D5.2 – Report on photodetector selection and characterization

StretchBio – D5.2

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Document author(s):

Entity	Contributor
ALU	Jens Goldschmidt
ALU	Leonard Nitzsche
UB-IN2UB	Albert Romano-Rodriguez
UB-IN2UB	Francisco Hernández-Ramírez
UB-IN2UB	Juliana Jaramillo-Fernandez
UB-IN2UB	Daniel Navarro-Urrios

Disclosure Statement:

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Executive Summary

This deliverable presents the results of the photodetector selection and characterization for the targeted wavelength range of 1350 to 1550 nm, as required by the designed photonic crystal device. The report outlines the criteria for selecting detectors that are sensitive enough to measure the resonance shift of the photonic crystal sensor, included the required detection bandwidth, spectral coverage, and noise characteristics.

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1 Introduction

1.1 Purpose of the document

This report is the second deliverable for WP5 (D5.2) of the StretchBio project and presents the results of photodetector selection and characterization for measuring changes in the mechanical properties of biological tissues applied to the photonic crystal sensor. For details on the project's overall purpose, please refer to the grant agreement.

The final sensor system will couple light from a near-infrared fiber-coupled laser into the photonic crystal cavity, and the photodetector will capture the sensor output.

The deliverable provides an overview of the necessary characteristics for the photodetectors to sensitively detect mechanical changes in the applied biological tissue thereby applying force on the photonic crystal. This report addresses the following questions:

- What is the required wavelength range?
- What is the necessary detection bandwidth for the detectors?
- What are the noise characteristics of the selected detectors?
- Can the selected detectors be integrated into the overall measurement device?

1.2 Scope of the document

Here, we provide an overview of the measurement of an optical resonance shift induced in the silicon pillars forming the photonic crystal due to lateral forces applied on the top surface of the pillars by the biological tissue. It is shown that commercially available InGaAs photodetectors, which cover a spectral range of 800 to 1700 nm, are suitable for detecting shifts in the optical resonance caused by bending forces on the pillars. Additionally, we present the measured noise characteristics of the selected detectors.

1.3 Related documents

As mentioned before, the report presents crucial information on the selection and characteristics of photodetectors for sensitively detecting mechanical changes in biological tissue on the photonic crystal sensor. For a comprehensive understanding, the reading of the first deliverable of WP5 (D5.1 – Report on the design and fabrication issues of the optical grating") may be helpful. The content of this deliverable (D5.2) will be fundamental to build up the first StretchBio prototypes in the frame of WP6.

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2 Methodology

In this section, we present the schematic for measuring resonance shifts caused by applied bending forces on the silicon pillars of the photonic crystal. This is based on the photonic crystal (PhC) cavity designed in WP2, which is coupled to a waveguide to allow for coupling of light into and out of the cavity through evanescent fields, as depicted in the Fig. 5[1]. Also, the measurement scheme to detect the resonance shift, as well as to detect the change of mechanical oscillations of the pillars via optomechanical coupling, is presented. We therefore refer to the report of deliverable D2.3 where this is described in more detail.

2.1 Resonance shift of a cavity under mechanical load

For the sake of simplicity and to provide an analogy for explaining the resulting resonance shift of a cavity induced by a mechanical load, we briefly describe the occurrence of a resonance wavelength shift of a linear Fabry-Perót cavity when one mirror is moved due to a mechanical load. If a laser is sent to an optical cavity consisting of two opposing highly reflective mirrors (see Fig.1a), the laser can be coupled into the cavity if its wavelength λ_0 matches the resonance condition of the cavity given by[2]

$$m\frac{\lambda_0}{2} = L \tag{1}$$

with the cavity length L and the mode number m. If the reflected signal is measured, one obtains an attenuated reflected signal at the resonance wavelength. If a mechanical force is applied to the movable mirror the length of the cavity is changed by ∂x and the resonance wavelength changes with $\partial\lambda_0 = \frac{\lambda_0}{L}\partial x$. If the laser wavelength is held stable, this resonance shift will lead to a change in the measured reflected intensity (see fig. 2 (b)). This principle can be applied to the photonic crystal cavity as described in D2.3. When no mechanical load is applied, the geometry of the PhC is unperturbed and the laser is in resonance with the cavity with finite linewidth due to losses. In a scheme where the transmission of the cavity is measured, one will see a minimum of the transmitted signal. However, if a mechanical load to one or multiple pillars is applied, they will be deflected. This will lead to a shift of the cavity´s resonance and the laser won´t be in resonance anymore so the transmitted measured signal will increase. In contrast, the shift of the resonance can be detected by measuring or referencing the laser emission wavelength while tuning the wavelength periodically, e.g. presented in frequency or wavelength modulation techniques[3].

