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Continuous Frequency Tuning of Y-Branched Terahertz Quantum Cascade Lasers with Photonic Lattice

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Abstract: We report electrically-controlled continuous frequency tuning over ~20 GHz by exploiting the additive Vernier tuning effect in a THz QCL based on a longitudinally-coupled Y-branched waveguide.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3570) Lasers, single-mode; (140.3600) Lasers, tunable.

1. Introduction

Terahertz (THz) quantum cascade lasers (QCLs) are compact semiconductor sources of radiation in the THz frequency band of the electromagnetic spectrum [1]. Devices are typically processed into a ridge waveguide structure that acts as a Fabry–Pérot cavity supporting multiple lasing frequencies. However, many potential applications of THz QCLs, such as gas spectroscopy and heterodyne radiometry, would benefit from a source that provides continuously-tunable single mode emission. Whilst devices providing ~50–300 GHz of frequency tuning [2,3] have been demonstrated, these tuning approaches are experimentally non-trivial, requiring controlled gas or dielectric deposition, or electro-mechanical control. Furthermore, the continuous tuning range that can be achieved electrically through control of the laser current in distributed feedback devices is limited to only ~7.5 GHz [4].

An alternative approach to achieve fast and wideband electrical tuning in monolithic lasers exploits the Vernier tuning effect. Such lasers, for e.g. coupled-cavity lasers [5], consist of multiple sections, each of which supports a comb of frequencies; emission is selectively favored at frequencies at which the lines of individual combs match. Coupled-cavity lasers are based on the '*multiplicative*' Vernier effect where the mode selection is based on a multiplication of frequency combs. However, mode selection can also be accomplished via an '*additive*' Vernier effect based on the addition of frequency combs. This latter approach is expected to result in higher side mode suppression of the first side modes compared to multiplicative Vernier effect lasers.

In this work, we develop a coupled-cavity scheme for THz QCLs based on the additive Vernier effect. In this scheme two QCLs are coupled optically to form a Y-branched device, in which continuous electrical tuning of the emission frequency can be achieved through exploiting the Stark effect and cavity pulling effects. Using this approach we report fast electrically-controlled continuous frequency tuning over ~19 GHz—the largest range reported to date.

2. Design and simulation

Our device structure is illustrated schematically in Fig. 1(a), and consists of two double-metal THz QCLs (WG_1 and WG_2) that are electrically isolated but optically coupled in the longitudinal direction through a 5-µm-wide air gap. Each QCL consists of four sections: a coupler containing a photonic lattice (PL) structure, which is connected to a 'Y-branch' power amplifier by an S-shaped bend and an impedance-matching tapered section.

The spectral behavior of a device with PLs incorporated on the coupler sections was modelled using a transfer matrix approach. In order to achieve the broadest continuous frequency coverage from the coupled device, the PL in WG_1 (pitch $\Lambda = 13.66$ µm, offset from center of the coupler section by $\Delta PL_1 = 6.5\times\Lambda$) was designed to provide a continuous frequency tuning, and the PL in WG_2 (pitch $\Lambda = 13.66$ µm, offset from the center of PL in WG_1 by $\delta PL = 0.5\times\Lambda$) was designed to allow discrete mode hops. WG_1 was simulated to lase at a frequency of f_1=3.356 THz and to provide continuous tuning over Δf_1=12 GHz when operating independently. Transmission peaks in WG_2 were simulated to be at 3.358, 3.332 and 3.293 THz, with a frequency separation of $\delta f_2 = 2 \times \Delta f_1 \approx 26$ GHz. In this case, emission in the coupled device was simulated to be at 3.357 THz due to Vernier alignment between modes in WG_1 and WG_2 [Fig. 1(b)]. In this study frequency tuning is controlled electrically by exploiting the Stark shift of the gain in the QCL, as well as cavity pulling in the coupled waveguides. The effects of the Stark shift and cavity pulling in WG_1 and WG_2 were calculated from the applied field (F) and the dipole matrix element of the QCL active region using a first-order perturbation [6]. A change in the refractive index of $|\Delta n| < 1\times10^{-3}$ was calculated by systematically varying the applied electric fields to WG$_1$ and WG$_2$ in the range 4–10 kV/cm. A continuous frequency tuning of ~17 GHz was predicted for the coupled device as the applied electric fields in WG$_1$ and WG$_2$ were varied heterogeneously [Fig. 1(c)].

