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Terahertz quantum-cascade vertical-external-cavity surface-emitting laser with high-contrast grating output coupler

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We report a twofold increase in slope efficiency of a terahertz quantum-cascade vertical-external-cavity surface-emitting laser enabled by an all-dielectric high-contrast grating output coupler. In contrast to a conventional metal-mesh output coupler on a quartz substrate, the dielectric grating eliminates losses associated with the metal. The device operates in pulsed and continuous-wave modes, with threshold current and maximum operating temperature comparable to those of the quartz-based output coupler. A circular beam pattern is maintained across the full tuning bandwidth.

The quantum-cascade vertical-external-cavity surface-emitting laser (QC-VECSEL) has emerged as a versatile source for high power¹ and widely tunable emission² in the terahertz regime, with various devices now spanning 1.76–5.74 THz.^{3,4} The external-cavity architecture enables flexible spectral control and power scaling while producing near-diffraction-limited beams, which makes it attractive for applications requiring bright and tunable terahertz radiation. QC-VECSELs can be used for rotational absorption spectroscopy⁵ and are candidates for future frequency-agile local oscillator sources for heterodyne receivers.^{6–8}

A crucial enabling component of a VECSEL is the partially-transmitting output coupler (OC) mirror. Proper choice of the OC reflectance R_{OC} is essential to optimize the VECSEL performance: high values of R_{OC} result in low round-trip cavity losses (which reduce threshold current density and increase the maximum operating temperature) whereas high values of the OC transmittance T_{OC} increase the slope efficiency. Because the amplifying QC metasurface has relatively low single-pass gain, OC reflectance values of 95% or higher are typically required, and for "bleeding-edge" frequencies where material gain is even lower (e.g. > 5 THz), $R_{OC} > 99\%$ is needed.⁴

While the first demonstration of the QC-VECSEL used a wire-grid polarizer external to the cryostat as the output coupler,⁹ nearly all THz QC-VECSELs since then have used an output coupler based on an inductive metal-mesh evaporated on a quartz or silicon substrate, which allowed realization of compact intra-cryostat laser cavities (details in Supplementary Material).^{10,11} Metal-mesh output couplers are desirable due to their broadband design, polarization insensitivity, tunable transmittance, and ease of fabrication and integration.¹² However, a key limitation of metal-mesh output couplers is the residual absorbance A_{OC} which arises primarily from free-carrier absorption losses in the metal, and to a lesser extent dielectric losses in the underlying substrate. Incorporation of this phenomenon into the analysis from Ref. 10, shows that the slope efficiency of the VECSEL can be approximated

as

$$\frac{dL}{dI} \approx N_p \frac{h\nu}{e} \eta_i \eta_u \frac{T_{OC}}{T_{OC} + A_{OC}} \frac{\ln(R_{OC})}{\ln(R_{MS} R_{OC})}, \quad (1)$$

where N_p is the number of QC periods, $h\nu$ is the photon energy, η_i is the internal quantum efficiency, η_u is the modal uniformity factor (including the modal uniformity within each microcavity and the slowly varying cavity mode profile), and R_{MS} is the cold-cavity metasurface reflectance (which contains the frequency dependence associated with the metasurface resonance(s)). The latter two factors together comprise the optical coupling efficiency, i.e. the fraction of generated photons that successfully escape the cavity, assuming no round-trip transmission losses due to diffraction and a unity transverse confinement factor. We define the output coupler efficiency to be $\eta_{OC} = \frac{T_{OC}}{T_{OC} + A_{OC}}$; such a term is not present in the standard expressions for waveguide-based semiconductor lasers where the facet reflectance is considered lossless.

The impact of η_{OC} on the slope efficiency becomes quite pronounced when high-reflectance output couplers are required, which benefit situations where one desires to maximize the operating temperature, maximize the broadband tuning range or comb bandwidth, minimize metasurface dispersion by using a low quality factor metasurface, or simply where the QC material itself provides little gain (e.g. above 5 THz). Even small absorption losses can cause significant degradation in performance. A typical case is shown in the Supplementary Material for a 3.4 THz QC-VECSEL using a common mesh output coupler design with nominal reflectance of 98.7%; in this case, where the simulated absorbance ranges from 0.6–0.8%; η_{OC} is estimated to be $\sim 45\%$ at the peak reflectance.

