Evidence of Light Guiding in Ion-Implanted Diamond

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We demonstrate the feasibility of fabricating light-waveguiding microstructures in bulk single-crystal diamond by means of direct ion implantation with a scanning microbeam, resulting in the modulation of the refractive index of the ion-beam damaged crystal. Direct evidence of waveguiding through such buried microchannels is obtained with a phase-shift micro-interferometric method allowing the study of the multimodal structure of the propagating electromagnetic field. The possibility of defining optical and photonic structures by direct ion writing opens a range of new possibilities in the design of quantum-optical devices in bulk single-crystal diamond.

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In the last decade single color centers in diamond have attracted an ever-growing scientific interest as a very promising platform for the implementation of hybrid optical–solid-state architectures for quantum information processing, due to their unique properties such as high quantum efficiency and coherence times, photostability and, most remarkably, the possibility of operating at room temperature [1–3]. Several luminescent centers based on different defects and/or impurities in the diamond lattice have been identified, with great potential in the fields of single-photon sources and quantum cryptography [4]. As a direct consequence, a significant effort is being devoted to optimize the fabrication of optical structures to integrate single color centers in scalable devices. Different architectures are under development, ranging from the fabrication of all-diamond structures in monocrystalline [5–10], polycrystalline [11], or nanocrystalline [12,13] substrates, to the interfacing of diamond color centers to hybrid devices [14–16]. The above-mentioned all-diamond architectures rely on the fabrication of waveguides and cavities based on the refractive index contrast between diamond and air; the air-diamond interface is defined by different microfabrication and nanofabrication strategies, based on the lift-off process [5], focused ion-beam (FIB) milling [10,11], or alternatively, optical [6,7] or electron-beam [8,9] lithography combined with reactive ion etching. In comparison, direct ion microbeam writing [17], a technique extensively employed in a range of materials including polymers [18] and glasses [19] to modulate the refractive index with high accuracy and spatial control via ion-induced damage, could offer unique opportunities for a more flexible and versatile design of micro-optical and photonic devices in diamond.

In this Letter we report about the fabrication of light-waveguiding microstructures in bulk single-crystal diamond by means of direct ion writing with a scanning 3 MeV proton microbeam. This determines a local modification of the optical properties of diamond, as a small modulation of the refractive index is induced in the bulk material in subsuperficial channels. We exploited our previous extensive work on the optical modifications induced in diamond by 3 MeV proton irradiation [20], to obtain controlled increments of the refractive index in rectilinear, 500 μm-long, 12 μm-wide structures below the diamond surface, down to a depth of about 50 μm below the sample surface. In previous works on the ion-beam fabrication of buried waveguides, laser coupling and optical micro-imaging were exploited to indirectly calculate the variations in the refractive index in target materials [19,21]. Here we present a different and innovative approach: the profile of the mode amplitude is directly measured with a phase-shift micro-interferometric technique, whose results are compared with the predictions of our finite element numerical models based on the ion-induced damage profile. We employed a $3.0 \times 3.0 \times 0.5$ mm^3 IIa single-crystal diamond. All its faces were cut along the $\langle 100 \rangle$ directions, and three adjacent sides were optically polished down to a roughness of a few nanometers. The sample was then implanted at the external scanning microbeam facility of the LABEC laboratory in Firenze [22]. After focusing to