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Citation: Appl. Phys. Lett. **99**, 171107 (2011); doi: 10.1063/1.3654154
View online: https://doi.org/10.1063/1.3654154
View Table of Contents: http://aip.scitation.org/toc/apl/99/17
Published by the American Institute of Physics

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(Received 10 August 2011; accepted 12 September 2011; published online 26 October 2011)

Generation of stable dual and/or multiple longitudinal modes emitted from a single quantum dot (QD) laser diode (LD) over a broad wavelength range by using volume Bragg gratings (VBG's) in an external cavity setup is reported. The LD operates in both the ground and excited states and the gratings give a dual-mode separation around each emission peak of 5 nm, which is suitable as a continuous wave (CW) optical pump signal for a terahertz (THz) photomixer device. The setup also generates dual modes around both 1180 m and 1260 nm simultaneously, giving four simultaneous narrow linewidth modes comprising two simultaneous difference frequency pump signals. © *2011 American Institute of Physics*. [doi:10.1063/1.3654154]

THz optoelectronics until relatively recently had been dominated by sub-picosecond (sub-ps) signalling technology such as photoconductive (PC) switches and antennas[1,2] and optimised electro-optic materials such as ZnTe,[3] typically driven by a sub-ps pulsed Ti:Sapphire lasers. However, these femtosecond-pulse driven methods are limited not only in their technical performance by factors such as poor frequency tunability and low electro-optic efficiency: they are inherently bulky, complex, expensive, and mechanically unstable. The development of practical and compact THz optoelectronic systems has grown significantly throughout ongoing improvements in sub-ps carrier performance of semiconductor materials, e.g.,[4] and efficiency of laser sources. A very promising technique for the generation of efficient CW THz radiation is the application of LD optical pump beams with PC semiconductor heterodyne, or photomixer,[5] materials to generate a THz signal within the PC photomixer material via optical difference frequency generation (DFG).[6] This method is now well established, and semiconductor materials operating over a range of technologically significant bandgap energies between 800 nm and 1550 nm have been developed and implemented in THz antenna devices for some time.[7,8]

CW THz signals may be generated in photomixer materials in which (photo)carrier lifetimes are limited to less than roughly 1 ps. An optical pump signal composed of two distinct, narrow linewidth modes with around a few nm wavelength difference is employed by either the spatial combination of two coherent optical pump beams, or by using a single beam generated by a coherent multi-mode source. The offset longitudinal wavelengths of the optical pump results in a THz difference frequency and the PC material is modulated ("switched") at this frequency. As the material is switched, an electrical potential applied across metallic electrodes integrated with the material is coupled through the PC medium and into free space, analogously to a traditional Hertzian-type dipole antenna.

Many different methods of modulating light emission specifically from LD sources to obtain dual- or multi-mode outputs with minimal setup complexity have been developed, such as monolithic dual-longitudinal-mode LD's modulated via integrated DBR;[9] setups based on an external cavity with an etalon[10] and gratings;[11] and the use of VBG's in an external cavity.[12] Recently, Naderi *et al.*[13] demonstrated optical feedback enhancement of ground-state (GS) transitions in a QD LD emitting primarily via exited-state (ES) transitions, obtaining simultaneous GS/ES operation of a few milliwatts with a difference frequency between GS and ES wavelengths of ∼8 THz.[13] The development of QD LD sources has opened up new opportunity for powerful, efficient, and broadly tunable semiconductor lasers.[14] In this letter, we present a very simple, practical, and efficient method of generating multiple high-power, distinct, dual-mode THz difference frequency signals from a single QD LD emitting in two broadly separated IR spectral ranges via both ground and excited state transitions. This was done in a simple setup using only a single VBG in an external cavity for each respective wavelength range.

A two-section QD LD was used which was anti-reflective/highly reflective coated on the front/back facets, respectively. The QD wafer was grown by Innolume by molecular beam epitaxy (MBE) using the Stranski-Krastanow growth mode. The active region incorporated 5 identical layers of InAs QDs grown on a GaAs substrate. The total length of the QD LD was 2 mm with a ridge width of 6 μm. The laser was tested at 20 °C, controlled by a Peltier cooler, and was pumped with a low-noise current source. The spectral characteristics were measured by optical spectrum analyzer.

