Micro-Transfer Printed Semiconductor Optical Amplifier with Saturable Absorber for Pulse Generation at 790 nm Wavelength

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Low-cost and low-noise ultra-fast pulsed laser sources are needed to replace expensive bulk sources for applications such as atomic clocks, optical coherence tomography, and quantum computing, driving the need for integrated photonic laser sources at near-visible wavelengths. To achieve low-noise operation, integration of III-V materials with low-propagation-loss photonic platforms such as silicon nitride is required. To this end, we present the heterogeneous integration of a semiconductor optical amplifier with saturable absorber through micro-transfer printing. The device is produced in a wafer-scale compatible process, wherein the saturable absorber is defined by electrically isolating a small part of the gain section. A gold mirror is deposited on one of the etched facets of the amplifier. The device is subsequently micro-transfer printed on a silicon substrate for characterization. An extended fiber-cavity laser is created using the amplifier, with output power exceeding 2 mW despite high intra-cavity fiber-to-amplifier coupling losses of 6 dB. The optical output at 0 V saturable absorber bias is recorded on a photodiode, which generates a radio-frequency signal showing distinct and narrow spectral peaks, suggesting mode-locked behavior. These results clearly show the potential of this process to integrate amplifiers with saturable absorbers on other material platforms to create mode-locked lasers.

Introduction

Gallium-arsenide-based quantum well lasers are commonly used for light emission in the near-infrared range for applications such as bio-photonics, spectroscopy, quantum [1], and optical atomic clocks using Rubidium [2]. For many such applications, most notably optical clocks, frequency combs are necessary to provide a spectral reference. However, current bench-top visible lasers and comb sources are costly and bulky. To make precise optical clocks more broadly available, a push is being made towards photonic integrated comb sources in order to bring down cost and size. Three main types of chip-scale comb sources have emerged: Electro-optic combs, Kerr combs, and mode-locked lasers. In both Kerr combs and electro-optic combs, a high-power single-frequency pump laser is required which is modulated using nonlinear or electro-optic effects. While effective at creating broad frequency combs, integration of a pump laser is still necessary. In contrast, a mode-locked laser directly creates a comb spectrum [3].

Mode-locking occurs in a Fabry-Perot or ring cavity when a non-linear element is introduced. The most common form of mode-locking is achieved using a saturable absorber (SA). Saturable absorption is a nonlinear effect in which the absorption of a material decreases with incident optical power. In a Fabry-Perot cavity, many longitudinal modes can exist in the laser cavity. With no mode selection, multiple modes will be generated with random and varying mutual phasing. By inserting a saturable absorber, the laser will preferentially generate modes with such mutual phasing that pulses are formed. This is because a pulse passing through a saturable absorber will lower the absorption for a small time-window, which makes the formation of pulses favorable in the laser cavity. This effect is called mode-locking. A commonly used way of creating a saturable absorber in semiconductor optical amplifiers (SOA) is by electrically isolating a small waveguide section and reverse biasing it, causing absorption in the quantum wells. When high optical powers are incident on the SA, electrons will accumulate in the conduction band, depleting ground states and occupying the final states through Pauli blocking. This effect causes saturation of the absorption, which recovers over time through intra-band thermal relaxation and recombination.

To achieve low-noise operation of a mode-locked laser, most commonly extended-cavity lasers are made. In such lasers, a short gain section is coupled to a long low-loss passive feedback cavity. Due to the long resulting roundtrip time and low losses, a long photon lifetime is achieved and therefore a narrow spectral linewidth. Furthermore, the low repetition rate of the pulses leads to a dense spectral comb. To achieve such a cavity, integration of an SOA with a low-loss platform such as silicon nitride is needed. While there has been a recent push towards hybrid and heterogeneously integrated single-mode laser sources on silicon nitride at the 780 nm wavelength [4,5], co-integration of a nonlinear element to enable mode-locking has not been shown. To this end, this work shows the heterogeneous integration of a gallium arsenide SOA, including saturable absorber, through micro-transfer printing.

