Contents

Nomenclature

Latin letters

variable	meaning	unit
A	area	m^2
w	width	m
c	concentration	wt.%
d	diameter	m
G	Gibbs free enthalpy	J
h	height	m
l	length	m
m	mass	kg
p	pressure	Pa
r	radius	m
Re	Reynolds-number	
t	time	s
V	volume	m^3

Greek letters

variable	meaning	unit
α	absorption coefficient	1/m
γ	surface tension	$^{N}/_{m}$
η	dynamic viscosity	$^{Ns}/_{m^2}$
θ	contact angle	°, rad
κ	curvature	$^{1}/_{m}$
λ	wave length	m
ν	kinematic viscosity	$^{m^2}/_{s}$
ρ	specific gravity	$^{kg}/_{m^3}$

Indices

index	meaning
lg	liquid-gas
sg	solid-gas
sl	solid-liquid
la	liquid-ambient

Abbreviations

abbreviation	meaning
2D	2-dimensional
AF	amorphous fluoropolymer
DFR	dry film resist
DI	deionized ultra-pure water
DRIE	Deep reactive ion etching
ICP	Inductive coupled plasma
MEMS	Micro-electro-mechanical system
PDMS	Polydimethylsiloxan
PEB	Post Exposure Bake
PMMA	Polymethylmethacrylat
UV-Vis	ultraviolet to visible wavelengths

1 Introduction

1.1 Motivation

Optical biopsy

Simultaneous

Multimode as key technology (include other modalities)

The next challenge lies in the size: The external diameter of an endoscope constrains its field of application. For example, in cystoscopy (endoscopy of the urinary bladder), probes with small diameter (under 5 mm) reduce the pain and trauma to urethra.

1.2 State of the Art

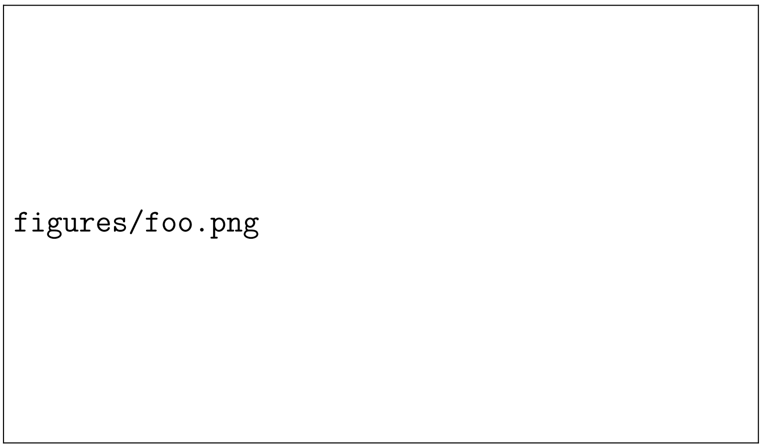

Figure 1.1: Simon bench, Tobias Scanner, Seibel scanner

1.3 Approach of this thesis

The presented work builds on the concept of a two layer, MEMS based silicon optical bench [1] that combines white light microscopy with OCT on a single integrated silicon microbench. In contrast to other approaches [2], the combination of white light microscopy with OCT is realized without the need of a coherent fiber bundle. With this design, the inherent drawbacks of such fiber bundles can be avoided, which are, for example, low light troughput, multi-modal coupling and poor resolution for a given field of view as stated in [3]. Furthermore, with the two level approach we can implement modalities with different requirements regarding the numerical aperture of the optical system as it is the case for white light microscopy and OCT.

2 Design & Simulation

The aim of this work is to design and test a miniaturized OCT microscope as a component of a multi-modal endoscope. As described in Chapter 1, this probe consist of two spectrally-separated optical paths that run partially in parallel through a micro-optical bench system. This approach allows independent tuning of the optical parameters of the two imaging modalities – such as the NA or depth of field – while still providing a geometrical overlap of the two acquired images. As OCT is a scanned-point imaging technique, a 2D scanning mechanism is integrated into the probe to reconstruct 3D volumes of the sample tissue.

