Dielectric deposition for tuning the frequency of THz quantum cascade lasers

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Abstract— We report an extensive study of the effect of an additional dielectric layer on the frequency of terahertz quantum cascade lasers (QCLs). QCLs with third-order distributed feedback structure at frequencies of 3.5 and 4.7 THz are used in our experiment. The dielectric layer applied is either Silicon-dioxide (SiO_2) or Polymethylmethacrylaat (PMMA). We find that both dielectric layers can down shift the lasing frequency up to 6GHz on a 3.5THz QCL, and 13GHz for a 4.7THz QCL. Full 3D FEM simulations suggest that the effect is dominated by the effective thickness of the dielectric on the vertical walls of the laser structure, and also confirm that for a given dielectric layer the effect is stronger in the 4.7THz QCL due to its larger out-distribution of electric-magnetic field. The knowledge provides guideline to shift the frequency of an existing QCL used as a local oscillator in practical applications.

INTRODUCTION

3'rd order DFB THz QCLs [1], which can be operated above 50K using a compact, low power stirling cooler, with a single mode emission in combination with reasonable output power (~0.5mW) and single spot far-field beam pattern, are good candidates for high resolution spectroscopy, especially in an astronomic instrument. However, due to the limited accuracy of the lithography, the limited electric tuning range, and the limited bandwidth of a practical mixer, additional fine frequency tuning possibility using an external dielectric layer would be extremely useful.

In this work we extensively study the effect of the dielectric layers of SiO2 and PMMA (both materials having reasonable refractive indices and low absorption coefficients) on the shift of the lasing frequency of a working QCL. The advantage of the latter is its reversibility, namely the dielectric is removable. We identify the importance of the thickness of the dielectric layer on the walls of the laser mesa-structure. Furthermore, we observe stronger effect in a 4.7THz than what in a 3.5THz QCL, which is supported by a 3D simulation.

QCLS AND DIELECTRIC LAYERS USED

We use 3'rd order DFB THz QCLs at two frequencies of 3.5 and 4.7THz. Since the resonance frequency is dependent on the effective index, it can be lowered by adding a dielectric layer around the laser where the electric-magnetic field exists. This is the essence of the technique studied in this work. The out extending electric field is shown in Fig.1, which is different for each QCL. For the 4.7THz QCL, it is more localized along the period edges, easy to be contacted by the additional dielectric layer whilst for 3.5THz QCL, it is more concentrated inside and around the air gaps, somewhere harder to be reached, suggesting a more effective frequency shift for 4.7THz QCL.

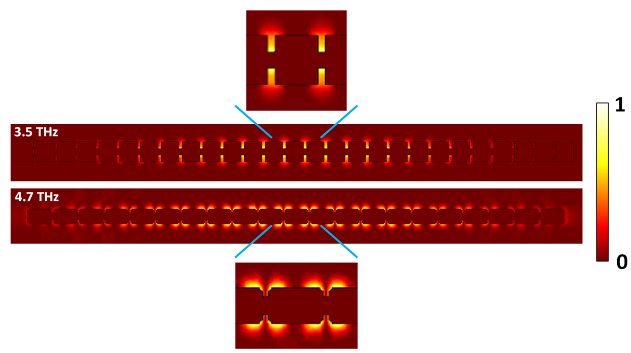

Fig. 2 Top view of the normalized magnitude of the extending electric field to the free space of two QCLs at 3.5 THz and 4.7 THz used for our experiments, showing different field distributions.

MEASUREMENT AND SIMULATION RESULTS

We measure the laser spectrum by a Fourier Transform Spectrometer (FTS) with a resolution of ~0.6GHz, and find the central frequency by fitting the data (the inset of the Fig.2.a). Fig.2.a shows the measured data of the 3.5THz QCL with the thicknesses of sputtered SiO2, varying between 0, 60, 240 and 480nm, corresponding to frequency down shifts of 2, 3 and 3.9GHz, respectively. We observe almost no effect on the output power.

Since we only measure the thickness on the flat surfaces of top and substrate (surface layer thickness), not on the side walls, we find the latter (lateral layer thickness) by 3D simulation using COMSOL 5.1.The results are plotted in Fig.2.b, where we get the lateral layer thicknesses of ~2, 5, and 20 nm for the measured surface layer thicknesses of 60, 240, 480nm respectively. We find that the shift is mainly due to the lateral layer thickness whilst the effect of the surface layer thickness in the same scale is so smaller. The Fig.2.b shows that the shift has almost a linear dependence to the lateral layer thickness with a rate of ~40MHz/nm for a fixed surface layer thickness.

