Single-mode tunable interband cascade laser emitting at 3.4 μm with a wide tuning range over 100 nm

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***Abstract*—We report a widely tunable monolithically integrated V-coupled cavity interband cascade laser (ICL) emitting near 3.4 μm. The mode selection is achieved using a half-wave V-coupler designed for the ICL in the mid-infrared range without any grating. The side-mode suppression ratio is demonstrated up to 35.7 dB. In the heat-sink temperature range from 130 K to 140 K, single-mode wavelength tuning range of over 100 nm from 3329.9 nm to 3431.3 nm has been attained by adjusting both current and temperature. These results show that the V-coupled cavity ICLs are very promising for multi-species trace gas absorption spectroscopy with a high sensitivity.**

***Index Terms*—interband cascade laser, tunable laser, mid-infrared laser.**

I. Introduction

Type-II interband cascade lasers (ICLs) represent a class of mid-infrared (MIR) semiconductor lasers with useful applications such as gas sensing, industrial processing control, free space communications, medical diagnostics, and MIR lidar [1-5]. The ICL is often viewed as a hybrid between a conventional diode laser that generates light from electron-hole recombination and an quantum cascade laser (QCL) [6]. Like intraband QCLs, every injected electron is reused for generating multiple photons in ICLs with high quantum efficiency. However, unlike QCLs, ICLs use transitions between the conduction and valence bands with opposite dispersion curvatures without fast phonon scattering. This leads to low-threshold current that makes it particularly well suited for power-constrained sensing applications [3, 4]. Type-II ICLs can be constructed from the nearly lattice-matched InAs/GaSb/AlSb III-V material system with wavelength coverage from the MIR to the far-IR [7-9].

For single-mode applications, distributed feedback (DFB) gratings are usually incorporated into ICLs [10, 11]. However, the tuning range of a DFB laser is limited to a few nanometers, based on small refractive index changes due to current heating. The external cavity lasers can achieve wide spectral tuning [12, 13]. However, discrete components make it large in size, complicated in packaging and slow in tuning, which is not conducive to low-cost manufacturing. This situation hinders their wide-scale deployment, despite robust societal demand.

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Recently, a compact V-coupled cavity laser (VCCL) with a half-wave coupler has been proposed for widely tunable single-mode operation and well developed at telecommunication wavelengths [14]. The VCCL is simple in structure, reliable in operation, and small in size without complex grating fabrication and multiple epitaxial growth. Only single electrode control is required for discrete tuning, which greatly simplifies the driving circuit [15]. In contrast to a conventional DFB laser, where the tuning range is limited by a few nanometers around the grating-determined wavelength, a VCCL can have a large tuning range without such a limitation. Initial effort to combine the ICL with a half-wave V-coupled cavity structure had demonstrated single-mode MIR semiconductor lasers with a tuning range of 60 nm near 2.9 μm. It validated the operating principle and feasibility of VCCLs in the MIR ICLs [16]. Nevertheless, IC VCCLs have yet to achieve their full tuning potential.

In this work, by improving the waveguide structure and device fabrication, we report V-coupled cavity ICLs capable of single-mode emission with a tuning range exceeding 100 nm near 3.4 μm, which further shows the great tuning capability of VCCLs to cover a wide wavelength range for practical multi-species gas sensing applications.

II. Device Structure and Fabrication

The ICL sample used for this work has 12 cascade stages sandwiched by two InAs/AlSb superlattice cladding regions and was capped by a 35-nm-thick n-type InAs contact layer. Each stage comprises a W-type quantum well active region [17-19] designed to cover the emission spectrum region from 3.2 to 3.5 μm, where CH_4, C_2H_6, C_3H_8, C_2H_5OH and HCl, etc. exhibit strong absorption lines. A piece of this ICL wafer was previously processed using wet etching into 15-μm-wide ridge laser devices that lased in pulsed mode at temperatures up to 300 K with a threshold current density of 1.9 kA/cm^2 and at an emission wavelength near 3.5 μm. In continuous wave (CW) operation, the device lased at temperatures up to 205 K with a threshold current density J_{th} ranging from ~18 A/cm^2 at 80 K to 42, 87, 182, 355, 533 A/cm^2 at 120, 150, 180, 200, 205 K, respectively, covering a wavelength range from ~3.25 (80 K) to 3.43 μm (205 K). Its slope efficiency was ~0.72, 0.5, 0.4, 0.26, 0.2 A/W at 80, 120, 150, 180, 200 K, respectively.

