# Bulk diamond optical waveguides fabricated by focused femtosecond laser pulses

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## ABSTRACT

Diamond's nitrogen-vacancy (NV) centers show great promise in sensing applications and quantum computing due to their long electron spin coherence time and their ability to be located, manipulated and read out using light. The electrons of the NV center, largely localized at the vacancy site, combine to form a spin triplet, which can be polarized with 532-nm laser light, even at room temperature. The NV's states are isolated from environmental perturbations making their spin coherence comparable to trapped ions. An important breakthrough would be in connecting, using waveguides, multiple diamond NVs together optically. However, the inertness of diamond is a significant hurdle for the fabrication of integrated optics similar to those that revolutionized silicon photonics. In this work we show the possibility of buried waveguide fabrication in diamond, enabled by focused femtosecond high repetition rate laser pulses. We use μRaman spectroscopy to gain better insight into the structure and refractive index profile of the optical waveguides.

**Keywords:** femtosecond laser, laser microfabrication, NV center, diamond, optical waveguide, quantum optics

## 1. INTRODUCTION

Diamond shows remarkable beauty when cut appropriately, making it the best friend a significant percentage of the population. Scientists instead are excited about diamond for a completely different reason. Although many think of diamond as the perfect material, there is actually a defect, the so-called nitrogen vacancy center, which could be used as the building block of advanced quantum computing platforms or ultrasensitive and nanoscale resolution magnetic field sensors. The magic of the nitrogen-vacancy (NV) center, in which a nitrogen sits next to an empty site in the carbon lattice, is that it is an optically active spin defect having a very long room temperature spin coherence time.

Due to diamond's inertness, it has proven difficult do develop an integrated optics platform which could optically link NV centers for magnetomery and quantum information applications [1], [2]. Recently, femtosecond laser microfabrication was proposed to enable a 3D photonics toolkit for diamond [3], [4]. Since focused femtosecond laser pulses damage the crystalline lattice [5], an indirect approach was used: optical mode confinement was achieved between two closely spaced and parallel laser-inscribed modification tracks.

In this work, we discuss the mechanisms for waveguiding using this type II fabrication method and provide better insight into the role the repetition rate. We demonstrate for the first time the fabrication of optical waveguides in ultrapure diamond which could address single NV centers in quantum information systems. In addition, we show shallow waveguide formation in the less pure optical grade diamond, of relevance for high resolution ultrasensitive magnetometry.

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# 2. RESULTS AND DISCUSSION

## 2.1 Femtosecond laser inscribed optical waveguides in diamond

The femtosecond laser used for optical waveguide writing in diamond was a regeneratively amplified Yb:KGW system (Pharos, Light Conversion) with 230 fs pulse duration, 515 nm wavelength (frequency doubled from 1030 nm wavelength [6]), focused with a 1.25 NA oil immersion lens. The repetition rate of the laser was variable from 500 kHz to single pulse. Computer-controlled, 3D motion stages (ABL-1000, Aerotech) were used to translate the sample relative to the laser to form optical circuits in diamond. A simplified schematic of the beam delivery setup is shown in Figure 1. Polished synthetic single-crystal optical grade (5 mm × 5 mm × 0.5 mm, type II, nitrogen impurities 100 ppb), and quantum grade (dimensions 2 mm × 2 mm × 0.3 mm, type II, nitrogen impurities <5 ppb) diamond samples were acquired from MB Optics.

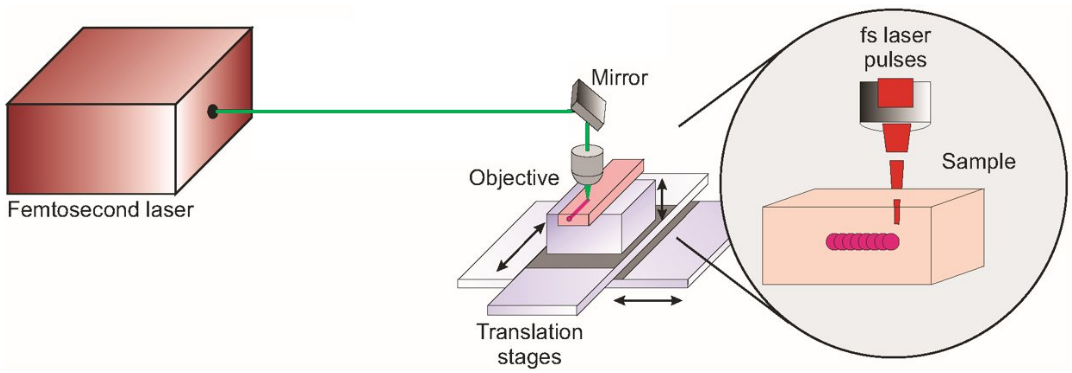


Figure 1. Schematic of femtosecond laser micromachining system where green laser light is focused by an oil immersion focusing lens (1.25 NA) beneath the surface of synthetic single-crystal diamond. Three-axis, computer-controlled motion stages are used to translate the sample relative to the laser to form the desired photonic circuits. In this work, the waveguides were formed by scanning the sample transversely relative to the incident femtosecond laser beam.

