Down-scaling grating couplers and waveguides in single-crystal diamond for VIS-UV operation

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Abstract
We report on the design, fabrication and experimental demonstration of single-crystal diamond (SCD) waveguide devices with integrated grating couplers optimized for 850 nm, 635 nm, and 405 nm wavelengths, respectively. The devices are fabricated on SCD thin films using electron-beam lithography and reactive-ion etching technologies. To reduce the wafer wedge typically present in commercial diamond plates, we introduce a novel tilted-etching technique in the preparation of the thin films. We obtain 60% reduction of the wafer wedge, namely from 300 to 120 nm mm⁻¹, enabling us to properly fabricate the devices designed for the short to ultra-short wavelengths considered here. Using light in- and out-coupling with 50 μm core tapered fibers, we measure total (input plus output) grating coupling losses of 20.6 dB and 22.7 dB, and waveguide losses of 11 dB mm⁻¹ and 20.5 dB mm⁻¹ for the 850 nm and 635 nm wavelength devices, respectively. The 405 nm wavelength devices, tested with a lensed 9 μm core input fiber and with the same tapered output fiber as employed for the other devices, also demonstrate light guidance, and feature total grating coupling and waveguide losses on the order of 33.1 dB and 46.7 dB mm⁻¹, respectively. These results showcase the possibility of down-scaling grating-coupled SCD devices for VIS-UV operation, and pave the way for exploiting diamond’s properties on photonic chips at extremely short wavelengths.

1. Introduction
Single-crystal diamond (SCD) is an attractive optical material due to its advantageous optical properties and its suitability for integrated photonics [1]. Besides featuring CMOS compatibility, SCD offers a very wide transparency window ranging from the UV to the mid-infrared (MIR) [2] as well as interesting nonlinear optical characteristics. In the infrared (IR) spectral domain, SCD’s relatively high Raman gain (e.g. 13.5 ± 2.0 cm GW⁻¹ at 1030 nm and 3.80 ± 0.35 cm GW⁻¹ at 1864 nm [3, 4]) and its exceptionally large Raman shift (40 THz) have been experimentally utilized for (on-chip) wavelength conversion from the near-infrared (NIR) to the MIR range [5]. In addition, SCD’s considerable Kerr nonlinearity (i.e. 8.2 ± 3.5 × 10⁻²⁰ m² W⁻¹ in the NIR range) has been experimentally explored for chip-scale frequency comb generation in the NIR spectral domain [6]. In the visible (VIS) spectral domain, a recent study has numerically demonstrated SCD waveguides as more suitable candidates than Si₃N₄ waveguides for VIS supercontinuum generation (SCG) due to SCD’s higher refractive index (2.412 at 635 nm [7]) allowing stronger light confinement and more possibilities for dispersion engineering [8]. In the UV spectral domain, studies have numerically demonstrated the promises of using SCD for wavelength conversion in the UV range by means of Kerr and Raman-resonant wave-mixing processes [9, 10]. Possible applications of SCG and wavelength conversion in diamond waveguides in the VIS-UV domain include short-wavelength spectroscopy and fluorescence measurements [11–13] integrated on a chip. Finally, in the field of quantum photonics, SCD can host optimally
active defects such as the negatively-charged nitrogen-vacancy (NV⁻) [14–20] and the negatively-charged silicon-vacancy (SiV⁻) centers [21–24] emitting in the VIS. Both are considered as essential resources for building quantum photonic systems [25, 26].

All these promising developments can only be properly exploited by developing nanophotonic structures in SCD suitable for operation at short wavelengths. To date, various photonic integrated components such as high performance optical ring-resonators with quality factors up to 10⁷ [6], millimeter-length single-mode waveguides [27], and efficient grating couplers for fiber-to-chip coupling [27] have been demonstrated in SCD for NIR telecom wavelengths. Earlier this year, Latwiec et al demonstrated an integrated SCD Raman laser with pumping just above the VIS wavelength region and with Stokes lasing in the short-wavelength NIR range [28]. This device featured a high quality-factor (Q > 300 000) resonator coupled to a bus waveguide, with the pump and Stokes waves edge-coupled in/out of the chip via two waveguide extensions connected to the bus waveguide. To withstand high powers at the desired wavelengths, these waveguide extensions were made from doped flowable glass (FOX-16, Dow Corning) that can be cured by electron-beam radiation. Very recently, the same research group also successfully demonstrated SCG in an edge-coupled SCD waveguide with the output spectrum spanning from 670 to 920 nm [29]. While these works represent very important device demonstrations, the operation wavelengths were still in the VIS-IR region. Well within the VIS spectral domain, the state-of-the-art SCD on-chip components are mostly individual optical resonators optimized for ~637 nm wavelength to enhance the zero-phonon line (ZPL) emission of the embedded individual NV⁻ centers [14–20].

