Fully Integrated III-V-on-Silicon Multi-Port DFB Laser Comb Source for 100 GHz DWDM

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Abstract: We demonstrate a 4λx8 output DFB laser comb source with 94GHz channel spacing. The comb source produces approximately 1mW of fiber-coupled power per wavelength per fiber with 2dB power variability across all 32 output channels.

1. Introduction

Silicon (Si) photonics is constantly evolving, driven by data transmission demands requiring improved speed (Gbit/s), transmission efficiency (J/bit), and efficient use of optical fibers (channels/fiber). The recent CW-WDM MSA was founded to support the deployment and supply of DWDM multi-port optical sources with lines spaced at 400 GHz, 200 GHz, and 100 GHz [1]. Such sources are used in the O-band, for short reach transmissions, to feed ring resonator modulator (RRM) arrays with resonance frequencies aligned on the source lines [2]. Two promising approaches to developing laser combs on such grids are mode-locked comb lasers, which produce all laser lines from a single device, and laser arrays, in which each laser produces a single line and the lines are then split and/or multiplexed among the outputs. Comb lasers produce a spectrum of evenly spaced and phase-locked lines, however, with all lines pumped by a single amplifier, the power per line is typically low [3,4]. Channel spacing ≥100 GHz requires either a prohibitively short laser cavity (~400 μm at 100 GHz) or additional filtering components to lock the laser to higher harmonics.

Laser arrays have received considerable attention in recent years for their application in various DWDM systems. The lasers should operate single-mode and mode-hop free over a broad temperature range (e.g. 0 to 80 °C). DFB lasers have been adopted in parallel and CWDM links, but achieving DWDM laser arrays in the O-band is more difficult as they require precise control of the laser frequency spacing (e.g. ±25 GHz on a 100 GHz grid). Numerous methods exist for setting the channel spacing in DFB laser arrays [5], which rely on changing the effective index, grating period, or longitudinal mode structure (e.g. with a sampled grating) of the lasers at a constant rate. When the laser frequencies are controlled through the grating period, achieving 100 GHz spacing requires adjusting the period by approximately 0.1 nm between lasers. Recently, DFB laser arrays have been demonstrated with frequency spacings of 400 GHz [6], 200 GHz [7], and 100 GHz [8]. The 400 GHz and 100 GHz demonstrations both consist of two chips, one integrating the lasers, and the other being a planar lightwave circuit (PLC) for splitting/multiplexing the lasers. The high efficiency (36%) of the lasers in [8] is limited by the assembly loss between the two chips and the power imbalance of the butt-assembled PLC. Integrating all components on the same chip has several advantages. The alignment step required to couple light between the two chips is replaced by alignment between layers defined in the photolithography, and the associated insertion loss (IL) and power imbalance from this step is replaced by that of robust, multi-layer transitions.

In this paper we demonstrate, to our knowledge, the first fully integrated multi-port O-band DFB laser combs targeting 100 GHz channel spacing. The comb lines of the III-V-on-Si laser array are distributed among output fibers using a splitting network defined in SiN on the same chip to improve output power uniformity and reduce loss. The 4λx8 fiber DFB laser combs produce approximately 1 mW of fiber-coupled power per wavelength per fiber at 220 mA bias with a channel spacing of 94 GHz.

2. Design and Fabrication

The DFB laser array was fabricated with our BackSide-on-Buried-Oxide (BSoBOX) process, which has been previously described [9]. A cross section of the BSoBOX platform used in this work is shown in Fig. 1(a), which includes a Silicon Nitride (SiN_x) layer for improved passive devices. The original SiN-on-Si wafer was fabricated in a commercial silicon photonics foundry, with all structures, including the DFB gratings, defined by photolithography. After fabrication of the Silicon-On-Insulator (SOI) wafer, the SOI was bonded upside-down to a Si handle wafer and the original substrate was removed, leaving the thin, planar BOX layer of the SOI substrate. A

