Invited Paper

Linewidth broadening caused by intrinsic temperature fluctuations in quantum cascade lasers

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Abstract

The intrinsic narrow linewidth of quantum cascade lasers (QCLs) promises wide applications such as high-sensitive trace-gas detection. However, so far limited work has been reported in intrinsic linewidth characteristics of QCLs. In this paper, we theoretically investigate the linewidth broadening caused by intrinsic temperature fluctuations in both mid-infrared and Terahertz QCLs. When microscopic features of the refractive index variations associated with the intersubband transitions and energy level broadening in mid-infrared QCLs are considered, the linewidth broadening increases up to a few hundred Hz in mid-IR QCLs.

Key words: Linewidth broadening, Intrinsic temperature fluctuations, Quantum cascade lasers

1. INTRODUCTION

Quantum cascade lasers (QCLs), since their invention in 1994,[1] have become important light sources in the terahertz (THz) and mid-infrared spectral ranges.[2-6] Their emission wavelength can be engineered across the mid-infrared (3-24 μm) and THz (1.2-5 THz, or 60-250 μm) regions for important applications including but not limited to: trace-gas absorption spectroscopy, optical free-space data communication, remote sensing and imaging.[4,7-8] For these applications, a narrow-linewidth, single-mode, coherent and compact source is highly desired.

Like all other lasers, narrow-linewidth QCLs can easily suffer from various noises, which play an important role in their laser performance especially in their spectral linewidth. Noise can be divided into external noise and intrinsic noise. External noise factors such as mechanical vibrations, external environmental temperature variations and bias-current fluctuations[9-12] can be potentially totally removed by various frequency-stabilization techniques, such as phase locking techniques. However, the intrinsic (fundamental) noises caused by *e.g.* spontaneous emission, carrier noise, blackbody radiation, and thermodynamical fluctuation of temperature cannot be overcome due to the fundamental quantum limitations. It was theoretically investigated the intrinsic linewidth based on the classical rate equations by considering the spontaneous radiation and blackbody effects. [13] However, another important contribution to the intrinsic linewidth of QCLs, *i.e.* the fundamental thermal noise, caused by thermodynamical fluctuation of temperature within the laser cavity, has not yet been investigated. Even for a cavity in the perfect thermal equilibrium with its surroundings, this thermal noise floor always exists.

On the other hand, for many applications, it is the intrinsic frequency noise spectrum of QCLs that is of the primary interest. The studies of the intrinsic frequency noise of QCLs have been focused on high frequency at 10 MHz and even up to GHz.[8] For most spectroscopic applications,[14-16] the detected signal is in the kHz range or below where the *1/f* noise is expected to dominate.[7] Unfortunately, there are no reports about frequency noise spectrum below 1 MHz in the literature. Thus it is of great interest to investigate the thermal fluctuation frequency noise at the low-frequency side.

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In this paper, the Green function methods and the Λ-theorem (*i.e.* the *Van Vliet–Fassett* form) are used to derive the analytical expressions of the frequency noise caused by temperature fluctuation for single-mode THz (in the double-metal waveguide structure) and mid-infrared (in the buried heterostructure) QCLs. The effects of the temperature, heat conductivity of active region and active region thickness on the fundamental frequency noise and linewidth broadening are theoretically investigated.

2. FUNDERMENTAL THERMAL FRQUENCY NOISE AND LINEWIDTH BROADENING IN THZ QCLS

For THz QCLs, there are two types of waveguides used, namely, the surface-plasmon waveguide[17,18] and the double-metal waveguide.[3] In this paper we focus on double-metal waveguides due to their high temperature performance.

The fundamental thermal frequency noise can be analytically derived by Green function methods and the Λ-theorem (*i.e.* the *Van Vliet–Fassett* form).[19] Figure 1 shows the temperature dependent frequency noise in the range of kHz and high frequency regime (1 MHz to 10 MHz), respectively. As shown in Fig. 1, the frequency noise caused by the temperature fluctuation influences device performance mainly in the low frequency range (below a few kHz). The frequency noise drops fast close to zero as the frequency exceeds 1 MHz. We find that this frequency noise doesn't exhibit the *1/f* characteristics. In terms of temperature performance, the frequency noise due to thermal fluctuations shows strong temperature dependence, which increases with the increase of the temperature. In simulations, we also find that the thickness of the active region and the substrate can also slightly influence the laser frequency noise.

