thick a-Si:H-on-insulator film deposited using plasma enhanced chemical vapor deposition [9]. The a-Si:H film was patterned using electron beam lithography and reactive ion etching. The fabricated a-Si:H waveguide was 400-nm wide, 250-nm thick, and 4.0-mm long, and was equipped with a simple spot-size converter at each of the ends. The linear propagation loss was measured using the cutback method and found to be 14 dB/cm for TE polarization. Figure 1 shows the experimental setup for observing FWM in a-Si:H waveguide. A mode-locked fiber laser (MLFL) is used to create a 2.5-ps pulse train operating at 1547 nm with a repetition rate of 10 GHz as pump light. The pump light is modulated by the Lithium Niobate intensity modulator. Here the pulse pattern generator (PPG) drives pseudo random binary sequence (PRBS) data with word lengths of 2^7-1 and 2^{31}-1. The probe signal is generated by a CW laser operating at 1563 nm with 10 mW.

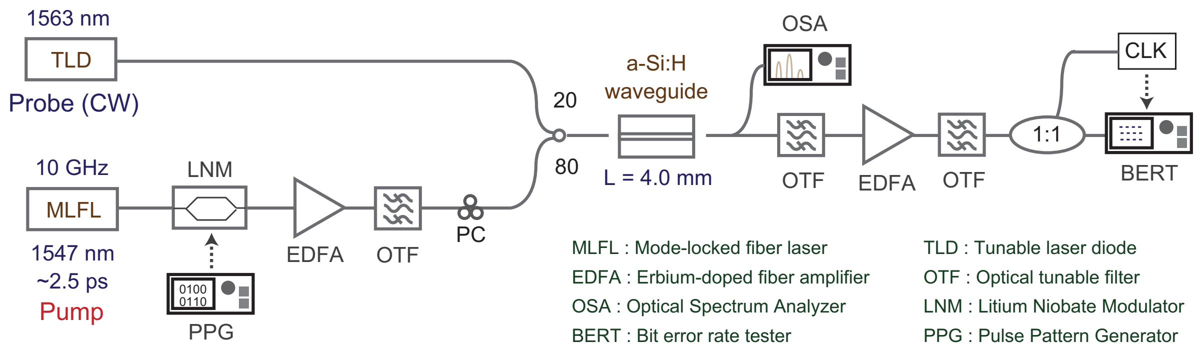

Fig. 1: (a) Experimental setup for wavelength conversion based on FWM with 4.0-mm-lomg a-Si:H waveguide.

