Low Divergence Dual-Grating Distributed Feedback Lasers Operating at 1.0 µm

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Abstract: A 1.0 µm laterally-coupled dual-wavelength distributed feedback laser is reported, with a frequency separation of 1.1 THz and near-circular output beam with small divergence angle of 20.6° (H) × 22.8° (V).

OCIS codes: (140.5960) Semiconductor lasers; (140.3490) Lasers, distributed-feedback; (140.7090) Ultrafast lasers.

Dual-wavelength diode lasers (DWL) are useful in applications such as dual-wavelength interferometry, optical switching, and mm-wave and THz radiation generation [1]. Monolithic and hybrid integration technologies can be used to reduce form factor and/or improve phase correlation between the lasing modes to reduce phase noise in the beating signal. Among the various DWL configurations reported to date, simultaneous emission of two longitudinal modes within the same cavity is particularly appealing because the beam path and polarization of the two modes are automatically matched, and the beating frequency is relatively insensitive to temperature variations of the surroundings [2]. Previously, we reported an 820 GHz DWL operating at 1.55 µm which used a laterally-coupled dual-grating distributed feedback laser (DFB) with different grating periods on either side of the ridge waveguide. This device was fabricated in the AlGaInAs/InP material system [3]. However, GaAs-based devices operating around 900 nm – 1000 nm are less temperature sensitive and offer higher slope and wall plug efficiencies than their InP-based counterparts. Here we report a laterally coupled dual frequency DFB laser in the InGaAs/GaAs material system, which has a higher slope efficiency and reduced temperature sensitivity. It also has a low divergence output which increases the coupling efficiency with a cleaved single mode fibre (SMF).

A schematic of the fabricated device along with its dimensions is shown in Fig. 1(a). The device comprises a DFB section (1200 µm) and an EAM section (30 µm), with an electrical isolation slot (20 µm) between them. The ridge waveguide is 2.5 µm wide and 1.97 µm high, and the effective index of the guided mode was calculated to be 3.352. The epitaxial structure contains a 6 nm-thick InGaAs quantum well active layer sandwiched between two 7.5 nm-thick GaAs barrier layers (Fig. 1(b)). The graded-index separate confinement heterostructure (GRINSCH) layers and the cladding layers are made of AlGaAs, with the Al composition varying in the GRINSCH lasers. An $Al_{0.3}Ga_{0.7}As$ optical trap is introduced between the *n*-doped $Al_{0.33}Ga_{0.67}As$ lower cladding layer and the *n*-GRINSCH layer to pull the optical field distribution towards the *n*-side of the waveguide, expanding the optical near-field and reducing the internal loss resulting from free carrier absorption in the *p*-cladding layers. The thickness of GRINSCH and $Al_{0.3}Ga_{0.7}As$ layers are optimized to reduce the vertical divergence of the output beam [4]. A cavity containing the EAM is formed by the DFB grating reflectors on one side and the facet on the other. It is resonant at both DFB wavelengths simultaneously. This cavity enhances coupling between the two longitudinal modes through four wave mixing in the EAM [3], to improve phase locking and stabilize the mode beating frequency. The gratings for the DFB laser are of first-order, with a 50% duty cycle and formed by etching 0.6-µm recesses into the sidewalls of the waveguide, as shown in Fig. 1(c). The periods of the gratings on each side of the ridge are 150.5 nm (Λ_1) and 151 nm (Λ_2), which select Bragg wavelengths of 1008.95 nm (λ1) and 1012.3 nm (λ_2), respectively. The separation between the wavelengths is 3.35 nm with a corresponding beating frequency of 1.0 THz. A λ/4 phase shift grating section was inserted in both gratings at the middle of the DFB laser cavity to ensure each line oscillated in a single longitudinal mode [see Fig. 1(c)].

The device fabrication steps are similar to those described in [3], i.e., negative tone Hydrogen Silsequioxane (HSQ) was used as an e-beam lithography resist and reactive ion etching (RIE) dry etching hard mask, as well as acting as the material for planarizing the 1.97-µm-high ridge waveguide and gratings. The side-wall grating was realized in a single dry etch step using a

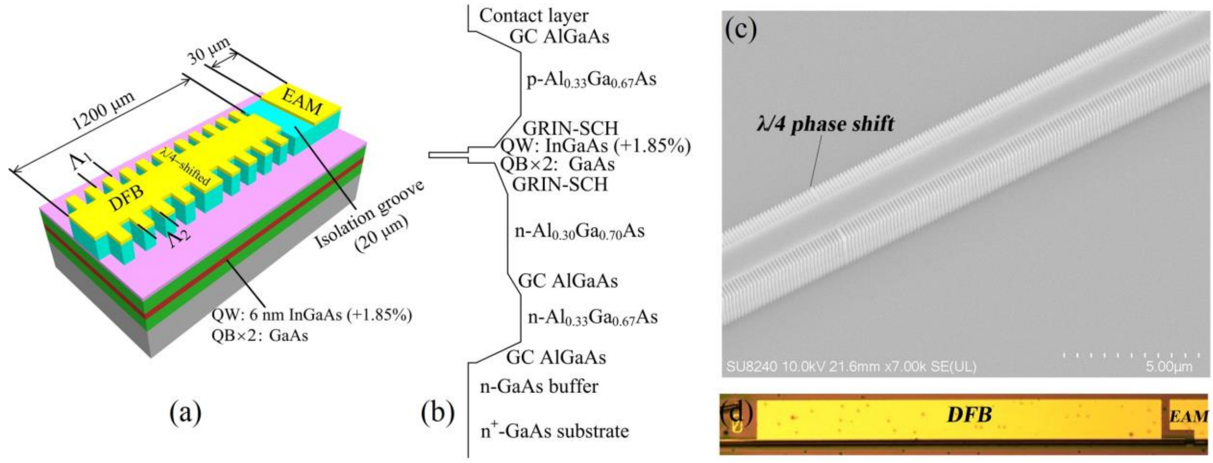

Fig. 1. (a) Schematic of the device; (b) bandgap structure of the wafer, (c) SEM picture of the first-order 50% duty cycle sidewall gratings with a 0.6-µm recess and λ/4 phase shift in the middle of the DFB laser cavity; (d) Micrograph of the fabricated device.

