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# MEMS-based tunable terahertz wire-laser over 330 GHz

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We demonstrate continuous tuning of a terahertz quantum cascade wire laser over a broad range of ~330 GHz (~8.6% of the 3.85 THz center frequency) with single-mode operation. Tuning is achieved with a narrow laser ridge ( $\sim\lambda_o/8$ ) and a moveable MEMS (microelectromechanical systems) side object (plunger) to manipulate the transverse optical mode. The frictionless MEMS plunger enables continuous and reversible tuning. We demonstrate ~30 GHz redshift tuning using a silicon plunger and ~300 GHz blueshift tuning using a metal plunger. The blueshift tuning range is limited by the bandwidth of the gain medium rather than the tuning mechanism. © 2011 Optical Society of America

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Tunable terahertz (THz) sources are highly desirable for sensing and spectroscopic applications [1,2]. The recent progress of the THz quantum cascade laser (QCL) [3,4] makes it an attractive candidate for this application because of its compact size and high output power. However, continuous tuning over a broad range with single-mode operation is difficult to achieve by conventional external-cavity mirror [5] or grating methods [6] in the terahertz region, mainly because of the poor coupling between the external reflector and the gain medium [6]. This difficulty is further exacerbated by the necessary cryogenic operation of THz QCLs. Thus maximally only ~30 GHz continuous tuning has been effectively realized. In another scheme, which couples an external cavity on top of a surface-emitting QCL, only ~20 GHz tuning was achieved [7]. Additionally, only 20–30 GHz tuning has been achieved by utilizing the cavity-pulling effect [8]. Recently, we demonstrated substantial improvement in tuning range in a THz wire laser [9] whose transverse dimension  $w$  is much less than the wavelength ( $w \sim \lambda_o/6$ ). By manipulating the transverse wavevector with a so-called “plunger,” which is a movable side object made of a small piece of metal or dielectric material, a continuous tuning of 137 GHz (3.6%) was achieved. However, due to a large friction between the plunger and the track, and the lack of a restoring mechanism, the movement of the plunger was discontinuous and irreversible [9], limiting practical applications for this prototype. In the present work, these problems are resolved using a MEMS-based plunger. In combination with a narrower wire laser ( $\sim\lambda_o/8$ ) compared to the previous work, we demonstrate controllable and reversible tuning over a record range of 330 GHz (8.6%).

The tuning mechanism is identical to that described in [9]. A first-order distributed feedback (DFB) grating fixes  $k_z$ , the longitudinal wave vector, of a particular resonant mode in the waveguide. The tuning is achieved by changing  $k_\perp$ , the transverse wave vector. This tuning scheme is enabled by a substantial fraction of the mode traveling outside the solid core of the waveguide, which is a trademark feature of wire lasers [10]. Pushing a metallic (dielectric) plunger towards a THz wire laser squeezes (expands) the mode in the transverse direction. Conse-

quently, the value of  $k_\perp$  increases (decreases) and a resulting blueshift (redshift) tuning is achieved. Clearly, narrower laser ridges increase the tuning range, because a larger fraction of the mode propagates outside of the waveguide and is accessible for manipulation.

