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A Proposal for Phase-locked Arrays of Terahertz Quantum Cascade Lasers

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***Abstract*—We propose a novel design of monolithic facet-emitting terahertz-quantum-cascade-laser (THz-QCL) array. The simulation shows the stable phase-locked range for coherent lasing, which is determined by the external cavity length. And its far-field beam divergence can be reduced when compared with the non-locked array. Such a monolithic QCL array with mutual injection of optical fields may provide not only a new method of achieving phase-locked arrays, but also a platform for studying complex dynamical behaviors in THz QCLs.**

I. Introduction

CONCRETE progress of phase-locked arrays of THz QCLs has been made in recent years. The phase-locked arrays of surface-emitting THz QCLs have demonstrated the single-mode operation as well as the great reduction of the divergence of the laser beam.[1,2] Compared with surface emission, although the output beam from the facet suffers higher divergence originated from the diffraction of the subwavelength size of the waveguide, facet emission is expected to give higher output power due to the longer length of the waveguide along the propagating direction. However, due to the difficulty of design and fabricating the high efficiency and low-loss coupling waveguide, the progress of facet-emitting phase-locked arrays is still limited. In 2014, Kundu et al. have demonstrated frequency-tunable THz QCL using a device comprising a two-section coupled-cavity. This device showed their stability under optical feedback in the coupled cavities [3]. Inspired by this work, our group proposed a novel scheme of monolithic facet-emitting THz-QCL array based on the similar two-section coupled-cavity. The schematic is shown in Fig. 1(a). The array consists of several facet-emitting QCLs (the lasing section) which are electrically biased above threshold. The QCLs are optically coupled via their rear facets by an external cavity (the coupling section), which is biased below threshold. This enables mutual injection of optical fields and also allows the injection strength and phase to be tuned by changing its refraction index. The two sections are optically coupled but electrically isolated through a narrow gap. This compact structure eliminates beam-steering error compensation usually required in non-monolithic external cavity device such as the arrangements in vertical-external-cavity surface-emitting-lasers, which would be more robust in controlling the beam quality.

II. Results

The aim of forming phase-locking over the whole THz array is to obtain pure super-mode emission with high beam quality. We investigate the dynamic behaviors of two coupled QCLs by Lang-Kobayashi equations [4], in order to simulate the locking condition and stability properties of the THz QCL array. In the simulation, both QCLs are assumed to be single-mode emission which may be ensured by fabricating a finite defect site photonic lattice. The free-running frequency of QCL A, f_A, is assumed to be 2.93 THz and f_B is assumed to have a detuning Δ from f_A. All other parameters of two QCLs are assumed to be same.

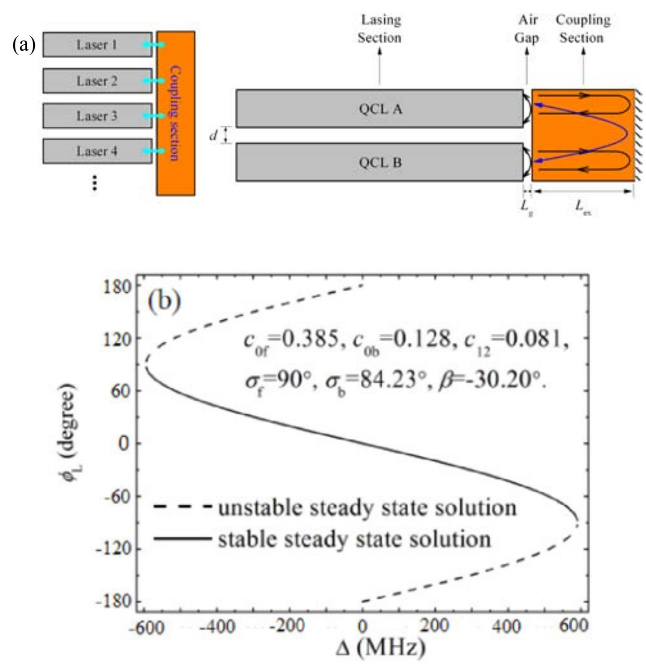

Fig. 1. (a) Schematic for the monolithic QCLs array. (b) Locked phase difference ϕ_L as function of the frequency detuning Δ of the two free-running QCLs.

