Enhancing the efficiency of fiber-coupled single-photon sources

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Development of an efficient all-fiber single-photon source (SPS) is a key step toward future quantum communication, particularly for long-distance secure data transmission, as well as for the realization of quantum nodes and devices required for quantum networks. The "plug-and-play" operation enabled by fiber coupling of the SPS is crucial when moving from laboratory demonstrations to real-world implementations. Previously developed fiber-coupled SPSs based on single semiconductor quantum dots (QDs) achieved above 70% efficiency of coupling into a single-mode fiber [1], produced indistinguishable photons at GHz rates [2], and enabled an important milestone of quantum key distribution (QKD) in all-fiber network [3]. All examples used SPSs emitting in the spectral band of 930-950 nm. QKD has also been demonstrated with an all-fiber SPS emitting at telecom wavelengths [4].

In this contribution, we demonstrate the possibility of further increasing the efficiency of fiber-coupled SPSs, applicable to any spectral band, including the most desired telecom O-band (around 1310 nm) and C-band (around 1550 nm). The improvements concern both the fiber-coupling element itself and the light-propagation path up to the SPS output. We also discuss fiber-integrated solutions applicable with resonant and quasi-resonant excitation.

The efficiency of light coupling between the fiber and the QD strongly depends on the overlap between the cavity mode and the fiber mode and is therefore correlated with the fiber core diameter and numerical aperture (NA). To maintain source stability, the fiber must operate in the single-mode (SM) regime, where the NA is technologically limited to approximately 0.4. We propose two methods to increase the effective output NA by modifying the fiber end face: thermal treatment using a CO_2 laser, and attaching lenses to the fiber tip. Both methods maintain possibility of fully deterministic coupling to cavities of various designs, including circular Bragg resonators and structures with sub-micron diameter.

The output efficiency of the source is strongly dependent on the losses in the system. Since the pumping laser power is several orders of magnitude higher than the resulting power of the SPS, it must be efficiently filtered maintaining low-loss at the wavelength of QD emission. While effective all-fiber spectral filters for two spectrally distant (>200 nm) ranges are relatively easy to implement, efficient low-loss filtering for quasi- and resonant excitation remains challenging. To overcome this limitation, we propose stacking and fine-tuning fiber Bragg gratings, to achieve laser-line suppression exceeding seven orders of magnitude. We also show that replacing standard telecom SM fiber with polarization-maintaining SM fiber during the development of the SPS, allows additional filtering through polarization control.

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