Coupled Micro Ring Lasers based on Hybrid Integration of Colloidal Quantum Dots

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Abstract: Coupled and Random laser require flexible fabrication methods for photonic integration. Series of (random) coupled micro ring resonators were made with colloidal quantum dots and their unique properties investigated in both linear and lasing regimes.

1. Introduction

Coupling optical resonators in a regime of lasing opens up avenues for using amplified non-linearities, programmable lasing and steerable output without moving parts [1]. The technical difficulty of combining on-chip resonators is alleviated by using solution processable gain media, such as colloidal quantum dots, leading to photonic designs at will. Lasing with Colloidal quantum dots (CQDs) via optical pumping has reached a mature stage and was achieved in integrated photonic chips [2] and under CW pumping [3]. Complex architectures can be made easily on a single chip without need for bonding or hetero-epitaxy. In this work, we investigate the ability of CQDs to fabricate such complex cavities, focusing on coupled micro ring resonators as a demonstration.

2. Materials and Methods

CQDs are an attractive gain material for lasing because of their wavelength tunability, temperature stability and low threshold [3]. They are made via a wet chemical synthesis [5], what makes them a very versatile material. Because of the quantum confinement, the band gap (E_g) changes with the radius (R) of the nanocrystals as $E_g \propto 1/R^2$. We use CQDs with a CdSe core and a CdS shell with an outer diameter of respectively 4 and 7 nm (5). They emit light between 625 and 655 nm with a central wavelength at 640 nm. This broadening is due to differences in the size of the CQDs (4). The fabrication of the device is done as outlined in (1). On top of SiO_2, a 100 nm layer of SiN_x is deposited via PECVD. The CQDs are then spincoated on the sample resulting in a layer of 50 nm. A second 100 nm layer of SiN_x is deposited to embed the QDs. This results in a high stability and good confinement of the optical mode in the CQD layer. On top of this stack, a resist is patterned via e-beam lithography. Finally, the envisaged structures are dry etched. The result is shown schematically in figure 1. Lasing is achieved by pumping the structure with a green femtosecond laser. The red laser light is scattered and can be directed to a spectrometer to characterize the lasing behavior.

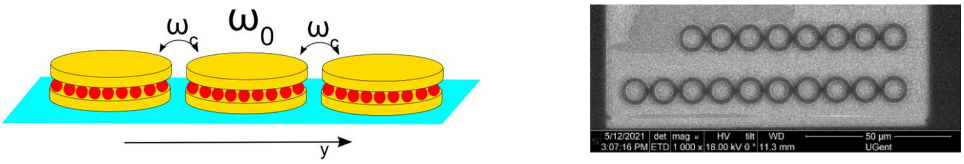

Fig. 1. (Left) The fabricated system of coupled disks. The SiO_2 is blue, SiN_x yellow and CQDs red. (Right) SEM image of fabricated microring arrays.

3. Results

3.1. Modelling of a system of coupled resonators

The lasing modes change when going from a single ring resonator to a system of multiple coupled resonators. To understand this, modelling based on coupled mode theory is used. Consider a chain of N equal ring resonators with a particular whispering gallery mode (WGM) with resonant frequency ω_0, as in figure 1. A photon in this resonator will than have an energy of $\hbar\omega_0$. Each resonator interacts with its neighbors with an interaction energy $\hbar\omega_c$. The Hamiltonian of the system is then an $N \times N$ matrix given by:

$$H = \hbar \begin{pmatrix} \ddots & \ddots & \ddots & & \\ & \omega_c & \omega_0 & \omega_c & \\ & & \ddots & \ddots & \ddots \end{pmatrix} \tag{1}$$

The resonant frequencies of the coupled system are then found as the eigenvalues (ω) of this Hamiltonian, and the distribution of the modes over the different resonators is represented by the eigenvectors (ψ) with:

$$(-H + \omega)\vec{\psi} = 0 \tag{2}$$

As a first example, consider the case of N = 2. The eigenvalues of the Hamiltonian can readily be obtained as $\omega = \omega_0 \pm \omega_c$. The coupling gives rise to a bonding (lower in energy) mode and anti-bonding (higher in energy) mode. In the case of many resonators, the first eigenvector is given by $(\vec{\psi})_n = \sin\left(\frac{n}{N}\pi\right)$. If one calculates the eigenvalues of a 10×10 Hamiltonian as in equation 1, this profile is indeed obtained. This can be seen by noting that the Helmholtz equation $(\Delta + \omega)\vec{\psi} = 0$ has a similar form as equation 2. Thus, we can get the eigenvectors of the Hamiltonian as eigenfunctions by solving the continuous differential $-\frac{\partial^2\psi}{\partial y^2} + \omega\psi = 0$ (with Dirichlet boundary conditions).

3.2 Experimental results

The measured spectrum of a system of 10 rings of 10 µm diameter is shown in figure 2. In the spectrum, taken from the whole system, one can distinguish three WGMs. The top graphs show the intensity of the different spectral lines along the chain of rings (y axis in figure 1). In this way, the mode profile can be obtained. One can see that the $\sin(n\pi/N)$-profile is present in the envelope of the first and second graph. There is also a modulation because of the ring structure. The WGM mode closest to the center of the gain also shows a secondary peak, corresponding to a mode profile that is pushed away from the center due to mode competition. This can be seen in the third mode profile. The bending of the LL curve confirms the mode competition and thus the extended states.

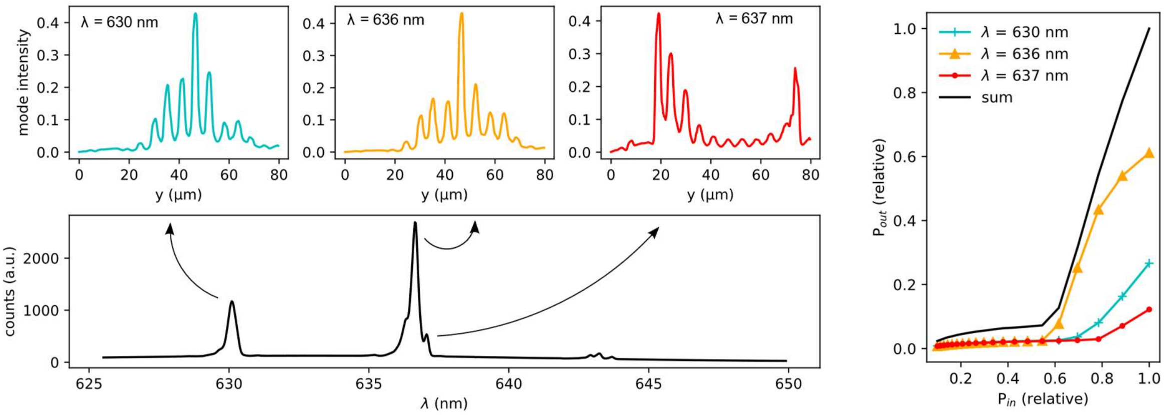

Fig. 2. Bottom: Measured spectrum of a system of 10 rings. Top: the mode profile corresponding with the different peaks. Right: LL-curve of the different modes, showing mode competition.

The same measurement was done on a sample whereby the diameter of the different micro-rings had a small random variation. The mode profile is than localized to one or two resonators. This effect is seen in both simulations and experiments. It illustrates that structural disorder in the lattice can confine light and reduce mode competition because of lower spatial overlap between lasing modes.

In conclusion, we demonstrated lasing in a complex cavity. Paving the way for the use of CQDs in random lasers.

3. References

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