Wavelength agile quantum dot laser for lab-on-chip optical biosensors

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***Abstract*—We report simulations of photonic, optoelectronic, and thermal properties of a wavelength agile photonic crystal laser for lab-on-chip optical biosensors. We find that with an optimized cavity, lasing can be achieved with a single layer of QDs, providing a tunability by self-heating over 5 nm.**

Keywords—biosensor, photonic crystal, multiphysics simulations

I. Introduction

Conventional laboratory-based tests require the transport of samples to a specialised laboratory, where experienced personnel perform lengthy and costly tests. For many infectious diseases, an accurate and timely diagnosis at the point of care is critical. A solution to these unmet needs is offered by biosensors, devices where a transducer converts the ability to recognise a target analyte into a measurable signal. Current biosensor technologies are often bulky, expensive, and often passive. Among the different transducing strategies, optical biosensors offer exquisite sensitivity, versatility, fast read-out and analysis [1]

To be suitable for point-of-care application, the ideal device must be compact, easy-to-use, with the excitation, transducers, and detecting elements fabricated on the same chip. Photonic crystals cavities (PhC) have been proposed as transducing elements, due to their ability to produce sharp resonant modes close to a surface. The capture of an analyte by a receptor immobilised on the surface of the cavity is probed by the mode evanescent field and can be detected via a change of the resonance frequency [2]. PhC have inherently a small footprint (~1μm^2) compatible with wearable technology, and can be fabricated from a compound semiconductor material, where the direct band gap allows lasing and detecting elements to be integrated on the same chip.

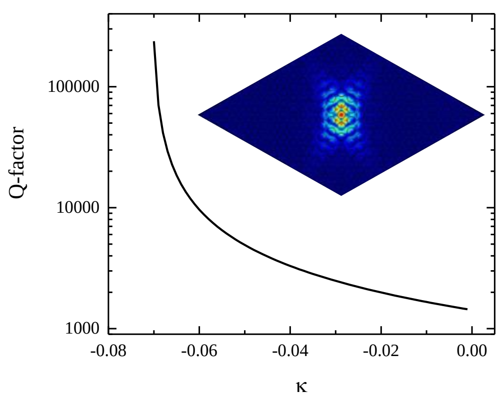

Fig. 1. Q factor of the M1 mode in a PhC L3 cavity as a function of the imaginary part of the refractive index of the gain material. The inset show the norm of the electric field of the M1 mode

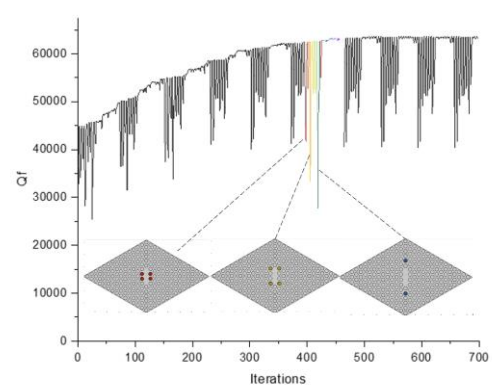

Fig. 2. Dependence of the Q factor on the iteration step of the optimisation protocol

We have investigated the optoelectronic and thermal properties of a PhC laser to be used as excitation element of a PhC based biosensor. The gain material is given by a layer of InGaAs quantum dots (QDs) in the centre of a p-i-n GaAs 2D photonic crystal

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slab. The PhC laser can be coupled to sensing PhCs via a photonic crystal waveguide. Multiple sensing cavities designed to resonate at different optical frequencies can be addressed by tuning the laser emission via current-induced local heating, allowing a multiplex diagnostic platform for the detection of many analytes at once. We find that lasing can be achieved with a single layer of QDs.

II. Results

A. Device structure

The properties of the laser have been simulated using a multiphysics modelling software (COMSOL). We have considered a GaAs photonic crystal with hexagonal lattice with lattice constant a=400nm and hole radius r=0.35a. The 2D slab thickness was set to 200nm and embedded in water. The InGaAs QDs have been modelled as a 5nm layer of gain material. The resonance frequency and quality factor of the PhC is determined from the eigenmodes of Maxwell's equations. A perfectly matched layer is positioned 400nm away from the slab to simulate outgoing boundary conditions.

B. Lasing threshold

To determine the material gain required to achieve lasing operations, we have simulated the Q factor of an M1 mode in a standard L3 PhC as a function of the imaginary part of the refractive index (κ) of the gain material (Fig. 1). The lasing threshold is indicated by a diverging Q factor. In the simulation, a κ of -0.07 of a 5nm layer is necessary to achieve laser operation for a nominal L3 cavity (Q~1400). We have extracted the material gain from the net modal gain measured in a InGaAs QD laser emitting at 1.3μm and we have obtained a saturation value of κ=-0.006, which is sufficient to obtain lasing for a Q factor of about 20000.

C. Optimising the cavity Q factor

We have developed an iterative algorithm to optimise the Q of a PhC by changing the position and radius of holes around the cavity. Each parameter is optimised independently. The step size is adapted to speed up convergence. As shown in Fig. 2, the Q of a nominal L3 cavity was increased from 1400 to >6e4 by this method, sufficient for lasing with a single layer of QDs as active material.

D. Wavelength tuning

Multiple sensing cavities which resonate at different frequencies can be interrogated by a single laser by tuning the emission wavelength via current-induced local heating. We have simulated the electronic properties of the proposed structure by introducing p and n doped layers. The dopant layers and diode conductivities have been calculated as a function of bias and temperature and used to define the total conductivity of the device. By engineering the thermal contact of the slab with the substrate, we have found that an increase of some 20°C due to resistive heating can be reached for a bias of 3V (Fig. 3), which also provides the required gain by population inversion. This corresponds to a tuning range equivalent to tens of sensing cavities with Q~10^4.

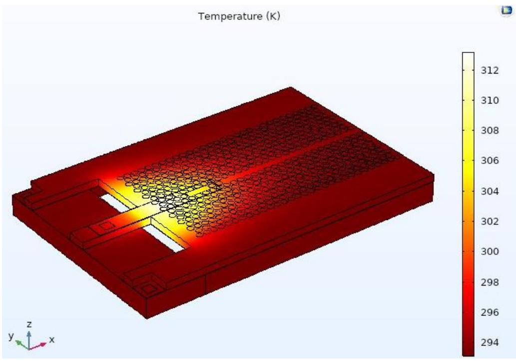

Fig. 3. Temperature distribution over the device geometry obtained for a bias voltage of 3V

III. Conclusions

We have investigated the opto-electronic and thermal properties of a PhC lasers for lab-on-chip biosensing. We found that lasing can be achieved with a single layer of InGaAs QDs for a resonator with Q larger than 20000. The laser can interrogate tens of sensing cavities via current induced local heating.

Acknowledgment

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References

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