is shown in transmission in the inset of Fig.3c with $Q \approx 9 \times 10^3$. The FTW enables efficient coupling to this mode with coupling depth $\Delta T = 0.92 \pm 0.02$, just short of critical coupling, ensuring almost complete transfer of power. By pumping on this mode, only QDs on the circumference of the disk are excited by the circulating pump. The 1300 nm tunable laser combined with the EOM enable cavity-resonant pulsed excitation. Using 2.1 ns pulses at 1304 nm (resonant with the mode) with 1 MHz repetition rate, the QDs emit a PL signal under 79 nW of average power as shown in the spectrum in Fig. 3c. The significant reduction in average power required to obtain a bright PL spectrum is due to the buildup of power in the cavity mode. In the spectrum, the modes of the microdisk in the emission band are clearly visible and dress the broad PL signal of the QDs. The significant difference between the spectrum in Fig. 3c compared to that of bulk QD emission (see Fig. 2b) verifies that the majority of the collected PL is emitted by QDs into the cavity modes at the circumference rather than directly into the FTW from QDs near to the center of the disk. Incorporation of the gated APD and requisite timing electronics enables a time-resolved measurement of the PL decay as shown in Fig. 3d. The lifetime extracted from this room-temperature measurement is 160 ns $\pm$ 20 ns. This lifetime is longer than that measured for the QDs dried directly on the FTW at room-temperature, but is of the same order of magnitude. We measure markedly different room temperature excited state lifetimes for different samples which implies strong density-dependent or environmentally-dependent decay dynamics such as Förster resonant energy transfer (FRET) [27]. These effects need to be investigated further and will be the focus of future work.

5. Discussion and Conclusion

We have demonstrated techniques for efficient collection of photons emitted by PbS QDs in the 1.5 μm band using FTWs in different environments as well as on microdisk cavities. Using these collection strategies, it is an important exercise to consider if it is experimentally feasible to detect the single photon emission from a single PbS QD in a lifetime measurement and in a Hanbury-Brown and Twiss setup, much like what is done with InAs QDs. In the collection geometries presented here, the fraction of spontaneous emission collected in the measurement mode should be on the order of 1 % to 28 % [20], neglecting any substantial Purcell enhancement. Coupled with assumed radiative lifetimes as long as 700 ns, photoluminescence photon rates from a single PbS QD should reach as high as $\approx 2 \times 10^5$ s^{-1} under saturated continuous wave excitation if the radiative efficiency at low temperature approaches unity. However, these seemingly high count rates are mitigated by the difficulties of single photon detection in the near-infrared [13]. In particular, for the InGaAs APD used in our experiments, the optimum detection parameters for a single-channel lifetime measurement like that found in Fig. 2d and Fig. 3d are a 20 % detection efficiency, 100 ns gate width, and 10 μs dead time for a 1 MHz trigger rate. These settings have a dark count rate of $\approx 1.7 \times 10^3$ s^{-1}, yielding a signal to noise ratio of $\approx$35.4 Hz$^{-1/2}$. Experimentally, this means that the excited-state decay will be observed with a dynamic range of 35.4 if each temporal point is integrated for 1 s, corresponding to a measurable decay over a time period of $\approx$ 3.5 times the decay constant. Compared to an upconversion, multi-channel Si APD measurement for InAs QDs, the dynamic range is approximately a factor of 30 times worse [28].

More important than a lifetime measurement is that of the second order intensity correlation $g^2(\tau)$, where

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t)a^\dagger(t+\tau)a(t+\tau)a(t)\rangle}{\langle a^\dagger(t+\tau)a(t+\tau)\rangle\langle a^\dagger(t)a(t)\rangle}, \tag{1}$$

and a ($a^\dagger$) is the photon annihilation (creation) operator, which yields information about the non-classicality of the emitted photon stream. Specifically, a measured value of $g^{(2)}(0) < 0.5$

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proves that the field is dominantly composed of single photons. Using a standard Hanbury-Brown and Twiss setup, a minimum measurable $g^{(2)}(0)$ value for a PbS QD would be $\approx$0.60 using a 10 % detection efficiency, 2.5 ns gate width, and 10 μs dead time for a 1 MHz trigger rate. While this is a reasonably low value (proving the field is non-classical but not single photon), the signal to noise under these measurement conditions is only ≈ 0.011 Hz$^{-1/2}$, requiring more than two hours of integration time to achieve unity signal to noise. A signal to noise of ≈ 0.16 Hz$^{-1/2}$ could be obtained by increasing the gate width to 50 ns, but the minimum measurable $g^{(2)}(0)$ under these conditions is ≈ 0.81. In summary, under the best possible collection conditions and assuming perfect radiative efficiency, it is not possible to measure $g^{(2)}(0) < 0.5$ using commercially available detectors. In addition, the assumption of perfect radiative efficiency does not match experimental observation, even at cryogenic temperatures. This could be caused by several factors including blinking [18, 29] and poor radiative efficiency out of solution [12]. Therefore, it appears that single QD measurements at these wavelengths may remain elusive until higher optical quality QDs can be regularly fabricated [30]. However, once these QDs are realized, measurement of single photons will likely require advanced detector technologies such as frequency upconversion [28] or superconducting single photon detectors [31]. Nonetheless, the efficient and flexible measurement techniques presented here will be of great use towards the development of PbS QDs as active emitters coupled to high-quality nanophotonic devices in the telecommunications-band.

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