Micro-waveguides to boost strong field effects in crystals

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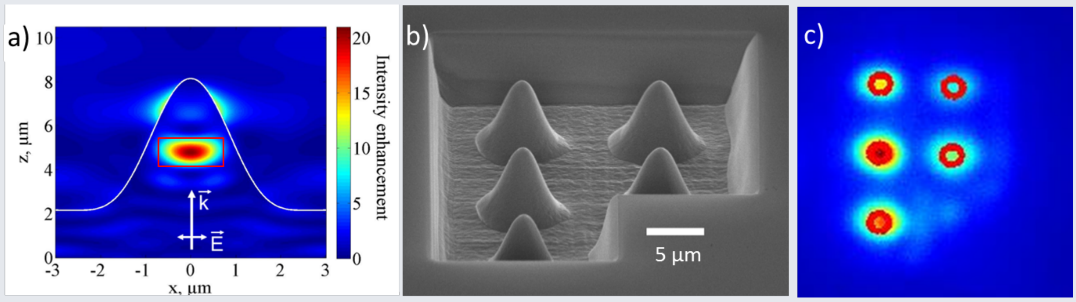
In 2008, researchers from Korea demonstrated for the first time the coupling of two up to then dissociated fields of physics, i.e. strong field physics and plasmonics [Kim, Nature 2008]. In their seminal experiment, they claimed that they could generate high order harmonics in rare gases from a laser oscillator, although this phenomenon necessitates intensities of the order of 1014 W/cm2. They used resonating plasmonic structures that coupled with the incident laser and locally enhanced the electromagnetic field amplitude by several orders of magnitude. However, it was later proven that the EUV emission they measured was due to atomic line emission. The main limitation of their experiment is the limited number of gas atoms in the strongly localized volume of amplified electric field, which prevents recording the low effiency harmonic generation.

We coupled two biases to circumvent those issues. First, we increased the density of emitters by several orders of magnitude by generating the high order harmonics in semiconductor crystals instead of gases. Second, instead of using metallic plasmonic structures with an inherent small interaction volume, we designed micro-waveguides directly at the surface of the crystal. This new geometry leads to a large interaction volume, and is more robust to laser induced damage. Figure a) shows a Finite Difference Time Domain simulation of the propagation of a laser field (l=3.1 mm) within a cone. Intensity enhancements higher than 10 are expected in a volume of more than 1 mm3 (compare to the nm3 volume from the Korean experiment). Moreover, the field distribution is smooth and without sharp gradients, which are detrimental for high order harmonic generation.



We performed the experiment at the IOGS/LCF laboratory, on a 3.1 µm source based on optical parametric chirped pulse amplification (70 fs pulse duration, 1.25 W power and 125 kHz rep. rate). To demonstrate the potential impact of our scheme, we lowered the pulse energy to below 0.25 nJ. A perspective (60°) SEM image of an array of nanocones is shown above. We patterned the ZnO crystal using a Focused Ion Beam. Figure c) shows a near field image of harmonic order 7 emission (l=500 nm) from the same array. While the signal from the bare crystal (visible in between the cones) is very low, the signal from the cones saturates the detector. When the incident laser intensity is of the order of 0.1 TW/cm2, the amplification of H7 reaches 700. Moreover, we were able to measure harmonic amplification up to the 15th order (l=233 nm). Finally, the signal does not decrease with time, proving that the cone structure is not damaged by the laser field, which is corroborated by a post experiment SEM analysis of the sample.

Thanks to this technique, strong field physics is now avaible to small scale, high power but low energy laser systems, and therefore affordable to more researchers. This will allow us to study electron dynamics during high order harmonic generation, and to shed light on the origin of this phenomenon.

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Résultats obtenus dans le cadre du projet HILAC financé par le thème 3 du LabEx PALM et porté par Wilem Boutu (LIDYL, CEA) et Marc Hanna (LC, IOGS).