Effective mode selector for tunable terahertz wire lasers

Qi Qin,[1,*] Ningren Han,[1] Tsung-Yu Kao,[1] John L. Reno,[2] and Qing Hu[1]
[1]*Department of Electrical Engineering and Computer Science & Research Laboratory of Electronics,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2]*CINT, Sandia National Laboratories, Department 1132, MS 1303, Albuquerque, New Mexico 87185, USA*
**Corresponding author: qiqin@mit.edu*

Received September 4, 2012; accepted October 31, 2012;
posted January 2, 2013 (Doc. ID 175483); published February 7, 2013

We demonstrate an effective mode selector design that enables a terahertz quantum cascade wire laser to have a robust single-mode operation at frequencies much lower than the gain peak. This is achieved by selectively guiding the undesired modes into a lossy session while keeping the desired lasing mode largely unperturbed. The large mode discrimination obtained by this mode selector is necessary to further extend the tuning range to the lower half of the gain curve. Additionally, the connectors of this mode selector conveniently provide electrical bias to the wire lasers without degrading the lasing performance. © 2013 Optical Society of America

OCIS codes: 140.3070, 140.3600.

Practical terahertz (THz) spectroscopic and sensing applications require compact and efficient tunable sources [1,2]. Much effort has been devoted to developing a tunable THz quantum cascade laser (QCL) because of its compact size, high output power, and spectral purity. Conventional tuning methods, such as external-cavity mirror or grating methods [3,4], only achieved limited success because of the poor coupling between the external reflector and the THz gain medium. Another tunable scheme by varying the anti-crossing of two resonant cavities achieved only ~20 GHz continuous tuning [5]. Recently, tunable THz quantum cascade wire lasers (QCWLs), whose transverse dimension w is much smaller than the wavelength, have demonstrated a continuous tuning range of ~330 GHz [6,7], which is ~8.6% of the center frequency. This continuous frequency tuning is achieved by manipulating the transverse wavevector with a so-called “plunger,” which is a moveable side object made of metal or dielectric material. Although a record tuning range is achieved, the tuning range is limited to frequencies higher than the gain peak due to poor mode selectivity. Therefore, an effective mode selector will enable the wire laser to operate at frequencies below the gain peak, potentially doubling the tuning range.

Two factors may limit the improvement of the tuning range. First, the tunability from changing $k_\perp$ is limited by the closest distance that the plunger can move toward the wire laser. The plunger cannot touch the laser sidewall due to the resulting short circuit or permanent physical damage. Here we assume a closest distance of ~1 μm. Second, the tuning range can be limited by the gain bandwidth. In the previous designs [6,7], the lasing mode (chosen to be the upper-band-edge mode [6]), which had the smallest modal loss, was designed around the gain peak in the absence of the plunger.

A controlled experiment was carried out to identify the dominant limiting factor. Devices M and N were based on the same gain medium (FL183S, VA0094), with different periodicities (Λ) (length per period) but the same width (10.5 μm). Device M lased at a lower frequency (~80 GHz) than device N when a plunger was not present. However, the tuning range of both devices, using a metal plunger, terminated at similar frequencies (~4.15 THz), as illustrated by Fig. 1. This indicated that the upper bound of the tuning range was limited by the gain bandwidth, since if the tuning range was limited by the plunger’s tunability, both devices should have the same tuning range and should be independent of the starting frequency.

From this controlled experiment, it is clear that the tuning range can only be expanded by utilizing the lower half of the gain spectrum, indicated by the red box in Fig. 1. Indeed, the key to enable single-mode lasing at a much lower frequency than the gain peak is to provide sufficient mode discrimination, because the desired mode sees a lower gain at that frequency than the higher-order modes. However, this goal is difficult to achieve based on the original design, in which the mode discrimination was achieved only with slightly different radiative losses (~1 cm^{-1}).

A design of comb-shaped connectors, illustrated in Fig. 2A, is developed. There are five connectors in the first design, arranged every six distributed feedback (DFB) periods, connected with the wide part of the DFB grating to minimize the interference with the desired lasing mode—the upper-band-edge mode. In THz wire lasers, the connectors’ top layer can guide the surface plasmon mode and the underneath GaAs has larger permittivity (~13.1) compared to vacuum. Thus, these connectors will guide modes into the lossy bonding pad if those modes have strong intensities at the locations of the connectors. For the upper-band-edge mode, the electrical field almost diminishes at the wide section

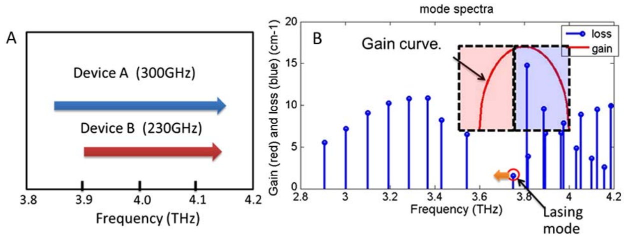

Fig. 1. (Color online) (A) Schematic tuning result, in which device M and N started from different frequencies and ended at similar ones. (B) Illustration of the gain-bandwidth usage. The blue (red) box indicates the estimated gain, plotted by the red curve, above (below) the lasing frequency of a bare wire laser.

