Widely tunable Y-junction lasers at 2.34 – 2.39 µm wavelength for trace-gas sensing applications

Thanh-Nam Tran, Saroj Kumar Patra, Kjetil Haddeland, Magnus Breivik, and Bjørn-Ove Fimland

***Abstract*— Widely tunable Y-junction lasers have been realized in the wavelength range of 2.34 - 2.39 µm for trace-gas sensing application. Y-junction structures with large bend radius and small length difference between the two cavities have been chosen to maximize the output power and wavelength tunability while having sufficient side mode suppression ratio (SMSR). By changing the electric currents in different sections of the Y-junction lasers, a tunable wavelength range of 50 nm with an SMSR > 23 dB was achieved.**

***Index Terms*—Tunable diode lasers, Y-junction, mid-infrared, Gallium Antimonide (GaSb), side mode suppression ratio (SMSR).**

I. Introduction

GaSb-BASED type-I semiconductor diode lasers with high optical gain, simple growth design and easy approach to continuous wave (cw) operation at room temperature (RT) are excellent candidates for mid-infrared lasers in the wavelength region of 1.5-3.3 µm [1-3], whose applications include the monochromatic light sources needed for trace-gas sensing systems based on tunable diode-laser absorption spectroscopy (TDLAS). The drawback of GaSb-based type-I lasers compared to the well-known quantum cascade lasers in trace-gas sensing applications [4-7] is that as the emission wavelength increases, the internal loss of this type of lasers rises due to stronger free-carrier absorption and restricts their operation at long wavelengths beyond 3.3 µm. Among edge-emitting laser structures for light source of TDLAS, Y-junction structure is an interesting alternative, thanks to its wide tunable range and less complex fabrication process. Most of widely tunable monolithic laser structures benefit from passive gratings and phase sections, requiring epitaxial regrowth of the laser structure [8]. This regrowth could be performed for GaSb-based laser structures [9], but has to overcome the reactive nature of AlGaAsSb [10] used for the cladding layers. Y-junction lasers provide a regrowth-free solution, using less complex processing steps and tools (such as conventional photolithography), resulting in potentially lower costs and higher yield. First studied by Wang, Choi and Fattah [11, 12], the Y-junction lasers were later further developed by other groups focusing on optical communication applications [13-17]. Recently, tunable lasers using Y-junction [18, 19] or related structures such as Mach-Zehnder (MZ) interferometer [20-23], V-coupled cavity [24], modulated grating Y-branch [25] and multimode interference couplers [26, 27] have been investigated, typically for gas sensing and communication applications. For the regrowth-free, low-cost tunable lasers, a tuning range of up to 55 nm and an SMSR exceeding 30 dB have been reported for the wavelength region of 1.5-1.6 µm [22, 26-28].

In the present work, the ridge waveguide Y-junction structure, which can be considered a “half MZ interferometer”, consists of two S-bend cavities with same bending radius sharing a common section, as shown in Fig. 1, but where one S-bend cavity is shorter due to a shorter bend section. The geometrical path difference ΔL allows the selection of the overlapped modes (supermodes) between two mode-combs of these two cavities, called the Vernier effect, thus enabling the interferometric tuning behavior of the Y-junction lasers when the mode-comb of one cavity is shifted relative to the other. Here, Y-junction lasers of different configuration (i.e., different bend radii r and ΔL) have been fabricated and characterized. The main goal is to maximize wavelength tuning range while keeping the SMSR sufficient for gas detection [29]. With the tuning range of 2.34 – 2.39 µm, several targeted gas molecules

Manuscript received …, revised …, accepted… Date of publication… This work was supported in part by the Norwegian University of Science and Technology through the Strategic Area Materials program, in part by the Research Council of Norway under Grant 177610/V30, and in part by the Norwegian Micro- and Nano-Fabrication Facility under Grant 197411/V30. *(Corresponding author: Bjørn-Ove Fimland.)*

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This article has been accepted for publication in IEEE Photonics Technology Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LPT.2023.3298354

can be detected such as CH_4 and CO, which have strong absorption lines in this wavelength regime [30-32].