The following section describes the conception and design of the endoscope, starting from the medical and geometrical requirements, through analytical modeling and towards the optimization of each component.

2.1 Design Requirements

The OCT microscope should fulfill the following requirements:

Mechanical Requirements

- The scanner, electrical connections and optics should fit in a $1\,\mathrm{mm} \times 1\,\mathrm{mm}$ square channel. Its length should be minimized.
- The field of view should be maximized for a 2 mm diameter objective lens.
- The scanning speed should be adequate for the sampling rates characteristic of OCT ($\sim 100\,\mathrm{kHz}$).

Optical Requirements

- The microscopy and OCT imaging fields should be coaxial to avoid parallax errors.
- The OCT field should be image-side telecentric to avoid field curvature distortions and to maximize the collection of backscattered light upon normal incidence to the tissue.
- The lateral resolution and depth of field should be adequate for OCT (NA $0.02 \sim 0.05$).
- The backreflections inside the probe should be minimized.

2.2 Design overview

The main challenge of this work is to design a scanning mechanism compact enough to be placed in a thin, buried channel of a multimodal probe. Although it is theoretically possible to keep a scanner at the proximal end of the endoscope and use a coherent fiber bundle (CFB) as a relay, there are inherent drawbacks of this method, such as low light throughput, cross-talk and mechanical rigidity [1].

Another challenging requirement is the superposition of the images acquired by the different modalities. If the optical axes are not coaxial, the fields will be shifted and tilted due to parallax error — which gains importance at the small working distances common in endoscopy.

To overcome these problems, and taking into account the above-mentioned requirements, we propose a design comprising a resonant fiber scanner followed by a beam splitter, as illustrated in Figure 2.1, as an evolution of the HYAZINT multimodal probe [2].

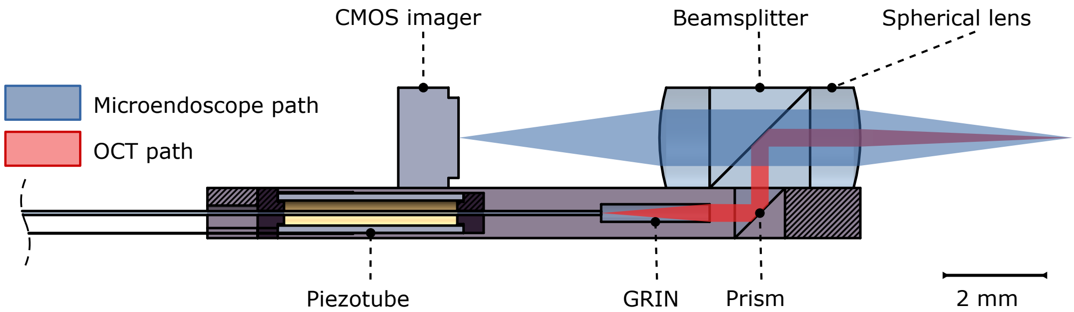

Figure 2.1: Bimodal probe cross section showing main components and optical paths.

This implementation uses a piezo tube actuator which drives a bending beam into a resonant oscillation. This bending beam is composed of an optical fiber with a GRIN lens glued to its tip which, due to the oscillation of the fiber, radially scans a collimated laser beam. An objective lens then transforms this angular displacement into translation, as explained in Chapter **??**. In order to merge the OCT field with the white light image, both fields are combined using a dichroic beam splitter.

