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Dynamics of Optically Mutual-injected Terahertz Quantum Cascade Lasers

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Abstract—Based on the rate equation model, we study the phase locking and self-mixing properties of optically mutual-injected terahertz quantum cascade lasers. Within the phase-locked range, the laser array works steadily at the same frequency, and the electric field amplitudes are stable. Out of the phase-locked range, the instantaneous frequencies and electric field amplitudes oscillate with time. The spontaneous emission noise of mutual-injected QCLs is higher than that of free-running lasers with the same parameters. Mutual-injected QCLs for self-mixing velocity measurement are also analyzed and simulated. When the array works in the phase-locked range, simulation with a moving target shows that self-mixing signals can be observed from each laser. These results are helpful for further understanding the nonlinear dynamic behaviors of THz QCLs under optical injection and provide theoretical support for the development of self-mixing measurement techniques using QCL arrays.

I. INTRODUCTION

QUANTUM cascade lasers (QCLs) are important light sources in the mid-infrared and terahertz (THz) spectral range. The power of THz QCLs has been improved through design optimization and manufacturing improvement. However, these devices are limited in their application in areas where spectral purity is critical, as they typically work with multiple modes. Moreover, the power of continuous operation single-mode THz QCLs is still low. In recent years, the on-chip integrated QCL array technology has significantly been developed [1, 2]. And optical mutual injection phase-locked laser arrays have been proved as an effective method to improve the output power and beam quality while maintaining the spectral purity of the lasers [3]. Due to the nature of ultrafast intersubband transition, THz QCLs have intrinsic high photon-to-carrier lifetime ratios, which are significantly different from that in conventional semiconductor lasers.

Noise in THz QCLs comes from spontaneous emission, non-radiative loss of carriers, the interaction between photons and carriers, carrier fluctuation, etc. Noise is a key factor affecting the performance of THz QCLs in potential applications, and it is one of our main research contents. The study of the basic dynamics of optically mutual-injected THz QCLs is helpful to the developments of phase-locked THz QCL arrays.

The self-mixing interferometric sensors are high precision phase measurement method using feedback effect. And recent studies have shown that QCLs are more stable under strong optical feedback than conventional semiconductor lasers, which indicates that self-mixing measurement of QCL has more advantages under strong feedback. Moreover, mutual-injected QCL array can improve the single-mode output power while ensuring the spectral purity. Therefore, the dynamics of phase-locked mutual-injected QCLs with feedback arouse our interest. Here we present the simulation of self-mixing velocity measurement based on two face-to-face mutual-injected QCLs.

II. RESULTS

The basic scheme of optically mutual-injected THz QCLs system is shown in the illustration of Fig. 1(a). The two THz QCLs are assumed to be single-mode with the same parameters but different stationary frequencies. The phase-locked range is shown in the shadow area of Fig. 1. It is found that the permissible frequency detuning range increases with the increase of coupling strength.

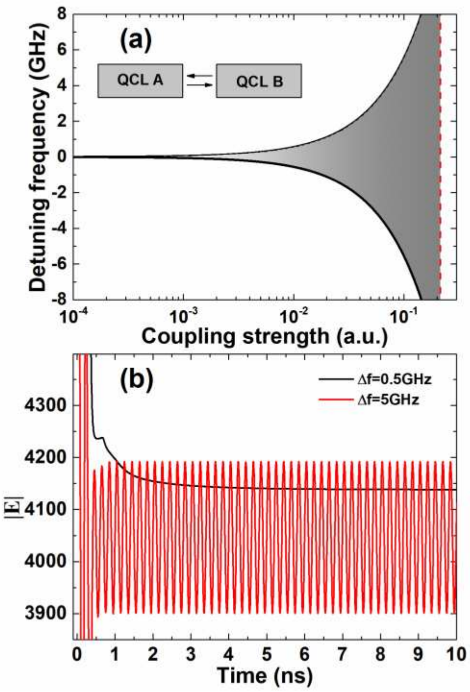

Fig. 1. (a) The phase-locking range of optically mutual-injected THz QCLs. Inset: the schematic diagram of mutual-injected THz QCLs. **(b)** The time evolution of the electric field of QCL A with different frequency detuning. The two lasers are phase-locked with frequency detuning Δf=0.5GHz (black line). And the lasers are working out of the phase-locked range with Δf=5GHz (red line).

Mutual-injected QCLs have quite different dynamic behaviors within and out of the phase-locked range. The amplitude of the electric field of QCL A with different frequency detuning is shown in Fig. 1(b) while the coupling strength remains unchanged. Within the phase-locked range, the two lasers operate at the same frequency, and their electric field amplitudes are stable. The time evolution of the optical field shows that the laser reaches a steady state rapidly after a short time of interaction, and the DC component of the output power is dominant. However, the electric field amplitudes of both lasers oscillate periodically with time out of the phase-locked range, and the instantaneous frequencies of the two lasers exhibit periodic oscillations. It is found that the coupling of THz QCLs is equivalent to mutual frequency modulation of detuning frequency when the detuning frequency is large enough. Unlike the conventional semiconductor lasers, which exhibit coherent collapse or chaotic behavior under strong light injection, mutual-injected THz QCL arrays are very stable under intense light injection, and no similar phenomenon is found in simulation.

