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# “Plug and Play” single photons at 1.3 $\mu$m approaching gigahertz operation

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We report a “plug and play” single photon source, fully integrated with an optical fiber, emitting at 1.3 $\mu$m. Micropillars were patterned on a single layer InAs quantum dot wafer to guarantee a single pillar per fiber core. The single exciton peak filtered with a tunable optical filter was fed to a Hanbury Brown and Twiss interferometer, and the second order correlation function at zero delay was less than 0.5, indicating single photon emission. The measured decay dynamics under double-pulse excitation show that the single photon device can be operated at speeds greater than 0.5 GHz. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2960549]

Single photon sources are in demand for quantum key distribution[1,2] and linear optical quantum computation.[3] Recently, investigations on single photon emission from semiconductor quantum dots (QDs) have concentrated on electrical pumping,[4–7] high repetition rates,[8] telecommunication wavelengths,[9–13] high temperature operation[14] and emission stability.[15] From a practical point of view, it is desirable to have a “plug and play” type, stable single photon source at telecommunication wavelengths, ideally with a high repetition rate.

In our previous work,[15] we have demonstrated a plug and play single photon source integrated with an optical fiber system. In this system, a bundle of single mode optical fibers (around 600) are bound together at one end and polished. The polished end of the fiber bundle is directly mounted on top of a $5\times5$ mm$^2$ wafer with a very low quantum dot density. All fibers in the other end are free and can be connected to a wavelength division multiplexing (WDM) device with two separate output fibers. One of these two fibers (input fiber) carries the excitation light and the other (output fiber) carries the emitted light. The exciton emission collected from a single QD via one of the fibers in the fiber bundle exhibits single photon emission. Great stability of nearly (but not limited to) one month has been demonstrated.[15] However, the emission wavelength from InAs QD was around 920 nm. In this work, we realize a plug and play single photon source at telecommunication wavelengths using the same system. The repetition rate of this type of photon source can be higher than 0.5 GHz, which is confirmed with two-pulse lifetime measurements.

The InAs QD wafer with a 1.3 $\mu$m wavelength emission is grown by molecular-beam expitaxy with an InGaAs capping layer. The QD layer is embedded in a 1-lambda cavity between one-period (top) and 15-period (bottom) GaAs/$Al_{0.9}Ga_{0.1}$ As distributed Bragg reflectors, in order to enhance the extraction efficiency. The collection efficiency of the fiber with a numerical aperture of 0.12 was 0.69%, calculated with the method described in Ref. 16. To achieve very low QD density (around $2\times10^8$ dots/cm$^2$), an ultralow growth rate was used for the sample growth.[17] With this growth technique, single photon emission at 1.3 $\mu$m was demonstrated using a confocal system with either InGaAs (Ref. 18) or superconducting single-photon detectors.[11] However, the dot density (around $10^8$ dots/cm$^2$) is still too high to isolate the light emission from a single QD collected by a single mode fiber in the fiber bundle. The schematic of the polished end of the fiber bundle is shown in Fig. 1(a). In order to match the dot density with the density of single mode fibers, an array of micropillars with diameters varying from 1 to 4 $\mu$m with 15 $\mu$m separation was patterned on the wafer [as shown in Fig. 1(b)].

The patterned QD wafer and fiber bundle assembly was dipped into liquid helium at $T=4.2$ K in a storage dewar. The QD were excited with a HeNe laser via the input fiber of the WDM and a single mode fiber in the bundle. Emitted light was collected with the same fiber and the output fiber. The spectrum of the emitted light was measured using a 0.55 m spectrometer and a linear InGaAs detector array. The exciton peak was isolated with an inline optical tunable filter (OTF) with a full width at half maximum (FWHM) of 0.75 nm. To verify the single photon emission, the exciton emission was fed into a Hanbury Brown and Twiss (HBT) setup, with a 50/50 fiber coupler and two InGaAs avalanche photodiodes

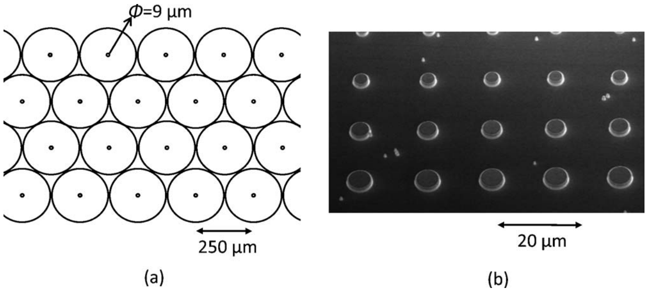

FIG. 1. (a) Schematic of the fiber array at the polished end of the fiber bundle. (b) Scanning electron microscopy image of micropillars with diameters varying from 2 to 4 $\mu$m. The pillars are separated by 15 $\mu$m from each other to guarantee a single pillar per fiber core.

