Electrically Tunable Terahertz Quantum Cascade Lasers

by

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Abstract
In this thesis, microelectromechanical systems (MEMS) assisted electrically tunable terahertz quantum cascade lasers (THz QCLs) are designed and demonstrated. Two MEMS tuner devices are proposed to achieve electrically tunable THz QCLs. One is the electrostatic comb drive actuated tuner design and the other one is a two-stage flexure design that is actuated by an external piezo nano-positioning actuator. The MEMS tuner devices are all fabricated using standard foundry process SOIMUMPs from MEMSCAP Inc. with some additional in-house post-processings. First order distributed-feedback (DFB) THz wire QCLs with robust mode selectors are designed and fabricated at the MIT Microsystems Technology Laboratories (MTL) using processes developed at our group. By integrating the MEMS tuner chips with the THz QCL chips, broadband electrically tunable THz QCLs are successfully demonstrated. This thesis work provides an important step towards realizing turn-key tunable THz coherent sources for a variety of applications such as THz spectroscopy and THz coherent tomography.

Thesis Supervisor: Qing Hu
Title: Professor
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Chapter 1

Introduction

1.1 Overview

Recent progress in Terahertz (THz) Quantum Cascade Laser (QCL) has proven itself to be a promising candidate for solid-state coherent THz source [1]. High power (over 100 mW) [2], high maximum operating temperature (∼200 K) [3], broad tunability (∼300 GHz) [4, 5] and good beam pattern [6, 7] together with its intrinsic compactness and reliability have made THz QCL extremely competitive as compared to other coherent THz sources that are currently available [8]. This thesis focuses on the development of broadband electrically tunable THz QCL, which is an essential component for many potential applications such as THz QCL enabled spectroscopy [5] and heterodyne receiver [9].

![Figure 1-1: The “THz gap” in the electromagnetic spectrum.](image-url)
1.2 Terahertz Quantum Cascade Lasers

Since its advent in 1994 [10], QCL has played a leading role in achieving semiconductor-based mid-infrared laser source. High power, room-temperature and broadly tunable QCLs have been demonstrated in the mid-infrared region [11] and are commercially available for practical applications [12]. Partially due to their great success in the mid-infrared range and high design flexibility, QCLs are also expected to become the major source in the terahertz (THz) region, thus help closing the so-called “THz gap” between 0.3 to 10 THz [13, 14] as shown in Figure 1-1.

QCLs are usually fabricated on alternating semiconductor quantum well substrates. InGaAs/AlInAs and GaAs/AlGaAs are the most commonly used substrate choices due to their mature material growth properties developed from the tele-communication industry. The quantum well heterostructures are usually a few monolayers thick which create energy subbands due to the quantum confinement effect. By carefully designing and engineering the quantum well structures, laser emission can be achieved through inter-subband transitions in repeated quantum well heterostructure stacks. Due to this fundamentally different lasing scheme compared to semiconductor inter-band lasers, QCLs cover much broader frequency range beyond materials intrinsic energy band characteristics, especially in the long wavelength regime [11].

The first QCL that operates in the THz regime was developed in 2002 [15]. Since then, continuous improvement on temperature and power performance, beam quality, spectral coverage and tunability have been demonstrated. Although cryogenic environment is still required for the operation of THz QCL, THz QCLs inside compact and low-cost Stirling coolers are already commercially available for research and industrial applications [16]. Up to date, no other compact THz source has demonstrated close competition as compared to THz QCL.
1.3 Tunable Terahertz Quantum Cascade Lasers

1.3.1 Overview

Among the many important characteristics which make THz QCL a useful THz coherent source candidate, single-frequency, continuous and broadband tunability is especially important for a wide range of applications [17]. The gain bandwidth can be engineered to be even larger than 1 THz is of great appeal for tuning applications [18, 19]. So far, many tuning schemes have been proposed to tune a THz QCL such as electric field tuning, external cavity tuning, THz QCLs with coupled microcavity and near-field tuning of THz wire lasers. An overview which is based on a recent review paper [20] of these tuning schemes is provided below to illustrate the rationale behind the scheme chosen by this thesis.

1.3.2 Electrical Field Induced Tuning

Perhaps the most appealing way to tune the emission frequency of THz QCLs is through direct electrical field tuning. Various methods have been proposed in order to achieve this goal [21, 22, 23, 24]. One way is to introduce considerable shape change of the gain spectrum with different applied electrical field, therefore changing the threshold gain for different modes. By carefully designing and optimizing quantum cascade module stacks, one can selectively excite certain fraction of the quantum cascade modules [21, 22] or certain radiative transitions [23] by changing the applied electrical field. In this manner, fully switchable emission on two or multiple wavelengths have been demonstrated. However, it is inevitable to have discontinuous tuning using this mechanism since the cavity modes are not tuned, leading to essentially mode hopping as opposed to continuous frequency tuning. Moreover, it is difficult to design gain medium controllably due to the complication involved in the gain medium design and material growth uncertainty. Therefore, other than providing a convenient switchable multi-color laser, it is impractical to utilize this tuning mechanism for any spectroscopic or other related applications.
Stark-shift in the inter-subband transition can also be used to obtain tuning in homogeneous structure. Walther et al. [24] reported THz QCLs with carefully designed diagonal transition that covers frequency range from 1.2 to 1.6 THz. The Stark-shift produced by the changing electrical field gradually shifts the peak of the gain spectrum and produces a maximum frequency tuning of 240 GHz (Figure 1-2). However, due to the same reason that the laser cavity modes remain unchanged, the frequency tuning obtained from this method is still discontinuous due to mode hopping.

![Figure 1-2: Stark-shift induced frequency tuning in a THz QCL. Discontinuous tuning with mode hopping is achieved by changing the applied electrical bias [24].](image)

In general, the existing electrical field induced tuning mechanism depends on modifying the gain spectrum only and typically employs the Fabry-Perot geometry. Thus tuning is mainly achieved through discontinuous mode hopping. In addition, designing and optimizing the gain medium to obtain well controlled tuning behavior is complicated and is difficult to apply for high-performance gain medium. Therefore, this method is not very applicable for general tuning purposes such as spectroscopic applications.

1.3.3 Tuning with External Cavity

External cavity QCLs in the mid-infrared regime have demonstrated many desirable traits in terms of tunability, operating temperature and output power [25]. They are seen to be an alternative technology compared to conventional Fourier Transform
Infrared Spectroscopy (FTIR) in their operating frequencies in terms of high-precision spectroscopic applications. However, the same tuning principle is rather challenging to apply for THz QCLs. The major issue is that for THz QCL waveguides, the electromagnetic wave is usually highly confined inside either a semi-insulating surface plasmon (SISP) [15] or a metal-metal waveguide [26]. The cross-section for the waveguide is typically on the order of or smaller than the wavelength, making it difficult to couple an outside element to the resonator modes efficiently.

Figure 1-3: (a), (b) External cavity QCL configurations with and without off-axis paraboloid mirror (OAP). (c) Normalized spectra of two QCL devices with external cavity and calculated atmospheric transmission (HITRAN 2008) [27].

Two implementations have been proposed and realized using the external cavity method with either a moving mirror [28] or an external grating [27]. An important aspect of the implementation is to incorporate anti-reflection (AR) on the facet which is facing the external element. In the moving mirror implementation, layered AR with SiO$_2$ coating is used to suppress the unwanted feedback. The tunable external cavity feedback is provided by moving the mirror and coupling the light into the laser cavity. Continuous tuning of $\sim 15$ GHz and discontinuous tuning over $\sim 90$ GHz with mode hopping have been observed [28]. In the external grating implementation,
a silicon hyper-hemisphere is placed in close contact with the cleaved laser facet, optically coupling the cavity mode to the external grating. Angle tuning of the grating provides the optical feedback and results in discontinuous tuning over \( \sim 165 \) GHz and continuous tuning of \( \sim 9 \) GHz [27]. Figure 1-3 illustrates the external grating configuration and normalized spectra in this work.

Although broadband discontinuous tuning over 100 GHz can be relatively easily realized using the external cavity method, controllable continuous tuning yet remains narrowband and is on the order of 10 GHz. In order to achieve robust single-mode continuous tuning, frequency selectivity needs to be enhanced in order to suppress unwanted mode hopping. This is generally difficult to realize using the Fabry-Perot configuration in these work with external cavity tuning. A more reliable way is to have frequency feedback element to enhance mode selectivity and single-mode operation.

1.3.4 Effective Index Tuning and Distributed Feedback

Terahertz Quantum Cascade Lasers

![Figure 1-4: (a) Tuning of the lasing frequency as a function of injection current for two THz QCLs [29]. (b) 30 GHz single-mode continuous tuning in photonic crystal QC devices [30].](image)

A distributed feedback (DFB) laser utilizes periodic grating on the laser structure to provide frequency feedback [6, 31, 32]. It is a relatively robust way to achieve single-frequency emission in THz QCLs and is thus the ideal tunable source for spectroscopic applications. For a simple first-order DFB laser, the introduction of the
Bragg grating creates two sets of standing wave solutions separated by a bandgap at resonant condition. Near the bandgap, each set of the resonant mode corresponds to one of the two resonant modes for an infinitely-long waveguide with the same Bragg grating multiplied by a slowly varying envelop introduced by the finite cavity length and the phase condition [33]. The resonant condition is met when the propagation wavelength $\lambda_0$ equals the Bragg wavelength $2n_{eff}\Lambda$, where $\lambda_0$ is the free-propagating wavelength, $n_{eff}$ is the effective refractive index for the mode, and $\Lambda$ is the grating period. Therefore, by changing the effective refractive index $n_{eff}$ of the gain medium, one can change the resonant frequency not just for a Fabry-Perot laser, but also for a DFB laser.

In order to change the effective refractive index $n_{eff}$, one can vary the heat sink temperature or the applied electric field/current. According to literature [34, 29], temperature tuning realized by injection current Joule heating is usually limited for THz QCLs (Figure 1-4 (a)). Tuning is typically below $\sim-5.0$ MHz/mA with Joule heating. On the other hand, there are various articles reporting opposite current tuning sign as compared to the temperature tuning with a tuning value up to $\sim 5$ MHz/mA [35, 36]. Some suggest that this is due to a mode-pulling effect with the Stark tuning of the diagonal inter-subband transition or changes in lateral charge distribution or optical nonlinearities [35]. Due to the co-existence of these two counter reacting effects in mode tuning, one has to carefully design the gain medium in order to maximize tuning. With the aids of additional techniques such as photonic crystal band edge THz lasers, single-mode continuous tuning as high as 30 GHz has been reported [30]. The tuning result is shown in Figure 1-4 (b).

It is worthwhile mentioning that although not in a conventional sense, DFB THz QCL arrays can function as tunable THz sources as well. In one particular application [16], an array consists of 10 third-order DFB QCLs covering from 2.08 to 2.4 THz is fabricated on one chip and forms a THz sweep source as illustrated in Figure 1-5. THz optical coherence tomography using this DFB QCL array is demonstrated with a depth resolution of 360 $\mu$m. Third-order DFB QCL arrays have the advantage of high frequency selectivity, high spectral purity, high power and good beam pattern.
Figure 1-5: (a) An SEM image of the 21-element third-order DFB THz QCL array packaged in (b). (c) Spectra of the THz QCL array showing a frequency coverage of around 320 GHz [16].

They are based on the well-developed third-order DFB QCL technology and are easily controlled through digital circuit. They are probably by far the best candidate to realize single-frequency discontinuously tunable THz source.

1.3.5 Tunable Terahertz Wire Lasers

Apart from the above-mentioned tuning mechanisms, there are a number of other ways to tuning THz QCLs such as coupling a DFB laser with a microcavity [37] or by gas condensation [38]. A more comprehensive and detailed review on tunable THz QCLs can be found in [20].

The work of this thesis is based on the tuning mechanism developed by Qin et al. in 2009 [4]. The tuning mechanism utilizes several distinct features of THz QCL waveguides and the long wavelength associated with the THz wave. The detailed tuning mechanism and implementation will be introduced in Chapter 2. Prior to the writing of this thesis, single-mode, mode-hop free, continuous tuning over $\sim 300$ GHz ($\sim 10\%$ of the center frequency) has been successfully demonstrated using this
mechanism with a MEMS platform [5, 39]. The tuning characteristics are ideal for many applications such as high-precision spectroscopy and THz sweep source for optical coherence tomography.

1.4 Thesis Overview

This thesis extends the previous work of manually tunable THz wire lasers into the regime of electrical tunability. By integrating THz wire lasers with MEMS tuner devices, turn-key electrically tunable THz QCLs have been successfully demonstrated during the time period covered by the work of this thesis. Chapter 2 will introduce the general principles of tunable THz wire lasers and the design and characterization of a mode selector for the wire laser. Chapter 3 will illustrate the design, fabrication and characterization for the MEMS tuner devices where two electrical actuation schemes have been explored and tested. Chapter 4 will provide detailed explanation on device integration, the experimental results of electrically tunable THz QCLs, and future projections on this project.
Chapter 2

Tuning Terahertz Quantum Cascade Wire Lasers

2.1 Introduction

2.1.1 Metal-metal Waveguide and Wire Lasers

In order to confine the THz wave inside the laser cavity, either a semi-insulating surface plasmon (SISP) waveguide [15] or a metal-metal waveguide [26] is employed. Both waveguides utilize the surface-plasmon mode formed between the metal layer and the gain medium to strongly confine and guide the THz wave inside the laser cavity. The SISP waveguide provides more output power and better beam pattern thanks to the smaller mode mismatch between the cavity mode and the free propagation mode. Due to the spatially extended transverse mode profile, a relatively low confinement factor ($\Gamma \approx 0.1 \rightarrow 0.5$) and reflectivity ($R \approx 0.3$) are typically expected [40]. On the other hand, the metal-metal waveguide tends to give better temperature performance since it has higher confinement ($\Gamma \approx 1$ for lateral dimension bigger than 40 $\mu$m) and lower intrinsic loss. However, due to the relatively high reflectivity ($R \approx 0.7 \rightarrow 0.9$) and the greater mode mismatch between the cavity mode and the free propagation mode, the output power is considerably smaller and the beam pattern is more divergent as compared to those of the SISP waveguide.
The high confinement provided by the metal-metal waveguide can be taken advantage of by making the waveguide lateral dimension smaller than the wavelength of the guided mode or comparable to the waveguide vertical dimension (usually about 10 µm). In this way, one can create a so-called ”wire laser” with interesting properties that are unique for tuning applications. As the waveguide lateral dimension becomes so much smaller than the cavity mode wavelength, fringing field starts to appear extensively outside the waveguide cavity. Figure 2-1 shows the 2D electric field magnitude profiles for metal-metal waveguides with different lateral widths at 3.6 THz calculated by finite-element method simulation using COMSOL. For simplicity, the cladding metal layers are set as perfect electric conductor (PEC) and the gain medium is set as lossless. Only the fundamental transverse modes are shown in the figure. As the waveguide width decreases, the fringing field begins to “spill over” the physical waveguide, whereas still being guided by the waveguide. If we assume $n_{\text{eff}}$ to be the effective refractive index for the guided mode, the power confinement factor $\Gamma_p$ can be defined as

$$
\Gamma_p = \frac{\int A \frac{1}{2} Re[\vec{E} \times \vec{H}^*] \cdot \hat{z} \, dx \, dy}{\int \frac{1}{2} Re[\vec{E} \times \vec{H}^*] \cdot \hat{z} \, dx \, dy}.
$$

As one can see from the figure, $\Gamma_p$ becomes progressively larger and asymptotically approaches unity with increasing waveguide width. It is very interesting to notice that, as the waveguide width decreases to $\sim 10$ µm, the field guided by the metal cladding layer starts to show significant concentration around the top corners of the waveguide. It is this concentrated field region that originates the high fringing field in the near-field of the metal-metal waveguide. It is also worthwhile noticing that, for waveguide with smaller width, the electric field distribution inside the waveguide is laterally more uniform as compared to that of the waveguide with larger width. When the waveguide width becomes comparable to or bigger than $\sim 20$ µm, the electric field distribution inside the waveguide become much more concentrated in the center part. Meanwhile, more than 90% of the average power are guided inside the waveguide,
therefore losing the traits of being a "wire laser". Since tuning a wire laser requires manipulating the outside fringing field and the inside field close to the edge of the waveguide, in order to maximize the tuning dynamic range, it is crucial to minimize the laser width (usually on the order of \( \sim 10 \mu m \)) while still maintaining enough modal gain to support lasing.

