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Phase-locked arrays of surface-emitting terahertz quantum-cascade lasers

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We report the demonstration of phase-locked arrays of surface-emitting distributed-feedback (DFB) terahertz quantum-cascade lasers with single-mode operations. Carefully designed “phase sector” locks several surface-emitting DFB laser ridges in-phase, creating tighter beam-patterns along the phased-array direction with full width at half maximum (FWHM) ≈10°. In addition, the phase sector can be individually biased to provide a mechanism of frequency tuning through gain-induced optical index change, without significantly affecting the output power levels. A tuning range of 1.5 GHz around 3.9 THz was achieved. This fine tunability could be utilized to frequency- or phase-lock the DFB array to an external reference. © 2010 American Institute of Physics. [doi:10.1063/1.3358134]

The best terahertz (THz) quantum-cascade lasers (QCLs) in terms of high-temperature operation have been demonstrated based on the metal-metal (MM) waveguides,1,2 which provide strong mode confinement and low waveguide losses. However, the subwavelength confinement in the vertical dimension results in divergent beam-patterns.3 The second-order surface-emitting distributed feedback (DFB) laser4,5 improves the far-field beam-patterns while preserving the benefit of MM waveguide; but due to the asymmetric dimension of light emitting area, the beam-pattern is tighter along the grating direction and much broader in the cross direction. In order to expand the coherent light emitting area in both directions, approaches such as two-dimensional photonic-crystal structures on MM waveguides,6,7 and integrated horn antennas8 have been developed. An ingenious solution for a tight and symmetric beam pattern was developed recently based on a third-order DFB structure.9 In this letter, we present another method of generating symmetric beam patterns by using phase-locked arrays of second-order DFB lasers. The physical separation of the DFB laser ridges reduces the average power dissipation per effective light emitting area, which is advantageous for continuous wave (cw) operations. Different DFB laser ridges in the array are coupled through carefully designed phase sectors. Each laser ridge is engineered to be locked in-phase with each other. This phase-locked laser array has tighter beam-patterns along the array-direction, which is orthogonal to the DFB grating direction. Furthermore, independent bias of the phase sector produces a fast and fine frequency tuning for frequency- or phase-lock the array to an external reference.

In order to phase-lock all elements in an array, there are four coupling schemes in integrated diode laser systems—laser ridges are coupled through exponentially decaying fields outside the high index dielectric core (evanescent-wave coupled10) or through the Talbot feedback from external reflectors (diffraction-wave coupled11) or by connecting two ridges to one single-mode waveguide (Y-coupled12) or through lateral propagating waves (leaky-wave coupled13). Among these coupling schemes, leaky-wave coupled devices show the most robust operation.14 The evanescent-wave coupled scheme suffers several disadvantages. First, due to the decaying nature of evanescent waves, couplings beyond nearest neighbors are negligible, leading to poor modal discrimination between adjacent modes. Besides, evanescent-wave coupled devices tend to favor out-of-phase mode and therefore it is not ideal for single-lobe operations.15 The diffraction-wave coupled scheme generally relies on external optical feedbacks. For a MM waveguide with 50 μm width, the reflectivity of a facet at THz can be ~90%,16 which makes sufficient feedbacks challenging. Y-coupled schemes have been demonstrated in mid-infrared QCLs,17 but in general, these devices show undesirable self-pulsation dynamics between in-phase and out-of-phase modes18 due to spatial hole burning effect.

In order to incorporate the leaky-wave coupled scheme, couplings between laser ridges must occur through propagating waves, which, for MM waveguides, does not exist in the lateral direction. A solution to that is as following: consider two identical DFB lasers which lase at the same frequency but with arbitrary phase relations. When connecting these two lasers through a phase sector in series, standing waves but with arbitrary phase relations. When connecting these two lasers through a phase sector in series, standing waves will form inside the phase sector and force the phase relation between the two lasers to be either 0 or π. The proposed laser arrays consist of two parts—DFB laser ridges and phase sectors. A series of apertures are opened on the top metal of the DFB ridges to form second-order gratings. A π shifter is implemented in the center of the grating to achieve single-lobe beam-patterns along the DFB direction. Tapered ends are used to connect the DFB ridges and the phase sectors (with a narrower width) in order to ensure single-lateral-mode operations across the whole array. The DFB laser ridges and phase sectors are electronically isolated by gaps on the top and side metals.