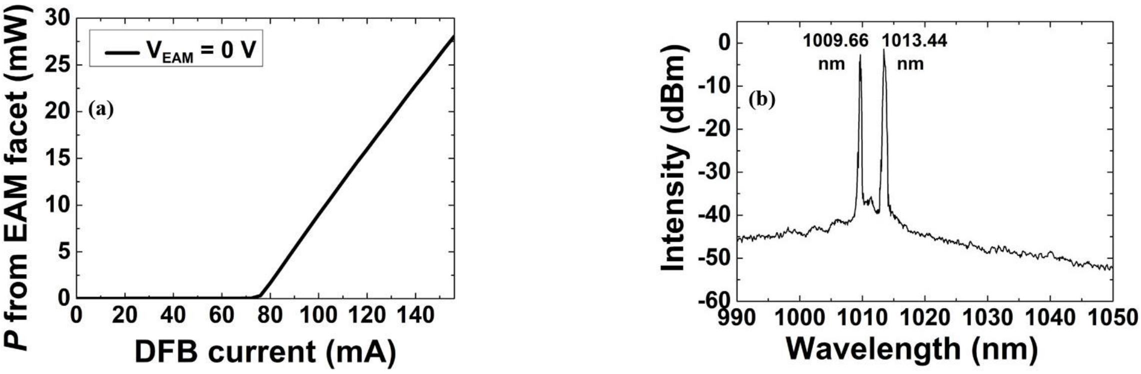

Fig. 2. (a) Measured output power as a function of I_{DFB} when V_{EAM}=0 V, (b) measured optical spectrum at I_{DFB}=104 mA and V_{EAM}= −0.8 V.

$SiCl_4/N_2/Ar_2$ recipe. The coupling coefficient, κ, for devices with identical gratings on both sides of the ridge was measured to be approximately 20 cm^{-1} using the sub-threshold spectral fitting method [5]. The 20-µm-long electrical isolation section between the DFB and EAM sections was formed by removing the highly doped 100-nm GaAs contact layer. As a final step, the sample was cleaved into individual laser bars with both facets left as-cleaved, as shown in Fig. 1(d). The devices were mounted epilayer-up on a copper heat sink on a Peltier cooler. The heat sink temperature was set at 20 °C, and the devices were tested under CW conditions.

Fig. 2(a) shows typical light-DFB current (L–I_{DFB}) characteristics from the EAM facet when the EAM reverse voltage (V_{EAM}) is 0 V. The threshold current and EAM facet slope efficiency were 76 mA and 0.35 W/A, respectively. Fig. 2(b) shows the optical spectrum of the DFB laser at I_{DFB} =104 mA and V_{EAM} = −0.8 V. The measured lasing modes were at wavelengths of 1009.66 nm (peak P_1) and 1013.44 nm (peak P_2), corresponding to a difference frequency of 1.1 THz, with a side mode suppression ratio (SMSR) >38 dB. The difference in intensities between P_1 and P_2 is <1.4 dB. The measured frequency difference between P_1 and P_2 is consistent within experimental error with that designed. The experimental wavelength peaks are slightly redshifted due device heating.

The far field pattern (FFP) from the EAM side was measured with a resolution of 0.9°. The inset in Fig. 3 shows the 3D FFP measured at V_{EAM} = −0.8 V, I_{DFB}= 104 mA. The output beam is almost circular (20.6° (H) × 22.8° (V)). Moreover, the butt-joint coupling efficiency with an SMF is around 30%, which is nearly three times that of a conventional semiconductor laser.

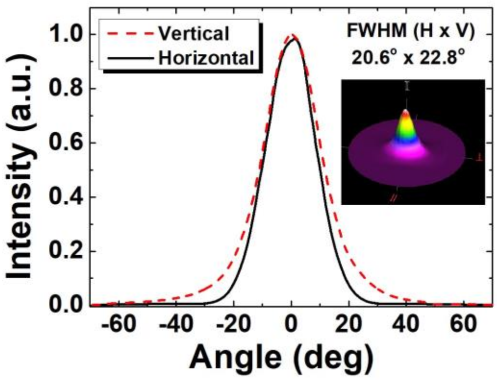

Fig. 3. Divergence angle of FFP at V_{EAM} = −0.8 V, I_{DFB} = 104 mA; the inset shows the 3-D FFP.

In conclusion, a laterally coupled dual-wavelength low-divergence-angle GaAs-based DFB laser integrated with EAM has been developed. The device emits two longitudinal modes simultaneously within the same cavity, separated by 1.1 THz at a wavelength of around 1010 nm. The devices were fabricated using simple first-order sidewall grating technologies, which have the advantage of eliminating crystal regrowth. These DMLs are expected to open many opportunities for future compact mm-wave and THz systems.

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