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A Proposal and Simulation for Phase-locked THz-QCLs Array by Mutual Injection of the Optical Fields

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1. Introduction

Phase-locked arrays can be used to improve both the output power and the beam quality of terahertz quantum cascade lasers (THz-QCLs). Although progress has been made with phase-locked arrays of surface-emitting THz-QCLs [1,2], the progress with facet-emitting devices have not yet been demonstrated. Mutual injection of the optical fields has been demonstrated as an efficient way to develop phase-locked arrays of facet-emitting semiconductor lasers [3]. However, whether such scheme is applicable in THz-QCLs is still an open question. The response of QCLs under mutual injection needs to be understood and a suitable waveguide design is also required to maximize the injection efficiency and reduce the loss. In this work, we propose a design for a monolithic QCL array with mutual injection of the optical fields and carry out a simulation on its dynamics to investigate the possibility of coherent lasing.

2. Simulated spectrum and beam profile of the array

Fig.1(a) shows a schematic of the proposed monolithic QCL array which is inspired by previous research into THz-QCLs with coupled cavities [4]. The QCLs consists of a pair of facet-emitting QCLs (the "lasing section") which are electrically biased above threshold. The QCLs are optically coupled via their rear facets by a "coupling section" which is biased below threshold. This enables mutual injection 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. The rate equations describing the dynamics of the optical fields of such a QCL array are as follows

$$\frac{\mathrm{d}E_{\mathrm{A}}(t)}{\mathrm{d}t}=\left\{\mathrm{i}[\omega_{\mathrm{A}}+\frac{1}{2}\alpha_{\mathrm{A}}N_{\mathrm{pA}}G_{0\mathrm{A}}\Delta N_{\mathrm{A}}(t)]+\frac{1}{2}[N_{\mathrm{pA}}G_{0\mathrm{A}}N_{\mathrm{A}}(t)-\frac{1}{\tau_{\mathrm{pA}}}]\right\}E_{\mathrm{A}}(t)+q_{\mathrm{AB}}E_{\mathrm{B}}(t-\tau_{\mathrm{AB}})$$
$$+\gamma_{\mathrm{Af}}E_{\mathrm{A}}(t-\tau_{\mathrm{f}})+\gamma_{\mathrm{Ab}}E_{\mathrm{A}}(t-\tau_{\mathrm{b}}) \quad (1)$$

$$\frac{\mathrm{d}E_{\mathrm{B}}(t)}{\mathrm{d}t}=\left\{\mathrm{i}[\omega_{\mathrm{B}}+\frac{1}{2}\alpha_{\mathrm{B}}N_{\mathrm{pB}}G_{0\mathrm{B}}\Delta N_{\mathrm{B}}(t)]+\frac{1}{2}[N_{\mathrm{pB}}G_{0\mathrm{B}}N_{\mathrm{B}}(t)-\frac{1}{\tau_{\mathrm{pB}}}]\right\}E_{\mathrm{B}}(t)+q_{\mathrm{BA}}E_{\mathrm{A}}(t-\tau_{\mathrm{AB}})$$
$$+\gamma_{\mathrm{Bf}}E_{\mathrm{B}}(t-\tau_{\mathrm{f}})+\gamma_{\mathrm{Bb}}E_{\mathrm{B}}(t-\tau_{\mathrm{b}}) \quad (2)$$

$$\frac{\mathrm{d}N_{\mathrm{A}}(t)}{\mathrm{d}t}=J_{\mathrm{A}}-\frac{2[N_{\mathrm{A}}(t)+N_{2\mathrm{A}}(t)]}{\tau_{3\mathrm{A}}}-2G_{0\mathrm{A}}N_{\mathrm{A}}(t)\left|E_{\mathrm{A}}(t)\right|^{2}+\frac{N_{2\mathrm{A}}(t)}{\tau_{2\mathrm{A}}} \quad (3)$$

$$\frac{\mathrm{d}N_{\mathrm{B}}(t)}{\mathrm{d}t}=J_{\mathrm{B}}-\frac{2[N_{\mathrm{B}}(t)+N_{2\mathrm{B}}(t)]}{\tau_{3\mathrm{B}}}-2G_{0\mathrm{B}}N_{\mathrm{B}}(t)\left|E_{\mathrm{B}}(t)\right|^{2}+\frac{N_{2\mathrm{B}}(t)}{\tau_{2\mathrm{B}}} \quad (4)$$

$$\frac{\mathrm{d}N_{2\mathrm{A}}(t)}{\mathrm{d}t}=\frac{N_{\mathrm{A}}(t)+N_{2\mathrm{A}}(t)}{\tau_{3\mathrm{A}}}+G_{0\mathrm{A}}N_{\mathrm{A}}(t)\left|E_{\mathrm{A}}(t)\right|^{2}-\frac{N_{2\mathrm{A}}(t)}{\tau_{2\mathrm{A}}} \quad (5)$$

$$\frac{\mathrm{d}N_{2\mathrm{B}}(t)}{\mathrm{d}t}=\frac{N_{\mathrm{B}}(t)+N_{2\mathrm{B}}(t)}{\tau_{3\mathrm{B}}}+G_{0\mathrm{B}}N_{\mathrm{B}}(t)\left|E_{\mathrm{B}}(t)\right|^{2}-\frac{N_{2\mathrm{B}}(t)}{\tau_{2\mathrm{B}}} \quad (6)$$

