Multimode interference reflector for anti-colliding III-V-on-silicon-nitride mode-locked lasers

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Abstract: We present a type of hybrid a-Si:H/SiN broadband reflector using a multimode interference reflector topology. This reflector is developed specifically to realize an anti-colliding pulse mode-locked laser using the III-V-on-silicon-nitride platform. In this platform the layer of hydrogenated amorphous silicon is also used to bridge the index contrast between the silicon nitride and active III-V layer.

1 Introduction

In previous years, integrated semiconductor mode-locked lasers (MLL) have become very promising frequency comb sources for several applications, such as dual-comb spectroscopy [1]. An example of such an integrated mode-locked laser was demonstrated in [2], where a III-V-on-silicon mode-locked laser with a 1 GHz repetition rate was reported. By implementing the saturable absorber (SA) above the output reflector, the MLL was made to operate in an anti-colliding mode, promising among others higher output powers when compared to other topologies such as colliding-pulse implementations and ring topologies [3]. The performance of these devices is however limited by the silicon waveguides, which suffer from nonlinear losses such as two-photon absorption. Silicon nitride offers a solution with many advantages such as ultra-low waveguide losses and lower sensitivity to fabrication errors. For a long time the integration of active devices on a passive silicon nitride platform remained challenging, but recently integration of III-V amplifiers and lasers has been demonstrated [4], [5]. We want to develop a high performance, low repetition rate anti-colliding mode-locked laser on a silicon nitride on insulator platform. A schematic drawing of such an anti-colliding MLL is shown in the top of **Figure 1**. To bridge the index difference between silicon nitride (Si_3N_4) and indium phosphide (InP) based amplifiers ($\Delta n \sim 1.4$), we use an intermediate layer of hydrogenated amorphous silicon (a-Si:H), similar to the approach in [4]. To achieve the high performance promised by the anti-colliding approach, a broadband output reflector close to the SA is necessary. However, broadband and compact reflectors such as broadband Bragg gratings are difficult to realize on the silicon nitride platform. A compact and broadband solution can be found in multimode interference reflectors (MIR), which are based on multi-mode interferometers combined with reflective waveguide facets. Theoretical analysis and measurement results for InP-based MIRs were presented in [6]. Because of the low refractive index contrast of silicon nitride photonic waveguides, MIRs cannot be realized in this platform. In this work, we demonstrate that these MIRs can be realized making use of the intermediate a-Si:H layer of our platform. This offers an excellent candidate as a compact and versatile output coupler for an integrated III-V-on-silicon-nitride anti-colliding mode-locked laser and offers a compact reflector for applications on the SiN platform where gratings and compact broadband reflectors are challenging to realize due to the low refractive index contrast.

2. Design and fabrication

As described in [6], MIRs are designed starting from a regular multimode interferometer (MMI) and etching two 45° degree facets in the MMI, which meet at the exact center of the MMI. This approach exploits the self-imaging properties of these MMIs, to create the desired reflection pattern. Given the need for total internal reflection an MIR cannot be realized in most silicon nitride platforms. For the purpose of our anti-colliding mode-locked laser, we require a 2-port MIR in the a-Si:H layer. Such a 2-port MIR was designed for a reflection/transmission ratio of 50/50. Starting from a chosen width W for the multimode waveguide section, the theoretical length and position of the input ports can easily be found as $L=3L_\pi/12$ and $P_1=W/4$, $P_2=3W/4$ respectively. Starting from these theoretical predictions, these MIRs were simulated and optimized using the Lumerical FDTD and varFDTD solvers. From these the following nominal parameters were obtained: W=4µm, L=29µm, P_1=1µm, P_2=3µm. The input and output single mode waveguides (W=0.6µm) are tapered towards the MIR to a width of 1.5µm, to achieve a better transition. The devices are fabricated starting from a silicon nitride wafer, where we deposit the hydrogenated amorphous silicon using plasma-enhanced chemical vapor deposition (PECVD), followed by 2 steps of e-beam lithography and reactive ion etching. In the first step the hydrogenated amorphous silicon is patterned and opened up and the silicon nitride is patterned in the second step. As grating couplers in the amorphous silicon are difficult, we use grating couplers in the silicon nitride and tapers to couple to the a-Si:H. To test the performance of these MIRs, we made a Fabry-Pérot interferometer using two MIRs as cavity mirrors. This makes the measurement results largely independent of the grating coupler losses and spectral shaping. A microscope image of such a Fabry-Pérot interferometer is shown in the bottom of **Figure 1**, with 2 MIRs connected by a 25µm long single mode (a-Si:H) waveguide. Both the input and output of the MIR-based Fabry-Pérot are coupled to a SiN waveguide using inversely tapering (a-Si:H) waveguides.

