A High Power and Ultrahigh Frequency Mode-Locked Laser Monolithically Integrated with an SOA

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Abstract: We report 628 GHz and 1.20 THz pulse repetition frequencies with 142 mW peak powers from a passively mode-locked side-wall SGDBR laser integrated with an SOA, demonstrating high reproducibility, controllability and a wide operation range.

OCIS codes: (140.4050) Mode-locked laser; (140.5960) Semiconductor lasers; (320.7090) Ultrafast lasers

Ultrafast mode-locked laser (MLL) diodes offer exciting opportunities in future telecoms systems, high speed data processing and miniaturized THz signal generators because they are compact, robust, cheap to manufacture, and can be integrated with other semiconductor elements such as semiconductor optical amplifiers (SOAs). Repetition frequencies of up to 1.5 THz have been achieved with the use of compound-cavity mode-locking (ML) (CCM) effects in distributed Bragg reflector (DBR) lasers [1], albeit operating over a narrow range of bias conditions and with limited reproducibility. The most extensive demonstration of ML used purpose-built AlGaAs/GaAs CCM Fabry-Perot (FP) lasers incorporating an intra-cavity reflector (ICR), where repetition frequencies up to 2.1 THz were demonstrated at the wavelength of 850 nm [2], in which the accuracy of the positioning of the ICR within the cavity was decisive in determining the ML frequency.

We have previously reported [3] a sampled-grating DBR (SGDBR) MLL in which the DBR section acts as an optical filter to mode-lock the laser at sub-THz repetition frequencies, i.e., ~640 GHz. Due to the nonlinear effects in the cavity, pulse trains at double the 640 GHz pulse repetition rate, i.e., ~1.2 THz, were observed as well. Here we report such a laser integrated with an SOA. The on-chip SOA section is used to significantly boost the output power. The devices reported here offer far superior reproducibility, controllability, and a wider operation range than all other reported types of mode-locked THz LDs [1, 2].

The epitaxial structure and fabrication processes used to develop the device are similar to those described in [3]. An optical microscope picture of the top view (p-side) of the fabricated device along with its dimensions is shown in Fig. 1(a). The device has a total length of 2295 μm of which the gain section is 960 μm, the saturable absorber (SA) section is 20 μm, and the SGDBR section is 675 μm. The ridge waveguide width (w) for these sections is 2.5 μm. The curved SOA is 550 μm long and its w is increased from 2.5 μm to 6 μm with a curvature radius of 3455 μm forming a tilt of 10° at the output facet to reduce the optical reflectivity [4]. The SGDBR sections use a side-wall grating as shown schematically in Fig. 1(b), where Z_0 represents the burst period of the grating and has a value of 67.5 μm. The ML frequency is then given by $F_r = c/(2n_gZ_0)$, where c is the velocity of light in free space, and n_g is the group index, ≈ 3.4889. Thus the SGDBR was used to spectrally select longitudinal modes with the precise mode spacing required to generate signals at F_r = 0.64 THz. Z_1 represents the length of the grating burst, which is 10 μm long and of first-order with a 50% duty cycle and formed by etching 0.6 μm deep recesses (d) into the sidewalls of the waveguide (inset of Fig. 1(b)). Λ represents the grating period and is 245 nm for a 1.56 μm Bragg wavelength. N_s (=10) and represents the number of sample periods, and the SGDBR length (L_{sg}) amounts to $N_s \times Z_0$. The λ_{peak} and mode spacing were determined by accurately determining Λ and Z_0 respectively. The mode spacing was essentially independent of the I_{SGDBR}, I_{SOA}, and temperature. Fig. 1(c) shows the average output power (P) versus the gain current (I_{Gain}) for different SOA currents (I_{SOA}) with an applied SA reverse voltage (V_{SA}) of -3 V and SGDBR current (I_{SGDBR}) of 0 mA. A maximum output power of 52 mW was achieved.