[1] The design of the PhC cavity is currently undergoing a patentability examination. In order to protect the interests of partners, the schematic diagram is included in the annex of this deliverable and is marked as confidential.

[2] B. E. A. Saleh & M. C. Teich, "Fundamentals of Photonics", ISBN: 9780471213741, John Wiley & Sons, Inc. 1991.

[3] J. L. Hall, L. Hollberg, T. Baer, H. G. Robinson, "Optical heterodyne saturation spectroscopy," Appl. Phys. Lett. 39, 680 (1981).

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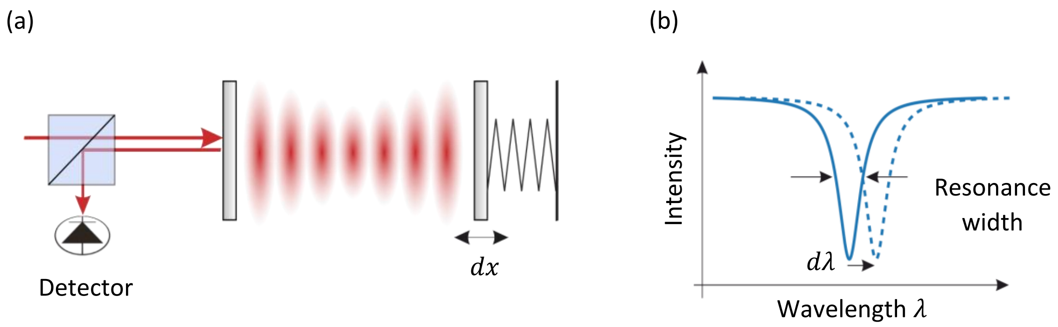

Figure 1. Schematic Fabry-Perót cavity with one movable mirror (a); cavity resonance shift due to mirror movement (b).

2.2 Measurement setup

The selected measurement setup for detecting the resonance shift is illustrated in Fig. 2. A fiber-coupled external cavity diode laser (ECDL, Lion Series, Sacher-Lasertechnik GmbH) with a spectral range of 1480 to 1570 nm and a linewidth of 100 kHz is used.

To ensure that the laser is correctly polarized and coupled to the PhC cavity – the PhC only shows a photonic bandgap for TM-polarized light – it is passed through a fiber-loop polarization controller and a polarizing beam splitter. The undesired polarization is filtered out by adjusting the paddles and reducing the power of the incorrect polarization. The laser is then split into three branches, with one branch serving as a reference and being directly coupled to a detector to track the laser emission intensity. The second branch is coupled to the PhC cavity on the chip, and the third branch, which contains a small fraction of the laser's power, is coupled to a wavelength meter for locking the laser to a desired wavelength during step scanning the transmission spectrum of the cavity or monitoring the laser's wavelength during continuous scanning mode.

If the laser is scanned over the cavity resonance at 1497 nm, with a resonance width of 10 pm, as simulated using COMSOL Multiphysics[4], an intensity dip at the resonance wavelength will be measured. With the reference branch, this can be normalized to obtain a transmission spectrum.

The goal of the project, as described in the grant agreement, is to measure a transmission difference of at least 50% by applying a bending force to the cavity´s pillars, such that the cavity is shifted by the half width at half maximum out of resonance. According to previous simulations, this is achieved by applying a force of less than 10 nN on pillars where the cavity mode is located.

The laser's maximum output power at 1500 nm is 10 mW. With the expected coupling losses to the PhC for in and out coupling, which are described in deliverable D5.1 (around 1% overall coupling efficiency), and the splitting into several branches, a laser power of 50 µW is expected on the detectors.

For such optical powers, detector noise can become a hindrance, which can be overcome by using modulation techniques and lock-in amplification. For modulation and detection, high-bandwidth electronics and detectors (~100 MHz) are advantageous.

[4] *COMSOL website (https://www.comsol.com/). Last search: February 15th 2023.*

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2.3 Measurement of detector noise

To test the noise characteristics of the selected detector, we use a PCIe data acquisition board (Spectrum Instrumentation, M4i.4421-x8) with a sampling rate of 250 MS/s, a bandwidth of 125 MHz and 16-bit resolution. We measure the laser intensity with the selected detector (with a power of ~50 µW) for 1 second and Fourier-transform and normalize the calculated spectrum with the carrier intensity at 0 Hz to retrieve a relative intensity noise spectrum. We repeat this procedure by measuring the signal with the laser turned off and then by turning off the photodetector to retrieve the relative intensity noise spectrum of the digitizer as well (both normalized to the carrier intensity of the laser).

