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# Development of tunable terahertz wire lasers

Qi Qin<sup>1</sup>, Benjamin S. Williams<sup>1,2</sup>, Sushil Kumar<sup>1</sup>, Qing Hu<sup>1</sup> and John L Reno<sup>3</sup>

<sup>1</sup>Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,

PH: 617-253-2431, FAX: 617-258-7864, email: qiqin@mit.edu;

<sup>2</sup>Department of Electrical Engineering, University of California, Los Angeles, CA 90095, USA;

<sup>3</sup>Sandia National Laboratories, Center of Integrated Nanotechnologies MS 1303, Albuquerque, New Mexico 87185-1303.

**Abstract:** We report a novel tuning mechanism based on a “wire-laser” with subwavelength transverse dimensions ( $w \ll \lambda$ ). By manipulating the waveguided mode propagating outside the cavity, frequency tuning of  $\sim 137$  GHz (3.6%) is demonstrated from a single-laser device at  $\sim 3.8$  THz.

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## 1. Introduction

Tunable terahertz quantum-cascade lasers (QCLs) are highly desired for applications in sensing/spectroscopy since many bio-chemical species have strong spectral fingerprints at terahertz frequencies. For these applications, mode-hop-free continuous tuning is required, which is usually achieved by using an external-cavity grating. In this configuration it is difficult to couple the beam diffracted from the grating back into the gain medium due to the long wavelengths ( $\lambda \sim 100$   $\mu\text{m}$ ) associated with THz frequencies compared to the sub-wavelength dimension  $w$  of the laser facet [1]. The difficulty is further exacerbated by the required cryogenic operation. As a result, continuous frequency tuning using an external-cavity grating has yet to be achieved. In addition, alternative electrical tuning by changing the refractive index due to temperature [2] or due to a cavity-pulling effect [3,4] only produces a relatively small fractional tuning ( $< 1\%$ ).

In this abstract we present a novel tuning mechanism based on a unique “wire-laser” device whose transverse dimension  $w \ll \lambda$ . In a uniform gain medium, the lasing frequency for a particular resonant mode is determined by its  $\omega$ - $k$  dispersion relation  $k_z^2 + k_\perp^2 = \omega^2 \mu \epsilon$ , where  $k_z$  ( $k_\perp$ ) is the components of  $\mathbf{k}$ -vector in the longitudinal (transverse) directions,  $\omega$  is the frequency,  $\mu = \mu_0$  is the vacuum permeability, and  $\epsilon$  is the dielectric constant. The lasing frequency,  $\omega$ , of an already fabricated device can be tuned by changing the values of  $k_z$ ,  $k_\perp$ , or  $\epsilon$ . Out of these three parameters, very little effort has been made to change  $k_\perp$  [5]. This is because for most solid-state and semiconductor lasers,  $\lambda$  is comparable, or often smaller than the transverse dimension of the cavity  $w$ . Consequently, little mode leaks out in the transverse directions and very little change can be made to  $k_\perp$ . However, THz QCLs based on metal-metal waveguides can be made with deep sub-wavelength widths, allowing manipulation of  $k_\perp$ . In a previous work [6], unexpected radiation patterns are attributed to a substantial fraction of the mode travels outside of the wire laser. This unusual feature allows tuning of the lasing frequency by changing  $k_\perp$ , which is realized by moving either a dielectric or a metallic “plunger”, close to the wire-laser, shown in Fig. 1. If a dielectric plunger is used (silicon in this work), as it is pushed towards the laser, it extracts the mode from the gain medium, effectively expanding the mode profile in the transverse direction, shown in Fig. 1b. Consequently, the value of  $k_\perp$  decreases, a red-shift tuning is achieved. Similarly, if a metal plunger is used (gold in this work),  $k_\perp$  increases as the plunger is pushed towards the laser as the mode approaches cut-off in the transverse dimension, resulting in a blue-shift tuning.

## 2. Results

Fig. 1(a) shows the schematic of the device design. In order to assure a continuous tuning of a single lasing mode, an asymmetric distributed feedback (DFB) corrugation structure is used, with the flat side facing the plunger. The laser ridge had 12.5  $\mu\text{m}$  average width, 3  $\mu\text{m}$  sinusoidal grating modulation, 30 periods and a grating period of  $\Lambda = 13.7$   $\mu\text{m}$ . In the same fabrication process that defined the DFB laser ridges, rails perpendicular to the laser ridges to guide the plungers were also fabricated. During operations, the plunger was pressed down and could only be pushed forward towards the laser ridge. After being mounted on a cold plate in a vacuum cryostat, the emitted laser light was collected without any optical components inside the cryostat. All the spectra were measured at 5 K using a Nicolet 850 spectrometer (purged with  $\text{N}_2$  gas) and a Ge:Ga photodetector in pulse mode with 90-kHz frequency and 200-ns duration. Due to stick-slip effect caused by the friction between the plunger and the guiding rails, continuous movement of the plunger was difficult to achieve. This resulted in the discontinuity of tuning. To partially solve this problem, a mechanical differential micrometer and a  $\sim 4:1$  lever were used. A red-shift tuning of 57 GHz and a blue