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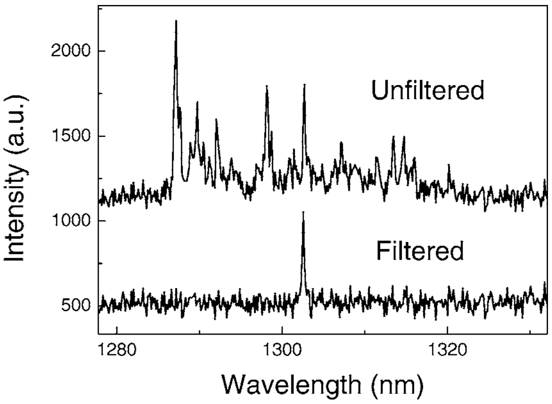

FIG. 2. PL spectra with and without an OTF.

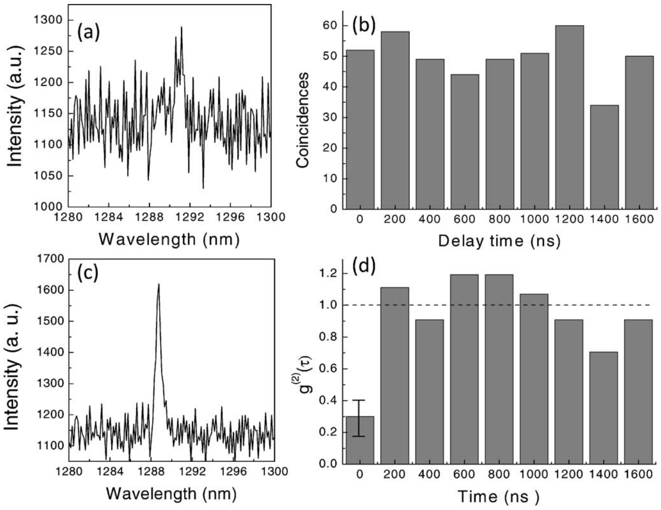

FIG. 3. (a) PL spectrum with a detuned OTF position. (b) Photon correlations of the spectrum in (a) as a function of delay time. (c) A PL spectrum with the OTF at an exciton position. (d) second order correlation function $[g^{(2)}(\tau)]$ of the exciton peak in (c) by subtracting the average counts in (b). The error bar at $g^{(2)}(0)$ indicates the measured results from different excitons in different fibers. The integration time for (b) and (d) is 1 h.

(APDs) for single-photon detection. The InGaAs APDs were operated in Geiger mode and gated at 5 MHz with a pulse width of 40 ns. The start and stop signals from two APDs were connected to a time-correlated single photon counting (TCSPC) board. The resulting histograms show the correlation events between the two signals as a function of time delay. The lifetime measurements were performed with a single or double 100 fs Ti:sapphire laser pulse excitation using the TCSPC technique. The center wavelength of the laser pulse is around 830 nm.

Figure 2 shows a typical photoluminescence (PL) spectra from the QD as detected from the fiber output. The top trace shows a PL spectrum from a single fiber without an optical filter. Using a tunable optical filter, the single exciton peak can be well isolated (bottom trace). The average photon counts of the filtered exciton emission are around 3000 counts/s, detected with an InGaAs APD. If we assume that each pump pulse at 80 MHz generates one photon, the measured efficiency is around $3.75 \times 10^{-5}$. Since the APD was gated at 5 MHz with a duty cycle of 20% and the detection efficiency of the APD is 20%, the collection efficiency is calculated to be 0.094%. This collection efficiency after the OTF is around 1/7 of the theoretical value of 0.69% at the interface between the wafer and fiber. The main reasons are due to the insertion losses of the WDM coupler (5%), the OTF (30%), the connector attenuation (7% × number of connectors) and the fiber attenuation.

The filtered single exciton emission was fed into the HBT setup to verify the single photon emisison. It is difficult to run the correlation measurements in a cw mode, as reported previously using Si detectors[4,15] due to the very high dark count rate of the InGaAs APDs. In the experiment, a second order correlation function was obtained from the coincidences between two detectors as a function of time delay. In order to estimate the background counts,[9,18] we perform the correlation measurement by tuning the OTF about 1 nm away from the exciton peak. The spectrum with 5 s integration time is shown in Fig. 3(a). A small broad peak corresponding to the filter width can be identified, which is due to the background emission. Figure 3(b) shows the autocorrelation results with an integration time of 1 h. It can be seen that there is no antibunching effect at zero time delay. We used the average coincidence here as the background count. Next we tuned the OTF to the exciton peak position, as shown in Fig. 3(c). The correlation result is shown in Fig. 3(d) by subtracting the average background counts in (b). The second order correlation function at zero delay $g^{(2)}(0)$ is around 0.3. We have done measurements on the exciton peaks from different dots with different fibers, the $g^{(2)}(0)$ varies from 0.2 to 0.4, as shown by the error bar in the figure. The $g^{(2)}(0)$ around 0.3 indicates single photon emission with this fiber system. The following reasons might have prevented us from obtaining a $g^{(2)}(0)$ close to zero: First, the background counts given by a detuned OTF position are not exactly the same as that given by the OTF of the exciton peak. Second, the random electronic noise generated by the long delay cable can be picked up and amplified by the inline signal amplifier.