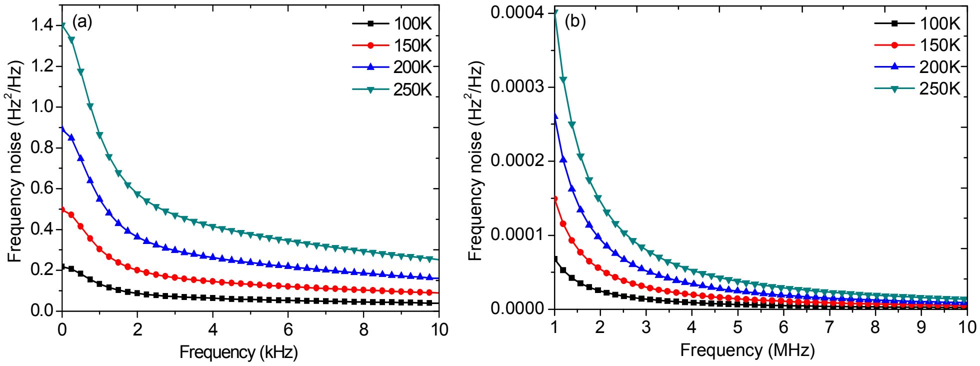

Fig. 1. Frequency noise of THz QCLs caused by temperature fluctuation at different lattice temperatures from 100K to 250K. (a) In kHz range of less than 10 kHz, (b) In MHz range from 1 MHz to 10 MHz.

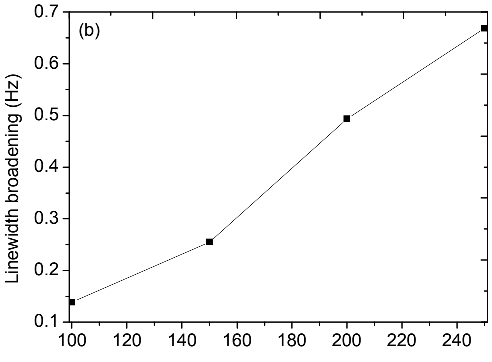

Fig. 2. The linewidth broadening as a function of temperature in THz QCLs.

Figure 2 shows the linewidth broadening at different temperatures. The linewidth caused by thermal fluctuation can nearly be neglected in THz QCLs. However, this linewidth broadening is comparable to the value of ~3 Hz caused by spontaneous emission, stimulated emission, and blackbody radiation, predicted by Jirauschek[20] in the high power regime in the THz QCLs.

3. FUNDERMENTAL THERMAL FRQUENCY NOISE AND LINEWIDTH BROADENING IN MID-INFRARED QCLS

Various device geometries have been used to improve the heat dissipation from the active region of mid-infrared QCLs.[21,22] In this paper, we use the ridge waveguide structure with a buried heterostructure mounted epilayer down on a diamond heat sink[23,24], which demonstrated a very good heat dissipation effect.

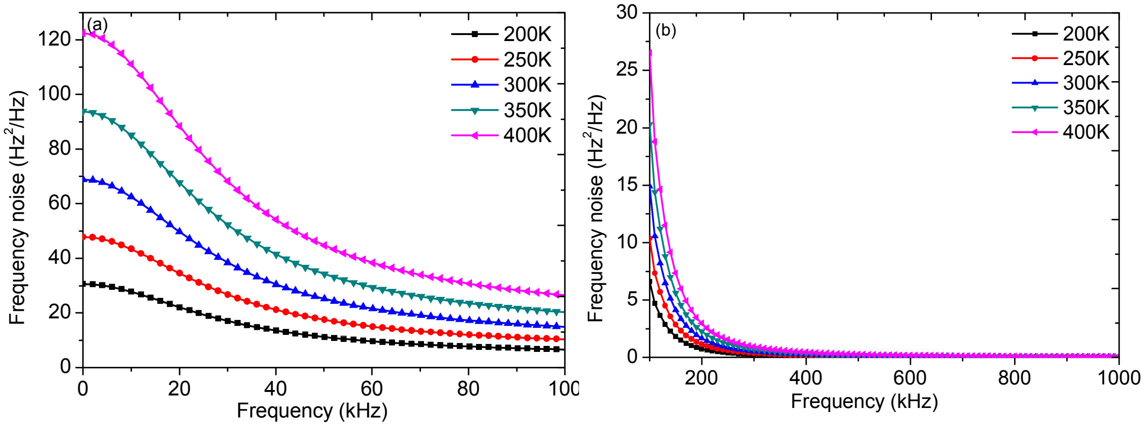

Fig. 3. Frequency noise of mid-infrared QCLs as a function of temperature from 200K to 400K. (a) In the frequency range less than 100 kHz, (b) In the frequency range from 100 kHz to 1MHz

As shown in Fig. 3, the same characteristics of temperature dependent laser frequency noise for mid-infrared QCLs are observed as for THz QCLs. The frequency noises can be almost neglected when the frequency exceeds 400 kHz. It is noted that the frequency noise does not show a *1/f* trend in the whole frequency region.

