

Integrated photonic and electronic building blocks for NV-diamond magnetometry

Lena Schäd¹, Steffen Epple¹, Tobias Hoose², Mathias Kaschel¹, Kevin Edelmann¹, Gregor Ronniger¹, Michael Thiel², Robert Rölver, Michal Kern³, Jens Anders^{1,3}

¹ *Institut für Mikroelektronik Stuttgart, 70569 Stuttgart, Germany*

² *Nanoscribe GmbH & Co. KG, 76344 Eggenstein-Leopoldshafen, Germany*

³ *Institute of Smart Sensors, University Stuttgart, 70569 Stuttgart, Germany*

Abstract

We present key building blocks for an integrated approach to NV-diamond magnetometry. The work combines application-specific integrated circuits (ASICs) for control and data processing with integrated optical waveguides within a compact architecture. The objective is to investigate miniaturized and scalable implementation strategies for diamond-based NV magnetic field sensors while maintaining suitable optical excitation conditions and compatibility with optical readout. Within a photonic integrated circuit (PIC), both the excitation path and the signal and reference paths were realized on a single chip. Two different photonic chip architecture concepts were implemented and characterized with respect to optical throughput and assembly complexity. Experimental results show that integrated Si₃N₄ waveguides, in combination with additively manufactured micro-optics, can provide efficient diamond excitation with power densities exceeding 1 kW/cm². In addition, preliminary feasibility experiments indicate that the presented approach is compatible with optically detected magnetic resonance (ODMR) measurements. The presented results provide a basis for future integrated NV-based sensing systems.

Keywords: magnetic field sensor, optical measurement methods, NV-diamond magnetometry, integrated photonics

Introduction

Applications in materials research and medical diagnostics demand high-performance magnetic field sensors. There is a particular need for sensors that can operate at room temperature, exhibit high magnetic field sensitivity in the picotesla range, and allow for significant miniaturization to enable integration into compact or portable systems. These requirements are becoming increasingly important, particularly in the context of human-machine interfaces in mobile diagnostic systems. Quantum sensors based on nitrogen-vacancy (NV) defects in diamond represent a promising technology for meeting these requirements [1]. NV color centers are point defects in the diamond lattice, consisting of a nitrogen atom in the immediate vicinity of a lattice vacancy. The ground state of this defect possesses an electron spin that can be optically detected and manipulated using microwave fields. This principle is utilized in the context of optically detected magnetic resonance (ODMR) [2]. A schematic image of the energy transitions is shown in Fig. 1 (a). If the spin state $m_s = 0$ is excited to the states $m_s = \pm 1$ by a resonant microwave field (2.87 GHz), the observed fluorescence intensity, indicated by the red arrow, is reduced due

to an increased transition to a non-radiative singlet state. The resulting dip in the fluorescence signal as a function of microwave frequency is shown in Fig. 1 (b). In the presence of an external magnetic field, the states $m_s = \pm 1$ are energetically split by the Zeeman effect, causing the characteristic fluorescence dips in the ODMR spectrum to split as well. The positions of these resonances depend directly on the strength of the external magnetic field, enabling precise determination of changes in the magnetic field. Due to the long coherence times of the spins, the high radiative quantum efficiency, and the optical accessibility of the NV centers, physical quantities, particularly magnetic fields, can be measured with very high sensitivity at room temperature [1]. NV-based quantum sensors thus offer a decisive advantage over other quantum sensors, such as optically pumped magnetometers (OPMs) and superconducting quantum interference devices (SQUID), which often have more restrictive operating conditions, such as shielding or cryogenic requirement [1]. For many applications, however, extensive miniaturization of the sensor system is required in addition to sensitivity. Whilst recent work has already integrated individual sub-components, a fully integrated system solution has so far been lacking [3], [4].

In particular, the integration of the various functional components like laser sources, optical filters, waveguides, microwave generators and resonators, as well as photodetectors, together with the necessary control and readout electronics presents a key challenge. At the same time, low-loss optical signal transmission and stable interfaces between the individual components must be ensured. Many current publications on miniaturized, portable NV-magnetometers continue to be based on free-space optics. Whilst this allows sensor heads to be realized on a centimeter scale [3], [4], scalable and reproducible manufacturing of such systems is only possible to a limited extent. In this context, approaches toward photonic and electronic integration are of particular interest, as they may enable more compact and scalable implementations. However, achieving low-loss optical routing, stable interfaces, and efficient excitation within such integrated systems remains a key challenge.