Another advantage of utilizing the wire laser structure is that it eliminates the concerns for high-order lateral modes. For waveguides typically bigger than around 20 \( \mu m \), higher order lateral modes start to have comparable threshold gain as compared to fundamental lateral modes. In order to suppress such higher order lateral modes, one has to employ techniques such as covering waveguide side walls with insulator/metal to introduce additional loss to the higher order lateral modes \([32]\). This introduces excess complexity to device design and fabrication and should in general be avoided if possible. Therefore, the concept of using a wire laser is very much appealing for single-mode continuous tuning purpose.

![Finite-element method simulation showing the fundamental transverse mode profiles (magnitude of the electric field) for metal-metal waveguides with different lateral widths at 3.6 THz, \( n_{\text{eff}} \) is the effective refractive index for the guided mode and \( \Gamma_p \) is the power confinement factor. The height for all the waveguides are 10 \( \mu m \).](image)

Figure 2-1: Finite-element method simulation showing the fundamental transverse mode profiles (magnitude of the electric field) for metal-metal waveguides with different lateral widths at 3.6 THz, \( n_{\text{eff}} \) is the effective refractive index for the guided mode and \( \Gamma_p \) is the power confinement factor. The height for all the waveguides are 10 \( \mu m \).

It is worthwhile pointing out that the power confinement factor \( \Gamma_p \) here is only meant to illustrate the portion of average power that is physically propagating inside the waveguide. It has been argued that \( \Gamma_p \) should not be used when constructing the rate equations for plasmonic lasers \([41]\). A more rigorous formulation of the waveguide confinement factor for plasmonic waveguide-based lasers can be found in \([41]\) where inhomogeneity and dispersion of the cavity media are taken into account.
2.1.2 Tunable Terahertz Wire Lasers

The unique characteristic of the field distribution of the metal-metal waveguide for THz QCLs allows novel ways to manipulate the waveguide mode. The tuning scheme of this thesis work relies on the idea of utilizing an outside MEMS tuner device to effective modify the boundary condition in the proximity of the laser waveguide and thus change the field distribution. The wire lasers employed are typically of around $\sim 10 \, \mu\text{m}$ wide. In order to enhance single-mode operation, sinusoidal Bragg gratings are patterned on one side of the laser to allow distributed feedback. The effect of the Bragg gratings on cavity mode can be visualized in Figure 2-2 and 2-4. In Figure 2-2, the gain threshold $g_{th}$ versus frequency and the longitudinal mode profile in terms of the magnitude of the electric field for a Fabry-Perot wire laser are plotted. The laser waveguide has a width of $10.5 \, \mu\text{m}$, height of $10 \, \mu\text{m}$ and length of $450 \, \mu\text{m}$. As one can see from the figure, without any distributed feedback, the resonator modes are almost evenly distributed across the frequency range of interest. The gain threshold $g_{th}$ is defined as

$$g_{th} = \frac{\alpha_i + \alpha_m}{\Gamma_{wg}}.$$

In the equation, $\alpha_i$ is the waveguide intrinsic loss and is in general related to the free-carrier loss of the gain medium and the metal cladding. $\alpha_m$ is the waveguide mirror loss which is directly related to the amount of power can be coupled out of the cavity. $\Gamma_{wg}$ is the waveguide confinement factor. While constructing the rate equation analysis for THz QCLs, $\Gamma_{wg}$ should be used to related the material gain to the modal gain. It should not be confused with the power confinement factor defined in Section 2.1.1. The exact derivation for $\Gamma_{wg}$ is beyond the scope of this thesis and can be found in [41]. In the finite-element simulations performed in this thesis, $\alpha_i$ is assumed to be 0 for simplicity. The imaginary part of the eigen-frequency analysis is thus a direct measure of the radiation loss (or mirror loss $\alpha_m$) of the laser cavity.

Multi-mode lasing is typically observed for Fabry-Perot lasers since the gain threshold $g_{th}$ is not very discriminative against frequency as can be seen in Figure
Figure 2-2: Gain threshold plot and longitudinal mode profile in terms of the magnitude of the electric field for a Fabry-Perot wire laser. Notice that the gain threshold increases gradually with increasing frequency due to less mode mis-match between the cavity mode and free propagation mode.

2-2. $g_{th}$ gradually increases with increasing frequency because for smaller wavelength, the mode mis-match between the cavity mode and free propagation mode is smaller, leading to higher power out-coupling.

The introduction of the Bragg gratings alters the mode profile for a wire laser significantly. The top and side views for a wire laser with sinusoidal corrugation on one side is shown in Figure 2-3. The gain threshold versus frequency and the longitudinal electric field magnitude distribution plots are shown in Figure 2-4. The sinusoidal Bragg gratings have an amplitude of 3 $\mu$m, period of 15 $\mu$m and 30 periods of corrugation with a total length of 450 $\mu$m. The average waveguide width is 10.5 $\mu$m. It can be easily observed from the figure that a resonator mode bandgap is opened due to the strong perturbation by the Bragg gratings. For the upper band-edge modes, the mode maxima are concentrated at the narrower part of the waveguide. On the contrary, for the lower band-edge modes, the mode maxima are concentrated at the wider part of the waveguide. In addition to the observed bandgap, the threshold gain discrimination also becomes very distinct, with the fundamental mode above the
Figure 2-3: Top and side view for the wire laser with sinusoidal corrugations on one side of the laser ridge.

bandgap experiencing the smallest threshold gain. This mode discrimination turns out to be sufficient for single-mode operation in many circumstances. The very first demonstration of tunable wire lasers utilized such resonator geometry to avoid mode hopping which is typically observed in Fabry-Perot tunable lasers \cite{4}. In addition, since the upper band-edge mode sees smaller effective waveguide width, it is also naturally advantageous to make it as the lasing mode in order to achieve higher tuning range.

In order to tune a THz wire laser, one needs to put a tuner device in close proximity to the laser ridge. The tuner device can either be an object coated with metal or a dielectric object such as silicon. In order to explain the tuning mechanism, two approaches are provided below. The first account starts from 2D electromagnetic mode solver and explains the tuning from the point of view of modifying the effective mode index. The second account, which starts from a more fundamental ground of the $\omega-k$ dispersion relationship, illustrates the key novelty of tuning the resonator eigen-frequency by manipulating the transverse direction wave vector only. Such approach differentiates this tuning mechanism from conventional effective index tuning methods which are usually based on changing the material property $\epsilon$. It is closely related to the unique resonator characteristics of a wire laser.

To start with the first account, the 2D waveguide effective index simulation is
Figure 2-4: Gain threshold plot and longitudinal mode profiles in terms of the magnitude of the electric field for a DFB wire laser. A resonator mode bandgap is opened and the gain thresholds for different modes become distinctively different. The longitudinal mode profiles show different envelop orders with the smallest order closest to the bandgap. (a) and (b): second-order and fundamental mode profiles for lower band-edge modes. (c) and (d): fundamental and second-order mode profiles for upper band-edge modes.
carried out. The electrical field distribution and the effective index calculation are shown in Figure 2-5. In the figure, subplot (a) shows the transverse field distribution in terms of the magnitude of the electrical field in the absence of any tuner device, with the metal tuner 1 µm away from the laser ridge and with the silicon tuner 1 µm away from the laser ridge. In (b), the horizontal x component of the electric field is plotted for the three situations whereas in (c), the vertical y component of the electric field is plotted. All waveguides in the simulation have a 10 µm height and 10 µm width. The effective indices are obtained from the 2-D mode solver simulation performed using COMSOL. The propagation constant $\beta$ for the three cases are fixed at $2.2 \times 10^5$ rad/m which corresponds to the case that the propagation constant is being fixed inside the DFB laser due to the Bragg gratings.

On the leftmost column, the field distribution is plotted for the unperturbed wire laser. The electric field inside the waveguide is mostly y-polarized due to the boundary condition imposed by the double-metal claddings. The electromagnetic wave can be thought of being guided by a combination of both the plasmonic mode formed in between the metal claddings and the waveguide core and the refractive index difference between the core and the air. The effective refractive index $n_{eff}$, which is obtained from the canonical identify $\beta = k_0 n_{eff}$, is calculated to be 2.921, where $k_0$ is the wave number in vacuum and the propagation constant $\beta$ is obtained through the eigen-solver for the 2D waveguide mode. This is substantially smaller than the refractive index of the GaAs core layer ($n_{GaAs} = 3.6$). The x component of the electric field is largely concentrated around the top metal corners of the waveguide due to the small waveguide width.

When the metal tuner moves towards the laser ridge in close proximity, $n_{eff}$ starts to drop. Particularly in the middle column of Figure 2-5, when the metal tuner is just 1 µm away from the laser ridge, $n_{eff}$ drops to 2.722 from 2.921. From a closer examination of the x and y components of the electric field, it becomes clear that the mostly y-polarized electric field inside the waveguide on the side that is facing the metal tuner is being depleted. This is due to the change of the boundary condition seen by the electromagnetic wave inside the waveguide when the metal surface moves in.
Figure 2-5: Finite-element method simulation of the fundamental transverse mode profiles for metal-metal waveguides in the presence of the tuner devices. Subplot (a) shows the magnitude of the electric field distribution. Subplots (b) and (c) show the magnitude of the x and y components of the electric field distribution. The leftmost column corresponds to the case of waveguide mode without any tuner device. The middle column corresponds to the case with the metal tuner and the rightmost column shows the mode profile with the silicon tuner. All mode analyses are carried out at a fixed propagation constant $\beta$ that equals to $2.2 \times 10^5$ rad/m. The gap sizes for the middle and rightmost columns are both 1 \, \mu m wide.
One can imagine that the $y$-polarized electric field is effective being "shorted" in the presence of the metal surface. Moreover, a strongly localized $x$-polarized electric field in between the top metal cladding of the laser and the metal tuner surface is formed, essentially draws the energy from the shorted waveguide core to the metal-air-metal region. Therefore, less of the mode sees the waveguide core and more are localized in air. This explains why $n_{\text{eff}}$ drops in the presence of the metal tuner.

In the case of a silicon tuner moving towards the laser ridge, $n_{\text{eff}}$ rises as can be seen from the rightmost column of the figure. In the presence of the silicon tuner, the index guiding part for the metal-metal waveguide becomes weaker since the gap between the laser ridge and the silicon tuner is of deep-subwavelength scale. Therefore the mode largely leaks out from the waveguide core region into the silicon tuner. As the silicon refractive index (modeled as $n_{Si} = 3.4$) is much larger than that of the air, the leaking mode sees higher refractive index as it propagates, resulting in higher $n_{\text{eff}}$.

The change of the effective index for the metal-metal waveguide in the presence of the tuner devices provides great insight on the tuning behavior of the wire lasers. In the DFB structure being employed in the current study, the propagation constant $\beta$ of the resonator modes are fixed due to the sinusoidal gratings on the side. From the identity $\beta = k_0 n_{\text{eff}}$, when the metal tuner moves in, $n_{\text{eff}}$ decreases as discussed earlier. Since $\beta$ is being fixed, $k_0$ has to increase, leading to frequency blue-shift for the resonator mode. On the contrary, in the presence of the silicon tuner, $k_0$ has to decrease with larger $n_{\text{eff}}$, resulting in frequency red-shift. These predictions coincide with the experimental results [4, 5].

Other than the above explanation based on changing the effective index $n_{\text{eff}}$, a more fundamental account can be obtained through the dispersion identity of $k^2 = k_\parallel^2 + k_\perp^2 = \omega^2 \mu \epsilon$ [4] without introducing any intermediate variables such as the effective mode index. The $k_\parallel$ direction is along the waveguide direction whereas the $k_\perp$ direction is perpendicular to the $k_\parallel$ direction. This $\omega-k$ dispersion relationship identifies the key feature of the tuning mechanism for the wire laser, which is not so obvious with the 2D waveguide effective index simulation. For most traditional tuning mechanisms, the resonator mode is changed through either tuning $k_\parallel$ by physically
changing the resonator length or facet wavelength selection such as the ones with external cavity [28, 27], or by changing the material property $\epsilon$ in order to tune the effective mode index $n_{eff}$ such as bias voltage tuning [42] or current tuning [43]. For wire laser tuning, both $k_\parallel$ from the resonator cavity geometry and $\epsilon$ from the material property are being fixed whereas $k_\perp$ is changed through pure electromagnetic wave manipulation. Although the end result is that the effective mode index $n_{eff}$ is being modified, it should not be confused with conventional effective index tuning which usually implies the change of the material property $\epsilon$ as introduced in Section 1.3.4.

A more physical picture for the change of $k_\perp$ can be obtained from examining the transverse mode profiles in Figure 2-5. One way to link the change of $k_\perp$ to the physical waveguide mode profile is by looking at the mode extent in the horizontal direction. When the metal tuner moves towards the laser ridge, due to the partial “shorting” of the electrical field inside the waveguide, the mode is squeezed into smaller transversal extent, thereby increasing the wave number count in the horizontal direction. On the other hand, in the case of a silicon tuner moving in, the mode extends to larger physical extent due to the weakening of the refractive index guiding, thereby decreasing the wave number count in the horizontal direction. Such mode profile manipulation is performed without any change to the waveguide geometry and material property and is solely related to the freedom of changing $k_\perp$ of a wire laser. The same approach, in principle, could be employed to tune wire lasers at any frequencies, although tuner precision control would be much more demanding for any frequency range higher than the THz regime.