II. Experimental

In this study, GaInAsSb/AlGaAsSb quantum well (QW) diode lasers emitting at 2.3 µm wavelength were grown on n-type GaSb (001) wafer by molecular beam epitaxy (MBE). The active region consisted of three 12 nm wide $Ga_{0.67}In_{0.33}As_{0.10}Sb_{0.90}$ QWs separated by 20 nm wide quaternary $Al_{0.35}Ga_{0.65}As_{0.026}Sb_{0.974}$ barrier layers and sandwiched between two 145 nm wide undoped $Al_{0.35}Ga_{0.65}As_{0.026}Sb_{0.974}$ separate confinement layers. For optical and electrical confinement, the active region was surrounded by n- and p-type doped $Al_{0.90}Ga_{0.10}As_{0.06}Sb_{0.94}$ cladding layers with the thickness of 2 and 1.4 µm, respectively. The carrier concentration in the cladding layers has been optimized to enhance the laser performance [33].

5 µm wide ridge Y-junction lasers, with locally symmetric Y-splitter structure and with different bend radii r and length differences ΔL, were processed into the structure shown schematically in Fig. 1. For the loss characterization in the Y-junction structure, straight lasers with the same waveguide width were also fabricated for comparison. To improve the light confinement in the Y-junction structure, especially in the bend sections, a deep etch (within 100 nm above the active region) is important. The etch depth can be precisely controlled by *in situ* reflectance monitoring [34]. For the contact planarization and waveguide sidewall isolation, photoresist ma-N440 was spin-coated followed by thermal hardening and O_2/CF_4 Reactive Ion Etching etchback. Prior to metallization, *in situ* cleaning of the GaSb surface by optimal-ion-energy (180 eV) Ar^+ irradiation was applied to remove the native oxide [35]. The conventional gold-based contacts, Ti/Pt/Au and Pd/Ge/Au/Pt/Au, were used for top and bottom laser contacts, respectively, followed by annealing. The lasers were cleaved into bars of 1.5 mm before being mounted epi-side-up on copper heat sinks. The laser diodes were characterized in cw operation at 16 °C without any facet coatings.

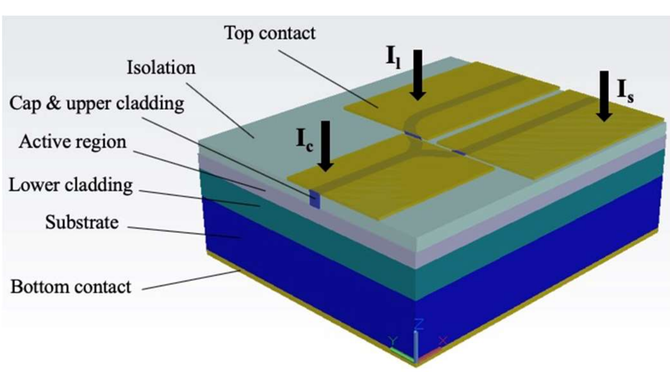

Fig. 1. Schematic of a fabricated Y-junction laser with three top electrodes for current injection, where I_c, I_s and I_l are the injected currents for the common section, the shorter arm and the longer arm, respectively.

III. Results and Discussions

Fig. 2 shows the output power characteristics of Y-junction lasers with different bend radii where all three currents were kept identical. The typical Y-junction laser (r = 1000 µm, ΔL = 20 µm) exhibits a relatively high threshold current density J_{th} of 1140 A/cm^2 (380 A/cm^2 per well) compared to the straight waveguide lasers (J_{th} = 750 A/cm^2). A significant contribution to the high threshold current density is the bend losses not found in the straight laser structures. The inset in Fig. 2 displays the single-mode behavior of the Y-junction lasers emitting at 2.37 µm with an SMSR of 25 dB. The laser linewidth or the full width at half maximum (FWHM) of laser peak is measured to be ~0.1 nm which is suitable for high accuracy gas sensing applications as simulated by Chan et al. [36]. The characteristic temperature (T_0) of 84.3 K measured from straight waveguide lasers of the same laser growth structure indicates a good thermal stability of the devices.