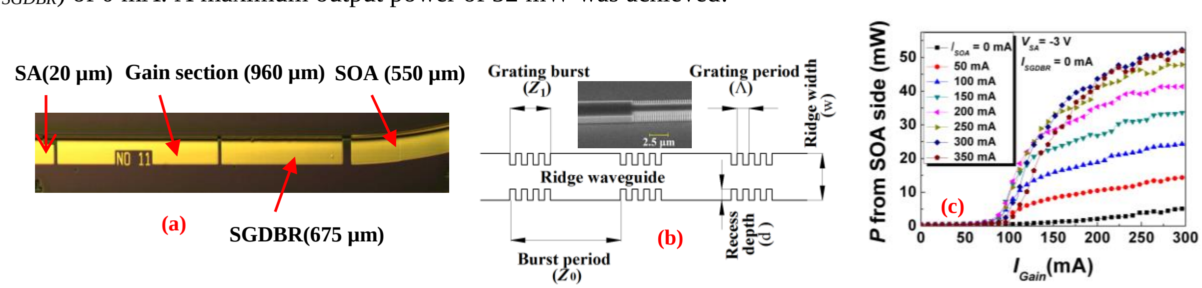

Fig. 1. (a) Optical microscope picture of the device, (b) schematic of the side-wall SGDBR and the inset shows the SEM picture of the side-wall grating burst of first-order with a 50% duty cycle and 0.6 μm depth recesses, (c) Typical output power from the SOA side vs the gain current with different I_{SOA} (from 0 mA to 350 mA with steps of 50 mA) when the V_{SA}= - 3V and I_{SGDBR}= 0 mA.

All results were measured from the SOA output facet. Pure ML operation at around 640 GHz pulse repetition frequency was observed for a large range of laser bias parameters: I_{Gain} varied from 40 mA to 290 mA, V_{SA} from 0 V to -3.0 V, I_{DBR} from 0 mA to 20 mA (below the I_{th} of the SG-DBR section), and I_{SOA} from 0 mA to >300 mA. When I_{Gain} was increased to >294 mA or $|V_{SA}|$ was decreased to -2.4 V, ML operation at the second harmonic frequency of F_r ~ 1.20 THz was observed.

Fig. 2(a) shows the 2D optical spectra for a range of I_{Gain} from 0 mA to 300 mA when V_{SA} = -3.0 V, I_{SGDBR} = 0 mA and I_{SOA}=300 mA. The optical spectrum with I_{Gain} = 288 mA is shown in Fig. 2(b). The central wavelength was 1570 nm with a channel spacing of 5.16 nm and a 3 dB bandwidth of 7.44 nm. The measured channel spacing corresponds to a mode-locked frequency, F_r, of ~628 GHz. The measured AC trace is shown in Fig. 2(c). The average period of the measured emitted pulse train was 1.59 ps, which also corresponds to an F_r of 628 GHz. The pulse width was 0.50 ps, assuming a sech^2 pulse shape. The time-bandwidth product (TBP) of the pulse is equal to 0.45. The average output power was 51.5 mW, with a corresponding peak power of 142 mW.

Fig. 3(a) shows 2D optical spectra for a range of I_{Gain} values from 0 mA to 300 mA when V_{SA} = -2.4 V and I_{SG} = 0 mA. An evolution to HML can be clearly seen at I_{Gain} > 294mA and the optical spectrum at I_{Gain} = 300 mA is shown in Fig. 3(b). The central wavelength was 1567 nm with a channel spacing of 9.6 nm and 3 dB bandwidth of 9.53 nm. The spacing of the peak wavelength of the adjacent channel was nearly double that shown in Fig. 2(b). The measured AC trace is shown in Fig. 3(c) where the average period of the measured emitted pulse train is 0.83 ps, which corresponds to an F_r of 1.20 THz (approximately the 2nd harmonic). The pulse width was 0.28 ps, assuming a sech^2 pulse shape. The TBP of the pulse is equal to 0.33. The average output power was 54.4 mW with a corresponding peak power of 142 mW.

