

Laser micromachining of diamond: A viable photonic and optofluidic platform

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Abstract. We describe how the ultrafast laser micromachining technique applied with different writing methods can be used for the creation of various building blocks essential for the realization of a photonic and optofluidic diamond platform. Waveguides, NV centers, conductive wires, microchannels and microholes can be obtained thanks to laser microfabrication with suitable pulse parameters, making use not only of standard Gaussian laser beams but also of non-diffracting Bessel beams, the latter especially in all those cases where single pass high aspect-ratio microstructures or ablated areas are needed.

1 Introduction

Diamond has attracted great interest as a quantum technology platform thanks to its optically active nitrogen vacancy (NV) center. The NV spin state with the brighter luminescence yield can be exploited for spin readout, exhibiting millisecond spin coherence times at ambient temperature. Since their energy levels are sensitive to external fields, NVs are attractive as a scalable platform for efficient nanoscale resolution sensing and for quantum information systems. Integrated diamond photonics would be beneficial for optical magnetometry, due to the enhanced light-matter interaction and associated collection efficiency provided by waveguides, and for quantum information, by means of the optical linking of NV centers for long-range entanglement. Diamond is also compelling for microfluidic applications due to its outstanding biocompatibility, with sensing functionality provided by NVs. Furthermore, laser written micrographitic modifications could lead to efficient and compact detectors of high energy radiation in diamond. However, it remains a significant challenge to fabricate photonics, NVs, and microfluidics in diamond.

Ultrafast laser micromachining with fs or ps pulses is one of the most efficient and precise techniques for microfabrication of transparent materials thanks to the minimization of heat transfer during the nonlinear absorption process [1]. Here we report the most important fabrication results of quantum emitters, optical waveguides, and microfluidics in diamond, in view of a combination of integrated quantum photonic and microfluidics components that will open the way to lab-on-chip devices enabled with quantum sensing capabilities [2,3].

2 Photonics components in diamond

2.1 Laser writing of waveguides

Femtosecond (fs) laser writing was first applied to glasses to inscribe optical waveguides [4] and has since been extended to other passive and active glasses, polymers, and crystals. Contrarily to glass, in crystals the use of tightly focused pulses leads to a decrease of the refractive index at the focus. In diamond, with suitable laser parameters, one can write two closely spaced modification lines leading to a stressed central region capable of guiding light. We have formed 5 mm long waveguides 50 μm below the surface, having an insertion loss of 6 dB, with a mode field diameter (MFD) of 10 μm at 635-nm wavelength (Fig.1a). Waveguides with larger separation have been laser written for guidance of near-IR, telecom and mid-IR wavelengths.

2.2 Creation of deterministically placed NV centers and NV ensembles

In a different pulse energy regime, fs laser pulses can be used to form single NVs in the bulk of optical and electronic grade diamond, useful for room temperature quantum sensing. When followed by annealing at very high temperatures, the vacancies created by static exposure are mobilized and can be captured by substitutional nitrogen impurities, which are randomly distributed in the diamond [5]. We show that single pulses are required to avoid amorphization and damage of the crystal lattice, and there is a range of pulse energies which

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can be tuned to control the concentration of laser formed NVs. To increase the sensitivity or the measurement speed, ensemble of NVs have also been written and integrated within a waveguide (Fig.1b).

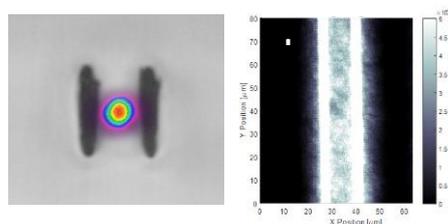


Fig. 1. (a) Transverse view of a waveguide in diamond (b) Cloud of NVs emission along the waveguide mode

2.3 Graphitic wire generation

In diamond, quantum emitters may be electrically controlled, both in their charge state and stimulated emission, with graphitic microchannels. Graphitic modifications can be realized by tailoring the laser processing, and will allow for both electrical interfacing within diamond and post-etching to produce conveniently buried microfluidics.