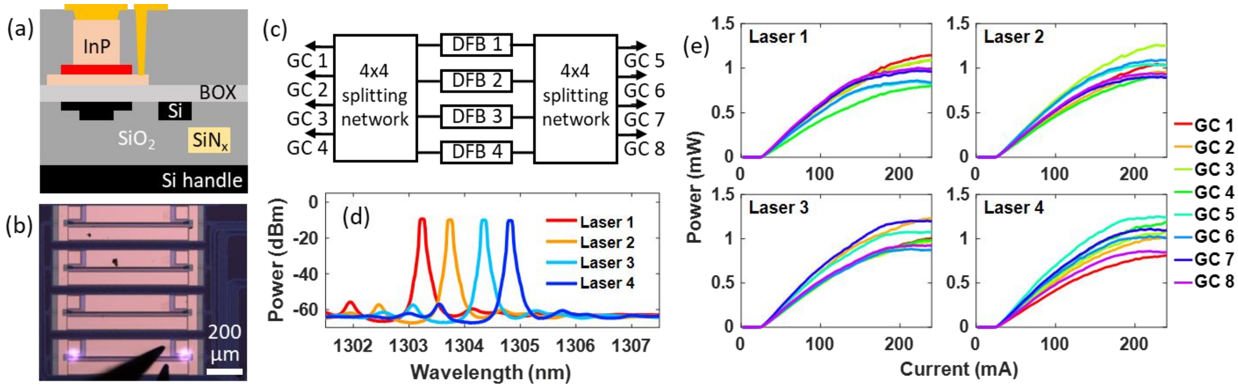

Fig. 1. (a) Cross section of the BSoBOX platform. (b) Die photo of the DFB laser array. The splitting network is located elsewhere on the chip. (c) Diagram of the DFB laser array. (d) Spectra from a laser array on die 3, at a common output GC. Each laser was measured individually, at 100 mA bias. (e) LI curves of the fiber-coupled power for the 4 lasers taken from all 8 GCs.

100 mm III-V wafer was then bonded to the BOX and the Si handle wafer was downsized for III-V patterning and contact metallization in a standard III-V foundry.

A die photo of the DFB laser array is included in Fig. 1(b). Quarter-wave shifted DFB lasers, which are innately single-mode and operate at the Bragg wavelength, were used to improve the DFB wavelength predictability. The DFB gratings are 340 μm long with a grating strength of about 65 cm^{-1} (extracted from measurement data). After exiting the DFB laser, the optical mode transitions to a passive Si waveguide, followed by a transition to a SiN waveguide. The Si-SiN transition loss was characterized on separate test structures to be 0.15 dB. Each side of the 4λ array is then routed through a 4x4 passive splitting network to a grating coupler (GC), also defined in the SiN, to form a 4λx8 fiber DFB laser comb.

3. Results

A grating loopback structure was used to align a fiber array to the 8 output GCs, and the lasers were measured individually. The GC loss at 1300 nm ranged from 3.2–4.6 dB per GC across 6 dies. A compilation of the individual laser spectra within a laser array from one die is shown in Fig. 1(c), each taken at 100 mA bias and a chuck temperature of 30 °C. The lasers operate single-mode with a SMSR of around 46–48 dB. Linear regression of the peak wavelengths indicates a channel spacing of 94 GHz. The LI curves for the 4 lasers, taken from the 8 output GCs at 30 °C, are shown in Fig. 1(e). The fiber-coupled power across all 32 outputs (4 lasers x 8 GCs) exceeds 0.5 mW at 120 mA bias. The total fiber-coupled power for a single laser, computed by summing the measured power at all 8 output GCs, ranged between 5.3–5.5 mW at 120 mA bias and between 7.7–8.2 mW at 220 mA bias. The variation in output power across the 32 outputs ranges from 2.3 dB at low currents (100 mA) to 2 dB at higher currents (220 mA).

Measurements taken from a common output (GC 8) in the temperature range of 20–80 °C are shown in Fig. 2(a) and (b). The lasers operate single-mode and are mode-hop free across the temperature range. The laser threshold current in Fig. 2(a) varies from 24 mA (20 °C) to 54 mA (80 °C) over the temperature range and the maximum achievable output power degrades by approximately 5.4 dB. The characteristic temperature, T0, is found by fitting the logarithm of threshold current against temperature, and depends on the temperature range (86 K for 20–60 °C, 73 K for 20–80 °C) due to the data deviating from a linear fit at 80 °C.

Plots tracking the peak frequencies against current are shown in Fig. 2(b) for several temperatures. Near-constant spacing is maintained across the entire current range, even as the devices red-shift due to Joule heating at a rate of 5.2 nm/W (910 GHz/W). Single-mode behavior and nearly constant spacing is similarly observed across the tested temperature range 20–80 °C, with the entire array red-shifting at a rate of 0.085 nm/K.