Previously, we demonstrated that higher repetition rates (~500 kHz) were beneficial for avoiding graphite during laser microfabrication in diamond [3]. The highest repetition rate of 500 kHz from our femtosecond laser was therefore applied to write two closely spaced modification lines, resulting in the first report of optical waveguiding in diamond using femtosecond laser writing (Figure 2). The optical waveguide in Fig. 2 was formed with 13 μm separation between modification tracks, 100 nJ pulse energy and 0.5 mm/s scan speed. The depth of the waveguide track, as measured from the surface to the center of modifications, was 40 μm. The near-field mode profile at 635 nm wavelength was imaged using a 60× aspheric lens to a CCD (620U, Spiricon), revealing a symmetric intensity distribution with a mode field diameter of 10 μm.

Using a lower 5 kHz repetition rate, we could not detect optical waveguiding between the closely spaced damage tracks. We attributed the lower damping losses at 500 kHz repetition rate to the reduced graphite formation as confirmed by μRaman spectroscopy and absorption characterization [3].

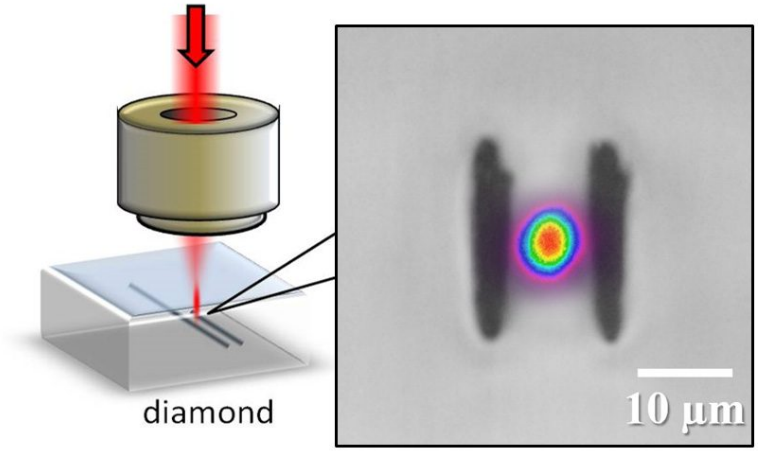


Figure 2. Type II modification of diamond with modification lines spaced by 13 μm to produce optical waveguiding at visible wavelengths. The laser writing conditions were 515 nm wavelength, 500 kHz repetition rate, 100 nJ pulse energy and 0.5 mm/s scan speed. The depth of the waveguide track, as measured from the surface to the center of modifications, was 40 μm. Overlaid mode profile at 635 nm wavelength shows a symmetric intensity distribution with 10 μm mode field diameter.

In parallel, Salter's group demonstrated that optical waveguiding in diamond was indeed possible using low (1 kHz) repetition rates [4]. Using an SLM to produce more symmetric modifications, the authors used a gentler interaction with lower energy pulses to modify the bulk of diamond. To form an optical waveguide, a multiscan writing method was employed, with 6 symmetrical modifications spaced 3 μm apart vertically to form elliptical cross section modification tracks, similar in shape to our work. It is likely that the lower intensity interaction resulted in the reduced formation of graphite at this lower repetition rate, to enable optical waveguides with a reasonably low damping loss.

The insertion loss for our type II waveguides is 11 dB, which includes 1.4 dB/facet coupling loss (0.5-cm waveguide length). The insertion loss is lower than previously reported [3] due to the use of a polarization maintaining fiber to launch TM polarized light into the optical waveguides.

### 2.2 Raman spectroscopy in waveguiding region

The repetition rate not only affects the graphite formation inside the modification tracks, but also the quality of the crystal in the waveguiding region. To study this effect, we wrote double-line structures at 5 kHz and 500 kHz repetition rates with other parameters held constant: a scan speed of 0.5 mm/s, a pulse energy of 200 nJ, a line separation of 13 μm and a depth of 40 μm. As shown in Fig. 3(a), the μRaman spectra within the waveguides showed a shift of the crystal peak towards higher wavenumbers, demonstrating compressive stress. The compressive stress was higher for the lower 5 kHz repetition rate condition. Previous studies have shown that compressive stress in diamond gives rise to a decrease in the index of refraction [7], which is of course detrimental for optical waveguiding. The mechanisms for waveguiding in diamond are still under investigation, which may be the result of increased polarizability [8] or a reduced refractive index in the modification lines.