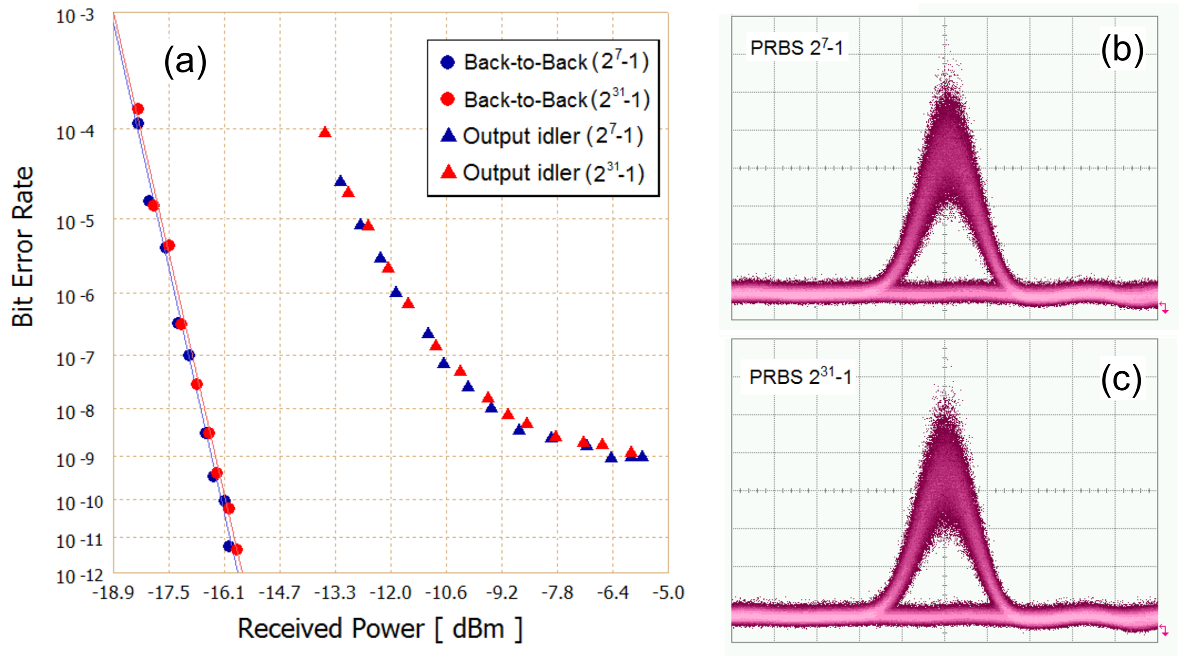

Fig. 2 (a) Bit-error-rate curves and (b)(c) eye diagrams of output idler light signals with PRBS 2^7-1 and 2^{31}-1.The Q-factors with both PRBS 2^7-1 and 2^{31}-1 are estimated to be Q=6.0, which is corresponding to a bit error rate of BER=10^{-9}.

After the pump light is amplified by an erbium-doped fiber amplifier (EDFA), the pump and the probe are co-polarized (TE) and combined by an 80:20 polarization-maintain coupler, then coupled into an a-Si:H waveguide with a coupling efficiency of 4.5 dB. The idler light is selected by inserting an optical band-pass filter (OTF) at 1532 nm and then amplified by a low-noise optical amplifier. The eye opening is monitored with a sampling oscilloscope. The received signal is analyzed using a bit-error-rate tester (BERT).

Figure 2(a) shows the BER curves of the idler signal after traveling our a-Si:H waveguide when the peak power of pump light is 1 W. We found that there was almost no difference between BER curves of the output idler signals with PRBS 2^7-1 and 2^{31}-1. Fig. 2 (b) and (c) show the eye diagrams of the idler light signals with PRBS 2^7-1 and 2^{31}-1, respectively. As we shall discuss subsequently, we infer the BER degradations from the Back-to-back cases are mainly due to ASE noise of EDFA, which can be reduced by improving the insertion loss including propagation loss and coupling loss of the waveguides.

3. Analyses of the Q factors and discussions

One of the drawbacks for evaluating the pattern effects in these experiments is that the conversion efficiency is not high enough so that the pattern effect can bury under the high ASE noise. In this section, we analyze and quantitatively compare the Q-factors with the ASE noise and pattern effects.

The Q-factor is defined as

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_0 + \sigma_1}, \quad \sigma_i = \sqrt{\sigma_{i,ASE}{}^2 + \sigma_{i,p}{}^2} \qquad (1)$$

,where μ_i and σ_i are the mean and standard deviations of the Mark (i=1) and Space level (i=0) distribution, respectively. Here we define the standard deviations due to ASE noise and pattern dependence as $\sigma_{i,ASE}$ and $\sigma_{i,p}$ (i=0,1), respectively. The mean and standard deviations of the ASE noise were measured by replacing the a-Si:H waveguide with an optical attenuator. Then, the parameters of $\mu_{0,ASE}$, $\mu_{1,ASE}$, $\sigma_{0,ASE}$, and $\sigma_{1,ASE}$ were estimated to be 0.2 mW, 4.4 mW, 0.1 mW, and 0.6 mW, respectively. And the corresponding Q-factor is 6.

