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Photonic Engineering Technology for the Development of Terahertz Quantum Cascade Lasers

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Terahertz (THz) quantum cascade laser (QCL) is an electrically pumped semiconductor laser based on the intersubband electron transitions in a multiple-quantum-well heterostructure. Comparing with many other THz wave generation methods, THz QCL has been mostly developed with compact footprint, high power, and high efficiency in the demanding frequency range of 0.8–5.4 THz with the aid of advanced electronic engineering technology of the active materials. This triggers various important applications including nonlinear optics, astronomy, imaging, sensing, and spectroscopy. However, the applications of THz QCL require good output characteristics in terms of the emission spectrum, beam quality, power efficiency, and polarization control, which are beyond the reach of electronic engineering techniques. This paper mainly focuses on photonic engineering of the THz QCLs with attention to the significant

improvement of THz QCL output characteristics. Various photonic solutions to manipulate the laser output have been thoroughly reviewed. Some innovative photonic designs with impressive achievements have been highlighted. Non-conventional cavities with exotic physics and special functionalities are also discussed in the end, which may be exploited for potential applications in the future.

1. Introduction

For years, the electromagnetic spectrum ranging from 0.3 THz to 10 THz has been denominated as ‘terahertz (THz) gap’ due to the lack of efficient radiation sources, detectors, modulators and transmission technology. Before the invention of THz quantum cascade lasers (QCLs), the generation of THz wave was achieved by solid-state electronic devices e.g. transistors, Gunn oscillators,^[1] and Schottky diode multipliers,^[2] or through optical approaches including optically pumped molecular gas lasers,^[3] free-electron lasers, down-conversion of near-IR waves utilizing nonlinear optical effects,^[4] and photoconductive effects.^[5] Owing to the limitation of the carrier (electron or hole) transit time and resistance-capacitance effects, the electronic approaches are intrinsically inefficient in the middle- and high-frequency range of the THz band (above 1 THz). Meanwhile, the optical approaches are limited by low efficiency, high cost, bulky size, and huge power consumption. p-Ge hot-hole lasers^[6] was regarded as a promising semiconductor-based THz source capable of generating high power at a broad THz spectral range. However, stringent requirements are necessary to achieve lasing, i.e. high operation voltage (hundreds of volts), low operation temperature (< 40 K), and the necessity of magnetic field or strain.^[7] The emerging of THz QCLs truly paves the way to miniature THz wave generators with high power, high efficiency, and broad spectral coverage.

QCLs are unipolar devices where the laser transition occurs between the quantized states confined in the same band (the conduction band in most cases) of the semiconductor multi-quantum-wells; i.e., only one type of carrier (electrons in most cases) is involved in the optical

amplification process. The achievement of QCL is based on the advanced electronic engineering technologies on the bandstructure design of multiple quantum wells and material growth through molecular beam epitaxy growth method.^[8] The former allows the precise tailoring of quantum electronic states, including the energy, state lifetimes, optical dipole matrix elements, tunneling times, and scattering rates of carriers, etc.; while the latter is capable of growing hundreds or even thousands of nanometer-scale quantum wells with good quality, perfect precision, and long-time stability. Even though these had already been well developed in the high-performing mid-infrared (IR) QCLs, the demonstration of QCLs emitting THz wave was not straightforward. To achieve coherent THz wave emission, three major challenges, i.e. short lifetime of the excited state of the laser transition, huge intrinsic material loss due to free carrier absorption, and large optical modal size due to long wavelength, must be addressed. Kohler *et al.* made the breakthrough by optimizing the ‘chirped superlattice’ active region design based on GaAs/AlGaAs material system for THz emission and developing a novel ‘semi-insulating surface-plasmon (SISP) waveguide’ to maintain relatively large mode confinement in the active region and reduce the material loss.^[9] Since then, continuous efforts of designing various THz QCL active regions have been devoted to improving the performance, which was comprehensively reviewed in the literature.^[10,11] So far, THz QCLs have been demonstrated to be available in the spectral range of 0.8–5.4 THz. 2.4 W peak power in pulsed mode operation at 10 K heatsink temperature^[12] and 230 mW in continuous wave (CW) mode at 15 K heatsink temperature^[13] by a single ridge waveguide THz QCL were reported. Meanwhile, the maximum operating temperature has also been remarkably improved from the initial 50 K^[9] to 199.5 K,^[14] and even 225 K with the assistance of a magnetic field.^[15] However, the operation still needs cryogenic cooling and the major impediment for further development is attributed to the degradation of the gain at high temperatures, mainly resulting from multiple thermally-activated processes of carriers in the GaAs/AlGaAs system which are widely discussed in many papers.^[10,16,17] As a solution, a nonlinear optical process through difference-

frequency generation (DFG) based on dual-wavelength InP-based mid-IR QCLs^[18–23] has been implemented for THz wave generation at room temperature. However, the intrinsic low-efficiency limits its output power to the microwatt level.^[24] Many other material systems like InGaAs/GaAsSb,^[25] InGaAs/InAlAs,^[26] InGaAs/AlInGaAs,^[27] and Ge/SiGe heterostructures,^[28–30] have also been proposed to achieve better temperature performance, but the understanding of the material properties and the material growth technologies are still in infancy. In brief, the electronic engineering of wavefunctions at the nanometer scale for THz QCL confronts a bottleneck in its further temperature performance improvement.

Undeniably, cryogenic cooling, which increases the system size and power consumption is not gratifying for applications, but it is not unacceptable in most of the applications and the problem can be partially alleviated with a portable Stirling cooler.^[31] In practice, other emission characteristics may play an even more important role. For example, the broadband frequency tunability is important for trace gas analysis. The good output beam profile is required for efficient coupling of local oscillator wave to a heterodyne mixer in astronomy applications.^[32,33] It also helps to enhance the image contrast and yield better spatial resolution when THz QCLs are used as sources for imaging application.^[34] However, the THz QCL in the form of a conventional ridge waveguide delivers raw output features including uncontrolled frequency, irregular beam profiles, and limited power, etc. Further refinery of the emission characteristics is necessary, which can only be achieved by photonic approaches. In this review, we will focus on taming the THz emission through photonic engineering of the THz QCL devices. At first, as an important part of the photonic design, it is necessary to briefly review the THz QCL ridge waveguides and the influence on laser emission properties. Next, the photonic engineering techniques to optimize the key aspects of emission properties including single-mode operation, frequency tuning, output beam quality, power efficiency, and polarization control will be sequentially elucidated, and some works will be highlighted. In what follows, we will discuss some of the works using novel cavities, which are appealing for interesting physics and special

functionalities. In the end, the concluding section summarizes the merits of photonic engineering on the development of THz QCLs with remarks on the future perspective.

2. THz QCL waveguide designs

The initial success of first THz QCL relies partially on the development of SISP waveguide which retains sufficient mode overlap with the relatively thin ($\sim 10 \mu\text{m}$) active region layers for THz wave. The SISP waveguide has a highly doped GaAs layer ($\sim 10^{18} \text{ cm}^{-3}$) between the THz GaAs/AlGaAs heterostructure and the semi-insulating GaAs substrate.^[9] The layer with a thickness of $0.2\text{--}0.8 \mu\text{m}$ has negative dielectric constants and supports surface plasmon mode at the layer interface like a ‘quasi-metal’, with polarization matching the inter-subband selection rules of QCLs.^[8] With the existence of the top metallic contact layer, a hybrid transverse-magnetic (TM) waveguide mode arising from the coupling of two surface plasmon modes is formed. As shown in **Figure 1c**, the mode is prominently confined to the epitaxial active region, but it also extends into the GaAs substrate, leading to free carrier loss in the substrate. In addition, another waveguide architecture called ‘double-metal (DM) waveguide’ has also been developed, of which the $10 \mu\text{m}$ epitaxial active region is sandwiched by two metal layers realized by the metallic wafer bonding processes.^[35] The surface plasmon mode is completely confined in the subwavelength active region layer with confinement factor $\Gamma \approx 1$, independent of the frequency. As the doped contact layers are normally very thin, the absorption of metal and the re-absorption of epitaxial active region dominate the waveguide losses. The subwavelength confinement imposes a large impedance mismatch between the waveguide modes and the free space propagating modes. This increases the facet reflectivity to $R \sim 0.9$ (for a $10 \mu\text{m} \times 100 \mu\text{m}$ waveguide facet and $\lambda = 100 \mu\text{m}$) and hence reduces the mirror loss. As a result, the DM waveguide has a slightly lower threshold ($g_{\text{th}} = (\alpha_w + \alpha_m)/\Gamma$, where Γ is the mode confinement factor, α_w is the waveguide loss and α_m is the mirror out-coupling loss). Due to a more uniform current injection and improved thermal sinking, it also has better high-temperature performance and most of the maximum operation temperature records were

achieved using this waveguide scheme.^[14,15,36,37] Conversely, the SISP waveguide is more favorable for high-power emission due to smaller facet reflectivity.