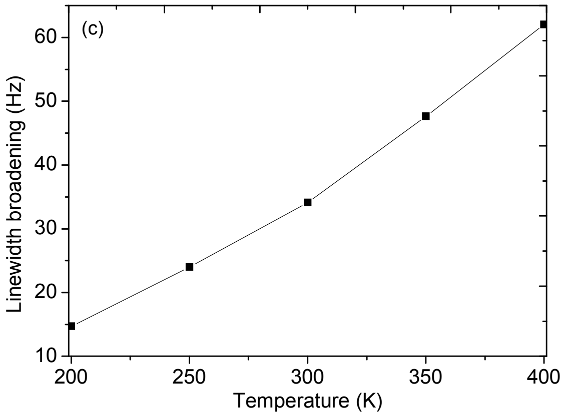

Fig. 4. The linewidth broadening as a function of temperature in mid-IR QCLs.

Figure 4 shows the linewidth broadening at different temperatures considering only the temperature dependence of the refractive index fluctuations caused by current-induced device self-heating. The linewidth increases from 14.74 Hz to 62.02 Hz as the temperature increases from 200 K to 400 K. In the above analysis, we only consider the macroscopic physics of the linewidth broadening. The microscopic physics of the gain medium of QCLs is ignored. We note that the refractive index can be affected by not only the current-induced device self-heating but also the laser transitions near the lasing wavelength, which can have a strong temperature dependence associated with electron populations and scattering rates, as discussed in Ref. 12. The thermal expansion and energy level broadening caused by current-induced device self-heating can also induce a significant linewidth broadening. If all of these above factors are considered, the linewidth broadening is at least four times larger than previous calculations, which achieves from 64.3 Hz to 266.4 Hz as the temperature of 400 K. However, it needs to be mentioned that the exact values of these three parameters are not available in the literature. Exact calculation of the linewidth broadening needs further theoretical and experimental investigations.

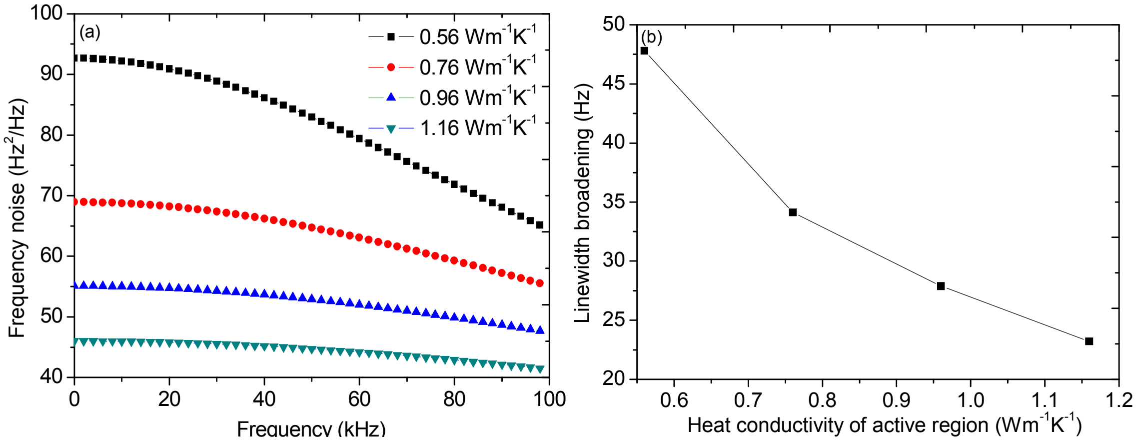

Fig. 5(a) Frequency noise as a function of the cross-plan conductivity of active region at 300 K. (b) Linewidth broadening at different the cross-plan conductivity of active region at 300 K.

The fundamental thermal frequency noise is strongly dependent on the heat conductivity of active region, as shown in Fig. 5(a). A higher heat conductivity of the active region induces a smaller thermal fluctuation, hence reducing the linewidth broadening (see Fig. 5(b)).