3. Results

The emission spectra of fabricated devices were recorded for different combinations of drive current supplied to sections WG$_1$ and WG$_2$ ($I_{WG,1}$and $I_{WG,2}$) [Fig. 1(d)]. A continuous tuning over 19 GHz (3.352–3.371 THz), with a side mode suppression ratio >30 dB, was recorded at 50 K when $I_{WG,1}$ was varied in the range 0.5–1.6 A and $I_{WG,2}$>1.2 A. This continuous tuning range is almost twice the tuning range observed from WG$_1$ (Δf_1=9 GHz), and is due to cavity pulling effects arising from the heterogeneous drive currents [4]. Furthermore, emission frequencies centered at 3.307, 3.335 and 3.361 THz with a continuous tuning ranges of 2 GHz, 7 GHz and 20 GHz, respectively, were recorded through simultaneous control of $I_{WG,1}$, $I_{WG,2}$ and at heat sink temperatures in the range 10–90 K.

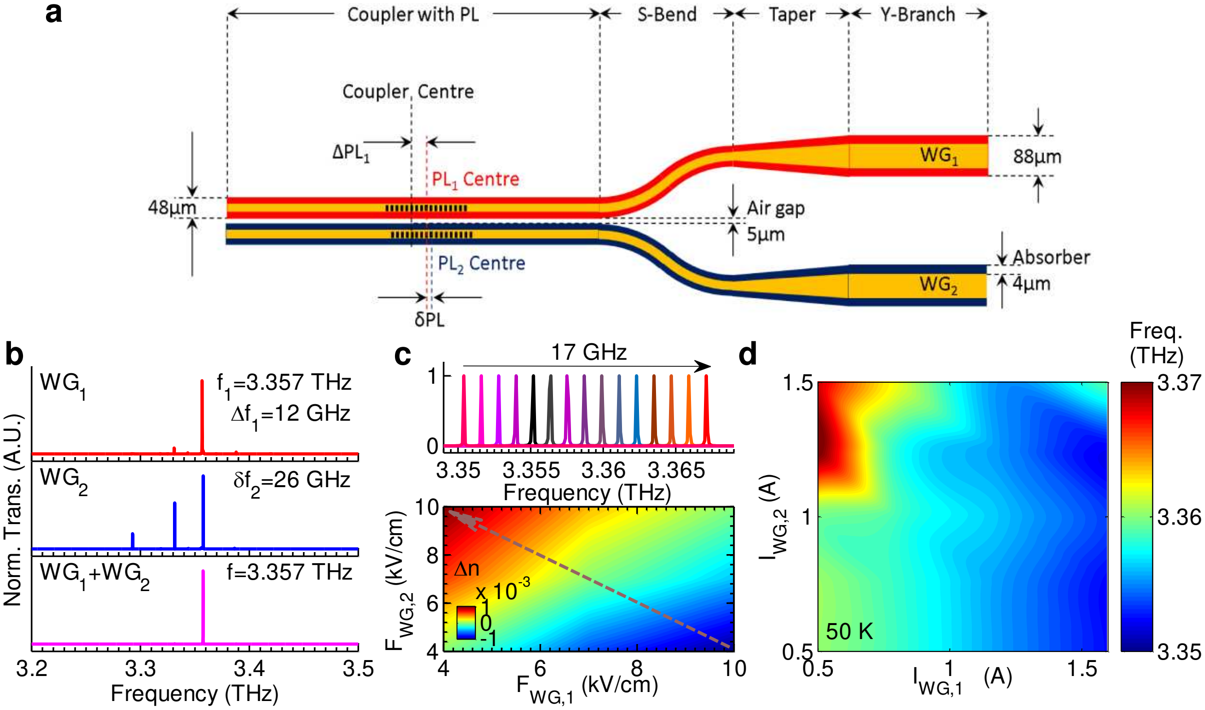

Fig. 1. (a) Illustration of the device geometry. (b) Simulated transmission from WG$_1$ and WG$_2$, when operating independently, and when both QCLs are coupled. (c) Simulated continuous tuning of ~17 GHz from the coupled device, through Stark shift and cavity pulling. (d) Contour map of emission frequency when both WG$_1$ and WG$_2$ are coupled. A continuous tuning of 19 GHz is recorded at a heat sink temperature of 50 K.

4. Conclusions

In conclusion, fast electrically controlled frequency tuning over 19 GHz (at 50 K) has been demonstrated by exploiting the additive Vernier tuning effect in a THz QCL based on a longitudinally-coupled Y-branched waveguide. These results represent the broadest electrically-controlled continuous frequency tuning reported for a monolithic THz QCL device.

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