Contrary to SISP waveguide where the optical confinement should be maintained with great care for enough gain, the DM waveguide has much greater flexibility for manipulating the electromagnetic wave thanks to its strong optical confinement. A simple example is that the lateral dimension of a DM waveguide can be reduced to the subwavelength scale, creating the microstrip laser^[38,39] or so-called photonic wire laser^[40] with a reduced threshold current. The cost for a lower threshold and better temperature performance of the DM waveguide are extremely large beam divergence ($>180^\circ$) and low output power. The conventional ridge THz QCLs, regardless in the form of an SISP waveguide or a DM waveguide, normally yield a multiple-mode output with uncontrolled wavelengths enveloped under the gain profile.

3. Spectral control

One of the most significant features of QCLs is the possibility to tune the single-mode emission over a broad frequency range,^[41] which is desired for many applications e.g. in THz frequency range as a local oscillator in the heterodyne receiver or as sources for chemical/biomolecular sensing and spectroscopy.^[33] On the one hand, it is possible to directly adopt the spectral control concepts well-developed in the short wavelength range. However, the special properties of THz QCLs, e.g. long wavelengths and the special waveguide schemes, impose challenges and lead to ineffectiveness of some techniques. On the other hand, taking advantage of the new features of THz QCLs may trigger novel spectral control alternatives and deliver a turn-up sometime. In this section, we will firstly discuss the techniques to achieve single-mode lasing and then proceed to broadband and continuous frequency tuning.

3.1. Single-mode operation

Distributed feedback (DFB) gratings have been widely utilized to control the emission wavelength and achieve robust single-mode operation of diode lasers in the telecommunication wavelength range.^[42] The backward Bragg scattering by periodic perturbations of the modal

refractive index (real part and/or imaginary part) inside the laser medium provides feedback to a defined frequency.^[43] The wavelength is determined by the grating period Λ following the equation $k_i - nk_G = -k_i$, where $k_i = 2\pi n_{eff}/\lambda_0$ is the incident wavevector with n_{eff} as the effective refractive index in the medium and λ_0 as wavelength in free space, $k_G = 2\pi/\Lambda$ is the grating wavevector and n is an integer which is defined as diffraction order. It is straightforward to use this concept in THz QCLs. Due to the strong coupling of the mode with top metal plate and the long wavelength of THz wave, the gratings can be defined conveniently with photolithography and liftoff processes, forming metallic rather than dielectric gratings as shown in **Figure 2b**. The periodic arrangements of Ohmic contact,^[44] photoresist,^[45] nickel-stripes,^[46] and air slit gratings^[47–52] — the alternating regions with and without metallization across the waveguide, have been employed to create a modal refractive index contrast. For the grating design based on an SISP waveguide, it is of great importance to enhance such grating contrast (or coupling strength as mentioned in other literature^[53]) for strong feedback at the defined frequency, i.e. robust single-mode selection. Meanwhile, additional attention should be paid to maintain the overall loss and confinement factor of the traveling waves with the active region. For DM waveguides with strong subwavelength confinement, a remarkable modal effective index contrast^[52] can be achieved by simply creating air slits in the top metal plate without much influence on the overall modal loss. And the design flexibility of DM waveguide even allows the creation of lateral corrugations^[54–56] with robust mode determination when the waveguide lateral size is comparable to or smaller than the wavelength (see Figure 2d and 2e). Owing to the large coupling strength of DFB gratings on a DM waveguide, high-order scatterings/diffractions by 2nd-order DFB grating,^[49,50] 3rd-order DFB grating^[57,58] and even 4th-order DFB grating can be exploited for laser feedback while the other order of scatterings/diffractions can be optionally used to couple the emission out to the free space in a certain direction, which will be elucidated in detail in the following sections. However, care

should be taken to prevent the excitation of non-DFB modes in the longitudinal direction and high-order modes in the transverse direction as the strong subwavelength confinement of DM waveguides leads to small contrast of overall loss for different modes. Absorbing waveguide ends with intact lossy GaAs contact layer^[52] and/or titanium^[47] were proposed to eliminate the Fabry-Perot (FP) resonance.^[49] The fabrication of narrow ridge, SiO₂/Au covered sidewalls,^[50] or side strips of highly-doped GaAs layer^[59] as absorbers was proposed to suppress the lateral modes in the higher order.

Photonic crystals (PhCs), the DFB in two dimensions with more enriched scattering/diffraction wavevectors, have also been widely implemented for tailoring the emission properties. Benefited from the great design flexibility, the laser can be engineered to work on a strong resonant defect mode with good confinement achieved by the surrounding PhCs.^[60] It can also be designed to work around a dispersion band edge, where a high photonic density of states (i.e. low group velocity) resulting from the DFB effect of the lattice contributes to a significant gain enhancement. At the first attempt in THz, PhCs were used as an external reflection mirror with a narrow reflectivity band for single-mode operation of an FP cavity laser.^[61] Then, the PhCs were developed as active resonators by patterning two-dimensional (2D) periodically arranged air holes or dielectric pillars. For the former, the holes are etched into the top metallic contact layer^[62,63] as shown in **Figure 3a**. The effective refractive index differs in the region with and without top metallization, inducing distributed scattering similar to the one-dimensional (1D) DFB gratings. The THz radiation is conveniently emitted through these air holes and the fabrication is simple. However, it is difficult to form 2D complete photonic bandgap (PBG) through this approach. Consequently, most of the THz PhC lasers based on perforated top metallic contact operate on several modes of which the wavevectors correspond to high-symmetry points in the momentum space,^[62–64] as indicated in Figure 3c. By elaborately engineering the PhCs such as introducing absorption boundary and grading the air hole sizes to enhance the loss contrast of modes, single-mode operation was achieved with

good emission characteristics^[65–68] which will be elaborated in the following sections. It is feasible to drill the air holes through the active region,^[69,70] but complete PBG can only be achieved with a very high filling factor of air holes in the PhC structure.^[71] In this case, the fabrication and laser operation condition are stringent due to increased scattering loss and reduced gain medium. For dielectric-pillar type PhCs, the pillars were created by dry-etching through the active region as shown in Figure 3e. Top metallization for electrode contact and vertical optical confinement was then realized by benzocyclobutene (BCB) planarization^[72,73] or wafer bonding to another n^+ wafer.^[74] In this scheme, the refractive index contrast is more pronounced and thus, results in large PBG where the gain spectral range of THz QCLs can be aligned to one of the strong bandedge resonances for robust single-mode operation.^[72–76]