There are many reasons why this design is preferred over other scanning topologies. First, the narrow dimensions of the piezo tube allow a compact implementation. Also, the field of view that can be achieved with this scanner is not limited to the space available for the GRIN lens to vibrate — instead, to its maximum angular deflection. As we want a telecentric system, a *4f* microscope could have been implemented instead of a Fourier plane scanner, but at the cost of duplicating the length of the optical system (Chapter **??**). Another advantage of using a fourier plane scanner is that it requires a GRIN lens glued to the tip of the fiber in order to collimate the beam. As a side-effect, this extra weight greatly reduces the resonant frequency of the scanner, allowing a denser sampling from the data acquisition system.

The rest of this chapter shows the design and development of the OCT imaging path for the multi-modal probe. However, in order to independently test the behavior of the OCT scanner and optics, a single modality probe was fabricated as a demonstrator. Both systems are mechanically and optically equivalent – the only difference is the presence of the beam splitter.

For completeness, both multi-mode and single-mode optical systems are described.

2.2.1 Optical Design

Fourier Plane Scanner

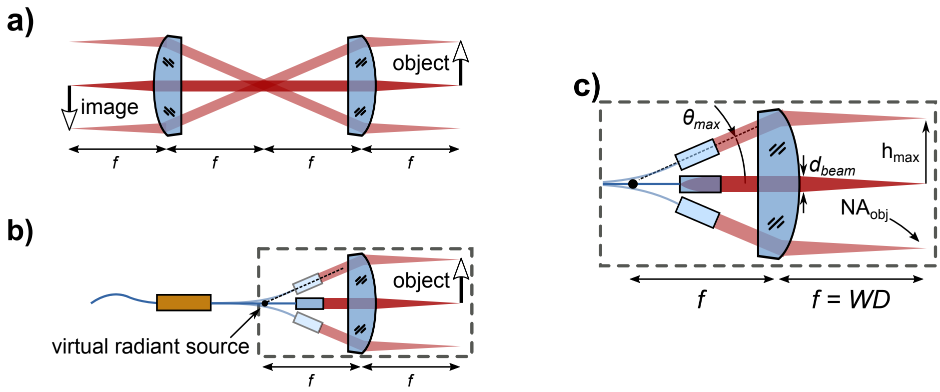

Figure 2.2: Fourier Plane Scanner

$$h_{max} = f_{obj} \cdot \tan\theta_{max} \tag{2.1}$$
$$d_{beam} = 2 \cdot f_{obj} \cdot NA_{obj} \tag{2.2}$$
$$f_{GRIN} \cdot NA_{fiber} = f_{obj} \cdot NA_{OCT} \tag{2.3}$$

Selection of Components

`figures/foo.png`

Figure 2.3: Fourier plane scanner indicating beam diameters, focal lengths and NAs

Equations for NA, focal lengths, telecentricity
Reasons for choosing each component

ZEMAX Simulation

Table with results

figures/foo.png

Figure 2.4: Layout

figures/foo.png

Figure 2.5: Spot through focus / Field aberrations

figures/foo.png

Figure 2.6: Implemented 1 mode probe

Minimization of backreflections

Origin of backreflections
ARC
Tilted surfaces
Position of lenses

figures/foo.png

Figure 2.7: Backreflections in probe

2.2.2 Mechanical Design

Design of the spiral scanning resonant beam

figures/foo.png

Figure 2.8: Radiant source with component sizes / Movement of spot in deltaT inside spiral

Analytical calculations (res freq, bending line, max radius)
Fsampling VS FOV -> Fres, Lfiber -> +Weight, -diameter

COMSOL simulation

figures/foo.png

Figure 2.9: COMSOL bending line at different voltages -> Single radiant point

2.2.3 Desired Design

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Figure 2.10: Bimodal Probe CAD render with annotations

Bibliography

[1] H. D. Ford and R. P. Tatam, "Swept-source OCT with coherent imaging fibre bundles," vol. 7503, no. 0, pp. 18–21, 2009.

[2] S. Kretschmer, *Entwicklung einer bimodalen mikrooptischen Bank für endoskopische Anwendungen.* PhD thesis.

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