# Parallel Recording of Single Quantum Dot Optical Emission Using Multicore Fibers

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*Abstract*—**Single Indium Arsenide Quantum Dot emission spectra have been recorded using a four-core, crosstalk-free, multicore fiber placed at the collection arm of a confocal microscope. We developed two different measurement set-ups depending on the relative configuration of the excitation and collection spots. In the single-matched mode, the emission from the excited area is collected by a single core in the multicore fiber, whereas the three remaining cores capture the emission from neighboring, non-excited areas. This procedure allows for the recording of the Quantum Dot emission from carrier diffusion between sample positions separated by more than 6 µm. In the multiple-matched mode, the excitation spot overlaps the four cores emission area. This configuration permits the acquisition of the micro-photoluminescence spectra at different sample positions without scanning. These results show the possibilities offered by multicore fibers for the spectroscopic analysis of single semiconductor Quantum Dot optical emission.**

***Index Terms*— Multicore fibers, Single Quantum Dot, Spectroscopy.**

## I. Introduction

Research in semiconductor quantum dots (QDs) has been extensively developed along the last two decades. A single QD represents a nano-laboratory where it is possible to probe a number of fundamental physical effects, such as coulombic interaction, spin effects, quantum non-local correlations or light-matter interaction in quantum electrodynamics (QED) approaches [1]. Single QD spectroscopy has been revealed as a powerful tool to study these fundamental optical properties. Within this context, a variety of novel spectroscopic tools incorporating fiber-optics techniques has been demonstrated. The use of a tunable Fiber Bragg Grating (FBG) as a wavelength filter of single QD emission was recently demonstrated [2]. This all-fiber filtering technology increases the collection efficiency by more than an order of magnitude in comparison with standard spectroscopic instruments, thus permitting the study of time-resolved single QD optical emission at 1300 nm [2]. Moreover, FBG reflection has been used recently in QED experiments, where QD emission is coupled to a fiber-based cavity [3,4]. Following these strategies, it has been demonstrated strong coupling regime of single QD emission [3]. In another all-optical fiber-based single QD spectroscopic strategy, a fiber taper was used to enhance the optical collection efficiency by evanescent light coupling [5]. Recently, a similar fiber taper strategy has been used to increase the single photon collection efficiency to an impressive 23% value [6], which offers an enormous enhancement compared to conventional free-optic set-up efficiency.

Multicore fibers (MCF), i.e., optical fibers containing several individual cores, have received a growing interest along the last decade [7]. Many applications are being proposed in fields like high-capacity optical communications exploiting space-division multiplexing [8], microwave photonics [9], optical shape sensors [10] or photonic lanterns devices [11]. State-of-the-art MCFs designed for digital communications incorporate up to 30 cores in an outer diameter ranging from 125 to 230 µm [12], while up to more than five hundred cores for astrophotonic applications [11].

In this letter we propose the use of a MCF as a collection element in a confocal microscopy set-up for the parallel recording of micro-Photoluminescence (µ-PL) spectra. In a series of proof-of-concept experiments, we explore the emission of the optically-pumped Indium Arsenide (InAs) QDs grown in Galium Arsenide (GaAs). In particular, we explore two different excitation/collection configurations. In the first, multiple-matched mode, we recorded single QD spectra from four sections of the excitation region, each collected by one of the four fiber cores. This procedure generates an instantaneous µ-PL four-pixel image without the need of scanning through the sample. In the second, single-matched mode, the emission of an optically-excited region is collected by only one fiber core, whereas the other three cores probe the emission in neighboring, non-excited sample regions. Using this procedure, we identified optical evidences of carrier diffusion through the GaAs barrier states. Both experiments constitute representative examples of novel fiber based spectroscopic measurement techniques for the characterization of light emitted by single QDs.