In this work, we demonstrate a QC-VECSEL utilizing a suspended all-dielectric high-contrast grating (HCG) output coupler with near-unity efficiency. High-resistivity float-zone silicon ($\rho > 10 \text{ k}\Omega\text{cm}$) is used, which has a remarkably low loss coefficient ($0.05\text{--}0.15 \text{ cm}^{-1}$) and flat dispersion in 3–4 THz range.¹³ By eliminating metallic losses, this approach significantly enhances optical efficiency while preserving the

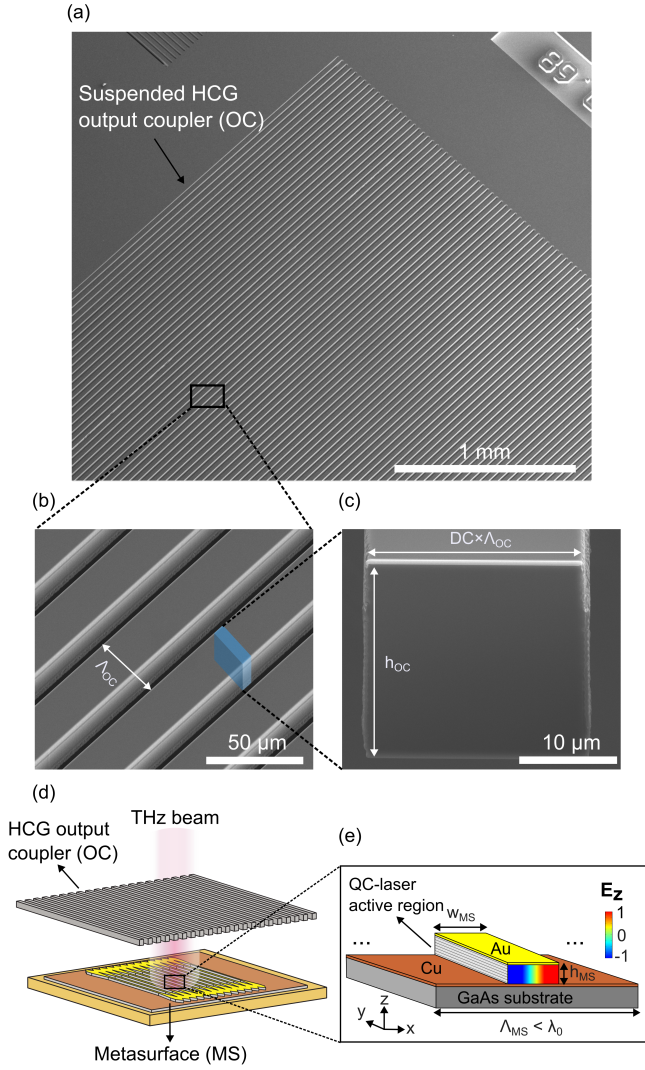


FIG. 1. (a) Scanning electron microscope (SEM) image of the suspended silicon high-contrast grating. (b) Close-up SEM image of the high-contrast grating. The grating period is labeled as Λ_{OC} . (c) Cross section SEM of a single grating bar. The grating width and thickness are labeled as $DC \times \Lambda_{OC}$ and h_{OC} , respectively. (d) QC-VECSEL architecture composed of an amplifying QC-metasurface (uniform ridge antennas loaded with GaAs/Al_{0.15}Ga_{0.85}As active material) and the suspended silicon high-contrast grating output coupler. (e) Schematic of a single period of the QC-metasurface with dimensions: $\Lambda_{MS} = 41.9 \mu\text{m}$, $w_{MS} = 11.9 \mu\text{m}$, $h_{MS} = 10 \mu\text{m}$. The E_z -component of the field profile under the ridge is shown.

tunability characteristic of QC-VECSEL systems. Additionally, removing the substrate and releasing the gratings removes the unwanted Fabry-Pérot oscillations in the OC reflectance and the residual substrate loss. Fig. 1 summarizes the device architecture. Fig. 1(a)–(c) show SEM images of the fabricated suspended silicon HCG output coupler, highlighting the grating period Λ_{OC} , duty cycle DC , and thickness h_{OC} . Fig. 1(d) illustrates the QC-VECSEL configuration, consisting of an amplifying QC metasurface and the external HCG output coupler. The external cavity length is $\sim 100 \mu\text{m}$ (not