Fabrication method

The fabrication steps are outlined in Fig. 1. (Al)GaAs epitaxially grown layers are processed to form ridge waveguide SOA coupons. The facets of the coupons are plasma-etched and passivated. The front facet of the coupon is angled to reduce reflections into the waveguide mode. The rear facet is coated with gold to form a mirror. A short waveguide section near the mirror is electrically isolated by plasma-etching the doped p-contact layer to form the SA, as shown in Fig. 1g. In order to transfer the coupon to a new substrate, it is encapsulated in photoresist, which anchors it to the GaAs substrate using photoresist tethers. Through holes in the encapsulation, the sacrificial release layer of InGaP is etched (Fig. 1c), suspending the coupons. Subsequently, the coupon is picked up using an elastomer stamp, breaking the photoresist tethers. It is then micro-transfer printed onto a silicon target with a thin benzocyclobutene (BCB) adhesion layer for testing and contact pads are added for electrical probing.

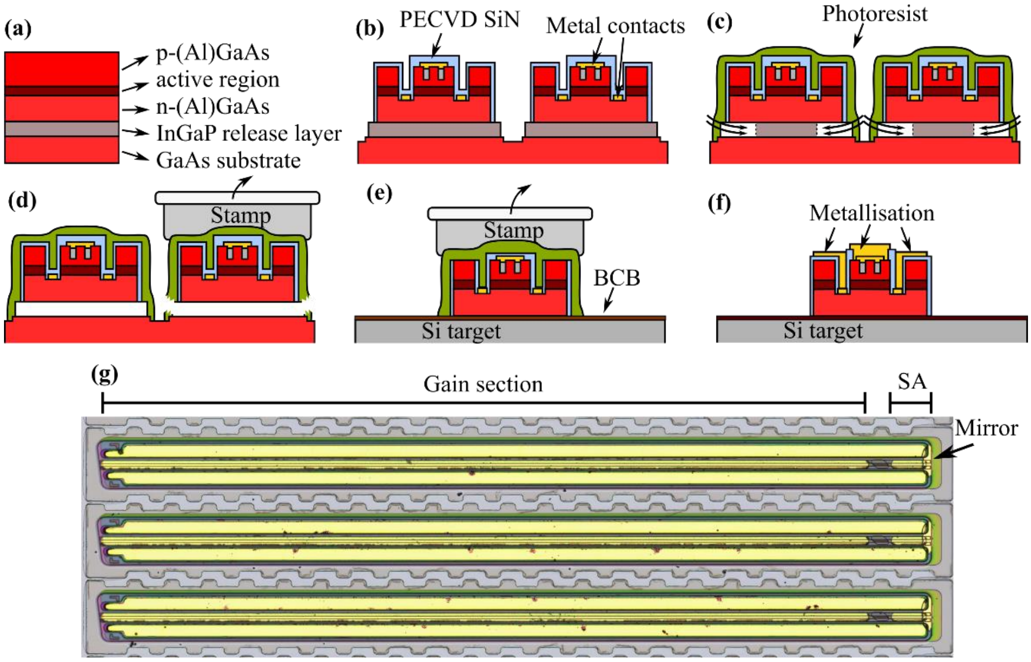

Fig. 1. Fabrication of transfer printed lasers: (a) Epitaxial layer stack. (b) Coupon fabrication, including metal contacts. (c) Encapsulation of laser coupons in photoresist and selective under-etch of InGaP release layer through holes in the photoresist. (d) Pick-up of laser coupon using an elastomer stamp. (e) Printing of laser coupon on Si target substrate with a thin BCB adhesion layer. (f) Subsequent encapsulation removal and metallisation of contact pads. (g) micrograph of laser coupons prior to encapsulation.

Experiment and results

The transferred SOA with SA is tested by forming an extended-fiber cavity using a lensed fiber to couple to the waveguide mode and a fiber loop mirror with 75% reflection, as shown in Fig. 2a. The fiber-to-cavity coupling efficiency using the lensed fiber is measured to be 6 dB one-way. Current is injected in the gain section of the SOA, while the SA is (reverse) biased. The resulting LIV curves at 0 V and -1 V SA bias are shown in Fig. 2b., showing threshold currents of 49 mA and 56 mA respectively and output power up to 2 mW at 70 mA. Furthermore, the laser output is measured on a photodiode. The resulting radio-frequency signal shown in Fig. 2c. shows strong beating of optical modes with a spacing of 2.708 GHz, suggesting mode-locking behaviour. Since the round-trip frequency of the cavity is estimated to be approximately 40 MHz, harmonic mode-locking is likely to occur, wherein many pulses are present in the cavity. The distinct, narrow beat notes clearly confirm the presence of a functional SA in the cavity.