Aside from the noise characteristics, the detection bandwidth of the photodetector is important because we also expect a modulation of the measured laser intensity induced for lock-in detection or induced by thermally excited mechanical oscillations of the pillars, which can be used to measure the tissue´s mechanical properties as well. These mechanical eigenmodes can be measured thanks to the so-called optomechanical coupling, where the optomechanical coupling strength – describing the strength of the resonance shift due to oscillating pillars – was simulated using *COMSOL Multiphysics* considering moving boundaries[5]. The information on the mechanical motion can be retrieved by Fourier-transformation of the detected laser intensity[6]. For that, we simulated the free-standing pillars and pillars fixed on the top to model an extreme case where the pillars are fixated by the tissue, which changes the mechanical resonances and thus the optomechanical coupling.

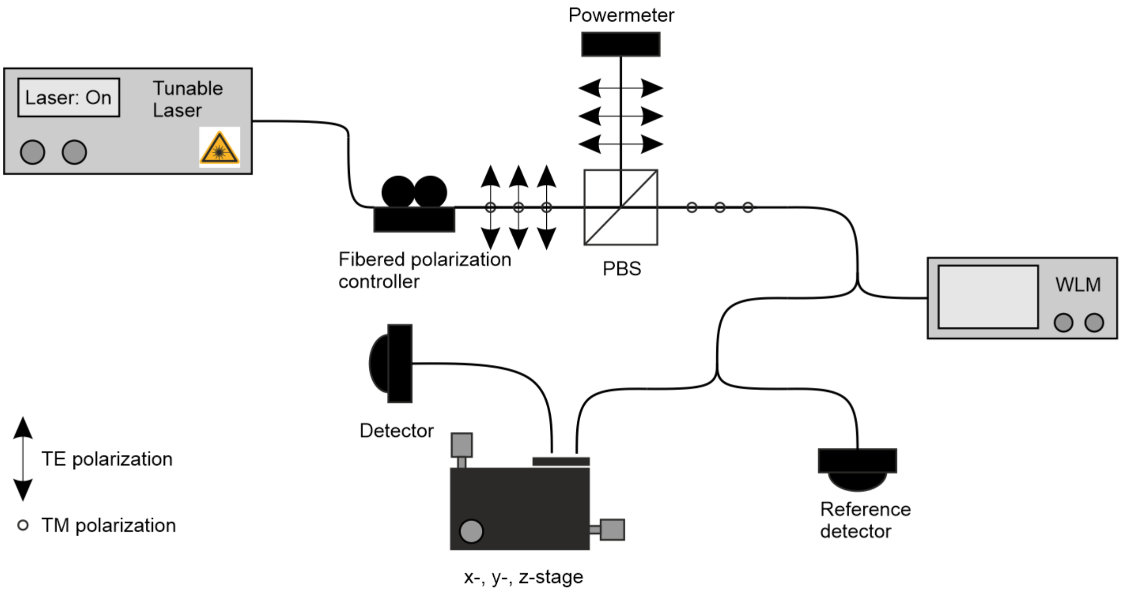

Figure 2. Setup to detect the resonance shift of the PhC cavity under applied bending forces on the pillars. PBS – polarizing beam splitter; WLM – wavelength meter; TE – transverse electric; TM – transverse magnetic.

[5] *Johnson, S. G. et al., "Perturbation theory for Maxwells equations with shifting material boundaries". Phys. Rev. E 65, 066611 (2002); doi: 10.1103/PhysRevE.65.066611*

[6] *T. J. Kippenberg et al., "Cavity Optomechanics: Back-Action at the Mesoscale". Science 321, 1172 (2008); doi:10.11/science.1156032*

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3 Results

In the previous section, we discussed the measurement setup for detecting the resonance shift and introduced the challenges related to the detection process. In this section, we will discuss the criteria used for selecting the photodetector based on the expected power on the detector and the simulation results of the optomechanical coupling. Additionally, we will present the specifications of the selected commercially available photodetector and the measured noise characteristics of the detector.

3.1 Simulation results of optomechanical coupling and detector criteria

Fig. 3 shows the simulated optomechanical coupling strengths for both the free-standing pillars and pillars fixated on the top. It shows that we can expect the highest coupling strengths around a mechanical oscillation frequency in a range of 5 MHz to 10 MHz with a maximum optomechanical coupling strength of 2.3 MHz for the free-standing pillars and around 100 MHz with a maximum optomechanical coupling strength of 3.9 MHz for the fixed pillars.