Inside a DFB laser, as opposed to the plane wave $\omega-k$ dispersion relationship of $k^2 = k_\parallel^2 + k_\perp^2 = \omega^2 \mu \epsilon$, an approximate $\omega-k$ dispersion relationship is derived here based on the grating conditions imposed by the DFB structure. With proper boundary conditions, the electric field inside the DFB laser can be represented by a sum of electric field components each corresponding to a specific grating diffraction order $i$ as

$$E = \sum_{i}^{\pm1, \pm2, \pm3, \ldots} E_i^{r\parallel} [e^{j k_i^\parallel r\parallel} (e^{j k_i^\perp r\perp} + e^{-j k_i^\perp r\perp}) e^{-j \omega t}].$$
In the equation, $k_{i\parallel}$ corresponds to the $i^{th}$ order diffraction term due to the gratings in either forward or backward waveguide directions depending on the sign. The wave in the $k_{i\perp}$ direction is assumed to be standing wave composed of the superposition of two counter-propagating waves. For simplicity, the wave envelop variations in the $k_{i\perp}$ direction is ignored. The $E_{i\parallel}$ corresponds to the slowly varying longitudinal envelop function for the $i^{th}$ order mode. The $E$ expression shown above is substituted into the wave equation $\nabla^2 E = \mu \varepsilon \frac{\partial^2 E}{\partial t^2}$. By ignoring the spatial derivative of $E_{i\parallel}$ due to its slow variation, we can reach the following equation:

$$\sum_{i=\pm 1, \pm 2, \pm 3, \ldots} E_{i\parallel}(k_{i\parallel}^2 + k_{i\perp}^2)[e^{jk_{i\parallel}r_{\parallel}}(e^{jk_{i\perp}r_{\perp}} + e^{-jk_{i\perp}r_{\perp}})e^{-j\omega t}] \approx \mu \varepsilon \sum_{i=\pm 1, \pm 2, \pm 3, \ldots} E_{i\parallel}^2\omega^2[e^{jk_{i\parallel}r_{\parallel}}(e^{jk_{i\perp}r_{\perp}} + e^{-jk_{i\perp}r_{\perp}})e^{-j\omega t}].$$

By matching the $e^{jk_{i\parallel}r_{\parallel}}$ and $e^{jk_{i\perp}r_{\perp}}$ terms, we can reach the following $\omega - k$ dispersion relationship for different diffraction orders as

$$k_{i\parallel}^2 + k_{i\perp}^2 \approx \omega^2 \mu \varepsilon.$$

As opposed to a freely changing $k_{\parallel}$ in the original plane wave dispersion relationship, $k_{i\parallel}$ is being quantized with the grating diffractions in the form of $i\frac{\pi}{\Lambda}$, where $\Lambda$ is the grating period in this case. For DFB lasers, different diffraction orders will have different dispersion relationships determined by $i$ and the grating condition. Such dispersion identify could in general help in the design of higher-order tunable THz wire lasers.

3-D eigen-frequency analysis is carried out to characterize the resonator mode frequency shift. Wire laser with the same width, length and grating dimension as before is simulated with tuner devices placed in close proximity to the laser ridge. Figure 2-6 shows the mode profiles for the fundamental mode under three conditions: without any tuner devices, with metal tuner, and with silicon tuner placed 1 $\mu$m away from the laser ridge. It is clear that the fundamental mode frequency shifts
Figure 2-6: Finite-element method simulation showing the fundamental mode frequencies for the QCL resonator under different scenarios: (a) without any tuner devices, $f = 3.6446$ THz, (b) with metal tuner 1 $\mu$m away from the laser ridge, $f = 3.9371$ THz, and (c) with silicon tuner 1 $\mu$m away from the laser ridge, $f = 3.5084$ THz.

as predicted when the tuner device is present, with 292.5 GHz blue-shift for the metal tuner and 136.2 GHz red-shift for the silicon tuner. The presence of the tuners is seen only to modify the transverse mode profile, pushing or extending it in the transverse direction, whereas inflicts little change in the longitudinal direction. This has been observed for all different longitudinal higher-order modes, which undergo similar frequency shift.

The situation where the tuner is placed at different distances away from the laser ridge is simulated as well. The resulted frequency shift versus tuner position relationship is plotted in Figure 2-7 (a). The frequency shift due to the tuner position change is non-linear for both the metal and silicon tuner and gets progressively larger when the tuner is closer to the laser ridge. Due to the evanescent nature of the tuning mechanism, an empirical curve fitting for the frequency shift versus tuner position is carried out and the result is shown in Figure 2-7 (b) and (c). It has been determined that the curve fitting equations of $f[THz] = 3.6446 + 0.5289e^{-0.4848g[\mu m]}$ and $f[THz] = 3.6446 - 0.1887e^{-0.3751g[\mu m]}$ could well represent the tuning behavior of the metal and the silicon tuner as shown in the figure. $f$ represents the lasing frequency and $g$ is the gap in between the laser ridge and the tuner surface. Two important design considerations can be drawn from these simulation results. Firstly, most of the tuning is achieved within the last $\sim 5$ $\mu$m distance. The effectiveness of tuning gradually diminishes after $\sim 10$ $\mu$m tuner-laser distance. This means that when designing the initial position for the tuner, it is desirable to keep at least 10 to 15
\( \mu \text{m} \) distance between the tuner and the laser ridge in order to keep most of the tuning range. Secondly, since for real-world applications, it is impossible to de-assemble one type of the tuner and re-assemble another type of tuner, the practical tuning range is limited to only one tuner type. Therefore metal tuner is chosen as it has larger tuning range as compared to the silicon tuner. All the subsequent work performed in this thesis utilizes the metal tuner alone for practical tuning applications.

Figure 2-7: (a) Frequency shift versus gap size between the laser ridge and the tuner plot for the metal and silicon tuners. (b) and (c) Empirical curve fittings for frequency shift versus gap size for the metal and silicon tuners. An exponential relationship is observed for both blue-shift and red-shift tuning.
2.2 Terahertz Wire Lasers with Enhanced Mode Selectors

2.2.1 Mode Selector Enhancement

![Gain Threshold vs. Frequency Plot](image)

Figure 2-8: (a) Gain threshold versus frequency plot for the first-order DFB wire laser. (b) Gain threshold versus frequency plot for the first-order DFB wire laser with enhanced mode selectors. A hypothetical gain curve is plotted as well to illustrate the case when higher-order longitudinal modes see more gain as compared to the fundamental mode.

Although the frequency selectivity provided by the sinusoidal corrugations on the side of the laser is sufficient for single-mode operation in many circumstances, it fails to provide enough frequency selectivity in cases where the higher-order longitudinal modes see much more gain from the gain medium as compared to the fundamental mode. The gain threshold versus frequency plot for the first-order DFB wire laser is plotted in Figure 2-8 (a), which is the same as the one shown in Figure 2-4. A hypothetical gain curve is plotted as well. Due to the small mode discrimination, the difference between the gain threshold of the fundamental mode and those of its adjacent modes could be as small as 1.6 cm$^{-1}$. If one designs the lasing frequency to be at the lower-frequency side of the gain curve, which is typically a Lorentzian shape, the higher-order resonator modes could see more gain which offsets the mode discrimination introduced by the sinusoidal corrugations. This could potentially lead
to lasing of unwanted modes.

Figure 2-9: Gain medium measurement performed by time-domain study for gain medium design FL183S (wafer number VB0481). Two gain peaks are observed at 3.41 THz and 3.75 THz. The valley in between the peaks is at 3.55 THz. The bias current for this measurement is at 1124.3 A/cm$^2$ and the temperature is at 45 K.

The uncertainty of which mode to lase could be further aggrandized due to the lack of knowledge for the exact gain curve, which happens for most gain media. Although it is commonly believed to have a Lorentzian-like gain curve for THz QCLs, there are exceptions which could complicate the resonator design. For example, the gain medium FL183S (wafer number VB0481) used in this thesis study has a double-peak gain profile as shown in Figure 2-9. Therefore, a mode discrimination of more than 10 cm$^{-1}$ would be required in order to achieve robust single-mode operation over a large frequency range.

In order to enhance the mode selectivity, wire lasers with finger-like mode selectors are proposed and realized as shown in Figure 2-10. The laser has the same dimension as the standalone first-order DFB lasers discussed before. The fingers have a width of 4.5 $\mu$m and a length of 110 $\mu$m and are centered at the widest part of the sinusoidal corrugations. The 11-finger geometry is obtained through iterative optimization to maximize the gain threshold discrimination. The bonding pad dimension is not critical and can be chosen arbitrarily. The gain threshold profile for the laser resonator with
the mode selectors is shown in Figure 2-8 (b). As can be seen, the gain threshold discrimination is improved to over $10 \text{ cm}^{-1}$ between the fundamental mode and other higher-order modes and lower band-edge modes, which shows the effectiveness for the mode selector design. The mode selector working principle is based on using fingers to spatially extract the unwanted mode out from the laser resonator, therefore increasing its radiation loss. The mode profiles for all the resonator modes considered are plotted in Figure 2-12 and 2-13, where the mode labels can be found in Figure 2-11.

For the upper band-edge modes shown in Figure 2-12, the mode nodes are concentrated at the narrowest part of the corrugation as discussed previously. The fundamental longitudinal mode is the desirable lasing mode. The higher-order longitudinal modes follow envelop functions that have progressively more nodes. From a closer examination on the fundamental mode profile, one can see that for most of its maximum electric field nodes, they align well with the narrowest part of the corrugated laser cavity. It is only close to the facet ends of the cavity where the mis-alignment begins to be noticeable. On the other hand, for higher-order longitudinal modes,
Figure 2-11: Gain threshold versus frequency plot for the wire laser with 11 fingers. The mode labels correspond to the mode profile labels in Figure 2-12 and 2-13.

The mis-alignment between the mode maximum nodes and the narrowest part of the corrugation becomes more obvious at various locations along the laser cavity. By placing a finger at the widest part of the corrugation where the mode maximum nodes are located due to mis-alignment, one can effective extract the mode through the finger into the bonding pad, which behaves like a “mode sink”. In this manner, the radiation loss for the higher-order longitudinal modes boost up significantly due to the more severe node mis-alignment for them as compared to the fundamental mode. It can be visually confirmed that for (b), (c) and (d), the resonator modes are extracted extensively through the fingers into the bonding pad whereas for (a), the mode extraction is much less.

Other than the upper band-edge higher-order longitudinal modes, the mode discrimination is also not so distinctive between the designed lasing mode and the lower band-edge modes for a standalone wire laser. From Figure 2-8 (a), the difference between the lower band-edge fundamental mode and the upper band-edge fundamental mode is only around 3 cm⁻¹. Fortunately, the introduction of the mode selectors significantly boosts up the radiation loss for the lower band-edge modes as well, in fact, more significantly as compared to the upper band-edge higher-order longitudinal modes.
Figure 2-12: Mode profiles in terms of the magnitude of the electric field for the upper band-edge modes inside the wire laser with mode selectors. The mode labels are indicated in Figure 2-11.

Figure 2-13: Mode profiles in terms of the magnitude of the electric field for the lower band-edge modes inside the wire laser with mode selectors. The mode labels are indicated in Figure 2-11.
The mode profiles are plotted in Figure 2-13. As the mode maximum nodes are mostly concentrated at the widest part of the corrugation for the lower band-edge modes, all the lower band-edge modes are significantly affected by the mode selectors with the gain threshold increased to more than 20 cm$^{-1}$. Therefore, the mode discrimination among designed and unwanted resonator modes is significantly enhanced with the mode selectors. This is crucial for a robust single-mode operation for broadband tunable THz lasers. Moreover, the same principle could be well extended to other frequency ranges with other types of semiconductor lasers to enhance the cavity mode selectivity.

The experimental characterization for the wire lasers with mode selectors confirms with the simulation result. More details on the experimental characterization will be covered in Section 2.4.2.

2.2.2 Electric Field Non-uniformity

![Figure 2-14: A schematic showing the direct metal contact region for three different configurations. For areas marked in blue, the top metal is in direct contact with the GaAs gain medium layer. For areas in grey, the top metal is not in direct contact with the GaAs gain medium layer due to an additional insulation layer (SiO$_2$ or Si$_3$N$_4$) in between. (a) Only the laser region is directly covered with metal. (b) Both the laser and a finger buffer region of 30 µm long are directly covered with metal. (c) All structures are directly covered with metal.](image)

Another purpose for the finger structures in the mode selector design is to provide electric connection between the laser top metal and the bonding pad. Since the wire
laser is only \( \sim 10 \, \mu m \) wide, it is very dangerous and vulnerable to use a gold wire bond (\( \sim 25 \, \mu m \) in diameter) for electric connection directly on the top metal. In previous works, one of the laser end facets is wet-etched to provide a slope in order to make a wire bond [4]. Such method introduces excess fabrication complication and would potentially reduce the yield rate due to the uncertainty in wet-etch.

Figure 2-15: Plots for electric field in the vertical direction for three cases corresponding to Figure 2-14. The left 2D slice cuts vertically at the middle of the finger and extends into the laser. The right 1D line plot cuts the 2D slice as indicated by the pink line. \( z \) is the vertical direction and the bottom plane of the laser is the \( z = 0 \) plane. The laser ridge is of 10 \( \mu m \) height.

With the mode selectors, it is natural to use the top metal on the fingers to
provide electric connection from the bonding pad to the laser top metal. In one of the earlier attempts, the corrugated laser resonator is directly in contact with the top metal layer (Ti/Au) whereas for the fingers and the bonding pad, there is one additional insulation layer (SiO$_2$) in between the top metal layer and the GaAs gain medium beneath. This is to prevent the finger and the bonding pad region from being active lasers themselves. The metal contact regions is illustrated in Figure 2-14 (a). However, such scheme introduces significant electrical field non-uniformity across the gain medium due the abrupt ending of the current path at the edge of the metal contact region. Finite-element simulation is carried out to quantify this effect. In all simulations carried out in this section, the laser structure has the same dimension as before. For simplicity, only one finger and part of the laser are simulated. The applied voltage at the top contact layer is 20 V. The conductivity for the GaAs gain medium is anisotropic and is set to be 500 S/m in the horizontal direction and 33 S/m in the vertical direction in accordance with the quantum well nature. The result is investigated and plotted in Figure 2-15 (a). Only electric field in the vertical direction is plotted as this is the most relevant to the QCL operation.

In order to have a reference to compare with, another simulation where all the top metal layers above the laser, fingers and the bonding pad are in direct contact with the gain medium layer beneath is carried out as indicated in Figure 2-14 (c). The result is plotted in Figure 2-15 (c). This represents the ideal case of biasing condition for the laser where the vertical electric field component is uniform across the whole laser region. All quantum well modules will be biased equally. However, this configuration has the problem of making the finger and the bonding pad regions lasing as well. In comparison, if one only covers the GaAs gain medium with direct metal contact on top of the laser region only as indicated in Figure 2-14 (a), severe non-uniform electric field distribution in most of the laser region would be observed as shown in Figure 2-15 (a). The abrupt stop of direct top metal contact region at the edge of the wire laser causes the underlying gain medium to be wrongly biased with the top part being biased close to 3 times higher than the lower part. Current will spread into the fingers due to the high quantum well conductivity in the lateral direction. In fact, for
a number of devices fabricated earlier with the one-well injector design OWI222G, the electric field non-uniformity issue killed lasing entirely, since one-well injector designs are more sensitive to non-uniform biasing condition in general.

One way to overcome the electric field non-uniformity issue is to employ the so-called “air bridge” structure to the fingers with wet etch as described in [7]. However, such method cannot be applied here as the fingers need to be intact in order to extract unwanted modes out from the laser resonator. Therefore, another method is proposed and realized in order to improve the electric field uniformity. In this method, the top metal and gain medium direct contact region is extended out to the fingers to create a buffer region as depicted in Figure 2-14 (b). In this way, even though the phenomenon of significant electric field non-uniformity still exists, the place it happens is moved into the fingers as indicated in Figure 2-15 (b). The buffer area length is chosen to be 30 $\mu$m to provide enough buffering whereas at the same time suppressing the fingers from forming active lasing cavity. As one can see, compared to the situation in (a), the electric field non-uniformity issue has been significantly reduced inside the laser cavity. All the quantum well modules are well biased within 2.5% of the desired biasing. In addition, no extra undesirable lasing happens inside the finger buffer region and the mode extraction functions as designed at the same time. Therefore, the operating robustness and reliability are greatly enhanced for the wire laser with the aid of the buffer region design at no additional processing complications.

