Monolithically Integrated, Sampled Grating DBR Laser Transmitter with an Asymmetric Quantum Well Electroabsorption Modulator

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Abstract

We present the first widely-tunable transmitter that employs intra-step quantum wells for intensity modulation. Fiber coupled output power is >2dBm with tuning range >40nm. EAMs show modulation depths >20dB, slope efficiency >7dB/V, and 10GHz bandwidth.

I. Introduction

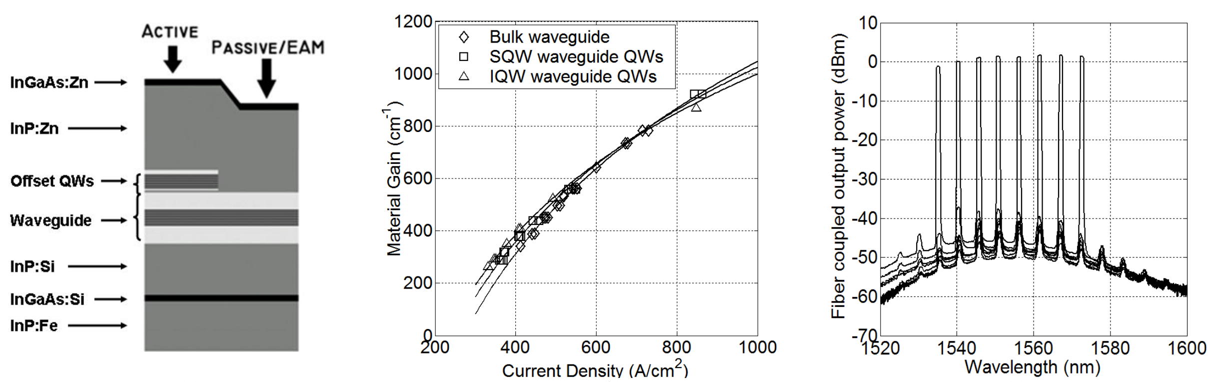
Monolithically integrated, widely tunable sampled grating DBR (SGDBR) laser transmitters with electroabsorption modulators (EAM)s are key components in next generation networks due to their compact size and their application in inventory reduction. The most common approach for fabrication of these devices is based on an offset quantum well (OQW) platform where a set of quantum wells above an optical waveguide is selectively removed to form passive/EAM regions and regions of optical gain (active). Recently, we have demonstrated a new dual quantum well (DQW) platform where a second set of square quantum wells (SQW)s is added to the waveguide layer of the OQW platform as shown in Fig 1a [1]. The additional waveguide SQWs significantly improve EAM performance over the OQW approach without additional processing or growth requirements.

In this work, we demonstrate for the first time, a novel SGDBR-SOA-EAM transmitter fabricated using the DQW platform that employs intra-step asymmetric waveguide quantum wells (IQW)s for intensity modulation. We show that the addition of IQWs does not affect the injection efficiency or material gain of the offset QWs used in the laser gain regions. Using photocurrent spectroscopy, we show that the presence of the potential discontinuity in the waveguide IQWs delays the exciton peak shift under applied bias as predicted in [2]. This delay in exciton shift has been used successfully to suppress the onset of EAM absorption and hence shift operating conditions to higher electric fields, where carrier screening effects are significantly reduced [3]. This work demonstrates that the DQW platform can employ exotic waveguide QW structures to taylor EAM properties, such as chirp and modulation efficiency, without degrading integrated laser performance and without additional growth requirements [4].

II. Transmitter Layout and Epitaxial Structure

The IQW tunable transmitter consists of a four section, sampled grating DBR laser, a 550 μm long SOA, and a 400 μm long EAM similar to that in [1]. Transmitters were thinned, anti-reflection coated, mounted on AlN carriers, and wirebonded for characterization. A low-K dielectric, photo-Bisbenzocyclobutene, is employed under EAM pads to reduce parasitic capacitance.

The waveguide layer in the DQW base structure contains 7x10 nm wide compressively strained IQWs and 6x5 nm wide tensile strained barriers. The IQW is divided into a deep 4 nm wide section, and a shallow 6 nm wide section, as shown in insets (i), (ii), and (iii) of Fig 2c. The band offsets to the deepest part of the IQWs are 100 meV and 125 meV, and the intra-step band offsets are 42 meV and 50 meV in the conduction and valence bands, respectively. The deep portion of the IQW is on the n- side of the waveguide PIN structure. The doping scheme in the waveguide is the same as in [1], with low n-type Si-doping (5×10^{16} cm^{-3}) employed outside the wells and barriers. The photoluminescence (PL) peak of the IQW stack is 1465 nm. The remaining layers of the base structure, including the design of the offset QWs above the waveguide, are identical to that in [1].



(a) (b) (c)

Figure 1. (a) The DQW epitaxial structure used for transmitter fabrication. (b) Material gain vs. current density extracted from BAL test structures. (c) Transmitter output spectra for various operating wavelengths with laser gain and SOA bias at 140 and 120 mA respectively.

III. Test Structures and Integrated Transmitter Results

To examine the impact that the waveguide IQWs have on optical gain regions, pulsed differential efficiency measurements were performed on a set of 50 μm wide Fabry-Perot broad area lasers (BAL) and 3 μm wide ridge lasers (RL) using the cleave back method. For comparison, an identical set of BALs and RLs employing either a bulk waveguide (PL = 1410 nm) or a set of SQWs in the waveguide (PL = 1480 nm) were fabricated and tested. From the threshold current and differential efficiency of the BALs, a two parameter fit material gain curve was generated for data from each of the three platforms. Results are shown in Fig 1b. The material gain parameter for the IQW, SQW, and bulk waveguide structures was 745, 764, and 826 cm^{-1}, and the transparency current density was 230, 270, and 246 A/cm^2. The injection efficiency extracted from the test RLs was 71%, 73 %, and 75% for IQW, SQW, and bulk waveguide designs respectively. The close agreement between the laser injection efficiency, material gain, and transparency current density results for devices fabricated from each structure indicates that arbitrary QW shapes could be used in the waveguide to taylor EAM performance without degrading laser characteristics.