To achieve a single-mode operation with a wide tuning range, the V-coupled cavity configuration is implemented into the ICL structure as shown in Fig. 1, in which two Fabry-Perot (FP) cavities of different lengths are connected through the half-wave coupler. The detailed operation principle of the VCCL has been described in Ref. 16. The coupler selects optical modes and ensures the single longitudinal mode output. The laser can be tuned in a wide range through the Vernier effect between two FP cavities of slightly different optical path lengths. For many applications, a single-mode is required not only in the longitudinal dimension but also in the lateral dimension. This usually requires the waveguide to be very narrow, which presents a challenging issue for the fabrication of low-loss ICL devices. This is because the ICL structure has more than a thousand layers, and consequently the lateral conductance is much higher than the vertical conductance. Therefore, a deep etching through the cascade core is typically required to confine the injected carriers laterally and ensure uniform injection of current into each cascade stage. However, this deep etching may cause substantial current leakage through side walls and light scattering loss, especially with the narrow ridge. To alleviate such an issue, a double-ridge waveguide structure is employed as shown in Fig. 2.

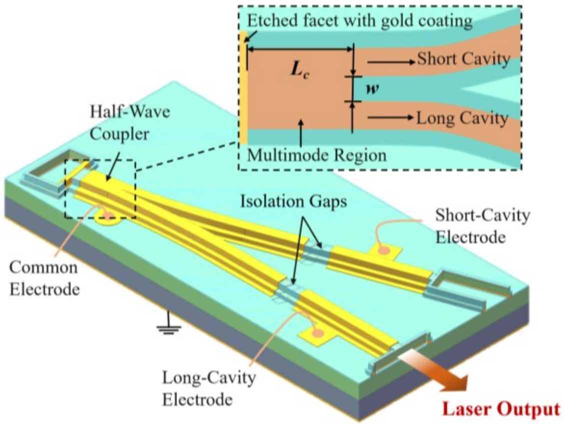

Fig. 1. Schematic drawing of a V-coupled cavity ICL.

In this double-ridge waveguide configuration, the wide and deep etched waveguide ensures the uniform current injection, while the narrow and shallow etched waveguide restricts the light field, similar to widely used narrow ridge in near-IR semiconductor lasers. Compared to the usual deep etched ICL waveguide that requires a narrow ridge for the single lateral mode, the double-ridge waveguide configuration allows the deep etched ridge ICL waveguide to be wider and still satisfies the condition of the single lateral mode. As such, the depth to width ratio for the deep etched ridge is substantially reduced and consequently the optical loss due to the possible sidewall roughness is significantly reduced since the mode field is relatively away from the sidewalls. However, the deep etched ridge should not be too wide to avoid the need of a large current and more heat generation, which is determined by the proper balance between the above-mentioned factors and heat management. The double-ridge structure was previously employed in DFB ICLs [20], but has not been used in V-coupled cavity ICLs until this work.

As shown in the inset of Fig. 1, the half-wave coupler, with a high reflection coating on the end facet for reducing the cavity loss, is composed of a multimode region that produces a specific bar-coupling and cross-coupling coefficients with a phase difference of π. With the relative π-phase difference, the two output ports produce synchronous power transfer functions, which is critical in the VCCL to realize a high sidemode suppression ratio (SMSR). As for the design of the half-wave coupler, the length (L_C) of the multimode region and the gap (w) of the two output waveguides were scanned in the FDTD analysis to reach the target phase difference and cross-coupling coefficient. Three electrodes were deposited for the current injection. The current I_C through the coupler electrode that covers 60% of the FP cavity, provides the most optical gain. Current I_L through the long-cavity electrode selects the wavelength channel by adjusting its magnitude. Current I_S through the short cavity electrode provides a fixed gain and auxiliary tuning.

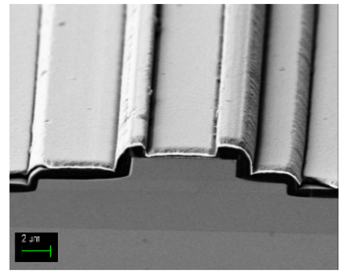

Fig. 2. SEM images of the cross-sectional view of the double ridge waveguide.