where $E_j(t)$ is the normalized complex electric fields of laser j (j =A,B); $N_j(t)=N_{3j}(t)-N_{2j}(t)$ is the carrier number difference between the upper and the lower laser levels; $\Delta N_j(t)=N_j(t)-N_{\mathrm{th}j}$ is the carrier number change due to optical feedback and light injection from the other QCL; α_j is the linewidth enhancement factor; G_{0j} is the optical gain coefficient of a single active region period in QCLs; $N_{\mathrm{p}j}$ is the number of stages; τ_{2j} and τ_{3j} represent the lifetimes of lower and upper laser levels, respectively; $\tau_{\mathrm{p}j}$ is the photon lifetime in the cavity; $q_{\mathrm{AB}}=q_{\mathrm{BA}}=q\mathrm{e}^{\mathrm{i}\beta}$ denotes the coupling efficiency between the two QCLs with modulus $q=c_{12}/\tau_{\mathrm{c}}$ and argument β, where c_{12} is the coupling coefficient, and τ_{c} is the laser cavity round trip time; $\gamma_{\mathrm{Af(b)}}=\gamma_{\mathrm{Bf(b)}}=\gamma_{\mathrm{f(b)}}\mathrm{e}^{\mathrm{i}\sigma\mathrm{f(b)}}$ represent the feedback efficiency on the front (back) facet of the coupling section with $\gamma_{\mathrm{f(b)}}=c_{0\mathrm{f(b)}}/\tau_{\mathrm{c}}$, where $c_{0\mathrm{f(b)}}$ is the feedback strength coefficient; τ_{AB} is the delay time for the light to travel the distance from one laser to the other; $\tau_{\mathrm{f(b)}}$ is the round trip time in the external cavity for light reflected by the front (back) facet; J_j is the current injected into the active region. In the following simulations, 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.

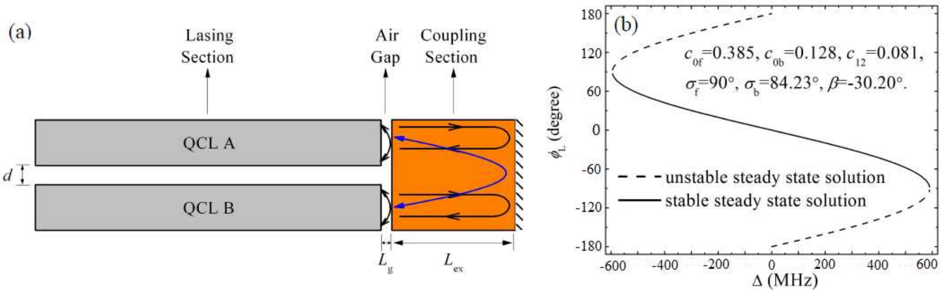

Fig.1. (a): Schematic for the monolithic QCLs array with mutual injection of optical fields. (b): Locked phase difference φ_L as function of the frequency detuning Δ of the two free-running QCLs.

The steady state solutions show the possibility of coherence between the two lasers. Fig.1(b) shows the locked phase difference φ_L as a function of the frequency detuning Δ of the two free-running QCLs. Phase-locked modes occur within the array 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). The calculated power spectrum has a single component at zero frequency corresponding to a single eigenfrequency if Δ is within the phase-locked range, as shown in Fig.2(a). Otherwise, as shown in Fig.2(c), the power spectrum may show sidebands which correspond to some oscillation behavior of the photon density. Correspondingly, the far-field beam of the phase-locked array will exhibit an interference pattern and a greatly reduced divergence compared with the non-locked array, as shown in Fig.2(b) and 2(d). These results indicate that coherent lasing effects may be observed from the array by using high-resolution spectroscopy and far field measurements.

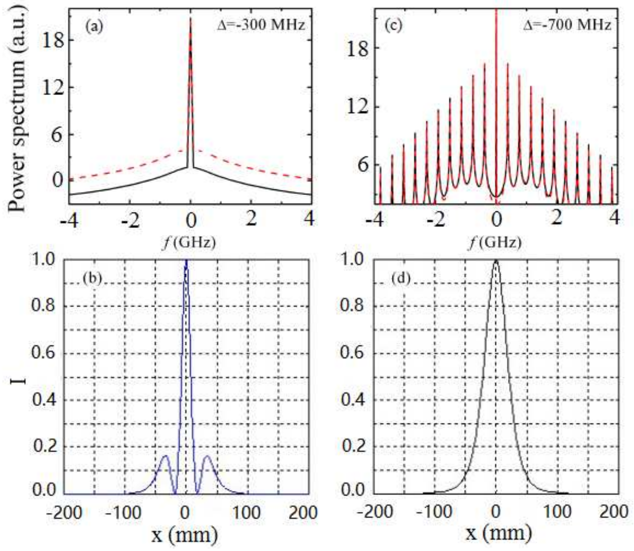

Fig. 2. Power spectrum and far-field pattern in horizontal direction of two QCLs within (a, b) and out of (c, d) phase-locked range.

3. Summary and Prospects

In summary, we have proposed a new design of monolithic facet-emitting THz-QCLs array to study the dynamics of QCLs under mutual injection of optical fields. The simulation shows the possibility of phase-locked lasing of the array as well as oscillatory behavior outside the phase-locking range. 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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