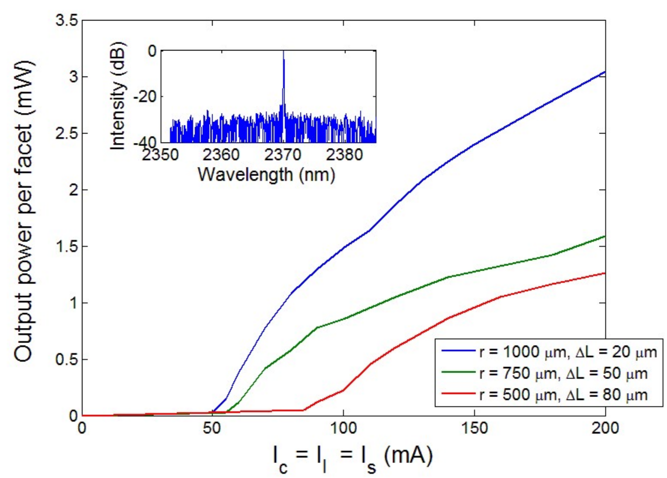

Fig. 2. Output performance of the Y-junction lasers with different bend radii. Single-mode emission with SMSR = 25 dB is shown in the upper inset, recorded for the Y-junction configuration with r = 1000 µm and ΔL = 20 µm. (See Fig. 1 for definition of I_c, I_l and I_s.)

The design of the bend section in the Y-junction structure significantly affects the performance of the final devices in terms of output power and wavelength tunability. As the bend radius decreases, the optical losses due to leakage in the bend section and the mode mismatch between the straight and bent waveguide segments increases, resulting in higher total loss and lower output power [37, 38], as seen in Fig. 2. Moreover, for a given waveguide separation, the bend radius also determines the length difference ΔL between two cavities in the asymmetric Y-junction structure. The larger the bend radius, the smaller ΔL can be, and thus a higher tuning range, given by $\Delta\lambda_Y = \lambda^2/2n_{g,eff}\Delta L$ where $n_{g,eff}$ is the effective group index, can be achieved. Therefore, larger bend radius is preferable to maximize the output power and the tuning range. With $n_{g,eff}$ = 3.75 (determined from mode spacing measurements), the theoretical tuning range of the Y-junction lasers with the largest r = 1000 µm and ΔL = 20 µm in this study is $\Delta\lambda_Y$= 36.5 nm, which is in agreement with the experimental results presented in Fig. 3(a) (i.e., by keeping $I_c = I_s$ = 120 mA and varying I_l, the tuning range is 37 nm with an average tuning rate of 0.6 nm/mA). The drawback of the Y-junction configuration is the tradeoff between increased tuning range and the associated reduction in SMSR [15]. However, a typical SMSR of 23 dB and up to 25 dB is obtained in this work, which satisfies the requirement for trace-gas sensing application.