shift of 80 GHz was achieved, shown in Fig. 1d, resulting in a combined tuning of 137 GHz, or a  $\sim 3.6\%$  of the 3.8 THz center frequency. Fig. 1d also plots the threshold current at different plunger positions, which exhibits a moderate increase as either a silicon or a metal plunger is pushed towards the laser ridge.

In order to overcome the stick-slip problem and to achieve continuous and reversible tuning, a plunger based on MEMS (Micro-Electro-Mechanical Systems) technology is being developed, which is conceptually illustrated in Fig. 2. This design of MEMS flexure will allow a better control of a suspended plunger without friction, which should result in a finer tuning over a broader frequency range in a reversible way.

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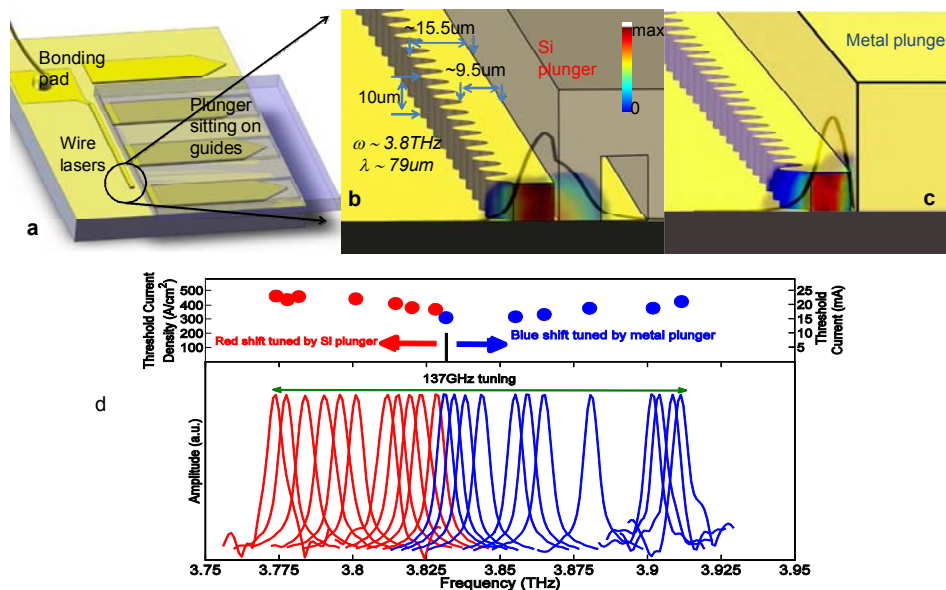


Fig. 1, a, Schematic of device configuration. b and c, Schematic illustration of the tuning mechanism with a silicon plunger and a metallic plunger respectively. The electrical-field profile at the laser facet is shown at the narrowest cross section of the DFB structure. The dark curve is the mode profile by integrating the electrical-field component perpendicular to the ground plane. d, Tuning results from device T114. In the upper part, plotted are the threshold current densities of the device at different frequencies. The lower part shows a broadband tuning of this device over a range of 137 GHz.

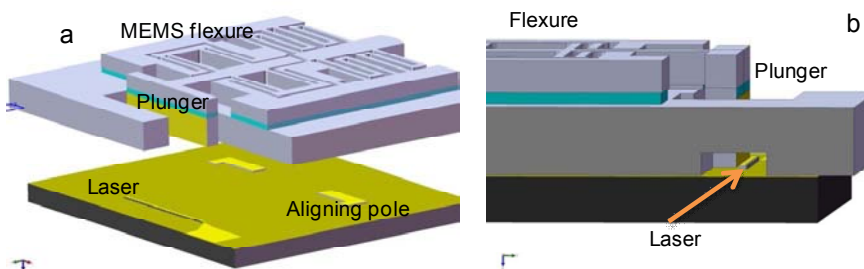


Fig. 2, Schematics of a tunable THz wire laser with a MEMS plunger. Shamrock, yellow, gray and black represent SiO<sub>2</sub>, gold, silicon and GaAs respectively. a, Device configuration before assembling. b, Schematic of assembled device.

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