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# Polarization-Independent Enhancement of Optical Absorption in a GaAs Quantum Well Embedded in an Air-bridge Bull's-eye Cavity

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**Abstract**

**Bull's-eye structures containing optically active media provide an attractive platform for implementing efficient photonic quantum interfaces. By exploiting their symmetric nature, we previously designed a bull's-eye optical cavity that enhances the optical absorption without polarization dependence, which can be applied to an efficient photon–spin converter using a gate-defined quantum dot (GQD). In this correspondence, we experimentally demonstrate that our bull's-eye cavity can enhance the optical absorption of a quantum well (QW) without polarization dependence. Photoluminescence excitation spectra from the fabricated cavities show the maximum 12-times enhancement of QW absorption. The enhancement is almost identical for orthogonal polarizations.**

## 1. Introduction

Gate-defined quantum dots (GQDs) formed in semiconductor quantum wells (QWs) are optically accessible spin qubits. They are especially advantageous for sophisticated quantum information platforms due to the mature technics for manipulating spins in the GQDs [1-3]. One of the applications is quantum repeaters which are indispensable in large-scale quantum networks. To date, the quantum state conversion from a photon polarization to an electron spin state in GQDs formed in a GaAs QW has been reported [4, 5]; however, suffering from low efficiency on the order of ~$10^{-5}$. One promising approach for significant enhancement is embedding the GQDs in resonant optical cavities. Bull's-eye structures [6, 7] could be one of the excellent platforms for realizing efficient photon–spin converters. The centrosymmetric bull's-eye structures equally function for any polarization state, which is an essential property for the quantum repeaters using polarization–spin conversions. We previously reported a design of bull's-eye cavities capable of introducing a single GQD at the center and numerically demonstrated that a significant enhancement of absorption in the GQD is attainable [8].

In this study, we fabricated bull's-eye cavities in an air-suspended GaAs QW slab and demonstrated the absorption enhancement by photoluminescence excitation (PLE) measurements. We confirmed that the enhancement possesses little polarization dependence, which is the core requirement for the photon–spin converters. The result is a direct proof-of-usefulness of the designed bull's-eye cavities toward efficient quantum repeaters using GQDs.

## 2. Cavity design and sample fabrication

Figure 1(a) represents a schematic of the fabricated bull's-eye cavity in this study. A six-period of a circular grating (period $a$, air-gap filling factor G = 0.4) embracing a circular cavity of a diameter $A_c$ (= $a$) is formed in an air-suspended 165-nm-thick semiconductor slab. The slab comprises a 15-nm-thick GaAs QW sandwiched between 75-nm-thick $Al_{0.33}Ga_{0.67}As$ layers. The partially filled regions (channels) crossing at the center with a width of $W = 0.29 \times a$ provide a space for introducing electrodes to form a GQD at the center. These channels also enable the air-bridge structure. The supported degenerate modes around a normalized frequency $f_0/a$ = 0.42 possess antinodes at the center of the cavity, enabling polarization-independent absorption enhancement by a GQD to be introduced at the center in our future work. The theoretical quality factor of the modes is $Q_{\mathrm{rad}} \sim 130$.

We used standard fabrication technologies of GaAs-based photonic nanostructures: electron-beam lithography, dry etching, followed by an under-cut process by the HF wet etching. Figures 1(b) and 1(c), respectively, show the top view and the angled view of scanning electron microscopic (SEM) images of fabricated devices.

## 3. Optical characteristics

We performed room-temperature micro-photoluminescence excitation (PLE) measurements for the fabricated cavities. In Fig. 2(a), we show a PLE spectrum taken from a sample with period $a$ = 333 nm. For comparison, typical above-band excited (635 nm) PL spectra from the same sample/unpatterned wafer are shown with solid/dashed lines. In the PLE experiment, we excite the samples with a monochromatic laser (continuous wave Titanium-Sapphire) and then monitor the QW emission (integrated within the main peak $\lambda_{\mathrm{QW}}$; 855

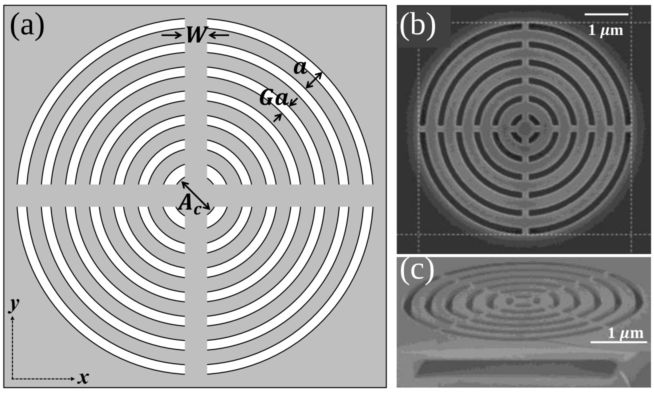


Fig. 1: (a) Schematic of fabricated bull's-eye cavity structure. (b-c) Top view (b) and angled view (c) SEM images of a fabricated Bull's-eye cavity (with *a*'s = 411, 372 nm respectively).