2.3 Tuning Third-order Distributed Feedback Wire Lasers

Third-order DFB THz QCLs have the advantage of high frequency purity, high power, good beam pattern and minimum negative impact on cw performance. Unlike first-order or second-order THz QCLs that have divergent beam pattern along at least one dimension, third-order DFB QCLs utilize the so-called end-fire antenna effect in order to achieve a single-spot beam pattern [6]. Due to these advantages over first-order
DFB lasers, some preliminary investigations in developing tunable third-order DFB wire lasers have been carried out and the results and observations will be discussed in this section.

Figure 2-16: The resonator design, gain threshold versus frequency plot and fundamental mode profile plots for the third-order DFB wire laser. (a) and (b) correspond to the lower and upper band-edge fundamental modes for the lasing cavity. $f = 3.856$ THz corresponds to the case of perfect phase matching condition where $n_{\text{eff}} = 3$.

The end-fire antenna effect utilized by the third-order DFB lasers is closely related to the phase matching condition of the laser resonator [7]. If the effective modal index $n_{\text{eff}}$ is close to 3, due to the fact that the phase of the waveguide mode at the emission aperture matches with the free-space propagating mode, radiations from each aperture will add constructively at the two far ends whereas destructively elsewhere. This results in tight beam pattern despite the fact of deep sub-wavelength wave confinement inside the resonator cavity. For third order diffraction gratings, the effective modal index $n_{\text{eff}}$ can be defined as $n_{\text{eff}} = 3 \frac{\lambda_0}{2\Lambda}$, where $\lambda_0$ is the free-space wavelength and $\Lambda$ is the grating period. 3 corresponds to the diffraction grating order. With this identify,
the grating period $\Lambda$ can be set in terms of the designed frequency by assuming $n_{\text{eff}} = 3$ for the perfect phase matching condition.

The resonator geometry used in this study, gain threshold versus frequency plot, and the resonator mode profiles are shown in Figure 2-16. The third-order DFB laser used in the simulation consists of periodic combination of block structures with different width and length as shown in the figure. The width for the main block is set around $\sim 10 \ \mu\text{m}$ in order to fulfill the wire laser requirement. The width and length of the narrower block are adjusted in order to fine-tune the phase matching condition and the frequencies of the resonator modes. The designed frequency is $3.856 \ \text{THz}$ which corresponds to a grating period of $38.9 \ \mu\text{m}$. The width of the main block is set as $11 \ \mu\text{m}$ and the width of the narrower block is set as $7 \ \mu\text{m}$. The duty cycle for the main block within one grating period is set as $87\%$ and 17 periods are employed in this simulation. As can be seen from the gain threshold plot, a resonant bandgap is open due to the introduction of the third-order gratings. The mode profiles in terms of the magnitude of the electric field for the lower and upper fundamental band-edge modes are plotted in (a) and (b) respectively. The lower and upper band-edge fundamental modes are at $3.792$ and $3.956 \ \text{THz}$ respectively. This corresponds to an effective mode index $n_{\text{eff}}$ of $3.051$ and $2.924$. For the lower band-edge modes, as can be observed from the mode profile plot, the mode maximum nodes are mostly concentrated at the main blocks of the wire laser with relatively large width. On the contrary, for the upper band-edge modes, some mode maximum nodes are concentrated at the narrower blocks of the wire laser. This contributes to the disparity in the effective mode index for the two modes. If a metal tuner is used to tune this third-order DFB laser, it is desirable to make the lower band-edge mode as the lasing mode since with the tuning from a metal tuner, $n_{\text{eff}}$ decreases as illustrated previously. Since $n_{\text{eff}}$ should be close to 3 as much as possible, it is more reasonable to start from a slightly higher-than-3 $n_{\text{eff}}$ and reduces $n_{\text{eff}}$ gradually with tuning in order to maintain a tight beam pattern. Therefore from the phase matching condition, the lower band-edge fundamental mode should be designed as the lasing mode.

Simulations to characterize the resonator mode frequency shift in the presence
Figure 2-17: Plots for the resonator mode profiles in terms of the magnitude of the electric field inside the third-order DFB wire laser. (a) and (b) correspond to the lower and upper band-edge fundamental modes in the absence of any tuner device. (c) and (d) correspond to these two modes with the metal tuner placed 1 µm away from the laser ridge. A resonator frequency blue-shift of 192 and 190 GHz is observed for these two modes.

of a metal tuner are carried out and the result is shown in Figure 2-17. In this figure, (a) and (b) correspond to the mode profiles for the lower and upper band-edge fundamental modes without any tuner and (c) and (d) correspond to the mode profiles for these two modes with the metal tuner placed 1 µm away from the laser ridge. The tuning for the lower and upper band-edge fundamental modes is seen to be 192 and 190 GHz respectively. As opposed to the case for first-order DFB wire lasers, the mode nodes rearrange their transversal and longitudinal position profiles slightly to form a “zig-zag” pattern along the resonator in the presence of the tuner object. Such mode perturbation rearrangement may have strong implications if ones wants to implement the finger-like mode selectors to enhance the mode selectivity as in general for the mode selector to function, the longitudinal mode profile should remain the same when the tuner moves towards the laser ridge to ensure that the right mode is being extracted. For the lower band-edge modes, as the mode nodes concentrate at the main block of the third-order DFB laser with a relatively large width, the tuning range is limited to below ~ 200 GHz. For the upper band-edge modes, even though some parts of the mode concentrate at the narrower block, due to the fact that the narrower blocks are further away from the tuner surface, the tuning is not seen to be
better as compared to the tuning for the lower band-edge modes.

Several observations can be drawn from the preliminary simulations, most not shown in this section, on third-order DFB wire lasers. First of all, due to the fact that $n_{eff}$ has to be around 3 in order to satisfy the phase matching condition, the effective width of the wire laser cannot be made as small as the one for the first-order wire lasers. From the first-order wire laser simulations, since upper band-edge mode is designed as the lasing mode, the effective width of the waveguide is essentially the narrowest width of the laser cavity, which could be as low as $\sim 6 \mu m$. This results in more than 300 GHz tuning from the simulation with the metal tuner placed 1 $\mu m$ away from the laser ridge. On the other hand, for third-order DFB lasers, in order to maintain $n_{eff} \approx 3$, the width for the main block has to be at least around 10 $\mu m$. Therefore, the tuning range for third-order DFB wire lasers in general would not be as high as first-order DFB wire lasers if one wants to keep the phase matching condition. Otherwise if $n_{eff}$ is set much lower than 3 with narrower device width, one may not be able to maintain the tight beam pattern for third-order DFB lasers, especially for long devices [7].

Secondly, as can be seen from the resonator mode profile, the gain threshold differentiation for third-order DFB wire lasers is much weaker as compared to first-order DFB wire lasers due to limited design freedom in mode adjustment with narrow device. This has been observed for all resonator geometries simulated with many of them having even worse gain threshold differentiation compared to the one shown in Figure 2-16. This could easily result in multi-mode lasing or lasing at the wrong frequency. Therefore mode selectors are necessary for robust frequency selectivity. Due to the mode profile being much more complicated, the finger position should be cautiously chosen in order to enhance the frequency discrimination. With the mode rearranging themselves as shown in Figure 2-17 (c) and (d), it is in doubt whether the finger-like mode selectors would be sufficient to extract the right modes. Therefore, enhanced mode selection in other forms may be needed for robust broadband tuning purpose.

Thirdly, in order to reach $\sim$ mW of output power level for practical applications,
one needs to increase the number of periods for the third-order DFB wire lasers. This puts additional complications on finger position design due to the large memory requirement in simulations for bigger devices in general. From a rough active area calculation, one needs at least millimeter-long third-order DFB wire lasers with $\sim 10 \, \mu m$ device width in order to achieve $\sim mW$ of output power level. Such a large device length is also not desirable for tuner alignment since angle mis-alignment tolerance is in general smaller for longer devices. Furthermore, with small device features like the ones in a wire laser, fabrication uncertainty and inconsistency across a large scale may influence device performance as well.

From the observations above, even though it may be possible to construct moderately tunable third-order DFB wire lasers with a reasonable output power level and a tight beam pattern, the design of a properly working third-order DFB wire laser with mode selectors of some form would be a much more time-involving process as compared to the case for first-order DFB wire lasers and may need multiple design iterations in order to achieve robust operation across a broad frequency range. The competing technology of feeding the output light of a tunable first-order DFB wire laser into a power amplifier attached with a silicon hyperhemispherical lens would seem to be a more appealing solution that allows higher tuning range from a single device, ensured broadband single-mode operation and possibly much shorter design cycle. Therefore further investigations on tunable third-order DFB wire lasers are not carried on. More efforts are put into fabricating and characterizing first-order DFB wire lasers with MEMS tuner chips.

2.4 Tunable Terahertz Wire Lasers: Fabrication and Characterization

2.4.1 Device Fabrication

Standard clean-room THz QCL fabrication procedures are carried out to fabricate the wire laser devices with some modifications in order to cater specific issues encountered
during the fabrication. The gain medium design used in this thesis is FL183S with wafer number VB0481. The fabrication steps can be summarized as follows.

The MBE grown wafers are first cleaved into 2 cm by 2 cm pieces. Together with cleaved n+ GaAs substrate pieces, they are dipped into 1:1 HCl:H$_2$O solution for 30 s to strip surface oxide before deposition and then deposited Ta/Au 100/2500 Å using e-beam deposition. After that, the MBE wafer pieces are thermally bonded with the n+ GaAs substrate wafer with Au-Au thermal compression bonding at $\sim$ 300 °C and $\sim$ 4 MPa for 60 mins using an EV501 wafer bonder. In order to improve the quality of the metal-metal bonding, all samples are subsequently put into the same machine for thermal annealing at 300 °C in N$_2$ environment for 45 mins. The samples are then deposited with 4000 Å SiO$_2$ on both sides with an STS-CVD machine for protection purpose.

The next step is mechanical lapping inside the Hu Lab in order to remove most of the MBE wafer substrate. A more controllable and selective wet etch in 3:1 citric acid:H$_2$O$_2$ solution ($\sim$ 500 mL) is carried out in order to etch the substrate down to the AlGaAs etch-top layer. The etch-stop layer is then etched away in HF for 15 to 30 s by visual inspection. The highly doped top contact layer remains unetched in this step.

The sample is then deposited with $\sim$ 3000 Å Si$_3$N$_4$ using the STS-CVD machine. The actual deposited Si$_3$N$_4$ thickness is later measured to be $\sim$ 2860 Å. After that, the first photo-lithography is carried out with photoresist Shipley 1813 in order to define the Si$_3$N$_4$ insulation layer pattern. The patterned photoresist subsequently serves as a dry etch mask when the sample is put into the Electron Cyclotron Resonance (ECR) dry etch machine Plasmaquest to etch the exposed Si$_3$N$_4$ layer. The photoresist is then removed using standard solvent cleaning and Asher treatment. A brief wet etch using 1:1:50 H$_3$PO$_4$:H$_2$O$_2$:H$_2$O for 30 s is then carried out in order to etch away part of the exposed highly doped top contact layer in order to smoothen the surface. The estimated etched thickness is about 600 Å whereas the highly doped contact layer is 1000 Å thick. After this, the second photo-lithography with image reversal photoresist AZ5214E is processed to define the top metal layer pattern. A prededposition oxide
strip etch followed by metal deposition of Ti/Au 200/3000 Å using e-beam deposition are carried out. The next step is the standard lift-off process to define the top metal layer.

Before the final dry etch to define the mesa structure, the sample is put into Plasmaquest again to etch the remaining exposed Si₃N₄ layer. The sample is then cleaned by putting into the Asher for 30 mins, dipped in 1:1 HCl:H₂O solution for 30 s and dipped in BOE solution for 30 s. After the cleaning, the mesa definition is performed by using the Inductively Coupled Plasma (ICP) dry etch machine SAMCO with a recipe developed by Kao for 65 mins. The top metal acts as a self-aligned etch mask and the bottom metal serves as the etch-stop layer. The sidewall passivation layer introduced by this dry etch is later removed by both wet etch inside BOE solution for 30 s and dry etch using Plasmaquest for 600 s.

![Figure 2-18: SEM images for the grass structures observed after the final dry etch step.](image)

The initially planned subsequent process is to perform the final backside lapping and metal deposition. However, it has been observed after the dry etch step that on the top surface of the processed piece, there exists an extensive and dense coverage of "grass" structures as shown in Figure 2-18. The grasses are typically of around 1 to 2 µm in diameter and are above 5 µm in height as shown in (b).

The alignment of the QCL chip and the MEMS tuner device depends critically on the surface finish of the QCL chip,
some efforts are devoted to investigate and remove the grass structures.

![SEM images](image)

**Figure 2-19:** SEM images for the laser structure after a brief wet etch in 1:1:25 $H_3PO_4:H_2O_2:H_2O$ solution. Severe undercut and non-uniform etching profile are observed due to the galvanic effect.

It has been later verified that the existence of the grass structures is due to particles in the AZ5214E photoresist. The photoresist at the time of the experiment is reaching the bottom part of the bottle and thus contains a fair amount of precipitates accumulated through years. The particles introduced by this photoresist subsequently serve as dry etch mask and are the main cause of the grass structure. Due to this reason, the grasses are considered mostly GaAs micro-wires. With this in mind, controlled wet etch is carried out in order to remove the grass. The first attempt is to dip the sample into 1:1:25 $H_3PO_4:H_2O_2:H_2O$ solution for 20 s. From the SEM images taken afterwards, even though the grass structures are completely removed after the wet etch, a severe undercut due to the galvanic effect at the top and bottom parts of the laser is simultaneously observed as shown in Figure 2-19. This is highly undesirable as it distorts the resonator structure and causes non-uniform biasing condition. Similar phenomenon is also observed when using 1:8:80 $H_2SO_4:H_2O_2:H_2O$ solution for a brief wet etch.

Diluted acid is tried later as the etchant, with the 1:1:25 $H_3PO_4:H_2O_2:H_2O$ solution diluted with water of various volume from 1:1 to 1:5. However, either the undercut remains to be problematic or the solution is too diluted such that the grasses are not
effectively removed. It is therefore determined that acid-based etchant is not suitable for unprotected clean-up etch.

![a](image1) ![b](image2)

Figure 2-20: SEM images for the laser structure after 20 s clean-up PA etch in 5:3:490 NH₄OH:H₂O₂:H₂O. The grass structures are mostly removed whereas the sidewall undercut issue is seen to be much less severe as compared to the case in previous acid-based etching.

Two approaches are carried out later where both methods result in cleaned surface finish and minimum undercut. As opposed to using acidic wet etchant, the first approach is to use diluted peroxide-ammonia (PA) wet etch with 5:3:490 NH₄OH:H₂O₂:H₂O for 20 s. The result is shown in Figure 2-20. The finished surface is very smooth and clean whereas the undercut is much less severe as compared to using acid-based wet etchant. The laser devices undergo such treatment are later tested and all perform comparably well as compared to other batches. Besides, the sidewall of the laser structure is very clean as can be seen from the figure which means the PA etch cleans up part of the passivation layer on the sidewall that cannot be cleaned by previous BOE dip or Plasmaquest clean-up. A closer look at the finished sidewall and the top metal step on the finger is shown in Figure 2-21.