The steady state solutions show the possibility of coherence between the two lasers. Figure 1(b) exhibits the locked phase difference ϕ_L as a function of the frequency detuning Δ of the two free-running QCLs. Phase-locked modes of the array occur only when the detuning ranges from -594 to 590 MHz, and the stability analysis indicates the stable branch of the steady state solutions (the solid line in the figure).

Obviously, the coupled cavity geometry has great effect on the range of the locked bandwidth. The coupling coefficient c_{12}, the phase shift β due to light propagating in the coupling section to inject into the other QCL, and the corresponding time delay τ_{AB} are all dependent on the variation of the length of the coupling section L_{ex}. To show the property of mutual injection, we calculate the maximum value of the positive locked bandwidth Δ^{+}_{max}, as a function of the external cavity length L_{ex}, and plot it by solid dot in Fig. 2. The calculation result indicates a dramatic variation of the bandwidth range when L_{ex} has a change of few micrometers. Through our calculation, we find that phases β and $\omega\tau_{AB}$ all have linear relationship with L_{ex}. Here, $\omega\tau_{AB}$ describes an additional phase due to propagation of the locked mode in the coupling section. When we substitute these linear fittings into the equation $\Delta^{+}_{\max} \approx -2q\sqrt{1+\alpha^2}|\cos(\theta - \beta + \omega\tau_{AB})|$ which is analytically deduced from the steady state solution, we can find that Δ^{+}_{max} as a function of L_{ex} (solid line in Fig. 4) coincides with the numerical calculation points. The fitting curve approximately represents the external cavity length effect on the range of the stable locked frequency detuning, and helps us choose appropriate length for the coupled cavity design.

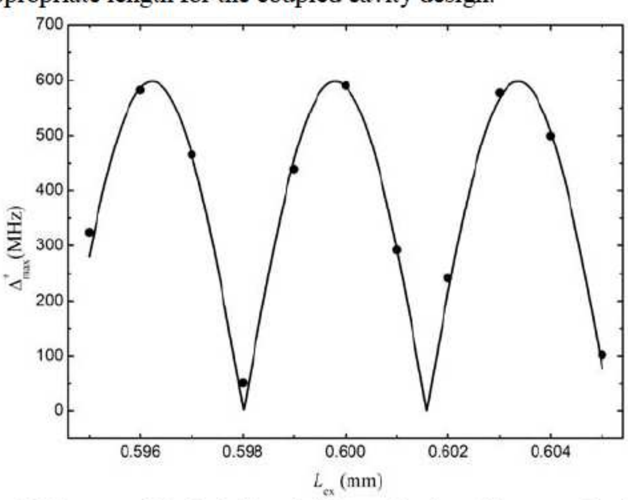

Fig. 2. The range of the locked bandwidth as a function of the external cavity length L_{ex}.

We also investigate the far-field property of the THz-QCL array. Simulation of the far-field beam property indicates that the phase-locked array will exhibit an interference pattern and a greatly reduced divergence compared with the non-locked array, as shown in Figs.3(a) and (b). These results indicate that coherent lasing effects may be observed from the array by using high-resolution spectroscopy and far field measurements.

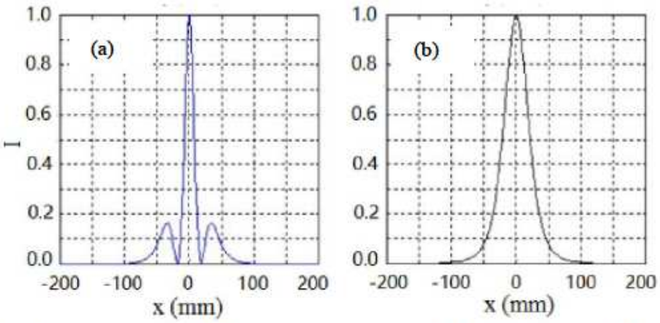

Fig. 3. Far-field pattern in horizontal direction of two QCLs within (a) and out of (b) the phase-locked range.

III. SUMMARY

We present a new design of monolithic facet-emitting THz-QCL array with optical mutual injection and show the possibility of coherent lasing and the reduction for the far-field beam. We aim to fabricate and characterize QCLs with mutual injection to demonstrate a new method of achieving phase-locked arrays, and also to provide a platform for studying complex dynamical behaviors in THz-QCLs.

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