Optical Design and Analysis of Additively Manufactured Optical Interfaces for Spin Qubits

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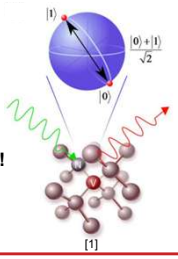
Integrated Spin Qubits

NV-Center in Diamond (negatively Charged)

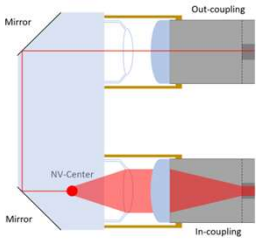
- Vacancy next to one nitrogen atom in the lattice
- Optically initializable (by green light)
- Behaves like a two level system, **even at ambient conditions!**
- State can be driven using Microwave Radiation at ~2.87 GHz
- Observable Zeeman Splitting



[1]

Fiber-Coupled Devices

- Quantum magnetic field sensors (ensembles)
- Integrated Photonic devices
- Nanoscale sensing (e.g. Bioassay applications)
- Qubits (single NVs)
- Single-photon sources (single NVs)

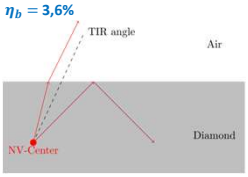


Fluorescence Collection

Total escaping light

$\eta_a = 4{,}5\%$

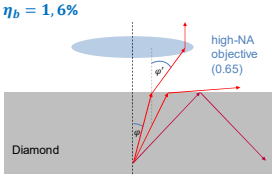
$\eta_b = 3{,}6\%$



Collected by Objective

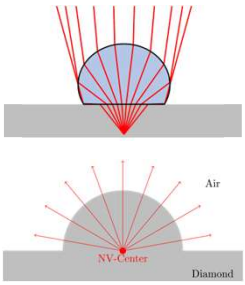
$\eta_a = 2{,}0\%$

$\eta_b = 1{,}6\%$



TIR in diamond

- High index mismatch on diamond-air interface prevent most rays to exit diamond crystal.
- Further losses by reflection („Fresnel losses")
- Mitigation by
  - Immersion objectives
  - Diamond surface shaping [3]
  - Weierstrass lenses



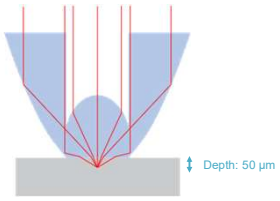
Micro-Optics Design

η_a Collection efficiency without fresnel losses

η_b Collection efficiency with fresnel losses (unpolarized)

F Improvement factor over flat surface

3D-Printed Refractive Lens + TIR Mirror



This design was already realized for quantum dots [2]

+ Less Surfaces, so potentially less Fresnel Losses

+TIR for all outer angles

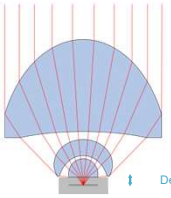
- Additional loss potential for steep angles due to TIR condition inside the polymer lens

$\eta_a = 11{,}0\%$

$\eta_b = 8{,}2\%$

$F = 2{,}3$

3D-Printed Refractive Objective



+ Polymer Weierstrass proves to be very efficient for bending wide angles even up to 180°

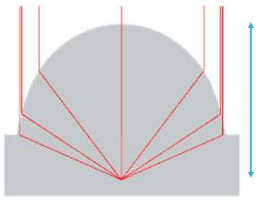
- Still limited by Diamond-Polymer TIR Angle

$\eta_a = 11{,}0\%$

$\eta_b = 7{,}7\%$

$F = 2{,}2$

Diamond SIL



+ More collimated light than total half-room emission for flat diamond

-The manufacturing of such an ellipse may be difficult depending on the depth of the NV-Center

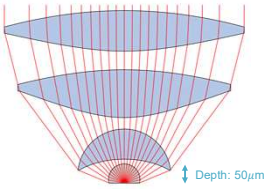
- High Fresnel Losses!

$\eta_a = 30{,}0\%$

$\eta_b = 14{,}6\%$

$F = 4{,}1$

Diamond SIL + 3D-Printed Objective



+ Diamond Weierstrass + refractive polymer lenses improve the collection efficiency by a factor of 9,1

+ No TIR Limitation

- Complex manufacturing process

$\eta_a = 49{,}5\%$

$\eta_b = 32{,}2\%$

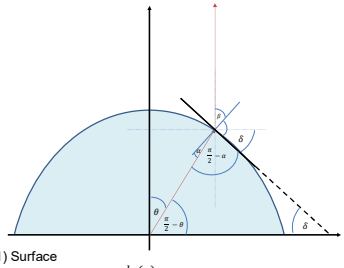
$F = 9{,}1$

All designs can be adapted for depths of less than 100μm below the diamond surface.

