Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

Demonstration of plasmonic amplifiers with optical pumping exhibiting 10dB gain

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Executive Summary

The fundamental properties of a novel QD material, HgTe, were characterised in depth using ultrafast absorption spectroscopy and nearly tresholdless gain was observed. From these measurements we could estimate a peak gain of at least 400dB/cm for a closed-packed film of this material, indicating that the project target of reaching 10dB gain under optical pumping should be within reach. The next step now is to demonstrate such gain also for QDs deposited on a substrate, either directly or dispersed into a suitable polymer. Efforts in this direction are now underway.

Change Records

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Contents

1. Introduction

This milestone report describes in short the progress we made towards developing a colloidal quantum dot (QD) based optical amplifier. Full details will be reported in the deliverable D4.4 *Report on SPP amplifiers using QDs*.
At the start of the project we focussed on several types of PbS-based materials. These were characterised in detail through transient absorption spectroscopy. From this study (details reported in D4.2) it became clear that these materials do not exhibit sufficient intrinsic gain to realize a practical device (i.e. to obtain optical gain in an integrated optics device under CW or quasi CW pumping circumstances).

Therefore, as reported at the mid-term review meeting (July 2013), UGent shifted efforts towards a completely novel material, HgTe. Preliminary results indicated this was indeed a very promising material with near thresholdless gain at 1300nm and at 1550nm. So the primary focus during this period was the in-depth investigation of the fundamental properties of this material. These are reported in the next section. Besides we also started to study their properties when embedded in a thin film and combined with plasmonic structures. These are reported in section 3.

2. Gain measurements: HgTe QD in solution

HgTe QDs were synthesised using a procedure adapted from literature[2]. The absorption and emission spectra of these HgTe QDs (Figure 1, left) feature the typical characteristics of the first exciton transition, albeit with a large apparent Stokes shift (120 meV for the data shown) between emission and absorption. By changing the reaction conditions, the absorption and emission spectrum can be tuned throughout the entire near-infrared spectrum (from 1100 nm to 1600 nm). Time-resolved photoluminescence under low-fluence excitation shows a non-exponential decay, which can be fitted using a double exponential with a short 30-40 ns and a longer 75 ns decay time. This is a very important difference with the earlier studied PbS based QDs which had 2 tot 3 orders of magnitude larger lifetimes.
Two samples, with emission peak at 1220nm and at 1300nm resp. were investigated in detail using ultrafast pump-prove absorption spectroscopy. The results are described in detail in the paper attached as an appendix to this document, which is currently being prepared for submission. Below we summarize the results relevant towards further development of the NAVOLCHI optical amplifier
Figure 1, right shows absorption spectra measured after photo-excitation, for different pump powers. The number indicated next to the curves indicates the average exciton population level <N> of the individual quantum dots. Negative values of the absorption correspond to gain. This figure shows there is gain for excitations as low as <N>=0.03, which is at least 1 order of magnitude lower then what was ever shown for any QD.

23. Keuleyan, S., Lhuillier, E. & Guyot-Sionnest, P. Synthesis of Colloidal HgTe Quantum Dots for Narrow Mid-IR Emission and Detection. *J. Am. Chem. Soc.* **133,** 16422–16424 (2011) , Kim, S. *et al.* Bandgap engineered monodisperse and stable mercury telluride quantum dots and their application for near-infrared photodetection. *J. Mater. Chem.* **21,** 15232–15236 (2011)

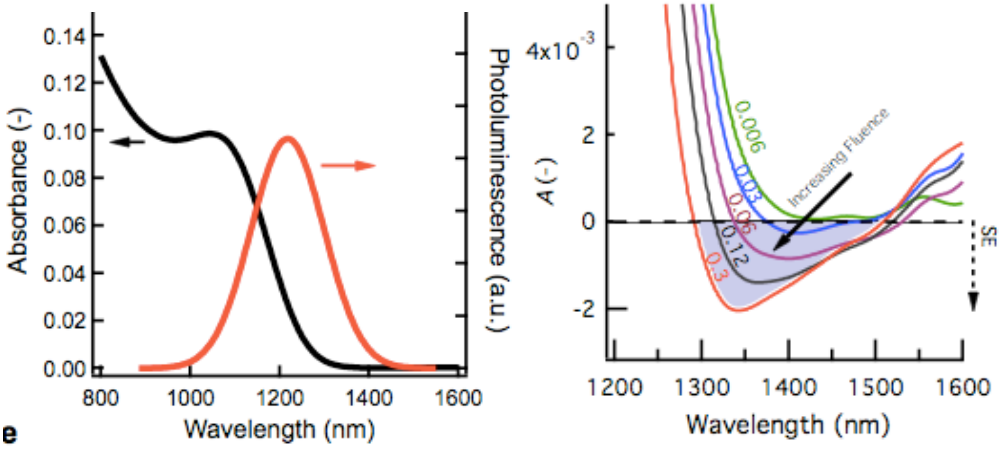

Figure 1 Absorption and photoluminescence spectra of HgTe QDs (left). Absorption spectra *A*, taken 2.5 ns after photo-excitation. Stimulated emission (SE) corresponds to $A < 0$. The maximum gain bandwidth extends from 1310 to 1500 nm at sub-X fluence (<N>=0.3)(right).

Figure 2 shows the intrinsic material gain of the quantum dots under optical pumping (blue and red for QDs resp. emitting at 1220nm and 1300nm). In an optical film, we have of course to take into account the fill factor of the film. Assuming a close-packed film a peak gain of 100cm^{-1} (or 400dB/cm is extracted from the measurements reported in Figure 1b.

