

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**REDUCED HARDWARE COMPLEXITY FOR VISCOSITY
MEASUREMENTS BY OPTICAL KNIFE-EDGE DETECTION
ON MICROPILLAR-BASED MICROFLUIDIC CHIPS**

M.Sc. THESIS

Ezgi ŞENTÜRK

Department of Electronics and Communication Engineering

Biomedical Engineering Programme

JULY 2024

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**MİKROSÜTUN TABANLI MİKROAKIŞKAN ÇİPLER
ÜZERİNDEKİ OPTİK BİÇAK KENARI TESPİTİ İLE VİSKOZİTE
ÖLÇÜMLERİ İÇİN AZALTILMIŞ DONANIM KARMAŞIKLIĞI**

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To my father,



FOREWORD

It is with great pleasure and a sense of accomplishment that I present this thesis, Reduced Hardware Complexity for Viscosity Measurements by Optical Knife-Edge Detection on Micropillar-Based Microfluidic Chips. This thesis supported in part by ITU BAP (Research Fund of the Istanbul Technical University) with a project number of MGA-2023-43956. Furthermore, this thesis published in the Sensors and Actuators A: Physical, 2024. Also, I would like to thank TUBITAK (Technical and Scientific Research Council of Turkey) for providing scholarship support throughout my master's education.

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TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xiii
SYMBOLS	xv
LIST OF FIGURES	xviii
SUMMARY	xix
ÖZET	xxi
1. INTRODUCTION	1
1.1 Microfluidics Technology	1
1.2 Viscosity and Its Measurement: Viscometers	2
1.2.1 Microfluidic Viscometers	4
1.3 Optical Detection for Microfluidics	6
1.3.1 Optical Detection with PDMS Microstructures	7
1.4 The Optical Knife-Edge Technique	9
1.5 Objectives of the Current Study	10
2. MATERIALS AND METHODS	13
2.1 Fabrication of the Microfluidic Chips	13
2.2 Optical Knife-Edge Implementation	16
2.3 Optical Modeling	19
2.4 Ray Tracing Simulations	22
2.5 Experimental Process	25
3. RESULTS AND DISCUSSION	27
3.1 Optical Power Measurement and Analysis	27
3.2 Analysis of Optical Detection in Glycerol-Water Mixtures	30
3.3 Mathematical Modeling of Bending Limitations	31
3.4 Discussion on Computational Efficiency	36
4. CONCLUSIONS	39
4.1 Concluding Remarks	39
4.2 Future Works	40
REFERENCES	43
CURRICULUM VITAE	51



ABBREVIATIONS

CMOS	: Complementary Metal-Oxide-Semiconductor
TIR	: Total Internal Reflection
PDMS	: Polydimethylsiloxane
PMMA	: Poly(methyl methacrylate)
LOC	: Lab-on-a-chip
POC	: Point-of-care
SPR	: Surface Plasmon Resonance
LGP	: Light Guide Plate
BLU	: Backlight Unit
LCD	: Liquid Crystal Displays
CNC	: Computer Numerical Control
NA	: Numerical Aperture
ND	: Neutral Density
CAD	: Computer Aided Design
FFT	: Fast Fourier Transform
PD	: Photodiode



SYMBOLS

η	: Viscosity
τ	: Shear stress
γ	: Shear rate
s	: Second
$\mu\mathbf{m}$	: Micrometer
$\mu\mathbf{l}$	: Microliter
cP	: Centipoise
Pa	: Pascal
R_P	: Radius of micropillar
R_{PD}	: Radius of photodiode
I_0	: Intensity of the light
Δp	: Optical power change
erf	: Error function
r	: Radial coordinates
n_p	: Refractive index of PDMS
n_s	: Refractive index of water



LIST OF FIGURES

	<u>Page</u>
Figure 1.1 : Illustration of the optical reading concept and applied methodology.	11
Figure 2.1 : Fabrication steps of micropillar-based microfluidic chip.	14
Figure 2.2 : An optical knife-edge detection scheme for micropillar bending in a microfluidic viscometer (L: lens, M: mirror, PD: photo-diode). In the inset above right shows, the pillar images obtained from the CMOS camera. 1th condition represents; rest pillar and, 2nd condition represents; pillar bending with flow [1].....	17
Figure 2.3 : Showcasing of light detection by the photodiode after light travels along the micropillar with TIR; a) resting pillar, b) the pillar bending with the flow manipulates the light as a guide, c) light begins to escape through the micropillar, depending on the increasing degree of bending.	18
Figure 2.4 : For different photodiode dimensions, the normalized light intensity was calculated as a function of the pillar's bending [1].	21
Figure 2.5 : Ray tracing simulation of the microfluidic chip; a) coupling of light into a rest and bent pillar, b) detector data (light output profile) taken from the simulation was processed, the detector area is shown with a rectangle drawn in red, c) normalized output light intensity vs. pillar displacement and comparison to analytical findings (ideal detector size according to pillar diameter) [1].	23
Figure 2.6 : The optical setup in the simulation; a,b) the microfluidic chip and detector from different directions, c) from left to right: the light source, lens to focus, micropillar-based microfluidic chip, and detector.	24
Figure 2.7 : Illustration of optical setup [1].	26
Figure 3.1 : The bending of micropillar as a function of time as observed by the photodetector and CMOS camera (knife-edge and circle-fit) [1]. Insets represents CMOS camera images, no flow state (1) and when air flow was given into the pillar (2, 3).	28
Figure 3.2 : The knife-edge reading for the glycerol-water mixture liquid experiments, recorded with both the photodetector and the CMOS camera (with the selected area). Normalized intensity results are shown comparatively for flow rates ranging from 1 to 6 ml/min. An illustration of the conducted experiment is shown in the inset [1].	31
Figure 3.3 : Mathematical modeling of micropillar's circular bending profile [1].	32

Figure 3.4 : Analytically calculated micropillar bending and micropillar tip displacement based on the refractive index, compared with simulation results. Figure presents the comparative analysis between the calculated values and simulated outcomes [1]..... **34**

Figure 3.5 : Ray tracing simulation screenshots. **35**



REDUCED HARDWARE COMPLEXITY FOR VISCOSITY MEASUREMENTS BY OPTICAL KNIFE-EDGE DETECTION ON MICROPILLAR-BASED MICROFLUIDIC CHIPS

SUMMARY

This study uses the innovative application of optical knife edge detection in micropillar-based microfluidic systems and aims to develop a new method for monitoring and analyzing viscosity changes of biological fluids such as blood, amniotic fluid, etc. in the microscale dimension. The basics of research are based on the placement of micropillars functionalized as both mechanical sensors and optical waveguides in a microfluidic chip. Each pillar within the microfluidic chip is designed to respond sensitively to liquid flow while maintaining the ability to effectively direct light. These dual functions become important for this study as they allow micropillars not only to detect changes in fluid flow but also to convert these changes into measurable optical signals. This microfluidic viscometer chip is made from Polydimethylsiloxane (PDMS); which is optically clear, inert, non-toxic polymer, and fabricated by basic soft lithographic processes.

Details were carefully considered when designing the experimental setup. This began with the selection of light emitting laser diode sources that could be used in microfluidic applications. Utilizing a carefully constructed lens system, this light beam is focused into a single micropillar. The focal lengths and positions of the lenses used were optimized to allow the maximum amount of light to enter the micropillar without significant loss. Through the micropillar, light is directed to an optical detection system for data acquisition with photodetector and CMOS camera for detection. These devices are calibrated to capture light emerging from micropillars and measure intensity changes caused by the bending of the pillars due to flow. In the first phase of the project, experiments were carried out with air flow using an air compressor. Afterwards, liquid tests were carried out at different flow rates using a glycerol-water mixture.