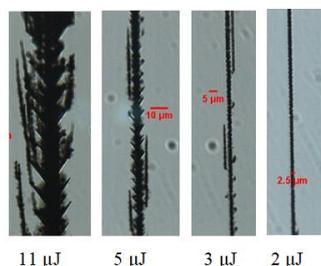


Fig. 2. Bessel beam laser-written graphitic wires in diamond

We report the fabrication of tailored graphitic wires throughout a 500 μm-thick CVD diamond sample, by means of Bessel beams with different geometries and pulse parameters, without any sample translation (Fig.2).

3 Microfluidics components in diamond

3.1 Laser writing of surface microchannels

The laser fabrication technique can be applied for a deep surface ablation of diamond. This can be done in single pass if using Bessel beams, obtaining high-aspect ratio V-shaped trenches featured by a micrometer size central channel, or in multiple pass with a more standard writing technique, leading to regular square shaped channels (Fig.3); the resulting microstructures offer a great potential for microfluidics or biosensing applications.

3.2 Microfabrication of through-holes

Through-holes in thick diamond samples can be realized by means of a micro-drilling process based on the combination of Bessel machining with a trepanning-like

technique. The combination of through-holes with surface microchannels allows the implementation of microfluidic lab-on-chip prototypes (Fig.4).

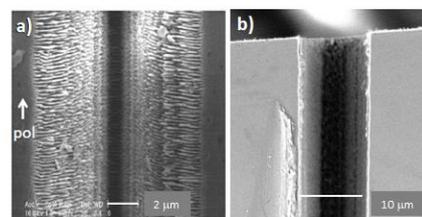


Fig. 3. Microfluidic channels realized by single pass Bessel beam (a) and multiple pass Gaussian (b) writing technique

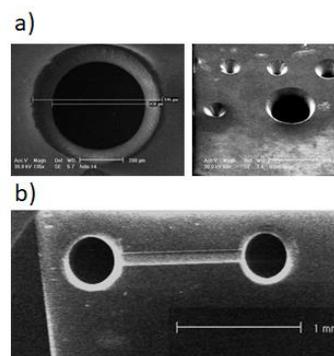


Fig. 4. (a) SEM images of through-holes in diamond (b) lab-on-chip prototype for microfluidics applications

4 CONCLUSIONS

The ultrafast laser writing technique can be applied to fabricate photonic and microfluidic networks in diamond. We have realized different building blocks such as NV centers, waveguides, graphitic wires, microchannels and micro-holes, whose integration will lead to prototype devices for use as quantum-based electric and magnetic field sensors.

References

1. R. R. Gattass, E. Mazur, *Nat. Photonics* **2**, 219 (2008).
2. V. Bharadwaj, O. Jedrkiewicz, J P Hadden, B. Sotillo, M. Ramos Vázquez, P. Dentella, T. T Fernandez, A. Chiappini, A. N. Giakoumaki, T. Le Phu, M. Bollani, M. Ferrari, R. Ramponi, P. E Barclay and Shane M Eaton, *J. Phys. Photonics* **1**, 022001 (2019).
3. K. Lim, C. Ropp, B. Shapiro, J. M. Taylor, and E. Waks, *Nano Lett.* **15**, 1481 (2015).
4. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, *Opt. Lett.* **21**, 1729 (1996)
5. J. R. Rabeau, P. Reichart, G. Tamanyan, D.N. Jamieson, S. Praver, F. Jelezko, T. Gaebel, I. Popa, M. Domhan and J. Wrachtrup, *Appl. Phys. Lett.* **88**, 023113 (2006)
6. O. Jedrkiewicz, D. Valetti, P. Di Trapani, *SN Applied Sciences* **1**, 1267 (2019).