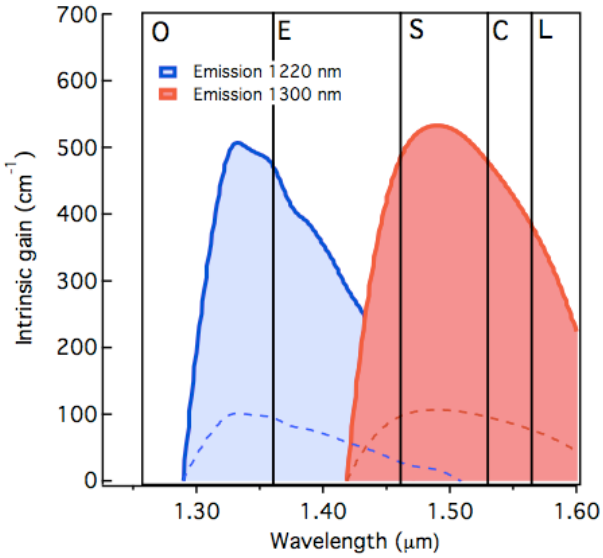

Figure 2 HgTe intrinsic material gain for two different samples emitting at 1220 nm (blue) and 1300 nm (red). The color-matching dashed lines indicate the volume-fraction corrected material gain. Note that the material gain provided by only 2 different sizes of HgTe covers the entire OESCL band with typical values over 100 cm.

3. HgTe QDs integrated in thin film

The next step towards realizing an optical amplifier using these novel QDs obviously is to integrate them into a waveguide structure. Several efforts in this direction were undertaken.

UVEG combined the HgTe QDs with PMMA based waveguide structures, either dispersed in a PMMA layer (Figure 3a) or as a close-packed layer between two PMMA layers (Figure 3b). In both cases luminescence was clearly observed and considerably stronger than for older samples with PbS QDs. Preliminary gain measurements using the variable stripe length method seem to indicate these samples exhibit an initial gain but the gain saturates rapidly and was not yet measured at the long wavelength side where gain under low pumping was measured in solution.

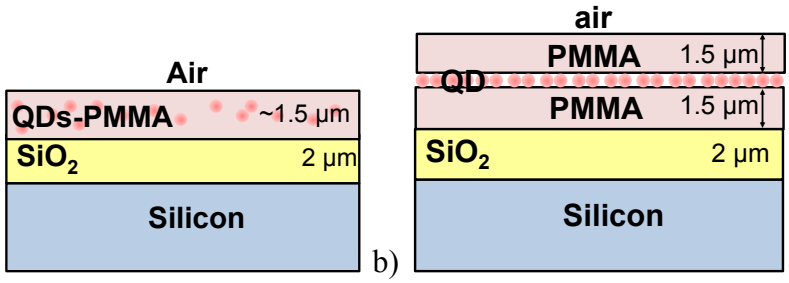

Figure 3 Waveguide structures studied: a) HgTe QDs dispersed homogeneously in a PMMA film and b) a dense close-packed HgTe QD layer sandwiched between two PMMA films. In both cases the polymers are deposited onto a SiO_2/Si substrate.

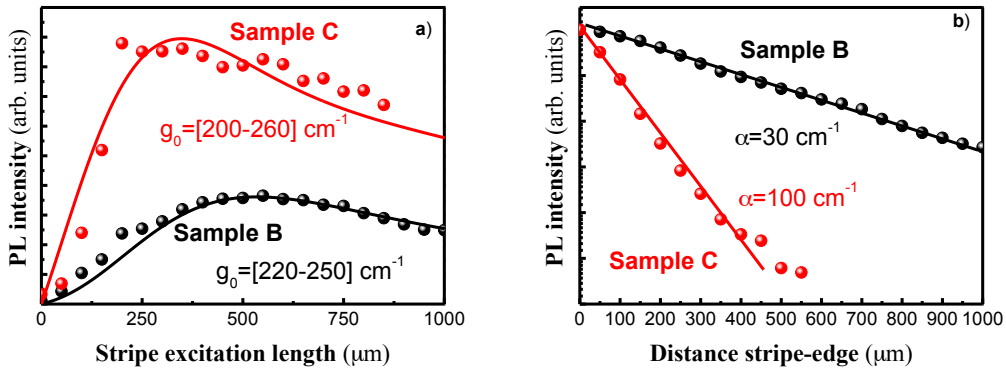

Figure 4 Peak photoluminescence (around 1000 nm) intensity as a function of the stripe excitation length (a, gain) and as a function of the distance between the stripe and the edge of the sample (b, losses). Samples A and B corresponds to QD filling factors of 0.008 and 0.08, respectively.

UGent measured the properties of HgTe QDs dispersed in polystyrene (PS) using pump-probe absorption spectroscopy. Films realized starting from such dispersions can form the basis for building an integrated waveguide structure. Unfortunately gain was not measured in these films. We believe this is associated to a change in the surface properties of the QDs. Work is now underway to further stabilize the QDs.

4. Conclusion

The fundamental properties of a novel QD material were characterised in depth using ultrafast absorption spectroscopy and nearly tresholdless gain was observed. From these measurements we could estimate a peak gain of at least 400dB/cm for a closed-packed film of this material, indicating that the project target of reaching 10dB gain under optical pumping should be within reach using this material. The next step now is to demonstrate such gain also for QDs deposited on a substrate, either directly or dispersed into a suitable polymer. Efforts in this direction are now underway.

Appendix A:

"Nearly Thresholdless Optical Gain using Colloidal HgTe Nanocrystals"
Manuscript prepared for submission