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Active terahertz quantum-cascade composite right/left-handed metamaterial

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We report the demonstration of a composite right/left-handed (CRLH) metamaterial waveguide for terahertz quantum-cascade (QC) lasers. By incorporating gap capacitors (~ 250 nm) in the top metallization of a metal-metal waveguide operating in a higher order lateral mode, we have realized a CRLH transmission line that supports traveling modes with negative effective phase indices (i.e., left-handed or backward-wave propagation). The CRLH metamaterial waveguide is employed as an active leaky-wave antenna for a terahertz QC-laser. Directional single-lobed beams launched in the backwards direction at angles of -4° and -63° were experimentally observed at excitation frequencies 2.59 and 2.48 THz, respectively. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4775666>]

The transmission-line metamaterial paradigm provides a formalism for the description of unusual electromagnetic metamaterial phenomena including left-handed (i.e., negative index or backward wave) propagation, where the group and phase velocities are antiparallel.¹ A variety of transmission-line metamaterials have been demonstrated in the microwave, including guided wave devices (e.g., multi-band and enhanced bandwidth components, power combiners/splitters, compact resonators, phase shifters, and phased array feed lines), as well as radiated-wave devices (e.g., 1D and 2D resonant and leaky-wave antennas).² In its simplest form, a composite right/left-handed (CRLH) transmission-line metamaterial is formed as follows. The unit cell in a conventional right-handed transmission line has a series inductance L_R and a shunt capacitance C_R . By periodically loading the line with a series capacitance C_L and a shunt inductance L_L , the line becomes highly dispersive and exhibits left-handed propagation over a finite bandwidth. Provided that the unit cell size is sufficiently small compared to the wavelength, the mode sees an effective medium, and can be described by an effective phase index $n_{\text{eff}} = \beta c / \omega$, where β is the propagation constant.

CRLH metamaterial concepts are scalable to frequencies in the 1–5 THz range, where they can be implemented in THz quantum-cascade (QC) laser waveguides such that intersubband stimulated emission provides a source of distributed photonic gain.^{3–5} The most suitable platform for active THz CRLH metamaterial implementation is THz QC-laser metal-metal waveguide,⁶ which is similar in form to microstrip transmission line. Because it provides good modal confinement and low loss in a structure with sub-wavelength transverse dimensions, metal-metal waveguide offers the best high-temperature laser operation (~ 200 K pulsed,⁷ 117 K cw⁸). The application of CRLH metamaterial concepts can offer terahertz QC-lasers new functionality by leveraging microwave antenna concepts, such as the use of leaky-wave antennas for beam steering.

A CRLH metamaterial waveguide is characterized by modes which propagate with effective phase indices within the light cone ($-1 < n_{\text{eff}} < +1$). Unless shielded, such a mode will radiate according to the leaky-wave mechanism into a directive fan beam in the surface (broadside) direction. The emission angle ζ with respect to broadside is dictated by the dispersion characteristic according to $\theta = \arccos(n_{\text{eff}})$, and $\zeta = \arctan(\cot\theta/\cos\phi)$ with θ, ϕ defined as the standard spherical coordinates angles. The beam can, in principle, be steered either by varying the frequency or transmission line characteristics. Unlike distributed feedback structures^{9–13} and two-dimensional photonic crystals¹⁴ which are commonly used to address the problem of poor outcoupling efficiency and beam patterns of metal-metal waveguides, the behavior of CRLH metamaterials does not depend on Bragg scattering. The dispersion is determined by the nature of the subwavelength unit cell and not the periodicity. Recently, we demonstrated a metal-metal waveguide leaky-wave antenna based upon the transmission-line metamaterial concept used as an output coupler from a THz QC-laser.¹⁵ That design achieved an effective shunt inductance L_L by operating in a higher-order odd lateral mode, which obviated the need to fabricate a lossy sidewall metallization to the ground plane.^{5,16} However, it lacked the series capacitance C_L , hence it exhibited a right-handed dispersion only (i.e., $n_{\text{eff}} \geq 0$), and all of the measured beams were directed in the forward direction ($\zeta > 0$).