Next, we discuss how fast this fiber based single photon source can be driven. The InGaAs APDs operated at Geiger mode at 5 MHz are not fast enough for this purpose. To check the output photon pulse rate, we measured the recombination dynamics of excitons from single QD, pumped with single/double optical pulses. The instrument response function of our lifetime measurement is Gaussian shaped with a FWHM around 200 ps. The fiber carrying the ultrafast laser pulses has a length of only 5 m, ensuring a negligible pulse dispersion and the accuracy of the lifetime measurement. Figure 4(a) shows the decay dynamics of a single exciton. The lifetime obtained with a single exponential fit is about 1.5 ± 0.2 ns, which is similar to the other results on InAs QD with a confocal system.[4,9,6]

For the two-pulse measurement, two optical pulses are combined into the input fiber and the separation between the two pulses is controlled by a motorized translation stage. The delay time between two pulses varies between 5 and 1 ns, corresponding to driving rates between 0.2 and 1 GHz. Figures 4(b)–4(e) show the time resolved PL intensity $I(t)$ with two pulses as a function of delay time. The two peaks are separated with a delay time of 5 ns, and can be well resolved with 2 ns. An output ratio has been introduced to show the output photon pulse rate.[6] This is the PL intensity of the single photons before the next excitation pulse arrives divided by the total emitted intensity within a single pulse

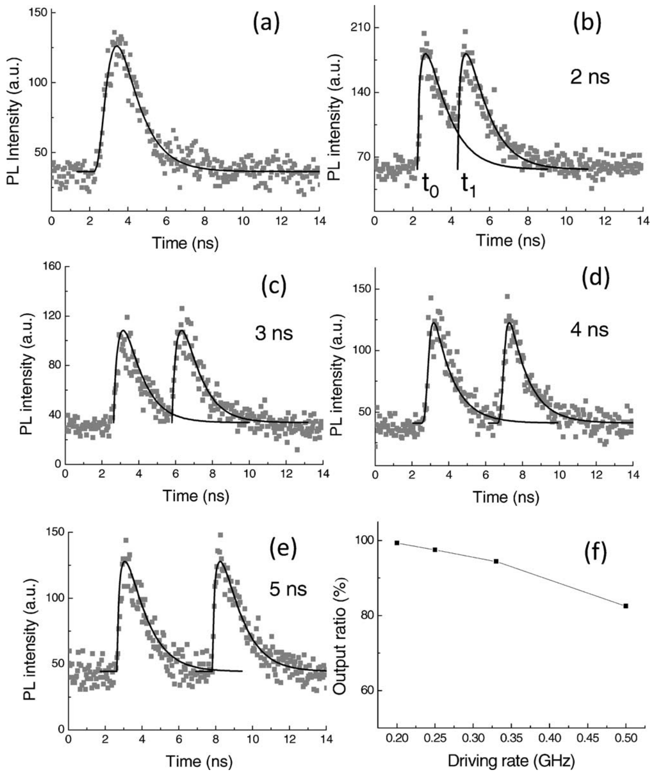

FIG. 4. (a) Time resolved PL of the exciton emission from Fig. 3(c) using single pulses. The solid line shows a fitting line of the convoluted function of the exponential decay and the instrument response function. [(b)–(e)] Time resolved PL measurements with two pulses separated with a delay time ranging from 2 to 5 ns. (f) Intensity output ratio as a function of driving rate.

$$\eta=\sum_{t=t_0}^{t_1} I(t) \Bigg/ \int_{t_0}^{\infty} I_0 e^{-1/\tau_{\exp}(t-t_0)}dt.$$

Here $I_0$ is the fitting parameter of the exponential function for single pulse decay, and $t_0$ and $t_1$ are the start times of two consequent optical pulses, as shown in Fig. 4(b). Figure 4(f) shows the output ratio as a function of driving rates. The output ratio decreases with increasing drive rates because of the radiative lifetime. It can be seen that the output ratio is more than 80% with a driving pulse rate at 0.5 GHz. We note that high repetition rates (up to 1.1 GHz) have been obtained before.[19] However, the pulsed injection scheme reduces the internal quantum efficiency. Resonantly coupled cavities enhancing the emission rate[20] are being investigated to increase the single photon repetition rates in this fiber system.

In conclusion, we have demonstrated a plug and play single photon source at telecommunication wavelengths. Single QD PL around 1.3 $\mu$m was observed via a single mode fiber using an array of micropillars. The single exciton line was well isolated with an OTF with a 0.75 nm window, and the collection efficiency was around 0.094%. The second order correlation function of a filtered single exciton peak at zero time delay was found to be around 0.3, indicating single photon emission. The decay dynamics have been investigated with two-pulse lifetime measurements. The output ratio is larger than 80% with a driving rate at 0.5 GHz. This shows that this fiber-based single photon source can be optimized to be operated in the gegahertz range. The plug and play nature of the device allows it to be easily integrated into a quantum key distribution system and a linear optical quantum computation system.

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