to scale in Fig. 1(d), which is provided for schematic illustration only). A schematic of a single metasurface period is shown in Fig. 1(e), where the metasurface is formed by a periodic array of ridge antennas characterized by period Λ_{MS} , ridge width w_{MS} , and active-region thickness h_{MS} . The THz HCG, shown in Fig. 1, is fabricated from a suspended device layer of a SOI wafer with high-resistivity silicon, and consists of a 1-D subwavelength air/Si array structure that achieves high reflectivity through interference between laterally guided grating modes.^{14,15} When these modes are excited, destructive interference suppresses transmission, which results in strong reflection from a single thin layer. HCGs were originally developed to replace distributed Bragg reflectors (DBRs) in VCSELs, and provide comparable reflectivity ($>99\%$) without thick epitaxial multilayer stacks. They exhibit high reflectance over a broad bandwidth, and are relatively insensitive to fabrication errors. In contrast to conventional VCSELs, the HCG here is implemented as a discrete external-cavity output coupler. In addition, the spectral response of the HCG can be engineered through the grating thickness h_{OC} , period Λ_{OC} , and duty cycle DC , enabling scalability to other wavelength ranges without lattice-matching constraints.

The HCG reflection mechanism is polarization dependent due to different electromagnetic boundary conditions at the high-index/low-index interfaces. For TM polarization, the electric field component normal to the dielectric interfaces enhances confinement within the high-index bars, yielding strong modal contrast and wide high-reflectivity bandwidths.¹⁵ In contrast, TE polarization exhibits modified modal dispersion and phase evolution because the tangential electric field is continuous across the interfaces, leading to different resonance conditions and optimal structural parameters.^{14,15} In this work, a TM-polarized HCG design is employed to exploit its strong confinement and broadband reflectivity in the targeted 3–4 THz range, by scaling the dimensions (thickness $h_{OC, \text{ref}} = 235 \text{ nm}$ and period $\Lambda_{OC, \text{ref}} = 380 \text{ nm}$) of a TM-HCG utilized for a VCSEL operating at 850 nm wavelength from Ref. 16. Since the exact scaled device layer thickness ($24.4 \mu\text{m}$) was not available from the SOI vendor, the next closest available thickness ($25 \mu\text{m}$) was chosen, and the grating periods were adjusted accordingly to achieve reflectance values $R > 95\%$ near the 3.4 THz design frequency for a duty cycle of $DC = 0.65$.

To quantify the design flexibility of the HCG output couplers and to optimize their output coupling performance, finite-element simulations were performed using COMSOL Multiphysics to evaluate the reflectance as a function of grating period under normal incidence. Periodic boundary conditions were applied along the lateral dimensions to accurately model an effectively infinite grating structure. The results reveal a systematic decrease in reflectance and bandwidth with decreasing period (Fig. 2). This tunability enables controlled reduction in the OC reflectance, albeit at the expense of bandwidth. The selected design parameters ($h_{OC} = 25 \mu\text{m}$, $DC = 0.65$, $\Lambda_{OC} = 34\text{--}37 \mu\text{m}$) yield HCG reflectance spectra near 3.4 THz, which provide nominal peak reflectance values of 97–99.7%.

A reliable SOI fabrication process was developed to make

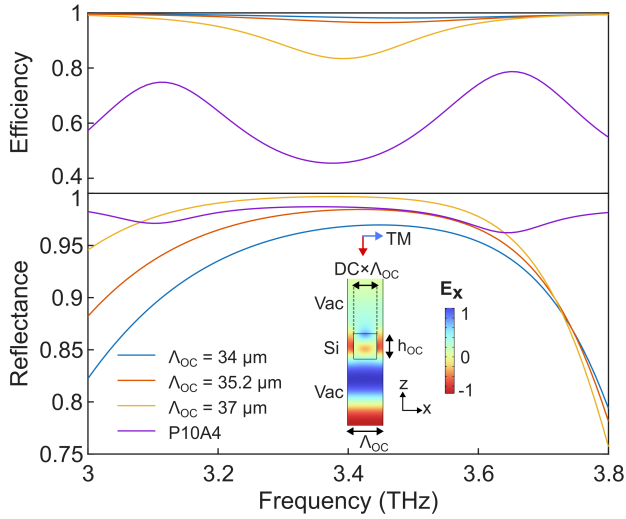


FIG. 2. Finite element electromagnetic simulation of the HCG (top) efficiency and (bottom) reflectance vs. frequency for TM-polarized THz radiation at normal incidence for several grating periods and $DC = 0.65$. The metal-mesh output coupler (P10A4) reflectance is overlaid for comparison. The inset in the bottom panel shows the E_x -component of the field profile. The red arrow shows the light propagation direction, and the blue arrow shows the E -field polarization direction.