Apart from the wavelength-selection mechanisms based on DFB and PhC geometries, other photonic structures also turn out effective in frequency engineering and single-mode operation. For example, a circular resonant cavity with wavelength-comparable size has a series of whisper-gallery modes with a large free spectral range. Robust single-mode operation over a broad dynamic range can be achieved by allocating only one of the modes into the gain spectral range.^[77,78] Coupled-cavity structure^[79,80] has also been utilized to achieve single-mode operation with a reported high side-mode suppression ratio (30–40 dB).^[81] It consists of two electrically isolated sub-cavities with different lengths which are therefore featured by different comb-like reflection spectra, and a deeply etched air gap between the sub-cavities. The laser is forced to emit at the wavelength where the peaks from the two reflection spectra coincide. Comparing with DFB and PhC structures, the coupled-cavity structure is advantageous in its simpler fabrication as it only needs to create an air gap of several micrometers in width on a laser ridge. In addition, the external cavity architecture — an external grating is coupled with a semiconductor laser ridge waveguide coated with an anti-reflection layer, can provide feedback to the gain material at a specific wavelength and thus achieve single-mode emission.^[82] Despite the lack of anti-reflection coating for THz QCLs, single-mode operation could also be achieved

in this way with an abutted antireflection-coated silicon lens to reduce the facet reflection.^[83] Recently, an elegant external cavity scheme, denominated as THz vertical-external-cavity surface-emitting laser (VECSEL) has been reported.^[84] In this configuration as shown in **Figure 4**, a metasurface reflector composed of an array of DM waveguide quantum cascade (QC) wires and a wire-grid polarizer form a plano-plano FP cavity. The wire-grid polarizer works as an output coupler as well as provides coherent feedback to feed the gain medium on the metasurface reflector. To achieve efficient energy coupling into and out of the subwavelength DM waveguide while maintaining reasonable optical interaction with the active region for amplification, the width of QC wires is devised to support TM₀₁ mode. TM₀₁ mode will not self-lase as it has a low quality (Q) factor in the vertical direction and its oscillation in the in-plane direction is intentionally suppressed. As a result, the effective gain spectral range is determined by the spectral broadening of the TM₀₁ mode and the emission characteristics are mainly determined by the master external cavity. In this scheme, single-mode operation can be conveniently achieved by inserting an intra-cavity etalon as a frequency filter^[84] or reducing the cavity length for a large free spectral range.^[85]

3.2. Frequency tuning

The eigenfrequency of a cavity resonant mode is normally determined by the dispersion relation $k_z^2 + k_\perp^2 = \omega^2 \mu_{\text{eff}} \epsilon_{\text{eff}}$, where k_z and $k_\perp$ are the wavevector components in the longitudinal and lateral directions, ϵ_{eff} and μ_{eff} are the modal effective permittivity and permeability, respectively. From the equation, k_z , $k_\perp$, and the modal effective dielectric constant ϵ_{eff} ($\mu_{\text{eff}} \approx \mu_0$, μ_0 is the permeability in vacuum) determine the resonant mode frequency ω . Therefore, the laser emission frequency can be effectively tuned by modulating different parameters as schematically illustrated in **Figure 5a-c**. Although huge progresses have been made in terms of controlled single-mode operation of THz QCLs, broadband and continuous frequency tuning is much more challenging. So far, various efforts based on this strategy have been proposed. Some special photonic designs have proved to be effective in THz QCL spectral tuning.

The most straightforward approach to tune the laser emission frequency is modulating the heat-sink temperature or driving current of a laser cavity, which would change the modal effective dielectric constant. In general, frequency tuning in this way is inefficient for THz QCL due to the small refractive index change as a function of temperature and its long wavelength. The frequency of a single-mode DFB laser can only be tuned for ~12 GHz with heatsink temperature modulated from 8 K to 97 K.^[54] Current-injection tuning resulting from the refractive index change of the gain material due to the Joule heating effect is even weaker.^[86] Therefore, it allows very precise frequency control. To enhance the frequency tuning range, complicated optical cavities, such as two-section coupled-cavity structures,^[87] aperiodic gratings within a standard FP cavity,^[88] were utilized to expand the tuning capability based on the so-called Vernier effect.^[41] A discrete frequency tuning over 160 GHz can be achieved at around 2.9 THz,^[88] whereas much more efforts are still required for side-mode suppression and continuous tuning. It is also feasible to perturb the modal effective dielectric constant through post-process nitrogen or dielectric layer deposition^[89,90] onto a DFB structure. Reversible, continuous, and mode-hop-free tuning (over ~57 GHz) with high-performance operation has been reported.^[90] But this technique is impractical for many applications due to the complicated tuning process and slow tuning speed. Along with the Joule heating effect, electrical pumping of a laser can also lead to other tuning mechanisms. The applied bias onto a THz QCL active region changes the gain profile, which leads to the changes in both real part and imaginary part of the dielectric constant, respectively. The former is normally called gain-induced optical index change effect, which was utilized in the spectral tuning in coupled/phase-locked array structures^[91,92] with negligible influence on the output power. The latter is referred to as mode-pulling effect in the literature,^[78,86,93] which is produced by the blueshift of the gain profile with the applied bias voltage. The frequency of the resonator mode can be pulled towards the gain profile maximum and thus, the tuning is more effective in the active region design with diagonal intersubband transition and large gain.^[78,86] With this mechanism, continuous tuning over a

frequency range of 30 GHz has been achieved based on PhC cavity (as shown in the Figure 3h)^[75] and microcavity^[77,78].

Another category of laser frequency tuning work is based on the tailoring of k_z , which could be routinely achieved by modulating the period of DFB Bragg gratings or rotating the external grating in an external cavity set-up. As the k_z of the mode is robustly determined by the wavevector of the Bragg gratings, an array of DFB lasers with gradually varied periods would cover a broadband spectral range.^[50,54,94,95] However, this requires complicated driving electronics and optical arrangements for beam collimation and it is also challenging to achieve single-mode operation at the predefined frequency for a large array of DFB QCLs. For years, external cavity tuning scheme has proved to be efficient in the near- and mid-IR range with broadband and continuous tuning capability^[96,97] even though it suffers from many problems such as bulky size, mechanical instability, and slow tuning speed. By rotating an external grating to select the feedback wavelength (i.e. k_z), the single-mode emission frequency can be tuned effectively. As mentioned previously, an external cavity configuration has been developed with an abutted antireflection-coated silicon lens coupled to an SISP waveguide facet to reduce the facet reflection and therefore enhance the coupling efficiency between the external cavity and the sub-wavelength gain medium.^[83] However, the continuous frequency tuning range was limited to just a few GHz,^[83,98] indicating the limited capability of this method. A novel coupled microcavity architecture with a wavelength-comparable external cavity strongly coupled to a surface-emitting DFB laser resonator was proposed to overcome the limit. The lasing emission frequency, which is the eigenfrequency of the coupled microcavity, can be mechanically tuned by changing the external cavity length.^[99,100] This scheme contributes to the development of a single-mode laser which is continuously tunable over 162 GHz, centered at 3.2 THz.^[100] More recently, THz VECSEL — a laser operating completely on the external FP cavity resonant mode, demonstrated single-mode lasing and continuous wavelength tuning

over 50 GHz without significant influence on the output power.^[101] The tuning range is mainly determined by the free spectral range of the master cavity and thus the tunability was further improved to 260 GHz using a shorter cavity length.^[85]

In addition, frequency tuning can also be realized by modulating $k_{\perp}$, which is even more effective for broadband tuning. DM waveguide endows THz QCL great mode confinements in the vertical as well as lateral directions. This allows reducing the lateral dimension of a waveguide ridge to a deep subwavelength scale, and therefore, a considerable fraction of the mode leaks out in the lateral direction. If a plunger, made of metal or dielectric, is placed along the side of the laser and can be modulated towards or backwards the laser with DFB gratings to fix the value of k_z , the $k_{\perp}$ will be tuned.^[102,103] If a dielectric plunger (made of silicon or other materials) is tuned towards the laser ridge, the mode will expand as shown in Figure 5d. Consequently, $k_{\perp}$ will decrease, leading to a frequency redshift as indicated in Figure 5e. On the contrary, if a metal plunger is pulled towards the laser ridge, the mode will be compressed in the lateral direction, causing an increase of $k_{\perp}$ and therefore a frequency blueshift. The object position can be tailored reversibly by well-developed techniques, such as mechanical actuator or microelectromechanical system (MEMS).^[103] This novel approach has achieved continuous frequency tuning of a single-mode THz QCL over 330 GHz with center frequency of 3.85 THz.^[103]

4. Beam engineering

Because of the metallic waveguides adopted, the THz QCLs suffer from poor beam quality with divergent and partly irregular profiles.^[104] The issue is especially prominent for DM waveguide design with limited dimensions in both vertical and lateral directions, which poses a great impediment for the power coupling into waveguides, antennas and detectors, etc.

