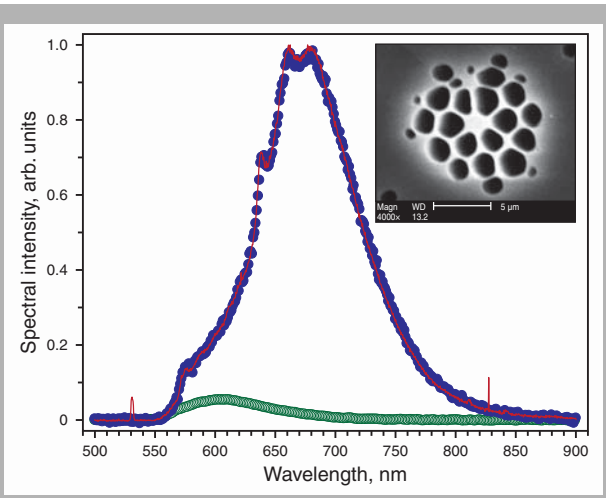
Abstract: A photonic-crystal fiber is used to demonstrate a fully fiber-integrated optical interrogation of nitrogen vacancies in diamond nanoparticles, where both pump radiation and the photoluminescent response of nitrogen vacancies are coupled to the fiber modes. A properly designed fiber is shown to provide a high-contrast guided-mode-coupled zero-phonon-line photoluminescent response from nitrogen vacancies, which is at least an order of magnitude higher than the Raman background signal from the fiber.



Photoluminescence spectra of (filled circles) NV-diamond nanoparticles in a photonic-crystal fiber (shown in the inset) and (solid line) a free ensemble of NV-diamond nanoparticles in a liquid

Photonic-crystal-fiber-coupled photoluminescence interrogation of nitrogen vacancies in diamond nanoparticles

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1. Introduction

Nitrogen-vacancy (NV) centers in diamond offer much promise for the emerging quantum information technologies [1–7], bioimaging [7,8], and nanoscale magnetic sensing [9–11]. Such centers have proven to be ideal candidates for the creation of robust and reliable single-photon sources (see, e.g., [3] for a review), suggesting attractive solutions for quantum computations, quantum communications, as well as single-photon spectroscopy. The low photon outcoupling of NV centers in a bulk crystal and the necessity to connect NV centers into large-scale quantum information systems and distributed quantum com-

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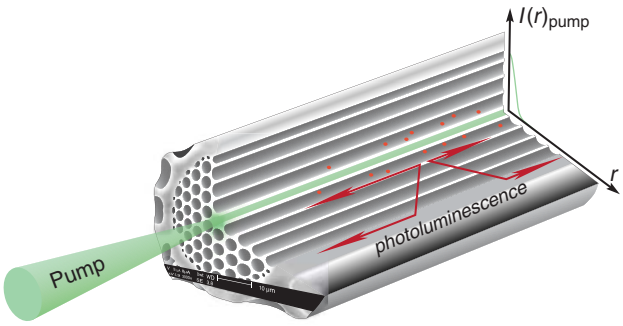

Figure 1 (online color at www.lphys.org) A photonic-crystal fiber light source based on NV centers in diamond

puters call for the development of efficient schemes allowing NV centers to be coupled to optical waveguides. Several attractive and elegant solutions to this problem have been recently demonstrated, including fabrication of NV-center-embedded diamond nanowires [12], placing diamond nanoparticles on a facet of a photonic-crystal fiber (PCF) [13], and coupling NV diamond centers to a semiconductor waveguide [14]. Using coherent transient phenomena [15] in combination with advanced fiber technologies [16] would be another interesting option in this context.

Here, we employ a specifically designed PCF to demonstrate a fully fiber-integrated optical interrogation of nitrogen vacancies in diamond nanoparticles, where both pump radiation and the photoluminescent response of nitrogen vacancies are coupled to the fiber modes. We show that a properly designed fiber can provide a high-contrast guided-mode-coupled zero-phonon-line photoluminescent response from nitrogen vacancies, which is at least an order of magnitude higher than the Raman background signal from the fiber.