[6] where the connectors are placed. Consequently, this mode is least perturbed by the connectors. However, for higher-order modes, they could have maximum intensities at the wide sections, which can be substantially perturbed by the connectors. Additionally, these modes can emit from the bonding pad, resulting in a greater radiation loss as well as absorption loss. Therefore, the undesired modes yield a greater loss and the mode discrimination is enhanced. Due to the broken periodic symmetry of the DFB with a finite length, there is still some overlap between the upper-band-edge mode and the widest section, so the loss of this lasing mode can increase slightly.

It is also important to realize that these comb-shaped connectors function as electrical bridges between the wire laser and the bonding pad. The original THz wire laser [6] had a tapered rear facet that was covered by a Ti/Au/SiO_2 multiplayer, which may introduce additional loss due to the mode leaking into the bonding pad. Moreover, this design requires a complicated fabrication process that involves the combination of wet and dry etching, which often led to a low yield. In the new design, the bonding pad is connected with the wire laser by comb-shaped connectors, while both the bonding pad and the connector metals are insulated from the gain medium by a thin SiO_2 layer (300 nm) under them.

In the design of comb-shaped connectors, if the connectors are too wide, then they can lead to a large loss of the desired lasing mode. On the other hand, these connectors should be strong (wide) enough to survive the fabrication process, so a width of ~4 μm was chosen. The connector length was designed to be ~80 μm to reduce the current spreading effect because the connectors and the bonding pad are not biased.

In the first attempt, the five-connector design failed to provide sufficient mode discrimination to ensure single-mode operation. Three wire lasers with 8.5 μm width and five connectors were designed at ~3.75 THz (device I), ~3.6 THz (device II), and ~3.4 THz (device III) based on the FL183S gain medium whose gain peak is at ~3.8 THz. Device I lased at ~3.85 THz, which is ~100 GHz higher than the designed 3.75 THz because the fabricated device was narrower than the design value (8.5 μm). But devices II and III lased at ~3.8 and ~3.97 THz in spite of the designed 3.6 and 3.4 THz, respectively. This discrepancy was due to poor mode selectivity so that a higher-order mode, which sees a greater gain, reaches the lasing threshold first.

In order to improve the mode selectivity, the losses of higher-order modes need to be increased substantially, and thus the connector number was increased, and their locations were carefully selected to maximize the mode discrimination. First, a nine-connector structure was designed to increase the mode discrimination. The modal loss difference between the first and second longitudinal modes was increased to >20 cm^{-1}. Then, two extra connectors were added to further increase the modal loss of the third-order mode, as illustrated in Fig. 2. The upper-band-edge mode maximum is aligned with the narrowest section of the waveguide (Fig. 3A). Additionally, this alignment is better at the center of the waveguide. Furthermore, the envelope function of the third-order mode has a maximum at the center and two minimums at five DFB periods away. Similar to the upper-band-edge mode, the third-order mode is aligned well with the waveguide narrow section at the center, and becomes misaligned away from the center as the intensity envelope decreases. In order to selectively extract the undesired modes, these two extra connectors should be placed in the middle between the maximum and minimum of the third-order mode's envelope function, two DFB periods away from the center in the actual design (Fig. 3B) where both the second- and third-order modes still have relatively large intensity and are misaligned with the DFB's narrow sections. In these places, the two connectors can only "see" the nodes of the desired upper-band-edge mode.

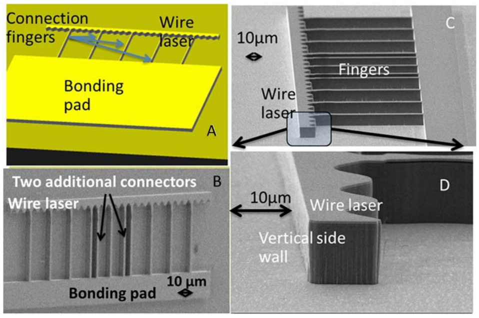

Fig. 2. (Color online) (A),(B) Schematics of the five-connector and 11-connector designs, respectively. The two extra connectors are indicated in (B). (C),(D) SEM images of a fabricated 11-connector device. The fabrication procedure is similar to that in [8].