To excite and read out these optical structures, it is necessary to provide optical coupling to external light sources/detectors. The I/O interfaces used in the state-of-the-art VIS devices are mainly based on microscope objective coupling [14–18] or fiber-taper enabled evanescent coupling [19, 20]. To the best of our knowledge, grating couplers for efficient fiber-to-chip coupling have rarely been experimentally demonstrated for wavelengths below the NIR telecom band. The existing NIR integrated diamond grating couplers have shown a relatively high coupling efficiency to fiber-connected lasers/detectors, versatility for various device layouts and a better compatibility to automated wafer-scale testing as compared to the microscope objective and fiber-taper coupling methods [27, 30]. Furthermore, these grating couplers are monolithically integrated with other photonic components in a single lithography step. This means that the fabrication process of grating-coupled SCD devices is simpler than that of edge coupled SCD devices, because the latter requires e.g. an additional overlay for creating waveguide extensions. Therefore, down-scaling the integrated grating couplers for VIS operation is an important route for further improving, among others, photon collection efficiency and design flexibility of the existing SCD quantum photonic devices. Additionally, to enable on-chip photon routing between multiple diamond color centers, hence creating more sophisticated quantum photonic systems, integrated waveguides with sufficient length also have to be scaled down in cross-sectional size for the VIS range. Beside providing improvements in SCD quantum photonic systems, the down-scaling process also paves the way towards experimental demonstration of the aforementioned novel nonlinear optical devices in the VIS range, and even in the (close-to-) UV spectral domain.

Literature shows that most of the SCD photonic integrated devices demonstrated so far are fabricated from diamond thin films. Currently, one of the main challenges of fabricating photonic devices in SCD thin films is the lack of uniform and large-area SCD-on-insulator wafers [27]. As discussed in our previous work [27], the commercially available SCD plates, produced by mechanical polishing, often have a wedge profile resulting in a variation of film thickness (about 300 nm mm⁻¹) [6]. Additionally, the commonly applied method to reduce the plate thickness to obtain a thin film relies on dry-etching these diamond plates. This generally does not affect the wafer wedge, and hence the resulting thin films will maintain the same wedged profile. Consequently, the optical characteristics of frequency sensitive components such as optical resonators, grating couplers, directional couplers, as well as dispersion engineered waveguides fabricated in wedged substrates would vary more due to the extra variation in device height, deteriorating the device performances.

When fabricating IR devices, one can mitigate the influence of the wafer wedge by aligning the device orientation perpendicularly to the wedge’s slope, or by applying curved device layouts to minimize the device footprint [27, 31]. However, these remedies become less effective when fabricating short-wave NIR and VIS-UV devices with feature sizes smaller than those of IR devices. In other words, novel techniques for creating uniform SCD films have to be developed. Recent progress in ion-slicing and homo-epitaxial growth techniques have shown potential for producing uniform large-area SCD membrane windows [32, 33]. IR devices have been fabricated on these substrates, but they are still modest in performance with an IR grating coupling efficiency of about 3% [33]. This suggests that the membrane windows are not yet a viable platform for short-wave NIR and VIS-UV devices. Therefore, other substrate preparation techniques should be explored to produce the SCD thin films suitable for fabricating high-performance short-wave NIR and VIS-UV components.

In this paper we propose a novel wedge reduction technique based on tilted-etching that can be directly applied during the diamond thinning process without increasing the process time and without the need of extra facilities for ion implantation or homo-epitaxial deposition. We obtain an effective 60% wedge reduction from
300 to 120 nm mm⁻¹. Using the SCD thin films with reduced wedge, we are able to down-scale and fabricate waveguides and grating couplers optimized for the short-wave NIR and VIS-UV range. We choose three target wavelengths (850, 635 and 405 nm wavelength) by taking into account their relevance to the key photonic applications mentioned above as well as the availability of cost-efficient semiconductor lasers for optical characterization. Wavelengths in the short-wave NIR around 850 nm can be potential pump wavelengths for VIS SCG [8]. The wavelength of 635 nm is also selected because it is very close to the ZPL emission wavelength (~637 nm) of diamond NV centres. Finally, the wavelength of 405 nm is chosen for demonstrating VIS-UV operation. We would like to note that the design and fabrication method demonstrated here can be applied analogously for creating other short-wave NIR or VIS-UV SCD grating couplers and waveguides. By means of optical transmission measurements using three lasers, we determine a total (input plus output) grating coupling loss and waveguide loss of 20.6 dB and 11 dB mm⁻¹ for the 850 nm wavelength devices, and 22.7 dB and 20.5 dB mm⁻¹ for the 635 nm wavelength devices. In addition, the 405 nm wavelength devices demonstrate light guidance with a waveguide loss on the order of 46.7 dB mm⁻¹ and a total grating coupling loss on the order of 33.1 dB. Furthermore, the devices also show considerable ~3 dB bandwidths of respectively 52 nm, 26 nm and 17 nm.

2. Methods

2.1. Design
For designing the waveguides and the grating couplers, we make use of, respectively, fully vectorial mode solver software (Lumerical MODE Solutions) and finite-difference time-domain (FDTD) simulation software (Lumerical FDTD Solutions). The optimization of the grating couplers is carried out using the ‘Particle Swarm’ algorithm preloaded in the software, [34] and the corresponding grating transmission is also calculated using a predefined procedure in the software [35].