2. Experimental methods

In our fiber-format NV-center light sources (Fig. 1), a photonic-crystal fiber (see, e.g., [16] for a review on PCFs) is infiltrated with a syringe-pressurized fluid containing NV-diamond nanoparticles (ND) with a mean diameter of 300 nm. The technology of PCF infiltration with liquids is described in detail elsewhere [17–19]. The NV centers impregnate the fiber as a result of this procedure, filling the air holes along the entire fiber length. Experiments were performed with a total number of diamond nanoparticles of approximately 10^3 per 1 cm of the fiber. The 532-nm, 100-mW second-harmonic output of a diode-pumped continuous-wave Nd:YAG laser was used as a source of optical pump (Fig. 2). The fibers used in our experiments have typical cross-section structures as shown in the insets to Fig. 2 and Fig. 3. The laser output was coupled into the

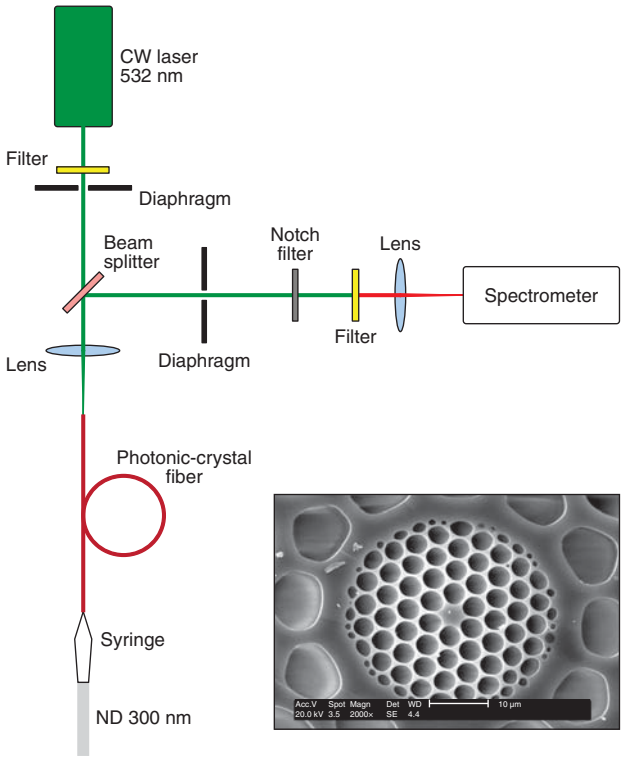

Figure 2 (online color at www.lphys.org) Diagram of the experimental setup. The inset shows an scanning electron microscope image of a typical PCF

PCF filled with NV-diamond nanoparticles using a 40×, NA = 0.65 lens. The photoluminescent response of the NV centers inside the fiber, detected in the backward direction, was separated from the pump with a notch filter and a set of color-glass filters and was analyzed with a standard spectrometer (Fig. 2).

The 532-nm radiation guided by the diamond-nanoparticle-doped PCF in the multimode regime [20,21] provides excitation of the NV diamond centers with its evanescent field. According to finite-element simulations of the PCF mode structure [22–24], the evanescent field of 532-nm radiation in the NV-center-doped PCF with a core diameter of 1.3 μm (inset in Fig. 3) carries approximately 12% of the total pump energy. The effective overlap area of the pump field and the NV-center-doped section of this fiber is about 25 μm^2. The spectra of the photoluminescent response collected from the front end of the NV-center-doped PCF (filled circles in Fig. 3) are identical to the spectra measured from an ensemble of nanoparticles in a cell or on a substrate (the solid line in Fig. 3). These spectra display well-resolved peaks centered at 575 and 637 nm, corresponding to the zero-phonon lines of the neutral and negatively charged NV centers in diamond. The efficiency of conversion of 50-mW, 532-nm pump to the photoluminescent response of NV centers in this regime for a PCF

