Terahertz quantum-cascade lasers based on transmission-line metamaterial waveguides

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BIOGRAPHY

Benjamin S. Williams: Prof. Williams received the Ph.D. degree from the Massachusetts Institute of Technology, Cambridge, Massachusetts in 2003 in Electrical Engineering and Computer Science. He was a Postdoctoral Associate at the Research Laboratory of Electronics at MIT from 2003-2006. In 2007, he joined Electrical Engineering Department at the University of California, Los Angeles, where he is currently an Assistant Professor, and is a Henry Samueli School of Engineering and Applied Sciences Fellow. His research interests include quantum cascade lasers, intersubband and intersublevel devices in semiconductor nanostructures, and terahertz metamaterials and sub-wavelength plasmonics. He is the recipient of the DARPA Young Faculty Award and the NSF CAREER award.

TECHNICAL ABSTRACT

The composite right/left-handed (CRLH) transmission line metamaterial concept was first developed in the microwave frequency range, and in the past decade has been used to explore both fundamental metamaterial phenomena and to demonstrate novel circuits and antennas [1]. CRLH structures are able to support backward-wave (left-handed) propagation, zero-index propagation, THz quantum-cascade (QC) lasers fabricated with double-metal (i.e. microstrip) waveguide can be adapted into a planar CRLH by the addition of lumped element capacitance $C_L$ and effective inductance $L_L$ into the series and shunt branches of the transmission line [2, 3]. In this scheme, the GaAs/AlGaAs multiple quantum well material is the dielectric of the transmission line – when properly injected with current it provides THz amplification via stimulated emission of photons due to intersubband radiative transitions.

Figure 1. Calculated dispersion relation of right handed leaky-wave antenna waveguide. (b) SEM image of THz QC-laser fabricated in metal-metal waveguide that feeds an active leaky-wave antenna. (c) Transmission line model of waveguide excited in higher order lateral mode. The shunt capacitor $C_R$ couples to THz QC-laser gain.

Figure captions:
(a) Calculated dispersion relation of right handed leaky-wave antenna waveguide. (b) SEM image of THz QC-laser fabricated in metal-metal waveguide that feeds an active leaky-wave antenna. (c) Transmission line model of waveguide excited in higher order lateral mode. The shunt capacitor $C_R$ couples to THz QC-laser gain.
d) Measured beam steering when LWA is excited with different frequencies as the laser mode-hops. Data from [4].

A THz QC-laser metal-metal waveguide can be made to operate as a CRLH transmission line when operating in the first excited lateral mode (TM$_{01}$). This is equivalent to propagation on two inductively coupled parallel transmission lines. The calculated dispersion relation for such a structure is shown in Fig. 1 (a), and the equivalent transmission line circuit is shown in Fig. 1(c). The mode cutoff at frequency $f_0$ can be considered to be an equivalent shunt circuit resonance $2\pi f_{0s} = (L_\parallel C_\parallel)^{-1/2}$, which defines the value of the shunt inductor $L_\parallel$. For effective indices $n_{\text{eff}} < 1$, the mode becomes leaky and will radiate at an angle $\theta = \sin^{-1}(\beta/k_0)$, where $\beta$ is the propagation constant. This scheme was used to demonstrate a leaky-wave antenna fed by a THz QC-laser. The structure is shown in Fig. 1(b). A beam is observed at a far-field angle approximately corresponding to the calculated dispersion relation. This initial implementation does not possess series capacitance $C_L$, and thus exhibits right-handed propagation only. Addition of a series capacitance will lead to a true CRLH waveguide capable of exhibiting forward to backward beam steering.

![Figure 2. Calculated radiative quality factor using the cavity model from Ref. [5] for a TM$_{01}$ mode in a 250 µm long metal-metal waveguide. The contributions due to the facet and sidewalls are explicitly separated.](image)

The radiative loss for such a TM$_{01}$ mode can be calculated using a cavity antenna model similar to that used for microstrip patch antennas, as detailed in Ref. [5]. This model is used to plot the radiative quality factor $Q$ as shown in Fig. 2. This method allows one to separate the contributions from the facets and the waveguide sidewalls. The radiation from the sidewall fields becomes dramatically stronger when the effective index $n_{\text{eff}}$ drops below unity, which represents the transition between the bound and leaky-wave regime. The longer the cavity, the sharper this transition will become. In the leaky wave regime, the radiative loss is larger than the ohmic losses within the cavity, which leads to a more efficient optical coupling efficiency from the subwavelength metal waveguides.

**Keywords:** quantum cascade laser, terahertz, transmission line metamaterial, leaky-wave antenna

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