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Modelling the polarisation mode control of single quantum-dot emission in elliptical micro-pillar microcavities based on DBR mirror pairs using the FDTD method

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Abstract: We use the finite difference time domain method (FDTD) to investigate polarisation control of single-photon emission from single quantum dots confined in elliptical micro-pillar microcavities. In contrast to circular pillars, one of the cavity modes has smaller modal volume and maintains high Q-factor.

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1 Introduction

Recently, single photon source have been realised by coupling InAs quantum-dots into a circular micro-pillar microcavity based on distributed Bragg reflectors (DBRs) [1-3]. These sources can be highly efficient because the high semiconductor refractive index collects a large fraction of the spontaneous emission into the waveguide mode. For quantum information application, polarization mode control of single-photon sources is important to allow encoding in polarisation and to avoid birefringence in the optical components. Hence we consider polarisation control of single-photon emitters in pillar microcavities and study the electromagnetic field distribution by changing the cross-section from circular to elliptical [4]. We aim to design highly efficient single-photon polarisation operation for very large Purcell factors ($F_p$).

2 Geometries of circular and elliptical micro-pillar microcavities

We use the 3-D finite difference time domain (FDTD) method to analyze circular and elliptical micro-pillar microcavities based on DBR mirror pairs as shown in Fig. 1. The micro-pillar microcavity is designed to be made of III-V semiconductor materials (AlAs/GaAlAs) with quarter-wavelength-period stacks resonant at the wavelength of 980 nm for large radius [5]. Here we will concentrate on the results from elliptical pillar with a 1.5 µm major axis (z-polarisation) and a 0.5 µm minor axis (x-polarisation) and on 0.6 µm circular pillars. The pillars consist of a GaAs λ-cavity between a 27 pair AlGaAs/GaAs DBR lower mirror and a 20 DBR pair upper mirror.

3 Simulation Results and Discussions

We place a broad band Ex-dipole source in the centre of the microcavity and input a short few-cycle excitation pulse to model the emission from the quantum dot. The cavity then rings at its resonant frequency and we monitor this using a probe above the pillar. Taking the Fourier transform of the ringdown signal (in time) allows us to determine the resonant frequencies of the of the cavity as shown in Fig. 2 (a) and also to an estimate the Q-factor.
We then focus solely on the cavity resonant frequency to plot electric field distributions in figures 2(b-j), and estimate emission efficiency and enhancement into the cavity mode (the Purcell factor).

In the elliptical pillar we find two resonant modes corresponding to the x- and z-polarisation modes. The x-polarised mode is a low Q-factor mode due to lowered mirror reflectivity for this polarization. However the Q-factor of the z-polarized mode remains high despite the small cross-sectional area of the elliptical pillar. This suggests we can maintain high Q-factor with a low effective mode volume \( V_{\text{eff}} \) and thus achieve high Purcell factors. In these preliminary calculations we have seen Q-factor of 10985 in the z-polarised mode and 1538 in the x-polarised mode for elliptical pillar with a 1.5 \( \mu \)m major axis and a 0.5 \( \mu \)m minor axis. Using the electric field distributions we can estimate \( V_{\text{eff}} = 0.07599 \mu^3 \) and thus predict a Purcell enhancement of \( F_p = 204.97 \) for z-polarisation. In contrast, for the circular Pillar of radius 0.6 \( \mu \)m we see a mode volume \( V_{\text{eff}} = 0.03855 \mu^3 \) and predict a Purcell enhancement of \( F_p = 251.52 \).

### 4 Conclusions and Further Work

We show the progress toward the polarization mode control of single-photon sources in elliptical micro-pillar microcavities using 3-D FDTD method. We have seen our preliminary result for the Purcell factor of 204.97 in z-polarisation. In the future, we will continue the study of various structure shapes to aim for the smallest possible modal volume with high-Q operation. This will eventually bring us to the strong coupling regime of reversible spontaneous emission in which the cavity dynamics are described by vacuum-field Rabi oscillations [6,7].

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**References**