1-GHz Monolithically Integrated Hybrid Mode-Locked InP Laser

Stanley Cheung, Jong-Hwa Baek, Ryan P. Scott, Member, IEEE, Nicolas K. Fontaine, Francisco M. Soares, Xiaoping Zhou, Douglas M. Baney, and S. J. Ben Yoo, Fellow, IEEE

Abstract—This letter demonstrates a 1-GHz hybrid mode-locked monolithic semiconductor laser fabricated on indium phosphide. Its operating regimes are explored and optical pulses as short as 36 ps were measured. The linear cavity is 41 mm long with integrated active quantum well and passive waveguide structures. To our knowledge, this is the lowest reported repetition rate for a monolithically integrated mode-locked semiconductor laser. We further describe optimization steps of the saturable absorber reverse bias, driving RF frequency, and the semiconductor optical amplifier gain current for minimal output pulsewidth.

Index Terms—Integrated photonic devices, mode-locked lasers (MLLs), optical pulses, semiconductor lasers.

I. INTRODUCTION

Semiconductor mode-locked lasers (MLLs) provide relatively high optical power and stable output on a very compact platform. Semiconductor MLLs with repetition rates of 10–50 GHz are widely reported in the literature, provide excellent performance, and they are being investigated as compact optical frequency comb sources for wavelength-division multiplexing (WDM) and optical code-division multiple-access (O-CDMA) systems [1]. On the other hand, there have been very few reports of low repetition rate (<2 GHz) monolithically integrated semiconductor MLLs useful for RF photonics, photonic-assisted analog-to-digital converters (ADCs), and other applications in which the combination of affordable low-speed electronics and ultrafast optics can be leveraged [2]. Several demonstrations of photonic ADCs utilized bulk-optics titanium–sapphire MLLs integrated with complementary metal–oxide–semiconductor (CMOS) ADCs [2]. An electrically pumped monolithic 1-GHz MLL provides opportunity to integrate the CMOS ADC and laser on the same compact chip.

This letter discusses a 1-GHz hybrid mode-locked (HML) monolithically integrated indium phosphide (InP) laser. The hybrid mode-locking scheme takes advantage of both the stability offered by an actively mode-locked system and the pulse shortening mechanisms provided by the saturable absorber (SA).

II. DEVICE FABRICATION AND EXPERIMENTAL ARRANGEMENT

The monolithically integrated 1-GHz semiconductor MLL requires a ∼41-mm cavity length, which is difficult to realize due to high cavity losses and high gain currents seen in typical semiconductor lasers. We overcome this challenge in three steps. First, we introduce active–passive monolithic integration to confine gain and saturable absorption in one short section of the cavity while keeping the rest as a low loss passive waveguide. Second, we introduce a single-moded waveguide with an adiabatic taper transitioned to a wider low-loss multimoded waveguide while maintaining the lowest order waveguiding with mode filters at the output. Third, we use compressively strained quantum wells to reduce transparency current in the gain region. Fig. 1(a) shows the schematic of the laser. The waveguide cross-section dimension of the quantum well active region used as the gain and the SA regions is 2.5 µm (width) and 0.5 µm (height).

The initial wafer for the laser is grown by metal–organic vapor phase epitaxy (MOVPE) and consists from top to bottom of a 2-µm-thick Zn-doped p-type InP upper cladding, a six quantum well active region, a 0.5-µm-thick Si-doped InGaAsP (Q1.15-Quaternary followed by bandgap absorption wavelength in µm) waveguiding layer, and a 1.5-µm-thick Si-doped n-type InP lower cladding layer. The active region contains six 9-nm-thick undoped InGaAs (Q1.55) quantum wells (QWs).
with 5-nm-thick InGaAs (Q1.17) barriers. The laser device fabrication begins with a 250-nm-thick plasma-enhanced chemical vapor deposition (PECVD) SiO$_2$ layer. The gain and waveguide layers are defined by the SiO$_2$ hard mask with lithography and reactive ion etching (RIE). The p-type InP cap layers are wet etched in HCl; H$_2$PO$_4$ (1 : 5) solution, stopping selectively at the top layer of the active region. The QW and SA sections are then wet etched in a H$_2$SO$_4$ : H$_2$O$_2$ : H$_2$O (10 : 1 : 1) solution. The patterning provides a 10-µm gap width and 359-nm gap depth between the gain and SA section. Many lasers with different SA lengths were fabricated on the same chip and the particular SA length of 150 µm resulted in the best HML operation. Our integration process, similarly described in [3] and [4], utilizes the same method in fabricating arrayed waveguide gratings (AWGs), amplitude and phase modulators, and Mach–Zehnder interferometers, providing a InP material platform viable for monolithic integration of many different functional components. While the optical loss in the 2.5-µm-wide waveguide section is ~2 dB/cm, the optical loss in the 5-µm-wide waveguide section is ~0.7 dB/cm, maintaining the overall loss of the cavity below 3 dB for the 41-mm cavity. The cavity includes an adiabatic taper from the 2.5-µm-wide waveguide section to the 5-µm-wide section (170-µm taper length), and another taper from the 5-µm-wide section to the 1.5-µm-wide section (185-µm taper length) at the output facet to filter out high-order modes. Fresnel reflections from the as cleaved facets define the laser cavity with approximately 30% reflectivity.