2.2. Fabrication
The diamond waveguide devices with grating couplers are fabricated along a process that has been developed for the larger part over the past years at Hewlett Packard Labs, and that relies on electron-beam lithography (EBL) and reactive-ion-etching (RIE) [14]. We note that specifically for this work we introduce a novel procedure in the sample thinning step, and this procedure together with the results it yields will be explained in section 3. The other parts of the fabrication process are described in [27] and can be summarized as follows.

First, a 3 x 3 mm² large and 5 μm thick synthetic SCD plate (produced by MBOptics) is cleaned and fragmented into several 1 mm² sized shards (samples). To create a layered diamond on insulator (SiO₂) structure, we transfer these diamond samples onto 1 cm² sized silicon carrier wafers which have been thermally oxidized to form a 2 μm thick SiO₂ top layer. This oxide layer serves as the bottom cladding of the final diamond devices. We clean the surfaces of the diamond sample and its carrier wafer so that they can establish an immediate bonding via van der Waals forces preventing delamination during the subsequent fabrication steps. To thin down the diamond samples, we dry-etch them using Ar/Cl₂ plasma. Once their thickness has been reduced to about 1 μm, we transfer the diamond samples onto new carrier wafers with the same properties as the original ones (i.e. silicon wafers with 2 μm thick SiO₂ on top) and then resume the thinning process until the desired thickness is achieved. This helps minimizing the height difference between the etched diamond surface and the etched carrier wafer, and hence allows achieving a more uniform resist coating in the subsequent EBL process step. The diamond thin films are coated with a 100 nm thick electron-beam resist (Dow Corning XR-1541, 6%) film via spin coating before generating the device patterns on the samples. We use an electron-beam writing tool (Raith 150-two) to create the device patterns in the electron-beam resist. The exposed electron-beam resist is developed by means of AZ300 MIF developer and then serves as an etch mask. In the subsequent Ar/O₂ plasma etching step, the mask patterns are transferred into the diamond film. Afterwards, we remove the residual electron-beam resist in a second etch step using Ar/Cl₂ plasma. Finally, a 2 μm thick SiO₂ top cladding is grown on the samples using plasma enhanced chemical vapor deposition [27] in order to reduce waveguide scattering losses [36].

2.3. Characterization
Before the top cladding is deposited on the samples, we examine the diamond devices using an optical microscope, a scanning electron microscope (SEM), and an atomic force microscope (AFM). To characterize the optical transmission efficiency of the newly fabricated devices we use 842 nm (Thorlabs LP852-SF30), 635 nm (Thorlabs S1FC635) and 405 nm (Coherent 1069413/AS) low-power (mW level) continuous-wave lasers and a power meter (Newport). The devices’ spectral response is characterized by means of a broadband halogen source and a violet light emitting diode (LED) (Thorlabs M405FP1) as well as an optical spectrum analyzer (Yokogawa).
We employ optical fibers to couple light in and out of the devices. We also make use of a polarization controller in the transmission efficiency measurements with the laser sources, and optimize the polarization of the incident laser light to ensure maximal performance of the grating couplers. In the spectral response measurements with the halogen source and LED, no polarization controller is employed, since polarization control has little use in combination with these broadband sources.

3. Results

3.1. Design of waveguides and grating couplers

We design strip waveguides comprising a diamond core encapsulated in a 2 μm thick SiO₂ cladding [27]. The core dimensions (width × height) are 500 × 250 nm², 300 × 250 nm² and 300 × 140 nm² for respectively 850 nm, 635 nm and 405 nm to ensure well-confined fundamental waveguide modes. The numerically simulated profiles of the fundamental quasi-transverse-electric (TE) and quasi-transverse-magnetic modes at the three wavelengths are shown in figure 1(a). In the simulations the refractive index values are taken at 2.3978, 2.412, and 2.4619 for 850 nm, 635 nm, and 405 nm wavelengths, respectively [7, 37].

Each diamond waveguide device features two binary grating couplers scattering the light in the waveguide out-of-plane to enable chip-to-fiber coupling and vice versa [27] (see figure 1(b)). To be able to perform during the optical characterization a linear regression and extract both the grating coupling loss and the waveguide loss from the measurement data, we employ four different device lengths, namely 220, 270, 320, and 370 μm, for each of the three wavelengths considered here. Since the integrated grating couplers have the same height as the waveguides they are attached to, the grating period and fill factor are the remaining parameters to be determined.

