Polarized micro-Raman studies of femtosecond laser written stress-induced optical waveguides in diamond

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Understanding the physical mechanisms of the refractive index modulation induced by femtosecond laser writing is crucial for tailoring the properties of the resulting optical waveguides. In this work, we apply polarized Raman spectroscopy to study the origin of stress-induced waveguides in diamond, produced by femtosecond laser writing. The change in the refractive index induced by the femtosecond laser in the crystal is derived from the measured stress in the waveguides. The results help to explain the waveguide polarization sensitive guiding mechanism, as well as provide a technique for their optimization. *Published by AIP Publishing.* https://doi.org/10.1063/1.5017108

Color centers in diamond, such as nitrogen-vacancy (NV) or silicon-vacancy (SiV) centers, show great potential for quantum systems,[1] temperature sensing,[2,3] or magnetic field sensing in the case of the NV center.[4] These defects can be initialized, manipulated, and read out using photons. Optical waveguides in bulk diamond could be used to optically link and address these color centers.[5] Several methods have been used for fabricating waveguides in diamond, such as ion beam assisted lift-off,[6] plasma etching,[7,8] or ion implantation.[9] Recently, optical waveguides[10,11] and Bragg gratings[12] in bulk diamond have been formed using the femtosecond laser technique, opening the possibility of creating 3D photonic circuits in this material. A deeper understanding of the physics underlying the writing of optical waveguides in diamond will help in the development of advanced devices integrating photonics circuits and color centers.[13]

Femtosecond laser writing relies on the nonlinear absorption of focused ultrashort pulses, which leads to a localized modification in the bulk of transparent materials.[14–16] In crystals such as diamond, laser interaction typically produces a decrease in the refractive index due to the damage of the lattice, and so, the strategy for fabricating the waveguides is to write two lines separated by several microns and confine the optical mode between these barriers.[10,17] In such waveguides, the increase in the refractive index is associated with the stress induced between the two lines due to the volume variation of the material inside the laser-written modifications.[18]

Micro-Raman spectroscopy has been previously applied to study the waveguides formed in different crystals.[19–21] However, to date, no works have managed to describe the relationship between the polarized Raman signal, the stress induced in the waveguides, and its relation with the change in the refractive index. Refracted near field profilometry is the only non-destructive measurement technique for direct quantitative characterization of the cross-sectional refractive index profile of bulk waveguides.[22,23] However, this technique requires index matching oil (maximum refractive index 1.8), incompatible with the refractive index of diamond (2.4). Although the quantitative phase microscopy method would allow the measurement of the refractive index change in waveguides within high refractive index materials,[24] its complexity and destructive nature make it undesirable for the characterization of diamond. On the other hand, confocal polarized μRaman spectroscopy is a non-destructive technique with a micrometer spatial resolution and is sensitive to the local stresses present in the material and thus will greatly benefit the understanding of the stress-induced waveguides in diamond, as well as in other crystalline materials.

The diamond samples used in this work were synthetic CVD grown single crystal diamond, type IIa, with a dimension of $5 \times 5 \times 0.5\,\text{mm}^3$. They were purchased from MB optics, with all the facets polished and with an orientation of 4 pt ({100}-planes) for the top and bottom larger surfaces and 2 pt ({110}-planes) for the side surfaces. If we define the crystal axis system as X = [100], Y = [010] and Z = [001] [Fig. 1(a)], the coordinate system for the sample will be defined as X′ = [110], Y′ = $[\bar{1}10]$, and Z′ = [001], as shown in Fig. 1(b), with X′Y′Z′ being obtained by a 45° rotation of the XYZ coordinates around the Z axis.

The femtosecond laser used for writing optical waveguides in diamond was a regeneratively amplified Yb:KGW system (Pharos, Light Conversion) with a 230-fs pulse duration and a 515-nm wavelength, focused with a 1.25-NA oil immersion lens (RMS100X-O 100× Olympus Plan Achromat Oil Immersion Objective). The repetition rate of the laser was 500 kHz, and the pulse energy was 100 nJ. Computer-controlled, 3-axis motion stages (ABL-1000, Aerotech) were used to translate the sample relative to the laser with a scan

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