To collimate the out-coupled THz beams in the free space, some discrete optical components have been proposed. The primitive idea was to utilize a silicon lens with an anti-

reflection coating coupled to the facet of a DM THz QCL ridge to collimate the emission beam.^[105,106] The method is effective and a narrow beam divergence of $\sim 2.4^\circ \times 2.6^\circ$ was recently achieved;^[106] however, meticulous operations were required to align the lens with the laser facet. Facet coupling to dielectric^[107] or hollow metallic^[108,109] waveguides was also adopted to improve the beam profile, but the results are not superior to that by lens coupling. Moreover, the new problems of increased coupling loss, complex manufacturing/integration work, reproducibility and stability cannot be neglected.

Monolithic integration of a beam shaper would be more desirable for practical applications. The electromagnetic horn antennas are widely exploited as an impedance-matching element to boost the out-coupling efficiency and directional emission in the microwave range. Inspired by this, a similar scheme has been applied to THz QCLs by integrating the horn antennas onto the laser facets.^[110–112] The overall performance is moderate and further optimization is required in this direction. Recently, a novel on-chip planar antenna scheme has been proposed by patterning antennas on top of a BCB polymer planarization layer at the end of a laser facet.^[113,114] Due to the successive DM waveguide from the laser ridge to the antennas, the antennas are efficiently fed with over 90% coupling efficiency.^[114] All antennas are kept in-phase by deliberately designing the electrical path differences between the patches to be multiples of 2π , and thus an impressive Gaussian beam is achieved.^[114] However, the output beam divergence is still large because of the small sizes of the antenna arrays (2×2 or 3×3). Further improvement could be made by utilizing a larger antenna array at the cost of more complicated calculations. It is worth to mention that these microwave antennas are not frequency sensitive, suggesting a potential for broadband applications such as the power extraction of frequency combs.

As PhC resonators including 1D and 2D structures have been widely implemented for spectral control, naturally one would consider using the same photonic components for output beam engineering and thus, realizing monolithic, compact, and multifunctional photonic

devices. The general idea is to utilize higher-order Bragg scattering $k_i - n_f k_{Gf} = -k_i$ (n_f here is the scattering order for feedback) to provide feedback to the laser cavity, while using lower-order Bragg scattering $k_i - n_{out} k_G = k_{out} \sin(\theta)$ for energy extraction, where n_{out} is the scattering order for output, k_{out} is the output wavevector and θ is the output direction as schematically shown in Figure 1a. 2nd-order DFB gratings were firstly implemented onto THz QCLs for this purpose, where the 2nd-order Bragg scattering provides sufficient feedback and 1st-order Bragg scattering couples the THz power vertically ($\theta = 0^\circ$) out of the QCL cavity.^[48–50,115] A narrow beam divergence of several degrees was achieved. In principle, such a surface-emission DFB grating tends to support asymmetric mode emission due to the lower surface emission loss, which induces an emission farfield profile with two lobes. A π -phase shift has been intentionally introduced in the grating center to impose a symmetric distribution of phase along the gratings.^[50,91] Narrow single lobes were achieved with considerable side-lobe intensity both in simulation and experiment. In these designs, the emission along (perpendicular to) the laser ridge is determined by the length (width) of the grating (the diffraction angle is determined by $\theta \approx \lambda/a$, where a is the aperture size^[116]). As a result, it is still highly divergent in the perpendicular direction due to the narrow ridge width. To achieve a narrow and symmetric farfield profile in two dimensions, some researchers tried bending the laser ridges into a disc or ring as shown in **Figure 7c**, resulting in vertical-emitting ring THz lasers.^[117–119] 2nd-order concentric-circular DFB grating was also reported to impose a rotational symmetry to the farfield patterns.^[120,121] In these proposals, robust single-mode operation and reduced beam divergence were reported. Nonetheless, the quasi-doughnut-shape or double-lobe farfield profiles are not satisfying due to the intrinsic structure symmetry and many other perturbation effects such as wire bonding,^[122] contact-connecting bridge, and structure anisotropic.^[120,121] An alternative solution is to phase-lock an array of surface-emission THz QCLs.^[91] This was realized by connecting one edge of each laser with a curved waveguide coupler. The length of

the coupler was designed to lock all the DFBs in-phase. By locking six DFB lasers, a tighter beam pattern with $\sim 10^\circ$ divergence in the phased-array direction (transverse direction of the ridges) was achieved.^[91] But for phase-locking a larger number of lasers, the structure design and fabrication should be more stringent to ensure in-phase single-mode operation.^[123]

2D PhC resonators are granted with more flexibilities in altering the surface emission of THz QCLs, which allows the engineering of farfield emission profiles and provides controllable emission properties.^[63,65–67] Indeed, the single-mode laser devices working at approximately 2nd-order Bragg scattering and a series of single-lobed farfield patterns have been reported using the airhole-type PhCs with a π phase shift in the structure center. As shown in Figure 7i, low beam divergence of $\sim 10^\circ \times 10^\circ$ has been achieved with a remarkable directivity of ~ 20 dB,^[67] which is defined as the beam brightness contrast to the background.^[124] However, it is non-trivial to achieve single-mode operation using these airhole-type PhC cavities as mentioned previously. Deliberate bandstructure engineering is required which is usually achieved through the calculation within a PhC unit cell with periodic boundary conditions, whereas the influence of the actual finite scale of the device is also necessarily taken into consideration. Moreover, it is challenging to predict and control the radiation losses of the PhC devices without 3D full-structure calculations, which are regularly computationally intensive.

In 2009, a 3rd-order DFB grating was reported to achieve beam collimation ($\sim 10^\circ$) in the longitudinal direction through the so-called end-fire antenna effect.^[57] This ingenious beam collimation was realized by matching the k vectors of the 1st- and 2nd-order diffracted modes to the k vector in free space while the feedback was provided by the 3rd-order intra-cavity diffraction. The out-coupled wave from different apertures was phase-shifted by 0 and π , and therefore constructively interfered at the edge ends. Contrary to the situation of normal DFB gratings, the farfield spot of the 3rd-order DFB grating is tight in directions parallel as well as perpendicular to the ridge and the ridge width has a negligible influence on the beam

divergence.^[125] This experimental result was found to be better explained by the end-fire microwave antenna theory, which treats every aperture as an in-phase subwavelength emitter.^[40,126,127] According to the theory, the longer the antenna array, the tighter the farfield pattern, which was evidenced by many research works.^[58,125] The k -vector matching can be satisfied by tailoring the effective refractive index of the oscillating mode n_{eff} close to 3.0. The smallest achievable beam divergence of a 3rd-order DFB grating is constrained by the coherent length, whose current record is 5.7 mm,^[58] leading to a beam divergence of $6^\circ \times 11^\circ$. Phase-locking of several 3rd-order DFB wire lasers through lateral antennas could further reduce it to $\sim 6^\circ \times 8^\circ$.^[92] Based on the similar principle, a hybrid DFB structure with 1st-order DFB lateral corrugation for feedback and an array of circular apertures in the top metallic layer for phase matching and power extraction was recently proposed with comparable performances.^[56] Furthermore, another novel DFB design based on so-called antenna-feedback mechanism reported an even smaller beam divergence ($4^\circ \times 4^\circ$).^[128] It is noteworthy that both of the recent progresses significantly relax the demanding phase matching requirement on the effective refractive index of optical modes.