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## II. Sample and Set-up

The QD sample has been grown by Molecular Beam Epitaxy (MBE) on a GaAs substrate. After a 100 nm-thick GaAs buffer, InAs has been deposited at a low growth rate (0.009 ML/s) at 535 ºC with an equivalent coverage of 2.5 MLs; the growth ended with a 100 nm-thick GaAs cap grown by atomic layer MBE at 360 ºC. During the InAs deposition, the substrate was not azimuthally rotated, thus obtaining a continuous variation of the InAs coverage throughout the sample surface. These conditions resulted in a density of InAs QDs of about 16 QDs $\mu m^{-2}$, as estimated from atomic force microscopy (AFM) images of uncapped samples grown under the same conditions [13].

Fig. 1.a shows the MCF µ-PL set-up. The excitation source is a Ti:Sapphire laser operating in continuous wave at 775 nm. This laser is coupled to a single-mode optical fiber connected to the excitation arm of a confocal microscope operating at liquid helium temperature (4K). As objective and collimating lenses we used two aspheric lenses with numerical aperture of 0.68 and 0.15, respectively, and the sample was held by XYZ piezo-motors. The µ-PL is collected with the MCF placed at the focal plane of the collimating lens. We used a 4-core MCF with a cladding diameter CD of 124.7 µm and a separation between adjacent cores of $\Lambda$ = 36 µm, each of which has a Mode Field Diameter (MFD) of 8.4 µm, as shown in Fig. 1.b. The four-core MCF allows for the parallel collection of four diffraction-limited spots in the sample plane, each of them with a spatial diameter of around 1.43 µm (for a wavelength of 980 nm) and with a mutual separation of 6 µm between adjacent spots. Spectral analysis of the collected emission is performed by use of a fan-out device that couples each MCF core output to a different SMF (Fig.1a). These four SMFs are coupled in succession to the entry slit of a double 0.3-m monochromator that disperses the µ-PL signal into a Si Charged Coupled Device (CCD).

In our microscopy experiments we operated the confocal microscope both in focus and also out of focus. Fig. 1.c and 1.d (left) show the collection spots in the sample plane, labelled as 1-4 as in Fig. 1.b. The visualization of these spots was carried out by coupling a 980-nm laser diode (in order to simulate the µ-PL wavelength) to the four fan-out outputs and recorded with the vision CCD camera, which was attached to a secondary exit of the confocal microscope (Fig. 1.a). In the in-focus mode (Fig. 1.c, left), the sample plane is located at the focus plane of the objective lens, so that the observed four spots correspond to the ≈ 1.43-µm FWHM diffraction-limited spots mentioned above. In turn, when the MCF plane is slightly displaced out of the focus of the collimating lens in the collection arm, the collection spots almost overlap, as shown in Fig. 1.d, left, and therefore it allows for the parallel recording of a four-pixel image of the sample area without the necessity of scanning through its surface.

These two collection modes, in-focus and out-of-focus, were used in conjunction with specific excitation spots position, as shown in Fig. 1.c and 1.d (right). When the MCF is in focus, the excitation spot was adjusted to match only one of the four collection spots, in this case number 1, and hence

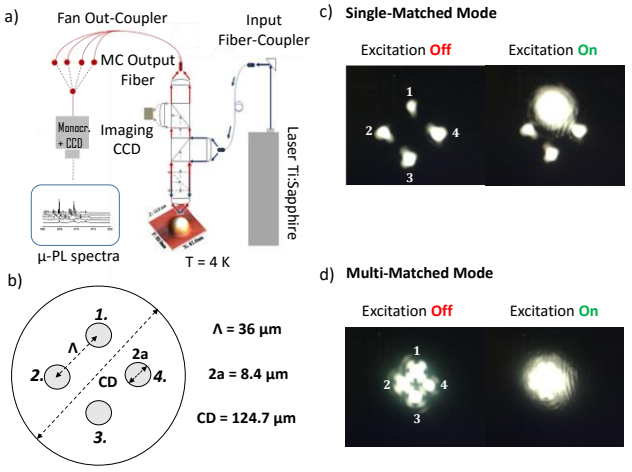


Fig. 1. a) µ-PL Set-Up with MCF in the collection arm of the confocal microscope. b) Scheme of the MCF. c) Images of the single-matched mode excitation and collection spots, when the excitation is turned off (left) and on (right). d) Images of the multiple-matched mode excitation and collection spots, when the excitation is turned off (left) and on (right). We labelled the four cores as 1-4, as in Fig.1.b.