For HML operation, a 1-GHz drive signal from an RF synthesizer was used in combination with a reverse dc bias to the SA via a bias-tee and high-frequency ground-signal microwave probe. A reverse bias voltage was used to decrease the absorber lifetime to passively mode-lock the laser, while the RF drive voltage enables active mode-locking. Current injection through dc probe tips forward biases the gain region. The temperature of the Al plate, which the laser is soldered onto, is maintained with a thermo-electric cooler (TEC). Light from the right facet of Fig. 1 was coupled into a lensed fiber and then the electrical power spectrum, electrical time domain, optical spectrum, and high resolution optical spectrum were measured with a 15-GHz lightwave receiver (Agilent 11982A) and a 26.5-GHz RF spectrum analyzer, a 65-GHz sampling oscilloscope (DCA) with 4.4-ps rise-time (86116B), a conventional optical spectrum analyzer (OSA), and a swept heterodyne optical spectrum analyzer.

III. RESULTS AND DISCUSSION

We verify lasing through continuous-wave (CW) operation studies (while the SA remained unbiased) that the laser threshold current is between 320 to 230 mA at laser temperatures of 12 °C to 3 °C, respectively.

Next, several different HML operation regions are studied that occur at various bias conditions. Fig. 2 shows an HML operation regime that produces clean pulses with 7.31 V of SA bias, 20 dBm of RF power at 1.0558 GHz, and 423 mA of injection current at an Al plate temperature of $T = 3 \, ^\circ\text{C}$. The pulse train has a peak fiber coupled output power of 0.59 mW, pulsewidth of 70 ps, and a repetition frequency of 1-GHz. Next, we optimize the current injection and reverse bias voltage for the minimum pulsewidth operation and compare mode-locking quality at a temperature of $T = 7 \, ^\circ\text{C}$ and $T = 4 \, ^\circ\text{C}$, as shown in Fig. 3.

The 20-dBm RF signal is kept constant at 1.0425 GHz. The results show the minimum pulsewidth as a function of the current injection, reverse bias voltage, and temperature. Increasing the reverse bias voltage and injected current, generally decreases the pulsewidth monotonically at both temperatures. The temporal pulsewidth decreases at stronger SA bias voltages because the carrier sweep out time decreases. There is more loss at faster absorber recovery times, therefore, stronger current injection into the gain region compensates for this excess loss. At $T = 7 \, ^\circ\text{C}$, the minimum pulsewidth (~51 ps) occurs at a current injection and reverse bias of 376 mA and 6.19 V, respectively. The minimum pulsewidth (36 ps) occurs at $T = 4 \, ^\circ\text{C}$ with 395 mA of injected current and 6.87 V of reverse bias. The insets illustrate the optimized pulse when the 1-GHz HML laser is optimized for both temperatures.

Figs. 4(a) and 5(a) show a close-up of the pulse obtained for the minimum pulsewidth operation regime at $T = 7 \, ^\circ\text{C}$ and $T = 4 \, ^\circ\text{C}$, respectively. Each pulse has a short main peak followed by a longer, low-amplitude wing/satellite pulse. This could be possibly from the pulse reshaping dynamics of the long quantum-well gain region as well as the coupling between
Fig. 4. (a) Measured pulse train in the time domain when a minimum pulsewidth of 51 ps was achieved at $T = 7^\circ C$. (b) Log plot of RF spectrum showing 1-GHz spacing. (c) Close-up of RF spectrum centered at 1.0385 GHz and a 1-MHz width measured $-20$ dB from the peak. (d) Relative optical spectrum of HML from heterodyne detection where 0 GHz corresponds to 1578 nm. (e) Close-up of optical modes in (d) showing 1-GHz spacing and an average full-width at half-maximum (FWHM) of 81 MHz for each mode.

The satellite pulses can also be caused by many phenomena such as finite linewidth-enhancement factor, dynamic detuning effects, and the gain section having a larger relaxation time than the absorber section [5]. Mode-locked operation can be identified in the RF spectrum if the height of the main peak at 1-GHz more than 25 dB above extraneous peaks and noise at lower frequencies [5]. Fig. 4(b) and (c) show a carrier-to-noise ratio (CNR) of $\sim 50$ dB at a resolution bandwidth of 10 MHz. Moreover, the narrow width of the RF-peak ($\sim 1$ MHz at $-20$ dB) indicates stable mode-locking. Also, the narrow width of the modes in the optical spectrum $\sim 81$ MHz in Fig. 4(e) and $\sim 70$ MHz in Fig. 5(e) indicates stable mode-locking.

From the measurements in Figs. 4 and 5, the time-bandwidth product is 5.1 and 3.6, respectively. The asymmetric pulse shape of the HML operation and the large time-bandwidth product suggests the existence of a frequency sweep or chirp impressed on the mode-locked pulse which is expected due to dispersion from the long InP cavity.

An upper limit for the timing jitter is estimated by integrating the single-sideband (SSB) RF spectrum between 20 kHz and 80 MHz around the first harmonic (1 GHz), to be 4.16 ps for the pulse in Fig. 5(a).

IV. CONCLUSION

We have investigated HML operation of a 1-GHz monolithically integrated laser on an InP platform. The results show a 1-GHz repetition rate with pulses as short as 36 ps albeit with additional satellite pulses that follow. Mode-locking is stable as indicated by the RF-peak power of 55 dB above the noise floor, the repetitive pulse shapes in the time domain, as well as the narrow and well-defined optical modes. The cavity can be further optimized by applying a high-reflectivity coating to the facets or choosing an appropriate output waveguide angle for optimal reflectivity to reduce the required threshold modal gain for lasing, thus lowering the CW injection current density and the heat generated in the device to achieve higher output powers. Further reducing optical losses and including dispersion compensation in the cavity should shorten the pulses. These improvements should enable low repetition rate semiconductor lasers to be useful for RF photonics and numerous other applications where low-cost electronics and high-speed optics (short pulse and low repetition rates) can be leveraged.

REFERENCES