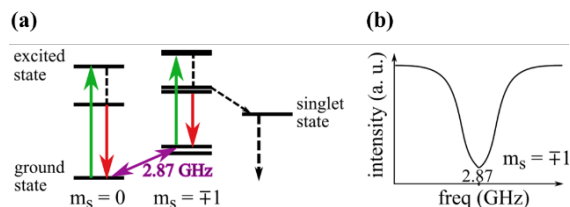


Fig. 1: (a) Simplified energy levels of the electron spin in the NV center. (b) Optical pumped and zero biased ODMR spectrum of the NV center according to microwave frequency. The graphic is based on [2].

We investigate a miniaturized approach based on integrated photonics and integrated electronics for NV-diamond magnetometry. Due to its broad transmission window of 400 nm to 4000 nm, Si_3N_4 is a suitable integrated photonic platform for visible wavelengths [5]. For in-plane fiber-to-chip coupling which is useful for scalable packaging, edge couplers with inverse tapers are widely used to match the large mode field diameter (MFD) of the fiber connected to a light source [5], [6]. Most developments focus on the short-wave infrared (SWIR) wavelength range. Since integrated waveguides become smaller with shorter wavelengths, the coupling requirements for 532 nm are more challenging. For instance, in [7], coupling losses of 7.5 – 11.3 dB/facet for TE were achieved in the wavelength range from 430 nm to 648 nm. Another group achieved around 4 dB per facet for 445 nm to 640 nm using a bi-layer coupling concept [8]. This illustrates that the fiber-to-chip interface is a critical component of visible-wavelength PICs. Therefore, this paper focuses in particular on the realization and

characterization of photonic integration concepts and their suitability for future integrated NV-diamond sensing systems.

Integrated system overview

The overall approach and the corresponding signal chains are shown Fig. 2. A central element is the optical transmission path, which transfers the excitation light (532 nm) from the light source through the diamond (D) to the signal photodiode (PD1) or reference photodiode (PD2). For this purpose, a photonic chip with integrated waveguides was manufactured at IMS CHIPS. Splitting the light into two optical paths enables balanced photodetection. To support future miniaturized implementations, three application-specific integrated circuits (ASICs) are being developed to drive, control, and read out the light source, microwave (MW), and photodiodes. A major challenge lies in integrating the various components — laser source, filters, waveguides, MW generators, resonator, and photodetectors — with the corresponding ASICs and peripheral electronics into a robust system. For this reason, a holistic view of the relevant subsystems is beneficial during implementation.

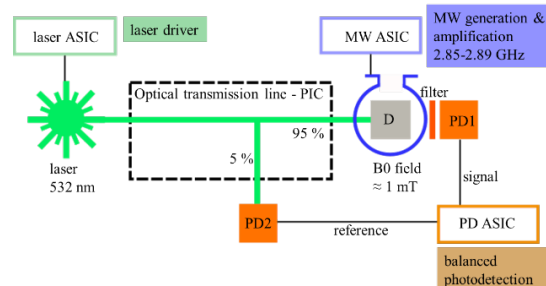


Fig. 2: System overview and signal chains of the integrated system concept.

The design of the optical signal paths influences the layout of the electronics and peripherals. A critical parameter for sensor performance is the diamond excitation power density. To balance thermal heating effects with sufficient excitation power below the saturation intensity, the power density is targeted between 1-10 kW/cm² [9], [10]. Based on this, an excitation density at the diamond of greater than 1 kW/cm² is targeted in this work. This gives rise to several requirements regarding the components to be used and their interfaces. Initially, the miniaturized passive components and subassemblies are operated using external laboratory equipment (a 532 nm fiber-coupled laser source and a MW generator) for optical and electrical supply during design and testing. In this work, the photonic chip is first developed for the optical transmission path and then combined with diamonds, filters, and photodiodes in a demonstrator

setup. The optical and electrical aspects are described separately below, with particular emphasis on the optical integration.

