Nano-rings for improved extraction of single-photons and disorder-induced efficient visible-light confinement on a chip

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Abstract: We report on the enhancement of the collection efficiency from epitaxial InAs/GaAs quantum dots through the deposition of metallic rings centered around single emitters, located with a nanometer-scale accurate photoluminescence imaging technique. Increases of up to x17 in the brightness of the single-photon emission are measured, due to an excitation and collection lensing effect. Furthermore, we demonstrate efficient confinement of visible light in disordered photonic crystal waveguides, reaching quality factors of ~10000, exceeding values previously reported in two-dimensional photonic crystals.

Bright single-photon sources are required for various quantum information technology applications. However, the photon extraction efficiency from solid-state emitters can be severely limited by the high refractive index mismatch between semiconductors (like GaAs) and air, resulting in most of the emitted light being trapped within the high-index material. Several approaches have been implemented in order to increase the extraction efficiency, including photonic nanowires[1], micropillars[2] and circular gratings[3]. Solid-immersion lenses[4], deposited on the materials surface or 3D printed via in situ lithography[5], have also been used to focus the excitation and the emitted light, thus increasing the emitted photon flux.

We report on two different approaches that we follow to control the light-matter interaction on a chip, based on broadband metallic rings and high-quality light confinement in disordered photonic crystal waveguides.

By implementing a photoluminescence imaging technique[6], we position single InAs/GaAs quantum dots grown by molecular beam epitaxy with accuracies of ~20 nm. We then deposit, by means of electron-beam lithography followed by a lift-off, metallic gold rings with inner diameter of ~440 nm, centered around single emitters (see Fig.1a). A confocal photoluminescence set up is used to excite selected single quantum dots with a continuous wave laser and the intensity of the single-photon emission is measured on a charge-coupled device (CCD), before and after the rings are deposited.

(a) (b)

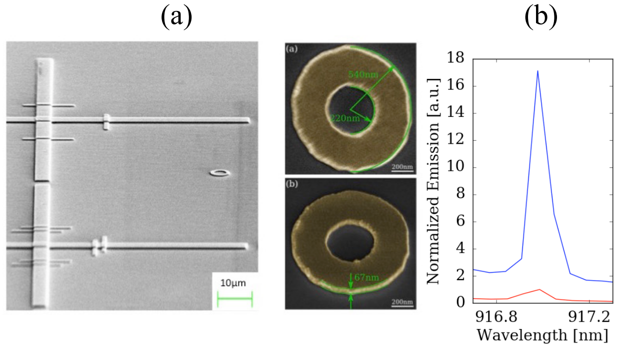

Fig.1: (a) Scanning electron microscope image of a gold ring deposited on a GaAs chip containing InAs quantum dots. (b) Photoluminescence spectra measured from a single quantum dot, before (red) and after (blue) metallic ring deposition (temperature T = 10K, laser excitation wavelength = 780 nm).

We measure enhancements of the emission intensity as high as ~17 (see Fig.1b), due to a lensing effect on the laser excitation light and on the emitted light. Compared to optical cavities, our ring devices are intrinsically broadband, since they do not rely on a high-quality factor photonic cavity, and can therefore be implemented with any kind of solid-state emitter. The performances of the rings, obtained with a much easier fabrication technique compared to in situ lithography, also surpass those of 3D printed solid-immersion lenses[5] by almost an order of magnitude. Given the dimensions in play, such metallic rings could also be fabricated using lower resolution techniques such as photolithography and nano-imprinting, thus improving scalability.

A variety of solid-state emitters like colloidal quantum dots, defect centers in diamond and in two-dimensional materials act as single-photon sources operating in the visible range of wavelengths. Being able to control the spontaneous emission dynamics and efficiently confine the emitted light in high-quality optical cavities is of paramount importance for the implementation of visible emitters in quantum photonic devices. However, the quality factors of visible light confinement on a chip so far reported in highly engineered photonic crystal cavities lie between a few hundreds and a few thousands: the enhancement of the light-matter interaction achievable is therefore limited compared to devices operating at longer wavelengths.

By using disorder as a resource, we demonstrate an improvement in the quality of light confinement on a chip of up to an order of magnitude, in optical cavities operating in the Anderson-localized regime (see Fig.2). We report quality factors reaching values of ~10000 in disordered photonic crystal waveguides operating in the visible range of wavelengths on a silicon nitride platform[7]. This is a significant improvement with respect to the state-of-the-art and proves the potential of disorder-induced confinement of visible light for on-chip photonics.

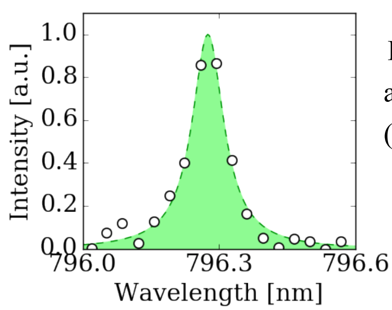

Fig.2: Photoluminescence spectrum of an Anderson-localized cavity (symbols) and its Lorentzian fit (dashed line), showing a quality factor Q = 9300±800 (temperature T = 300K, laser excitation wavelength = 473 nm).

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