To ensure control of experimental measurements, ray tracing simulations are performed to visualize and analyze how light behaves under different conditions within the micropillar structure. These simulations help improve the optical path setup and validate theoretical models developed to predict light behavior in response to flow-induced micropillar bending. The simulation results were used to adjust the detection system to improve sensitivity and specificity in measuring light intensity changes and the applicability of the method. Besides, an optical model that can be used to determine the detector size that can detect all of the light power coming from the micropillars without losing it is proposed. Additionally, a comparison of the normalized output light intensity with respect to the pillar displacement of the detector data from the simulation results and the results obtained from the analytical modeling is presented. Data from experiments show that the knife-edge detection technique

provides reliable and consistent measurements of light intensity changes that agree well with liquid flow rates and viscosity. Experimental data confirms the effectiveness of the optical setup and micropillar design in capturing and converting liquid flow into optical signals that can be analyzed quantitatively. For the proposed technique, photodiode and CMOS camera based pillar bend detection were compared, and a good match between the results was shown. At the same time, advantages of the proposed technique, such as reduced computational load and cost reduction, are presented.

In addition, a comparison of pillar bending angles based on the circle detection method, which will contribute to the accuracy of the proposed method, is also shown. Our work included an important investigation of bending limitations in micropillars, significantly influenced by the varying refractive indices of different liquids used in the microfluidic system for viscosity calculation. This variability has been identified as an important parameter because different fluids can change the conditions under which total internal reflection (TIR) occurs, for which micropillars can be used as waveguides. A simple mathematical model was proposed to determine these limits, and comprehensive ray tracing simulations were performed using different fluid indices available in the literature to predict how changes in the fluid refractive index affect the light-directing abilities of micropillars. This mathematical model was based on determining the limits of micropillar waveguides by measuring the critical angles and minimum radius of curvature for TIR in various liquids such as blood, cerebrospinal fluid, etc. The theoretical model was compared with data obtained from ray-tracing simulations. By gaining an understanding of the optical behavior within micropillars, its usability has been demonstrated in clinical diagnostic applications where the properties of fluids can vary significantly.

The incorporation of a knife-edge detection system with micropillars into a microfluidic device represents a substantial advancement in optical fluid dynamics measurement. The research findings may facilitate the creation of novel microfluidic devices that are smaller in size, more cost-effective, and capable of delivering quicker and more precise outcomes. Subsequent investigations could prioritize the continued reduction in size of the device, broadening the scope of observable fluid characteristics, and exploring the practical implementation of this technology.

MİKROSÜTUN TABANLI MİKROAKIŞKAN ÇİPLER ÜZERİNDEKİ OPTİK BİÇAK KENARI TESPİTİ İLE VİSKOZİTE ÖLÇÜMLERİ İÇİN AZALTIĞI DONANIM KARMAŞIKLIĞI

ÖZET

Bu çalışma, mikro-sütun tabanlı mikroakışkan sistemlerde optik bıçak kenarı tespiti için yenilikçi uygulamasını kullanarak kan, amniyotik sıvı ve benzeri biyolojik sıvıların viskozite değişikliklerinin mikro ölçekte izlenmesi ve analiz edilmesi için yeni bir yöntem geliştirmeyi amaçlamaktadır. Araştırmanın temelleri, hem mekanik sensörler hem de optik dalga kılavuzları olarak işlevselleştirilmiş mikro-sütunların mikroakışkan bir çip içerisinde yerleştirilmesine dayanmaktadır. Mikroakışkan çipin içindeki her bir sütun, ışığı etkili bir şekilde yönlendirme ve manipüle etme yeteneğini korurken sıvı akışına hassas bir şekilde yanıt verecek şekilde tasarlanmıştır. Bu ikili işlevler, mikropillerin yalnızca sıvı akışındaki değişiklikleri tespit etmesine değil aynı zamanda bu değişiklikleri ölçülebilir optik sinyallere dönüştürmesine de olanak tanıdığından bu çalışma için önem kazanmaktadır.

Bu çalışmada, bıçak-sırtı tekniği, mikro-sütunların akış altında mekanik tepkisinin nasıl değiştiğini ölçmek için kullanılan bir tekniktir. Önerilen yöntem, optik okuma ile sıvının viskozitesi gibi reolojik özelliklerinin tespit edilmesi üzerine kuruludur. İşlem, bir ışık kaynağının mikroakışkan cihaz içindeki seçilen bir mikro sütuna bağlanmasıyla başlar. Işık kaynağı mikroakışkan çipin altına yerleştirilir ve fotodiyot, mikropillerin bulunduğu mikrokanal tarafına konumlandırılır. Bu mikro-sütun, ışığı uzunluğu boyunca hassas bir şekilde yönlendirmek için bir dalga kılavuzu görevi görecek şekilde konumlandırılmıştır. Lazer ışık kaynağı, mikro sütunun bir ucuna girecek şekilde hizalanmış, sütun çapına uyacak şekilde odaklanmış bir ışık hüzmesi yayar. Mikro sütuna maksimum ışık miktarının girmesini sağladığından ve böylece algılama sisteminin hassasiyetini ve doğruluğunu optimize ettiğinden hassas hizalama çok önemlidir. Işık mikro sütun boyunca ilerlediğinde, Toplam İç Yansıma (TIR) için kritik açıyla eşleşecek veya bu açıyı aşacak şekilde seçilen malzemenin doğal optik özellikleri (PDMS'nin kırılma indeksi) tarafından kapsanır. Bu optik özellik, ışığın önemli bir kayıp olmaksızın sütun boyunca ilerleyerek fotodiyot sisteminin bulunduğu karşı uca ulaşmasını sağlar.

Deneyler için hassasiyet ve işlevsellik sağlamak, mikroakışkan viskozimetre çiplerinin imalatına bağlıdır. Burada mikroakışkan viskozimetre çip üretimi için Polidimetilsiloksandan (PDMS) kullanılmıştır; optik olarak berrak ve toksik olmayan bir polimerdir. Mikroakışkan çip üretimi temel yumuşak litografik aşamalara dayanmaktadır. Üretimde, mikroakışkan çip tasarımı için negatif bir kopyası olan ana kalıbı oluşturmak için bir Bilgisayarlı Numerik Kontrol (CNC) makinesi kullanılarak 200 µm çapında 1 milimetre derinliğinde kuyulardan oluşan bir dizinin (3x16) işlendiği ana kalıp oluşturuldu. Daha sonra kalıba 10:1 (bazı:çapraz bağlayıcı) oranlı PDMS iki aşamalı olarak döküldü. Mikrokuyulara PDMS'in homojen olarak dolması için kalıbın

gazı giderildi ve vakumlu bir fırında 75°C’de 1 saat süreyle sertleştirildi. Kürlenmiş PDMS daha sonra kalıptan soyuldu ve akışkan giriş ve çıkışları biyopsi zımbaları kullanılarak delindi. Son olarak, PDMS levhası, oksijen plazma işleminden sonra, mikroakışkan kanalın kapatılması için bir mikroskop cam slaytına bağlandı.

Ayrıca mikro-sütundan çıkan ışık gücünün tamamının kayıp olmadan algılanabilmesi için ideal dedektör boyutunun mikro-sütun çapına göre belirlenmesinde kullanılabilecek bir optik model önerilmiştir. Toplam optik güç, farklı fotodedektör boyutları için mikro-sütun ucu yer değiştirmesinin bir fonksiyonu olarak modellenmiştir. Mikro-sütundan daha küçük bir dedektör boyutu, ilk sütun konumunda toplam optik ışık gücünün yarısını yakalayamazken, mikro-sütun çapından daha büyük bir dedektörün bitişik sütundan gelen ışığı yakalaması, yani çapraz bağlanma yaşaması muhtemeldir. Mikro-sütun çapından daha küçük bir dedektör için, toplanan optik güç, ışın demetinin detektör alanına girmesiyle eş zamanlı olarak artarken, ışın boyutu detektörden büyük olduğu için demetin bir kısmının aynı anda detektör alanından çıkmasıyla azalır. Genel olarak, verilen senaryo için algılamanın en uygun noktası olarak mikro-sütunun çapını ve fotodedektörün algılama alanının eşleştirilmesinin en optimal sonucu verdiği gösterilmiştir. Seçilen mikro-sütun ışık çıkışının, dışbükey bir mercek kullanılarak diğer düzlemlerde haritalanabileceğini ve bunun üzerine optimum dedektör boyutunun görüntünün büyütmesine göre ölçeklendirilebileceği de göz ardı edilmemelidir.