The design considerations were verified with a finite-element simulation, as shown in Fig. 3B. The loss of the desired upper-band-edge mode was almost unchanged. In contrast, the second- and third-order modes were significantly extracted into the lossy bonding pad (Fig. 3B). The third-order mode has a loss of 53 cm^{-1} compared to 34 cm^{-1} with only five connectors. Even the loss of the second-order mode was further increased from 27 cm^{-1} (five-connector design) to 34 cm^{-1}. As the results show in Fig. 4, this enhanced mode discrimination is sufficient

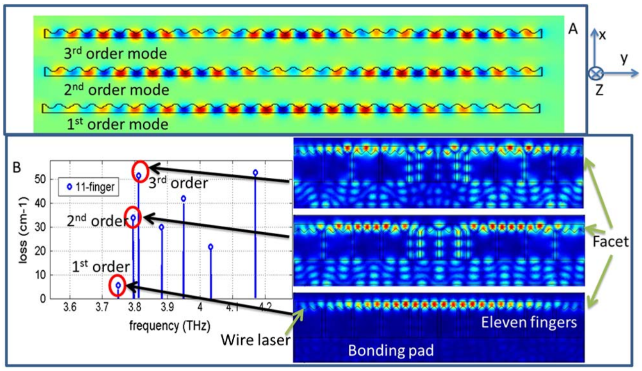

Fig. 3. (Color online) (A) Color plots of the E_z-field intensity for the first three upper-band modes for a bare DFB wire laser. (B) Mode spectrum of a typical 11-connector design (10.5 μm wide, 14.3 μm periodicity) and plots of the electrical field intensity of the E_z component. Compared to the first-order mode (upper-band-edge mode), the other two are guided into the bonding pad, resulting in a much greater loss. The device boundary can be seen more clearly when the figure is enlarged.

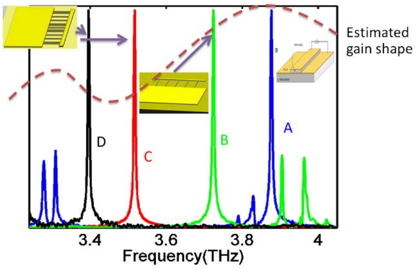

Fig. 4. (Color online) Normalized spectra of different designs and a schematic gain spectrum. Devices (A) and (B) were a Fabry–Perot device and a five-connector design, respectively. Spectra (C) and (D) were from the 11-connector devices. The 11-connector design provided sufficient mode discrimination for robust single-mode operations, compared with the five-connector design, which resulted in a multimode operation due to limited mode discrimination.

to ensure a robust single-mode operation at frequencies far below the gain peak of ~3.9 THz.

Figures 2C and 2D show SEM pictures of an actual device that has nice vertical sidewalls etched with an inductively coupled plasma reactive ion etcher. Lasing spectra of different designs are plotted in Fig. 4. Spectrum A shows a Fabry–Perot device lasing at ~3.9 and ~3.3 THz simultaneously. An estimated double-hump gain curve, according to [9], is plotted along with the measured spectra. Spectra B, C, and D were from the DFB wire QCLs with 10.5 μm width. Among them, device B (periodicity $\Lambda = 14.3$ μm) has five connectors, while devices C ($\Lambda = 15.3$ μm) and D ($\Lambda = 15.8$ μm) have 11-connectors. The single-mode operation of devices C and D, compared with the multimode operation of device B, clearly demonstrated that the 11-connector design yields a more robust single-mode operation than the five-connector design. Consequently, a robust single-mode operation was achieved in a THz QC wire laser at a frequency much lower than the gain peak. In this case, device D lased at ~3.4 THz, which is ~0.5 THz lower than the main gain peak (~3.9 THz). This highly effective mode selector will enable a further increase of the tuning range by utilizing the lower half of the gain spectrum.

In conclusion, we have demonstrated an effective mode selector that enables a THz QCWL to lase single-mode at a frequency much lower than the gain peak. This is achieved by selectively extracting the undesired modes into a lossy session while keeping the desired mode largely unperturbed. The strong mode discrimination of this mode selector is a necessity to further increase the tunability of THz wire lasers.

The work at MIT is supported by NASA and NSF. The work at Sandia was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

1. D. Mittleman, *Sensing with Terahertz Radiation* (Springer, 2003).
2. P. H. Siegel, IEEE Trans. Microwave Theor. Tech. **52**, 2438 (2004).
3. J. Xu, J. M. Hensley, D. B. Fenner, R. P. Green, L. Mahler, A. Tredicucci, M. G. Allen, F. Beltram, H. E. Beere, and D. A. Ritchie, Appl. Phys. Lett. **91**, 121104 (2007).
4. A. W. M. Lee, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, Opt. Lett. **35**, 910 (2010).
5. L. Mahler, A. Tredicucci, F. Beltram, H. E. Beere, and D. A. Ritchie, Opt. Express **18**, 19185 (2010).
6. Q. Qin, B. S. Williams, S. Kumar, J. L. Reno, and Q. Hu, Nat. Photonics **3**, 732 (2009).
7. Q. Qin, J. L. Reno, and Q. Hu, Opt. Lett **36**, 692 (2011).
8. B. S. Williams, S. Kumar, H. Callebaut, Q. Hu, and J. L. Reno, Appl. Phys. Lett. **83**, 2124 (2003).
9. S. Kumar and Q. Hu, Phys. Rev. B **80**, 245316 (2009).