In this work, we experimentally demonstrate a CRLH metamaterial waveguide in which series capacitance C_L is realized by incorporating gaps in the top waveguide metallization. The concept is illustrated in Fig. 1(a). It is comprised of two parallel transmission lines with subwavelength transverse dimensions ($5 \mu\text{m}$ tall, $6 \mu\text{m}$ wide) coupled to each other via narrow inductive current paths ($5 \mu\text{m}$ wide, $3 \mu\text{m}$ long) of an effective inductance $2L_L$. By employing alternating gap capacitors, a meander-type structure is obtained which is DC connected so that an electrical bias can be applied to the QC active material. Unlike the gapless design of Ref. 15, the meander structure exhibits CRLH properties

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FIG. 1. (a) Schematic representation of the 1D CRLH metamaterial waveguide with staggered gap capacitors incorporated in the top metallization and its equivalent transmission-line model. The lumped element values in the circuit diagram are chosen such that each unit cell has total values of C_R , C_L , L_R , and L_L . (b) The dispersion characteristic obtained by full-wave finite element simulations of one unit cell. Inset shows eigenmode quality factors due to radiation loss only (Q_{rad}), and radiation and ohmic metallic losses ($Q_{\text{tot}}^{-1} = Q_{\text{rad}}^{-1} + Q_{\text{met}}^{-1}$). A finite-conductivity Au metallization was employed in simulations using a Drude model with $n = 5.9 \times 10^{22} \text{ cm}^{-3}$, $\tau = 60 \text{ fs}$, $m^* = m_0$, $\epsilon_{\text{core}} = 1$.

such as left-handed propagation in addition to the conventional right-handed propagation as shown in the calculated dispersion diagram of Fig. 1(b). The overall unit cell length, however, has increased to $p = 16 \mu\text{m}$, which translates to a larger series inductance L_R and helps achieving a nearly balanced design. Due to the proper choice of C_L and L_L in our design, the CRLH waveguide exhibits a so-called “balanced” behavior where there is a gapless transition from left-handed (2.3–2.6 THz) to right-handed propagation (from 2.6 to 3.0 THz). In the circuit model, we can consider that this condition occurs when $L_R C_L = L_L C_R$.² In a balanced CRLH metamaterial line, the modes at $\beta = 0$ maintain a nonzero group velocity $v_g = d\omega/d\beta$; no band-edge standing wave is formed. This characteristic is particularly important for leaky-wave antennas, since the power loss coefficient per unit length α is inversely proportional to the group velocity according to $\alpha \approx \frac{\omega}{Q v_g}$, where Q is the quality factor of the mode. Therefore, for non-balanced leaky-wave antennas with sharp cutoff frequencies, near $\beta = 0$, v_g becomes small and α diverges. This leads to very small emitting apertures of size $\sim \alpha^{-1}$ and broad beam patterns for radiation in the broadside direction. This shortcoming no longer exists when a balanced design is employed. Moreover, in theory, impedance matching to a balanced CRLH transmission line is much easier than the right-handed-only gapless design as the Bloch impedance is constant across the entire CRLH bandwidth.¹ Quality factors due to both radiation (Q_{rad}), and metallic losses (Q_{met}) have been calculated using full-wave finite element simulations, and are shown in Fig. 1(b) inset. Compared to the gapless design—where losses are dominated by radiation—the meander CRLH metamaterial exhibits significantly higher metallic losses particularly in the

left-handed range. Moreover, Q_{rad} is calculated to be approximately $2\times$ larger in the CRLH design compared to the gapless RH design. For the gapless design, all the electric field energy is stored in the shunt capacitors C_R , which is associated with strong radiation from the sidewalls. This E-field also couples to the QC gain medium that contributes to the stimulated emission via intersubband radiative transition. In a balanced CRLH line, at $\beta = 0$, the electric field energy is stored equally in the series capacitor C_L and the shunt capacitor C_R . However, due to the odd-symmetry of the E-fields in the opposing gaps, the equivalent radiating magnetic currents are antisymmetric and cancel; thus, energy stored in C_L contributes negligibly to radiation.¹⁷ Full backward to forward scanning of the main beam for a CRLH metamaterial antenna of this design was previously verified via full-wave finite element HFSS simulations in Ref. 17.