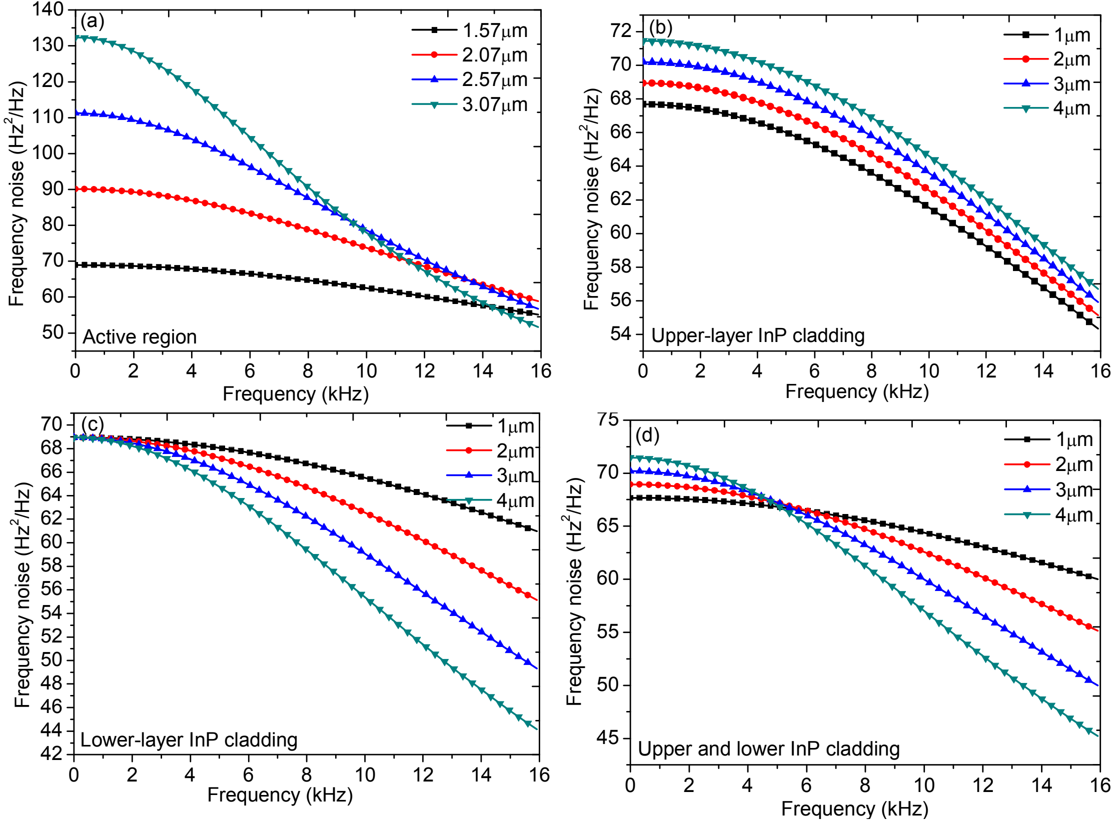

Fig. 6. Frequency noise as a function of the thickness of mid-infrared QCL structure at 300 K. (a) Active region. (b) Upper-layer InP cladding. (c) Lower-layer InP cladding. (d) The thickness of the two-layer InP cladding changes simultaneously.

We find that unlike the case in THz QCLs, the active region can greatly influence the temperature fluctuation in mid-IR QCLs. Figure 6 shows this influence of the thicknesses of the active region and the metal cladding on the laser frequency noise caused by temperature fluctuations. The frequency noise first increases with the increase of the thickness of the active region, then decreases. The effects of the thicknesses of the InP cladding layers are more complicated. Decreasing the thickness of the upper cladding layer can reduce the frequency noise, while decreasing the thickness of the lower cladding layer can increase the temperature fluctuations. Therefore the overall effect is that reducing simultaneously the thicknesses of both cladding layers can reduce the frequency noise at the beginning, but increase it at around 5 kHz, as shown in Fig. 6(d). With the optimized cladding layers, the temperature fluctuation can be effectively minimized.

4. CONCLUSION

In this paper, we theoretically investigate the fundamental frequency noise and the linewidth broadening caused by intrinsic temperature fluctuations in both mid-infrared and THz QCLs. The analytical derivation is based on the Green function analysis and the *Van Vliet-Fassett* theory. The results show that the fundamental frequency noise caused by temperature fluctuations is prominent in the low frequency range (below a few kHz) and is sensitive to the temperature, heat conductivity and the thickness of the active region/substrate. It also shows that this fundamental frequency noise does not show a *1/f* trend in the whole frequency spectra for both THz and mid-infrared QCLs. For mid-infrared QCLs, this frequency noise leads to the linewidth broadening from 14.74 Hz to 62.02 Hz as the temperature increases from 200 K to 400 K. When the microscopic features of the refractive index variations associated with the intersubband gain transition, the self-heating-induced thermal expansion and energy level broadening in mid-IR QCLs are considered, an estimation shows that the linewidth broadening increases greatly by a factor of at least a few times.

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