We carry out numerical optimizations which maximize the coupling efficiency between the gratings and their matching single-mode fibers (namely SM800, 630HP and S405-XP) for TE polarized light at 850 nm, 635 nm, and 405 nm wavelengths, respectively [7, 37]. In our simulation model, there is a 2 μm thick buried oxide layer, and the interface between the oxide and the silicon substrate is included in the simulation window. This way the reflection from the silicon/oxide interface is taken into account in the simulation. We here assume the same oxide layer thickness of 2 μm for all devices to reduce fabrication complexity. The default fiber angle θ in the plane orthogonal to the grating grooves is θ = 9°, so that the grating reflection does not couple back into the fibers. This is also the incident angle we have used in the simulation. The default fiber angle φ in the plane orthogonal to the waveguide is φ = 0°. To enable a fast convergence of the numerical optimization, we calculate an initial approximate grating period for each wavelength by scaling down the earlier determined grating period.
of 950 nm for 1550 nm wavelength [27] by the wavelength ratio (e.g. for 850 nm wavelength this yields an initial grating period of 522 nm). We also choose 0.5 as the initial fill factor. The optimizations converge at grating periods of 560 nm, 401 nm and 254 nm, as well as fill factors of 0.41, 0.43 and 0.41 for respectively 850 nm, 635 nm and 405 nm wavelength gratings (see figure 2).

3.2. Device fabrication using a novel tilted-etching technique

While the fabrication is performed for the larger part along the standard EBL and RIE process [27], we introduce here a novel procedure for one of the fabrication steps, namely for thinning down the commercially obtained diamond substrates. The sample thinning is carried out by means of dry-etching with Ar/Cl₂ plasma [27].

Normally, the etch rate is uniform on the sample surface, so that the thin films produced this way inherit the large wedge angle from the diamond plates commercially provided. However, as we will show here, the etch rate can be adjusted across the sample surface if the sample is tilted in the etching chamber. As depicted in figure 3(b), after a tilted-etching step, the thermal oxide (SiO₂) layer at the upper side of the carrier wafer is completely removed and the (gray color) Si substrate underneath is exposed. The SiO₂ layer on the lower side of the carrier wafer remains, with the color lines (due to the SiO₂ thin film interference) indicating a continuous thickness decrease from the lower side to the upper side of the carrier wafer. Hence the etch rate is higher on the upper side than on the lower side of the tilted surface. To explain this effect, we consider the etching chamber as a capacitor with parallel top and bottom metal plates, where the tilted wafer is connected to the bottom plate of the capacitor causing the wafer’s upper side to experience a stronger electric field than the lower side [38]. More detailed studies on the effect taking place are planned for future work.

We observe that this effect is able to artificially create a wedge in the initially uniform SiO₂ film. Consequently, it can also be used to counteract the wafer wedge in the commercial SCD plates hence improving the uniformity of the resulting thin films. As illustrated in figure 3(a), by mounting the carrier wafer with a tilt angle of about 45°, we can lift up the thicker side of the diamond sample to achieve a higher etch rate on this side.

Our tilted-etching analysis results are shown in table 1. The thickness data are measured at four fixed locations on the SCD sample using a stylus profiler after the diamond sample has been transferred onto a new carrier wafer. In table 1 we also compare the etch results of the tilted and flat wafer-mounting positions. After a 30 min flat-etching step, the wedge ratio showed a negligible increase from 215 to 225 nm mm⁻¹, which is most likely due to measurement uncertainties. On the other hand, the subsequent 30 min tilted-etching step significantly decreased the wedge ratio by 22% from 225 to 185 nm mm⁻¹, demonstrating our tilted-etching technique is able to improve the uniformity of the diamond thin films by reducing the wafer wedge. We determine an average diamond etching rate of 39.1 nm min⁻¹ and an average wedge reduction rate of 2.02 nm mm⁻¹ min⁻¹ for the tilted-etching process. Once the SCD sample thickness reaches e.g. 250 nm which is the target thickness for the 850 and 635 nm devices, the wedge ratio will be reduced by 60% from about...
In the subsequent fabrication steps, we reduced the wedge ratio of the resulting waveguide taper region next to a grating coupler. The root mean square surface roughness in this area is approximately constant.

3.3. Characterization of the fabricated devices

3.3.1. Microscopic inspection

The optical microscopy images of 850, 635 and 405 nm wavelength gratings are given in figures 4(a)–(c), and their SEM images are shown in figures 4(d)–(f). As we can see from figure 4(b) for the 635 nm wavelength device, the optical image shows the taper areas are in ‘cyan’ color due to diamond thin film interference, but the grating areas are in ‘red’ color. This is the result of ‘red’ light near 635 nm wavelength being scattered upwards more efficiently than other colors, which is expected from the 635 nm grating couplers. A similar effect is also observed in figure 4(c) indicating the 405 nm grating couplers scatter ‘violet’ light near 405 nm wavelength more efficiently than other colors. Next, we measure from figures 4(d)–(f) grating periods of approximately 550 nm, 390 nm and 255 nm, as well as fill factors of about 0.45, 0.5 and 0.46 for the 850 nm, 635 nm and 405 nm wavelength gratings respectively. The measured grating periods are very close to their design values with less than 2.6% deviation, but their measured fill factors are up to 16% larger than their design values because of variations in the e-beam lithography and plasma etching processes. Despite this fabrication error in fill factor, we can still obtain considerable grating coupling efficiencies (see next section). In addition to optical microscopy and SEM measurements, we also analyze AFM measurements carried out over a 5 μm × 5 μm area on top of a waveguide taper region next to a grating coupler. The root mean square surface roughness \( R_q \) equals about 4 nm, which is larger than the typical roughness on the upper surface of silicon waveguides (\( R_q < 1 \) nm over similar area sizes) [39]. The higher surface roughness measured here for SCD waveguides mainly originates from the initially applied mechanical polishing of commercial SCD plates.

