On-chip Hybrid Silicon Quantum Dot Comb Laser With 14 Error-Free Channels

Kurczveil, Geza; Zhang, Chong; Descos, Antoine; Liang, Di; Fiorentino, Marco; Beausoleil, Raymond G.

Hewlett Packard Labs
HPE-2018-07

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Photonics; Comb laser

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We present a quantum dot-based hybrid silicon comb laser using wafer bonding. Multimode interferometer-based on-chip mirrors and grating couplers are integrated on the silicon for wafer-level testing. We show error-free operation in 14 channels.
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Geza Kurczveil, Chong Zhang, Antoine Descos, Di Liang, Marco Fiorentino, Raymond Beausoleil
Hewlett Packard Labs, 1501 Page Mill Rd, Palo Alto, CA 94304
geza.kurczveil@hpe.com

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Keywords: 250.0250 Optoelectronics; 250.5960 Semiconductor lasers; 250.5590 Quantum-well, -wire and -dot device

1. INTRODUCTION

Next generation supercomputers require optical interconnects with aggregate bandwidths of several PB/s [1]. The current approach is to use multiple single-wavelength lasers on one chip. These lasers can be either modulated directly or a separate modulator can be integrated on chip. Their outputs are then multiplexed using either ring-, AWG-, or Echelle grating based multiplexer.

A more promising approach is to use a comb laser – a multi-wavelength laser. Such a device can be realized by using a cavity with a free spectral range (FSR) that is much smaller than the gain bandwidth of the gain medium. One benefit of this approach is that the channel grid is determined by the cavity FSR. In a device with integrated mirrors, the cavity FSR is determined lithographically, and as a result, the individual wavelengths don’t have to be tuned to fall on a grid.

The wide gain bandwidth of ~60 nm (10 THz at 1310 nm), typical for an InAs dot in a GaAs well gain material, is particularly attractive for comb lasers. By growing dots of different sizes, the gain bandwidth can be widened to ~100 nm. In addition, the fast gain dynamics of quantum dots ensures a low relative intensity noise in each comb line [2], even in simple Fabry-Perot laser cavities [3].

The integration of such lasers on silicon is the next step. This allow for the fabrication of lasers in high volume and high-yield CMOS fabs. In addition, the silicon can be used for high quality and low loss passive photonic devices such as mirrors, (de)multiplexers, and grating couplers.

2. DEVICE DESIGN AND FABRICATION

The device design is shown in Fig. 1(a). It consists of a 2.3-mm-long (17 GHz) laser cavity that is formed by multimode interferometer based front and back mirrors with reflectivities of 50% and 100%, respectively. Light is coupled out using a grating coupler. The reflection from the grating coupler is on the order of 10% and this forms an external cavity of 51 GHz. The 17 GHz laser cavity consists of a 120-µm-long saturable absorber (SA) that is placed at the center of the cavity, a 1200-µm-long semiconductor optical amplifier (SOA), and mode converters to transfer the optical mode between the active hybrid waveguide and the passive Si waveguide. Proton implantation is used to electrically isolate the SA from SOA. The device was fabricated using the same process flow as outlined in [4].

An optical image of the fabricated device is shown in Fig. 1(b).

A cross-sectional diagram of the SOA/SA is shown Fig. 1(c). The GaAs mesa is 10 µm wide and proton implantation is used to create a 4-µm-wide current channel (‘m’ in Fig 1(c)). The optical mode is transferred from the SOA to the Si waveguide using a mode converter. This is realized by linearly tapering the width (‘w’ in Fig. 1(c)) of the silicon waveguide underneath the GaAs mesa from 0.68 µm to 1.8 µm and then tapering the GaAs mesa from 10 µm to a 200-nm-wide tip.

Figure 1: (a) Schematic diagram of the comb laser. The probe pads of the laser were omitted for clarity. The MMI-based mirrors are drawn as grating. (b) Micrograph of the manufactured device. (c) Cross sectional diagram of the SOA and SA.

3. DEVICE CHARACTERIZATION

The device was characterized on a temperature controlled stage at 25 °C, and it has a threshold current of 36 mA when the SA was unbiased. The optical spectrum of the device at an SOA current of 395 mA and an SA voltage of -5.9 V is shown in Fig. 2, and we observe an FSR of 102 GHz. This is caused by two effects. First, the centering of the SA suppresses every even mode of laser cavity, thus changing the FSR from 17 GHz to 34 GHz. Second, the 51 GHz external
cavity causes a Vernier effect that only transmits every third mode of the 34 GHz cavity. Both effects combined ensure that the 17 GHz cavity operates at the 6th harmonic – 102 GHz. We hypothesize that the width of the comb is limited by dispersion.

Figure 2: Optical spectrum at an SOA current of 395 mA and an SA voltage of -5.9 V. The SOA and SA bias conditions were tuned carefully for maximum suppression of all the modes between the comb lines. The dotted line is 3 dB below the highest-power channel.

The 15 highest power comb lines labeled in Fig. 2 were amplified using a praseodymium doped fiber amplifier and the comb lines were filtered out individually using an external tunable band-pass filter with a bandwidth of 130 GHz. They were modulated using an external optical modulator with a 10 Gb/s pseudo-random bit sequence. Light was collected by a photodetector and the amplified signal was measured using a digital communications analyzer. The eye diagrams for the 15 channels are shown in Fig. 3, and we note an extinction ratio (ER) of 9.6 or better. We also measure a bit error rate (BER) of $10^{-12}$ or better in 14 channels.

Figure 3: Eye diagrams of the 15 highest power channels with respective ER and BER values.

4. CONCLUSION

We demonstrated a quantum dot-based hybrid silicon comb laser using wafer bonding with on-chip mirrors and grating couplers for easy wafer-level testing. Because of the high reflection of the grating coupler, we observed a higher than expected FSR. Nevertheless, we measure open eye diagrams at 10 Gb/s for the 15 highest power channels, and 14 of those channels have a BER $10^{-12}$ or better.

We expect improved performance by (1) using dispersion compensation and (2) properly managing the feedback from the external cavity. Feedback management can be accomplished by reducing the feedback of the grating coupler [5], or by adjusting the external cavity length.

Finally, on-chip modulators [6] can be added to realize a fully integrated transmitter.

REFERENCES