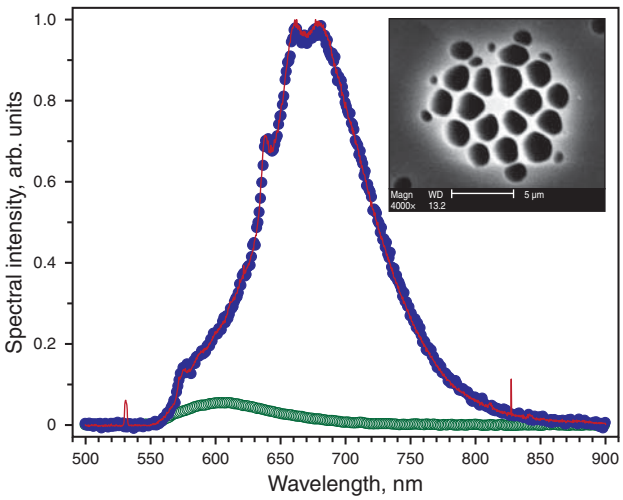

Figure 3 (online color at www.lphys.org) Photoluminescence spectra of (filled circles) NV-diamond nanoparticles in a photonic-crystal fiber (shown in the inset) and (solid line) a free ensemble of NV-diamond nanoparticles in a liquid. Also shown is the spectrum of the Raman signal from the same fiber (open circles)

with a core diameter of 1.3 μm (the inset in Fig. 3) is estimated as 10^{-6} for a 10-cm piece of NV-center-doped PCF. With the fiber loss for the pump and photoluminescence signal in our experimental scheme estimated as 10 and 100 dB/km, a pump-to-photoluminescence conversion efficiency at the level of 10^{-4} is expected for a 10-m-long NV-diamond PCF-format light source.

3. Results and discussion

Unlike the earlier elegant demonstration of a fiber-integrated single-photon source where diamond nanoparticles were placed on a facet of a PCF with an impressive accuracy [13], the fiber-format NV-center source implemented in our work does not require a high-precision positioning of nanoparticles on the fiber end. At the same time, our approach provides much higher densities of NV centers inside a fiber and much larger overlap areas for the optical pump and NV-center-filled section of the fiber. Moreover, in the NV-center-doped PCF, both the optical pump and the photoluminescence of NV centers are coupled into the waveguide modes, enhancing the excitation of NV centers and improving the efficiency of collection of their photoluminescent response. All these factors translate into a highly efficient conversion of optical pump into the photoluminescence of NV centers, promising high photon-emission rates for PCF-format single-photon sources using NV centers in diamond.

The PCF architecture of the NV-based source is instrumental in addressing the problem of the Raman background [25], which is inevitably generated by the optical pump inside the fiber, making it one of the key issues of fiber components intended for the delivery of low-intensity optical signals. In the PCF format, the level of the Raman background can be radically reduced by decreasing the content of silica in the fiber, i.e., by increasing the air-filling fraction in the PCF. For a PCF with the cross-section structure as shown in the inset to Fig. 3, the high air-filling fraction of the cladding helps keep the Raman background (open circles in Fig. 3) well below 10% of the photoluminescence response from the NV centers. Since both the Raman signal from the fiber and the photoluminescence from NV centers scale linearly with the pump power, this ratio of the NV photoluminescent signal to the Raman background is expected to remain unchanged for the pump power level necessary for the single-photon regime of the PCF-format NV light source.

4. Conclusion

To summarize, we have demonstrated a fully fiber-integrated optical interrogation of nitrogen vacancies in diamond nanoparticles, where both pump radiation and the photoluminescent response of nitrogen vacancies are coupled to the fiber modes. We have shown that a properly designed fiber can provide a high-contrast guided-mode-coupled zero-phonon-line photoluminescent response from nitrogen vacancies, which is at least an order of magnitude higher than the Raman background signal from the fiber. The approach demonstrated in this work suggests an attractive platform for the integration of NV diamond centers into fiber-optic networks.

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