the µ-PL at the spot areas 2, 3 and 4, recorded by use of the other three single mode cores, only collect emission if carriers photogenerated at area 1 diffuse through the sample before recombination. For this reason, the in-focus collection mode will be used here to discuss diffusion effects at two different spatial separations, corresponding to the closest (spots 2, 4) or farthest (spot 3) collection spots. This operation mode will be referred to as single-matched mode. On the other hand, when the MCF is placed out of focus, the excitation spot of the Ti:Sapphire laser was directed to the center of the four collecting spots, covering the whole four collection spots, as shown in Fig. 1.d, right. This multiple-matched operation mode permits the recording of a four-pixel image of the µ-PL emission in the excited area.

## III. Experimental Results

In a first series of experiments we used the MCF-based confocal microscope in single-matched mode to investigate the emission of our QD sample at four different collection spots. Fig. 2.a shows temperature-dependent µ-PL spectra, where numbers in blue circles identify the four collection spots, as defined in Fig. 1.b. A broad emission band centered at about 870 nm and sharp emission lines in the range 880 - 920 nm characterize all µ-PL spectra. The broad emission at 870 nm arises from exciton recombination at the InAs wetting layer (WL) [14], whereas the sharp emission lines are associated to exciton recombination in single QDs [13]. All emission lines are more intense in spot 1, given that this collection spot spatially overlaps with the excitation area (Fig. 1.c). Noticeably, we also found a significant signal at the collection spots 2, 3 and 4 located far from the excitation area.

The relatively large µ-PL signal in these spots (2-4), which is only a factor of ≈ 10 times smaller than that collected in 1, can be attributed to the diffusion dynamics of the photogenerated carriers at the GaAs substrate. These carriers are partially captured by the QDs through the WL at the sample area defined by the excitation spot 1, and partially

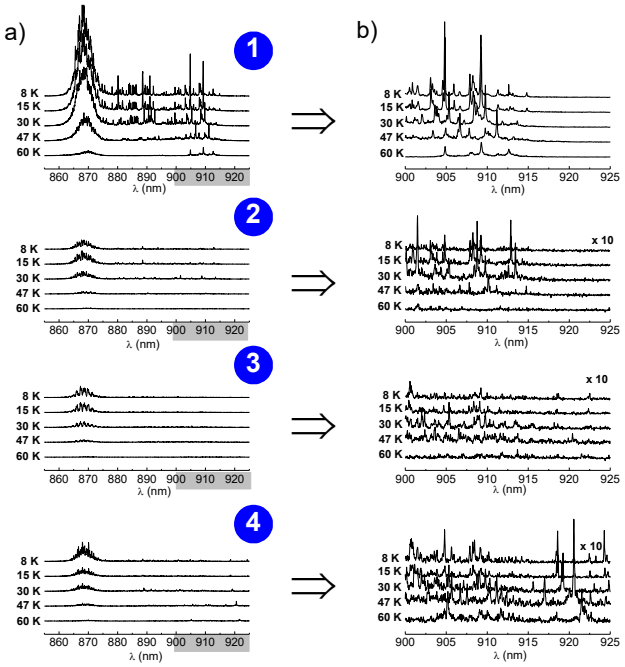


Fig. 2. a) Temperature evolution of the μ-PL from InAs WL and QDs, recorded with MCF confocal microscope operated in single-matched mode (Fig. 1.c). Excitation spot matches with core number 1. μ-PL recorded at cores numbers 2, 3 and 4 comes from carrier diffusion at GaAs. b) Spectral zoom of Fig. a) over the 900 – 925 nm (grey shadow in λ axis in Fig. a)).

diffuse out radially from this region. Let us recall that carrier diffusion lengths in GaAs range between tens and hundreds of microns [15]. Since collection spots 2 – 4 and 3 are separated 6 and 8.5 μm from spot 1, respectively, these areas are expected to show a less intense exciton recombination in the WL, since carriers arrive by diffusion from GaAs states excited at spot 1. In order to compare these μ-PL results with a possible QD emission at spots 2-3-4 from the tail of the excitation beam, we modeled the excitation Airy-disk and calculated the relative excitation intensity incident at spot 1 and spots 2-3-4. This tail excitation effect is more than two orders of magnitude weaker than the relative intensity calculated from our μ-PL acquisition, showing that carrier diffusion through GaAs is the main source of the optical emission at spots 2-3-4.

