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Supporting Information
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Influence of higher order transverse modes on the operation of the transverse grating

In the main text, the ideal operation of the transverse grating for polarization controlled emission is discussed for excitation by the TM_{00} waveguide mode of the terahertz QCL. Whereas exclusive lasing on the TM_{00} mode comprises the optimal case for the emission of circularly polarized radiation by the grating, lasing of higher-order transverse modes does not compromise polarization control by the grating, as long as the different transverse modes are not phase-locked.

The key point of the antenna grating operation is the relative phase of excitation by the waveguide mode between the individual antenna elements. Now, transverse modes of the ridge waveguide are either symmetric (TM_{j0} with even j) or anti-symmetric (TM_{j0} with odd j) with respect to the ridge center. For operation of the transverse grating, the field amplitude at four distinct positions on the waveguide per longitudinal period is of relevance. Put differently, we “sample” the standing wave of the cavity at four different points per period. It is further essential that the antenna elements be placed at transverse positions y_1, y_2, $-y_1$, and $-y_2$ with respect to the waveguide center, for the following considerations. For antenna excitation by different uncorrelated transverse modes, two different scenarios can occur: Longitudinally subsequent antennas of equal orientation are either excited in phase with each other or with a phase shift of π. Owing to the symmetry of transverse modes and the antenna positioning these two possible phase relations apply to both antenna orientations equally and do not mix for a given excitation scenario. Put differently, for excitation by uncorrelated transverse modes either both orthogonal antenna sets in the grating are excited in phase or π-phase-shifted to their equally oriented longitudinal neighbors. Fig. S1A and C illustrate the two different scenarios, where the red and green coloring indicates the relative phase in excitation of the antenna elements, considering the phase variation of the waveguide mode in both longitudinal and transverse direction for the representative TM_{00} and TM_{10} modes.

Fig. S1A illustrates the situation in which longitudinally subsequent antennas of the same orientation are excited with a π-phase shift, which is the case, for example, for coupling to the TM_{00} mode. The π shift in excitation between the antenna elements results in destructive interference in the far field along the surface normal direction, and surface emission is only possible at a certain transverse angle Θ to the surface normal, allowing the compensation of the excitation phase shift during free-space propagation, as illustrated in Fig. S1B. At this emission angle Θ a phase of $\pi/2$ is accumulated during free-space propagation between the orthogonally polarized emission components of the two differently oriented antennas, resulting in circularly polarized surface emission for these cases. The grating therefore operates ideally and couples out circularly polarized radiation as targeted by the design.

For the phase configuration illustrated in Fig. S1C, which occurs for excitation by, for example, the TM_{10} mode, longitudinally subsequent antenna rows are excited in phase with each other, and the transverse grating operates analogously to a second-order grating. Constructive interference and surface emission occurs in surface normal direction, as sketched in Fig. S1D. As a consequence of surface normal emission, there is no accumulation of an additional phase difference during free-space propagation, and the two emission components of orthogonal linear polarization oscillate in phase (or, equivalently, phase shifted by π), resulting in linearly polarized output of the grating. However, even though the phase configurations represented by Fig. S1C result in linearly polarized emission, the respective farfield lobe is spatially separated from the circularly polarized farfield intensity peaks excited by the ideal cases shown in Fig. S1A: The former emit at $\Theta = 0$, the latter at $\Theta = \arcsin[\lambda_0/(2d_1)]$. For a suitably chosen d_1, the circularly and linearly polarized emission lobes from the different transverse modes are well separated in the far field and can be collected accordingly for use in the respective application.

Therefore, the operation of the transverse grating design presented here is robust in the face of simultaneous lasing on different transverse modes and is predicted to provide circularly polarized emission at certain emission angles even in such a case, as long as the different transverse modes are not phase-locked. In the case of phase locking between multiple transverse modes, the symmetry of the exciting standing wave in the cavity with respect to the waveguide center is broken, and cases different from those shown in Fig. S1 can occur. Phase configurations resulting in a mixing of the two scenarios in Fig. S1, each one applying to one of the two antenna orientations, are possible. The result is a separation or partial overlap between the emission from the two sets of orthogonally oriented antennas, where one of the antenna sets emits in the surface normal direction and one at a finite angle *Θ*. Furthermore, a variation of the coupling strength between the radiation inside the cavity and the individual antennas can lead to broad emission by one set of antennas and a collimated emission by the orthogonal set, possibly leading to a complex direction-dependent polarization pattern in the far field, such as observed for device 6 in this work. However, phase locking between different transverse modes in QCLs (1) is a complex and relatively unexplored topic, and although coherent-coupling phenomena between transverse modes are a possible explanation for the observed deviation of the transverse grating operation from the ideal behavior, as discussed in the main text, a conclusive study of the influence of transverse mode coupling exceeds the scope of this paper.