Alternatively, monolithic beam collimation can be effectively achieved by designing passive photonic components outside of the laser cavity. It provides more freedom for structure design and fabrication without affecting the emission performance of laser itself. However, how to efficiently couple the emitted THz wave to the external photonic components is a critical issue. One of the most well-known solutions on this is the spoof surface plasmon (SSP) waveguide/collimator fabricated on an emitting facet of a ridge THz QCL.^[130] As shown in **Figure 8a**, the SSP structure with rich subwavelength features was milled by focus ion beam (FIB) on the highly doped semiconductor substrate (functions like poor metal at THz frequencies) closely below the emission aperture of a DM waveguide ridge. The emitted THz wave could efficiently couple to the structure and excite SSP^[131] and then the SPP propagates

a long distance along the laser facet plane. Through this means, the laser emission aperture was effectively enlarged and the beam divergence was reduced to $\sim 10^\circ$.^[130] Even though good directionality was achieved, complicated fabrication, e.g. requiring the usage of FIB technology poses a challenge for inexpensive and mass production. A planar beam collimator is better for real applications and can be created conveniently during the fabrication of THz QCLs. Planar integration of a tapered THz QCL with the similar SSP waveguide/collimator has been developed,^[132] as shown in Figure 8f. The SSP waveguide was patterned as an SSP out-coupler by introducing periodically arranged gratings outside of a tapered cavity. The QCL consists of a back distributed Bragg reflector and the tapered structure devised to increase the THz emission intensity as well as output a quasi-parallel beam which would be better coupled with the 1D SSP waveguide. With the intrinsic design freedom for large collimator size (both in the lateral and longitudinal directions), a beam divergence as narrow as $\sim 4^\circ \times 10^\circ$ was demonstrated.^[132] Besides the SSP scheme which has low propagation loss and strong confinement of THz waves at the interface, a novel planar THz waveguide design called dielectric-loaded surface plasmon (DLSP) waveguide has also been developed with similar properties.^[133] Contrary to the subwavelength-structured metallic surfaces, it simply comprises a GaAs-coated metallic layer, a part of the original THz DM waveguide as illustrated in Figure 8h. High coupling coefficient and low loss make it a flexible platform for THz QCL beam manipulation. As shown in Figure 8l, a low-divergent beam of $\sim 12.9^\circ \times 8.5^\circ$ was realized by patterning a 2nd-order metal antenna array as collimator on the waveguide.^[133] The above external collimators are not frequency filter, but single-mode emission can be easily achieved by integrating frequency controllers such as DFBs in the laser cavity. In addition, simultaneous control of the operation frequency and emission beam profile has also been reported by integrating a single-mode dielectric PhC QCL with DFB out-couplers/collimators on the boundaries.^[73]

5. Power efficiency

Single-mode operation with high power efficiency is highly desirable across the mid-IR and THz spectrum for chemical and biomolecular sensing and spectroscopy applications. However, in DM THz QCLs, the large modal mismatch between the strongly confined waveguide modes and the near-field modes at the emission aperture imposes high facet reflectivity and distorts beam patterns, seriously limiting the power efficiency. For semiconductor lasers, wall-plug efficiency (WPE) and power slope efficiency (PSE) are two important figure-of-merits to characterize the power efficiency. WPE is a direct measurement of electrical-to-optical power conversion efficiency while PSE is closely related to the radiative and collection efficiency of a resonant mode. It is defined as $PSE = \eta_{ce} \cdot \alpha_R / (\alpha_w + \alpha_R)$, where η_{ce} , α_R , α_w are detector power collection efficiency, radiative loss, and waveguide loss, respectively. Obviously, improving the collection efficiency by reducing the beam divergence and, enhancing the radiative loss while simultaneously maintaining the overall loss at a reasonable level are two effective strategies to enhance the power efficiency.

In the previous section, various photonic techniques have been adopted to reduce the beam divergence and thus improve the power collection efficiency. Among them, an abutted high-index silicon hyper-hemispherical lens has ever been coupled to the facet of a DM ridge THz QCL. The emission power was enhanced by multiple times with a high PSE of $dL/dI=296$ mW/A, mainly resulting from the increased collection efficiency instead of mirror outcoupling efficiency since the laser threshold remained.^[105] Various antennas^[110–114] were also exploited as an impedance-matching element to boost the out-coupling efficiency and to ensure the directionality of emission. However, the improvement is quite limited. For 1D- and 2D-PhC THz QCLs, it is possible to engineer the photonic parameters, such as the slit duty cycle of DFB gratings,^[122] air hole sizes of PhCs^[65–67] and the periods across the structure^[120,121] to enhance the power extraction/out-coupling efficiency of the resonators. Nevertheless, most of these designs output a comparable power level to their DM ridge equivalents. This is due to the fact

that these devices operate on the antisymmetric band-edge modes,^[115,129,134] which are typically more favored to lase due to the lower total loss. As shown in **Figure 9a**, the magnetic field of these band-edge modes is antisymmetric around the emission aperture, and thus destructive interference around the emission apertures suppresses the radiative efficiency, leading to a higher resonator Q factor to lase but low output power. A radical output power improvement could be achieved by engineering the laser to work on the symmetric band-edge mode which is much more radiative due to the constructive interference around the emission apertures. For this purpose, a dual-slit 2nd-order grating design has been employed,^[51] but the enhancement is still constrained as the ‘radiative’ mode exhibits higher total loss than the ‘non-radiative’ mode. A graded photonic heterostructure (GPH) was then devised to stimulate the ‘radiative’ symmetric mode in THz QCLs.^[115] The schematic photonic band diagram and the corresponding SEM image of the device are shown in Figure 9b and 9c, respectively. By gradually reducing the grating period from the center towards each end of the laser ridge, the photonic band diagram is similar to the band structure of a type-II semiconductor quantum well with a potential well for photon confinement in the center. The radiative symmetric modes are forced to oscillate inside the cavity while the non-radiative antisymmetric ones leak to the absorbing boundary, analogous to the spatial separation of electron and hole wavefunctions in a quantum well. Consequently, the symmetric mode will be promoted to lase due to lower total loss and narrow emission lobe can be obtained because of its in-phase outcoupling nature. At 20 K, a remarkably high peak power of 100 mW and PSE of 230 mW/A was achieved by a GPH device operating at 3.4 THz.^[115] The WPE is ~0.35%, comparable to those of single-plasmon edge-emitting lasers. GPH is a flexible means to engineer the emission characteristics of THz QCLs and it is intuitively compelling to implement this strategy in 2D-PhCs to further reduce the beam divergence.^[68] Recently, a new grating scheme that uses a superposition of hybrid 2nd- and 4th-order Bragg gratings was reported to have a remarkable power efficiency (peak power of 170mW and PSE of 993mW/A).^[135] The additional 4th-order gratings were

introduced to tailor the radiative efficiency of antisymmetric and symmetric bandedge modes at will as shown in Figure 9h and both of the modes become radiative in this sense. By carefully choosing the structure parameters, single-mode single-lobe emission was robust over the whole dynamic range and the performance enhancement was independent of the temperature (Figure 9i), similar to those of GPH lasers (Figure 9d).

For 3rd-order DFB gratings, a phase-matching between the emission apertures and the free space will be guaranteed when the mode effective refractive index is tuned to 3. This results in a great enhancement of output efficiency compared with conventional DFB gratings, but without prominent influence on the lasing threshold. PSE of 130 mW/A and 200 mW/A were reported in the initial reports.^[57,125] Due to the subwavelength transverse ridge dimension, the waveguide modes of photonic wire laser extend substantially outside of the active region core. Therefore, it is attainable to manipulate the out-coupling of mode energy by monolithically integrating side-emitter structures. It was found that the power efficiency could be further improved (WPE ~0.57% and PSE ~450 mW/A) when antenna loop structures were laterally integrated to the 3rd-order DFB wire lasers to enlarge the effective emitting facet area.^[55,92] By coupling one reflector along with the antenna loop to control the lasing mode propagating direction, unidirectional emission was achieved along the waveguide with an enhancement of WPE (~1%) in the predefined direction.^[136]