large-area gratings (up to $9 \times 9 \text{ mm}^2$) with a yield exceeding 95%. The process flow starts with a 4-inch SOI wafer with a $25 \mu\text{m}$ device layer, a $0.5 \mu\text{m}$ buried oxide, and a $500 \mu\text{m}$ thick silicon handle. After patterning the gratings with DRIE producing vertical sidewalls, the silicon substrate was removed also with DRIE, and then the buried oxide was removed using ICP-RIE to suspend the structure. Several measures were implemented to ensure the gratings remain intact. First, wet etching was avoided for both the substrate and buried oxide layers to avoid collapse due to stiction and capillary forces. Second, fillet curves are introduced between adjacent grating ridges instead of rectangular terminations to reduce stress concentration and prevent crack formation. As a result, the suspended structures retained strong mechanical integrity during handling and mounting. Detailed fabrication procedures are provided in the Supplementary Material. Designs with the three values of the period Λ_{OC} shown in Fig. 2 were fabricated to experimentally evaluate the tradeoffs associated with varying the reflectance.

Experiments were performed by pairing various HCG couplers with a well-characterized and high-performance QC metasurface designed at 3.4 THz in an external cavity configuration. The cavity length is tuned using a piezoelectric linear nanopositioner (attocube systems) driven in open-loop operation. The piezo displacement is controlled by the applied voltage, enabling continuous scanning of the external cavity length for resonance tuning. The same QC metasurface device was used for all measurements reported in this work; only the output coupler was exchanged between experiments. The metasurface consists of a subwavelength array of ridge

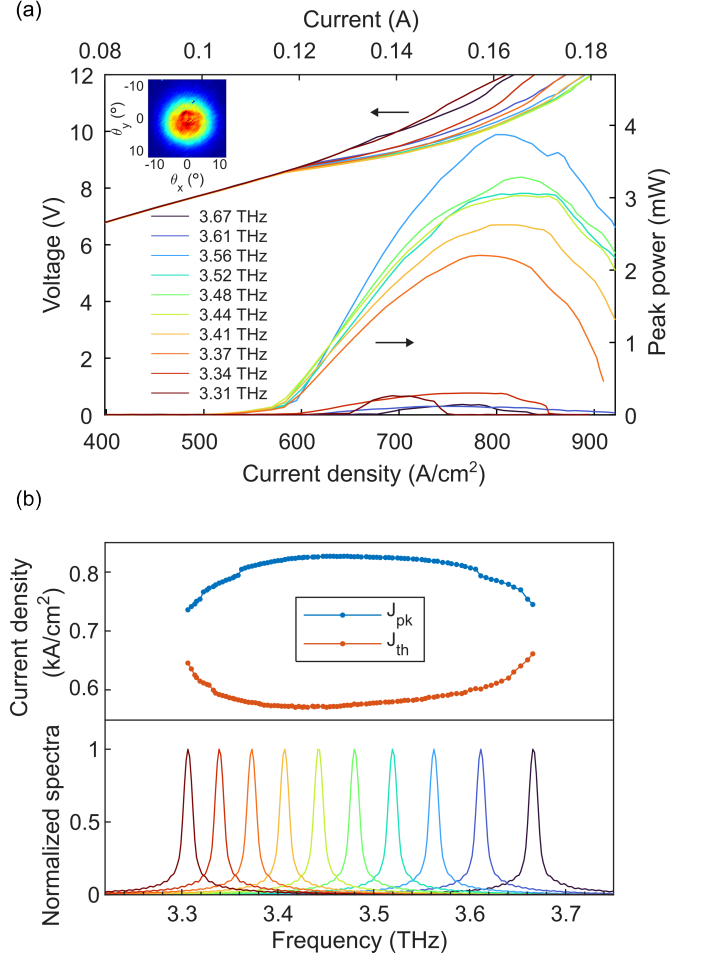


FIG. 3. (a) Pulsed light-current-voltage characterization of the QC-VECSEL with HCG ($\Lambda_{OC} = 35.2 \mu\text{m}$) at 77 K as the cavity length is tuned across the $m = 2$ longitudinal mode. The inset shows the far-field beam pattern at 3.45 THz . (b) top: threshold and peak (at 10.6 V) current densities versus laser frequency; bottom: laser tuning spectra ($m = 2$) which is color-coded with the corresponding L - I - V in (a).