Çalışmanın başlangıçta iki ayrı kolda aynı anda devam ettiğini söylemek mümkündür; optik kurulum ve ışın izleme simülasyonları. Projenin temelleri, lazeri tek bir mikro-sütuna bağlanıp, dalga klavuzu olarak kullanılabilen sütundan optik güç okumak üzerine kuruludur. Ancak başlangıçta, lazer kaynağından çıkan ışık hüzmelerinin, çapı 200 µm olan tek bir mikro-sütuna odaklanıp odaklanmayacağı bilinmiyordu. Deney kurulumundan önce sistemin çalışabilirliği simülasyonla doğrulanmış ve iki aşama eş zamanlı olarak yürütülmüştür. Deneysel ölçümlerin kontrolünü sağlamak için, mikro-sütun yapısı içerisinde ışığın kurulan optik sistemde nasıl davrandığını görselleştirmek ve analiz etmek amacıyla ışın izleme simülasyonları gerçekleştirildi. Bu simülasyonlar, optik yol kurulumunun iyileştirilmesine ve akışın neden olduğu mikro-sütun bükülmesine yanıt olarak ışık davranışını tahmin etmek için geliştirilen teorik modellerin doğrulanmasına da yardımcı oldu. Tüm ışın izleme simülasyonları, optik tasarım için kullanılan pratik bir yazılım olan Ansys Zemax OpticStudio yazılımında gerçekleştirildi. Işın izleme modeli, gerçek deney düzeneğini olabildiğince yakından yansıtabilecek şekilde yazılımdaki 'Sırasız' modda tasarlandı. Işık yolunu izlemek için yaratılan optik kurulum oldukça basit şekilde tasarlanmıştır. Mekanizma bir ışık kaynağı, odaklamak için bir mercek, mikroakışkan çip tasarımı ve bir detektörden oluşur. Mikroakışkan çip tasarımları Solidworks Bilgisayar Destekli Tasarım (CAD) programında çizildi ve daha sonra CAD dosyası olarak Zemax’a yüklendi. Mikro-sütunlar, kırılma indisi, boyutu ve ışık kaynağına ve dedektöre göre yönelimi de dahil olmak üzere hassas geometrik ve malzeme özellikleriyle modellenmiştir. Her mikroakışkan çip çizimi, farklı bir sütun ucu yer değiştirmesine karşılık gelecek şekilde, farklı sütun bükülme mesafesini temsil eder. Anahtar parametreler arasında dalga boyu 600 nm ve Gaussian’a yakın bir ışın yayan bir lazeri kopyalayacak şekilde ayarlanmış ışın profili gibi ışık kaynağı özellikleri yer alır. Mikro sütunun kesit alanıyla karşılaştırılabilir bir alana sahip bir

dedektör, mikro sütunlar hareketsizken tam optik gücü yakalayacak şekilde stratejik olarak konumlandırılmıştır. Bu yerleştirmenin bir sonucu olarak, ışık yolunda bükülme nedeniyle meydana gelen herhangi bir sapma, dedektörün okumalarını doğrudan etkileyerek sütun deformasyonunun hassas ölçümlerini sağlar. Simülasyon sonuçları, ışık yoğunluğu değişikliklerinin ölçülmesinde duyarlılığı, özgüllüğü ve yöntemin uygulanabilirliğini geliştirmek için algılama sistemini ayarlamak için de kullanıldı. Daha sonra her farklı bükülme mesafesi için dedektörden alınan yoğunluk verileri kaydedilerek Matlab’da işlendi. Simülasyon sonuçlarından ve analitik modellemelerden elde edilen sonuçlardan alınan dedektör verilerinin mikro-sütun yer değiştirmesine göre normalleştirilmiş çıkış ışık yoğunluğunun bir karşılaştırması da sunulmaktadır.

Deney düzeneği tasarlanırken ayrıntılara önem verilmiştir. Bu, mikroakışkan uygulamalarda kullanılabilecek lazer ışık kaynağının seçimiyle başladı. Dikkatlice oluşturulmuş bir mercek dizini kullanan bu sistemde, ışık demeti tek bir mikro-sütuna odaklanmak üzere ayarlanmıştır. Kullanılan lenslerin odak uzunlukları ve konumları, maksimum miktarda ışığın, önemli bir güç kaybı olmadan, mikro-sütuna ulaşmasına izin verecek şekilde optimize edildi. Deney düzeneği, 100 mm odak uzaklığına sahip plano-dışbükey mercek kullanılarak seçilmiş tek bir mikro-sütuna bağlanan bir lazer kaynağı içerir. Mikro-sütun ucundan çıkan ışık önce yönlendirilir, ardından yansıtıcı Nötr Yoğunluk Filtresi (ND Filter) yardımıyla ikiye bölünür. Ardından, bölünmüş ışık, bir fotodiyot ünitesi ve bir CMOS kamera üzerine düşürülür. Fotodiyota yönlendirilen ışık hüzmesi, önce 50 mm odak uzaklığına sahip, 10 kat büyüten bir plano-dışbükey bir mercekten geçirildi; böylece lazer noktası çapı fotodiyot detektör alanıyla (3,2 mm x 3,2 mm) karşılaştırılabilir hale getirilmiş oldu. Bu cihazlar, mikro-sütunlardan çıkan ışığı yakalayacak ve sütunların akış nedeniyle bükülmesinden kaynaklanan ışık yoğunluk değişikliklerini ölçmek için kullanılmıştır. Tasarlanan optik kurulumda, CMOS kamera, fotodiyot konumuna karşılık gelen piksel grubu üzerindeki optik gücün izlenmesi ve sütun konumunun gözlemlenmesi için kullanılmıştır. Kamera ile kaydedilen görüntüler, görüntü ikilileştirme adımından sonra Hough Dönüşümü tabanlı daire tespiti yöntemi kullanılarak gerçekleştirildi. Bu yöntem, MATLAB yazılımındaki 'imfindcircles' komutu aracılığıyla uygulandı ve akışla birlikte bükülen mikro-sütun uçlarının bükülme açıları tespit edilmiş oldu. Elde edilen veriler, fotodiyot ölçümleri ile karşılaştırılarak yöntemin doğruluğunu kanıtlamak için kullanıldı. Projenin ilk aşamasında bir hava kompresörü kullanılarak hava akışı ile deneyler yapıldı. Daha sonra gliserol-su karışımı kullanılarak farklı akış hızlarında sıvı testleri gerçekleştirildi.

Sütunların izin verilen eğrilik yarıçapının belirlenmesi, önerilen optik bıçak-sırtı okumasının limitlerini belirlemek için kullanılmıştır. Işık mikro sütun içerisinde TIR yoluyla hareket eder. Bu olay, geliş açısının kritik açısı verilen belirli bir sınır açısından büyük olması durumunda meydana gelir. Mikropillerin bükülme derecesi arttıkça ışığın geliş açısı azalır ve ışık dışarıya kaçmaya başlar, yani mikro-sütun dalga kılavuzu işlevini yerine getirememeye başlar. Tasarımımız için mikro-sütun bükülme davranışının sınırlamalarını anlamak amacıyla, su, kan, amniyotik sıvı, beyin omurilik sıvısı gibi diğer bazı biyolojik sıvılar için basitleştirilmiş bir matematiksel model önerilmiştir. Bu hesaplama yapılırken, akış altında mikro-sütunun bilinen uzunluğundan (1 mm) dairesel büküldüğü varsayılarak modellendi. Bükülme derecesi ve eğrilik yarıçapı hesaplandı. Ek olarak, bu matematiksel hesaptan elde edilen

değerler, farklı kırınım indislerine sahip sıvılar için ışın izleme simülasyonları yoluyla doğrulanmıştır.