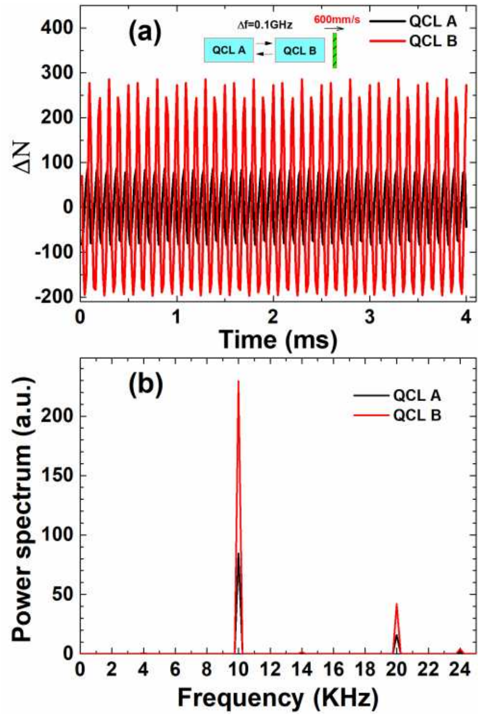

Fig. 2. (a) The variations of inversion population of the mutual-injected THz QCLs. Inset: the schematic of the self-mixing interferometer based on two mutual-injected THz QCLs. **(b)** Fourier transform results of self-mixing signals of two phase-locked THz-QCLs. The moving velocity of the target is 600 mm/s, and the corresponding Doppler shift is 10 KHz.

The fluctuation of the complex electric field caused by photon spontaneous emission is an important noise source affecting the dynamics of THz QCLs and cannot be ignored. The relative intensity noise spectrum of phase-locked mutual-injected THz QCLs is frequency-independent in the low-frequency region and exhibits white noise characteristics. There is no characteristic peak corresponding to relaxation oscillation in relative intensity noise spectrum, which indicates that relaxation oscillation is over-damped for mutual-injected THz QCL. We also find that optical injection makes THz QCLs have higher white noise level than the free-running ones. Through the simulation of different operating parameters, it is found that increasing the current and reducing the coupling can reduce the noise level of the QCL array [4].

In recent years, THz QCLs have been widely used in self-mixing measurement experiments [5]. The mutual-injected QCLs are more stable under strong feedback than conventional semiconductor lasers and have a strong output power. These advantages are beneficial for self-mixing interferometers in fields of imaging and fine displacement measurements. The inset of Fig. 2(a) shows the schematic diagram of self-mixing velocity measurement sensor based on two mutual-injected QCLs. The target moves at speed v = 600 mm/s, and the frequency detuning is fixed at 0.1GHz to ensure that the lasers are always phase-locked. The movement of the target will change the length of the external cavity, so any different position of the target will lead to different working states of the array. Therefore, the terminal voltage variations which are proportional to the inversion population can be obtained experimentally and used as self-mixing signals. Figure 2(a) shows the variation of the inversion population relative to its average value. It can be seen that the self-mixing signals of the QCLs have obvious periodicity but different amplitudes. Although only laser B receives feedback light, the inversion population of both lasers can respond to the target's motion due to the mutual coupling effect.

To obtain the velocity of target motion, the Fourier transform of self-mixing signals is needed. Figure 2(b) shows the Fourier transform results of self-mixing signals of the phase-locked THz QCL array. The main peak at frequency $2\upsilon_0/\lambda$=10KHz is associated with the velocity of the target. In particular, the Doppler shift component can be found in the self-mixing signal of each laser in the phase-locked array, but the peak height is different for each laser. We find that for any fixed position of the target, the time required for QCL to reach stability is less than 20 ns, which is much less than our sampling frequency 50μs for the current speed of 600 mm/s. Therefore, mutual injected THz QCL can be extended to measure higher speeds.

III. SUMMARY

In summary, we theoretically analyzed the basic dynamic characteristics of two face-to-face optically mutual-injected THz QCLs. The phase-locked range of the lasers is determined, and the working state of lasers under different parameters is explained. The spontaneous emission noise characteristics of mutual-injected QCLs and their comparison with free-running QCL are discussed. In addition, mutual-injected THz QCL can also be used for self-mixing interference sources. These results may help to further understand the nonlinear dynamic behavior of THz QCLs under light injection. The work is supported by the National Natural Science Foundation of China (U1730246 and F040302).

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