Broadly Tunable External Cavity Terahertz Source from 1.2 ~5.9 THz

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Abstract—We present room-temperature broadly tunable external cavity terahertz sources based on Cherenkov intra-cavity difference frequency generation in dual-wavelength mid-infrared (mid-IR) QCLs. Devices demonstrate continuous THz emission tuning from 1.2 THz to 5.9 THz at room temperature with peak power output varying between 5 and 45 μW, depending on the operating frequency.

I. INTRODUCTION

Wide tunable room temperature, electrically-pumped semiconductor THz sources are highly desired for spectroscopy and imaging application. Recent developments in THz sources based on intra-cavity difference-frequency generation in dual wavelength mid-infrared (mid-IR) QCLs are particularly attractive for its room temperature working ability and broad tunability. In Ref. 7, we reported for the first time a broadly tunable Cherenkov THz generation in quantum cascade lasers from 1.7 THz to 5.25 THz using a Littrow type external cavity system, which is operated by fixing one mid-IR pump frequency (ω1) by a monolithic DFB grating etched in the laser cavity while tuning the other mid-IR pump frequency (ω2) with an external diffraction grating as shown schematically in Fig. 1(b) . Terahertz radiation at frequency ω1-ω2 is emitted into the substrate based on Cherenkov phase matching scheme. Here we describe an optimized widely tunable room temperature EC THz DFG-QCL system with record continuous tuning range from 1.2 THz to 5.9 THz and dramatically reduced beam steering. Improvements in tuning range are achieved principally by depositing dielectric anti-reflection (AR) coating on the back facet of the laser chip facing the external grating, while THz beam steering is suppressed by bonding a THz DFG-QCL chip to a substrate made of high-resistivity Si that has virtually no refractive index dispersion in 1-6 THz range.

II. RESULTS

THz beam steering in our system was suppressed by replacing the InP substrate of devices with a high-resistivity silicon substrate. A 350-μm-thick SI InP substrate in some devices was thinned down to 120 μm thickness and the devices were bonded, substrate-down, to a 1-mm-thick high-resistivity silicon substrate using a 500-nm-thick adhesion layer of SU-8 photoresist. The assembly was then cured at 65 °C for 30 minutes, then at 95 °C for 30 minutes and finally at 140 °C for 10 minutes under the pressure of 4 MPa. The front facet of the silicon substrate was then polished at 10° angle to allow for extraction of Cherenkov THz radiation in forward direction and the back facet of the silicon substrate was aligned with the laser back facet. Two-layer mid-IR AR coating made of a 650 nm layer of YF3 followed by 360 nm layer of ZnSe was deposited by electron beam evaporation on the laser back facet. We got the 1.4% facet reflectivity of the AR coated facet and 32% reflectivity of the EC system.

To balance gain and loss between EC modes and DFB mode, a coupling strength KL ~ 4 of the DFB grating need to be designed. With one mid-IR pump fixed by DFB grating at v1 = 963 cm⁻¹, the other mid-IR pump v2 tuned with an external grating from 1004 cm⁻¹ to 1187 cm⁻¹, the corresponding THz tuning vTHz = v1-v2 of this optimized EC THz DFG-QCL system could be tuned from 1.2 THz to 5.9 THz as shown in Fig. 1, also shown in Fig. 1(b) are THz peak power of 5-45 μW depending on different THz frequency.

The angle of THz emission in the silicon substrate can be calculated as:

\[ n_g = n_{gSi} \cos \theta_{gSi} = n_{gInP} \cos \theta_{gInP} \]

where \( n_{gSi} \) and \( n_{gInP} \) are the refractive index of and Cherenkov THz emission angle in InP (silicon), respectively. This small refractive index dispersion ensures a constant Cherenkov emission angle of approximately 10 degrees into the silicon substrate over the entire 1 - 6 THz range. Far field profile of this system from 3.0 ~ 4.4 THz tuning range (maximum THz power range) were obtained by placing the bolometer 15 cm away from the fixed laser, and monitoring the received power while sweeping the bolometer in the x-z plane, no obvious beam steering is observed. For comparison, we also measured the EC performance of an AR-coated DFG-QCL chip on an InP substrate that has achieved similar tuning range, but show significant THz beam steering, a 15° beam steering was measured from 3.0 ~ 4.4 THz tuning range. Refractive index dispersion of InP substrate in 1-6 THz region, will result in the change of Cherenkov angle for 10 degrees and the change of far field direction for 40 degrees for a 30° polished InP substrate for 1-6 THz frequency range.

High-resistivity silicon is also highly-transparent at THz frequencies compared with SI InP. But the remaining 120-μm-thick SI InP substrate still have high THz loss and the unpolished InP facet partly blocks THz Cherenkov wave from outcoupling to free space. Also 500-nm-thick SU-8 bonding layer will introduce 50% reflection loss of Cherenkov THz wave. Current device on silicon substrate shows 1.3 times higher mid-IR-to- THz conversion efficiency compared to identical device on SI InP substrate.
Fig. 1 (a) Mid-infrared frequency tuning range and corresponding power for EC-THz-DFG QCL system implemented with a device on silicon substrate, $v_1$ fixed at 963 cm$^{-1}$ by DFB grating, $v_2$ tuned with the external grating from 1004 cm$^{-1}$ to 1187 cm$^{-1}$, both mid-IR pump powers are recorded as a function of $v_2$. (b) Corresponding THz spectra and THz peak power from 1.2 THz to 5.9 THz at a current density of 9.0 kA cm$^{-2}$. Top inset shows the schematic of device.

REFERENCES