Plasmonic Antenna Integrated Quantum Cascade Laser for Mode Confinement used for High Sensitivity Bio-Sensing Applications

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We present metal-dielectric-metal bow-tie antenna integrated Quantum Cascade Laser where the optical mode has been squeezed within ~ 100nm and its interaction with AFM tip (~50nm) can affect laser cavity mode (~6um). Such compact device with high sensitivity can be useful for building mid-infrared bio-sensors.

Sensitivity is a key requirement to upgrade any bio-sensing devices. In the mid-infrared region of operation, this criterion becomes extremely challenging as the interaction strength of the tiny probed molecules (~ order of nm) with the large operating wavelength (2-10um) gets naturally weak. Researchers have tried to improve it by using resonance cavity with high quality factor (Q)[1]. The fundamental reason behind it is that high Q-factor increases the number of times the optical mode crosses the probed molecule and thus the chance of detecting the molecule increases. But it comes with a cost of using ultralow optical bandwidth (inversely proportional to Q) and thus the device gets heavily limited with probing capability for very specific objects. We have used a fundamentally different approach where the interaction strength has been enhanced by squeezing the mid-infrared optical mode itself into nanometric length scale[2]. We will also show that it not only helps avoiding a compromise with the frequency bandwidth but also keeps the high sensitivity intact.

We have used plasmonic optical antenna, which works based on the principle of surface plasmon resonance to compress the volume of the optical mode by more than a million times. In addition to producing such extreme mode compression, our novel nano-antenna is directly integrated with a quantum cascade laser (QCL) and hence the compressed plasmonic mode is strongly coupled with the laser cavity mode. We have shown that the plasmonic mode can be compressed about $10^{-5}\lambda^3$, while the volume of the laser mode is about $10^3\lambda^3$, or 100 million times larger. We observed that the near field optical intensity reduced by ~70% of its power when the tip-surface distance changed from 5nm to 100nm. This modulation is caused by the interaction of the AFM tip (radius ~ 50nm) with the cavity mode of the laser (~6μm). Although there is ~ 100 times dimensional mismatch between the cavity and plasmonic mode, this highly unusual coupling can be a result of such strong mode coupling, Thus, it shows that the small change in position of the probing AFM tip can produce a very large change of power in near field optical mode.

Our device has been fabricated by defining a metal-dielectric-metal based bow-tie antenna structure on the facet of the Quantum Cascade Laser. We have previously developed such composite material based nano-antenna and showed an improved performance in terms of near field intensity enhancement[3, 4]. The design has been optimized using full 3D- Finite-difference-time-domain (FDTD) simulations. The antenna structure consists of two bow-tie arms separated by a gap of 100nm. After optimizing the design, the MDM bow-tie structure was fabricated on the coated facet of the QCL using a Focused Ion Beam (Hellios FEI). The QCL was first tested at room temperature for its performance and operation and then one of the facets was coated with a buffer magnesium fluoride(MgF_2) followed by Au/SiO2/Au using ebeam evaporation. The buffer layer is required for electrical insulation and we used MgF_2 for its low absorption in the operating wavelength of our laser operation. The laser was operated in pulsed mode with 1% duty cycle (100kHz and 100ns). The plasmonic mode that resonates with the optical antenna exists only in the near field and thus cannot be studied with an ordinary microscope. Thus, we used apertureless near field scanning optical microscopy (NSOM) for such measurement. Our home-made NSOM setup is based on a commercially available atomic force microscope (AFM). During the measurement, the AFM is operated in non-contact mode such that the AFM tip can scan the surface of the active device where the tip-sample distance varies between ~ 5 to 100nm. Due to capacitive coupling between the two arms of the bow-tie antenna, the near-field gets further squeezed within an even smaller "hot spot". Figure -1 shows a direct comparison between the size of the optical modes emitting from the facet of the QCL with and without antenna. In Figure-2, we have shown the sensitivity of the optical power output with respect to the position of the AFM tip. This can be due to strong mode coupling of the laser cavity mode and the plasmonic mode despite their extremely small overlap integral. Note that the plasmonic mode is "compressed" dramatically below the diffraction limit, while the laser cavity mode is much larger than diffraction limit due to the weak confinement. Such strong mode coupling means that the "hot spot" is now part of the laser cavity and can greatly influence the laser intensity. The AFM probe at

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the hot spot can be replaced with a bio-molecule or any probing agent which can thus affect the laser intensity. This effect can be useful for building mid-infrared bio-sensor where the interaction strength and sensitivity is key hurdle to overcome.