Deneylerden elde edilen veriler, bıçak sırtı tespit tekniğinin, sıvı akış hızları ve viskozite ile iyi uyum sağlayan ışık yoğunluğu değişikliklerinin güvenilir ve tutarlı ölçümlerini sağladığını göstermektedir. Deneysel veriler, optik kurulumun ve mikro sütun tasarımının, sıvı akışının niceliksel olarak analiz edilebilecek optik sinyallere yakalanması ve dönüştürülmesindeki rolünü doğrulamaktadır. Önerilen teknik için fotodiyot ve CMOS kamera tabanlı sütun bükülme tespiti karşılaştırılmış ve sonuçlar arasında iyi bir uyum gösterilmiştir. Aynı zamanda önerilen tekniğin hesaplama yükünün azaltılması ve maliyetin düşürülmesi gibi avantajları da sunulmuştur.



1. INTRODUCTION

In the first chapter of the thesis, the concepts of microfluidics technology and viscosity are introduced with a thorough literature review, while the concept of optical detection techniques used in microfluidics are also defined and explained. These techniques are essential in the design of the microfluidic chip and the optical setup. Meanwhile, the proposed detection method optical knife-edge will also be explained in this chapter.

1.1 Microfluidics Technology

The origins of microfluidic technology can be attributed to important advancements in electronics and microfabrication, which subsequently impacted the creation of contemporary microfluidic systems. In 1947, a significant advancement occurred with the creation of the transistor, which established a standard for reducing the size of electronic parts [2]. In 1952, the advancement of photolithography techniques allowed for the creation of smaller hybrid integrated circuits, which furthered the process of shrinking and paved the way for compact electronic devices [3]. In 1979, these microfabrication techniques were used to create a small gas chromatograph on a silicon wafer, marking the beginning of a new age for downsized laboratory equipment [4]. It began to take shape in the early 1980s when methods originally developed for the semiconductor industry were used to create narrow channels in materials such as silicon and glass [5].

The term "microfluidics" gained popularity in the late 1990s as the capabilities of these techniques grew beyond their original industrial uses to include more specific sectors like as medical diagnostics and biochemical testing [6]. The advancement of the field resulted in the incorporation of intricate features into microfluidic systems, which gave rise to the creation of lab-on-a-chip (LOC) devices [7,8]. These devices utilize miniaturization and automation to streamline operations like as PCR amplification [9], and synthetic chemistry [10].

In recent decades, microfluidic technology has gained considerable attention due to its remarkable ability to enable a wide range of biological and chemical studies. This technique utilizes the exact regulation and manipulation of small amounts of fluid on a very small scale, allowing for significant improvements in various scientific disciplines. The uses of this technology are varied, encompassing tasks such as DNA sequencing [11,12], protein analysis [13,14], cell sorting [15,16], and experiments on both cells [17] and model organisms [18,19]. Moreover, it has been demonstrated to be beneficial for the monitoring of the environment [20,21] as well as in a wide variety of fields [22], including the cutting-edge subject of viscosity analysis [23]. The demand for accurate viscosity measurements in areas like pharmaceuticals and biomedicine led to the incorporation of microfluidic technology into viscometry [24]–[26].

1.2 Viscosity and Its Measurement: Viscometers

Viscosity is an essential physical characteristic of fluids that indicates their ability to resist deformation at a specific rate, commonly known as the internal friction of the fluid [27,28]. Understanding this attribute is crucial for comprehending the flow of fluids, whether it be in natural phenomena like the circulation of blood in the human body or in industrial scenarios like lubricating systems in equipment [29]. Viscosity, at a molecular level, quantifies the degree of molecular contact within a fluid. High-viscosity fluids such as honey have robust molecular interactions that hinder flow, while low-viscosity fluids like water have fewer associations, enabling smoother flow. In other words, viscosity is a fundamental property that governs the response of a fluid to external forces. This notion is of utmost importance for engineers and scientists working in various industries such as medicine.

The exploration of viscosity has its roots in ancient civilizations, but it was Isaac Newton who first established a quantitative understanding of this property [30]. Newton proposed that, for numerous fluids, the rate of flow is directly related to the stress applied to them. The relationship shown here is fundamental to our understanding of Newtonian fluids, which are characterized by a constant viscosity independent of the applied stress. Non-Newtonian fluids, such as ketchup or blood, display a variable viscosity in response to stress or over time [31].

Rheological properties are essential for understanding the behavior of fluids under stress. One key property of the viscosity is defined as the ratio of shear stress to shear rate [32]. The link between viscosity (η), shear stress (τ), and shear rate ($\dot{\gamma}$) is expressed by the formula $\eta = \tau / \dot{\gamma}$ [33]. Viscosity is measured in Pascal seconds (Pa·s) in the International System of Units. The viscosity of a fluid directly correlates with the amount of energy needed to maintain a steady speed when moving one layer of the fluid over another [34]. Viscosity is not a fixed characteristic and can fluctuate depending on alterations in temperature, pressure, and, in the case of non-Newtonian fluids, the rate of shear [35]. Comprehending these dynamics is crucial for precise management and manipulation of fluids in diverse scientific and practical scenarios.

The viscosity of a liquid can be measured by using a device called a viscometer, which has been specifically designed to measure the viscosity under a variety of conditions. Various traditional viscometers exist, each designed for certain fluid types and measurement requirements. Capillary viscometers, a classic form of viscometer, function by measuring the speed at which a fluid moves through a small tube due to the force of gravity [36,37]. The duration required for the fluid to traverse the distance between two indicators on the tube is utilized to determine the viscosity. Rotational viscometers quantify the amount of force used to rotate a disk or spindle that is submerged in a fluid [38]. The fluid's resistance to torque is directly related to its viscosity. Falling ball viscometers employ the method of releasing a ball into a fluid within a vertical tube and quantifying the duration it takes for the ball to descend a specific distance [39,40]. The velocity of the ball's drop is affected by the viscosity of the fluid. Vibrational viscometers employ a probe that undergoes oscillation at a predetermined frequency [41]. The oscillation's amplitude is influenced by the viscosity of the fluid that comes into contact with the probe.

There are several challenges associated with the conventional methods of measuring viscosity, despite their effectiveness. These techniques frequently necessitate substantial quantities of samples, which can be inconvenient or costly, especially when working with scarce or dangerous substances. In addition, conventional viscometers sometimes require complex arrangements and time-consuming procedures for setup, preparation, and cleaning, which impede their capacity to conduct quick readings

on-site. The precision and reproducibility of the measurements can be influenced by external factors, such as temperature fluctuations, due to the sensitivity of these approaches [42].

1.2.1 Microfluidic Viscometers

The measurement of viscosity has been significantly transformed by microfluidic viscometers, particularly in the field of medical diagnostics and biomedical domain, where accurate and timely analysis of physiological fluids is critical for the diagnosis of diseases. These devices leverage the benefits of microfluidic technologies by minimizing the volume of samples required for analysis, which is especially advantageous when dealing with valuable biological fluids like blood, plasma, cerebrospinal fluid, and amniotic fluid [43]. By doing so, limited samples are not only preserved but also expenses related to reagents and disposal are also diminished.

Microfluidic viscometers consist of several designs, each customized for certain measuring dynamics to guarantee precise and effective measurements of viscosity including: pressure sensing [44,45], flow-rate sensing [46,47], surface tension [48,49], comparators [50,51], and droplet-based devices [52,53]. Pressure sensing microfluidic viscometers estimate viscosity by monitoring the pressure drop as the fluid runs through a small channel, while flow-rate sensing devices compute viscosity depending on the speed of the fluid passing through specific channels. In addition, viscometers that rely on surface tension measure the changes in shape of fluid droplets in order to determine viscosity, whereas comparator-based viscometers improve precision by comparing the behavior of the sample fluid with a recognized standard. Droplet-based microfluidic systems, which monitor the distortion of droplets, are very skilled at manipulating fluids, providing flexible applications in several scientific disciplines [54].

