Design of mid-IR and THz quantum cascade laser cavities with complete TM photonic bandgap

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Abstract—We present the design of mid-infrared and THz quantum cascade laser cavities formed from planar photonic crystals with a complete in-plane photonic bandgap. A novel effect is introduced for metal-metal waveguides.

***Index Terms*—Photonic crystal, intersubband, quantum cascade laser, THz, mid-infrared**

I. Introduction

Quantum cascade (QC) lasers are semiconductor laser sources based on intersubband (ISB) transitions in multiple quantum well systems [1]. Their emission wavelength can be tuned across the mid-infrared (mid-IR, 5μm<λ<24μm) and THz (65μm < λ < 200 μm) ranges of the electromagnetic spectrum. Most of the activity in the QC laser field has concentrated on edge-emitting devices due to the intrinsic transverse-magnetic (TM) polarization of ISB transitions, and corresponding difficulty in implementing vertical-cavity surface emitting lasers. Besides the implementation of 2[nd] order DFBs [2], the application of photonic crystal technology to QC lasers [3] is a possible solution to achieve surface emission. Two-dimensional (2D) photonic crystals can be used to create localized microcavity laser sources that can be built as two dimensional arrays on a single chip or for large-area, single-mode surface emitting laser sources.

II. Results

Here we report the use of a connected honeycomb lattice for creating 2D photonic crystal QC laser structures. We review the properties of this lattice *via* a 2D planewave expansion (PWE) analysis. A full 2D optical bandgap for TM polarization can be obtained, and localized resonant modes can be formed around a simple point defect in the lattice, shown in Fig. 1a. Full three-dimensional (3D) finite-difference time-domain (FDTD) simulations are then used to analyze the properties of the honeycomb lattice in the two cases of realistic mid-IR and THz QC laser structures. Note: of particular importance in determining the properties of any photonic crystal structure is the effective refractive index contrast attainable. The higher the index contrast, the stronger the optical dispersion of the photonic bands and the greater the ability to localize, diffract, and reflect light within the photonic lattice.

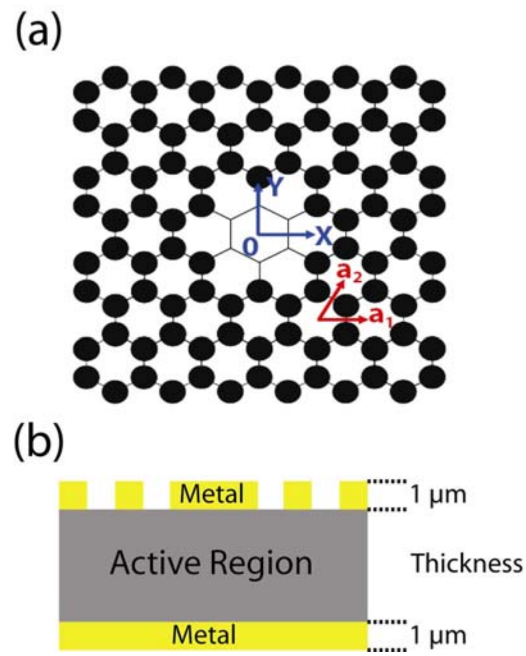

Fig. 1. (a) Illustration of the 2D honeycomb lattice defect cavity (background dielectric material shown as white, air holes shown as black). (b) Cross-section of the simulated metal-metal microcavity structure. Only the top metal layer is patterned.

In the mid-IR, a surface-plasmon QC laser structure is considered. The high-index contrast in this waveguide is obtained by air holes that penetrate deeply into the semiconductor layers. We study the localized resonant modes (see Fig. 2), and we obtain the effective quality factors associated with in-plane ($Q_{//}$), topside vertical (Q_t), and bottomside vertical (Q_b) radiation losses.

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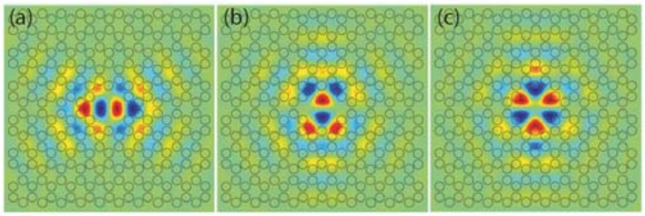

Fig. 2. In-plane mode profiles (Ez) for the (a) x-dipole, (b) y-dipole, and (c) hexapole defect modes of the surface-plasmon vertical waveguide structure with an "etched" hexagonal defect cavity in the honeycomb lattice.

In the THz range, we consider a metal-metal waveguide geometry, as in Fig. 1b. We demonstrate a novel phenomenon: the effective index contrast, and therefore the photonic band structure, is strongly dependent on the waveguide thickness. In particular, below a certain critical waveguide thickness, a full photonic TM gap, and corresponding localized resonant modes around point defects in the lattice, can be induced by the sole patterning of the metal layers (Fig. 3).

This effect could be useful for the development of a variety of THz lasers, including PC surface-emitting lasers. In addition this possibility greatly reduces the required fabrication complexity and avoids potential damage of the semiconductor active region.

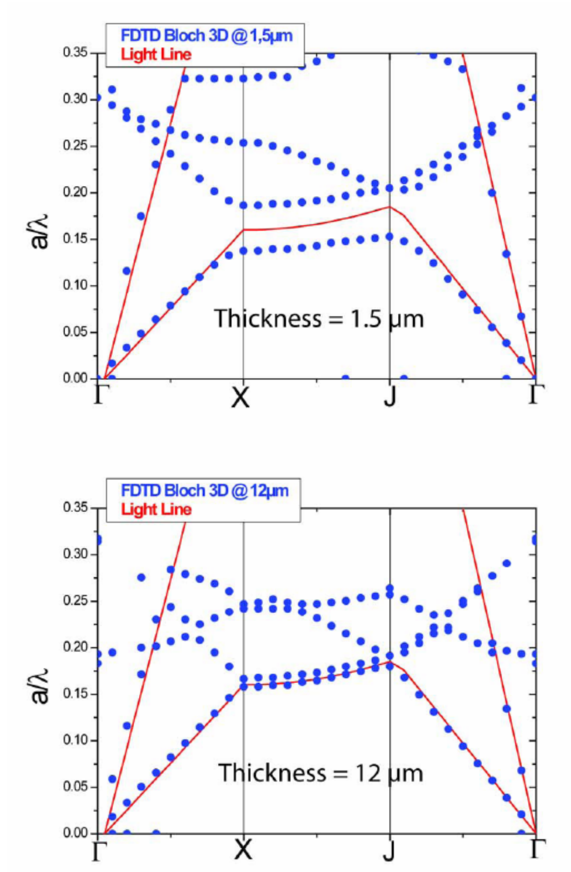

Fig. 3. Photonic band dispersion of a honeycomb lattice patterned in the metal top layer of a metal-metal structure, for two different active region core thicknesses: 12 and 1.5 µm. A full TM gap opens when the structure is made thinner.

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