antennas incorporating a $10 \mu\text{m}$ -thick $\text{GaAs}/\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ quantum-cascade active region grown by molecular beam epitaxy (wafer VB0739). Electrical injection is provided through a circular biased region with a diameter of $300 \mu\text{m}$. The active region is a hybrid bound-to-continuum/resonant-phonon design and provides a gain bandwidth exceeding 1 THz centered at 3.4 THz . This device originates from the same wafer as the device from Ref. 2. Fabrication of the metasurfaces was carried out using the standard Cu-Cu thermocompression wafer-bonding process.¹⁷ Throughout these experiments, we will make comparisons with a VECSEL using a conventional inductive metal-mesh output coupler with a quartz substrate. This OC, here labeled P10A4 ($10 \mu\text{m}$ mesh period, $4 \mu\text{m}$ line width), is described in more detail in the Supplementary Material, but is designed to have a simulated peak reflectance of 98.7% at 3.45 THz , as shown in Fig. 2.

First we present a baseline characterization of the VEC-

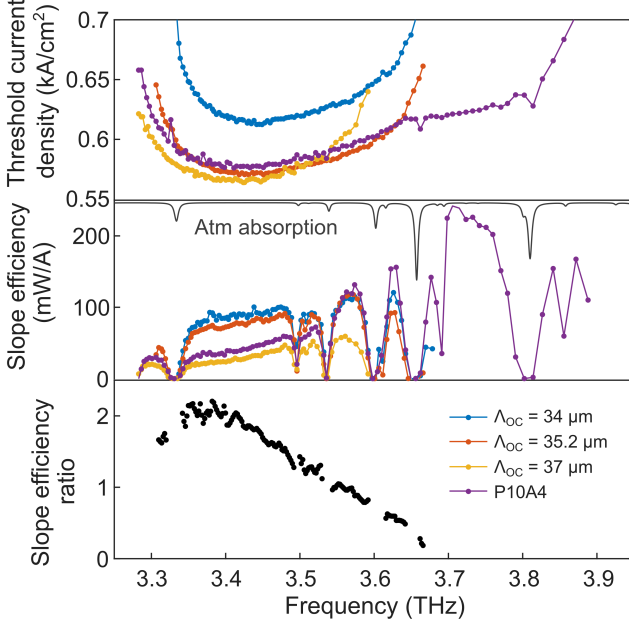


FIG. 4. Extracted (top) threshold current density and (middle) slope efficiency as a function of output-coupler period for high-contrast grating (HCG) and metal-mesh output couplers. The atmospheric absorption spectrum (Atm) is overlaid on the slope-efficiency plot. Because the optical path was not purged, atmospheric absorption manifests as prominent dips in the measured slope efficiency. (Bottom) Ratio of the slope efficiencies obtained with the HCG ($\Lambda_{OC} = 35.2\mu\text{m}$) and metal-mesh output couplers.

SEL using the $\Lambda_{OC} = 35.2\mu\text{m}$ HCG, which is designed to have a very similar reflectance as the P10A4 mesh OC, and as we will show below, exhibits perhaps the best overall performance. The device exhibits stable single-mode laser operation across the 360 GHz tuning range at 77 K as the cavity length is stepped with a piezoelectric motor. Light-current-voltage characteristics are shown in Fig. 3(a) at various cavity lengths, with the corresponding emission spectra shown in the bottom panel of Fig. 3(b). The power was corrected for the dewar HDPE window transmission ($\sim 65\%$). While the exact cavity length is not known, we estimate that the device is lasing on the second longitudinal mode order of the Fabry-Pérot cavity ($m = 2$), and the estimated cavity length is 85–120 μm from FEM simulations. The lasing bandwidth is consistent with the expected region of high reflectance for the HCG. The output coupler reflectance strongly influences the threshold J_{th} and peak current densities J_{pk} , as shown in the top panel of Fig. 3(b). J_{pk} is taken as the point before the power roll-off, at 10.6 V. When the operating frequency aligns with the maximum output coupler reflectance, the intracavity mode intensity is highest. This reduces the total round-trip cavity loss and enhances photon-assisted transport in the active region, resulting in the lowest threshold current density and the highest peak current density. The inset of Fig. 3(a) shows the circular beam, maintained throughout the entire tuning range and consistent with the expected behavior of VECSEL architecture. The device lased up to 133 K in

pulsed mode (1% duty cycle) and 101 K in CW mode (supplementary material), which is similar to the results when tested with the metal-mesh P10A4 output coupler (pulsed $T_{max} \sim 129$ K, CW $T_{max} \sim 103$ K). This, along with similar threshold current density values, suggests comparable reflectance values for the HCG ($\Lambda_{OC} = 35.2\mu\text{m}$) and metal-mesh output coupler, which is consistent with the simulations. The results demonstrate the suitability of HCGs as QC-VECSEL output couplers.