The other approach is to incorporate an additional photo-lithography process. A thick photoresist AZP4260 of ∼ 10 μm thickness is spin coated on top of the wafer and exposed using an additional mask that covers the laser and the bonding pad structures. The features in the additional photo-lithography mask is made 5 μm bigger than the metal layer mask features in order to make sure that the critical structures
are well covered. Since the important device features are protected by the patterned photoresist, the laser is then immersed in 10:6:480 NH$_4$OH:H$_2$O$_2$:H$_2$O for about 1 min to completely remove any exposed grass or mesa structures. The final SEM image is shown in Figure 2-22 (a). For some of the laser devices, a severe undercut on one facet edge of the laser is observed as can be seen in Figure 2-22 (b). This is due to the incomplete photoresist coverage on the device in the last step which means 5 µm larger feature size for this photo-lithography mask is not sufficient for complete and safe device coverage. Fortunately, all devices tested with such wet etch flaw still lase as well as ones that are not damaged at all. This is probably due to the reason that the damaged area is small as compared to the overall laser area and most of the resonator mode is concentrated at the center part of the laser resonator as shown in Figure 2-4.

After the device pieces are cleaned with wet-etch, they are backside lapped to around 250 µm thick and deposited with Ti/Au 100/3000 Å on the backside using e-beam deposition for better thermal contact. At last, standard device cleaving is carried out to separate individual QCL chips for testing and characterization.
Figure 2-22: SEM images of the finished laser structures processed with additional photo-lithography step for wet etch protection. Due to the underestimated mask feature size for the last lithography step, undercut at one of the facet edges of the laser structure can be observed as seen in (b). This does not introduce observable performance deterioration for devices tested due to the small damaged area and the center-concentrated mode profile of the lasing mode.

2.4.2 Design, Measurement and Characterization

First-order DFB wire lasers with designed frequencies from 3.5 to 3.9 THz have been designed, fabricated and characterized. The designed frequency spans across 3.5 to 3.9 THz as indicated in Table 2.1. The gain medium FL183S has a gain curve profile as indicated in Figure 2-9. It can be seen that the designed frequency coverage centers around the second gain curve peak at 3.75 THz. Some device testings with different cavity designs indicate that at least lasing at 4.1 THz could be achieved on the same gain medium wafer, which means that even for lasers with designed frequency at 3.9 THz, there is at least ∼ 200 GHz tuning potential with gain medium bandwidth constraint only. In addition to the designed frequency variations, the average laser width is also varied as 9.5, 10.5 and 11.5 μm. Although it is certainly true that narrower devices could in theory have more tuning range due to larger fringing field with lower confinement factor, narrower devices in general would have lower modal gain at the same time, making them more susceptible to the free carrier loss introduced by the metal tuner surface. This could potentially kill lasing when the tuner moves
close enough to the laser ridge. For devices with a designed frequency of 3.7 THz and below, the 11-finger mode selector configuration is used to provide robust frequency selectivity. For devices with a designed frequency of 3.8 THz and above, a 5-finger mode selector configuration is used since the lasing frequency will be tuned away from the gain peak with blue-shift. In this case, the first-order sinusoidal corrugation is already sufficient to provide enough frequency selectivity as proven in [5]. Therefore only 5 fingers are used in this case to reduce the excessive loss introduced by the 11-finger design for the fundamental lasing mode.

Standard THz QCL measurement is carried out to characterize the fabricated devices. All data presented in this section are obtained through pulsed operation with a pulsing frequency of 20 kHz and a pulse width of 500 ns. This results in 1% duty cycle. Two boxcars are used to average the measured current and voltage readings. A Winston Cone is attached at the end of the device to increase the power collection efficiency. The device characterization plots for device No. 41, 43, 45 and 53 are shown in Figure 2-23 to 2-26. It can be observed that device No. 41, 43, 45 and 53 lase at 3.54, 3.72, 3.83 and 3.72 THz respectively. The characterized frequencies are in general very close to the designed frequencies with consistent blue-shift of less than 50 GHz. This validates the material parameters used in the simulation and also the high fidelity in the fabrication. Single-mode operation is maintained throughout all biasing conditions below negative differential resistance (NDR) point for all the devices characterized ranging from around 3.5 to 3.9 THz. This strongly corroborates the outstanding performance of the mode selector design used for this study. For a comparison between the frequency performance of a standalone wire laser and a wire

<table>
<thead>
<tr>
<th>Wire Laser Design</th>
<th>3.5 THz</th>
<th>3.6 THz</th>
<th>3.7 THz</th>
<th>3.8 THz</th>
<th>3.9 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5 µm</td>
<td>No. 11</td>
<td>No. 12</td>
<td>No. 13</td>
<td>No. 14</td>
<td>No. 15</td>
</tr>
<tr>
<td>11.5 µm</td>
<td>No. 21</td>
<td>No. 22</td>
<td>No. 23</td>
<td>No. 24</td>
<td>No. 25</td>
</tr>
<tr>
<td>10.5 µm</td>
<td>No. 31</td>
<td>No. 32</td>
<td>No. 33</td>
<td>No. 34</td>
<td>No. 35</td>
</tr>
<tr>
<td>9.5 µm</td>
<td>No. 41</td>
<td>No. 42</td>
<td>No. 43</td>
<td>No. 44</td>
<td>No. 45</td>
</tr>
<tr>
<td>10.5 µm</td>
<td>No. 51</td>
<td>No. 52</td>
<td>No. 53</td>
<td>No. 54</td>
<td>No. 55</td>
</tr>
</tbody>
</table>

Table 2.1: Wire laser device labels with corresponding average nominal widths (left column) and the designed frequencies (top row).
Figure 2-23: Performance characterization for device No. 41. (a) Lasing frequency versus biasing condition. The laser lases in single-mode for all operating biasing conditions tested. (b) Current density versus voltage at different temperatures. (c) Normalized collected output power versus current density at different temperatures. (d) Normalized collected output power versus current density at different temperatures.
Figure 2-24: Performance characterization for device No. 43. (a) Lasing frequency versus biasing condition. The laser lases in single-mode for all operating biasing conditions tested. (b) Current density versus voltage at different temperatures. (c) Normalized collected output power versus current density at different temperatures. (d) Normalized collected output power versus current density at different temperatures.
Figure 2-25: Performance characterization for device No. 45. (a) Lasing frequency versus biasing condition. The laser lases in single-mode for all operating biasing conditions tested. (b) Current density versus voltage at different temperatures. (c) Normalized collected output power versus current density at different temperatures. (d) Normalized collected output power versus current density at different temperatures.
laser with the mode selectors, readers are referred to reference [44].

It is also interesting to compare the temperature performance and power-current-voltage relationships among the tested devices. As different average widths would in general result in different confinement factors that could affect the modal gain, comparison among devices with the same average width is first carried out. For a typical wide Fabry-Perot laser fabricated from the same wafer, the maximum operating temperature ($T_{\text{max}}$) is observed to be around 166 K. From Figure 2-23 to 2-25, it can be noticed that as the lasing frequency moves from 3.54 to 3.72 to 3.83 THz, $T_{\text{max}}$ increases from 85 to 100 to 125 K. This is not difficult to understand as from Figure 2-9, the gain monotonically increases from around 3.55 to 3.75 THz. Meanwhile, it should be noted that the gain measurement shown in Figure 2-9 only provides a qualitative understanding of the overall gain curve shape as it is taken at one particular temperature (45 K) and one specific biasing condition (1124.3 A/cm$^2$). Shift of the gain peak/valley does occur when the operating temperature or the biasing condition changes. The operating temperatures for all the device measurements are at liquid helium temperature ($\sim$ 4 K). This could account for the slight gain curve change that leads to the 3.83 THz device having higher $T_{\text{max}}$ as compared to the 3.72 THz device.

The lasing dynamic range is seen to be positively correlated to the $T_{\text{max}}$ performance. The dynamic range is estimated as the current range from the threshold current density to the peak-power current density. Notice that due to the transient nature of pulsed measurement, for some L-J or L-V data, the collected power has a small gradient before rising up significantly with increasing voltage or current density. This part is not counted in the dynamic range estimation. The dynamic range for device No. 41, 43 and 45 are estimated to be around 210, 270 and 380 A/cm$^2$ respectively. The increase in the dynamic range coincides with the increasing $T_{\text{max}}$. This further confirms that the laser experiences more modal gain as moving from around 3.5 to 3.8 THz.

Other than comparing the lasing performance among devices with the same average width, it is also important to compare the performance of devices with different average width but lase at the same frequency. This comparison can be best performed by looking at the performance data for device No. 43 in Figure 2-24 and No. 53 in Figure
Figure 2-26: Performance characterization for device No. 53. (a) Lasing frequency versus biasing condition. The laser lases in single-mode for all operating biasing conditions tested. (b) Current density versus voltage at different temperatures. (c) Normalized collected output power versus current density at different temperatures. (d) Normalized collected output power versus current density at different temperatures.
2-26 where both devices lase at 3.72 THz. Device No. 53 has an average width of 10.5 \( \mu m \) which is 1 \( \mu m \) larger than the average width of device No. 43. As a result, device No. 53 has around 20 K higher \( T_{\text{max}} \) as compared to device No. 43. The dynamic range for device No. 53 is around 350 A/cm\(^2\) which is around 80 A/cm\(^2\) higher than the dynamic range of device No. 43. This improved lasing performance is directly related to the fact that narrower device has a smaller confinement factor, which results in lower modal gain. This effect is further exaggerated for first-order DFB wire lasers as the mode profile for the lasing mode concentrates at the narrowest part of the laser cavity. The effective cross-sectional width for device No. 43 and 53 are 6.5 and 7.5 \( \mu m \) respectively. Therefore even 1 \( \mu m \) change in average width is significant for the performance of a wire laser.

### 2.4.3 Manually Tunable Terahertz Wire Lasers

At the early stage of this thesis work, characterizing manually tunable THz wire lasers with enhanced mode selectors using the MEMS structure fabricated in-house [5, 39] has been carried out. The MEMS tuner devices, termed as "plungers", are fabricated on silicon-on-insulator (SOI) wafers as described in [39]. The schematic for such manually tunable THz wire lasers is shown in Figure 2-27. The MEMS tuner design utilizes a two-stage folded-beam flexure structure. The first stage is to minimize any shaft tilt resulting from oblique angle force exertion. The second stage is connected to the tuner object for actual tuning. The patterned structure is on the SOI top device layer and the tuner surface is obtained through deep dry-etch into the SOI bottom handle layer. In order to actuate the MEMS tuner chip, a differential micrometer is used to push one end of a level that exerts force on the tuner shaft with the other end. The manual tuning is achieved by gradually turning the knob on the differential micrometer and recording the lasing spectrum. For more details about the MEMS tuner fabrication, experimental setup and results from previous testings, readers are referred to references [5, 39].

The tuning demonstrated in [5] spans across a range of around 3.85 to 4.18 THz. This covers the upper gain spectrum after the gain peak as can be seen from Figure
Figure 2-27: A schematic illustration of the manually tunable THz wire lasers with MEMS tuner devices fabricated in-house [5]. (a) A schematic for the cryostat configuration in the experimental setup. (b) An SEM image of the fabricated MEMS tuner device. (c) A schematic for the two-stage MEMS tuner device design. (d) An illustration for the alignment scheme between the THz QCL chip and the MEMS tuner chip.
Figure 2-28: Spectrum for the manually tunable THz wire lasers with the 11-finger mode selector design. The lasing frequency for the unperturbed wire laser is at 3.52 THz. The manual tuning exhibits single-frequency continuous tuning to up to 3.82 THz without mode-hopping. This corresponds to the tuner surface being less than 1 µm away from the laser ridge.

2-9. With the enhanced mode selectors, one should be able to tuning the laser with single-frequency operation across the lower gain spectrum below the gain peak as well. The resulting tuning spectrum is shown in Figure 2-28. The laser tested has an average width of 11.5 µm and an unperturbed lasing frequency of 3.52 THz without the tuner chip. It has the 11-finger mode selector design as shown in Section 2.2. The metal tuner chip is then mounted onto the QCL chip by utilizing the alignment structures shown in Figure 2-27 (d). Only the metal tuner is mounted and tested as practically one could only engage one type of the tuners at a time. The whole setup is maintained at liquid helium temperature throughout the tuning experiment. As the micrometer is actuated manually, the laser exhibits continuous tuning from 3.52 to 3.82 THz with around 300 GHz tuning range where single-frequency operation is maintained throughout the entire operating range. Meanwhile, the tuning is completely reversible which means by retracting the micrometer, the lasing frequency can be restored from 3.82 to the original 3.52 THz. The 300 GHz tuning corresponds to the case where the MEMS tuner surface is less than 1 µm away from the laser ridge. This result shows
that the mode selector is suitable for broadband single-frequency tuning applications. Due to the significantly enhanced mode selectivity, one can fully utilize the entire gain bandwidth by combining two or more tunable wire lasers with different designed frequencies that are fabricated on the same wafer. In this way, tuning across the entire gain bandwidth of around 1 THz is possible with a single QCL device chip.

As can be seen from this chapter, manually tunable THz wire lasers with enhanced mode selectors have shown impressive tuning behavior. Nonetheless, there exists large room for improvement which will be addressed in the following chapters. Specifically, several problems observed are listed below which lay down the rational for subsequent works.

- Firstly, the manual tuning scheme is not suitable for practical applications. In order to tune the device with the micrometer, one has to gradually turn the micrometer knob very carefully. This prevents any fast tuning or feedback control from being incorporated into the system. In addition, the micrometer feed-through greatly reduces the dewar holding time and is cumbersome to carry and operate. It is also almost impossible to perform the experiment inside a non-specialized cryostat without significantly modifying the cryostat configuration to allow the feed-through port.

- The repeatability and reproducibility of the tuning experiment are low. On average, only around tens of GHz tuning could be achieved before the tuner metal surface touches the laser ridge and burns the device. Very large inconsistency can be observed with different tuner devices and different QCL chips. This is most likely due to problems in the MEMS fabrication and the alignment scheme used. In the MEMS fabrication, the device layer patterning and the alignment feature patterning are performed in two photo-lithography steps. It is almost inevitable to have misalignment between these two patterning steps. As aligning the tuner surface with the laser ridge is crucial to the tuning performance [5], it is more desirable to define all the critical features (tuner surface and the alignment features) in one photo-lithography step, thus improving the reproducibility of
the tuning result.

- The MEMS fabrication is complicated and time-consuming. The MEMS fabrication includes many steps of photo-lithography, etching and material deposition. It would be much more desirable if the MEMS fabrication could be out-sourced to commercial open-foundry processes, leveraging their fabrication consistency and high customizability.
Chapter 3

MEMS Tuner Devices

3.1 SOIMUMPs

3.1.1 Overview

Since standard silicon-on-oxide (SOI) MEMS device fabrication is sufficient for the tuner design proposed in this work, it is very desirable to look for commercial foundry platform to perform the device fabrication. Several commercial MEMS fabrication platforms have been researched and evaluated and eventually the Multi-User MEMS Process (MUMPs) from MEMSCAP Inc. is chosen due to its cost-effectiveness, process reliability and structure compatibility with the tuner design. MUMPs offers three different MEMS fabrication processes, namely PolyMUMPs, SOIMUMPs and MetalMUMPs where the device material and process complexity vary across these different processes. From the three offered processes, SOIMUMPs is chosen as it fits the MEMS tuner structure requirement the most and has relatively low design complexity. So far, many functional MEMS devices have been successfully demonstrated through SOIMUMPs such as gyroscopes [45], optical choppers [46], micro-grippers [47, 48], and vibration sensors [49]. The cross-sectional schematic for devices fabricated from SOIMUMPs is shown in Figure 3-1. A thorough and detailed experimental study for the design-critical characteristics of the SOIMUMPs platform can be found in [50].
3.1.2 SOIMUMPs Process Flow

The SOIMUMPs starts with a standard SOI wafer which consists of a handle layer (400 µm), a buried oxide layer and a device layer. The device layer thickness can be of either 10 µm or 25 µm. The 10 µm thickness device layer corresponds to 1 µm thick buried oxide layer whereas for 25 µm thick device layer, the buried oxide layer is of 2 µm thick. The fabrication flow, design specifications and design rules can be found in the SOIMUMPs handbook [51]. A schematic overview of the fabrication process is shown in Figure 3-2.