The active CRLH device was fabricated in metal-metal waveguide technology using copper-to-copper thermocompression wafer bonding. The active material was a four-well resonant-phonon depopulation design similar to that described in Ref. 8, except 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 $5 \mu\text{m}$ thick active region. The fabricated prototype consists of a compound cavity with the CRLH metamaterial antenna ($500 \mu\text{m}$ long) fed by a metal-metal QC-laser cavity of $500 \mu\text{m}$ length and $40 \mu\text{m}$ width (see Fig. 2). The width of the master-oscillator metal-metal QC-laser is adiabatically tapered to $15 \mu\text{m}$ over the last $100 \mu\text{m}$ to provide a smooth laser-to-antenna transition. The metallization for the antenna top contact (Cr/Au::20/100 nm) was defined by electron-beam (e-beam) lithography using a

FIG. 2. Scanning electron microscope (SEM) image of the fabricated CRLH antenna-coupled device fed by a THz QC-laser source, and close-up of the meander-type CRLH metamaterial waveguide with staggered gap capacitors in its top metallization.

bilayer of polymethyl methacrylate (PMMA) e-beam grade positive resists (495-A4 and 950-A2) and lift-off process to accommodate the fabrication of submicron (~ 250 nm) gaps in the antenna section. Dry etch mask for the antenna section was deposited next by performing a second round of e-beam lithography/metal evaporation (Ni::200 nm) using the same bilayer of PMMA resists. Finally, top metallization for the feed section and the bonding pads (Ti/Au/Ni::20/150/250 nm) was defined by contact lithography, which was also used as a dry etch mask. Prior to this step, 200 nm of PECVD oxide was deposited and patterned to electrically isolate the bonding pads from active gain material.

Several CRLH antenna-coupled THz QC-laser devices were tested with the primary goal of identifying directive radiation in the backward direction as a signature of left-handed propagation. The 1D far-field beam patterns were measured along the axis of the antenna, and angle-resolved Fourier transform infrared spectroscopy of the THz radiation was performed to experimentally map the dispersion of the CRLH metamaterial antenna. The angular resolution of beam pattern and spectroscopy measurements was 1.5° and 3.4° , respectively. All measurements were performed in pulsed mode with 400 ns pulses repeated at 10 KHz. The results are shown in Fig. 3 for a representative device where the coupling gap between the metamaterial antenna and THz QCL is zero. At

FIG. 3. Backwards beam scanning with frequency (polar representation). Data were collected in pulsed mode (400 ns pulses repeated at 10 KHz) with the QC-laser and the CRLH antenna biased synchronously. Inset shows the spectra of the two backward beams corresponding to excitation frequencies 2.484 THz (blue) and 2.594 THz (red).

77 K, a relatively narrow beam (FWHM $\sim 15^\circ$) is observed at about -4° from broadside direction. The detected THz radiation is dominantly polarized in the direction perpendicular to the antenna axis with the frequency of radiation measured to be 2.59 THz. The measured frequency and angle of the directive beam are approximately consistent with the calculated dispersion relation of Fig. 1(b). Compared to the gapless RH-only design, the balanced CRLH antenna exhibits a significantly narrower beamwidth for emission close to broadside.¹⁸ This is attributed to a non-zero group velocity at the transition frequency ω_0 , which is accompanied by a non-diverging power loss coefficient $\alpha \propto 1/v_g$. A narrower far-field beamwidth (inversely proportional to the emitting aperture size) is achieved as a result of the increase in antenna effective length.