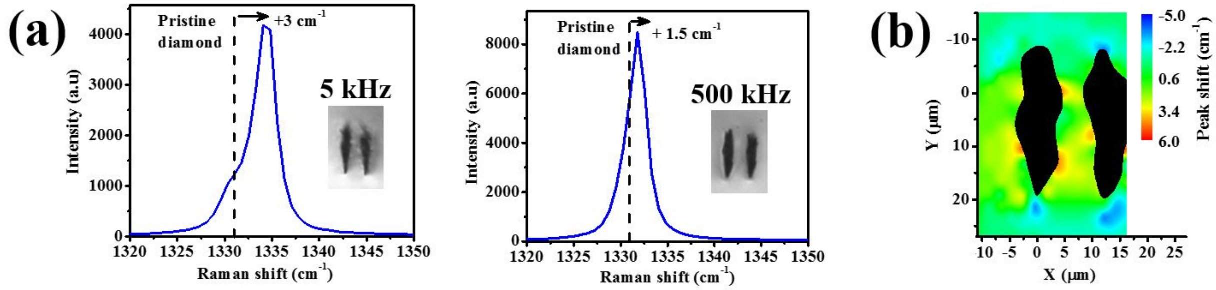


Figure 3. Effect of the repetition rate on the stress for double-line structures (13 μm separation) (a) Shift of the Raman diamond peak at the center of the waveguide for 5 kHz (left) and 500 kHz (right) repetition rates. The scan speed and pulse energy were held constant at 0.5 mm/s and 200 nJ, respectively (b) Map of the shift of the Raman peak in a waveguide fabricated with 5 kHz repetition rate.

At 500 kHz repetition rate, the peak width is about 2 $cm^{-1}$ and similar to the pristine value, which indicates that the crystalline structure is preserved. However, this peak width increases as the repetition rate is lowered, reaching a value of 3 $cm^{-1}$ at 5 kHz repetition rate, which indicates a slight disordering of the crystalline lattice. Further evidence of this disorder is the decrease in the Raman intensity at the lower repetition rate (Figure 3(a)). The stress in the guiding region is not only higher for the lower repetition rate, but also more nonuniform, as shown in the Raman shift map in Figure 3(b). The Raman shift observed for the 5 kHz structure guiding region ranges from 1 to 4 $cm^{-1}$, whereas for 500 kHz the shift shows a uniform value of about 1.5 $cm^{-1}$ [3].

Therefore, the higher losses observed for lower repetition rates could be due to several effects: increased graphite formation within the damage lines, higher compressive stress resulting in less optical confinement, and increased disorder in the guiding region.

### 2.3 Shallow waveguides for sensing and magnetometry

For the type II modification in Figure 2, optical modes could be coupled at three different vertical locations within the waveguide. We showed that true single mode operation was possible using a four line type II modification, where modification tracks were written above and below the guiding region [3]. In the present work, we studied a range of depths for waveguide formation, with emphasis on shallow waveguides, which could be used for interacting with near-surface NV centers for use as magnetic field sensors.

We found that for depths less than 30 μm, the two line type II modifications showed single mode behavior. We attribute this transition to single mode guiding at shallower depths to the reduced spherical aberration, which results in less vertically elongated modifications. As a result, the guiding region between the two modifications has less vertical extent, allowing for the coupling to only a single vertical location. For waveguides characterized at visible wavelengths (532 nm – 800 nm) we found the minimum waveguide depth to be approximately 15 μm, as shown in Figure 4.

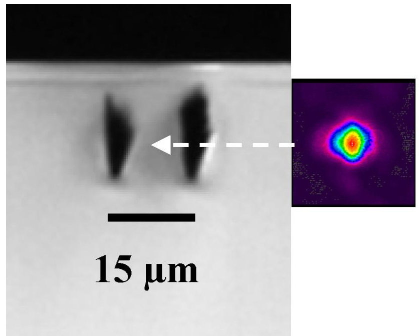


Figure 4. Transverse optical microscope image of Type II modification in diamond. The laser processing conditions were 500 kHz repetition rate, 60 nJ pulse energy, 0.5 mm/s, 15 μm line separation and ~15 μm depth. The mode profile is shown for 635 nm characterization wavelength.

We also explored a range of separation distances between the modification tracks for extending the guiding capabilities to longer wavelengths, in particular 1550 nm, which is of interest for evanescent coupling to surface photonics such as microspheres [9], [10]. For 1550 nm wavelength, the optimum separation distance was 19 μm, for which we achieved single mode operation. A similar insertion and mode profile were found at 1550 nm compared to waveguides optimized for visible wavelength operation.

The above reported waveguide results were achieved in optical grade diamond. In ultrapure quantum grade diamond, nearly identical waveguide properties were observed. Waveguides operational in quantum grade and optical grade diamond could find use as photonic devices for applications in quantum information systems and magnetometry, respectively.

## 3. CONCLUSIONS

In this paper, we have demonstrated that femtosecond laser microfabrication can form buried and single mode optical waveguides in diamond using a type II modification. The waveguides can be tuned to operate between 532 nm to 1550 nm wavelength by increasing the separation between the modification tracks from 13 to 19 μm. The highest repetition rate of 500 kHz was found to produce less graphite in the modifications and also a higher quality guiding region, leading to lower propagation losses. However, further research is needed to better understand the mechanisms for waveguiding in diamond. Laser-written optical circuits may serve as building blocks for a diamond photonics platform that could enable both quantum information systems with optically-connected entangled qubits and ultrasensitive and high resolution optical magnetometers.

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