Table 1. Our novel tilted-etching technique allows reducing the wafer wedge in the diamond plates.

| Wafer mounting position | Tilt | Tilt | Flat | Tilt | Tilt | Tilt |
|-------------------------|------|------|------|------|------|------|
| Etching time (minute)   | 0    | +10  | +10  | +20  | +30  | +30  |
| Average thickness (μm)  | 5.240| 4.861| 4.505| 3.703| 2.723| 1.533|
| Wedge ratio (nm mm\(^{-1}\)) | 300  | 260  | 250  | 215  | 225  | 185  |

Note: The average thickness is calculated from four thickness values measured at four fixed measuring locations on the SCD sample. We determine an average etch rate of 39.1 nm min\(^{-1}\) and an average wedge reduction rate of 2.02 nm mm\(^{-1}\) min\(^{-1}\) for the tilted-etching process.

Table 1 shows an approximate wedge ratio of 300 nm mm\(^{-1}\) to about 120 nm mm\(^{-1}\). The resulting thin diamond films with reduced wedge are then employed in the subsequent fabrication steps [27] for manufacturing the waveguides and grating couplers designed in the previous section. We would like to note that additional optimizations in tilt angle and etching recipe may further reduce the wedge ratio of the resulting film and potentially allow producing wedge-less thin films.
3.3.2. Characterization of optical performance

The radiation of the three laser sources and of the broadband halogen and LED sources, used for measuring, respectively, the transmission efficiency and the spectral response of the fabricated devices, is injected into the devices by means of optical fibers. Instead of using three different pairs of specialized single-mode fibers for the three laser wavelengths plus a pair of large core diameter multi-mode fibers for the halogen source and LED, we simplify the measurement setup by using the two pairs of fibers shown in figures 5(a) and 5(b). Setup (a) employs two identical tapered tip fibers with a core diameter of 50 μm (Lase Optics). The tapered fiber tips can focus light to a spot size of about 3 μm (for 850 nm wavelength). Since the large core diameter is beneficial for collecting more light from the halogen source and the LED, setup (a) is used to characterize the transmission spectra of the 850, 635 and 405 nm wavelength devices. This setup is also employed together with the 842 and 635 nm lasers to measure the optical transmission efficiency of the 850 and 635 nm wavelength devices. An important advantage of the 50 μm core tapered fiber is that its tapered shape ensures that the camera image of the input grating does not get blocked by the image of the fiber itself, hence allowing better visual guidance in the coarse alignment between the fiber core and the grating. Only for coupling 405 nm laser light into 405 nm wavelength gratings, we switch to a 9 μm core lensed input fiber (OZ Optics). This is because the smaller core of this fiber is more suitable for focusing the 405 nm laser beam onto the small 405 nm input gratings. We point out that the 9 μm core lensed fiber used at the input of setup (b) is in fact designed for single-mode transmission of longer wavelengths around 1550 nm. As such, the different fibers used in setup (a) and (b) will not be single-mode at the wavelengths in the VIS-UV range, however, their tapered/lensed tips allow narrowing down the spot size at these wavelengths to match the grating area. Furthermore, the diamond waveguide cross-sections are sufficiently small to only allow good confinement for the fundamental waveguide mode.

Figure 4. Optical microscope and SEM images of the waveguide devices for 850 nm (a) and (d), 635 nm ((b) and (e)), and 405 nm ((c) and (f)) wavelengths.

Figure 5. Two setups (a) and (b) are used to characterize the optical transmissions of the diamond devices. (a) Two identical tapered tip fibers with a core diameter of 50 μm are aligned to the grating couplers of a 635 nm wavelength device to measure the transmission efficiency for 635 nm laser light. Setup (a) is also used to measure the transmission efficiency of the 850 nm devices with the 842 nm laser, as well as to characterize the transmission spectra of all devices with the broadband sources. (b) A lensed tip fiber with a core diameter of 9 μm coupling 405 nm laser light into a 405 nm device. At the output of the device, the same tapered tip fiber as in (a) is used to collect the light coming out of the device. This setup is only used for 405 nm laser transmission measurements. The fiber image at the bottom is due to reflection.
We use the optical transmission data (obtained from 12 devices for each wavelength) to calculate the average transmission \(T\) and the standard deviation (error bar) which are given in figure 6. Then we perform a linear regression \([27]\) to fit the total (input plus output) grating coupling loss and average waveguide loss at each wavelength. The high \(R^2\) coefficients obtained for the linear fitting functions underline the validity of the linear regression. From the fitting functions we extract the following grating coupling loss and average waveguide loss values: 20.6 dB and 11 dB mm\(^{-1}\) for 850 nm wavelength devices as well as 22.7 dB and 20.5 dB mm\(^{-1}\) for 635 nm wavelength devices. The 405 nm wavelength devices also demonstrate light coupling and guidance with total grating coupling loss and waveguide loss on the order of 33.1 dB and 46.7 dB mm\(^{-1}\), respectively. The high \(R^2\) coefficients obtained for the linear fitting functions underline the validity of the linear regression.