As in [9], asymmetric DFB corrugation in a metal-metal waveguide is used, enabling a robust single-mode operation while facilitating access to the optical mode on the uncorrugated side. In a QCL wire laser, the lasing mode has the lowest threshold gain  $g_{th}$ , which is equal to  $(\alpha_w + \alpha_m)/\Gamma$ , where  $\alpha_w$  and  $\alpha_m$  are waveguide and mirror loss, respectively, and  $\Gamma$  is the mode confinement. In a THz wire laser whose transverse width is  $\sim 10 \mu\text{m}$ , higher-order lateral modes have much less mode confinement  $\Gamma$  than the fundamental mode (~60%), and they can be safely ignored. In the longitudinal direction, there are two standing-wave solutions on the two sides of the grating stop band that is centered around the resonance condition  $k_z = \pi/\Lambda$ , where  $\Lambda$  is the grating period. The upper-band-edge (lower-band-edge) mode has the maximum intensity located at the narrow (wide) part of the grating [Figs. 1(b) and 1(c)]. These two modes have different frequencies but similar waveguide loss. It is desirable to select the upper-band-edge mode [9] as the lasing mode for its larger tuning range. This can be realized by choosing the front facet of the wire laser to be at the widest part of the grating, which has been assumed for the discussion below. The metal-metal waveguide of the THz QCLs can be modeled with a transmission-line theory. Because the reflection of the facet is high [11], the facet is essentially an open-circuit load, which requires the maximum electric field intensity of the mode located exactly at the facet. However, the upper-band-edge mode requires minimum electrical-field intensity at the open facet if it is at the widest part of the waveguide, which conflicts with the result from the transmission-line model. This conflicting requirement results in an envelope function that is localized in the center and vanishes at the facet, as illustrated in Fig. 1(e). On the other hand, the boundary condition for the lower-band-edge mode is consistent with both the transmission-line and DFB requirements, resulting in an envelope function with a large amplitude at the facet. As a result, the upper-band-edge one has the

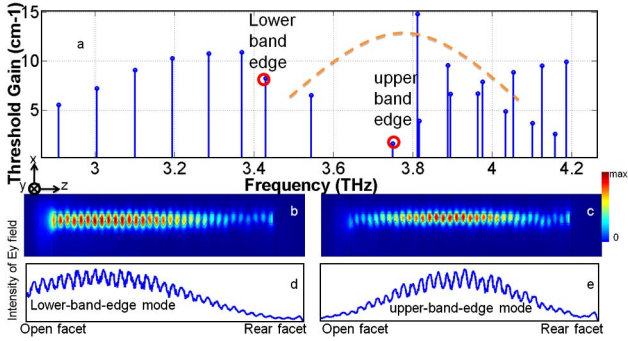


Fig. 1. (Color online) Band-edge-mode properties with the open front facet chosen to be at the widest location of the DFB ridge to select the upper-band-edge mode as the lasing mode. (a) Grating mode spectra of a typical DFB THz wire laser. Plotted is the radiation loss from the open facet. The dashed curve is a schematic gain spectrum with a Lorentzian linewidth of  $\sim 0.5$  THz. (b), (c) Intensity map (top view) of  $E_y$  of the lower- and upper-band-edge modes. (d), (e) Intensity plot of  $E_y$  of the lower- and upper-band-edge modes along the longitudinal direction of the device.

lower radiation loss and thus becomes the lasing mode. In comparison, for the same reason, if the open facet is chosen at the narrow position of the waveguide, the envelope function will have maximum (minimum) close to the open facet, resulting in a higher (lower) loss for the upper (lower) band-edge mode. In addition, as described in [9], the rear facet is tilted and covered by gold, which causes the asymmetry of the mode. For this specific upper-band-edge mode with device A, described below, the simulated tuning range for blueshift tuning is  $\sim 340$  GHz with the metal plunger moving from  $20\ \mu\text{m}$  to  $1\ \mu\text{m}$ , compared to  $\sim 190$  GHz for the lower-band-edge mode, clearly showing the advantage of operating with the upper-band-edge mode.

