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Memory assessment of nonlinear optical waveguides using standard DSP

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Abstract: Linear equalization is used to assess the impact of memory effects on 10 Gb/s OOK signals induced by wavelength conversion in a deuterated amorphous silicon waveguide. A longer equalizer is required for higher pump powers.

1. Introduction

The most promising materials for compact Kerr single-pass devices are those with high nonlinearity and minimal nonlinear absorption. In high index contrast platforms where two-photon absorption is mitigated, absorption and free-carrier generation can still occur via surface defect state mediated absorption [1, 2]. In crystalline silicon waveguides, the recombination rates of photo-generated carriers is dependent on the free-carrier density and the density of trap states [3]. While these physical processes can be quantified by careful studies of the power- and time-dependent absorption and relaxation time, a detailed and complete waveguide model is needed to accurately predict the device performance in a communications system and understand which phenomena limit the system performance. Such models are typically difficult to obtain and/or fit, making the physical modeling task challenging. While digital signal processing (DSP) has been employed to maximize throughput, it can also be leveraged to investigate the system or device under test itself.

In this paper, we propose an alternative device characterization method based upon receiver DSP to probe the effects of nonlinear waveguide impairments on the communication channel, in particular the memory. We demonstrate this using wavelength conversion in a partially deuterated amorphous silicon waveguide having a core refractive index of 3.47 and 60 % isotopic fraction of deuterium [4]. Nonlinear impairments induced in the waveguide include nonlinear absorption which is not sufficiently described by two-photon absorption and a single-valued carrier lifetime [5].

2. Experimental setup

The experimental setup is illustrated in Fig. 1a, consisting of a signal and pump path to the waveguide. For wavelength conversion, the signal laser is set to 1580 nm, such that the idler is received at 1550 nm. Alternatively, the “signal” can be received by setting the signal laser to 1550 nm and thus dumping the idler. In the back-to-back (B2B) measurement, the signal passes directly to the receiver, bypassing the waveguide. The 10 Gb/s OOK signal is sampled at the receiver at 40 GSa/s and is then aligned with the known transmitted symbol sequence

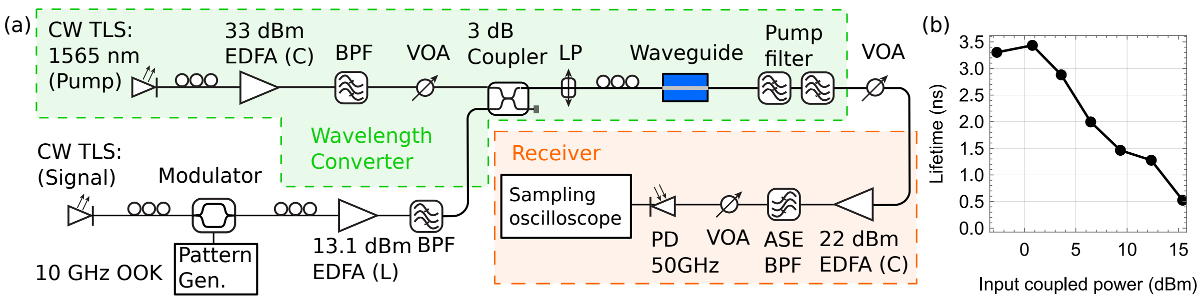

Fig. 1: (a) Experimental setup. ASE: Amplified spontaneous emission. BPF: Bandpass filter. CW: Continuous wave. EDFA: Erbium-doped fiber amplifier. LP: Linear polarizer. OOK: On-off keying. PD: Photodiode. TLS: Tunable laser source. VOA: Variable optical attenuator. (b) Measured free-carrier lifetime versus input coupled continuous-wave pump power at a wavelength of 1550 nm.