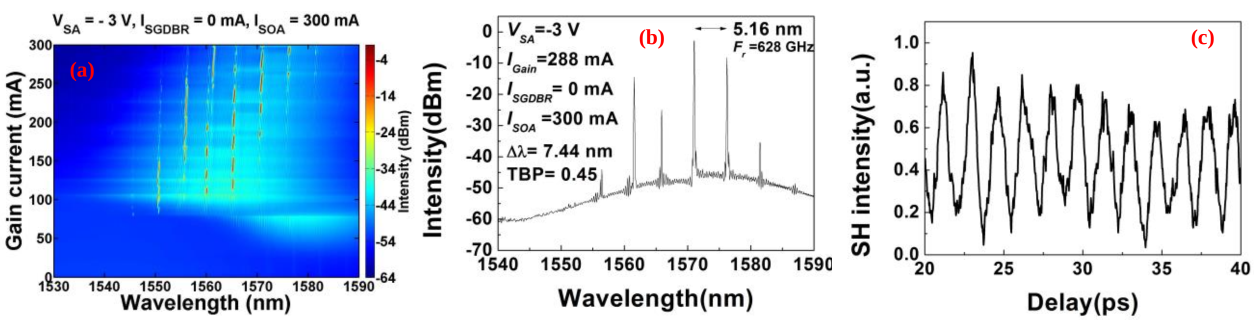

Fig. 2. Device performance under the operation conditions of V_{SA}= -3 V, I_{SGDBR} = 0 mA, I_{SOA} =300 mA: (a) 2D optical spectra as a function of gain current, (b) optical spectrum at the point of I_{Gain}=288 mA, (c) corresponding AC showing ML F_r of 628 GHz.

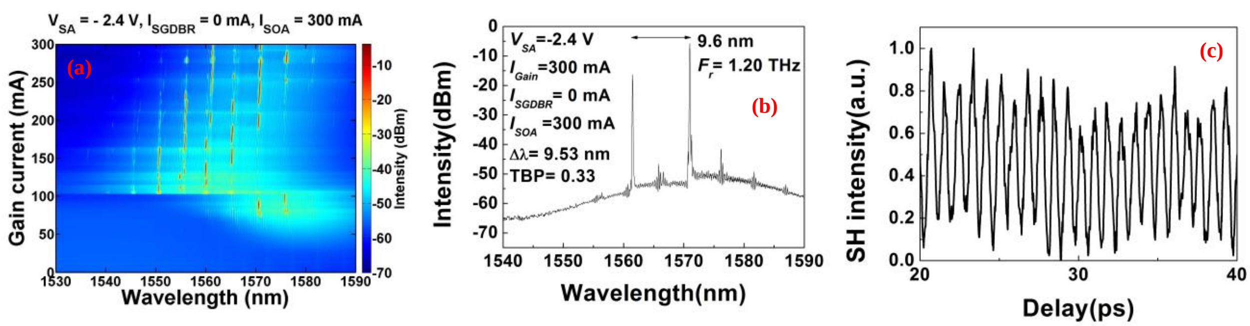

Fig. 3. Device performance under the operation conditions of V_{SA} = -2.4V, I_{SGDBR} = 0 mA, I_{SOA} =300mA: (a) 2D optical spectra as a function of gain current, (b) optical spectrum at the point of I_{Gain} = 300 mA, (c) corresponding AC traces showing ML F_r of 1.20 THz.

In conclusion, we have demonstrated both 628 GHz and 1.20 THz optical pulse generation with peak power of 142 mW using a 1.5 μm range AlGaInAs/InP side-wall SG-DBR MLL integrated with a SOA. The sampled gratings provided a high finesse optical frequency filtering, creating a comb of lines separated in frequency by the desired mode-locked frequency (or for 2nd harmonic operation, at half the mode-locked frequency). These high power LDs are expected to open up many opportunities for future compact THz applications.

References

[1] S. Arahira et al., IEEE J. Quantum Electron. **32,** 1211-1224 (1996).

[2] D. A. Yanson et al., IEEE J. Quantum Electron. **38**, 1-11 (2002).

[3] L. Hou et al., Opt. Lett. **38**, No.7, 1113-1115 (2013).

[4] A.J. Collar et al., IEEE Photon. Technol. Lett., **2**, 553–555 (1990).