When the plunger slides on the laser wafer surface [9], continuous tuning is difficult to achieve because of a known stick-slip effect [12] due to the difference between the static and dynamic friction. Additionally, the lack of the restoring mechanism prevents controllable exploration of the entire tuning range. These issues are addressed by using a MEMS-based plunger, which is suspended from the substrate and can be moved forward and backward, as illustrated in Figs. 2(c) and 2(d). The MEMS plunger was fabricated from a silicon-on-insulator (SOI) wafer. In order to avoid the tilting of the plunger relative to the wire laser in the in-plane direction, which could result in a significant reduction of the tuning range [9], a two-stage flexure structure was designed to isolate the plunger from the external actuator. This movable flexure has a maximum movement range of  $40\ \mu\text{m}$  and it was defined in the  $40\ \mu\text{m}$  thick device layer of the SOI wafer which has a resistivity of  $\sim 10\ \Omega \cdot \text{cm}$  due to the difficulty in getting the high-resistivity SOI wafer. To avoid friction, the movable plunger, attached with meandering springs, was anchored on the  $500\ \mu\text{m}$  thick handle wafer by releasing the  $1\ \mu\text{m}$   $\text{SiO}_2$  embedded layer underneath. For the metal plunger, the vertical sidewall of the MEMS plunger was coated with Ti/Au by directional e-beam deposition. Currently, the tuning speed is limited by manually controlled micrometer, but the potential tuning speed can be up to  $\sim 15$  KHz which is the resonant fre-

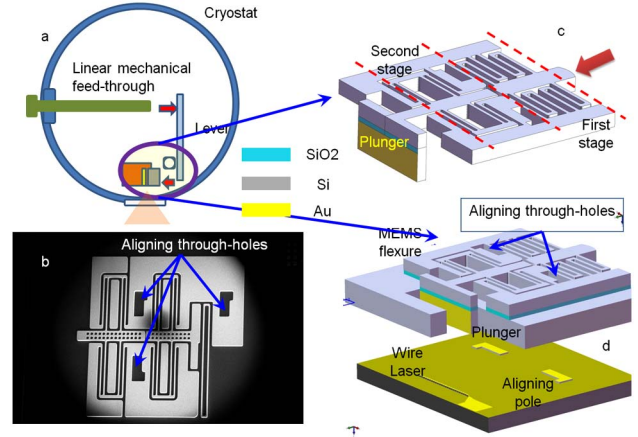


Fig. 2. (Color online) (a) Schematic of the experimental setup, in which a differential micrometer is used to push the long end of a lever, whose short end in turn pushes a MEMS plunger. (b) SEM picture of a MEMS plunger device layer (top view) before the release of the embedded  $\text{SiO}_2$  layer. (c) Schematic of the two-stage flexure design of a MEMS plunger. (d) Illustration of the alignment scheme between a MEMS plunger and a wire-laser die.

quency of the MEMS structure. (The detail of the MEMS design and fabrication is reported in [13].) The wire laser followed the same fabrication steps and used the same wafer as in [9] (wafer VA0094, design FL183S, which is a resonant phonon design). This design has a gain peak around  $3.8$  THz [14]. The average width selected for the laser ridge was  $10.5\ \mu\text{m}$  to achieve a large tuning range. After the wire laser and plunger were fabricated separately, they were aligned and assembled according to the predefined alignment holes and poles on the plunger and laser wafers. The gap between the plunger and the flat side of the DFB laser is  $\sim 20\ \mu\text{m}$  in a nonactuated position. The external differential micrometer can push the plunger all the way toward the laser. When the micrometer is reversed, the meandering MEMS springs retract the plunger reversibly. The assembled device was mounted in a cryostat [Fig. 2(a)] and similar steps for measurement were taken as in [9]. Thus, the absolute value of optical power is difficult to measure, as explained in [9].

Continuous tuning of  $330$  GHz, or  $8.6\%$  fractional tuning, was achieved with the MEMS plunger in device A, which has  $10.5\ \mu\text{m}$  average width,  $3\ \mu\text{m}$  sinusoidal grating modulation,  $30$  periods, and a grating period of  $\Lambda = 14.5\ \mu\text{m}$ . As illustrated in Fig. 3,  $\sim 30$  GHz tuning is achieved using a Si plunger and  $\sim 300$  GHz is achieved using a metal plunger. Although the range of blueshift tuning is impressive, the range of the redshift is underwhelming, even compared to that achieved ( $\sim 57$  GHz) from a rudimentary system which demonstrated a  $\sim 1:2$  red:blue tuning range [9]. This is due to the use of a doped Si plunger. Even though the free carriers are frozen out at this temperature, the lasing frequency ( $\sim 4$  THz) coincides with the absorption spectra of the impurities, which causes a significant loss when Si plunger is close to the wire laser. This loss is evident with the rapid increase of lasing threshold shown in Fig. 3(a). On the other hand, a much larger tuning range from the metal plunger was achieved, not only because a slightly narrower laser ridge ( $10.5\ \mu\text{m}$  as opposed to