The starting material for SOIMUMPs is a 150 mm n-type double-side polished SOI wafer. The device layer is first deposited with a phosphosilicate glass (PSG) layer and annealed at 1050 °C for an hour in Argon as shown in Figure 3-2 (a). The PSG layer is subsequently removed through wet chemical etch. The typical resistivity for the device layer is around 1 to 10 ohm-cm. This layer is denoted as SOI in the design handbook.

A metal layer consisting of 20 nm of Cr and 500 nm of Au is then patterned through photo-lithography and lift-off shown in Figure 3-2 (b). This layer has 3 µm minimum line and space feature size and has a 3 µm alignment tolerance with respect to the SOI layer feature. It is termed as the PADMETAL since the main purpose for this layer is for providing electrical connection as opposed to low-loss optical mirror applications due to its high surface roughness.

The SOI layer feature is then defined with the second lithography process. Afterwards, deep reactive-ion etching (DRIE) is performed with an Inductively Coupled
Figure 3-2: Fabrication process flow for SOIMUMPs. Figures are extracted from reference [51].
Plasma (ICP) machine as illustrated in Figure 3-2 (c). The nominal minimum line and space feature size for the SOI layer is 2 $\mu$m. However, it is suggested by the foundry technical staff that it is safer to assume a minimum feature size of at least 3 $\mu$m due to fabrication uncertainty.

In the next step shown in Figure 3-2 (d), the SOI layer is first protected by depositing a protection layer. A third photo-lithography for the substrate layer is performed on the backside of the SOI wafer. Another DRIE silicon etch is carried out to etch through the substrate, which is termed as TRENCH layer, till the buried oxide layer. This is to facilitate the release of the suspended SOI layer feature. A wet oxide etch from the backside is then performed to etch away the exposed buried oxide region. Due to the thick silicon layer that needs to be etched, the minimum feature and line size for the TRENCH layer is 200 $\mu$m and the alignment tolerance with respect to the SOI layer is 5 $\mu$m.

Afterwards, the frontside protection layer is etched away through a dry etch process followed by a vapor HF etch to remove any exposed buried oxide area seen from the frontside as shown in Figure 3-2 (e). The vapor HF etch also leaves around 1.8 to 2 $\mu$m undercut in the oxide layer. An SEM image of the SOI layer undercut is presented in Figure 3-3. This undercut will prevent any metal short due to subsequent metal deposition process between the SOI layer and the Si substrate (TRENCH layer).

![Figure 3-3](image.png)

Figure 3-3: An SEM image showing the SOI layer undercut after vapor HF etch. Figures are extracted from reference [51].

Next, a separate side polished silicon wafer is prepared as the shadow mask shown
in Figure 3-2 (f). A photo-lithography followed by DRIE silicon etch is carried out on this silicon wafer to define the shadow mask. On one side of the silicon wafer, “standoffs” are prepared to avoid direct contact between the shadow mask and the SOI layer feature.

The shadow mask is then aligned and bonded to the SOI wafer. Another metal deposition using 50 nm Cr and 600 nm Au is performed to define the final metal layer named BLANKETMETAL. Due to the DRIE silicon etch and coarse alignment performed in this step, the BLANKETMETAL layer has a minimum line and space feature size of 100 µm and an alignment tolerance of 40 µm with respect to the SOI layer. The schematic illustration for this step is in Figure 3-2 (g).

After the metal deposition, the shadow mask is removed, leaving the final structure look like the one shown in Figure 3-2 (h). The wafer is then laser-cutted into individual dies of around 1.1 cm × 1.1 cm squares and are subsequently packaged for shipping.

A summary for the layer thickness, minimum feature resolution and the corresponding layer names in the design handbook and photo-lithography mask is shown in Table 3.1. In addition, the layer alignment requirement for each layer with respect to the SOI layer is shown in Table 3.2. A few critical design considerations can be drawn from the process characteristics. First of all, the only critically defined layer is the SOI layer which is either 10 or 25 µm thick doped Si layer. Ideally, all crucial

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (µm)</th>
<th>Min. Resolution (µm)</th>
<th>Layer Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad Metal</td>
<td>0.52</td>
<td>3</td>
<td>PADMETAL</td>
</tr>
<tr>
<td>Device Layer</td>
<td>10.0 or 25.0</td>
<td>3</td>
<td>SOI</td>
</tr>
<tr>
<td>Oxide Layer</td>
<td>1.0 or 2.0</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Handle Layer</td>
<td>400</td>
<td>200</td>
<td>TRENCH</td>
</tr>
<tr>
<td>Blanket Metal</td>
<td>0.65</td>
<td>100</td>
<td>BLANKETMETAL</td>
</tr>
</tbody>
</table>

Table 3.1: Summary for the layer thickness, minimum feature resolution and the corresponding layer names in the design handbook and photo-lithography mask.

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Overlay Tolerance (µm)</th>
<th>Edge-Edge Bias (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PADMETAL</td>
<td>±3</td>
<td>±3</td>
</tr>
<tr>
<td>TRENCH</td>
<td>±5</td>
<td>&lt;50</td>
</tr>
<tr>
<td>BLANKETMETAL</td>
<td>±35</td>
<td>±40</td>
</tr>
</tbody>
</table>

Table 3.2: Summary for the alignment requirement for each layer with respect to the SOI layer.
MEMS features should be defined on this layer. Secondly, the TRENCH layer should only be used for releasing the SOI layer through backside DRIE silicon etch. No actual functional structure should be constructed from this layer. In addition, the finished silicon wall has an inclined slope as shown in Figure 3-1. This could result in unexpected suspending feature on the SOI layer if one does not take this slanted etch wall into account. Thirdly, in order to release the SOI layer that is not directly above a TRENCH through-hole feature, one should make the minimum SOI feature size at most around 5 µm. Otherwise, the structure will not be fully suspended due to limited under-etch in the vapor HF etch process.

3.2 MEMS Tuner Design

3.2.1 Overview

Two schemes of electrically actuated MEMS tuner structures have been proposed, realized and characterized with the QCL chip. These two schemes differ in the way of electrically actuating the tuner object: one actuates the tuner object by utilizing microscopic electrostatic force with the so-called comb drive structures whereas the other one actuates the tuner object by applying a macroscopic force with a piezo nano-positioning actuator. Despite different actuating mechanisms of the two schemes, both methods share common elements including the flexure design, alignment technique and device separation technique. These common elements will be analyzed in this section.

3.2.2 Flexure Design

Flexures are almost essential elements for any free-suspending MEMS structure that restores to its original position after the actuating force is withdrawn. A detailed analysis for commonly used flexures in MEMS design including the fixed-fixed flexure, the crab-leg flexure, the folded-beam flexure and the serpentine flexure is provided in Fedder’s thesis [52]. The folded-beam flexure design is chosen in this thesis study due
Figure 3-4: Schematic illustration of the folded-beam flexure design. (a) Top view of the folded-beam flexure design. (b) Side view of the folded-beam flexure design.

to its excellent spring constant linearity in the actuating direction and mechanical stability in the lateral direction. An illustration of the folded-beam flexure is shown in Figure 3-4. The center load beam is supported by the two folded-beam flexures on both the left and the right side. All supporting beams in the lateral direction are of the same length to minimize excess stress when the load beam is being actuated. The supporting beam has a beam width of \( w \), a beam length of \( l \) and a beam thickness of \( t \). In the case of a stiff truss, the mechanical spring constant \( k_x \) for the folded-beam flexure design has been well studied and has an analytical form of \([52, 53]\)

\[
k_x = \frac{2Etw^3}{l^3}.
\]

In the equation, \( E \) is the Young’s Modulus for the material of the folded-beam flexure. On the other hand, the spring constant for the folded-beam flexure in the lateral direction is shown to be \([54]\)

\[
k_y = \frac{2Etw}{l}.
\]

Combining the spring constants in both directions gives the stiffness ratio of
\[ \frac{k_x}{k_y} = \left( \frac{w}{l} \right)^2. \]

Figure 3-5: (a) Applied force versus displacement plot from both analytical method and numerical simulation for the flexure design used with the comb drive actuator. The spring beam length is 745 \( \mu \text{m} \), the beam width is 6 \( \mu \text{m} \), and the beam thickness is 25 \( \mu \text{m} \). (b) Displacement field plot for the flexure. The displacement unit is in \( \mu \text{m} \).

The parameters used in the folded-beam flexure design are decided by the amount of force that can be supplied by the actuating mechanism. For typical comb drive actuators, the actuation force is below \( 10^{-4} \) N, therefore the folded-beam flexure is designed to have small spring constant in the actuating direction. This directly results in small beam width \( w \) and long beam length \( l \) in order to have small \( \left( \frac{w}{l} \right)^3 \) term. This puts on additional design considerations for the comb drive flexure design in order to conform with the SOIMUMPs design rules on minimum lithography resolution and maximum etching area. On the other hand, the piezo actuator has an actuation force of more than 1 N [55], the flexure structure designed for piezo actuator therefore can have a much higher spring constant as compared to that of the comb drive actuated flexure design. Therefore there is no stringent requirement on minimizing the flexure spring constant. Higher spring constant also increases the flexure stability in the
actuating direction with respect to actuation force fluctuation and environmental perturbation.

Figure 3-6: (a) Applied force versus displacement plot from both analytical method and numerical simulation for the flexure design used with the piezo actuator. The spring beam length is 745 µm, the beam width is 6 µm, and the beam thickness is 25 µm. (b) Displacement field plot for the flexure. The displacement unit is in µm.

The applied force versus flexure displacement relationships for the two tuner flexure designs are characterized both analytically and numerically with the finite-element simulation software COMSOL. The force versus displacement plot and the displacement field plot are shown in Figure 3-5 and 3-6. From both figures, it can be seen that the analytical method and the numerical simulation match with each other very well. The folded-beam flexure exhibits almost perfect linear behavior in the range of interest. The device layer thickness for both devices is set as 25 µm. Due to the small force that can be provided by the comb drive actuator, the flexure beam width is designed to be 6 µm and the length is 745 µm. On the other hand, the flexure design for direct piezo actuation has a beam width of 25 µm and a beam length of 602 µm. The maximum von Mises stress experienced by the two flexure designs are $5.1 \times 10^7$ and $4.8 \times 10^7$ N/m² respectively. Since these values are well below the Si yield strength on the order of $\sim$ GPa, the material response is elastic deformation as opposed to plastic deformation with respect to the applied force. The required force for the same displacement is of two orders of magnitude difference for the two flexure
designs, highlighting the aspect ratio difference for the two spring beams utilized.

### 3.2.3 Device Alignment

![Figure 3-7](image)

Figure 3-7: (a) Finished QCL chip showing the position of the female alignment structure. (b) Finished MEMS tuner chip showing the position of the male alignment structure.

![Figure 3-8](image)

Figure 3-8: A closer look at the alignment feature on the MEMS tuner chip showing the metal buffer layers on top of the SOI layer. The total buffer layer thickness is around 1.2 µm.

Since all critical MEMS features are defined in one photo-lithography step on the SOI layer, a back-flip alignment scheme is used in order to align the MEMS tuner chip with the QCL chip. The alignment features are illustrated in Figure 3-7. For the QCL chip, the female alignment structures are defined by the GaAs ICP dry etch. The C-shaped alignment marks are of 10 µm height. For the MEMS tuner chip, the male alignment structures are defined as a rectangular block that is of the
device layer thickness (either 10 or 25 µm). In order to provide a buffer layer which allows the MEMS device layer to move freely in the actuating direction, the top surface of the male alignment structure on the MEMS chip is deposited with both the PADMETAL layer and the BLANKETMETAL layer in the SOIMUMPs process. A closer examination on the alignment feature of the MEMS tuner chip is shown in Figure 3-8. The total buffer layer thickness is around 1.2 µm, meaning that the device layer is suspended around 1.2 µm above the QCL chip surface after the alignment and chip bonding process.

Figure 3-9: A schematic showing the alignment illustration for the QCL chip and the MEMS tuner chip. After the alignment, the two pieces are bonded by cryogenic adhesive epoxy Stycast.

Figure 3-10: An SEM image showing the final assembled device.

A schematic for the final aligned device is shown in Figure 3-9. The tuner object
surface is around 15 \( \mu m \) away from the laser ridge at the resting position. An SEM image for the final aligned device chip is shown in Figure 3-10. It is observed that the tuner surface is very well aligned with the laser ridge with almost no visual mis-alignment. Such robust and repeatable alignment scheme is crucial for maximum tuning with THz wire lasers. The experimental alignment and device assembly techniques will be elaborated in detail in Chapter 4.

### 3.2.4 Device Separation

![Figure 3-11](a) A schematic showing the comb drive chip before the final wafer dicing to define the extended tuner object. A wafer die saw will cut along the dashed lines in the schematic. (b) The final finished comb drive chip which allows direct alignment and interaction with the QCL chip.

The shipped individual MEMS dies are of around 1.1 \( \times \) 1.1 cm\(^2\) area. In order to maximize the usable chip area, four MEMS tuner devices are fabricated on one single die. Standard wafer dicing with a die saw machine is used to separate each individual MEMS device. Crystalbond mounting adhesives are applied first on the MEMS die to protect the device. For every MEMS device on the die, the through-hole area in the TRENCH layer serves as a crucial role in defining the final device chip. As illustrated in Figure 3-11 and 3-12, for regions where the extended tuner object or the actuating shaft are, the through-hole trench is intentionally widened in the lateral direction.
When the wafer die saw cuts along the mark shown in the figure, the wafer region in front of either the tuner surface or the actuating shaft will subsequently fall off the chip, leaving the tuner surface or the actuating shaft extending out of the device chip. Such post-processing with deliberate chip design allows seamless integration of the MEMS tuner chip with the QCL chip without employment of excessive and expensive procedures such as laser cutting. It dramatically reduces the fabrication time and cost. After device dicing, the remaining Crystalbond can be easily removed with standard solvent rinse using acetone.

Figure 3-12: (a) A schematic showing the two-stage flexure chip before the final wafer dicing to define the extended tuner object and the actuating shaft. A wafer die saw will cut along the dashed lines in the schematic. (b) The final finished two-stage flexure chip which allows direct alignment and interaction with the QCL chip and the piezo nano-positioning actuator.

### 3.3 Electrostatic Comb Drive Actuators

#### 3.3.1 Analytical Analysis for Comb Drive Actuators

Comb drives are electrostatic MEMS actuators first introduced in 1989 by Tang et al. [56]. The load body is often supported by folded-beam flexures introduced in Section 3.2.2. The actuating force is provided by biasing parallel plate capacitors in the form of inter-digitated comb fingers. With the applied bias, opposite charge
Figure 3-13: (a) Side view showing the comb drive configuration. (b) Top view of the comb drive actuating comb beam. (c) A closer look at the inter-digitated fingers on the two comb beams.

accumulates on the comb pairs facing each other to provide the actuating force. A typical comb beam is shown in Figure 3-13. The two comb beams are anchored at the two ends whereas the comb beam and the fingers are suspended through the anchoring. Assuming that the comb beam and the fingers have a device layer thickness of $t$, and the finger overlap and the finger gap between adjacent inter-digitated fingers are $x$ and $g$ respectively, the capacitance between the two comb beams is

$$C = \frac{2n\varepsilon_0 tx}{g}.$$  

In the equation above, $n$ is the number of finger pairs on the two comb beams and $\varepsilon_0$ is the permittivity of air or vacuum surrounding the device. With such a capacitance value, the energy stored in the comb drive can be expressed as

$$E = \frac{1}{2}CV^2.$$  

Therefore, the force applied on each comb beam can be express as [54, 57, 58]

$$F = \frac{\partial E}{\partial x} = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{n\varepsilon_0 t}{d} V^2.$$  

It can be seen from the equation above that as long as the comb fingers are in the
regime of parallel plate capacitors, the force each beam experiences is independent of the finger overlap \( x \). Such characteristics is extremely useful in determining the comb drive displacement with respect to biasing voltage using analytical equations for the comb pair force calculation and folded-beam spring constant analysis.