At 4 K, the frequency of radiation shifts to 2.48 THz as a result of the lower threshold voltage and reduced Stark shift of the intersubband transition.^{7,8} Under this condition, a single narrow beam with FWHM $\sim 10^\circ$ is observed at about -63° from broadside direction. The measured frequency and angle of the directive beam are well within the left-handed (backward wave) bandwidth of the CRLH antenna and consistent with the calculated dispersion relation. The detected THz radiation, however, is dominantly polarized in the direction parallel to the antenna axis. Under ideal circumstances, one would expect the leaky-wave modes of our metamaterial waveguide to primarily radiate through the lateral fringing fields associated with the shunt capacitance C_R for which the far-field radiation is polarized transverse to the transmission-line axis.¹⁹ However, if symmetry is broken in the meander structure, it may radiate strongly through the longitudinal electric fields associated with the series capacitance C_L for which the far-field radiation is polarized parallel to the transmission line axis.²⁰ We attribute the observed polarization as due to fabrication imperfections, such that there is sufficient phase or amplitude difference in between opposing radiating dipoles across the two gap capacitors of a unit cell that they no longer destructively interfere in the far field, and the radiation from C_L becomes comparable or dominant over that of C_R . This is particularly important for β points away from the transition frequency ω_0 on the dispersion relation where there is inherently a phase accumulation across the unit cell itself between the opposing capacitive gaps. Bragg scattering can be ruled out as the source of the beams, since the periodicity of the holes at the center of our CRLH metamaterial waveguide is sufficiently small ($8 \mu\text{m} \sim \lambda_0/4n_{GaAs}$) to avoid such scattering effects.

Since the CRLH metamaterial antenna is DC connected to the master-oscillator metal-metal QC-laser, it is synchronously biased with the same pulse trains and may provide amplification. The device exhibits a superlinear $L-I$ characteristic (see Fig. 4(a)) once mounted at an angle ($+60^\circ$) with respect to the cryostat window which indirectly implies amplification in the active antenna. We can justify this conclusion using a simple model. Let power propagating inside the antenna be $P(z) = P_0 \exp[-(\alpha - g)z]$, where $P_0 = (I - I_{th}) \frac{dI}{dI}$ is the power emitted by laser into antenna, α is the total loss (dominated by radiation), and $g = \gamma(I - I_{tr})$ is the modal gain coefficient beyond transparency current I_{tr} . The power radiated per unit length is $\alpha_{rad}P(z)$, so that the total radiated power is given by $P_{rad} = \frac{\alpha_{rad}}{\alpha - g} P_0$. Thus, one

FIG. 4. (a) Pulsed L - I - V for the -60° beam at 4 K. Peak THz power was measured using a thermopile detector in the surface direction for the antenna structure with no collection optics in the cryostat but mounted at an angle ($+60^\circ$) with respect to the cryostat window. A superlinear fit to the LI curve is also plotted with $I_{th} = 116$ mA, $I_{tr} = 69$ mA, and $\alpha/\gamma = 92$ mA. (b) 1D cuts of beam pattern in the surface direction along the longitudinal direction at various bias currents. Inset shows the spectrum of radiation.

expects a superlinear dependence on I in the presence of amplification

$$P_{\text{rad}} = \frac{dL}{dI} \alpha_{\text{rad}} \frac{I - I_{th}}{\alpha - \gamma(I - I_{tr})}. \quad (1)$$

This is further evidenced in measured far-field beam patterns and angle-resolved spectra of Fig. 4(b) where the -60° -beam grows in intensity as the bias on the device is increased within the superlinear dynamic range while remaining single mode at 2.48 THz.

In conclusion, we present an active terahertz quantum-cascade leaky-wave antenna based on a CRLH metamaterial waveguide that supports left-handed wave propagation. Experimental evidence for left-handed propagation is found in directive beams observed both in the backwards and broadside directions—phenomena that would not be possible in leaky-wave antennas based upon a Bragg grating, or in a leaky-wave antenna with RH propagation only. The enabling feature for left-handed propagation is the inclusion of submicron gap capacitors in the top metallization of the antenna. While the beam is relatively directive along the axis of the

antenna it is wide in the transverse direction, due to the sub-wavelength width of the waveguide, and forms a fan beam in the far field.¹⁷ A directive beam in two dimensions could be obtained by implementing a leaky-wave antenna array.²¹ These CRLH metamaterial antennas can be used to obtain a continuously scannable THz beam from backfire to broadside to endfire direction, either by varying the laser frequency, or varying the antenna dispersion characteristic. The strong dependence of the dispersion on the capacitive gap size opens the possibility of dynamic tuning of the metamaterial dispersion characteristics by dynamically changing the gap capacitance C_L .^{19,22}

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²⁰See supplementary material at <http://dx.doi.org/10.1063/1.4775666> for numerical simulations verifying this change in far-field beam polarization due to broken symmetry.

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