This coupling strengths directly translates to a shift of the frequency of the resonance. If we consider a simulated optical quality factor of 10^5 of the PhC cavity (as showed in the report of D2.3) the coupling strength results in a amplitude modulation in the transmission domain of 10^{-3}.

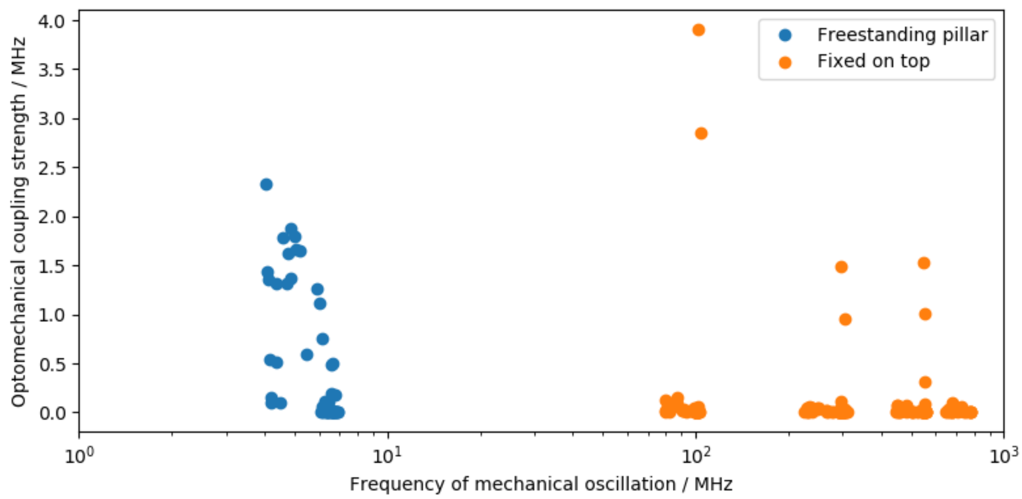

Figure 3. Simulation results of the optomechanical coupling strengths for freestanding pillars (blue) and pillars fixed at the top (orange).

3.2 Measured noise characteristics of selected photodetector

For the next stage of the project, we have chosen the InGaAs amplified photodetector PDA0CF2 (https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA05CF2) from Thorlabs. It has a wavelength range of 800 to 1700 nm, a bandwidth of 150 MHz (DC to 150 MHz) and a noise equivalent power (NEP) of 12.6 $\frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$.

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The measured intensity noise spectra of the laser, photodetector, and digitizer are shown in Fig. 4. The maximum relative intensity noise measured is -60 dBc at a frequency of 50 Hz, which corresponds to the frequency of the power supply. This translates to a maximum noise power of 50 pW (regarding the expected 50 µW on the detector), which should not affect the measurement of the resonance shift. In the frequency range of 1 MHz to 100 MHz, where we expect to measure mechanical resonances of the photonic crystal cavity, the noise spectrum of the laser is dominated by in-coupled external sources, such as radio towers, at a level of around -80 dBc. However, we plan to reduce these spurious signals by implementing immission shielding in the future. Due to the low noise amplitude, we expect no significant influence on the measurement with the selected detector.

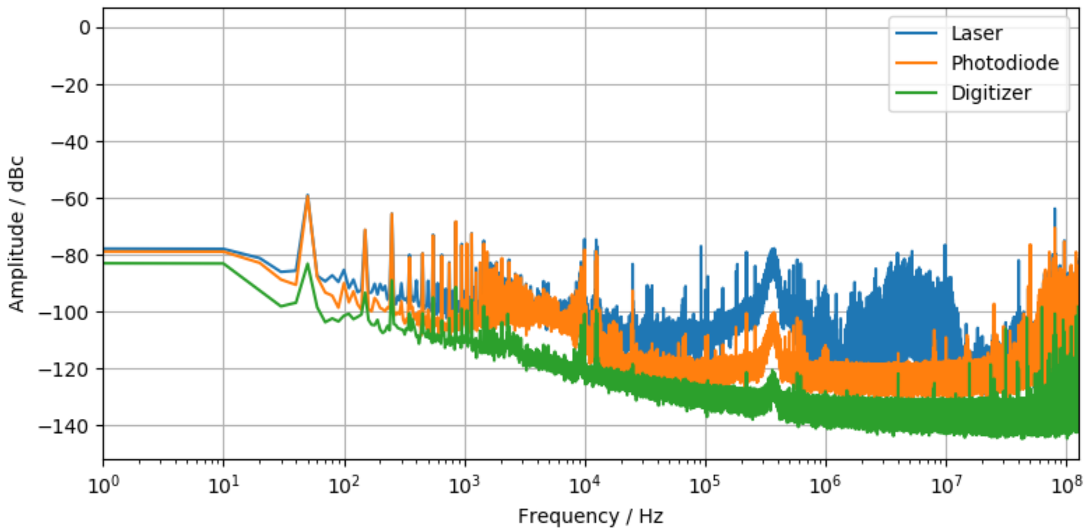

Figure 4. Relative intensity noise spectrum of the used laser, photodiode, and digitizer in a 125 MHz bandwidth.