1. Yu N, et al. (2009) Coherent coupling of multiple transverse modes in quantum cascade lasers. Phys Rev Lett 102:013901.

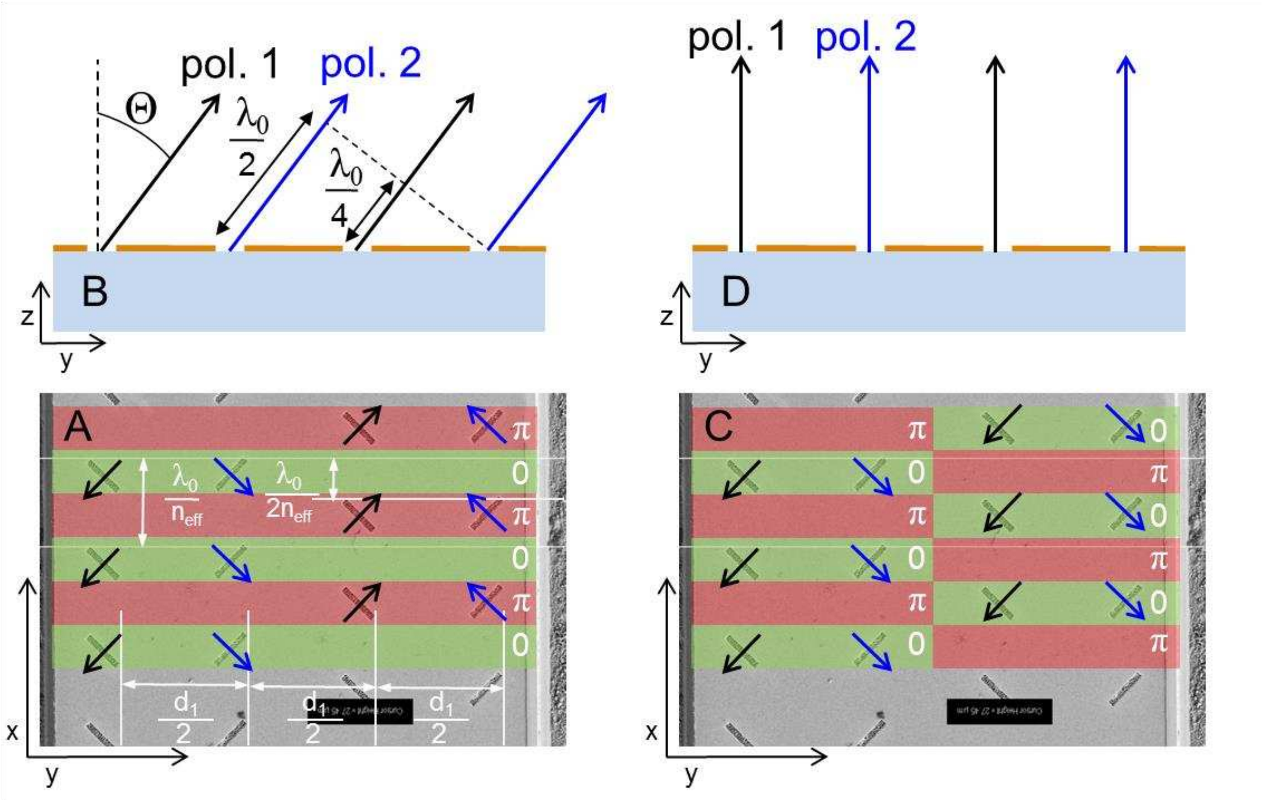

Fig S1. Operation of the transverse antenna grating for different transverse modes.

(A) Top-view electron micrograph of device 6 colored to indicate the relative phase of the standing field pattern of the TM_{00} cavity mode, together with an illustration of both the linear polarization state and the relative phase of the radiation emitted by the two antenna types.

(B) Side-view sketch illustrating constructive interference in the far-field at $\pm\Theta$ in the y-z-plane for antenna excitation by the TM_{00} mode, as well as a phase shift of $\pi/2$ between the two linear polarizations 1 and 2.

(C) Colored top-view electron micrograph indicating the relative phase of the standing field pattern of the TM_{10} mode, for which all of the antennas are excited in phase.

(D) Side-view sketch illustrating constructive interference in the far-field in the surface normal direction for antenna excitation by the TM_{10} mode, resulting in linear polarization of the emitted radiation.