One of the most important developments in microfluidic viscometry has been the advancement of micropillar-based microfluidic viscometers, which represent an important advancement. The fluid flow paths of these devices are designed with an array of microscopic pillars strategically located within them. It is the deformation of these pillars that serves as an indication of changes in fluid viscosity, which allows

extremely precise measurements to be made as a result. With this design, fluid dynamics can be intimately assessed on a microscale, allowing insights into fluid dynamics that are critical for accurate disease diagnosis and research applications. Micropillar-based microfluidic viscometers have been greatly improved by recent technical breakthroughs. For example, Judith et al. were able to accurately determine viscosities ranging from 5 to 5000 cP using only a 20 μ l sample volume by utilizing magnetically controlled micropillars [55]. This method demonstrates the capacity for exceptional sensitivity and extensive measurement ranges that can be achieved with small sample quantities. In a similar manner, Esfahani et al. developed a technique called quartz crystal microbalance substrate viscometry. This method involves using the vibrations of Poly(methyl methacrylate) (PMMA) micropillars and a quartz substrate to accurately measure viscosity [56]. The method is capable of delivering precise results within a viscosity range of 1.2 – 5.4 cP using only a 200 μ l sample. In addition, Mustafa et al. showed a direct correlation between the displacement of the micropillar tip made of elastic polydimethylsiloxane (PDMS) and viscosity [57]. They were able to quantify viscosities ranging from 2 to 100 cP with an accuracy of up to 0.5 cP. The examples highlight the strength and adaptability of micropillar-based systems in dealing with both Newtonian and non-Newtonian fluids in different situations.

By incorporating these accurate measurement techniques into a microchip, microfluidic viscometers not only simplify the process of measuring viscosity but also improve its dependability [58]. These devices are extremely important in clinical settings because they are less affected by changes in the environment and can provide real-time data. Their ability to accurately detect viscosity quickly can have a substantial impact on patient outcomes. The consolidation of numerous functions into a single chip also enables efficient and rapid testing, which is essential for applications such as real-time monitoring of blood flow and other dynamic biological processes. In this context, the chip design to be addressed in this thesis is a microfluidic chip based on micropillar structures. The employed methodology similarly relies on the movement of micro

pillars to optically detect this deflection. This is extensively discussed in the Materials and Methods section.

1.3 Optical Detection for Microfluidics

Optical detection in microfluidics pertains to the methodologies employed for observing, examining, and measuring the optical characteristics of fluids or particles within microfluidic devices. This technology is vital in disciplines such as diagnostics, research, and process control, where it is critical to visualize and comprehend the behavior of small amounts of fluids. In addition to achieving high throughput and reducing reagent consumption, can perform precise, real-time analysis of minuscule fluid samples by harnessing the inherent properties of light, such as wavelengths, phases, and intensities [59]. By leveraging the interaction between light and microscale samples, optical detection in microfluidics extracts valuable data. This interaction is crucial for facilitating a wide range of applications, such as the live tracking of chemical reactions [60], the examination of intricate biological matrices [61], the incorporation of lab-on-a-chip systems [62], and evaluating the fluid characteristics in industrial operations [63]. Diagnostics and analyses are can made more efficient and accessible with these systems, which were previously time-consuming and cumbersome.

Optical detection in microfluidics employs many sophisticated approaches that leverage distinct features of light to examine and interpret the composition, behavior, and attributes of fluids. These techniques encompass fluorescence, absorbance, and chemiluminescence [59,64]. Fluorescence involves using specific wavelengths of light to stimulate dyes or naturally fluorescent molecules in a sample, resulting in the emission of light at different wavelengths that can be measured [65]. Absorbance measures the amount of light absorbed by a sample at specific wavelengths to determine the concentration of different compounds [66]. Chemiluminescence detects light emitted from chemical reactions occurring within the microfluidic channels [67]. In addition, optical detection can utilize interferometry to accurately measure small variations in the phase of light as it passes through samples, allowing for extremely precise measurements of cell size, shape, and density [68]. It can also employ Surface

Plasmon Resonance (SPR), which examines alterations in the refracted light from a surface to monitor molecular binding events [69]. Each of these techniques utilizes the distinct interactions between light and matter on a microscale to offer precise observations of the sample being examined.

Conceptualization of opto-fluidics combines optical technologies with microfluidics, expanding the capabilities and potential uses of these devices beyond conventional limits [70]. To facilitate enhanced imaging, sensing, and optical data processing capabilities, optofluidics manipulates light within microfluidic channels. Innovative developments in PDMS-based optofluidic systems demonstrate how this integration is instrumental to improving the precision and expanding the scope of microfluidic analyses [71].

1.3.1 Optical Detection with PDMS Microstructures

Optimizing optical detection techniques in microfluidic chips relies heavily on the careful selection of materials utilized in their fabrication. In addition to polydimethylsiloxane (PDMS), glass and other polymers are frequently utilized because of their distinct optical characteristics. Glass, for instance, possesses exceptional optical clarity and chemical stability, rendering it suitable for applications that demand precise regulation of biological interactions and superior transparency for imaging purposes [72]. PDMS is particularly notable in the realm of optofluidics due to its distinctive blend of optical transparency, pliability, and gas permeability. This makes it particularly valuable for conducting dynamic experiments that require both mechanical and optical qualities.

Polydimethylsiloxane (PDMS) is widely used in the manufacturing of microfluidic devices because of its optical transparency, flexibility, and ability to allow gases to pass through [73]. PDMS possesses features that make it highly appropriate for integrated optical detection systems. The transparency of PDMS is essential for procedures that necessitate visual observation of the sample, such as in micropillar based viscometers where the accurate monitoring of the deformation of micropillar tips, which indicates fluid viscosity, is required. In addition, PDMS possesses the ability to be readily shaped into intricate forms and adhered to different substances, enabling the creation

of complex microfluidic channels and structures that are crucial for optical monitoring [74].

These devices showcase the combination of PDMS's beneficial features with modern optical detecting techniques, with a specific focus on micropillar-based microfluidics. The micropillar-based viscometers employ PDMS for two main reasons: its ability to create flexible structures that can correctly adapt to fluid dynamics, and its optical qualities that enable precise monitoring necessary for effective measurement. Studies, such as those conducted by Mustafa et al., utilize these characteristics by establishing a correlation between the movement of micropillar tips and the viscosity of the fluid [57]. This correlation is seen using optical techniques, such as camera and microscope systems.

In addition to its optical transparency, PDMS possesses optical characteristics that make it well-suited for applications as light guides. It has been extensively employed in a range of inventions, such as microfluidic sensing [75], imaging [76], displays [77,78], and spectroscopy [79]. For example, Cho et al. employed PDMS as an optofluidic waveguide by applying Teflon amorphous fluoropolymers (Teflon AF) to coat PDMS-based microfluidic channels, resulting in the formation of a water/Teflon AF optical waveguide [75]. Shin et al. showed that PDMS may function as a sole light guide plate (LGP) in a compact multicolor fluorescence imaging system [76]. This PDMS LGP has the ability to effectively direct transmitted light towards fluorescent samples, hence avoiding the requirement for numerous filters. This feature makes it well-suited for a range of biomedical applications. Lee et al. have created a straightforward backlight unit (BLU) for liquid crystal displays (LCD) by utilizing a solitary PDMS LGP sheet [77]. PDMS's flexibility allows for the novel application of BLU, resulting in cost and thickness reductions in LCDs, making it an optimal choice for flexible displays. In addition, the authors created a PDMS LGP with cylindrical microstructures as a light source for reflecting displays [78].