Figure 1(b) shows the surface losses versus eigenfrequencies of the fundamental lateral modes from a finite-element three-dimensional simulation of a three-ridge surface-emitting DFB array. By choosing a proper phase sector length, the desired in-phase mode will have the lowest surface loss and therefore will be the lasing mode. The transverse magnetic fields for the in-phase, out-of-phase, and ad-

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To obtain outward sloped sidewalls for biasing the laser ridge from the side, the same special wet-etching techniques described in Ref. 4 was used to define laser ridges and phase sectors. A 300-nm-thick SiO$_2$ was blanketly deposited as the electric isolation layer, followed by a buffered oxide etch to open the top of ridges. The bonding pad and the metal on sidewalls were defined by another lift-off process (Ta/Au, 25/250 nm) using negative photoresist NR71–3000P (Futurrex, Inc.). The wafer was further lapped down and the bottom electric contact (Ta/Au 25/250 nm) was deposited. The devices were then cleaved, die sawed into smaller subchips, In/Au die-bonded to a copper chip carrier, wire bonded, and then mounted to a pulsed tube cryorefrigerator, where the laser array can be operated in either in-phase or out-of-phase modes. The proper length of the phase sector used in the simulation, the in-phase and out-of-phase modes. The in-phase mode has single-lobe, while out-of-phase mode has dual-lobe far-field beam-patterns along the array direction for in-phase and out-of-phase modes. The proper length $s$ of the phase sector is determined by the so called “resonance condition” in Ref. 14,

$$s = \frac{\lambda_{ps}}{2},$$

where $\lambda_{ps}$ is the wavelength along the propagating direction inside the phase sector and $m$ is an integer number. The laser array is operated in the in-phase/out-of-phase mode when $m$ is odd/even.

The THz QCL gain medium, labeled as FL183S grown by molecular-beam epitaxy (wafer VA0094) was first Cu–Cu thermal bonded with a $n^2$ GaAs receptor wafer, annealed, and substrate-removed to expose the 10 $\mu$m thick QCL structure. The highly doped top contact layer was then etched away. The gratings was defined by using image reversal photoresist AZ5214 and a lift-off process (Ta/Au, 25/350 nm).

![Diagram of a three-ridge surface-emitting DFB array.](Image)

**FIG. 1.** (Color online) (a) Diagram of a three-ridge surface-emitting DFB array. (b) Computed surface losses vs eigenfrequencies from three-dimensional finite-element method simulations on the same array. For the particular length of the phase sector used in the simulation, the in-phase mode (a) has the lowest surface loss. Adjacent mode (b) and out-of-phase mode (c) are also labeled. The insets show the far-field beam-patterns along the array direction for in-phase and out-of-phase modes. (c) Computed transverse magnetic fields for different spatial modes and their corresponding H-field magnitude diagrams along x direction.

The $J_0$ of six-ridge device is 815 $A/cm^2$ as compared with 810 $A/cm^2$ of the single-ridge device. The emission spectra from the six-ridge device are single-mode at all biases. The scanning electron microscope (SEM) picture of a similar array device is also shown in the inset. The main laser ridges and the phase sectors have different bonding pads (labeled as A and B in the picture, respectively).
The phase-locking is achieved through frequency- or phase-locking applications. For single-ridge device, the simulated curve is the diffraction pattern of a single slit with the width of ridge. From top to bottom: single-ridge laser, a double-ridge array operated in the out-of-phase mode, another double-ridge array operated in the in-phase mode, and the six-ridge array (as shown in Fig. 2). The THz emission image from the six-ridge array taken by the microbolometer camera used in Ref. 19 is shown in the inset. The one-dimensional beam-pattern was measured along the dotted line.

The phase sector can be individually biased to provide another frequency tuning mechanism through gain-induced optical index change, without significantly affecting the output power levels. For a gain medium with 60 cm\(^{-1}\) peak gain at 3.8 and 1 THz Lorentzian linewidth, about 0.4\%-0.6\% change in optical index can be achieved, assuming 10\% of field energy resides in the phase sector. This will induce \(\sim 0.05\%\) change in frequency (corresponding to \(\sim 1.9\) GHz). Figure 4 shows the measured frequency shift in the emission from a seven-ridge laser array versus different phase sector biases. A tuning range of 1.5 GHz out of 3.9 THz (\(\sim 0.04\%\)) was observed. This fine and fast (compare to temperature tuning) tunability is desirable for frequency- or phase-locking applications.

In summary, we report the phase-locked array implemented in THz QCLs. The phase-locking is achieved through phase sectors between laser ridges. Up to six laser ridges are locked in-phase with single-lobe far-field beam-pattern (FWHM \(\sim 10^\circ\)) along the array direction. The laser array can be further modified to enable biasing individual lasers and thus control the amplitude of the wave front across laser arrays, obtaining beam-steering capability. Even though the phase-locked arrays are demonstrated with surface-emitting lasers, the same coupling method can be applied to other types of MM waveguide lasers, such as the third-order DFB lasers\(^9\), for additional functionality.

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