We report the demonstration of a one-dimensional waveguide for terahertz quantum-cascade (QC) lasers, which acts as a leaky-wave antenna and tailors laser radiation in one dimension to a directional beam. This scheme adapts microwave transmission-line metamaterial concepts to a planar structure realized in terahertz metal-metal waveguide technology. The active leaky-wave antenna is fed by a master oscillator QC-laser with a mode that propagates with an effective phase index smaller than unity, such that it radiates in the surface direction. The direction of emission of the main beam is governed by the antenna dispersion characteristic. 25° of beam steering is observed as the lasing frequency of the QC-laser is varied from 2.65–2.81 THz.

The terahertz quantum-cascade (QC) laser is an emerging technology for continuous-wave (cw) generation of terahertz radiation with milliwatt-level power or greater. The best temperature performance so far (186 K pulsed, 3 117 K cw (Ref. 4)) has been achieved using the so-called metal-metal waveguide, where the active gain material is sandwiched between metal cladding layers. Due to the sub-wavelength transverse dimensions of the metal-metal waveguide, however, obtaining a directive beam pattern and efficient out-coupling of THz power is non-trivial.

One attractive approach to this problem is to use monolithically integrated waveguides and cavities designed to couple radiation in surface or endfire directions. This includes second-order6–8 and third-order9 distributed feedback structures and two-dimensional photonic crystals,10,11 all of which are fundamentally based on Bragg scattering of propagating waves. Recently, we introduced an alternative design approach: a terahertz waveguide based on composite right/left-handed (CRLH) transmission-line metamaterial concepts.12 In our proposed implementation, CRLH behavior is obtained by loading a metal-metal waveguide/transmission line (typically described by distributed series inductance L_R and shunt capacitance C_R) with shunt inductance L_L and series capacitance C_L elements on a scale much smaller than guided wavelength. Such a transmission line exhibits dispersive characteristics not normally achievable by conventional (purely right-handed) transmission lines, such as left-handed (negative index or “backward wave”) propagation or zero phase shift (infinite wavelength) propagation.13 Moreover, modes that propagate within its leaky-wave bandwidth with an effective phase index smaller than one (−1 < n_{eff} < +1) will radiate into a directive beam.

In this letter, we demonstrate the leaky-wave characteristics of such a one-dimensional (1-D) terahertz metamaterial waveguide by using it as an active coupler antenna for a THz QC-laser. The concept is illustrated in Fig. 1(a). It is comprised of two closely spaced transmission lines with subwavelength transverse dimensions (5 μm tall, 6 μm wide) coupled to each other via narrow inductive current paths. These paths play the role of the shunt inductance L_L which was originally realized in the Ref. 12 design by introducing vertical stubs on the waveguide sidewall to provide current paths to the ground plane. This requirement has been removed in this planar design by moving the virtual ground to the center of the shunt inductance L_L, i.e., symmetry plane of the structure. There are two major advantages to this approach: (a) a flat, low-loss waveguide that radiates in a directed pattern; and (b) a means of controlling the direction of radiation via a tunable electrical circuit model.
scheme. First, this approach does not require metallization on ridge sidewalls or virtual ground capacitors, which eases fabrication and reduces ohmic losses. Second, this structure is designed to operate in a lateral mode with odd symmetry, i.e., opposite sign of electric field in each branch, which exhibits the right hand portion of CRLH leaky-wave behavior. While the design reported in this work lacks the series capacitance $C_s$, it can readily be added to achieve backwawps (left-handed) propagation. Compared to the design of Ref. 12, which operates in the fundamental waveguide mode, this structure radiates more efficiently in the broadside direction due to constructive interference of radiating dipole sources on the waveguide sidewalls.

One can envision such a waveguide as a periodic cascade of unit cells, where each unit cell is composed of an LC resonator (two capacitors in series with an inductor). Dispersion behavior of such an infinite periodic metamaterial reveals that the zero-index resonance occurs at $f_0 = \frac{1}{2\pi \sqrt{LC_s}} = 2.7(\pm 0.1)$ THz with the light cone ($0 < \theta_{\text{eff}} < 1$) extending to 3.0 THz (Fig. 1(b)). The dispersion relation was calculated from full-wave finite element simulations of the complex eigenfrequencies of the waveguide odd mode using periodic boundary conditions. The uncertainty bars for the calculated eigenfrequencies represent the strength of radiative losses ($\Delta \nu = 23(\nu)$). Operation within the light cone is accompanied by a penalty in loss, primarily due to highly efficient radiative coupling, but also due to a modest increase in metallic losses compared to conventional Fabry-Pérot (FP) modes. For example, we calculate that an infinitely long self-resonating cavity of this design lasing in the zero-index mode requires 100 cm$^{-1}$ and 19 cm$^{-1}$ of intersubband gain to overcome radiative and metallic losses, respectively.