![Figure 6. Averaged optical transmissions (T) and standard deviation (error bar) of 850 nm, 635 nm and 405 nm wavelength devices at the laser wavelengths of 842 nm, 635 nm and 405 nm respectively. The linear fitting is applied on the averaged values to extract waveguide loss and total grating coupling loss. The results indicate a total (input plus output) grating coupling loss and a waveguide loss of respectively 20.6 dB and 11 dB mm\(^{-1}\) for 850 nm wavelength devices as well as 22.7 dB and 20.5 dB mm\(^{-1}\) for 635 nm wavelength devices. The 405 nm wavelength devices also demonstrate light coupling and guidance with total grating coupling loss and waveguide loss on the order of 33.1 dB and 46.7 dB mm\(^{-1}\), respectively. The high \(R^2\) coefficients obtained for the linear fitting functions underline the validity of the linear regression.](image-url)

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The measured transmission spectra for three representative devices fabricated for the three considered wavelengths are given in figure 7. We find that the peak transmission wavelengths of these three types of devices are 863, 632 and 411 nm, close to their design target of 850, 635 and 405 nm. Additionally, these devices demonstrate relatively wide \(-3\) dB bandwidths of respectively 52 nm, 26 nm and 17 nm around the transmission peaks. To compare the measured transmission spectra with theory, we numerically simulate the grating response versus wavelength using the grating periods and fill factors measured from the SEM images. The simulated spectra, also shown in figure 7, show a small offset in peak transmission wavelength as compared to the experimental spectra. To understand the origin of this offset, we have to consider the dependence of the gratings’ peak transmission wavelength on the refractive index of the SCD material. In our numerical simulations we employ refractive index values calculated with a Sellmeier equation from early literature \([7]\). The Sellmeier equation reported there had been determined based on measurements with natural diamond rather than synthetic diamond, but still it is often employed nowadays because of the overall shortage of experimental refractive index data for synthetic SCD at short wavelengths. This can explain the observed offset between the simulated and measured peak transmission wavelengths in figure 7. Despite this offset, the simulated spectra still have a reasonably good correspondence with their experimental counterparts.
4. Discussion

To understand the origin of the reported waveguide losses, we point out that the diamond material used for device fabrication is Type II(a) and that its one-photon absorption at all three wavelengths is virtually zero as the corresponding photon energies are below the material’s bandgap energy (5.47 eV) \[37\]. Among the three wavelengths considered, nonlinear absorption could only occur at 405 nm due to two-photon absorption, but only at sufficiently high powers \[9\]. Therefore, the waveguide losses observed in our low-power measurements are not due to material absorption. Instead, they are induced by scattering which is mainly attributed to the sidewall roughness of the waveguides. We note that the scattering loss tends to be higher at shorter wavelengths: a recent study on diamond waveguides showed that at UV wavelengths the scattering loss can be up to two orders of magnitude larger than at IR telecom wavelengths \[10\]. Hence, to reduce the waveguide losses at the three short wavelengths considered in our paper, the waveguides’ sidewall roughness should be further decreased and this could be achieved through technological improvements both regarding SCD sample quality and waveguide fabrication. Particularly the sample wedge plays a crucial role here. The wedged nature of the currently available SCD samples can cause non-uniformity in the e-beam resist layer spincoated on top, and as such the e-beam exposure across the sample area will not be uniform either. The latter increases the sidewall roughness of the fabricated devices, but this could be avoided if one could start from flat and uniform SCD plates.

The measured grating coupling losses depend on the grating design as well as the fiber used. The numerical aperture (NA) plays an important role here. The tapered tip fiber used at the devices’ output is fabricated from a multi-mode 50 μm core fiber with a NA of about 0.2. When tapering such a fiber, its NA is increased. A general rule of thumb to estimate the multiplication factor is to take the ratio of the core diameter in front of the taper (50 μm) to the core diameter at the end of the taper (12 μm) \[40\]. This yields an estimated multiplication factor higher than 4. Taking into account that this is just a rule of thumb, let us assume a more conservative value of 3, and as such use an NA estimation of 0.6 at the end of the tapered fiber, corresponding to a full acceptance angle of about 74°. Turning now to the grating properties, the total angular spread of the beam that is emitted from a single-mode grating coupler is about Δφ = 10° in the plane orthogonal to the waveguide, and Δθ = 5° in the plane orthogonal to the grating lines \[41\]. This means that the gratings’ emitted single-mode beam can be well accepted by the tapered multi-mode fiber even if an angular misalignment of a few degrees is present. This is beneficial for coupling light out of the grating couplers at the device’s output \[42\]. However, due to the same effect, the input coupling loss will be high when using a tapered multi-mode fiber at the device’s input grating coupler.