The output spectra from the SGDBR-SOA-EAM transmitter is shown in Fig 1c. The SGDBR laser is tunable over greater than 40 nm ranging from 1535 to 1578 nm, and fiber coupled output power from the device was up to +2 dBm with gain section and output SOA biased to 140 and 120 mA respectively. On chip light vs. injected current (LI) was measured by reverse biasing the SOA positioned after the front mirror of the SGDBR laser. The threshold current at 1550 nm was 35 mA, which is in agreement with data from SGDBR lasers fabricated in the standard OQW platform, and greater than 12 mW of on-chip optical power was achieved with 100 mA gain bias. DC extinction characteristics of the 400 μm long integrated EAM are shown in Fig 2a. We observe > 7 dB/V slope efficiency along with modulation depths of > 20 dB over output wavelengths from 1535 to 1565 nm at -7V bias. Electrical to optical S_{21} measurements of the 50 Ω terminated EAM showed a 3dB bandwidth of 10 GHz.

Photocurrent spectroscopy measurements were performed on a set of test diode structures to compare the absorption coefficient of the EAM IQWs to a set of standard EAM SQWs. The experimental set-up and the diode dimensions are identical to that used in [5]. The SQWs waveguide region contained 7x10 nm wide compressively strained and with 6x5 nm wide tensile strained barriers. The PL peak of the SQWs was 1470 nm and the band offsets in the conduction and valence bands are the same as on deep side of the IQWs. Material absorption coefficient results from the spectroscopy measurements are shown in Fig. 2b and Fig. 2c respectively. Results for the SQW material absorption coefficient under applied bias shows a typical square QW exciton peak shift and corresponding decrease in exciton intensity as the wavefunctions polarize to opposite sides of the well. Simulated wavefunctions at (i) 0V, (ii) 1.5V, and (iii) 4V reverse bias are shown as insets in Fig. 2b to illustrate the polarization effect. For the IQWs, the absorption coefficient measurements show a high intensity, well resolved exciton peak that does not shift under applied bias. This confirms the predicted delay in exciton peak shift [2] that comes as a result of the intra-step barrier. Simulated wavefunctions for the IQW wells are shown in the insets of Fig 2c at (i) 0V (ii) 1.5V, and (iii) 4V applied reverse bias, where clear distortion of the heavy hole wavfunction is visible at 1.5V due to the intra-step barrier. This effect can be used to delay absorption in the EAMs, shifting operation to high biases and reducing the potential for carrier screening effects.

V. Conclusions

We have shown for the first time a monolithically integrated tunable transmitter that uses asymmetric IQWs in the EAMs for intensity modulation. The integrated SGDBR laser shows fiber coupled output powers up to +2 dBm and greater than 40 nm tuning between 1535 and 1578 nm. Integrated EAMs show modulation efficiency greater than 7dB/V, and modulation depths greater than 20 dB between 1535 and 1565 nm. The excellent agreement of the BAL gain data using active regions with various waveguide layers demonstrates the potential of the DQW platform to use arbitrarily shaped QWs for EAM modulation efficiency without degrading laser performance and without introducing additional growth complexity. Photocurrent spectroscopy has been used to measure the broadband absorption coefficient of the IQWs and we have observed a delay in the exciton peak shift under applied bias, which agrees with predicted performance.

References

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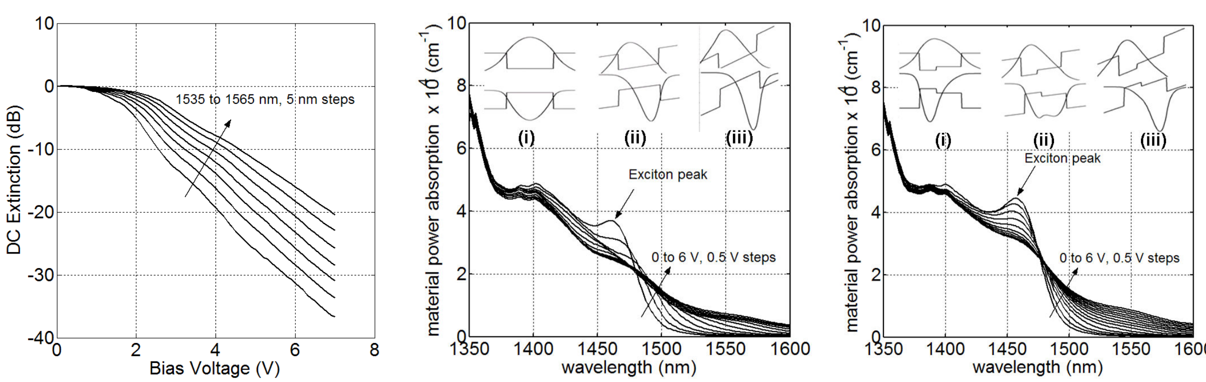

(a) (b) (c)

Figure 2. (a) DC extinction characteristics of integrated 400 μm long EAM. (b) Material absorption coefficient extracted from photocurrent spectroscopy for standard square QWs. (c) Material absorption coefficient extracted from photocurrent spectroscopy for IQWs.