Fig. 2.b shows a zoom of the spectral range marked for the whole μ-PL spectra in Fig. 2.a (900-925 nm range). In this spectral range single QD emission is detected for all four collection spots. Also, as it was shown in the previous figure, the μ-PL intensity is weaker in collection spots 2, 3 and 4. The μ-PL signal from these single QDs located in zones 2-4 is due to partial trapping of carriers arriving by diffusion through GaAs and WL states. Furthermore, spot 3 shows the weakest single QD emission, consistent with its larger distance to the excitation spot.

The temperature dependence of the μ-PL signal is also shown in Fig. 2.b. It is observed a shift towards low energy of the single-QD excitonic transitions and an intensity quenching, due to thermal promotion of carriers towards high energy levels. The low-energy shift follows the semiconductor band gap redshift, and the linewidth suffers thermal broadening due to exciton-phonon interaction [14]. At the

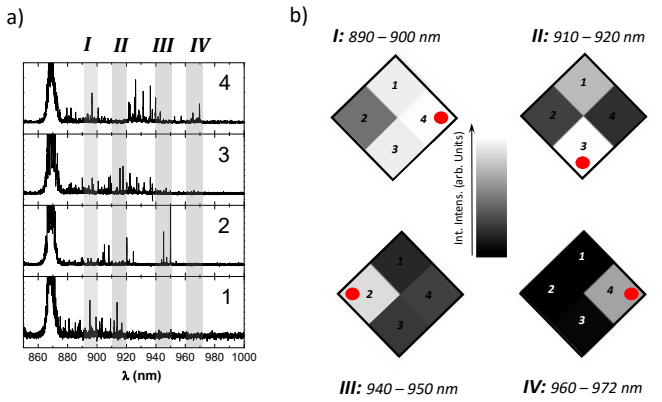


Fig. 3. a) μ-PL spectra of InAs QDs recorded with MCF confocal microscope operated in broad-area mode (Fig. 1.d). The excitation spot is manipulated to cover all collection spots (from 1 to 4). b) Four-pixel representation of the integrated intensity in each core (1 to 4) corresponding to four different μ-PL spectral ranges (I, II, III and IV), visualized with grey strips in a).

same time, spectra from spot 4 in Fig. 2.b show an increase and a subsequent quenching of the μ-PL signal from the single QD emitting around 920 nm, as temperature increases from 10 to 60 K. This particular form of μ-PL signal enhancement has been previously observed in a similar sample, and was attributed to the thermal promotion of carriers from the WL to QD by diffusion process activated around 40 K [14].

Subsequently, we used the MCF-based confocal microscope in multiple-matched mode to record four-pixel images of the emission. Fig. 3.a shows μ-PL spectra recorded at very low power excitation (≈ 400 nW). Again, numbers 1 to 4 label the collected μ-PL spectra in Fig. 3.a in the four MCF collection spots of Fig. 1.d. Now, all μ-PL spectra are characterized by similar intensities, and by a common broad emission at ≈ 870 nm associated to exciton recombination at the WL, and a set of discrete emission lines in the range 880 – 970 nm from single QDs emission. In Fig. 1.d, inter-spot distances are ≈ 2.5 – 3 μm (square side) and ≈ 3.7 – 4.2 μm (square diagonal). With this data, the principal Airy-disk (with diameter ≈ 1.43 μm) is not affected from any spot overlapping, while secondary Airy-disks could suffer from some mixing, as it is shown in Fig. 1.d. However, this spot mixing is presumed to be under weak influence. In fact, our micro-PL analysis in Fig. 3.a shows a completely different QD scenario in each spot collection (from 880 to 970 nm), which represents an experimental evidence of a null or very weak spot mixing effect. We define four spectral ranges, labelled with roman numbers as I (890 – 900 nm), II (910 – 920 nm), III (940 – 950 nm) and IV (960 – 972 nm), which correspond to the shadowed strips in Fig. 3.a. These four spectral regions were selected because of the observation of significant single QD emission in some of the regions 1-4. In Fig. 3.b we plot using a gray level the corresponding integrated intensity for each collection spot 1-4. We observe that the brightest area of the four-pixel image, marked with a red circle, corresponds to a different MCF core (1 to 4), showing that the most intense QD emission in each of the selected spectral ranges I to IV is located in a different spatial region.