Optical Integration - Design

This approach uses integrated Si_3N_4 waveguides to enable the scalable splitting of signals and references on a chip, facilitating a compact optical architecture with dimensions on the order of a few millimeters. In addition, a hybrid approach involving on-chip printed microstructures for a robust, long-term assembly technology solution is being considered. This will be addressed in more detail later in the section. As previously mentioned, developing an efficient and robust solution for fiber-to-chip and chip-to-diamond coupling is the main challenge here. As shown in Fig. 3, two chip arrangements are being investigated: (1) a vertical arrangement with grating couplers (GC1 and GC2) and (2) a horizontal arrangement with edge outcoupling. The main part of the transmitted light should excite the diamond (D). For balanced photodetection, 5% of the transmitted light should be split to reach the reference diode (PD2) [11]. In arrangement (1), splitting occurs based on the grating coupler design, whereby only a small portion of the light passes GC1 without being decoupled. The partially etched grating coupler has a width of $1.4\text{ }\mu\text{m}$, a period of 250 nm , and a duty cycle of 0.7 . It consists of 150 periods. In (2), a directional coupler (DC) splits the light. It has a gap width of 400 nm and a coupling length of $18\text{ }\mu\text{m}$. Both concepts adopt an edge coupling approach on the input side. Because the fiber-chip interface is the most critical component, this work examines its development in greater detail.

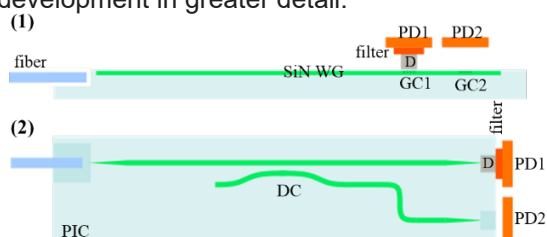


Fig. 3: Integrated optical concepts. (1) Side view of the vertical arrangement with grating couplers (GC1 and GC2); (2) top view of the horizontal arrangement with directional coupler (DC).

The proposed edge coupler is illustrated in Fig. 4 (a) and consists of two tapers (taper 1 and taper 2) ending in a single-mode waveguide (SM WG) that is 180 nm high and 280 nm wide. The performance of the edge coupler depends largely on the taper tip geometry and taper length. Taper 1 is designed to optimize mode overlap between the fiber and the waveguide

tip. To achieve the required mode expansion near the fiber, an additional shallow etch was applied to the entire taper 1 and the outer regions of taper 2, ensuring an adiabatic transition to the SM WG height level. A polarization-maintaining fiber (PMF, PM460-HP) was selected as the coupling fiber. Fig. 4 (b) shows the mode overlap as a function of the taper tip geometry. Dark red squares indicate the highest coupling efficiencies between the fiber mode and the waveguide tip fundamental transverse-electric (TE) mode. Considering manufacturing tolerances, a taper tip geometry with a height of 75 nm and a width of 90 nm was chosen, resulting in around 87% mode overlap.

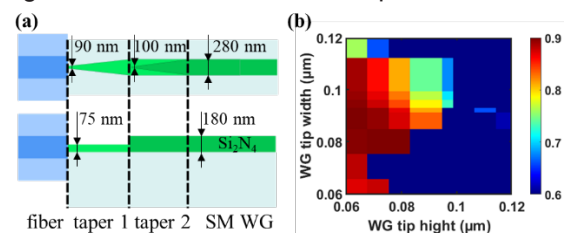


Fig. 4: (a) Schematic of fiber to Si_3N_4 edge coupler. (b) Mode field overlap between fiber and Si_3N_4 taper tip related to tip height and width.

Lumerical Eigenmode Expansion (EME) was used to simulate beam propagation and determine the taper lengths. Fig. 5 (a) displays a side view of the field distribution from the fiber to the SM WG. The transmitted power of the fundamental TE mode, as a function of the taper 1 length, is shown in Fig. 5 (b). Transmission only increases minimally beyond a length of $200\text{ }\mu\text{m}$. Therefore, the length of taper 1 was set to $200\text{ }\mu\text{m}$. For the selected geometry, Fig. 5 (c) displays the field profiles at the marked positions. It is evident that the mode over the tapered edge coupler experiences increased confinement within the waveguide. Position 1 belongs to the tip of taper 1 and its MFD has dimensions of $1.53\text{ }\mu\text{m}$ and $1.82\text{ }\mu\text{m}$ in the horizontal and vertical directions, respectively. Using the same procedure, the length of the second taper was set to $100\text{ }\mu\text{m}$, with a taper tip 100 nm wide and 280 nm high. The input coupler described above was simply mirrored for the output edge couplers without the shallow etch step.