The performance of the HCG output couplers was systematically benchmarked by comparison with a conventional inductive metal-mesh design (P10A4) to quantify both the advantages and the trade-offs associated with the dielectric approach. To accomplish this, the same metasurface was tested in the tunable cavity setup with a metal-mesh output coupler (details of the output coupler in the Supplementary material) and then retested with different periods of the fabricated HCG output coupler. From these measurements, the threshold current density and slope efficiency were extracted as a function of the laser frequency for $m = 2$ and were then used as quantitative metrics to infer the reflectance and loss characteristics of the output couplers. The extracted threshold current density for various HCG periods, along with the metal-mesh output coupler, is shown in upper panel of Fig. 4. Several key observations can be made. First, the HCG output couplers exhibit a smaller tuning bandwidth compared to the metal-mesh output coupler, which is expected as the metal-mesh output coupler is intrinsically a broadband design. Second, the minimum threshold current density for the HCG output couplers aligns with the designed HCG center frequency, validating the accuracy of the simulations. Third, the threshold current density increases as the HCG period decreases. This is consistent with the expected rise in cavity losses as the HCG transmittance is increased, and experimentally confirms that the transmittance of the HCG output couplers can be controlled by design via the grating period.

The extracted slope efficiency for HCG OCs with various periods is shown alongside the metal-mesh output coupler in the middle panel of Fig. 4. As expected, the slope efficiency increases as the output coupler period decreases, corresponding to the reduction in reflectance. For any given output coupler, a further increase in slope efficiency is observed when the laser operates above the metasurface resonance at 3.4 THz; this phenomenon is expected from Eq. (1) as the cold cavity metasurface reflectance R_{MS} approaches unity off resonance. For the P10A4 output coupler, this increase in slope efficiency is even more noticeable since the output coupler efficiency almost doubles from 3.4 THz to 3.65 THz as the laser frequency is tuned from the peak OC reflectance to a local minimum caused by Fabry-Pérot effects in the OC (see Supplementary material). The dips in the slope efficiency plot correspond to the atmospheric water absorption.

To enable a direct comparison of slope efficiencies between the HCG and metal-mesh output couplers and to evaluate potential reduction in loss, we select the HCG with a threshold current density—and therefore a reflectance—comparable to that of the metal-mesh output coupler. Specifically, we use the HCG with a period of $\Lambda_{OC} = 35.2\mu\text{m}$. This choice

ensures that any observed increase in slope efficiency arises from reduced losses rather than from an increase in optical efficiency alone. It is worth noting that we have assumed similar diffraction losses for both, which is a valid assumption given both measurements are from the same longitudinal mode order ($m = 2$)—and thus roughly equal cavity lengths—and followed the same VECSEL alignment procedure. Therefore, it is reasonable to attribute the identical threshold current density to the same output coupler reflectance. The lower panel of Fig. 4 presents the experimentally measured slope efficiency ratio (HCG / P10A4). The HCG output coupler exhibits a notably enhanced slope efficiency, approximately a factor of two higher, near 3.4 THz. This agrees well with their corresponding simulated output coupler efficiency ratio, which is also about two.

In summary, we have demonstrated all-dielectric high-contrast gratings that operate in the THz range, and used them as output couplers in the QC-VECSEL architecture. The reflectance is controlled by adjusting the grating period, which was experimentally verified by the change in threshold current density. Single-mode broadband tuning is achieved with a twofold enhancement in slope efficiency, with no degradation in threshold current or maximum pulsed or continuous-wave operating temperature. Thus, dielectric HCGs are a viable low-loss alternative to conventional output couplers for terahertz VECSEL architectures. Since the efficiency of conventional mesh OCs is only significantly degraded for very high reflectance values (i.e. $\sim 99\%$), we anticipate that the value of HCG OCs will be most important for low-gain QC-VECSEL conditions which demand such high reflectance OC values. This includes situations where one wishes to maximize operating temperature or operate at "bleeding-edge" frequencies (e.g. > 5 THz) where the material gain drops.

SUPPLEMENTARY MATERIAL

The supplementary material includes additional device schematics, fabrication procedures, simulation results, optical alignment and characterization, temperature-dependent laser performance, longitudinal mode analysis, and cavity misalignment simulations that support the results presented in the main text.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available within the article and its supplementary material.

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