Femtosecond laser microfabrication of waveguides and NV centers in diamond

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Diamond is one of the most appreciated materials by humans. Apart from its remarkable beauty when suitably cut, it is the hardest naturally occurring bulk material, has a record high thermal conductivity and offers excellent transparency from the ultraviolet to far infrared. It is also attractive to the quantum optics scientists due to a point defect called the nitrogen-vacancy (NV) center.

Analogous to semiconductors and conventional electronics, the key to making diamond functional is an impurity: nitrogen. The nitrogen impurities can be found in both natural and synthetic diamonds, and they form the nitrogen-vacancy (NV) center when they sit next to an empty site in the carbon lattice (vacancy). These defects, isolated from environmental perturbation inside the diamond matrix, have optically active spin with long coherence time at room temperature, making them attractive as quantum bits. Unlike classical computers which rely on digital 0s and 1s, quantum bits can be in 0 and 1 states simultaneously, enabling an exponential speed increase for certain calculations. Quantum computers are particularly useful for solving challenging multivariable problems such as nanoscale simulations in modern science or macroscale problems like predicting the world climate or fluctuations in the stock market. Due the magnetically sensitive ground state of NV centers, they can be used to measure weak magnetic fields with nanoscale resolution, which has triggered significant research into diamond-based optical magnetometers.

The NVs can be easily initialized, manipulated and read out using light. Therefore, an important breakthrough for its application in quantum computing and magnetometry would be in connecting, using optical waveguides, multiple diamond NVs. However, despite some previous attempts it remains a challenge to fabricate optical waveguides in diamond due to its hardness and chemical inertness.

In this work we propose to use femtosecond laser writing to fabricate optical waveguides in diamond and produce NV centers on demand at the desired position. We recently demonstrated the fabrication of 3D optical waveguides in bulk diamond using focused ultrashort laser pulses [1] (Figure 1). As confirmed by optically detected magnetic resonance, μRaman spectroscopy and μPhotoluminescence measurements (μPL), we showed that the high repetition rate laser writing produced a waveguide with preserved crystallinity. Crucially, we found that the remarkable properties of the pre-existing NV centers were preserved, allowing photons to be efficiently carried between the defects, a crucial step in building a scalable quantum photonic platform.

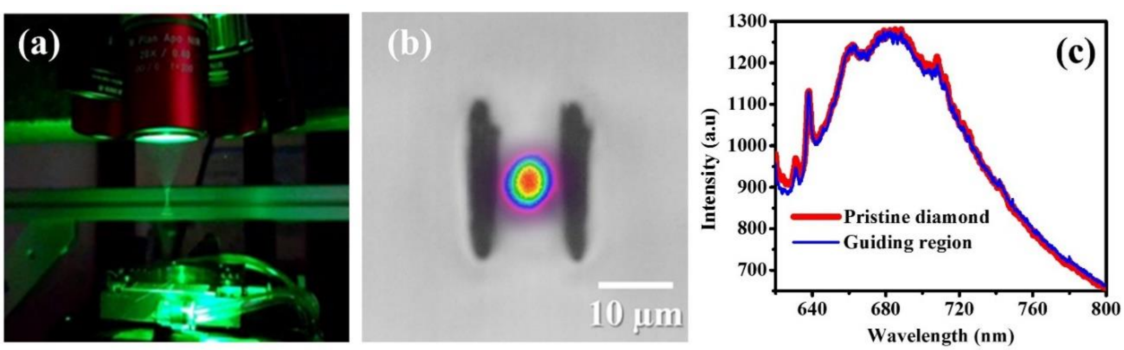

Figure 1. Optical waveguide fabrication in diamond. Femtosecond laser focused below the surface of a diamond sample (a) is used to write two modification tracks separated by 13 μm, being the optical mode is guided between these two lines (b). The μPL spectrum inside the waveguide is the same as the pristine diamond (c), demonstrating preserved nitrogen vacancy properties, crucial for applications in quantum computing and magnetometry.

The concentration of NV centers depends on the purity of the diamond, however the defects are randomly distributed throughout the volume. It is highly desirable to deterministically produce NVs on demand with submicron resolution, pre-aligned with existing photonic circuits. Recently, Chen et al. demonstrated that femtosecond laser static exposures produced vacancies in the bulk of diamond. After annealing at 1000°C (Figure 2a), the laser formed vacancies diffused toward nitrogen impurities to produce on-demand and high quality single NVs [2,3].

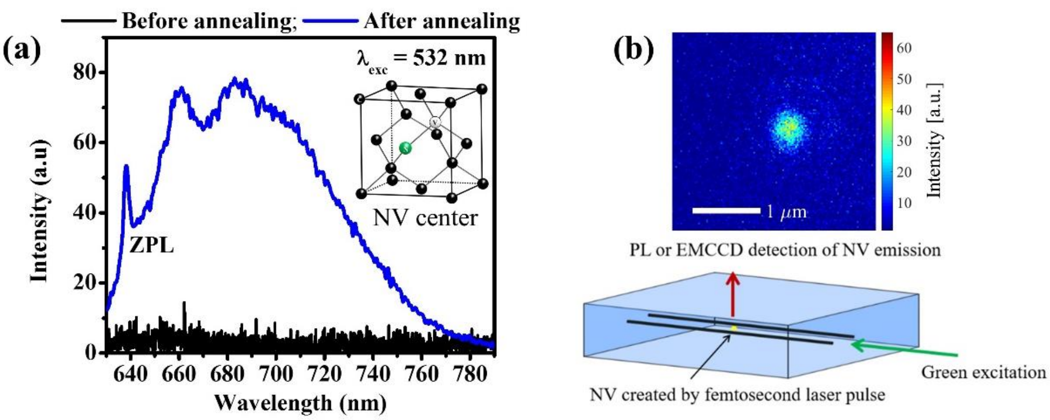

Figure 2. NV formation in diamond and optical waveguide with NV center device. (a) μPL signal of an ultra-pure (low concentration of nitrogen impurities) before and after femtosecond laser single pulse irradiation and annealing. The detection of the NV signature after annealing is an indication of the formation of the center. (b) 532-nm wavelength excitation of single NV center using optical waveguide. Emission is captured from above using confocal photoluminescence collection raster scan or EMCCD imaging.

We have taken these pioneering works of laser fabrication of optical waveguides and NVs [1, 2] a step further, by incorporating these important building blocks on the same integrated diamond chip, to enable the robust excitation and collection of light at NVs [4]. Because a single laser microfabrication system is used, the alignment between NVs and waveguides is achieved with submicron resolution. Using confocal photoluminescence microscopy and wide-field EMCCD imaging, we demonstrated the coupling of single NVs using optical waveguides (Figure 2b).

Optically addressed NV centers could open the door for more sophisticated quantum photonic networks in diamond. For example, in quantum grade diamond, the optically linked single NVs could be exploited for single photon sources or solid state qubits. In lower purity diamond, the laser writing of high density NV ensembles within waveguides could enable robust excitation and collection of the fluorescence signal for magnetometry.

It has been possible to carry out this work thanks to an international collaboration between several research groups located in different countries: coordinated by the group hosted in the Institute for Photonics and Nanotechnologies IFN – CNR (led by Dr. Shane Eaton and Prof. Roberta Ramponi), this work benefited from important contributions from other *DiamondFab* partners in Japan (University of Kyoto) and Turkey (Koç University). In addition, other groups from Italy (IFN -CNR Trento and Como) and in Canada (University of Calgary) contributed to this research.

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