# Simulation of InGaAs Quantum Dot Photonic Cavities for 850 nm Free-Space Optical Communication


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***Abstract*—On-demand and pure single photons are the backbone of various quantum applications. Popular nonlinear conversion-based spontaneous parametric downconversion suffers from its probabilistic nature and the trade-off between brightness and purity. However, quantum dots, vacancies, and 2D material based on-demand single photon emitters are viable. Here, we focus on solid-state quantum dots because of their dimension tunability and their emission. In this communication, we focus on a specific wavelength of 850 nm, emitted from a dot, important for free space optical communication, unexplored previously. The proposed structure includes quantum dot made of InGaAs within a DBR cavity or without. We have studied the electric field, cavity mode and extraction efficiency of the proposed structures using 3D FDTD simulations.**

***Index Terms*—molecular beam epitaxy, quantum dot, FDTD, free space communication, quantum emitter**


## I. Introduction

Epitaxially grown semiconductor quantum dots (QDs) are presently considered as one of the most promising sources of on-demand single and entangled photons, essential for both fundamental research and practical applications [1]–[3]. Out of various material combinations studied so far in the past few years, the much-studied QD system is based on GaAs and InAs QDs. GaAs dots can be grown by local droplet etching method and InAs QDs by Stranski-Krastanov (S-K) method on GaAs (001) substrate [4]–[6]. To achieve 850 nm, important for free space communication, InGaAs QD can be grown by local droplet etching (LDE) technique by in-filling both In and Ga together in the nanohole created by LDE [7]. In this article, considering the above possibility [7], we have simulated the few optical parameters of a distributed Bragg reflector (DBR) cavity structure which will be required to embed the InGaAs dot for the emission at 850 nm.


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## II. Structure

Before growing QDs using molecular beam epitaxy, it is necessary to know the position of the dot in the structure to align it with electric field antinode and to optimize the thickness of different layers. Since we focus on 850 nm, important for free space communication compared to popular 780 or 795 nm out of a LDE grown GaAs QD [8], we can avoid the absorption by GaAs substrate as the dot emission energy is smaller than GaAs layer at low temperature like ($\sim$ 10 K). Here, we present a DBR cavity structure designed to contain QD, as shown in Figure 1.

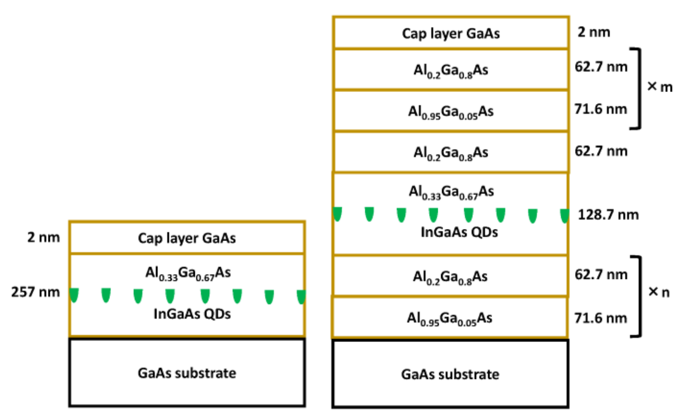


Fig. 1. Proposed structure for a designed dot emission wavelength of 850 nm - left one without cavity and the right one with nxm 1-$\lambda$ DBR cavity. We have used m as 9, 10, 12, 16 and n as 2, 4 and 5. The barrier to the InGaAs QD is the $Al_{0.33}Ga_{0.67}As$ matrix. $Al_{0.20}Ga_{0.80}As$ and $Al_{0.95}Ga_{0.05}As$ are used to make DBR layers.

## III. Simulation Results and Analysis

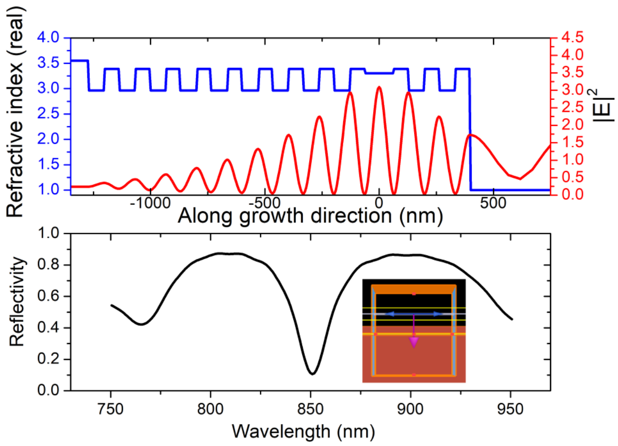


Fig. 2. Refractive index and electric field intensity profile for a 9x2 DBR cavity structure for 850 nm cavity mode position. Reflectivity profile of a 9x2 DBR cavity structure showing cavity mode at 850 nm. The inset shows a snapshot of the cross-section view of the photonic structure from the Ansys-Lumerical 3D FDTD engine.