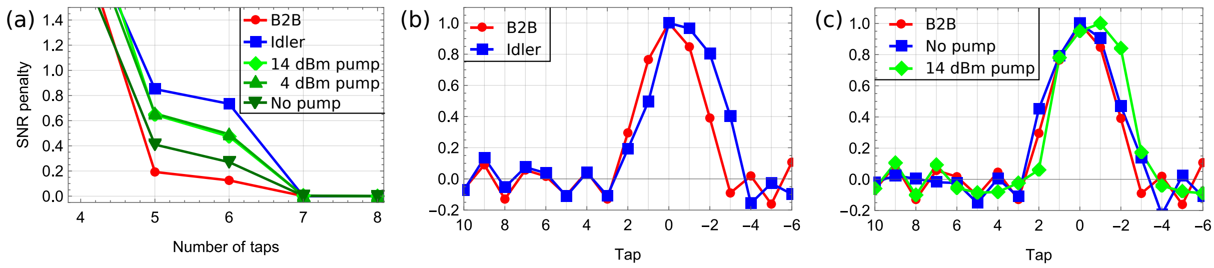

Fig. 2: (a) SNR penalty for varying number of equalizer taps. (b) Impulse responses from equalizer. Amplitudes are normalized by pulse power. Comparing back-to-back and idler. (c) Comparing back-to-back and signal.

using a correlation over the whole symbol sequence. A linear minimum mean squared error (MSE) equalizer of a given length is then trained on 100 000 symbols. A further 100 000 symbols, independent of the training symbols, are then used to estimate the performance of the equalization, which in this case is an estimate of the signal-to-noise ratio (SNR) derived from the MSE of the equalized waveform. The SNR and MSE are related by $\mathrm{SNR} = 10\log_{10}(1/\mathrm{MSE})$ for a bi-polar symbol sequence.

3. Results and discussion

In Fig. 2a, we look at the equalizer length requirements to reach an output SNR of 8 dB, corresponding to a typical forward error correction threshold bit error rate of 10^{-2} [6]. With this as reference we can indirectly assess the memory length by evaluating the SNR penalty induced by a too short equalizer length. Equalizer taps are assigned such that 4 taps cover a single bit of 4 samples and subsequent taps are added sequentially before and after a bit. For B2B, 5 taps are sufficient to reduce the SNR penalty to 0.2 dB. In the case of idler, the penalty is around 0.8 dB for both 5 and 6 taps, indicating the memory introduced by the waveguide. By varying pump power and measuring the signal (green), we see that longer memory is associated with higher pump powers.

In Fig. 2, the estimated impulse response of the system is shown for B2B, the idler (Fig. 2b) and the signal (Fig. 2c) co-propagating with a pump. The impulse response is obtained from the equalizer taps, by training on 10 batches of 25 000 symbols and then averaging the impulse response from these batches. The impulse response from the waveguide channel, both for signal and idler appears broader than the response from the B2B setup, reinforcing the observation from Fig. 2a.

In amorphous silicon films, a generation-rate dependence to the free-carrier lifetime has been observed [7]. Using pump probe measurements with an additional continuous wave pump at 1550 nm to adjust the average power in the waveguide, we extracted carrier lifetimes in the waveguide under test which decrease from 3.5 ns at 0 dBm average power to 0.5 ns at 15 dBm average power, Fig. 1b. The decreasing lifetime with increasing pump power suggests that memory effects would be more pronounced at lower average powers where the waveguide response is slower. Here, we observe through the proxy of number of equalizer taps, that the waveguide imparts less memory on the channel at lower powers, in contradiction to the expected result. We tentatively attribute this to the varying concentration of free carriers in the waveguide at different average powers. While the carrier lifetime is longer at lower powers, fewer free carriers are generated through nonlinear absorption, hence their impact on the channel memory is lower than at higher average optical power where more free carriers are present.

4. Conclusion

Varying equalizer lengths and measuring signal quality is a simple method of assessing the impact of waveguide memory effects on a communication system. The channel-induced memory effect was observed against the back-to-back baseline and was seen to vary depending on the pump power, confirming its origin in the waveguide.

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