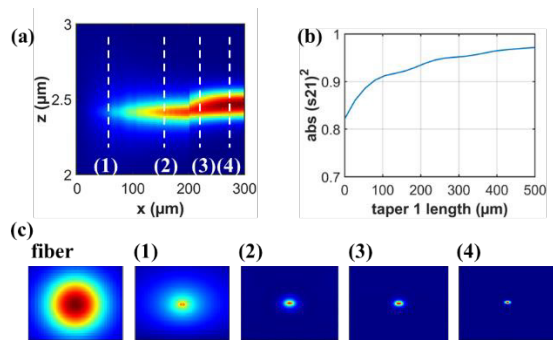


Fig. 5: (a) Sideview of the field distribution along the two-level taper from the fiber to the SM WG (E_{abs}) (b) Transmission as $\text{abs}(s_{21})^2$ in relation to taper 1 length. (c) WG mode fields along edge coupler.

To ensure a secure, long-term connection between the PIC and the laser fiber for a scalable setup, 3D-printed microstructures are employed. Microfiber clamps are used to mechanically position the fiber on the PIC. As a further solution to make the fiber-chip coupling more robust, the approach of using microlenses between the fiber facet and the chip facet, in combination with the micro clamps, is being investigated. The focusing microlens is designed and optimized to match the fiber mode field to the WG tip mode field (Fig. 5 (c) position1) and to provide increased optical assembly tolerance in the demonstrator setup, which is intended to enable scalable production. The simulated maximum achievable coupling efficiency from the fiber to the WG tip of the designed lens is 88 %. This represents a slight improvement over the simulation without the lens; however, it is expected that this will yield a benefit in terms of stable assembly technology.

Optical Integration - Fabrication and Measurement

To measure and characterize the photonic structures, the optical transmission lines were arranged on a 6-inch wafer in a chip-wise manner. The specified chip size is 12.5 mm x 3 mm. An exemplary chip layout is shown in Fig. 6 (a). The devices were fabricated and diced at IMS CHIPS. An oxide etch process in combination with a Si deep etch process was used to create smooth, vertical edge surfaces for in- and out-coupling. Samples of concepts (1) and (2) were fabricated on a silicon wafer coated with a 2.38 μm thick buried oxide (BOX) layer and a 180 nm thick Si_3N_4 film. First, shallow etching of the initial taper 1 and the grating coupler was performed using an e-beam lithographic process. Then, in the second step, full-depth waveguide etching was performed using the same procedure. A 2 μm SiO_2 layer was then

deposited as top oxide (TOX) which acts as cladding. An etch trench through the SiO_2 layers into the Si substrate was finally performed to realize the input and output ports of the devices. In Fig. 6 (b), the deep-etched in-coupling facet and input taper is visible. The scanning electron microscope (SEM) image of section A-A presents clearly a vertically edged oxide facet.

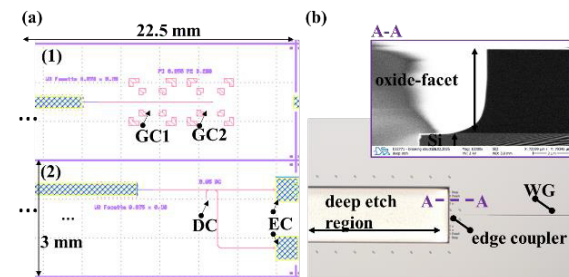


Fig. 6: (a) Layout image of the designed photonic concepts (1) and (2). The chip dimensions and the splitting or coupling structures are marked. (b) Microscope images of fabricated deep-etched in-coupling facet and edge coupler. Section A-A shows a SEM image of the etched oxide facet.