Simulations for the wavelengths used in this paper show that for an estimated NA of 0.6, the input coupling efficiency would only be 20%–30% of the coupling efficiency at the output (see figure 8 for the shortest and

**Figure 7.** Simulated and measured optical transmission spectra of representative diamond waveguide devices with grating couplers designed for 850, 635 and 405 nm wavelengths. The simulations are performed using the grating periods and fill factors measured from the gratings’ SEM images. The measured transmission spectra show −3 dB bandwidths of respectively 52 nm, 26 nm and 17 nm. In addition the peak transmissions are found at 863 nm, 632 nm and 411 nm wavelengths, respectively, which are close to their simulated values of 860 nm, 630 nm and 408 nm.
Assuming for the sake of simplicity a lower-limit factor of 20% (i.e. −7 dB) between input and output coupling efficiencies for all devices (i.e. for both the 850 and 635 nm devices with the tapered input fiber and the 405 nm devices with the lensed input fiber), we can make the following preliminary estimations: 13.8 dB input/6.8 dB output coupling loss for the 850 nm devices with 20.6 dB total coupling loss; 14.85 dB input/7.85 dB output coupling loss for the 635 nm devices with 22.7 dB total coupling loss; and 20.05 dB input/13.05 dB output coupling loss for the 405 nm devices with 33.1 dB total coupling loss. We emphasize that these values are just rough estimates based on a preliminary NA value, but they do give us an idea of how much the input and output coupling losses could differ.

The large input coupling losses could be reduced by employing small-NA single-mode input fibers such as those considered in the grating simulations (see section 3.1); we intend to use such fibers in future experiments. Considering the applications mentioned in the introduction, it is likely that the obtained input coupling losses, although quite high, will still allow for the realization of quantum-optical devices in view of the low powers required for these devices. For other applications relying on higher powers, a reduction of losses including the waveguide losses would be desirable, and this could be achieved through technological improvements in SCD sample preparation and in the lithographic fabrication. Yet, the results presented here can be considered as a first important step forward in the practical realization of these different applications at short to ultra-short wavelengths in on-chip SCD diamond devices.

5. Conclusion

In summary, we have demonstrated the design, fabrication and the characterization results of waveguide devices with grating couplers optimized for 850, 635 and 405 nm in SCD.

To reduce the wafer wedge in commercial SCD plates for producing suitable SCD thin films for such short-wavelength devices, we have introduced a novel tilted-etching technique that can be directly applied during the diamond thinning process. We have achieved a strong reduction of 60% in wedge ratio from 300 to 120 nm mm⁻¹. We believe further improvements in the tilt angle and etching recipe could even allow production of wedge-less thin films.

Using the wedge-reduced SCD thin films fabricated by the tilted-etching technique, we have successfully realized up to 370 μm long waveguide devices with grating couplers for the short wavelengths under consideration. By means of optical tests using two tapered tip fibers with a core diameter of 50 μm, we have determined total (input plus output) grating coupling losses of 20.6 dB and 22.7 dB, and waveguide losses of 11 dB mm⁻¹ and 20.5 dB mm⁻¹ for 850 nm and 635 nm wavelength devices, respectively. The 405 nm devices are tested using a lensed tip input fiber with a core diameter of 9 μm and a tapered tip output fiber with a core diameter of 50 μm. Although being more lossy, they do show coupling and guiding of 405 nm light with a waveguide loss on the order of 46.7 dB mm⁻¹ and a total grating coupling loss on the order of 33.1 dB.

Furthermore, optical transmission spectra show a considerable −3 dB bandwidth of respectively 52 nm, 26 nm

![Figure 8. Simulated 405 and 850 nm grating input coupling efficiency with various fiber NA and at different angles θ in the plane orthogonal to the grating grooves. The results are normalized and the peak values are found at NA = 0.12 and θ = 9°.](image-url)
and 17 nm for the fabricated devices. To maximize input coupling performance, we plan to employ dedicated single-mode fibers with a small NA at the device input grating in future experiments.

The devices reported here represent an important expansion of the currently existing SCD nanophotonic structures for short-wavelength operation (i.e. mostly individual optical resonators for quantum applications). Indeed, the waveguides and integrated grating couplers that we optimized for short-wave NIR/VIS spectral operation not only give the opportunity of transforming these discrete resonators into on-chip quantum networks with out-of-plane fiber connectivity, but also allow pushing SCG demonstrations with SCD waveguides further into the VIS wavelength region. Additionally, the down-scaled grating couplers and waveguides demonstrated for 405 nm operation are an important step forward to e.g. on-chip VIS-UV wavelength conversion. Therefore, our results represent a significant advance in the on-chip exploitation of SCD’s unique optical properties present in the short-wave NIR/VIS and even the UV range.