Assume that two sets of identical folded-beam flexure designs are used to supported the moving combs. The flexure beam parameters are defined as before with the width of the flexure beam as \( w \) and the length of the flexure beam as \( l \). The flexure layer thickness is the same as the thickness for the comb beam and the fingers. By balancing the electrostatic force with the folded-beam flexure restoring force, the relationship between the applied voltage \( V \) and the comb drive displacement \( d \) can be obtained through

\[
F = \frac{n\varepsilon_0 t}{d} V^2 = 2 k_x d = \frac{4Etw^3}{l^3}d.
\]

With further simplification, the comb drive displacement \( d \) can be written as

\[
d = \frac{n\varepsilon_0 l^3}{4Edw^3} V^2.
\]  

(3.1)

Therefore, the comb drive displacement \( d \) is proportional to the square of the applied voltage \( V^2 \). Such linear prediction between \( d \) and \( V^2 \) has been well corroborated by many researchers [54, 57, 58], even though the exact proportionality between \( d \) and \( V^2 \) may not be exactly as predicted by the analytical equation due to the finite aspect ratio of the device layer structure [58].

### 3.3.2 Device Design and Characterization

With the analytical equation described above, three comb drive actuators with slightly different structure parameters are designed and fabricated. All the comb drive actuators share the same overall geometry as shown in Figure 3-14. Two sets of folded-beam flexures are used to provide balanced support for the actuating body. All suspended structures are defined above the TRENCH layer through-hole area for the ease of releasing in the fabrication process. An extra pair of buffer stands are included to
Figure 3-14: A schematic top view of the comb drive actuated tuner chip showing the locations for various features.

prevent the structure from tilting against the QCL chip by increasing the contact region area. Three bonding pads are included for the purpose of biasing, ground and capacitance sensing. A list of the designed parameters for the three comb drive devices is shown in Table 3.3. In total, 8 out of the 15 device dies ordered are made of 10 µm thick SOI layer wafer and the rest are made of 25 µm thick SOI layer wafer. The design parameters are chosen to ensure that the desirable displacement of around 15 µm can be readily achieved whereas the feature design conforms with the SOIMUMPs design rules. For all the three designs, the voltage required to displace 15 µm is well below 100 V. This is to make sure that the required displacement can be achieved with the existing voltage drive with a maximum supply voltage of 150 V, given that there might be some fabrication uncertainties and the device will work at cryogenic environment. Two SEM images showing the fabricated MEMS comb drive devices are shown in Figure 3-15. The fabricated devices in general exhibit high fabrication fidelity and robustness. As the design rules are strictly followed during the design process, no device layer feature break or fracture is observed. The finest feature size
<table>
<thead>
<tr>
<th>Device No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Length (µm)</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Finger Width (µm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Finger Gap (µm)</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Finger Overlap (µm)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Finger Pair Number</td>
<td>380</td>
<td>420</td>
<td>470</td>
</tr>
<tr>
<td>Comb Pair Number</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Flexure Beam Width (µm)</td>
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<td>6.5</td>
<td>8</td>
</tr>
<tr>
<td>Flexure Beam Length (µm)</td>
<td>745</td>
<td>745</td>
<td>745</td>
</tr>
<tr>
<td>Voltage Required for 15 µm Displacement (V)</td>
<td>67</td>
<td>60</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 3.3: Summary table for the design parameters used in the three different comb drive designs.

of the 4 µm wide finger gap is clearly defined. The DRIE silicon device layer etch shows vertical etching profile as can be observed in Figure 3-15 (b).

(a) (b)

Figure 3-15: SEM images showing the fabricated comb drive devices from SOIMUMPs platform.

Since the working environment is around 4 K at liquid helium temperature, the moderately doped silicon device layer is no longer conductive at such low temperature. Special treatment is carried out in order to make the comb drive body conductive. Metal sputtering deposition is performed prior to the device dicing process. Ti/Au 150/2000 Å is blanket deposited to both the front and the back side of the MEMS device die. Due to the high conformity of the sputtering process, not only the top and the bottom surfaces of the comb drive actuator are coated with metal, the sidewall of the structure is coated with the deposited metal as well. The deposition on the
side wall could be visually inspected. However, due to the high conformity of the sputtering process, for some comb drive devices, the device layer is shorted with the substrate wafer. This is due to the oxide layer undercut region shown in Figure 3-3 being partially covered with the deposited metal. Such problem is resolved by passing gradually increased microsecond current pulse until the weak contact in the undercut region is burned-off due to overwhelming current heating. Such technique is proven successful in making the comb body conductive at around 4 K whereas at the same time maintaining electrical insulation between the device layer and the substrate.

![Optical microscope images showing the comb drive displacement under various biasing conditions at liquid helium temperature.](image)

**Figure 3-16:** Optical microscope images showing the comb drive displacement under various biasing conditions at liquid helium temperature. The displacement can be visualized through the level of beam deflection for the supporting flexure. (a), (b), (c) and (d) correspond to biasing point of \( V = 0 \text{ V} \), \( V = 30 \text{ V} \), \( V = 43 \text{ V} \), and \( V = 50\text{V} \). The resulting comb drive displacement are 7.2, 8.9, 11.6 and 14.2 \( \mu \text{m} \) respectively.

The comb drive devices are tested inside a cryogenic dewar with liquid helium in the shield to maintain the temperature at \( \sim 4 \text{ K} \). A quartz window is used to provide clear view through the cryogenic dewar for monitoring purpose. An optical microscope with a 1.2 cm working-distance objective lens is placed outside the cryogenic dewar...
Figure 3-17: (a) Comb drive displacement plot based on analytical equation used in Equation 3.1. The Young’s Modulus is assumed to be 170 GPa in this calculation. (b) Measured voltage versus displacement plot for the tested comb drive device. A quadratic curve fitting is used to extract the Young’s Modulus for the device layer at liquid helium temperature.

to record the comb drive movement. The comb drive actuator is biased at various voltage values and the image is recorded by a CCD camera attached to the microscope. Several images taken by the optical microscope at different biasing points are shown in Figure 3-16. The device for this particular comb drive chip is No. 2 with 25 µm SOI layer thickness. It is interesting to note that due to some residual stress introduced at liquid helium temperature, the comb drive exhibits a small displacement even without applied bias as shown in Figure 3-16 (a). The occurrence of such initial displacement is relatively random across different devices and is in general not observed at liquid nitrogen temperature around 77 K. With increasing bias, the comb drive exhibits increasing displacement as expected. Both the analytical and the measured relationship between applied voltage and the displacement are plotted and shown in Figure 3-17. The analytical relationship plotted in Figure 3-17 (a) is based on Equation 3.1 with an assumed Young’s Modulus of $E = 170$ GPa. The measured relationship between the applied voltage and the displacement is plotted in Figure 3-17 (b). A quadratic curve fitting based on the analytical relationship is employed and also plotted in Figure 3-17 (b). By comparing the curve fitting with the analytical
result, the Young’s Modulus of the SOI device layer at liquid helium temperature is estimated to be 252 GPa as opposed to 170 GPa at room temperature. This is qualitatively intuitive as materials in general become harder at cryogenic temperature.

As the applied voltage continues to rise above around 55 V, the comb pairs experience sudden motion where the comb pairs start to stick with each other as shown in Figure 3-18. Such phenomenon has been observed for all comb drive samples tested with critical displacement of around 15 to 20 µm. The comb pairs either side-stick or front-stick with each other as shown in Figure 3-18 (b). This electromechanical instability, due to either lateral or actuating direction pull-in, could be mitigated by modifying the design parameters or incorporating feedback control into the system [59, 60].

![Figure 3-18](image_url)

Figure 3-18: Optical microscope images showing the comb pairs stick with each other under a biasing voltage of higher than 55 V.

### 3.4 Two-stage Flexure with a Piezo Nanopositioning Actuator

#### 3.4.1 Two-stage Flexure Design

The second type of the electrically actuated MEMS tuner device is made of a two-stage flexure design with a piezo nano-positioning actuator. An illustration schematic for
the two-stage flexure design is shown in Figure 3-19. As with the MEMS comb drive actuated tuner design, the two-stage flexure design has the same tuner geometry, alignment features and buffer stands. The reason of having two stages for the folded beam flexure is to allow the first stage to mitigate the effect of any tilted force exertion on the actuating shaft, thereby minimizes any lateral torque applied on the second stage flexure. For the folded-beam flexure design, both stages have a flexure beam length of 602 µm. The first stage has a flexure beam width of 20 µm whereas the second stage has a flexure beam width of 25 µm. The gap in between the two stages in resting position is set as 10 µm. The stage-connecting shaft geometry for both stages are set as circular to minimize any lateral torque to the second stage flexure since only the center part of the shaft would be in contact with each other when the second stage flexure is being displaced. SEM images showing the fabricated two-stage flexure chips are shown in Figure 3-20.

The structure releasing for the two-stage flexure design is performed by a combination of backside wet oxide etch and frontside vapor HF etch. As both the tuner surface and the actuating shaft are extended features on the two-stage flexure chip, it is not possible to completely release the entire structure by a single backside wet oxide etch
through the TRENCH layer through-hole area as in the case of comb drive actuated tuner chip. This would result in the handle wafer breaking into two pieces and being connected only through the SOI device layer folded-beam flexures. Due to this concern, the substrate TRENCH layer through-hole area is only defined underneath the two flexures and the stage-connecting region, whereas the rest of the device layer releasing is performed through defining a nested-hole structure on the shaft as shown in Figure 3-21. Figure 3-21 (a) shows the SEM image for the nested-hole structure and Figure 3-21 (b) shows the mask design for the nested-hole feature. Most through-holes are of around 5 μm wide and the remaining silicon feature size in between the through-holes is of around 3 μm wide. Since the vapor HF etch creates around 1.8 to 2 μm undercut beneath the exposed SOI device layer edge, the 3 μm wide feature size is to ensure that the nested-hole structure on the device layer will be fully released after the vapor HF etching process. All the handle substrate beneath the nested hole region remains intact, thereby maintaining the integrity of the entire chip.

By combining the analysis for the single folded-beam flexure structure in Section 3.2.2, the force versus displacement relationship for the tuner object or the second stage flexure can be obtained and is displaced in Figure 3-22. An initial applied force of around 0.003 N is needed in order to displace the first stage flexure enough to touch the second stage flexure. Afterwards, the applied force needs to be sufficient enough to displace two flexures simultaneously. Under the assumed Young’s Modulus of 170 GPa, 0.017 N of the applied force is required to displace the tuner till the 15
Figure 3-21: (a) An SEM image showing the nested-hole region on the main shaft of the two-stage flexure chip. (b) The mask design for the nested-hole region. The holes are to promote full release of the structure through frontside vapor HF etch without etching the handle substrate underneath.

Figure 3-22: Force versus displacement relationship for the two-stage flexure design obtained through numerical simulation. The displacement corresponds to the displacement of the second stage flexure or the tuner object. The initial zero displacement regime corresponds to the case where the two flexure stages are not yet in contact with each other.
\( \mu m \) displacement. With the Young’s Modulus correction of 252 GPa obtained from measurement of the comb drive displacement, the force required is around 0.025 N. With the piezo nano-positioning actuator that provides up to Newtons of force, such force requirement could be easily achieved.

### 3.4.2 Piezo Nano-positioning Actuators

As opposed to a purely expanding piezo stack actuator, a piezo stepping motor-based piezo nano-positioning stage actuator is chosen for the actuation purpose. The reason for this choice is that the piezo stack actuators usually consist of many piezoelectric ceramic layers assembled in series mechanically and have a limited maximum displacement of typically around tens of micrometers at room temperature. The achievable displacement for piezo stack actuators is further reduced with cryogenic operating temperature, making them extremely hard to position and control. Early attempts of testing these stack actuators at liquid helium temperature revealed that they are not suitable for actuating the tuner device in many ways. On the other hand, piezo stepping motors usually incorporate locking and stepping mechanisms with the piezoelectric effect to achieve much higher displacement with a stick slip manner. The actuating scheme allows the actual displacement not limited by the absolute displacement of the individual piezoelectric elements. Therefore, even under extremely low temperature such as liquid helium temperature environment, the piezo stepping motors can still have large displacement with nanometer level precision despite the fact that each individual piezoelectric ceramic material may have much smaller deformation as compared to the case of room temperature operation. An example of a piezo stepping motor which is based on the PiezoWalk Linear Motors from PI is shown in Figure 3-23 [61]. In the figure, (a) to (f) correspond to a series of snapshots of an actuating cycle. It can be seen that as opposed to the loading shaft being a piezoelectric material itself, it is being actuated by many piezoelectric ceramic structures that either lock or step the main shaft. Most piezo stepping motors employ similar locking or stepping schemes although maybe with different geometric configurations. Despite the fact that it is not the exact configuration for the piezo
stepping motor used in this study, it is instructive to understand the advantage of piezo stepping motor based actuators over purely expanding piezo stack actuators.

Figure 3-23: A series of snapshots for the operation of PiezoWalk Linear Motor from PI [61]. The loading shaft is being actuated through a sequence of locking and stepping mechanisms by the piezoelectric actuating structures attached to it.

PI miCos Piezo Positioner PP-17 is chosen for this project for the actuating purpose. Although the original PP-17 nano-positioner has ceased production and the product datasheet is no longer available, its successor PP-20 has very similar performance in terms of both function and operation. Therefore information from the datasheet of PP-20 is used in this section to illustrate the performance specifications for the piezo nano-positioning actuator [55]. The PP-20 is a compact linear piezo-actuated stage designed for open loop applications. It utilizes a duel-direction piezo stepping motor to drive the loading stage. Such piezo stepping motor combined with a steel ball bearing allows the positioner to operate with load up to 1 kg. It provides up to 11 mm traveling range with a resolution as small as 1 nm. The compact footprint allows easy integration into the cryogenic dewar without the need of redesigning the dewar. Separate controller unit and control software are available for turn-key operation and easy integration with other electronic components. Although PP-20 is designed only for open loop operation, more advanced piezo nano-positioning actuators such
as PP-22 which includes an optical encoder are available for high-precision closed loop operations. The PP-17 nano-positioning actuator has been tested with visual inspection at liquid helium temperature under vacuum level of $10^{-5}$ mbar to ensure its functionality at such high vacuum and low temperature. The experimental tuning result with this piezo nano-positioning actuator will be presented in Chapter 4.
Chapter 4

Electrically Tunable Terahertz Quantum Cascade Lasers

4.1 Device Preparation and Assembly

The device preparation and assembly technique to post-process, align and bond the MEMS tuner chip with the THz QCL chip has been designed, implemented and optimized throughout the course of this thesis work. The challenge of precisely aligning two separate microelectronic chips with sub-micrometer precision has been overcome with this technique. The experimental details will be explained in this section.