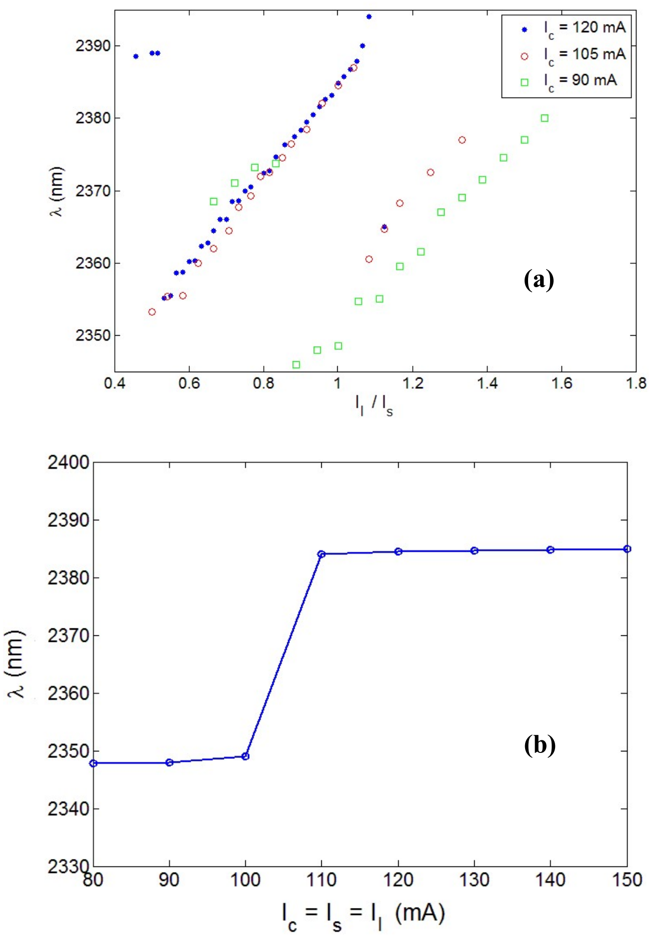

Fig. 3. Tuning behavior of Y-junction laser with r = 1000 µm and ΔL = 20 µm. (a) Variation of the MZ filter across the FP modes. (b) Variation of the whole gain curve across the MZ filter.

The tuning behavior of the Y-junction lasers has been characterized as shown in Fig. 3. By adjusting the injection currents into each section, the emitted wavelength can be tuned in two different ways which allow the largest variety of controllable applications [15]. The first tuning scheme is based on the variation of the MZ filter across the Fabry-Perot (FP) modes. By varying the ratio of the injection currents into the longer arm (I_l) and the shorter arm (I_s), the sawtooth-shaped tuning behavior can be observed as shown in Fig. 3(a) when the position of the MZ loss minimum is tuned across the allowed FP modes (continuous tuning) until the neighboring minimum reaches the same low level (step-like tuning). The single-mode lasing spectra with a tuning range of 32 nm covered in steps of 1-3 nm is displayed in Fig. 4. By combining with variations of the injected current into the common section (I_c), a wide tuning range of up to 50 nm can be obtained. This would be advantageous as it can enable several gases to be detected by one single laser. The second tuning scheme is achieved by changing all of the injected currents simultaneously (usually equal) to shift the whole gain curve across the MZ filter. Step-like tuning behavior can be observed, as shown in Fig. 3(b), resulting from the switch of the supermode when the level of the next MZ loss minimum has reached the value of the previous one.

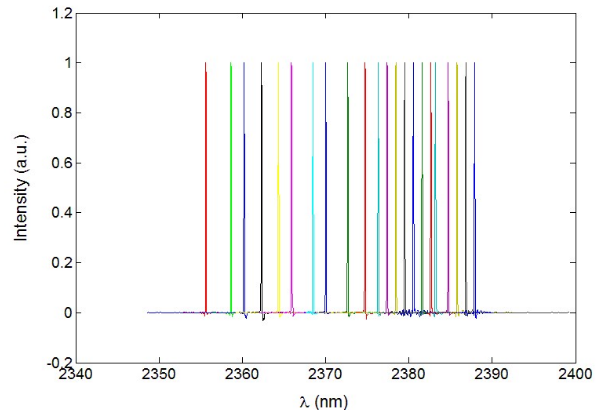

Fig. 4. Single-mode lasing spectra (with normalized peak intensities) of the Y-junction laser (r = 1000 µm, ΔL = 20 µm) with a 32 nm tuning range.

IV. Conclusions

Tunable Y-junction lasers lasing at 2.34 – 2.39 µm wavelength have been successfully fabricated and characterized. A single-mode emission tuning range as wide as 50 nm is demonstrated for Y-junction laser with bend radius of 1000 µm and length difference of 20 µm between the two cavities. In addition, the devices exhibit good output performance in terms of power, FWHM and SMSR that makes Y-junction laser a promising candidate for trace-gas sensing applications.

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