The VBG's were etched throughout $4 \times 3 \times 4$ mm photo-thermorefractive (PTR) glass windows, produced by OptiGrate. PTR glass is a silicate glass doped with Ce, Ag, F, and Br and is photosensitive. Under UV holographic exposure and a thermal development process, a refractive index change is induced in the window volume within the features defined by holographic pattern, which may be designed as successive planes throughout the window to form a Bragg grating.[15] "Multiplexed" VBG's may be designed to reflect two specific wavelengths when two gratings are "interlaced" within the window. "VBG1" was engineered to selectively return wavelengths 1177 ± 0.5 nm and 1182 ± 0.5 nm and VBG2 returned

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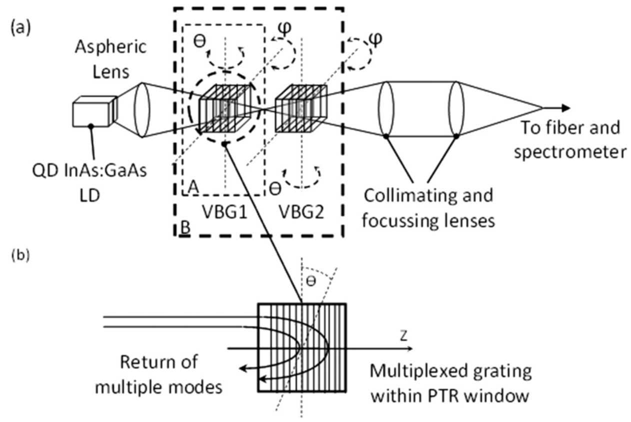

FIG. 1. The experimental setup and the configuration of: (a) one (box "A") or two (box "B") multiplexed VBG's in series with the LD output to form the external cavity; and (b) the grating itself. The distance between VBG1 and VBG2 is small (~15 mm) and the beam is adequately focussed throughout this region.

wavelengths 1257 ± 0.5 nm and 1262 ± 0.5 nm. The diffraction efficiency of both VBG's was 15% ± 5%, the grating thickness was 4 ± 0.75 mm and the grating tilt relative to the PTR window facets was 1° ± 0.7°, which prevents back-reflections between the grating and the window facet(s). The resultant separation of wavelengths returned by each VBG is configured as 5 ± 0.1 nm, which corresponds to difference frequencies of 0.946 ± 0.019 THz and 1.078 ± 0.021 THz for emission through VBG1 and VBG2, respectively.

The laser and VBG(s) were configured as in the setup shown in Figure 1. As the gain section of the LD was driven at a current of 70 mA, emission from GS transitions at 1260 nm wavelength is observed. At a LD drive current of 150 mA, the observed emission spectra confirmed that the laser was simultaneously emitting from both the GS and the ES at 1180 nm. As the LD gain current was increased to 210 mA, GS emission was observed to decrease and ES emission dominated the output. These emission spectrum are shown in separately Figures 2(a) and 2(b).

In the single VBG setup (box "A," Fig. 1), the LD output beam was focussed onto the VBG window using an AR-coated aspheric lens with focal length 4.5 mm. The VBG was tilted over angles ⊖ and φ as shown, and the dual-mode beam was transmitted from this cavity and refocused into an APE WaveScan IR spectrometer for analysis. The alignment of the VBG was monitored by observing the spectral output from the cavity as the VBG tilt was altered. Once each grating is aligned, the dual-mode spectrum remained perfectly stable so long as the VBG window was mechanically stable in its alignment. In the "double-VBG" setup (box "B," Fig. 1), the beam focus through the first VBG was altered slightly to accommodate an optimal focus over the two separate VBG's.[16] The two VBG windows were placed ~25 mm apart in series and each was aligned independently. The cavity could be setup at effectively any length, in this case, the cavity was kept at 7 cm.

The spectrum obtained from the cavity in each setup is shown in Figure 2. In each case, the output power and spectral profile remained stable during operation. As the gain current of the QD LD was increased to tune the relative output levels from GS and ES emission, the GS transition-dominant