The individual MEMS dies obtained from MEMSCAP are of 1.1 cm × 1.1 cm area and each die consists of four individual tuner devices. These MEMS dies are first taken into a metal sputtering equipment to deposit metal layers onto both top and bottom sides in order to provide conductivity at cryogenic temperature and also to coat the tuner surface with metal. Afterwards, individual chips are separated with a wafer dicing equipment. A silicon wafer piece is used as the substrate handle wafer to load the MEMS chip. Crystalbond is first applied and melted on the surface of the silicon wafer. The thickness and the area of the Cyrstalbond should be comparable or larger than the thickness and the area of the MEMS die. The Crystalbond acts as both the bonding agent and the protection coating for the MEMS chip during the dicing process. Afterwards, the MEMS chip is gently put on top of the Crystalbond
and a die bonder tip is used to press the MEMS die such that the Crystalbond would flow through the substrate trench through-holes to cover the suspended structure. All the critical device layer structures should be well covered by Crystalbond after this step. Some additional Crystalbond is then applied onto the remaining areas to entirely enclose the MEMS chip inside the Crystalbond coating. The MEMS die is then taken for the wafer dicing process that separates the individual devices. Due to the bonding between the MEMS chip and the substrate handle wafer, each MEMS chip will not fly-off during the dicing process. Just as important, the Crystalbond coating protects the MEMS devices from falling powders and sharps generated during the dicing process. At last, samples are immersed and rinsed inside organic solvent acetone to remove the Crystalbond for complete device separation.

Figure 4-1: The pickup micro-manipulation stage used to align and align the MEMS tuner chip with the QCL chip. The x-y-z positioning stage with micrometer knobs allow coarse positioning whereas exact positioning is achieved through the fine-positioning joystick. A clamp is used to attach the copper wire with the MEMS tuner chip to the micro-manipulation stage.

After the MEMS chip separation, an individual tuner chip is selected to bond with the QCL chip. For comb drive actuated tuner chips, wire bonds to the bonding pads are made at this time and microsecond current pulse is passed through the bonding
pads to burn-off the metal contact around the device layer undercut region. Then the
gold wires are de-attached with the chip carriers at one end whereas remain attached
to the bonding pads on the MEMS chip at the other end. Subsequently, the MEMS
tuner chip is back-flipped and put on top of a clean glass slide which is heated to
more than 100 °C. A bifurcated copper wire is used to bond to the backside of the
MEMS chip with Crystalbond. Once the tuner chip is bonded to the copper wire,
the copper wire is attached to an x-y-z micro-manipulation stage as shown in Figure
4-1. The micro-manipulation stage allows both coarse position with micrometer knob
adjustment as well as fine positioning with a micro-positioning joystick. The MEMS
tuner chip is then brought above the QCL chip which sits on a goniometer stage
that allows rotational adjustment in three orthogonal axes as shown in Figure 4-2.
An optical microscope at around 45° is used to monitor the alignment process and
another one is mounted horizontally to exam the parallel alignment between the two
chips. After a visual alignment process, the two chips are brought together in contact
with each other gently and the fine-positioning joystick is used to probe the MEMS
tuner chip against the QCL chip. The advantage of using copper wire to hold the
tuner chip is that it allows some level of compliance such that fine-alignment can
be achieved automatically through the self-adjustment of the copper wire once the alignment features match roughly with each other. This dramatically reduces the complexity of fine-alignment as opposed to the case of using a rigid body or a vacuum tip to hold the tuner chip. In addition, once the chips align with each other, it is visually obvious from the microscope image by judging the distance between the tuner surface and its mirror image formed through the QCL chip surface metal. An image showing the scenario when the tuner chip is aligned with the QCL chip through the pressing of the copper wire is shown in Figure 4-3.

![Figure 4-3: An image showing the MEMS tuner chip aligned with the QCL chip with the copper wire pressing on it. The copper wire is subsequently de-attached with the tuner chip by using a soldering iron to heat it up and melt the Crystalbond.](image)

After confirming the alignment, a thin wire is used to apply a minuscule amount of super glue at the interface of the tuner chip and the QCL chip. Once the glue is cured, a hot soldering iron tip is put in contact with the copper wire to melt the Crystalbond and de-attach the copper wire with the tuner chip. As super glue does not hold the two chips at cryogenic temperature due to large thermal expansion coefficient mismatch, cryogenic adhesive epoxy Stycast is applied in addition to the super glue to ensure device bonding at liquid helium temperature. Once the alignment is finished, for comb drive actuated tuner devices, the dangling wire bonds are attached to chip carriers using conductive silver epoxy. For the two-stage flexure devices, the sample is taken to a device mount that is attached to the piezo nano-positioning actuator and a
Winston Cone as shown in Figure 4-4. Same mount without the piezo nano-positioning actuator is used for comb drive actuated tunable QCL device testing.

![Figure 4-4: An image showing the mount used for tunable THz wire laser testing. A copper arm is attached to the piezo nano-positioning actuator for actuating the tuner shaft of the two-stage flexure tuner design. A Winston Cone is used to collect the output beam from the wire laser.](image)

### 4.2 Problems with the Comb Drive Actuated Tuner Testing

A number of QCL devices aligned with the comb drive actuated tuner chips have been made and tested. Although functioning at cryogenic temperature for the comb drive devices alone has been tested and observed as illustrated in Section 3.3, all of the assembled devices suffer some issues which prevent the comb drive from being electrically actuated. Therefore electrical tuning could not be achieved with comb drive actuated tuner devices. The reason that prevents the comb drive devices from functioning is mostly due to the uneven top surface for the QCL chip, either with the MBE growth defects, dry etch residue mesas, or even dusts or dirts that fall onto the chip during processing. Such small mesas or dirts on the QCL chip surface tend to either short the comb pairs or prevent the comb from moving due to the inherently small force the comb drive could provide. Despite the fact that electrostatically actuated comb drive device does not suffer from high vacuum and cryogenic operation
in terms of functionality, efforts of trying more devices with comb drive actuated tuner chips ceased thereafter as it is determined that comb drive actuated tuner devices are not ideal for robust operation, fine control and reliability. A summary of the evaluation on comb drive actuated tuner device is provided below.

- Comb drive devices in general have very limited actuation distance, usually on the order of 10 to 20 \( \mu m \). Although the supporting flexure beam aspect ratio is commonly designed to be more than 100 in terms of the beam length to width ratio in order to reduce the flexure spring constant, the limiting factor is still the small force that the comb drive can provide, which is usually comparable or smaller than \( 10^{-4} \) N. With the small feature size that is necessary for large-displacement purpose, the effect of fabrication uncertainty makes the actual travelling distance less predictable. In addition, issues such as electromechanical instability in the lateral and actuating directions further limit the maximum travelling displacement and increases the chance of finger sticking during operation. Limited displacement range reduces the tuning range as noticeable frequency shift usually takes place when the tuner is placed around 10 \( \mu m \) away from the laser ridge. Ideally the tuner object should be placed at least 20 \( \mu m \) away from the laser ridge at the resting position, which is difficult to realize with comb drive actuators.

- Although techniques have been developed to provide position feedback to enable closed-loop control of the comb drive displacement [58], precise position control below several hundred nanometers is still challenging. Without feedback position control, due to the small spring constant in the actuating direction, the comb drive body usually experiences small-scale vibration at the structure’s resonant frequency. Such vibration could be problematic when the tuner surface is sufficiently close to the laser ridge as any position wobbling would result in frequency perturbation, making frequency stabilization difficult. In addition, the vibration also increases the chance of touching the laser ridge, therefore burning the QCL due to large current passing through the contact region. On the
other hand, off-shelf cryogenic piezo nano-positioning actuators with closed-loop control at a precision of 5 nm is already available. Incorporating such device with the tunable THz QCL scheme would reduce the development cycle and cost dramatically. Furthermore, the flexure spring constant for piezo actuation can be made much larger than the comb drive flexure spring constant. The microscopic resonant vibration for structure supported by stronger flexures would be much less problematic as compared to the case for the comb drive actuators. Stronger flexure also increases the flexure stability with respect to actuation force fluctuation and environmental perturbation.

- In order to maintain high alignment precision, all critical structures including the alignment features and the tuner geometry should be defined in one photolithography step in MEMS fabrication. The scheme of back-flip alignment requires the SOI device layer features to be suspended around 1 µm above the QCL chip surface. It is almost unavoidable that some device layer features will be in contact with small mesas or dirt on top of the QCL chip surface. Such contact would either short the device or prevent the comb drive from moving due to the inherent small force that comb drive actuators can provide. Alignment schemes other than back-flip alignment may be possible but in general would be much more demanding in terms of design and alignment complexity. A more ideal actuation scheme would be to use a macroscopic force that is much less susceptible to microscopic obstacles on the QCL chip surface to actuate the tuner device. In such a way, the small microscopic mesas or dirt on top of the QCL chip surface would be much less troublesome, therefore increasing the actuation robustness and reliability.

- Although it has been more than 20 years since the inception of comb drive actuators, it is still rare to see commercial applications that utilize the comb drive for actuating purpose, possibly due to the reasons listed above. The lack of outside-academia application for comb drive actuators may be an indication of the device’s actuating robustness, reliability and ease of control as compared
4.3 Tuning with the Piezo Nano-positioning Actuators

Electrically tunable THz QCLs have been successfully demonstrated with piezo nano-positioning actuator-based MEMS tuner design. The piezo nano-positioning actuator is controlled through computer program that is connected to the miCos MMC-100 piezo motor controller unit. Various travelling parameters such as velocity, distance, acceleration, deceleration, step resolution etc. can be modified through the control program in open-loop mode. A schematic showing the assembled device with the piezo actuator is shown in Figure 4-5. A copper arm is attached to the piezo nano-positioner in order to actuate the actuation shaft on the MEMS tuner chip. The copper arm is first brought in contact with the actuation shaft on the MEMS tuner chip at room temperature. Then the actuation arm is backed-off for...
Figure 4-6: SEM images showing the fully assembled tunable QCL device with the two-stage flexure tuner chip. The side view shows that the tuner structure layer is suspended around 1 to 2 μm above the QCL chip surface as designed. No visual misalignment can be observed from the SEM image.

Figure 4-7: Normalized spectrum for the electrically tunable THz QCL with a piezo nano-positioning actuator-assisted MEMS tuner device. The tuning starts from 3.72 THz and covers ~ 240 GHz to 3.96 THz with single-mode continuous tuning behavior. No mode hopping or multi-mode lasing has been observed which shows the robustness of the single-frequency operation for THz wire lasers with enhanced mode selector design.
around 100 µm before putting the device into the cryogenic dewar. Due to the liquid helium temperature operation of the piezo actuator, a displacement scaling factor of around 0.2 times is observed as compared to the displacement performance at room temperature. For closed loop control of the piezo actuator position, an optical encoder is needed to determine the exact position of the actuator. The optical encoder can be acquired from the same company that sells the piezo nano-positioner.

![Burning Mark](image)

**Figure 4-8:** An SEM image showing the burning mark on the laser ridge due to the tuner surface touching the laser ridge during tuning operation. The process is irreversible and the laser ceases lasing afterwards.

A number of devices have been tested with the piezo nano-positioning actuator. All the devices have demonstrated over 200 GHz single-mode continuous tuning at liquid helium temperature which shows the repeatability and robustness of the alignment scheme. Two SEM images showing the finished device are shown in Figure 4-6. It can be seen that the tuner device layer suspends around 1 to 2 µm above the QCL chip surface as designed. No visual misalignment can be observed from the SEM image. The Stycast bonding remains intact with several thermal cycles. The normalized tuning spectrum for device No. 43 is shown in Figure 4-7. By moving the piezo nano-positioning actuator with the control program, the lasing frequency from the laser is altered in a reversible manner. The coverage of the lasing spectrum spans across 3.72 to 3.96 THz which has an active tuning range of around 240 GHz. No mode hopping or multi-mode lasing has been observed which shows the robustness of the single-frequency operation for THz wire lasers with enhanced mode selector design.
Beyond 3.96 THz, no active signal has been detected with the FTIR measurement. This is likely due to a wide water absorption dip roughly across 3.95 to 4.00 THz, as even though with nitrogen gas purging, the humidity inside the FTIR chamber is still above 10%. When putting the photodetector directly adjacent to the laser cryogenic dewar, signal could still be detected when the tuner is closer to the laser ridge than at 3.96 THz which verifies this postulation. When the tuner object moves further and touches the laser ridge, the laser is burned at the contact region due to the large current passes through it. An SEM image showing the burning mark on the laser ridge and the burning residue on the tuner surface is shown in Figure 4-8.

4.4 Conclusion and Suggestions for Future Work

In summary, the work performed in this thesis extends the previous manually tunable THz QCLs into the regime of turn-key electrical tunability. By leveraging the commercial foundry platform SOIMUMPs, highly robust, reproducible and cost-effective solution to integrate electrically actuated MEMS tuner devices with THz wire laser chips is demonstrated. Such implementation greatly reduces the cost and iteration time for producing electrically tunable THz lasers and can be employed for commercial THz product development. In addition to the work performed in this thesis, a few suggestions for future steps towards realizing high power bench-top THz tunable lasers is listed below for future reference.

- Perhaps the most important next step is to increase the power output and improve the beam pattern of the tunable THz wire lasers. Due to the near-field manipulation nature of the tuning mechanism, the laser employed has a small active area, leading to small output power in general. In addition, because of the deep sub-wavelength wave confinement inside a wire laser, the output laser beam is extremely divergent [62]. Even with a Winston Cone, the collection efficiency is well below 10%. Therefore, a master oscillator power amplifier (MOPA) is needed to boost up the power output and improve the beam pattern at the same time. MOPA geometry such as a tapered structure [63] coupled with a silicon
hyperhemispherical lens [2] could possibly provide a working solution to this problem.

![Diagram](image)

Figure 4-9: (a) A schematic for tuning two wire lasers covering different frequency ranges that are coupled to the same MOPA structure. One tuner device is utilized to tune the two wire lasers simultaneously. (b) Frequency coverage spectrum for the tuning scheme depicted in (a). The overall tuning range is the sum of the tuning range from each individual wire laser.

- After MOPA incorporation, it is natural to pursue frequency stablization technique with electrically tunable THz lasers. Due to the mechanical nature of the flexure structure used in the tuner chip design, frequency modulation achievable by the tuner is limited to the resonant frequency of the flexure design which
is usually on the order of $\sim$ kHz. Therefore the MEMS tuner based tuning should only be employed as a first-stage rough tuning. Once such rough tuning is achieved, either bias voltage tuning [42] or current tuning [43] should be employed as a second-stage fine tuning scheme in order to lock the lasing frequency to a reference such as a gas line or a microwave reference. The broadband first-stage coarse tuning with narrowband second-stage fine tuning would provide an ideal scheme to achieve accurate and stable frequency-tunable THz source.

- A more aggressive approach to achieve even higher tuning range is to cascade two or more tunable wire lasers and feed into one MOPA structure for power amplification as shown in Figure 4-9 (a). The frequency coverage for each individual laser is shown in Figure 4-9 (b). The two wire lasers are designed to lase at two different frequencies $\omega_1$ and $\omega_2$ when stand alone and cover different frequency ranges when being tuned. If each individual laser can be tuned by 500 GHz, the overall frequency coverage of the tuning scheme would be as high as 1 THz. Through digital control over the operating condition of each individual laser and the MEMS tuner, ultra-broadband frequency coverage can be realized which would be ideal for spectroscopic applications.
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