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References

[1] Aharonovich I, Greenstreet A D and Prawer S 2011 Nat. Photon. 5 397–405
[2] Mildren R and Rabeau J 2013 Optical Engineering of Diamond (New York: Wiley)
[3] Feve J P M, Shortoff K E, Bohn M J and Brasseur J K 2011 Opt. Express 19 913–22
[4] Sabella A, Spence D J and Mildren R P 2015 IEEE J. Quantum Electron. 51 1–8
[5] Latapie P, Venkataraman V, Burek M J, Haussmann B, Bulu I and Lončar M 2015 Optica 2 924–8
[6] Haussmann B, Bulu I, Venkataraman V, Deoarte P and Lončar M 2014 Nat. Photon. 8 369–74
[7] Peter F 1923 Z. Phys. 15 358–68
[8] Feigel B, Castelló-Lurbe D, Thiennpont H and Vermeulen N 2017 Opt. Lett. 42 3804–7
[9] Vermeulen N, Sipe J, Helt L G and Thiennpont H 2012 Laser Photonics Rev. 6 793–801
[10] Feigel B, Thiennpont H and Vermeulen N 2016 J. Opt. Soc. Am. B 33 B5–18
[11] Fodor S P A, Rava R P, Hays T R and Spiro T G 1985 J. Chem. Soc. 107 1520–9
[12] Consani C, Auböck G, Van Mourik F and Chergui M 2013 Science 339 1586–9
[13] Bhartia R, Salas E C, Hug W F, Reid R D, Lane A L, Edwards K J and Nealson K H 2010 Appl. Environ. Microbiol. 76 7231–7
[14] Faraon A, Barclay P E, Santori C, Fu K M C and Beausoleil R G 2011 Nat. Photon. 5 301–5
[15] Faraon A, Santori C, Huang Z, Acosta V M and Beausoleil R G 2012 Phys. Rev. Lett. 109 033604
[16] Faraon A, Santori C, Huang Z, Fu K M C, Acosta V M, Fattal D and Beausoleil R G 2013 New J. Phys. 15 025010
[17] Haussmann B et al 2012 Nano Lett. 12 1578–82
[18] Haussmann B et al 2013 Nano Lett. 13 5791–6
[19] Santori C, Barclay P, Fu K C, Beausoleil R, Spillane S and Fisch M 2010 Nanotechnology 21 274008
[20] Burek M et al 2017 Phys. Rev. Appl. 8 024026
[21] Rogers L I et al 2014 Phys. Rev. B 89 235101
[22] Neu E, Hepp C, Hauschild M, Geßl S, Fischer M, Sternschulte H, Steinmüller-Nethl D, Schreck M and Becher C 2013 New J. Phys. 15 043005
[23] Neu E, Agio M and Becher C 2012 Opt. Express 20 19956–71
[24] Hepp C et al 2014 Phys. Rev. Lett. 112 036405
[25] Aharonovich I and Neu E 2014 Adv. Opt. Mater. 2 911–28
[26] Lončar M and Faraon A 2013 MRS Bull. 38 144–8
[27] Gao F, Huang Z, Feigel B, Van Ers J, Thiennpont H, Beausoleil R G and Vermeulen N 2016 J. Lightwave Technol. 34 5576–82
[28] Latapie P, Venkataraman V, Shams-Ansari A, Markham M and Lončar M 2018 Opt. Lett. 43 318–21
[29] Latapie P, Shams-Ansari A, Okawachi Y, Venkataraman V, Yu M, Atikian H, Harris G L, Picqué N, Gaeta A L and Lončar M 2018 OSA Tech. Dig. STuX6.6
[30] Rath P, Khasminkaya S, Nebel C, Wild C and Pernice W H 2013 Beilstein J. Nanotechnol. 4 300–5
[31] Gao F, Van Ers J, Huang Z, Thiennpont H, Beausoleil R G and Vermeulen N 2018 IEEE J. Sel. Top. Quantum Electron. 24 6100909
[32] Piracha A H, Ganesan K, Lau D W, Stacey A, McGuinness L P, Tomljenovic-Hanic S and Prawer S 2016 Nano Scale 8 6860–5
[33] Piracha A H, Rath P, Ganesan K, Kühn S, Pernice W H and Prawer S 2016 Nano Lett. 16 3341–7
[34] Robinson J and Rahmat-Samii Y 2004 IEEE Trans. Antennas Propag. 52 397–407
[35] Lumerical 2018 Grating coupler 2d-fdtd (https://kb.lumerical.com/en/pic_passive_grating_coupler_2d.html)
[36] Hausmann B J, Bulu I, Deotare P, McCutcheon M, Venkataraman V, Markham M, Twitchen D and Lončar M 2013 Nano Lett. 13 1898–902
[37] Weber M J 2002 Handbook of Optical Materials (Boca Raton, FL: CRC Press)
[38] Feynman R, Leighton R and Sands M 2013 The Feynman Lectures on Physics vol 2 (New York: Ingram)
[39] Cardenas J, Poitras C B, Robinson J T, Preston K, Chen L and Lipson M 2009 Opt. Express 17 4752–7
[40] Cole H B 1975 Numerical aperture expansion in fiber optic devices Patent US3874783A
[41] Van Acoleyen K, Rogier H and Baets R 2010 Opt. Express 18 13655–60
[42] Pelc J S, Rivoire K, Vo S, Santori C, Fattal D A and Beausoleil R G 2014 Opt. Express 22 3797–810