Alternatively, phase-locking of low-Q cavities is also an effective strategy to achieve high power efficiency while maintaining directional emission. Recently, a ‘global antenna mutual coupling’ mechanism was proposed to build definite phase relations between the emission antenna apertures of several tens of short 2nd-order DFB cavities through farfield radiations as shown in **Figure 10**. The individual lasers with low Q factors and divergent beam patterns were strongly phase-locked to oscillate coherently. Consequently, the emission aperture area was dramatically increased. A narrow emission lobe (<10°×10°) and high slope efficiency (450 mW/A) were achieved by this novel scheme.^[137] Nevertheless, the emission power is

constrained by the small cavity size even though a large number of cavities are coupled. In THz VECSELs, the external FP cavity ensures the phase coherence among the QC wires (work effectively as antenna emitters).^[84] The configuration characteristics of THz VECSELs, i.e. efficient energy out-coupling of the gain cavities and scalable array size, contribute to good performance including single-mode emission, small beam divergence ($\sim 3^\circ \times 3^\circ$),^[138,139] high power (1.35 W at 6 K and 830 mW at 77 K in pulse mode),^[101] and high efficiency (PSE ~ 767 mW/A and WPE $\sim 2\%$).^[101,140]

6. Polarization control

The polarization control of the laser output beam is compelling for a breadth of applications ranging from communications to polarization-sensitive imaging, vibrational circular dichroism spectroscopy, and ellipsometry. Conventionally, the manipulation of beam polarization can be achieved using external optical components such as polarizers and wave plates. However, such external polarization control methods will render the system to be slow, bulky and expensive. Using external optical components also inevitably incurs a fractional output power loss (e.g. commercialized THz continuous polarization converters have a transmission of $< 30\%$ ^[141]). Therefore, it is desirable to achieve simple, fast and power-efficient polarization control.

In QCLs, the electric field of waveguide modes in the active region polarizes perpendicularly to the plane, dictated by the selection rule of intersubband transitions.^[8] The output polarization can be altered through the interaction of the electric field with the emission apertures. It can be effectively achieved by implementing photonic structures, such as modifying the ridge waveguide as a TM-to-TE polarization converter,^[142] patterning plasmonic polarizers on the laser facet to generate linearly or circularly polarized light.^[143] In the THz range, the electric field is strongly confined to the top metallization layer, and the out-coupled light through the slot apertures in the top metallization layer polarizes perpendicularly to the slot elongation. Therefore, linear polarization can be easily obtained by fabricating surface-emitting DFB gratings^[48–50,115] or antennas.^[114] In addition, the polarization direction can be

manipulated by the antenna orientation at will.^[144] By integrating two sets of orthogonally oriented slot antennas onto a wide laser ridge waveguide, the out-coupled light beams with cross-oriented polarization states superimpose and interfere in the far field. If the relative positions of the two sets of antennas are deliberately designed to achieve an accumulated phase difference of $\pi/2$ between the two beams, the overall output will have a circular polarization if the two beams have the same intensity.^[144] However, in reality, a lot of unforeseen problems hinder the free tailoring of polarization, such as unequal coupling strength between the waveguide modes and the two types of antennas, the existence of higher-order transverse modes, to name a few.

The above work only achieved polarization state alteration that is predefined at the time of structure design and fabrication. Dynamic control of the laser's polarization from linear to circular is more interesting and of great significance. To this end, two sets of orthogonally oriented polarizers were proposed to be elegantly loaded on the waveguide outside of the laser cavities and fed separately by the lasers with well-controlled beam intensity. The capability of dynamically modulating the beam polarization state from linear to near-circular was demonstrated.^[133] The system architecture, as shown in **Figure 11a**, consists of two tapered THz QCLs for emission amplification, a half racetrack structure to phase-lock two lasers, and two low-loss DLSP waveguides which are integrated at the facet of tapers. Along each DLSP waveguide, an array of subwavelength gold antennas arranged as a 2nd-order grating is patterned to scatter the light into the far field vertically, with its polarization along the orientation of the antennas. The two sets of antennas at the end of two QCLs are cross-oriented and shifted by one quarter of the SP wavelength ($\sim 21 \mu\text{m}$), inducing a $\pi/2$ phase difference between the two beams. Consequently, the two beams will superimpose and interfere in the far field and result in an elliptically polarized light. Due to the large patch of antennas, the tight farfield spots are observed even when two beams superimpose. The emission power from each QCL can be independently adjusted through the pumping current and thus, the polarization of the combined

beam will evolve continuously from linear to circular. The experimental results, as shown in Figure 11c, indicate a continuous tuning of output beam polarization from excellently linear to near-circular state when the pump intensity of one laser is fixed and another one is varied. The optical power is collected within a central $5^\circ \times 5^\circ$ region for these polarization measurements, where two beams are well overlapped. The near-circular state, the black curve in Figure 11c, has a degree of circular polarization (DOCP) of 99% (calculated according to Ref.^[144] with $I_{\max} : I_{\min} = 56:44$ in experiment). Later, the dynamic polarization control was also demonstrated using a THz VECSEL based on the similar principle. In this work, two sets of linear polarizers (orientation separated by 80°) are integrated onto the metasurface reflector and work as a polarization-selective gain medium. As usual, good beam quality and high-power performance are maintained when any set of polarizers are switched on. Electrically controlled linear polarization switching between two states separated by 80° is achieved; however, it is incapable of continuously varying the polarization of the output state due to the cross-coupling effect between the two antenna sets.^[138]

7. THz QCLs with novel cavities

With the great advances in the understanding of THz QCL photonic properties, various novel resonant cavities have been devised and integrated onto the THz QCLs for exploring interesting physics and demonstrating special functionalities.

The strong optical confinement of the DM waveguide in both vertical and lateral/planar direction offers the possibility to design the microcavities for miniature THz sources with low power consumption, high brightness, and potential for ultrafast modulation speed. Microdisk lasers working on whispering-gallery modes (WGMs) were demonstrated to yield ultralow threshold currents of a few milliamps thanks to the small cavity size and high modal quality factors.^[77,145–147] The mode volumes of these lasers are on the order of λ^3 .^[146] Due to its proximity with microwaves and electronics, THz QCLs based on DM waveguide configuration allow one to borrow the well-developed concepts of microwave devices to further compress the

mode volume into the subwavelength regime.^[148] This was accomplished by designing laser resonators with effective modal volume $V_{\text{eff}} = 0.12(\lambda/2n_{\text{eff}})^3$ based on inductance-capacitance (LC) circuits, as shown in **Figure 12c**. The extremely confined photonic mode contributed to a Purcell factor of 17 which leads to a great enhancement of the spontaneous emission.^[148] The emitting microcavities can also play an important role in the study of ultrastrong-coupling effects, e.g. THz intersubband polaritons.^[149]

As mentioned previously, PhC structures with photonic elements periodically arranged in 1D or 2D topology have been widely implemented in the THz QCLs for spectral control and beam engineering. These periodic structures are typically featured by discrete Bragg peaks in the Fourier spectrum which are positioned at the integer multiples of primitive reciprocal vectors. In the laser cavities, the optical diffractions through these Bragg peaks are utilized to determine the operation wavelengths, engineer the emission profiles, or to control the emission angle. These photonic configurations are well-defined, but stubborn to some extent in achieving higher optical complexities. As an example, it is challenging to realize single-mode, directional, and high-power operation simultaneously using periodic PhCs, which is restricted by the structural symmetry.^[115] This intrinsic limit could be alleviated by designing dual periodicity gratings^[150] or grading the structural parameters^[115] manually to break the symmetry. In this way, higher radiation efficiency was achieved while maintaining single-frequency lasing. Alternatively, the photonic structures of a different category, i.e. quasi-periodic or aperiodic structures, could also undertake the role. Comparing with its periodic counterparts, the aperiodic order significantly enriches the diffraction components in the reciprocal Fourier space and thus, gives more freedom to engineer the device optical properties.^[151,152] One typical example about this is the 1D quasi-periodic gratings of Fibonacci type patterned in the top metallization layer of a DM waveguide. The singular continuous Fourier spectrum enables the researcher to engineer the lasing frequencies at arbitrarily chosen Bragg resonances or to tailor

the emission far field without affecting the feedback conditions.^[153] 2D photonic Penrose lattice, a quasi-crystal photonic structure with pentagonal rotational symmetry, was also incorporated into a laser cavity. In this laser, a so-called critically-localized mode^[151,154] emitted without power cancellation issues in the periodic counterparts, leading to a higher power extraction efficiency.^[155]