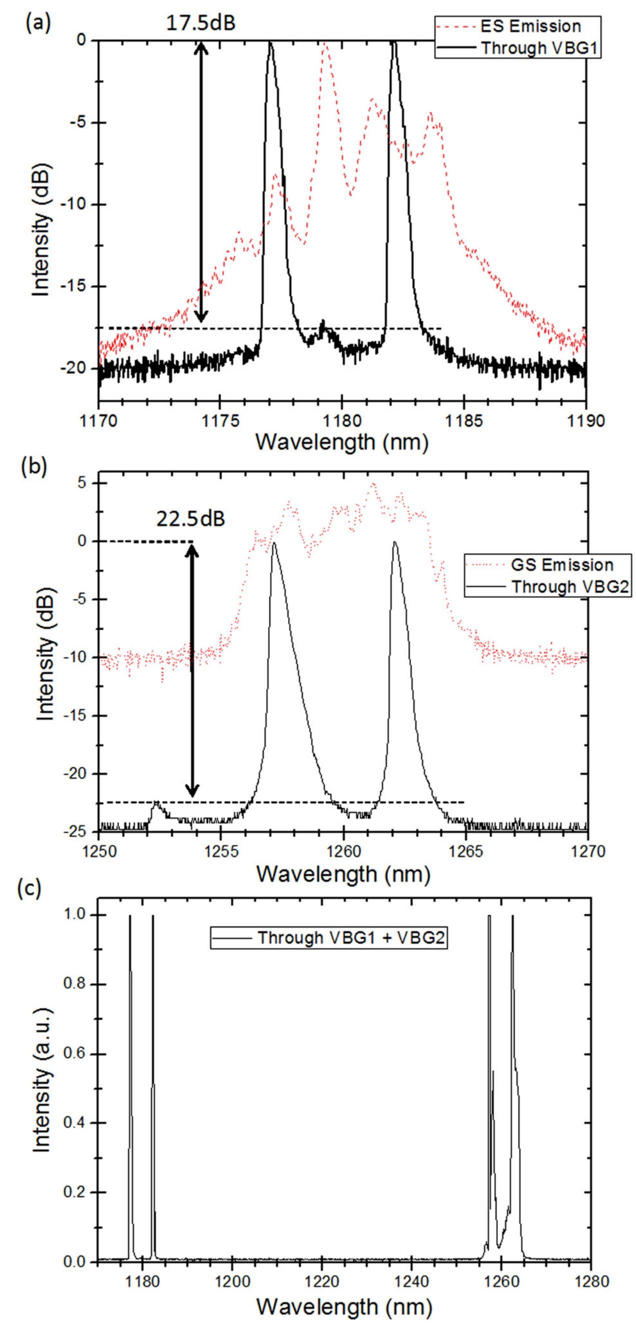

FIG. 2. (Color online) Spectrum obtained from the setup: (a) whilst driving the LD at 220 mA for ES emission and through VBG1; (b) at 80 mA for GS emission and through VBG2; and (c) at 150 mA for both GS and ES emission and through both VBG1 and VBG2 in series.

emission was stably and predictably reduced as the ES transition-dominant emission increased and no mode-hopping between these regimes was observed. The observed optical output power was 40 mW in ES operation through VBG1, 36 mW in GS operation through VBG2 and 50 mW in the double-VBG setup. The full width at half maximum (FWHM) of mode peaks 1 and 2, respectively, through VBG1 (Figure 2(a)) are 0.50 nm and 0.43 nm; and through VBG2 (Figure 2(b)) are 0.42 nm and 0.35 nm. The intensity of the signal through VBG1 is plotted in Figure 2(a). This indicates a side-mode suppression ratio (SMSR) of at least 17.5 dB for the grating's selected modes. The SMSR of the modes passed from VBG2 was at least 22.5 dB, as shown in Figure 2(b).

The VBG's may be configured to reflect any longitudinal mode/s at practically any wavelength region. QD-based LD materials may be engineered for tunable operation over a very wide range of wavelengths with high output powers.[14] The stability between GS and ES transitions appeared to be very good, and future work will investigate this stability over nano- and pico-second timescales. The system is capable of spectral control of high power optical signals as inorganic VBG's of this type perform without degradation up to tens of Watts average power or hundreds of kilowatts peak power (e.g., see Ref. 17). Using one LD and both VBG1 and VBG2 in series[16] and altering the LD gain current to give both GS and ES emission, simultaneous four wavelength output (at 1177/1182/1257/1262 nm) is also achievable, as shown in Figure 2(c). Spectral control of dual-modes is possible in a InGaAs/GaAs quantum well (QW) laser,[12] but the independent simultaneous spectral tuning at broadly separated spectral regions of a multi-QW laser designed for ultra-broadband spectral output may not be so straightforward, and one would expect a considerably lower electro optical efficiency. Demonstrated here is the exploitation of highly efficient QD gain material for the generation of broadband spectra[18] which is emitted from relatively simple semiconductor structure design produced using existing MBE techniques. Here, specifically, we have demonstrated up to two independent difference frequency optical signals at broadly separated gain medium carrier transition energy regimes that do not appear to compromise the stability of either signal. The ability to modulate the optical spectrum of a single QD LD in this way may open up the development of ultra-compact, practical solutions to a range of applications. The direct application of dual-wavelength optical signals in this case is the generation of THz radiation when used with photomixer devices but generating multiple modes is also useful in applications such as spectroscopy, and the ability to produce more than one dual-mode THz photomixer pump signal indicates the feasibility for applications such as two-colour THz imaging. We have also demonstrated broadly separated modal control of the QD LD using a single multiplexed grating ("VBG3") configured for modes at 1180 ± 0.5 nm and 1260 ± 0 nm. Using VBG3 in this setup (configuration "A," Fig. 1), dual-wavelength control with 80 nm modal separation was achieved.

In conclusion, we have demonstrated stable multi-modal optical beam outputs from a single QD LD emitting from GS and ES transitions modulated via either a single or multiple multiplexed reflective VBG's as an external cavity mirror. Simultaneously, broadly separated multi-wavelength outputs have also been demonstrated.

The authors would like to thank Dr. I. Krestnikov and Dr. D. Livshits of Innolume GmbH, Germany, for production of the QD diode lasers. This project was funded by EPSRC under Grant No. EP/H015795/1.

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