1.4 The Optical Knife-Edge Technique

Knife-edge is a widely used optical technique used to measure light intensity on an object. A key characteristic of its operational framework is its inherent simplicity. The object is initially illuminated directly by a light source. After that, light is transmitted from one side of the object to the other side. The opposing side of the object uses a sharp-edged blade or equivalent obstruction. The blade obstructs the entire light, emanating from the source and then slowly moves towards the object. It basically involves blocking a portion of the beam with a sharp edge and moving the edge across, measuring the amount of light transmitted as a function of location. During this process, the amount of light passing through the light source decreases gradually, and this change is detected and recorded by sensors. An intensity profile graph is constructed based on these recorded data sets, revealing the object's optical properties.

In addition to its versatility in scientific applications, the knife-edge method has also been utilized to characterize optical spots and serve as spatial filters in optical beam deflection systems, particularly for in-plane displacement sensing. Knife-edge optical displacement sensors have been developed to improve measurement accuracy in dynamic applications such as: nonlinear displacements in high-speed atomic force microscopy [80], measuring delicate displacements within nanomechanical beams [81], devised a method to amplify displacements [82]. These applications highlight the technique's ability to make precise measurements with high resolution.

The versatility and accuracy of the optical knife-edge technique are emphasized by these improvements and uses, which span across diverse fields such as microfluidics, nanomechanics, and high-speed imaging systems. This technique provides valuable insights into the dynamics of materials and systems at the microscale. Through the ongoing improvement of optical knife-edge technology and its integration with other cutting-edge technologies, researchers can expand the limits of precision measurement and optical characterization.

In microfluidics, this methodology is used to quantify small changes within microfluidic channels, such as displacements of micropillars. In fact, these pillars

can bend as a result of fluid dynamics, and the pressure and viscous forces exerted by the flowing fluid can bend these pillars. The optical knife-edge approach can precisely assess fluid parameters such as viscosity or flow rate by evaluating the alterations in light intensity and distribution resulting from the bending of these pillars. The optical knife-edge approach plays a significant role in improving microfluidic technology by enabling precise monitoring, which is essential for effective measurement due to its intrinsic features.

1.5 Objectives of the Current Study

This thesis showcases the application of an optical knife-edge approach to microfluidic chips that utilize micropillars with the purpose of conducting viscosity measurements. In many applications, such as those involving micropillar based microfluidic viscometry, cameras and microscopes assist in observing the sample and allow recording of images or videos that can later be analyzed to determine important properties such as viscosity, flow rate, and particle behavior.

These monitoring techniques are critical for accurately assessing the performance and behavior of microfluidic devices and can provide valuable information for a wide range of scientific and industrial applications but these techniques typically require expensive and bulky hardware. There is also significant computational cost involved. Our demonstrations utilize a single-pixel photodetector, providing a notable benefit in terms of cost, size, and computational efficiency compared to CMOS camera detection.

Our reading methodology, which explained in the 'Materials and Methods' section in detail, employs pillars as waveguides. A laser is coupled from the backside of the fluidic chip, and when the flow occurs, the output light is monitored using a photodiode with knife-edge detection. A bending angle can be determined by the measured intensity of light changing when the pillars are bending with flow. In 'Simulation' part, demonstrated ray tracing simulations and performed proof-of-concept experiments using to microfluidic chip with focus laser source on a single micropillar. The bending of the pillars caused by the liquid flow changes the perceived intensity of light, allowing for the determination of the angle of bending. The bending of the pillar recorded using the photodiode with the knife-edge approach closely matches that

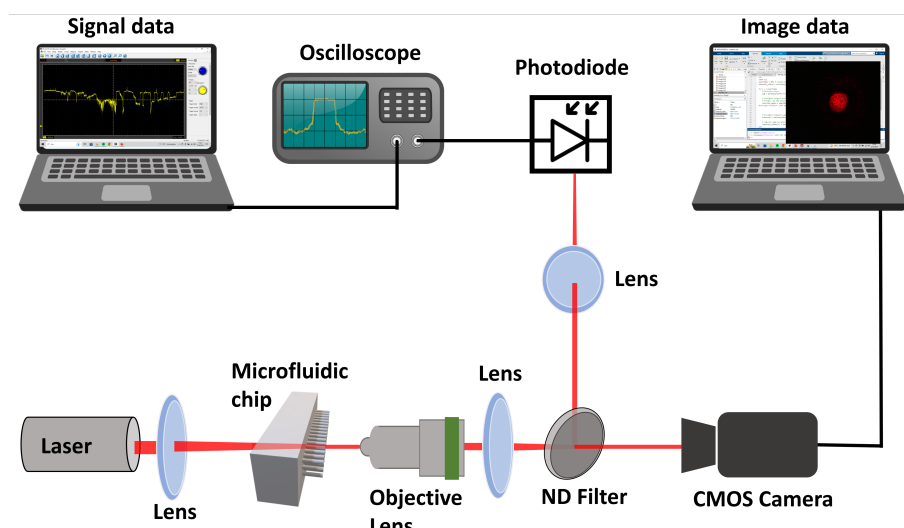


Figure 1.1 : Illustration of the optical reading concept and applied methodology.

observed using a camera, and in the experimental process, recording was made with both of them as shown in the Figure 1.1 for proof of concept. With further refinement, the suggested approach can produce a small and inexpensive device for measuring viscosity in real-time at the point of care. We will discuss these approaches in the Conclusion chapter.



2. MATERIALS AND METHODS

This chapter outlines the precise methods and tools used to comprehensively study the optical knife tip technique used in microfluidic systems based on micropillars. The procedures involve accurate fabrication of microfluidic chips using standard soft lithography processes, which is essential to guaranteeing the precision and consistency of our experimental findings. In the study, optical modeling is proposed that uses the principles of wave optics to evaluate different detector sizes to capture the total power of the light emerging from the micropillar. Ray tracing simulations are performed to visually enhance understanding of light behavior about coupling on a single pillar and PDMS scattering properties in microfluidic environments and provide a predictive tool to aid experimental design.

Experimental procedures are meticulously outlined, providing a detailed description of the setup and implementation of experiments that measure optical properties by microscale manufactured chips. Additionally, the air flow and liquid flow experiment setups are also described in this part. This chapter offers an in-depth account of the practical steps taken, as well as a clear explanation of the reasoning behind each methodological decision, directly connecting them to the study's main objectives of enhancing optical measurement techniques in microfluidics.

2.1 Fabrication of the Microfluidic Chips

Providing precision and functionality for experiments depends on the fabrication of microfluidic viscometer chips. The first step in the manufacturing process is the creation of the master mold (Figure 2.1.a), which will be used in shaping the microfluidic channel and microwells. In production, to craft a master mold, which is a negative copy of our microfluidic chip design, utilized a desktop Computer Numerical Control (CNC) machine. The material used for the create master mold is wax. The mold consists of an array of 3x16 wells. Each well is 1 millimeter deep and 200