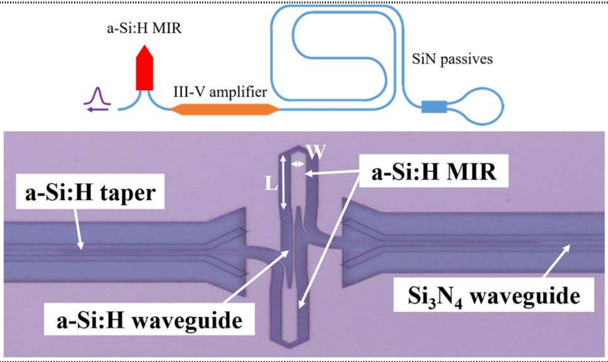

Figure 1: Schematic drawing of an anti-colliding mode-locked laser (top). Microscope picture of the fabricated Fabry-Pérot test structure containing the 2 MIRs in the amorphous silicon layer (bottom).

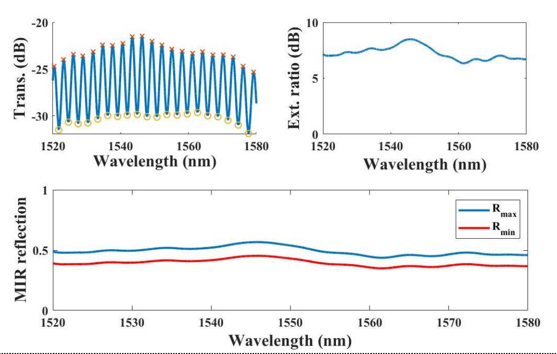

Figure 2: Transmission spectrum (top left), extinction ratio (top right) and estimated upper and lower bound on the MIR reflection (bottom).

3. Results and discussion

A set of 24 of these test structures were fabricated, with slight variations of width, length and position of the input ports. Measurements were performed by sweeping a tunable semiconductor laser source (Santec TSL-510), with 10 pm resolution, and recording the output spectrum using an optical power meter. After some filtering in the Fourier space to remove spurious ripples, the Fabry-Pérot fringes could be isolated from the transmission spectra. By interpolating the maxima and the minima of the spectra, we could obtain estimates for the extinction ratio, which in turn enabled us to determine the reflection of a single MIR. **Figure 2** shows these experimental results for an MIR device of dimensions W=4µm, L=28µm, P_1=1.15µm, P_2=2.85µm. On the top left, the Fourier filtered transmission spectrum is shown, from which the extinction ratio on the top right can be extrapolated. On the bottom, the estimated upper and lower bound on the reflection of this MIR device is shown. Even though we were not yet able to exactly determine the loss factor, we assume that the actual reflection lies somewhere in between the cases of no intra-cavity losses of the MIR Fabry-Perot and 1 dB loss, as the distance between the two ends of the reflectors is only ~100µm. For this device, a reflection of around 40% is then obtained, with only slight variations over the entire measurement range. The other MIR variations showed similar or slightly reduced performance, although it was difficult to attribute differences in performance to either design variations or fabricational variations.

4. Conclusion

In conclusion, we present a broadband, compact reflector created in the hydrogenated amorphous silicon layer of our III-V-on-silicon-nitride platform. This is a first step that will enable us to make high-performance anti-colliding mode-locked lasers on silicon nitride.

5. References

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