The chips were characterized using the setup shown in Fig. 7. Light from a laser source (RLTMGL-532UPM-250-5, Roithner) was coupled into the input facet via a PMF. Fiber alignment was performed using a microscope and a 6-axis stage. Light emitted from the photonic chip's output coupler was collected with a 400 μm core-diameter multimode fiber (MM), which was connected to an optical power meter (PM100USB, S154C, Thorlabs). When using a grating coupler as the outcoupling port, the MM fiber was placed vertically above the coupler. The transmitted light of the PMF-PIC-MM transmission lines for the signal and reference paths were measured, respectively. The measured power ratio is relative to the fiber-to-fiber (PMF-MM) coupled power. Due to system-level considerations, this publication considers only the overall transmission. The total throughput is calculated by adding the power emitted by the reference and signal paths. The results of concepts (1) and (2) are compared in Tab. 1. Clearly, Concept 2's total throughput is much higher than that of the grating coupler. It was found that a large proportion of the light is guided in the direction of the beam without being decoupled by the grating couplers. Clearly, Concept 2's total throughput is much higher than that of the grating coupler. It was found that a large proportion of the light is guided in the direction of the beam without being decoupled by the grating couplers.

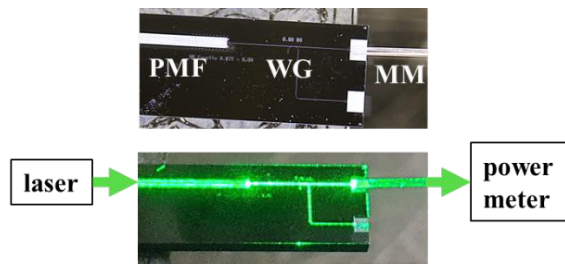


Fig. 7: Schematic measurement setup of concept (1) without and with excitation light

Tab. 1: Characterization results.

Concept	Reference path (%)	Signal path (%)	Total throughput (%)
(1)	0.3	10	10.3
(2)	2	27	29

Since it is not possible to accurately measure the power density with the employed setup, it is estimated from the radiating area and the out-coupled power. Assuming a distance of 2-3 μm from the decoupler to the diamond and 10 mW laser excitation, the radiating area for the grating coupler approach is approximately 20-30 μm^2 , leading to a power density in the range of 3-5 kW/cm². For the edge coupler, the estimated radiating area is 3-5 μm^2 , and the power density is 50-100 kW/cm². Despite the edge coupler being more efficient, both concepts reach the target value of greater than 1 kW/cm². Due to the higher efficiency, only the edge coupler architecture will be considered for the system demonstrator.

As part of the hybrid mechano-optical interface solution, the microstructures were directly printed onto the Si₃N₄ chips with a Quantum X align system, making use of Nanoscribe's Aligned 2-Photon Lithography (A2PL®) micro-fabrication technology. Initial printing trials and tests were conducted to print the structures into the deep-etched trenches and couple light into the waveguide. Fig. 8 shows the printed structures placed in the deep-etched groove at the coupling facet. The marks in the Si₃N₄ layer are used to align the structures relative to the Si₃N₄ waveguide during printing. The clamp, into which the PMF can be easily clipped, manages the x-, y-, and z-positioning of the fiber. As can be seen, these structures enable fiber positioning and light coupling into the waveguide without hexapod positioning. Additionally, clamp-based fixation enables robust adhesion of the fiber to the photonic chip.

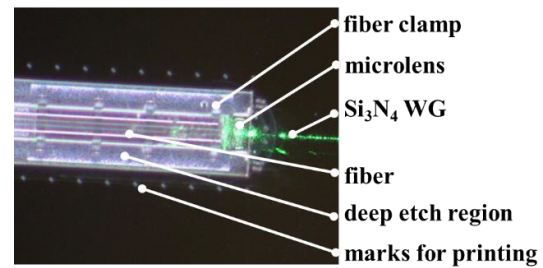


Fig. 8: Fiber-to-chip interface with a hybrid mechano-optical solution. 3D-printed microstructures at the facet of the PIC. A fiber clamp is used for mechanical positioning, and an in-coupling micro-lens increases assembly tolerances.

Electrical Integration

As already described, the electrical signal transmission involves driving the laser source, reading out and driving the photodiodes, and supplying the microwave power. To achieve the desired integrated system design from Fig. 2, the three ASICs must be integrated with the peripheral electronics.

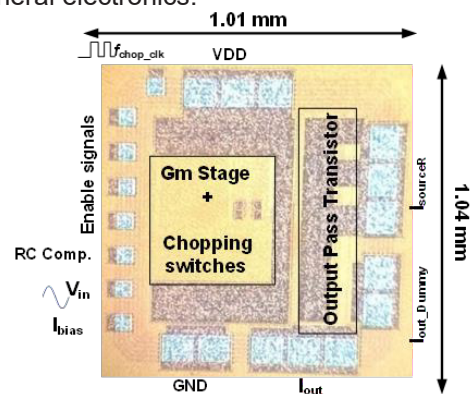


Fig. 9: Floorplan of the laser driver ASIC.