We then simulated the waveform of the idler light under the conditions of the above experiments using the nonlinear Schrödinger equation taking into account the TPA and TPA-induced FCA with finite decay time. Figure 3 shows the calculated waveforms of idler light by FWM with PRBS 2^7-1 for different carrier decay times assuming

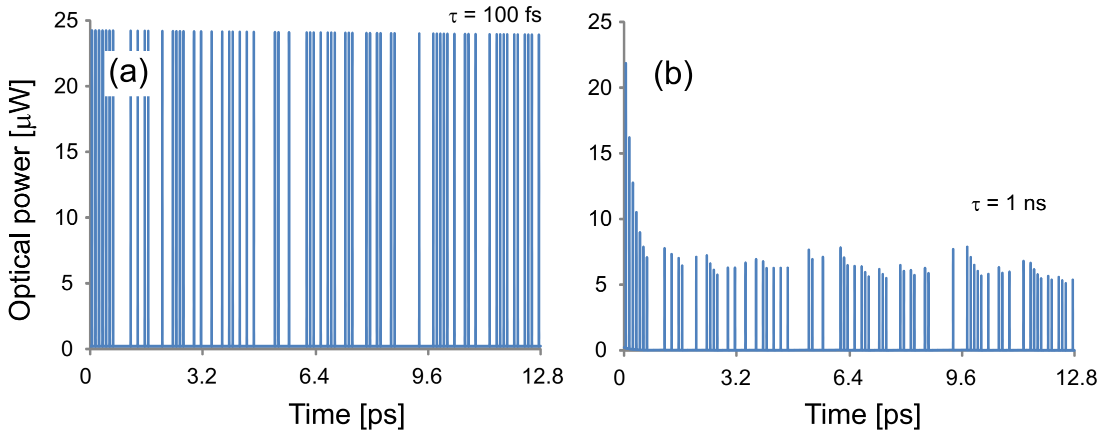

Fig. 3: The calculated waveform of the idler light without ASE noise by FWM with the carrier decay times of (a) 100 fs and (b) 1 ns for PRBS 2^7-1 assuming that the power of probe light (CW) and the peak power of pump light are assumed 10 mW and 1 W, respectively.

Table 1: Q-factors including ASE noise for different word patterns and carrier decay times

	PRBS 2^7-1	PRBS 2^{31}-1
τ=100 fs	Q=6.0 (BER=10^{-9})	Q=6.0 (BER=10^{-9})
τ = 1 ns	Q=5.1 (BER=1.4×10^{-7})	Q=3.7 (BER=10^{-4})

that the repetition rate, pulse width, and peak power of pump light are 10 GHz, 2.5 ps, and 1 W, respectively. The pattern dependence in the case of a carrier decay time of τ=100 fs is found to be negligible, while for a carrier decay time of 1 ns, which is corresponded to the typical carrier decay time of c-Si waveguides, the pattern dependence would be significant as shown in Fig. 3(b). From Fig. 3, we can calculate the overall Q-factors. We also simulated the pattern dependence in the case of PRBS2^{31}-1 assuming that the maximum length sequence (MLS) of '0' signal is 30 bits (3 ns) after MLS of '1' signal is 31 bits (3.1 ns) for the worst case. We then estimated $\sigma_{i,p}$ and Q-factors with the ASE noise for different word patterns and carrier decay times using equation (1). The results are shown in Table I, along with the corresponding BERs. From these results, we can see that for τ=1 ns even under these experimental conditions with high ASE noise, a significant BER penalty due to the pattern effect could have been observed. Therefore, we conclude that the pattern dependence of an a-Si:H waveguide is almost negligible due to its ultra-fast carrier decay time.

4. Summary

We have investigated all-optical wavelength conversion based on FWM using a-Si:H waveguide for RZ-OOK 10-Gb/s signals with a pulse width of 2.5-ps. We found there was no difference between the BER curves with PRBS 2^7-1 and 2^{31}-1. We thus demonstrated the pattern effects of an a-Si:H waveguide were negligible due to its ultra-fast carrier recovery time. The a-Si:H waveguides with such an ultra-fast carrier decay time has a great potential to realize various ultra-fast optical signal processing devices.

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