The isolation gap was first defined in the fabrication process by wet etching to prevent current crosstalk between electrodes. Since the InAs contact layer is only 35 nm thick, a 150 nm thick Ti/Pt/Au layer was deposited before the ridge etching to avoid the destruction of the InAs layer during the etching of the top via window. BCl_3-based inductively coupled plasma (ICP) etching process was used with contact lithography to form the ridge waveguide. The deep dry-etching process was controlled to stop at the bottom cladding layer with a depth of 2.6 μm, while the shallow etch was stopped at the top cladding layer with a depth of 1.7 μm. A 500 nm-thick SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition on the top surface for the insulation, followed by via etching and contact pad deposition through a lift-off process. Then the substrate was thinned to about 150 μm, and a common ground electrode was deposited on the backside. Fig. 2 shows the scanning electron micrograph (SEM) of the cross-section.

III. Experimental Results and Discussions

The ICL devices were cleaved close to the facet of the long cavity and mounted epitaxial-side-up onto a copper heat-sink, which was then installed in a liquid-nitrogen cooled cryostat (from CYRO company) with a CaF_2 optical window (~10% transmission loss) and a temperature controller. A Thorlabs S180C MCT power meter was used to measure the output optical power. The CW emission spectra were obtained by a Fourier transform IR (FTIR) spectrometer from Bruker Vertex 70 with a spectral resolution of 0.3 cm^{-1}. This Vertex70 FTIR spectrometer has a finite dynamical range, which limits the SMSR measurement of laser spectra to about 35 dB. This is verified by examining and comparing the emission spectra of a single mode DFB laser at 1550 nm using this FTIR spectrometer and a grating-based spectrometer.

Table I. Structural Parameters

Parameter	Value
Shallow-etched waveguide width	8.0 μm
Deep-etched waveguide width	18.0 μm
Coupler length	76 μm
Coupler gap	5.1 μm
Long-cavity length	1.05 mm
Short-cavity length	1.0 mm

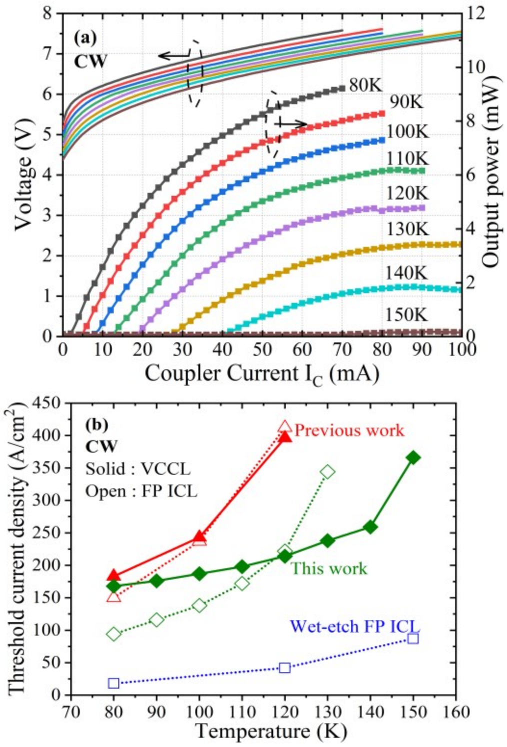

Fig. 3. (a) The CW voltage- and power-current (I_C) characteristics of a V-coupled cavity ICL at several temperatures with I_L=30 mA and I_S=30 mA. (b) Comparison of the CW threshold current densities for VCCLs and FP ICLs from this work (diamond) and previous work (triangle) [16].