Once the photonic unit cell arrangement is in complete disorder, the system comes to the amorphous or random regime, where many complex optical properties and fascinating physics arise. In the periodic or aperiodic PhCs, the light diffraction, scattering, and interference only occur in the limited directions determined by the lattice symmetry. The periodic PhCs normally support extended Bloch eigenmodes. The transmission spectrum is discontinued by the energy stop bands where the propagation of light is prohibited. The size of these stop bands varies according to the lattice direction. Conversely, the light takes a random walk in the random photonic structures as the reciprocal Fourier spectrum has a uniform and isotropic pattern without obvious dominant peaks. Even so, the wave interference still maintains, leading to typical random modes with gigantic field intensity fluctuations and even subwavelength localization profiles,^[156] analogous to the Anderson localization of electrons in the disordered semiconductors.^[157] Thanks to the special characteristics, random photonic structures of various configurations have been implemented as laser cavities for the study of the fundamental physics (e.g. the feedback mechanism, light-matter interaction, modal localization) as well as practical applications (e.g. speckle-free imaging, display lighting, medical diagnostic and sensing).^[158] The random lasing based on THz QCLs has been achieved recently.^[52,159–163] Comparing with other random laser systems, e.g. nanocrystalline ZnO powders,^[164] ceramics,^[165] organic composites,^[166] nanoparticles dispersed in fluorescent dyes,^[167] and semiconductor membranes,^[168] random laser based THz QCL is advantageous for its electrical pumping scheme and compact fingerprint. DM waveguide serves strong mode confinement in the vertical direction and accommodates the fabrication of 2D various random medium with large index

contrast for in-plane confinement.^[160,161] As a result, such a random laser could achieve multiple strongly localized mode lasing with subwavelength modal volumes as shown in **Figure 13f**, allowing for device miniaturization. Despite the intrinsic randomness, modulation of scatterer densities, adoption of short- or long-range order^[52,160] and disk boundary,^[162,163] were implemented to tailor the THz random laser emission properties including the lasing threshold, operation wavelengths, and farfield patterns, indicating the possibility of taming the laser for specific functionalities.

8. Concluding Remarks

THz QCLs are currently the only miniaturized and efficient source with high output powers above 1 THz. They have many important applications including local oscillators for astronomy, biomedical analysis, gas sensing, nondestructive imaging, and security screening, etc.^[169] However, most of the applications stand in need of full control of the spectrum, beam quality, and the polarization of the THz QCL output. To this end, various photonic solutions have been proposed to push the frontiers. Due to the spectral position in the midst of optics and electronics, mature concepts in the telecommunication and microwave technologies can be exploited to manipulate these emission features. Well-developed DFB gratings and PhC structures have been elegantly incorporated into the THz QCLs for spectral control and beam engineering. Due to the long wavelength and strong optical coupling with the top metallic layer, the implementation can be conveniently achieved by photolithography perforating the top metallic layer without complex fabrication procedures. It also allows flexible geometry optimization for simultaneous control of radiative efficiency, beam profile and feedback strength. Because of its proximity with the microwaves and electronics, the THz QCL based on DM waveguide configuration is an appealing testbed for new photonic structure concepts adapted from the microwave realm. The concept of wire laser prevails in the field to minimize the power consumption while gaining good control over the spectral purity and tunability. The THz antennas, operating similarly to those in microwave devices, are on-chip integrated as

generalists for beam, power and polarization manipulation. The innovative integration of functional THz metasurface with the active material paves the way to engineer the device externally with fairly good and simultaneous control of the emission characteristics. With more than ten years' efforts, the progress in the understanding of the THz QCL optical properties and the development of photonic design techniques have led to unprecedented achievements on single or plural aspects of THz QCL outputs. It is foreseeable that low-power consumption, great wavelength and polarization agility, and good beam quality without compromising in the output power will be achieved by a monolithic THz QCL in the near future. In this aspect, the different technological solutions may be the candidates including arrays of wire lasers, active antennas or even microresonators which have exotic properties to be explored. Exploitation of the quasi-periodic structures and random resonators is also a possible option for their design flexibility.

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Figure 1. Schematic diagrams of (a) a semi-insulating surface-plasmon (SISP) waveguide and (b) a double-metal (DM) waveguide used in terahertz (THz) quantum cascade lasers (QCLs). The typical electric field intensity is plotted with arrows indicating the electric field polarization.

Figure 2. (a) Schematic diagram of the distributed feedback (DFB) scheme. (b) A DFB THz QCL based on SISP waveguide with its cross-section optical profile and scanning electron microscopy (SEM) image of the device top view. (b) The emission spectra of the DFB laser with varied periods. (d) The SEM image of a corrugated ridge DFB laser based on a DM waveguide. (e) Spectra from DFB devices with varied grating periods. Inset, spectra taken at multiple biases from a device with the period of $15.5 \mu\text{m}$. (b, c) Reproduced with permission.^[47] Copyright 2005, AIP Publishing. (d, e) Reproduced with permission.^[54] Copyright 2005, Optical Society of America.

Figure 3. (a) Optical microscopy image of a photonic crystal (PhC) THz QCL with air holes drilled through the top metallic contact layer. (b) and (c) are the corresponding electric field intensity distribution and photonic bandstructure, respectively. The shaded area corresponds to the potential operation frequency range with high-Q bandedge modes. (d) The photonic bandstructure of a dielectric-pillar type PhC. (e)-(g) are the SEM images of the corresponding PhC THz QCL. (h) Lasing spectra at different injected currents of a device with lattice constant $a=18 \mu\text{m}$. Inset is the E_z field distribution of the PhC lasing state at band edge k point. (a, c) Reproduced with permission.^[64] Copyright 2009, Optical Society of America. (d, h) Reproduced with permission.^[75] Copyright 2010, AIP Publishing. (e-g) Reproduced with permission.^[72] Copyright 2007, Optical Society of America.

Figure 4. (a) Schematic of an active metasurface reflector with DM waveguide sub-cavity array. (b) SEM image of an active metasurface reflector. (c) The schematic for the THz vertical-external-cavity surface-emitting laser (VECSEL) cavity configuration with a wire-grid polarizer as an out-coupler and a silicon window as an intra-cavity etalon. (d) The typical characterization result of a QC-VECSEL. The inset is the lasing spectrum. (a-d) Reproduced with permission.^[84] Copyright 2015, AIP Publishing.

Figure 5. Tunable THz QCL with different frequency tuning mechanisms. (a)-(c) Illustration of three frequency tuning mechanisms by manipulating the longitudinal wave vector (k_z), dielectric constant, and lateral wave vector ($k_{\perp}$) of the lasing mode based on the dispersion relation $k_z^2 + k_{\perp}^2 = \omega^2 \mu_{\text{eff}} \epsilon_{\text{eff}}$. The operation frequency ω is determined by the radius of a particular curve that intersects a specific value of k_z and $k_{\perp}$. The black curves represent the condition that determines the original lasing frequency. The blue and red dashed curves

represent the conditions when the laser tuning is either blue- or redshifted. (d) SEM image of a THz wire laser with a frequency-tuning plunger. Inset: the schematic of a DM waveguide with a deep-subwavelength lateral dimension. The black curve shows the cross-section modal profile. (e) 330 GHz continuous spectral tuning (bottom row) from a device with the atmospheric transmission spectrum (HITRAN 2008, middle row) and threshold current densities (top row) at the corresponding frequencies. The gaps in the tuning spectra are attributed to the strong absorption band indicated in the atmospheric transmission spectrum. (a-d) Reproduced with permission.^[102] Copyright 2009, Springer Nature. (e) Reproduced with permission.^[103] Copyright 2011, Optical Society of America.

Figure 6. (a) The schematic diagram of a DM THz QCL with anti-reflection coated silicon lens. (b) Typical farfield beam pattern of a DM THz QCL with anti-reflection coated silicon lens for collimation. (c) Microscope image (top) and a schematic drawing of a 3×3 patch antenna array (bottom). (d) Beam shape of the 3×3 patch antenna fed device, together with one-dimensional cuts through the peak. The measured power density distribution has a good Gaussian fit to the FWHM of 35°. (a, b) Reproduced with permission.^[106] Copyright 20018, Optical Society of America. (c, d) Reproduced with permission.^[114] Copyright 2016, Optical Society of America.