To enable system integrated NV-diamond magnetometry, it is necessary to precisely set the DC operating of deployed laser diodes. The noise performance needs to be close to the electrical shot-noise limit of the photodiodes. For realizing this, the laser driver ASIC shown in Fig. 9 is implemented. It is manufactured in a 130 nm SOI CMOS technology with a chip area of about 1 mm² and a supply voltage of 2.5 V. Driving currents in the range of 50 mA – 300 mA are possible, while the output noise is 210 pA/ $\sqrt{\text{Hz}}$ in the low-noise mode. Driving the system in DC mode is possible, as well sinusoidal and pulse modulation. The modulation frequencies of the laser current around the DC operating point range from 1 kHz to 40 MHz. The ASIC is integrated on a PCB with all peripherals for power supply, control and modulation within a size of about 3 x 3 cm².

Optical readout of the magnetic field sensor is done by commercial photodiodes (LAPD45HP1) connected to an ASIC-integrated Current-to-digital ADC with about 12-bit ENOB, 75 dB SNR, corresponding to an input-referred noise of about $32 \text{ pA}/\sqrt{\text{Hz}}$. The ASIC also implements an autobalancing circuit to reduce common-mode noise from the optical system. The ASIC has a power consumption of 50 mW at a size of 1.2 mm^2 in a 130 nm SOI technology.

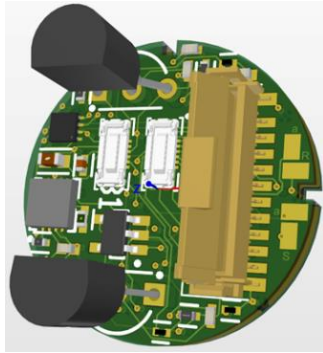


Fig. 10: PCB for balanced photodetection.

Photodiodes (PD1 and PD2) and the ASIC are combined on a round PCB shown in Fig. 10 with a diameter of 2 cm and all peripherals and connectors for external control and further signal processing e.g. lock-in detection.

The concept for stimulating the NV-diamond with microwaves in the GHz range is based on an ASIC-integrated PLL, combined with a mixer and a power amplifier, to synthesize the base-band signal. It shall enable system-integrated hyperfine stimulation and frequency modulation for lock-in detection. Finally, the GHz signal is delivered to the NV diamond by a customized patch resonator.

As an intermediate step towards system integration, the microwave is supplied by the commercial Windfreak Synth USB3 RF signal generator and a Mini Circuits ZX60-63GLN+ amplifier.

ODMR-Demonstrator

To assess the compatibility of the presented photonic and electronic building blocks with ODMR-based sensing, a preliminary demonstrator was assembled, as shown schematically in Fig. 11. The setup combines the developed PIC with a diamond-filter-photodiode arrangement as well as MW and photodiode readout electronics. At this stage, the arrangement serves as a feasibility platform for evaluating optical excitation, fluorescence collection, and microwave-driven spin manipulation under conditions relevant for future integrated implementations. According to the schematic configuration, the demonstrator was set up

except for the absence of the Halbach ring for the B0 field.

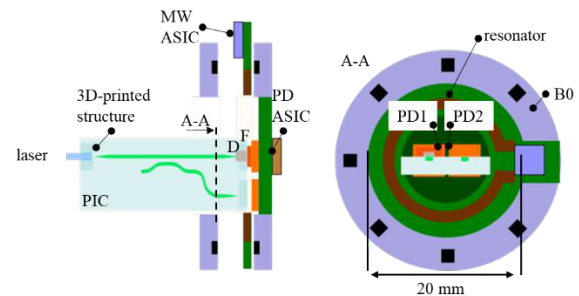


Fig. 11: Schematic ODMR demonstrator setup. On the left side, top view of the demonstrator setup. On the right side, cut A-A view.