All shown designs were optimized and analyzed using Ansys Zemax Opticstudio®.

ODE Approach

Inner Lens (small angles)



1) Surface

$$\frac{dy(x)}{dx} = -\tan\delta$$

2) Snells Law

$$n_1 \sin\alpha = n_2 \sin\beta$$

3) Collimation of output Beam

$$\beta = \delta$$

4) Relationship between Angles

$$\delta = \alpha + \theta$$

5) Angle to scalable Geometry:

$$\tan\theta = \frac{x}{y(x)}$$

Using all of those constraints, we arrive at

$$\frac{dy(x)}{dx} = \frac{\sin\theta}{\frac{n_2}{n_1} - \cos\theta}$$

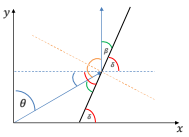
Solution: Ellipse with eccentricity $e = n_1/n_2$

Outer Lens (steep angles)

$$\frac{dy(x)}{dx} = \frac{\sin\theta}{1-\cos\theta}$$

The analytic solution to this equation is of the form

$$y(x) = \frac{1}{2}\left(\frac{x^2}{x_0} - x_0\right)$$



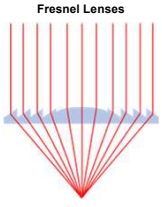
Special case of a CPC (Compound Parabolic Concentrator)

Outlook

Optical Design & Analyses

- Sensitivity & tolerance analyses
- Construction of holding structures
- FEM analyses
- Fiber Coupling

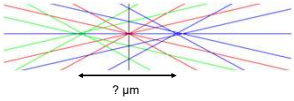
Fresnel Lenses



Chromatic correction

Optimization for:

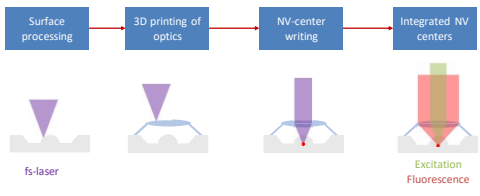
- Excitation @ 532nm
- Fluorescence @ 650nm
- Fs-laser Writing @780/1064/532

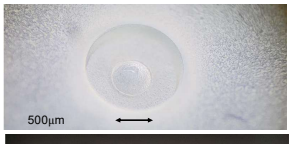


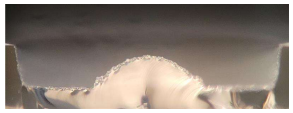
Position of foci in an elliptical diamond SIL (Green 532nm, Red 620nm, Blue 780nm TiSa; NV Depth: 100µm) Since the excitation and fabrication spot are seperated by orders of wavelengths, chromatic correction may be neccessary

Single NV centers & Micro-Optics

- Deterministic fs-writing of single NVs
- Micromilling of diamond surface via fs-laser
- 3D-Printing of the here presented (and more) lens designs
- Innovative generation and integration processes







Ablation tests in borosilicate glass using a ps-pulsed modelocked oscillator with regenative amplifier (Nd:YVO4).
Current investigations for microfabrication of optical elements in diamond focus on the use of fs-pulsed lasersystems.

Images: M. Sc. Andreas Giese, Prof. Dr. Bernd Braun, Photonics Research Group TH Nürnberg

References

[1] V. Bharadwaj u. a., „Femtosecond laser written photonic and microfluidic circuits in diamond", J. Phys. Photonics, Bd. 1, Nr. 2, S. 022001, März 2019, doi: 10.1088/2515-7647/ab0c4e.

[2] L. Bremer u. a., „Quantum dot single-photon emission coupled into single-mode fibers with 3D printed micro-objectives", APL Photonics, Bd. 5, Nr. 10, S. 106101, Okt. 2020, doi: 10.1063/5.0014921.

[3] J. Hadden u. a., „Strongly enhanced photon collection from diamond defect centres under micro-fabricated integrated solid immersion lenses", Applied Physics Letters, Bd. 97, Juni 2010, doi: 10.1063/1.3519847.

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