## IV. Discussion and Conclusions

In this letter we have shown how standard single QD characterization techniques benefit from MCF technology to develop new experimental schemes. We have proposed two different fiber-based microscope arrangements, depending on the excitation and collection spots alignment and matching, namely single-matched and multiple-matched modes.

In single-matched operation mode, the confocal microscope modified with the parallel collection capability of the MCF was used in conjunction with standard spectroscopic tools to study non-coincident excitation and collection spots. In our experiments we have used this setup to observe emission after carrier diffusion from the GaAs barrier to both the InAs WL and the QDs. This technique can be of use in the study of carrier diffusion effects in other fields of semiconductor physics, such as solar cells, offering new and versatile spectroscopic instruments where the MCF is used instead of standard single core fibers [16]. Furthermore, the use of MCFs in this mode is expected to be of interest in the study of other physical phenomena, such as surface plasmon polariton transmission and propagation experiments [17], or optical control of nanophotonic plasmon networks [18], where parallel collection of non-coincident excitation and collection spots are of importance.

On the other hand, the multiple-matched mode allows for the parallel acquisition of µ-PL images without scanning. We recorded a four-pixel spectral image of the emission of the InAs QD sample surface at different wavelengths. Although it is apparent that this low-resolution spectral image does not offer a high spatial resolution for sample characterization, single-mode MCF can be currently fabricated with up to 30 cores and hence provide sufficient spatial resolution and number of pixels to study site-controlled QD samples [19] or cavity-single QD coupled systems [20]. Moreover, in order to record a spectral PL image, we had to couple sequentially the four fan-out outputs into the detection fiber to measure the PL spectrum at each pixel. However, single-shot parallel recording can be implemented using a TIGER 2D slit configuration [21], where a slight rotation between the dispersion axis of the spectrograph and the MCF prevents the spectra of different cores from overlapping on the CCD camera, allowing for multi spectral recording in a single acquisition sweep.

The spatial selectivity provided by the use of the MCF in the collection arm of a confocal microscope offers new interesting set-up possibilities for µ-PL analysis. However, our MCF spectroscopy strategy presents some disadvantages that must be taken into account. For example, collection efficiencies in fiber tapered waveguide near-field optics for single QD spectroscopy are calculated from 0.1 % [5] to 25 % [6], where our combined fiber and free-optic spectroscopic schemes show a collection efficiency of 0.02 % in single-matched mode, for collection spot 1 at Fig.1.c, and 0.003 % in multiple-matched mode (both values are calculated following the process described in [5]). The lower value of the collection efficiency when the multiple-matched mode is used comes from the displacement of the MCF plane from the collimation lens focus, and the subsequent light losses in the fiber coupling. Despitethis reduced collection efficiency, all the novel operational spectroscopic schemes described above, including high-resolution imaging without scanning, represent clear and interesting alternatives for new µ-spectroscopic experiments with MCF.

## References


[1] P. Mitchler, Ed., Single Semiconductor Quantum Dots, Berlin-Heidelberg: Springer-Verlach, 2009.

[2] G. Muñoz-Matutano *et al.*, "Time resolved emission at 1.3 µm of a single InAs quantum dot by using a tunable fibre Bragg grating," *Nanotechnology*, no. 25, pp. 035204, 2014.

[3] J. Miguel-Sánchez *et al.*. "Cavity quantum electrodynamics with charge-controlled quantum dots coupled to a fiber Fabry–Perot cavity," *New J. of Phys.*, vol. 15, pp. 045002, 2013.