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4 Conclusions and future work

In conclusion, this report has presented the selection and characterization of the photodetectors for operation in the near-infrared range between 1350 nm and 1550 nm, which is required by the designed photonic crystal cavity. Criteria for detector selection were established by determining the expected power on the detectors using a measurement setup to detect wavelength shifts of the photonic crystal cavity resonance induced by applying biological tissue.

Additionally, simulations of optical measurements with shifts of the mechanical resonance of the cavity via optomechanical coupling were performed to determine the required detection bandwidth. Based on these criteria, the InGaAs amplified photodetector (PDA05CF2, Thorlabs) was selected, which has a detection bandwidth from DC to 150 MHz and a noise-equivalent power of 12.6 $\frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$. An analysis of the noise intensity spectrum showed a maximum relative intensity noise of -60 dBc at the power supply frequency, which does not pose any issue for future measurements.

In first experiments we also observed mechanical resonances in the GHz range which couple to the optical resonance. For this, photodetectors with higher bandwidths might be needed, for example the 1544-B New Focus (https://www.newport.com/p/1544-B) with a bandwidth of 12 GHz. For this, the setup has to be slightly adapted by using a high bandwidth spectrum analyzer to be able to measure these resonances. This comes with the cost of a higher noise equivalent power of the detector of 24 $\frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$.

Moving forward, a balanced detection scheme will be considered for detecting the mechanical spectrum of the photonic crystal cavity. The noise spectrum of the laser presented in this report showed in-coupled radio frequency noise (1 MHz to 100 MHz), which can be suppressed by using balanced detection to further improve the noise spectrum. As a result, the sensitivity of the optomechanical measurement can be increased because the detector suppresses the strong carrier background.

The findings of this report provide a foundation for future work on the first end-to-end StretchBio prototypes.

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Glossary

Abbreviation	Explanation
µm	Micrometers
D	Deliverable
dBc	Decibels relative to the carrier
ECDL	External Cavity Diode Laser
Hz	Hertz
N	Newton
nm	Nanometers
PhC	Photonic crystal
W	Watt
WP	Work package

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Annex I

The design of the PhC cavity is currently undergoing a patentability examination. In order to protect the interests of partners, the schematic diagram is included here and is marked as strictly confidential.

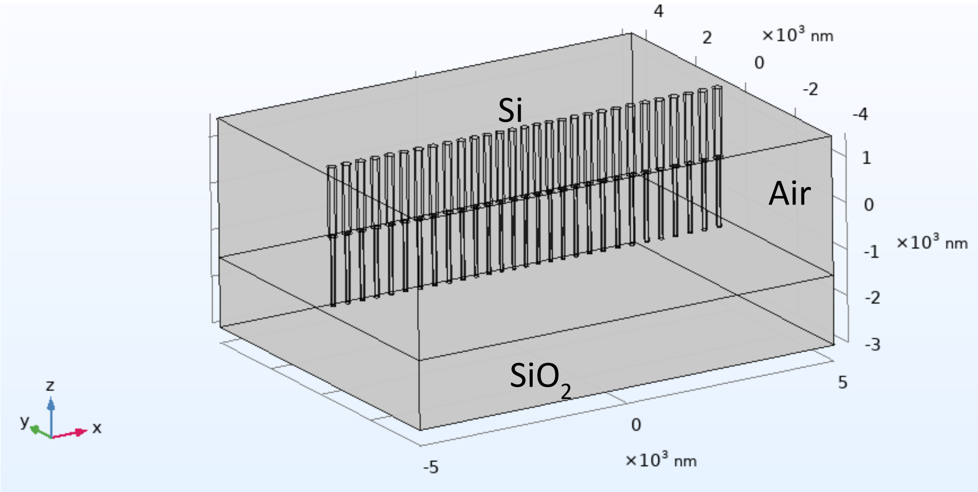

Figure 5. Simulation model of the one-dimensional photonic crystal cavity.

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