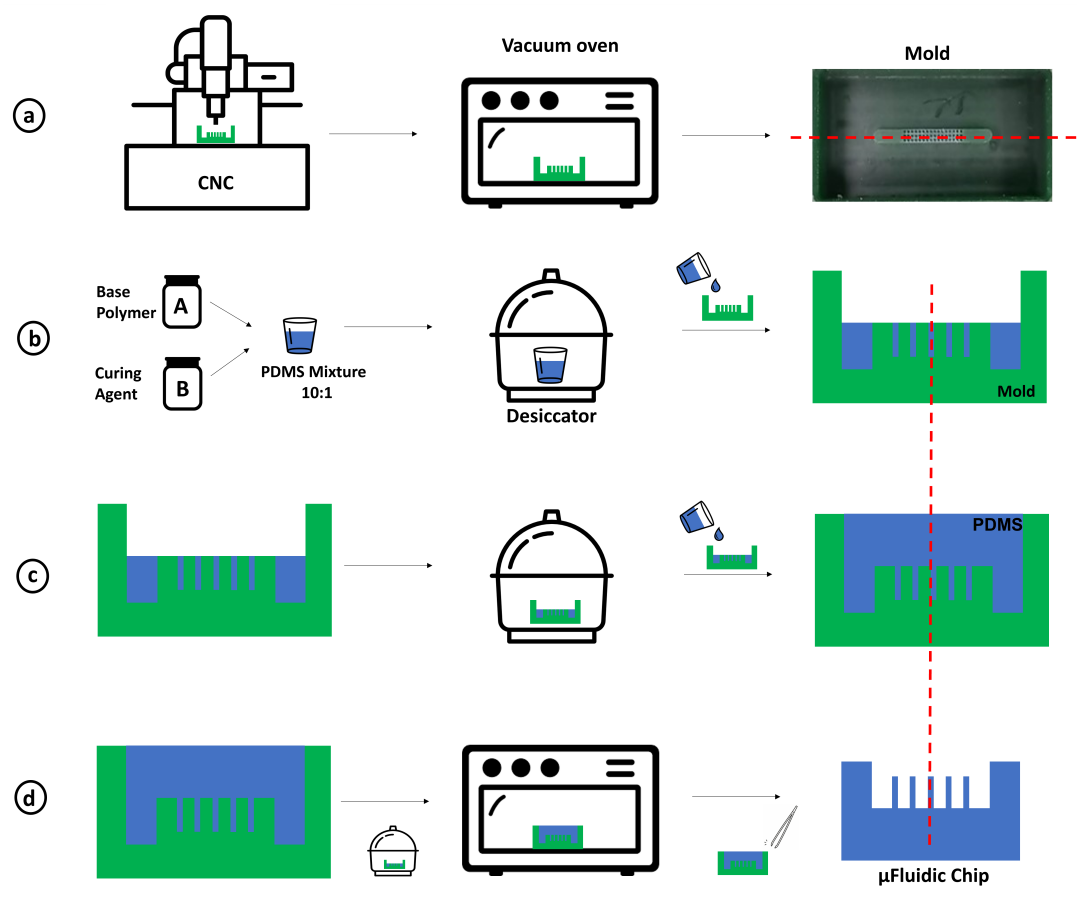


Figure 2.1 : Fabrication steps of micropillar-based microfluidic chip.

micrometers in diameter. As a result of this precise machining, uniformity in the well dimensions is achieved, which is crucial for the consistency of fluid dynamics and optical properties across several experiments. Before pouring PDMS into it, the mold must harden and hold its form, for this it is cured in a vacuum oven at 50 degrees for 2 hours.

Following the curing of the master mold, a mixture of polydimethylsiloxane (PDMS), specifically RTV 615 silicone elastomer base (RTV 615 A) and curing agent (RTV 615 B) purchased from Momentive Performance Materials [83], Waterford, NY, USA, is prepared at a ratio of 10:1 (base:curing agent) (Figure 2.1.b). PDMS mixtures have previously been formulated at various ratios (5:1, 10:1, and 20:1) to optimize the final product's mechanical properties and transparency based on previous experiments [23]. Due to its excellent optical clarity, biocompatibility, and flexibility, PDMS is ideal for microfluidic applications requiring precise optical measurements and fluid control.

The PDMS mixture is then poured into the mold, filling half of it. To eliminate any air bubbles that could compromise the structural integrity and clarity of the final product, the mold is degassed. This step is performed in a desiccator. Then it is repeated for the other half of the mold (Figure 2.1.c). The reason for two-stage vacuuming is to ensure that the mixture is well filled into the microwells that will form the pillars. The curing process is conducted at 75 °C for 1 hour in a vacuum oven (Figure 2.1.d) to ensure that the PDMS concretizes into a shapely, resilient structure that retains the precise dimensions and geometry of the mold.

Once PDMS has undergone the process of hardening, it is meticulously detached from the master mold with the aid of a tweezer. This procedure is executed carefully to prevent any ripping or distortion of microstructured surfaces. After removing the mold, the fluid inlets and outlets are punctured using biopsy punches. This technique facilitates the creation of exact and precise openings in the PDMS sheet so that tubing and other connections can be safely and accurately integrated for fluid injection and withdrawal using a syringe pump.

The final step in the fabrication process involves attaching the PDMS microfluidic chip to a microscope glass slide. In this way, the open microchannel of the PDMS microfluidic chip is closed which allows fluid tests to be performed. This is achieved by oxygen plasma treatment, which alters the surface properties of PDMS, making it temporarily hydrophilic, a critical factor in creating strong and reliable chemical bonds. The plasma bonding process ensures that the PDMS and glass surface adhere perfectly to each other, preventing leaks that could affect liquid tests. After the two surfaces are connected, the microfluidic chip is ready for use in experiments. Thus, a robust platform is created to perform optical measurements and integrate into the established optical setup.

The knife-edge technique is a refined technique to measure how the micropillars mechanical response changes when liquid flows through them. This give a rough idea of the viscosity of the liquid. This technique leverages the optical properties of micropillars, enabling them to not only ensure the mechanical stresses of fluid dynamics but also serve as efficient light guides.

The process begins by coupling a light source to a selected micropillar within the microfluidic device. The light source is placed under the microfluidic chip, and the photodiode is positioned on the microchannel side, where the micropillars are located. This micropillar has been carefully positioned so that it will act as a waveguide for directing light along its length with precision. The laser light source emits a beam of light focused at 200 μm to match the pillar diameter, aligned to enter one end of the micropillar. Precise alignment is crucial as it ensures the maximum amount of light enters the micropillar, thus optimizing the sensitivity and accuracy of the detection system. When light travels through the micropillar, it is subsumed by the inherent optical properties of the material (refractive index of PDMS), which are chosen to match or exceed the critical angle for Total Internal Reflection (TIR). This optical property allows light to travel the length of the pillar without significant loss and reach the opposite end, where the photodiode system is located. Light transmission with TIR is the bending limit for micropillars to work as wave guides, which is explained in the following chapter under the Results and Discussion part of this thesis.

2.2 Optical Knife-Edge Implementation

In the detection phase, a light-sensitive element (such as a photodiode in this case) is strategically placed to collect the light beam coming out of the micropillar (Figure 2.2). This placement is critical. The detector collects the full power of the light under no-flow conditions (Figure 2.3.a). This power point has been meticulously calibrated to be the rest position of the light output and serves as the basis for subsequent measurements. It is worth mentioning that there is no physical knife edge in the system. When the micropillars bend with the flow, they begin to escape from the photodiode detection area (Figure 2.3.b-c). When the pillars are bent in the direction of flow, the collected light power decreases monotonically. As the liquid begins to flow through the microfluidic device, it applies force to the micropillars, causing them to bend in the direction of flow. Bending the pillars changes the path of light inside; it typically changes the angle at which light exits the pillar.

Due to this micropillar tip bending, the light beam shifts according to the fixed position of the photosensitive detector, that is, it begins to leave the detection area (serving