The PIC was assembled with a diamond-filter-photodiode stack, the photodiode readout, and the MW electronics. Due to the horizontal edge coupling approach, fixing the diamond-filter-photodiode stack is more difficult, as the PIC cannot serve directly as a mechanical sub-mount. As a filter, a 550 nm long-pass filter (15-446, Edmund Optics) was cut to the target geometry of $1.4 \text{ mm} \times 1 \text{ mm}$ and glued to the signal photodiode using an optical adhesive. The diamond (DNL-B14) with a cube edge length of $500 \mu\text{m}$ was glued to the filter using an optical adhesive. For the input connection, the PM laser fiber was fixed using the on-chip 3D-printed micro-fiber clamps. The resonator and photodiode boards were connected via 3D-printed structures to position the diamond stack at the center of the resonator and at the outcoupling edge coupler of the PIC. Fig. 12 presents the assembled demonstrator. As shown on the right side, optical excitation of the diamond and the generation of a measurable fluorescence signal were achieved.

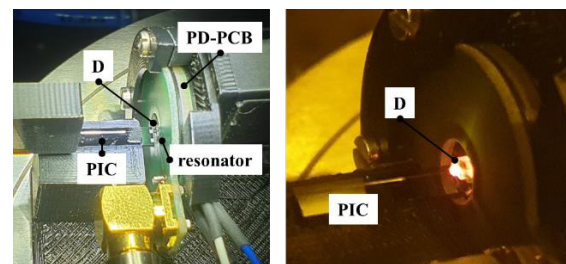


Fig 12: ODMR demonstrator setup. On the left side assembly of the sensor head. On the right side long-pass filtered image of the sensor to suppress the source light.

For an initial ODMR feasibility measurement, the diamond was adhered to a multimode fiber and positioned at the center of the MW resonator. In this preliminary configuration, the signal

photodiode and filter were placed outside the sensor head. A total of ten consecutive frequency sweep measurements were recorded in the range from 2.850 GHz to 2.890 GHz using a microwave power of 6 dBm. Fig. 13 shows the ODMR dip in the individual measurements (top) and in the average signal (bottom). Despite the absence of an integrated B₀ field, a splitting of the dip is observable, indicating the presence of an ambient magnetic field. These results confirm the general compatibility of the employed optical excitation concept with ODMR measurements, while a fully integrated quantitative evaluation remains the subject of future work.

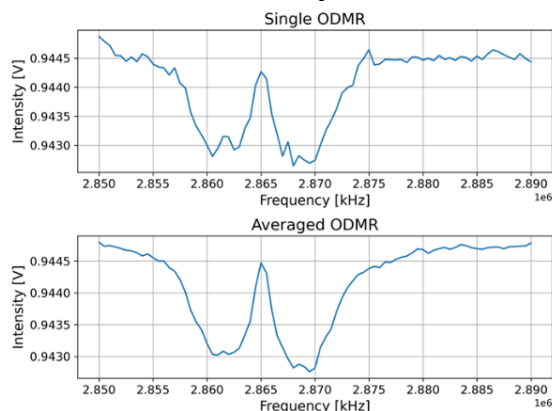


Fig 13: ODMR demonstrator measurement result. Top: result of a single ODMR measurement; bottom: average of 10 consecutive single ODMR measurements

For future ODMR measurements with the PIC-diamond-filter-photodiode stack, it is essential to protect the signal photodiode from unfiltered stray light. In particular, light incident from the side and bypassing the filtering layer is problematic. Future work will therefore include an optimized shielding and integration concept for the photodiode in order to enable quantitative measurements in a more highly integrated configuration.

Conclusion

In conclusion, this work presented key photonic and electronic building blocks for a miniaturized approach to NV-diamond magnetometry. The photonic integrated circuit was described in detail, and two coupling concepts were investigated and compared. Due to its superior transmission efficiency, the edge coupling approach was selected for further development despite its increased assembly complexity. The realized photonic transmission line achieves a power density exceeding 1 kW/cm², which is sufficient for optical excitation of diamond-based sensing elements.

The presented approach offers a path toward compact and scalable sensor implementations with dimensions on the order of only a few millimeters. In particular, the achieved excitation power density and the compatibility with compact optical integration are promising with regard to future miniaturized NV-based sensing systems. Preliminary ODMR feasibility measurements further indicate that the developed optical excitation concept is suitable for ODMR-based operation.

Future work will focus on quantitative evaluation of lens-to-chip coupling strategies in order to further improve optical efficiency. In addition, optimized integration of photodiodes and dedicated ASICs will be investigated to enable quantitative system-level characterization in more highly integrated demonstrator configurations.

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