Fig. 3(a) shows the voltage-current and power-current characteristics of the V-coupled cavity ICL at different temperatures in CW operation. The beam is emitted from the facet of the long cavity. The structural parameters of the ICL device are listed in Table I. As the coupler provides the major gain, the output power mainly varies with the current I_C. In the experiment, with both the fixed long cavity current and short cavity current at 30 mA, the output power increased with the coupler current and then saturated at a relatively high current of I_C. Output powers of most tested devices could reach nearly 10 mW in CW mode at low temperatures. They can still deliver 1 mW at relatively high temperatures (e.g., 140 K), sufficient for in-situ gas sensing applications. The smooth power-current curves in Fig. 3(a) indicate that no mode-hop occurs during the tuning of the I_C current, which is ensured by the VCCL design where the waveguide lengths covered by the coupler electrode in the two cavities have the same proportion to their respective cavity lengths. Fig. 3(b) shows the CW threshold current densities of VCCLs and FP ICLs from this work, compared to those of the previous work [16]. The total threshold current of the device in Fig. 3(a) was 62 mA at 80 K and increased to 135 mA at 150 K, corresponding to the threshold current density J_{th} of 168 and 366 A/cm^2, respectively. The slope of the power-current curve below 10mA at 80K gives a differential electrical-to-optical power conversion efficiency of 5%. At 120 K, its J_{th} was 214 A/cm^2, almost half of the value (~396 A/cm^2) for the initial V-coupled cavity ICL at the same temperature in Ref. 16. Also, the slope efficiency (*e.g.*, 356 mW/A at 80 K, 172 mW/A at 120 K) was more than doubled compared to the previous one and the maximum CW operating temperature was increased from 130 K to 150 K. These results indicate that the double-ridge waveguide configuration substantially improved device performance of the V-coupled cavity ICLs compared to initially fabricated ones in Ref. 16 based on purely deep etched waveguides. At low temperature, the J_{th} of the VCCL is higher than the FP laser of about the same length, with dry-etched facets. However, at temperatures of 120 K and above, its J_{th} is lower than that of the dry-etched FP laser from the same wafer. These and similar results from Ref. [16] suggest that the possible loss due to the half-wave coupler does not make a significant difference in the threshold current density under the same processing conditions. Nevertheless, its J_{th} was substantially higher than that of the wet-etched FP lasers, which is consistent with their differences in slope efficiency, suggesting a significant room for further improvement in device fabrication with dry etching on VCCLs.

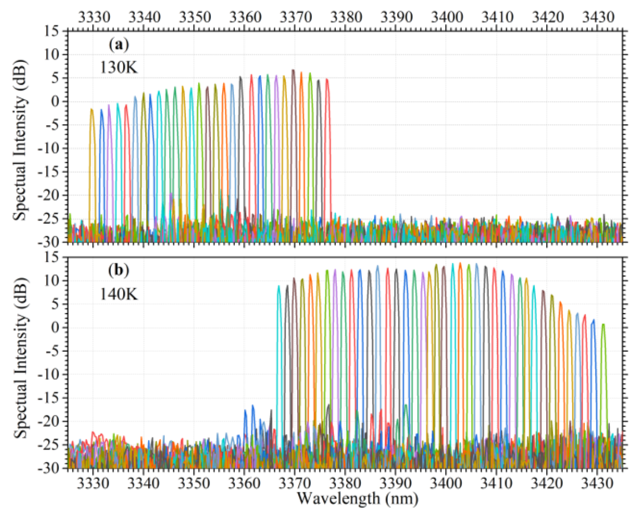

Fig. 4. CW emission spectra of a V-coupled cavity ICL at (a) 130 K and (b) 140 K with a total tuning range of 101.4 nm.

In the V-coupled cavity laser, the lasing wavelength is selected by the common resonance mode from the two frequency combs of the long and the short cavities, respectively, which are joined via the half-wave coupler for synchronous power transfer [14]. The wavelength tuning is achieved by shifting one comb spectrum (or two combs) with current heating or adjusting the heat-sink temperature. At each temperature, by changing the short cavity current and the coupler current simultaneously, the laser can work at different free spectral range (FSR), which is about 35 nm as determined by the cavity length difference in this V-coupled cavity ICL.

Fig.4 (a) shows the superimposed CW spectra at 130K. The wavelength tuning range was 46.7 nm, much larger than a single FSR. This was due to the chip heating caused by the increase of current during tuning, which red shifted the gain spectrum. This red shift is along the same direction of the wavelength tuning, thus expanding the tuning range. This is also why we usually choose the long cavity electrode as the tuning electrode. On the contrary, if a short cavity electrode was used for tuning, the wavelength tuning direction would be opposite to the moving direction of the gain spectrum, which would reduce the tuning range. Hence, the short cavity electrode is generally used to assist the long cavity electrode to achieve quasi-continuous wavelength tuning.