The average channel spacing of the 4λx8 array across dies from this wafer is 96 GHz, shown in Fig. 2(c), found through linear regression of the laser peak frequencies at 100 mA bias and 30 °C. The fitting error, error between the individual laser peak frequency and the best-fit channel spacing of the array, which is caused by device-to-device variation, is shown in Fig. 2(d). The worst-case fitting error was 26 GHz, with 67% of lasers within 10 GHz. Fig. 2(e) shows the error when fitted to 100 GHz channels and demonstrates the importance of accurate spacing in the DFB array. Higher channel error occurs when the best-fit channel spacing deviates from 100 GHz (e.g., dies -3 and -2) due to cumulative deviation from the 100 GHz grid near the ends of the array.

4. Discussion

All of the layers in the lasers described here, including the DFB gratings, were patterned with photolithography. Some issues with the DFB grating design were mitigated by narrowing the width of the P-InP on the photomask

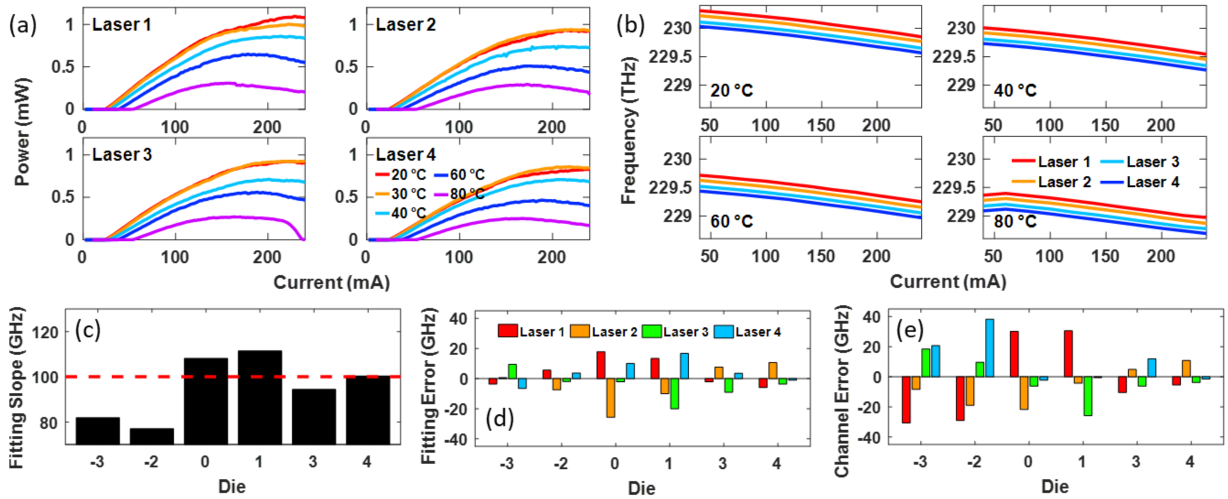

Fig. 2. (a) Fiber-coupled power vs. current for one output of the array. (b) Peak frequency vs. current for the 4λ DFB laser array at elevated temperatures. (c) Best-fit laser array channel spacing, from linear regression over the peak frequencies of an array, at 100 mA bias. (d) Deviation between the individual peak frequencies and their best-fit channel spacing. (e) Deviation between the individual peak frequencies and a 100 GHz grid.

from 3 µm (standard size) down to the contact lithography minimum feature size of 1.5 µm. This led to a low waveguide aspect ratio (width:height) of approximately 1:2 and introduced variations in the geometry of the wet-etched InP and the index of the hybrid waveguide. With such narrow InP width, the κL product was also higher than the optimal value for maximizing the output power and wall plug efficiency of these devices. In the future, the output power and frequency spacing uniformity can likely be improved by using standard InP widths. The fiber-coupled power can also be improved by using low loss edge couplers instead of the GCs used here, which are more convenient for wafer-scale measurements.

5. Conclusion

This work introduces the first fully integrated multi-port DWDM DFB laser combs targeting 100 GHz channel spacing. The 4λx8 fiber DFB laser combs operate single-mode, mode-hop free with fiber-coupled power of ~1 mW per wavelength p0er fiber. The output power level varied by 2-2.3 dB across the 32 output channels (4 lasers x 8 GCs), and the measured average spacing across multiple arrays on the wafer was 96 GHz. Packaging of the devices shown here for further characterization is ongoing. Future work will focus on improving the accuracy of the fabricated channel spacing and improving the available power and power uniformity between dies. By minimizing packaging costs, complexity, and losses, the full integration approach validated in this work promises a power-efficient and cost-effective route to the high channel count and high power per channel laser arrays needed to drive next-generation optical communications.

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