While the losses of this design are too large to allow use as a laser resonator, the strong radiation coupling suggests that such a structure would be an efficient antenna. The fabricated prototype consists of a compound cavity with the metamaterial antenna (408 $\mu$m long) fed by a metal-metal QC-laser cavity of 390 $\mu$m length and 25 $\mu$m width (see Fig. 1(c)). The metal-metal waveguide section is designed to serve as a master oscillator laser that feeds the antenna with the desired mode of odd lateral symmetry. The antenna, however, is active and can be separately biased to provide amplification. The active region was based on a resonant-phonon depopulation scheme, in a four-well design similar to that described in Ref. 4, but modified to operate in the range of 2.4–2.9 THz. The GaAs/Al$_{0.15}$Ga$_{0.85}$As quantum well heterostructure was grown by molecular beam epitaxy with 86 cascaded modules to form a 5 $\mu$m thick active region. The structure was fabricated in metal-metal waveguide technology using copper-to-copper thermocompression wafer bonding. The metallization for the top contact (Ti/Au/Ni) was defined by contact lithography, and then used as a dry etch mask to define the ridges. In our design, tapered terminations at the rear facets of the metamaterial antenna and the QC-laser were employed that serve both as a preferential selection mechanism for the odd lateral mode and electrically isolated bonding pads for DC bias. A thin (200 nm) PECVD oxide underneath these bonding pads serves as an electrical isolation layer.

We examined polarization dependent 1-D far-field beam patterns of the device along with angle-resolved Fourier transform spectroscopy of the THz radiation to identify the metamaterial antenna operation within its leaky-wave bandwidth. The angular resolution of beam pattern and spectroscopy measurements was 1.5° and 3.4°, respectively. For the measured data presented in Fig. 2, the metal-metal waveguide QC-laser was operated at a fixed DC bias (in cw mode) beyond its lasing threshold while the metamaterial antenna was separately biased in pulsed mode (1 µs pulses repeated at 10 KHz) at 5 K. Terahertz power was detected using a Ge:Ga photodetector in a differential scheme with the lock-in amplifier synchronized to the bias pulse train on the antenna. A relatively narrow beam (full width at half maximum (FWHM) ~15°) is observed at about 40° from broadside direction, which grows in intensity as the bias on the antenna is increased. This is an indication of power amplification due to addition of gain in the antenna section. The frequency of radiation at 40° (±5°) was measured to be 2.74 THz which is well within the leaky-wave bandwidth of the calculated dispersion diagram. Further increasing the bias on the antenna section is accompanied by the onset of a broadside beam which is measured to have a frequency of 2.56 THz, i.e., below the cut-off frequency $f_0$. This is attributed to a new mode that begins to lase within the master oscillator cavity, which couples to the antenna evanescently. The detected THz radiation is polarized in the direction perpendicular to the antenna axis. This is characteristic of the radiation from this transmission-line metamaterial and opposite of what one would expect from a metal surface Bragg grating. Occasionally, for some devices, the metal-metal QC-laser oscillates in its fundamental lateral mode, for which the antenna does not exhibit leaky-wave behavior. The beam patterns are dramatically different in that case; they are non-directional with strong fringes in the far-field, typically with detectable powers of order(s) of magnitude smaller, and are polarized along antenna axis.

The measured frequency and angle of the directive beam are approximately consistent with the calculated dispersion relation of Fig. 1(b). Within the light cone, the direction of radiation main beam is dictated by the metamaterial waveguide dispersion relation according to $\theta = \sin^{-1}(\beta(\nu)/k_0)$, where $\theta$ is the angle measured from broadside, $k_0$ is the free-space wave vector, and $\beta(\nu)$ is the propagation constant.

![FIG. 2. (Color online) Measured longitudinal far-field beam patterns with $V_{\text{MM}} = 7.10$ V (cw) and $V_{\text{MTM}} = 5.65$ (i), 6.15 (ii), and 6.35 V (iii) (pulsed). Inset shows the angle-resolved spectra collected at $V_{\text{MM}} = 7.10$ V and $V_{\text{MTM}} = 6.35$ V.](image-url)
By changing the bias on the metal-metal QC-laser, we force the laser to hop between different axial modes, which allows us to excite the antenna at several discrete frequencies; the corresponding beam patterns are shown in Fig. 3. A single beam (FWHM~10°–15°) with significant sidelobes is observed, likely due to the short extinction length of the THz mode in the lossy leaky-wave antenna (estimated to be ~50–300 μm at these frequencies). Beam scanning from 35°–60° is observed as the lasing frequency of the QC-laser varies from 2.65–2.81 THz. This method provides an experimental approach to measure the dispersion of a metamaterial waveguide within its leaky-wave bandwidth.

The antenna-coupled device exhibits current-voltage (I-V) characteristics and threshold current densities comparable to those of a conventional metal-metal FP cavity fabricated from the same wafer. This is illustrated in Fig. 4, where, for low bias current densities (480–560 A/cm²), the master oscillator QC-laser lases at 2.60 THz, outside the antenna leaky-wave bandwidth, resulting in a slope efficiency of ~5 mW/A similar to that of the FP laser. At high enough bias current densities (560–610 A/cm²), however, the antenna is fed with a 2.73 THz mode within its leaky-wave bandwidth which yields a much higher slope efficiency (~20 mW/A). This is attributed to higher radiation coupling and improved collection efficiency of the directive beam launched by the antenna. Nevertheless, the beam in the transverse direction is extremely broad due to the subwavelength width—an issue which can be addressed using array techniques.16

In conclusion, we present an active leaky-wave metamaterial antenna realized in quantum-cascade structures that exhibits frequency-dependent direction of radiation. We emphasize that the periodicity of the metamaterial is sufficiently small (p = 8 μm ≈ λg/4), so that the antenna is not acting as a Bragg surface coupler. This is experimentally verified by measuring polarization-dependent far-field beam patterns. While the radiative losses of this initial demonstration structure are excessive, they can be reduced by engineering the waveguide dimensions and structure—for example, by reducing the height. With the addition of series capacitance, this structure is suitable for development of an active THz CRLH transmission-line metamaterial.12

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