In addition, the tuning range can also be expanded by adjusting temperatures. At the heat-sink temperature of 130 K, the wavelength can be tuned from 3329.64 nm to 3376.26 nm. When the temperature is raised to 140 K, the wavelength tuning range reached 64.48 nm from 3366.84 nm to 3431.32 nm as shown in Fig. 4(b), and the SMSRs exceeded 30 dB during the tuning. Combining the two temperatures, the wavelength is tuned over 62 channels (101.4 nm) from 3329.9 nm to 3431.3 nm, where the channel interval is about 1.7 nm.

The wavelength tuning with the injection current I_L at different temperatures with various values of I_S and I_C is given in Fig. 5(a), along with the corresponding SMSR. The SMSR was higher than 25 dB throughout all the current and temperature adjustment. As shown in Fig. 5(b), the maximum SMSR is 35.7 dB, significantly higher than the previously reported value (28 dB) [16]. Moreover, as the maximum SMSR could be limited by the finite dynamic range and sensitivity of the Vertex70 FTIR, the actual SMSR for this V-coupled cavity ICL may be even higher.

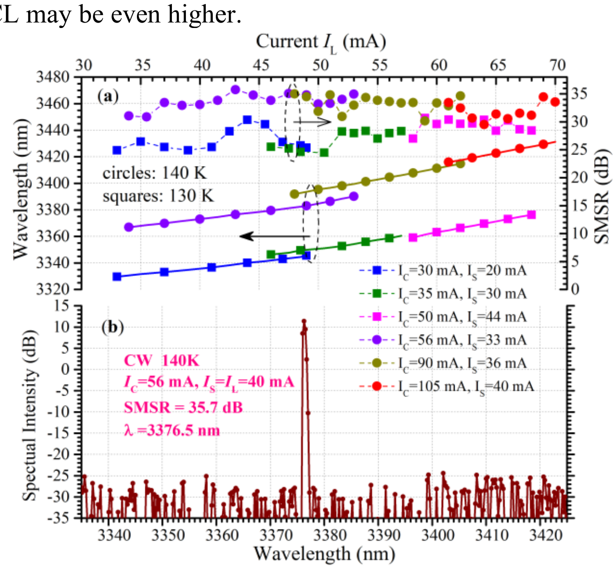

Fig. 5. (a) The CW wavelength tuning and the corresponding SMSR against current I_L at 130 and 140 K with various values of I_C and I_S. (b) Measured single-mode spectrum with a maximum SMSR of 35.7 dB.

The substantial heating and poor thermal dissipation caused the saturation and decrease of output power at high currents (130 K and 140 K) as shown in Fig. 3(a), as well as the significant increase of threshold current density with temperature for both FP ICLs and VCCLs, as shown in Fig. 3(b). One reason might be that the metal contact on the back of the device substrate was not bonded well to the heat sink because of the uneven surface of the heat sink. Consequently, the device could not hold a relatively high current and its maximum CW operating temperature was limited to 150K. This thermal issue can be significantly alleviated by improving device fabrication and packaging such as deposition of a thick Au layer on top of the device and epi-layer-side down mounting. Hence, once the thermal management is improved so that the laser can endure higher injection currents and voltages, the tuning range can be expanded further. Also, ICL wafers with fewer stages that are able to reduce heat generation can be implemented with the V-coupled cavity so that they can be operated in CW mode at above room temperature for many practical scenarios.

IV. CONCLUSION

In conclusion, based on a monolithically integrated V-coupled cavity structure and double-ridge waveguide configuration, a single-mode mid-infrared tunable ICL has demonstrated with a SMSR as high as 35.7 dB and a tuning range exceeding 100 nm when both current and temperature were adjusted. This V-coupled cavity ICL had a significantly reduced threshold current density compared to the early reported values in the initial V-coupled cavity ICLs [16]. These results suggest that widely tunable single-mode V-coupled cavity ICLs, with advantages of no grating, no epitaxial regrowth and compactness, are very promising for high-sensitivity multi-species gas sensing in the mid-infrared.

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