We apply PMMA on the 3.5THz QCL in the mentioned way and assume that it sits on the structure uniformly since the liquid covers the entire laser and evaporates slowly. We observe a frequency down shift of ~6.3GHz corresponding to 340nm of the layer thickness found by simulation and a linear relation of the frequency shift to the PMMA thickness by a rate of ~10MHz/nm. The smaller rate than what is found in the SiO2, is due to the lower refractive index of PMMA (~1.54) [2] comparing to SiO2 (~2) [3] and also its higher absorption coefficient that reduces the influence on the neff. The latter is also responsible for a drop of ~18% in the output power.

Now we describe the results of the same experiments of 4.7 THz QCLs, which are motivated directly by our instrument applications (such as NASA balloon borne telescope STO2) due to existence of an astronomic important oxygen [OI] line at 4.745THz. By sputtering of 410nm of SiO2 on the surface we find a down shift of ~13.3 GHz, nearly 3 times larger than the case of 3.5THz QCL with a comparable thickness. A drop in power of ~20% is observed which is due to the higher absorption in 4.7THz and also stronger interaction of the field with SiO2. We couldn't find the lateral layer thickness based on simulation, since it shows a larger shift than the experiment even with zero lateral layer thickness. We attribute it to the problematic surface condition of this laser which may partly absorb the EM field on one hand, and have a poor adhesion to SiO2 or PMMA on the other hand. The simulation results of the frequency shift dependence of the 4.7THz QCL on the lateral layer thickness of SiO2 and uniform layer thickness of PMMA, show much larger effect, by rates of ~200 and ~88 MHz/nm respectively, which actually confirms the intuitional estimation of a stronger effect on 4.7THz laser due to its different out extended field.

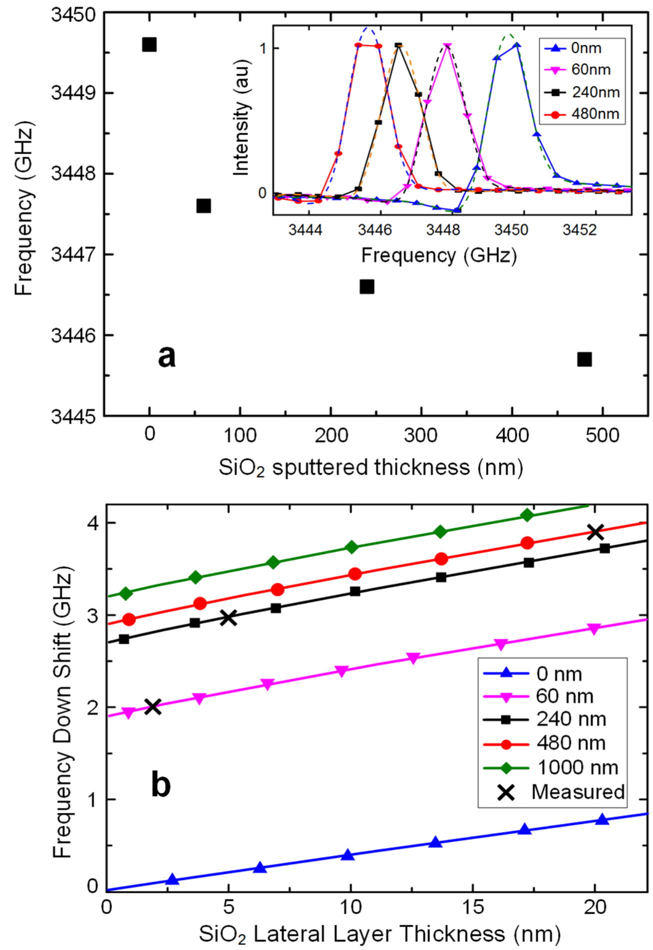

Fig. 2 a) The measured frequencies of the 3.5THz QCL before and after of the SiO2 sputtering in thicknesses of 60, 240 and 480nm. Inset shows the raw FTS spectrums (solid lines) together with the fitted curves (dashed lines). b) The simulated dependence of the frequency downshift on the lateral layer thickness, in five surface layer thicknesses of 0, 60, 240, 480 and 1000nm. The crosses show the experimental data points.

References

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