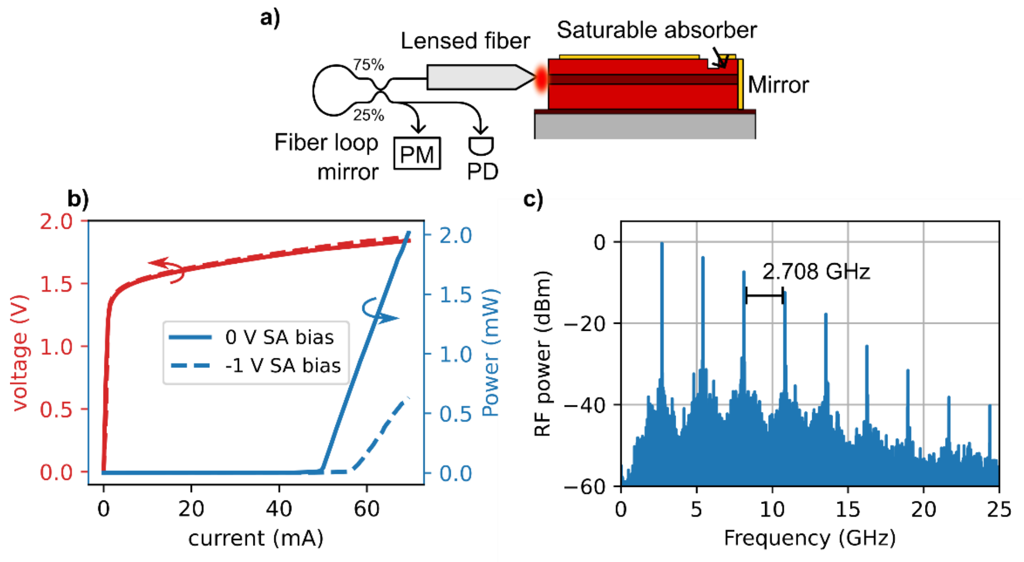

Fig. 2. a) Schematic of extended-fiber cavity laser where PM is power meter and PD is photodiode. b) LIV characteristics of the laser at 0 V and -1 V SA bias voltage. c) RF spectrum as measured on the photodiode showing a 2.708 GHz repetition rate.

Conclusions

In this work, we demonstrate the micro-transfer printing of a gallium arsenide semiconductor optical amplifier with included saturable absorber. The saturable absorber is verified and shows clear mode-locking capabilities. Due to the high flexibility of the micro-transfer printing approach, this SOA can be integrated on different waveguide platforms. Future micro-transfer printing of this device on a low-loss platform such as silicon nitride may enable high-quality low-cost comb sources.

References

[1] G. Moody, V. J. Sorger, D. J. Blumenthal, et al., "Roadmap on integrated quantum photonics," *J. Phys. Photon.*, vol. 4, p. 012501, 2022.

[2] D. Ludlow, M. M. Boyd, J. Ye, et al., "Optical atomic clocks," *Rev. Mod. Phys.*, vol. 87, pp. 637-701, Jul. 2015.

[3] H. Haus, "Mode-locking of lasers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 6, no. 6, pp. 1173–1185, Nov./Dec. 2000.

[4] Prokoshin, M. Gehl, S. Madaras, W. W. Chow, and Y. Wan, "Ultra-narrow-linewidth hybrid-integrated self-injection locked laser at 780 nm," *Optica*, vol. 11, pp. 1024-1029, 2024.

[5] Z. Zhang, B. Shen, M. A. Tran, W. Lee, K. Asawa, G. Kim, Y. Shen, T. J. Morin, A. Malik, J. E. Bowers, T. Komljenovic, and C. Zhang, "Photonic integration platform for rubidium sensors and beyond," *Optica*, vol. 10, pp. 752-753, 2023.