~ 862 nm). As indicated by the arrow, we can identify the cavity mode peak in the PL spectrum; however, it is more clearly observed in the PLE measurements. Figure 2(b) shows the PLE spectra from the cavities with several periods and the unpatterned wafer. A clear red-shift of PLE spectra as increasing the period *a* is confirmed, indicating the absorption is resonantly enhanced by the cavities. The measured quality factor from the sample with *a* = 337 nm is *Q* = 80, which is very close to the theoretical value of *Q* considered with the QW absorption ($Q_{abs}$ = 216 [8]): $Q^{-1} = Q_{rad}^{-1} + Q_{abs}^{-1} = 81^{-1}$. Compared with the PLE from the unpatterned wafer, there is a large enhancement (~ ×12), demonstrating the absorption enhancement by the cavity. We then measured the polarization dependence of the PLE spectrum in the cavity with *a* = 337 nm, as plotted in Fig. 2(c). The closed and opened circles represent the PLE spectra with horizontal (*H*, electric field along to the *x*-direction) and vertical (*V*) polarization incidence, respectively. The result shows that the resonance peak for both polarizations is almost identical: the cavity is polarization-independent.

## 4. Conclusions

In conclusion, we fabricated a bull's-eye optical cavity containing a GaAs QW and demonstrated polarization-independent absorption enhancement. The PLE spectrum measured on the cavity shows × 12 enhancement compared with the unpatterned area, with a quality factor of *Q* ~ 80 as predicted by theory. Because our fabricated structures allow the GQD to be placed at the center, our result is direct evidence that the designed bull's-eye cavity can significantly enhance the efficiency of photon–spin conversions in GQDs. We believe that we can measure cavities integrated with electrodes forming the GQDs shortly.


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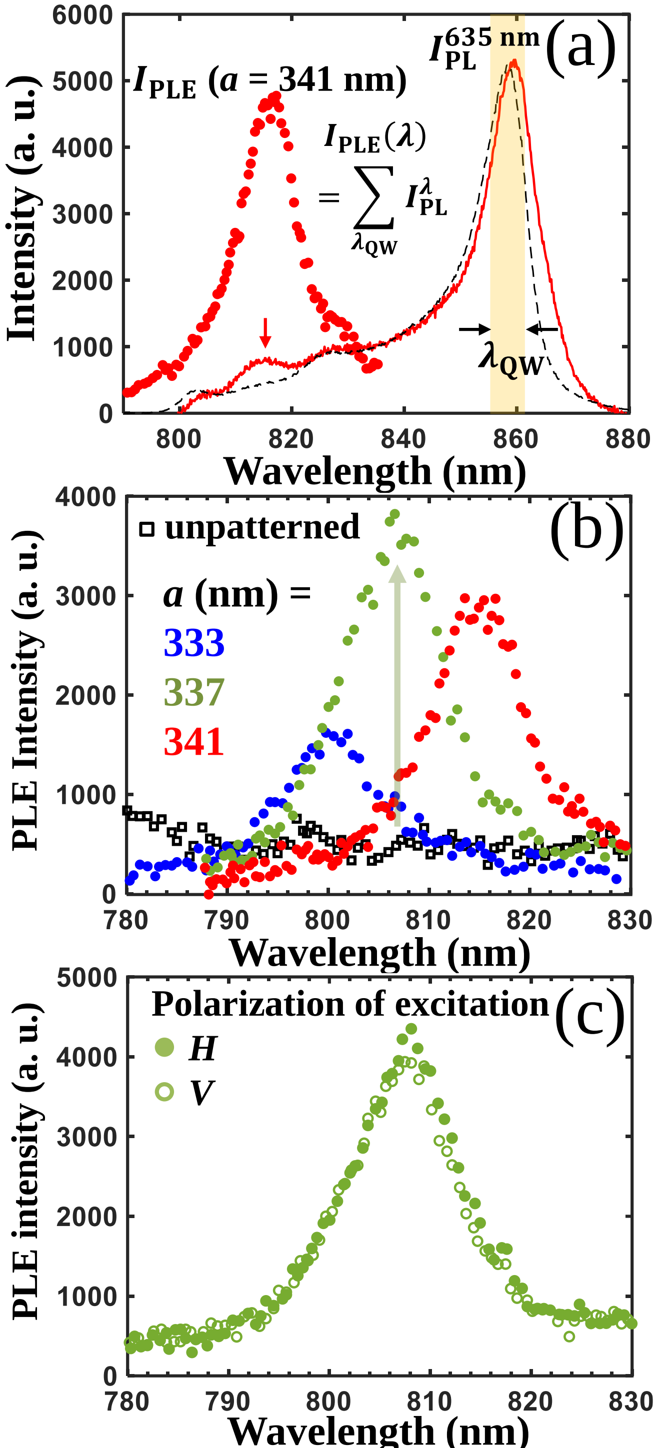


Fig. 2: (a) PLE spectrum taken from cavity with *a* = 341 nm. Solid/dashed lines represent typical PL spectra from the same sample/unpatterned wafer. (b) PLE spectra measured on the cavities with period *a*'s 333, 337, and 341 nm. Black squares represent PLE spectrum from unpatterned area. (c) Polarization dependence of PLE signal (*a* = 341 nm) to the excitation polarization.