In Figure 2, a refractive index profile for a DBR cavity with 9x2 (bottom x top) pairs and corresponding simulated electric field intensity ($|E|^2$) is shown, which indicates that QD is to be placed at the zero position to access the antinode. With plane wave normal-incidence on the DBR cavity structure with periodic boundary conditions, we have simulated the cavity mode to be at the expected position of 850 nm (see Fig. 1) by properly putting the thickness of the DBR layers and the $Al_{0.33}Ga_{0.67}As$ barrier. Notably, the simulation for the quantum dot emission extraction can be simulated considering QD as a dipole and only performing simulation within one quadrant only by leveraging the symmetry of the structure, considerably reducing the simulation time.

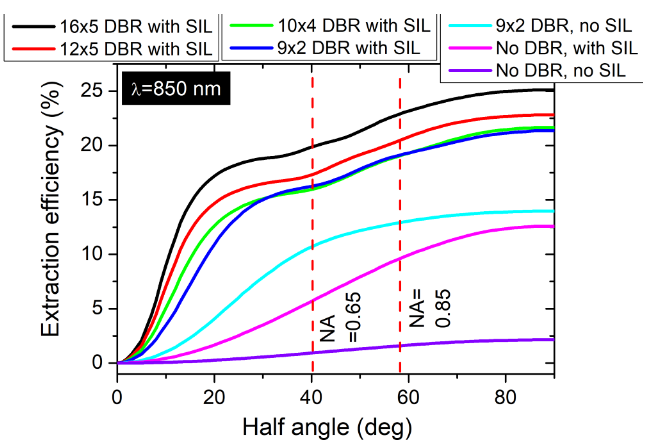


Fig. 3. Extraction efficiency of different structures plotted as a function of half-angle corresponding to the designed dot emission wavelength of 850 nm.

Light emitted by the QD is collected from the top of the structure generally using an objective. Various numerical apertures (NAs), such as 0.65 or 0.85, can be utilized for this purpose. Extraction efficiencies are calculated for different half angles (see Figure 3). Furthermore, while keeping an NA fixed, extraction efficiency can be calculated across different wavelengths; Figure 4 shows the same for NA of 0.65. Notably, we have used solid immersion lens (SIL) with refractive index of 2.1 on the epitaxial structure to collect more light, where SIL can be approximated here as a semi-infinite medium. From the simulation, SIL helps extracting more photons towards the top with a better farfield without using it. Also, around the cavity mode position, photon extraction is enhanced with introduction of more top/bottom pairs as shown in the Figure 3 and Figure 4. However, while increasing top/bottom pairs enhances extraction, there are limitations if the structure cannot be grown optimally. Therefore, challenges arise in efficiently extracting both X and XX photons using the same cavity mode.

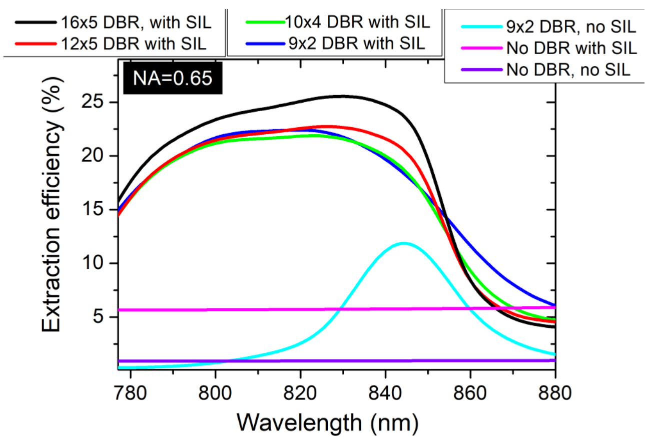


Fig. 4. Extraction efficiency of different structures plotted as a function of wavelength corresponding to a numerical aperture of 0.65.

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