Integrated artificial saturable absorber based on Kerr nonlinearity in silicon nitride

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Abstract: An integrated artificial fast saturable absorber at 1.9 μm is demonstrated in a CMOS-compatible process. It is based on the Kerr effect in a nonlinear Mach-Zehnder Interferometer using silicon nitride waveguides embedded in SiO_2.

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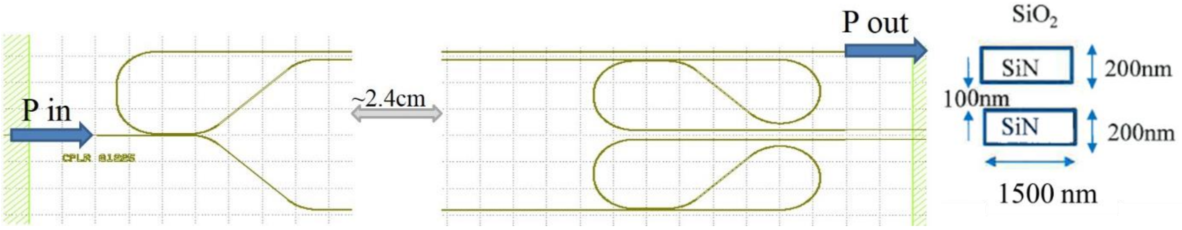
1. Introduction

High repetition rate femtosecond lasers in integrated systems are desired for compact mass producible frequency metrology devices, low-noise oscillators, photonic analog to digital conversion, sensor and spectroscopy applications. One of the key elements of such lasers is the mode-locking mechanism. The most common approach to achieve passive mode-locking involves using a saturable absorber device, which has been often implemented with a semiconductor saturable absorber [1], but also with graphene, quantum dots, and other materials. While such devices have been shown to be robust, they require numerous fabrication steps, and are not necessarily compatible with CMOS processes. In this work, we present a fully integrated CMOS-compatible artificial fast saturable absorber device using additive pulse mode-locking based on the Kerr nonlinearity[3]. We demonstrate saturable absorption behavior, with power-dependent device reflection, and a modulation depth of 4%.

2. Design and Fabrication

The saturable absorber device, referred to as nonlinear interferometer (NLI), shown in Figure 1(a), consists of a Michelson-like integrated interferometer, which has an input coupler with a 90/10 coupling ratio into the two respective arms of the interferometer. Each arm has a section of silicon nitride waveguide ending with an integrated loop mirror, based on 50/50 directional coupler, reflecting ideally 100% of the light. In the current implementation, both arms of the interferometer have the same dimensions and length, making a linear phase difference on the output equal to zero. A power-dependent nonlinear phase difference between the two arms of the NLI, due to 90/10 coupler ratio, is given by $\Delta\phi = \frac{2\pi}{\lambda} n_2 L \frac{\Delta P}{A_{eff}}$, where n_2 is the nonlinear refractive index of the waveguide, L is the length of each arm, A_{eff} is the nonlinear effective area of the waveguide, and ΔP is the power difference between two arms. The output of the interferometer (i.e. the reflection of the device) has a sinusoidal dependence on the input power. Provided the phase bias between the two arms allows for increased reflection for increased input power, the device acts as a fast saturable absorber. In case there is a linear phase difference, a phase bias can be implemented in one arm in order to balance the interferometer correctly. Because the response time of the Kerr effect in silicon nitride is on a few femtosecond time scale, the NLI operates as an ideal fast saturable absorber.

We implement the device using a double silicon-nitride waveguide embedded into a SiO_2 cladding. The waveguide cross-section, shown in Figure 1(b), is designed to be compatible with our fully integrated mode-locked laser cavity [3], and to show the largest artificial saturable absorption, and the smallest dispersion. Because our integrated mode-locked laser operates at 1.9 μm, the NLI in question was designed and optimized for this wavelength. Simulated “reflection” and “transmission” of the device, using varying incident input power levels, are shown in Figure 2(b).



(a) (b)

Figure 1. (a) Saturable absorber implementation / schematic. (b) Cross-section of the main waveguide

We have tested our integrated nonlinear interferometer using an optical parametric oscillator, with 200fs pulses centered at 1.9µm at 80MHz repetition rate. The device was measured through the "transmission" output port. Measured transmission vs input pump power is shown in Figure 2(c,d), and shows a sinusoidal dependence with a 4% modulation depth. We estimate our on-chip mode-locked lasers will have 200 mW intracavity power at 700 MHz repetition rate, and 200 fs pulse duration to achieve kW peak powers fully exploiting the modulation depth of the NLI and reliably self-start the laser. Further work involves testing this device with a properly designed mode-locked laser cavity.

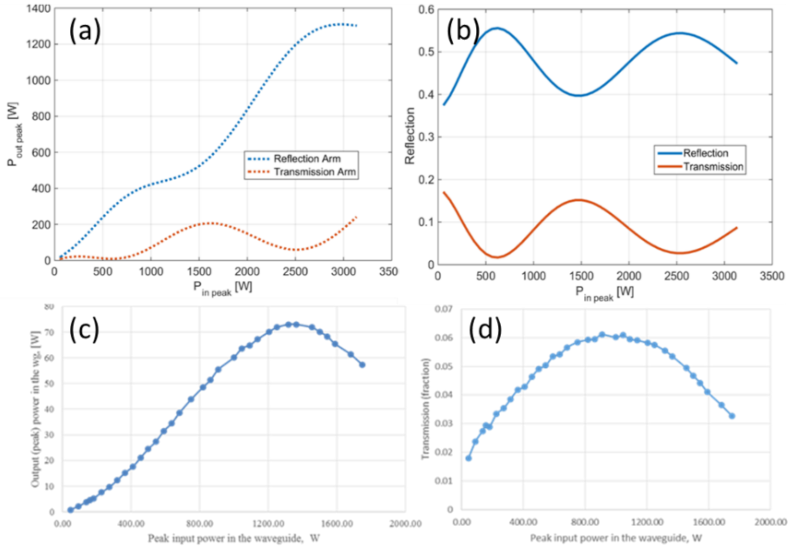


Figure 2. (a) Simulation of the device, output vs input power. (b) Simulation of the device, reflection and transmission vs input power. (c) Measured output vs input power. (d) Measured transmission of the device.

Conclusion

We have demonstrated a fully on-chip Kerr-nonlinearity-based saturable absorber device operating at 1.9µm, implemented using a silicon nitride waveguide. The device has 4% modulation depth and enough Kerr nonlinearity to support ultrafast pulse formation in an integrated mode-locked laser cavity.

Acknowledgements

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