[4] A. Muller *et al.*, "Coupling an epitaxial quantum dot to a fiber-based external-mirror microcavity," *Appl. Phys. Lett.*, vol. 95, pp. 173101, 2009.

[5] K. Srinivasana, O. Painter, A. Stintz and S. Krishna, "Single quantum dot spectroscopy using a fiber taper waveguide near-field optic," *Appl. Phys. Lett.*, vol. 91, pp. 091102, 2007.

[6] C-M Lee1 *et al.*, "Efficient single photon source based on µ-fibre-coupled tunable microcavity," *Sci. Rep.*, vol. 5, pp. 14309, 2015.

[7] T. Hayashi, "Multicore Optical Fibers," in *Optical Fiber Telecommunications Volume VIA: Components and Subsystems*, I. P. Kamiow, T. Li and A. E. Willner, Eds., Elsevier, 2013, pp. 321.

[8] D. J. Richardson, J. M. Fini and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nat. Photonics*, vol. 7, pp. 354-362, 2013.

[9] I. Gasulla and J. Capmany, "Microwave Photonics Applications of Multicore Fibers," *Photon. J.*, vol. 4, pp. 877, 2012.

[10] D. Barrera, I. Gasulla and S. Sales, "Multipoint Two-Dimensional Curvature Optical Fiber Sensor Based on a Nontwisted Homogeneous Four-Core Fiber," *J. Lightw. Technol.*, vol. 33, pp. 2445, 2015.

[11] T. A. Birks, I. Gris-Sánchez, S. Yerolatsitis, S. G. Leon-Saval and R. R. Thomson, "The photonic lantern," *Adv. Opt. Photon.*, vol. 7, p. 107, 2015.

[12] K. Saitoh and S. Matsuo, "Multicore fiber Technology," *J. Lightw. Technol.*, vol. PP, no. 99, 2015.

[13] G. Muñoz-Matutano, B. Alén, J. Martínez-Pastor, L. Seravalli, P. Frigeri and S. Franchi, "Selective optical pumping of charged excitons in unintentionally doped InAs quantum dots," *Nanotechnology*, vol. 19, p. 145711, 2008.

[14] G. Muñoz-Matutano *et al.*, "Size dependent carrier thermal escape and transfer in bimodally distributed self assembled InAs/GaAs quantum dots," *J. Appl. Phys*, vol. 111, p. 123522, 2012.

[15] K. S. A. Butcher, D. Alexiev and T. L. Tansley, "Minority Carrier Diffusion Lengths for High Purity Liquid Phase Epitaxial GaAs," *Austr. J. Phys.*, vol. 46, p. 317, 1993.

[16] P. C. Sercel *et al*, "A novel technique for the direct determination of carrier diffusion lengths in GaAs/AlGaAs heterostructures using cathodoluminescence," in *Electron Devices Meeting IEDM*, Washington DC, 1989.

[17] A. L. Falk *et al.*, "Near-field electrical detection of optical plasmons and single-plasmon sources," *Nat. Physics*, vol. 5, pp. 475-479, 2009.

[18] H. Wei, Z. Wang, X. Tian, M. Käll and H. Xu, "Cascaded logic gates in nanophotonic plasmon networks," *Nature Comm.*, vol. 2, p. 387, 2011.

[19] J. Martín-Sánchez *et al.*, "Single Photon Emission from Site-Controlled InAs Quantum Dots Grown on GaAs(001) Patterned Substrates," ACS Nano, vol. 3, pp. 1513-1517, 2009.

[20] S. M. Thon *et al.*, "Strong coupling through optical positioning of a quantum dot in a photonic crystal cavity," *Appl. Phys. Lett.*, vol. 94, p. 111115, 2009.

[21] C. Betters, J. Bland-Hawthorn and S. Leon-Saval, "The Photonic TIGER: A multicore fiber-fed spectrograph," in *Proceedings of SPIE: Modern Technologies in Space and Ground-based Telescopes and Instrumentation II*, 2012.