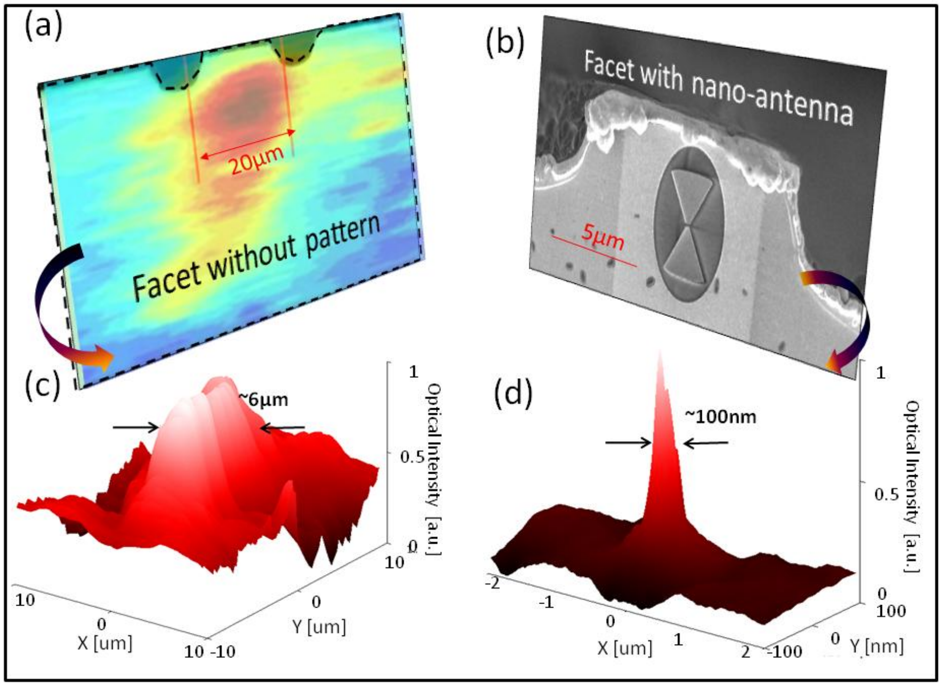

Figure 1 – Facet of a QCL (a) w/o and w/ optical antenna. Optical mode emitting from QCL facet (c) w/o and (d)w/ antenna

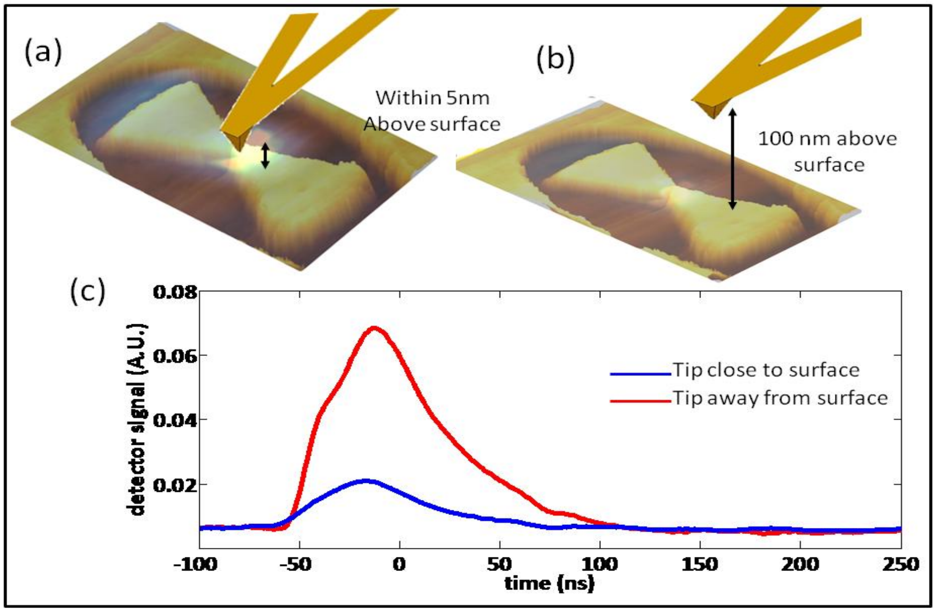

Figure 2 – Schematic diagram showing the near-field optical mode with AFM tip (a) 5nm and (b) 100nm above the top surface of the optical antenna (c) Measured variation of the detector signal with different tip position.

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