Figure 7. (a) SEM images of the 2nd-order DFB grating THz QCLs. (b) Farfield radiation measurements along the longitudinal and lateral direction of a ridge waveguide. (c) The power performance of a THz ring laser with 2nd-order DFB grating on top. The inset shows a processed laser device. (d) 2D surface emission farfield profile of a ring laser. (e) The schematic of a three-ridge surface-emitting DFB array. (f) Farfield plots of a six-ridge array along the array direction. (g) Operating principle of a surface-emission PhC THz QCL based on the DM waveguide configuration. The top metallization layer is patterned with the desired PhC design. The PhC works as a resonator to provide feedback, while simultaneously diffracting light vertically. (h) Microscope image of an optimized PhC QCL with graded air hole sizes and a π -phase shifter. (i) Farfield profile of the optimized PhC laser. (j) SEM images of 3rd-order DFB structures with a zoom-in view of the grating region. (k) Measured farfield pattern of the 3rd-order DFB laser with an estimated effective refractive index of 3.5. Inset shows the angle notation. (a, b) Reproduced with permission.^[50] Copyright 2007, Optical Society of America. (c, d) Reproduced with permission.^[119] Copyright 2009, AIP Publishing. (e, f) Reproduced with permission.^[91] Copyright 2010, AIP Publishing. (g) Reproduced with permission.^[129] Copyright 2013, Springer Nature. (h, i) Reproduced with permission.^[66] Copyright 2010, AIP Publishing. (j, k) Reproduced with permission.^[57] Copyright 2009, Springer Nature.

Figure 8. (a) Schematic of a THz QCL patterned with a spoof surface plasmon (SSP) collimator on the facet. Artificial coloring in the figure indicates deep (pink) and shallow (blue) SSP grooves. (b) Cross-section of the design for a 3 THz device. The groove bottom and top, the period and depth are labeled as b , t , p , and h , respectively. (c) SEM image of the device facet with measured (d) and calculated (e) 2D farfield intensity profiles. (f) Schematic and SEM image of the tapered THz QCLs integrated with a planar SSP waveguide/collimator. The right-bottom figure shows simulated 2D light intensity distribution along the metasurface collimator. (g) The measured farfield pattern of a device with planar SSP waveguide/collimator. (h) Schematic of the THz QCL with an integrated dielectric-loaded surface plasmon (DLSP) waveguide. (i) Cross-sectional electric field distribution, showing the efficient THz wave coupling to the integrated DLSP waveguide. The guiding mode of DLSP waveguide is tightly confined at the GaAs-air interface. (j) Calculated propagation length and coupling efficiency of the THz radiation into the DLSP waveguide as a function of the GaAs thickness. (k) Microscope image of a 2nd-order antenna array fabricated on the DLSP waveguide. The inset shows the strong coupling of the guiding mode with the antenna. (l) 2D farfield pattern achieved by a surface-emitting antenna array fabricated on a DLSP waveguide. (a-e) Reproduced with permission.^[130] Copyright 2010, Springer Nature. (f, g) Reproduced under the terms of CC BY 4.0 license.^[132] (h-l) Reproduced under the terms of CC BY 4.0 license.^[133]

Figure 9. (a) Transverse magnetic fields (H_y) of the radiative and nonradiative bandedge modes which are located above and below the bandgap of a 2nd-order DFB grating. (b) Schematic diagram showing the effect induced by a graded photonic heterostructure (GPH) resonator: the symmetric, radiative modes are localized in the center, whereas the nonradiative modes leak out of the structure to the highly absorbing boundaries. (c) SEM image of the GPH lasers. (d) Light–current characteristics of a GPH laser at different operating temperatures with a typical single-mode emission spectrum (inset). (e) The farfield profile of the GPH laser. (f) Schematic of a hybrid grating concept combining 2nd-order and 4th-order Bragg gratings. (g) Symmetric and antisymmetric modes of the 2nd-order Bragg grating. An added 4th-order grating serves to enhance the out-coupling of the antisymmetric mode and reduce that of the symmetric mode. (h) Surface emission losses of the band-edge modes for the hybrid DFB structures. (i) Light–current–voltage (LIV) characteristics of the hybrid grating THz QCL and emission spectrum (inset) at different pumping intensity at a heat-sink temperature of 62 K. (j) The measured farfield radiation pattern of the hybrid grating laser. (a–b) Reproduced with permission.^[129] Copyright 2013, Springer Nature. (c–e) Reproduced with permission.^[115] Copyright 2012, Springer Nature. (f–j) Reproduced under the terms of CC BY 4.0 license.^[135]

Figure 10. (a) Schematic of the coupling between two aperture antennas. (b) Schematic of the mutual coupling between two short DFB lasers. Each can be modeled as six-aperture antennas. (c) SEM image of the device consisting of four antenna mutual-coupled laser arrays with each laser array occupying a quadrant of the whole device. (d) Zoom-in view of the grid configuration. (e) A single short DFB laser. The laser consists of one short half-wavelength

center cavity and two one-wavelength cavities on both sides. The current injection is achieved through the metal contact on the air-bridge structure. (f) Farfield profiles of different quadrants of the phase-locked laser arrays. Reproduced with permission.^[137] Copyright 2016, Springer Nature.

Figure 11. (a) Optical microscope image of the polarization tunable THz QCLs integrated with DLSP waveguides. The two cross-oriented antenna arrays are fabricated on the DLSP waveguides with a vertical offset of 21 μm. Inset is the schematic of an antenna. (b) Simulated electric field distributions when only right THz QCL is pumped and when both THz QCLs and the half-racetrack structure are pumped, but with different injection currents. (c) The measured polarization state of the right THz QCL (top) and the evolution of the polarization states when changing the injection current of the left QCL while maintaining that of the right QCL at 3.67 A (bottom). (d) SEM image of the fabricated metasurface with zigzag QC wires. (e) Schematic of a plano–plano VECSEL cavity with the polarization-selective metasurface reflector. (f) The design of the metasurface illustrated with dimensions given in micrometers. (a-c) Reproduced with permission.^[133] Copyright 2017, American Chemical Society. (d-f) Reproduced with permission.^[138] Copyright 2017, Optical Society of America.

Figure 12. (a) SEM image of a microdisk THz laser. Left inset: schematic of the layer sequence in the cross-section view. (b) The typical whispering gallery optical modes of the

microdisk laser. (c) Schematic of an inductance-capacitance (LC) laser. (d) SEM image of the LC laser device. (e) Simulated electric field distribution of a resonant mode in the LC laser. (a, b) Reproduced with permission.^[77] Copyright 2007, AIP Publishing. (c-e) Reproduced with permission.^[148] Copyright 2010, The American Association for the Advancement of Science.

Figure 13. (a) SEM image of a THz QCL with quasi-periodic gratings. (b) The farfield pattern of a quasi-periodic grating device emission. Inset: the Fourier transform spectrum of the grating. The emission angle is determined by k_{om} , k_B and k_{rad} which are optical mode wavevector, Bragg wavevector and radiation wavevector, respectively. (c) SEM image of a 2D quasi-crystal THz QCL. (d) A critically localized eigenmode supported by the quasi-crystal structure of Penrose lattice type. (e) Schematic of a 2D random THz laser with dielectric pillars. (f) The typical strongly localized mode of the random structure consisting of dielectric pillars. (a, b) Reproduced with permission.^[153] Copyright 2010, Springer Nature. (c, d) Reproduced under the terms of CC BY 4.0 license.^[155] (e, f) Reproduced with permission.^[160] Copyright 2016, American Chemical Society.

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Photonic methods are effective to manipulate the output characteristics of a terahertz quantum cascade laser, in terms of its emission spectrum, beam quality, power efficiency, and polarization control etc. This article reviews various photonic designs for this purpose, including distributed feedback gratings, photonic crystals, metasurfaces and photonic antennas. Non-conventional optical cavities with exotic physics and special functionalities are also discussed.