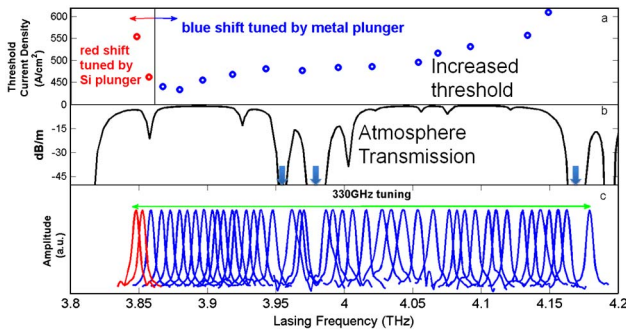


Fig. 3. (Color online) Tuning results from device A. (a) Threshold current densities of the device at different frequencies. (b) Atmospheric attenuation at different frequencies (HITRAN 2008). The three arrows indicate strong absorption lines. (c) Tuning over a range of 330 GHz in device A. The gaps in the tuning spectra are due to the absorption lines indicated in (b).

12.5  $\mu\text{m}$  in the previous work [9]) was used, but primarily because the MEMS plunger enables controllable and reversible tuning with a more precise alignment, enabling full exploration of the available tuning range. The increased threshold current density with blueshift tuning [Fig. 3(a)] is due both to additional loss introduced by the metal plunger and more likely to a decreased gain when the frequency is further away from the gain peak. In the tuning spectra, there are several gaps, highlighted by the arrows in Fig. 3(b), that are due to strong atmospheric absorption [Fig. 3(b)] and the long beam path ( $\sim 0.5$  m) used in the spectra measurement, rather than a discontinuity of the tuning.

The tuning illustrated in Fig. 3 covers the range from  $\sim 3.85$  THz to  $\sim 4.18$  THz. A natural question is whether this range is limited by the tuning mechanism or the available gain bandwidth. To resolve this issue, we measured another device (device B) from the same gain medium with a higher designed lasing frequency by using a shorter DFB grating period. Device B has similar design parameters with device A except a grating period of  $\Lambda = 14.1 \mu\text{m}$ . Its lasing frequency is 3.93 THz without plunger and can be tuned up to 4.16 THz, which is similar to the upper limit of device A shown in Fig. 3. The fact that the upper-frequency limits for both devices are the same even though their lasing frequencies without the plunger are different suggests that the tuning is limited by the vanish of net gain in the end of blueshift tuning. If the tuning range were limited by the tuning mechanism, this upper limit would have changed accordingly with a change of the original lasing frequency. This conclusion suggests that even larger tuning range can be achieved by increasing the gain bandwidth in future designs, for example, by using heterogeneous cascade structures [15].

In conclusion, we have demonstrated a continuous and reversible tuning range of  $\sim 330$  GHz with single-mode operation. This result is achieved by using a MEMS plunger, and by using a narrower laser ridge compared to our previous work. This broad tuning range could be extended further in the redshift with the present gain medium if a high-resistivity Si plunger is used. It can be extended even further by using heterogeneous gain media with broader gain bandwidths in future development. The gaps in the tuning spectra from atmospheric water absorption illustrate the utility for spectroscopy applications. Furthermore, the implementation of a MEMS plunger opens a possibility for fast electrical tuning.

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