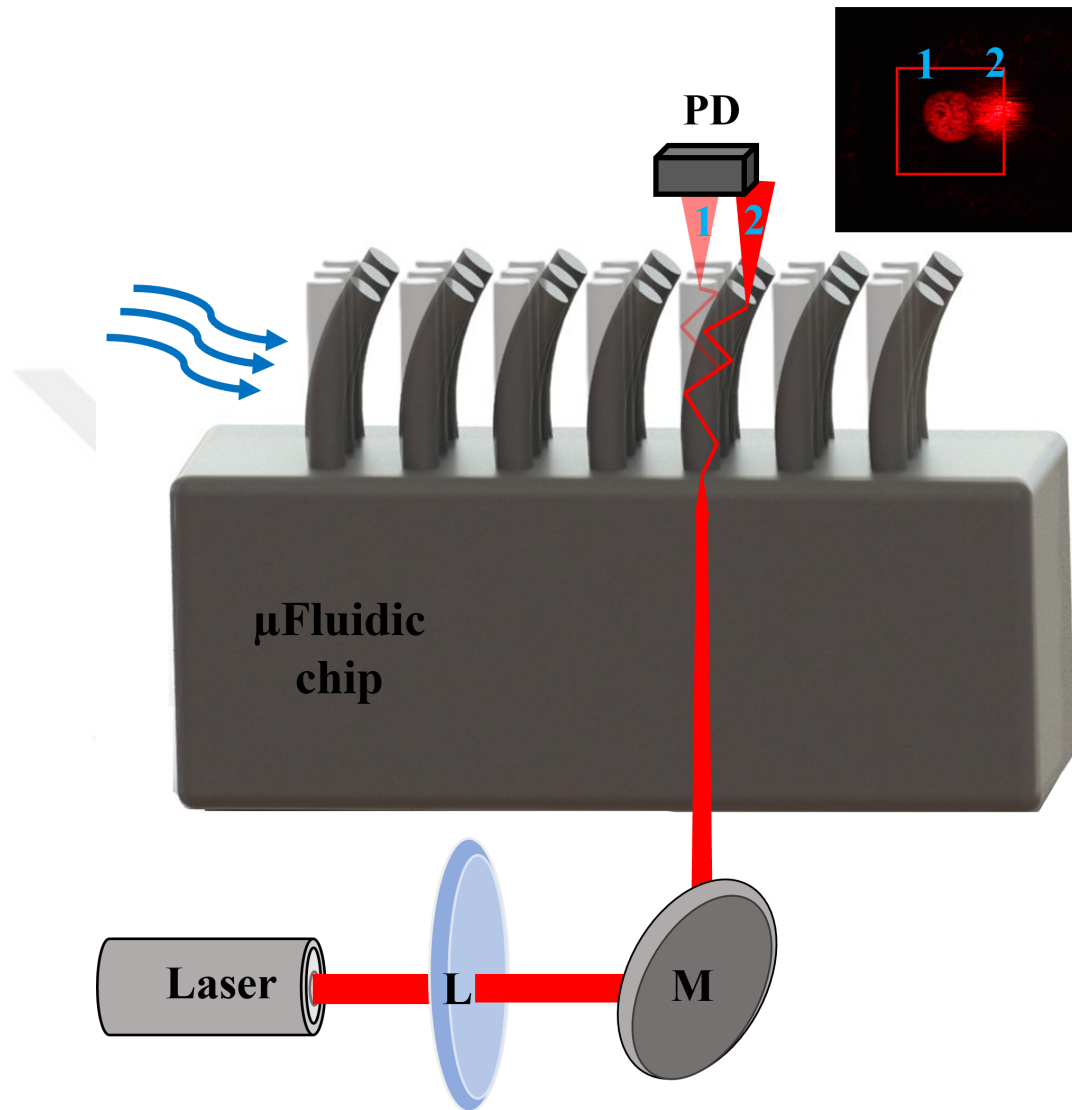


Figure 2.2 : An optical knife-edge detection scheme for micropillar bending in a microfluidic viscometer (L: lens, M: mirror, PD: photo-diode). In the inset above right shows, the pillar images obtained from the CMOS camera. 1th condition represents; rest pillar and, 2nd condition represents; pillar bending with flow [1].

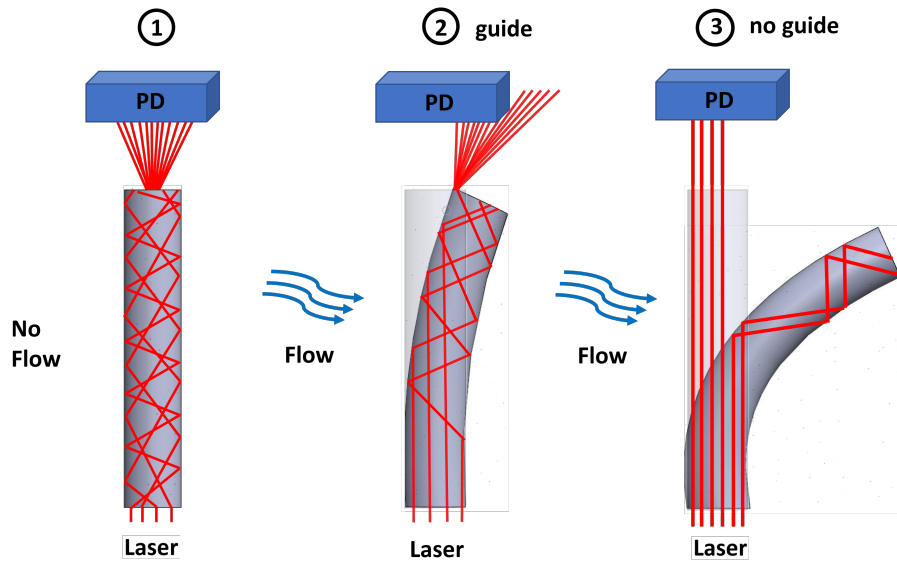


Figure 2.3 : Showcasing of light detection by the photodiode after light travels along the micropillar with TIR; a) resting pillar, b) the pillar bending with the flow manipulates the light as a guide, c) light begins to escape through the micropillar, depending on the increasing degree of bending.

as the knife-edge). As the pillars bend more and more with increasing flow rates, the amount of light captured by the detector gradually decreases. It should be noted that this decrease in light power is directly proportional to the bending degree of the micropillar and, accordingly, to the flow rate and viscosity of the fluid under test. The data obtained from the photosensitive element is then processed to measure changes in light intensity. The purpose of this analysis is to convert light intensity measurements into electrical signals that are analyzed further to determine flow properties based on the electrical signals. The relationship between the detected light intensity and the displacement of the micropillar provides a quantitative measurement of the dynamic properties of the fluid, including its viscosity.

This detailed application of the optical knife edge technique in a micropillar-based microfluidic viscometer was recorded with a CMOS camera along with the photodiode for comparison and to prove the accuracy of the method. The optical setup is explained in detail in the Experimental Process section.

2.3 Optical Modeling

Optical modeling is proposed in the development of micropillar-based microfluidic viscometer to optimize the performance of the system, in particular to determine the ideal detector size relative to the pillar dimensions to ensure accurate measurements. Optical modeling focuses on simulating and analyzing how the laser, modeled as a Gaussian beam, propagates from micropillars that act as waveguides within the device.

Gaussian beam modeling is very important in optical systems as it allows accurate prediction of the behavior of laser light during propagation. A Gaussian beam is defined by its Gaussian-shaped intensity profile, which describes the power concentration at the center of the beam and its exponential decay as it moves away from the center [84]. This model is advantageous due to its simplicity and accuracy in depicting laser beams. Properties of the beam; It is determined by important factors, including the beam waist, which represents the narrowest part of the beam with maximum intensity, and the Rayleigh gap, which describes the distance the beam can travel before it begins to spread noticeably. The optical system in this study was used to predict how the light beam propagates and interacts with the detection system.

Using a 100 μm (R_P) radius micropillar, the light output at the pillar tip was modeled to understand the interaction of light with the microfluidic environment. Considering the coherent nature of the laser light source used, Gaussian modeling is an ideal representation of the light coming out of micropillars. The intensity of the light, which peaked at the center of the light and decreased with radial distance from the center, was defined by the function I_0 . This behavior is critical for determining how the distribution of light changes as it exits the micropillar, and this distribution is captured mathematically by the Gaussian beam:

$$I(r) = I_0 e^{-\frac{2r^2}{R_P^2}} \quad (2.1)$$

where r is the radial coordinate.

The photodiode is positioned near the light output end of the micropillar. R_{PD} represents the radius of the photodiode. It captures incoming light, and its detection efficiency depends largely on the alignment of the detector and the size of the detection area. The photodiode is positioned so that the detector initially captures half of the beam power when the micropillar is in its rest position ($\Delta p = 0$). The flow causes bending in the pillars, changing the direction and focus of the light beam. This physical change causes a measurable change in the light intensity captured by the photodiode, and the light intensity continues to decrease as the bending increases. Optical power that is a function of bending of the pillars (Δp):

$$I_{PD} = I_0 \int_{r=-R_{PD}-\Delta p}^{r=R_{PD}-\Delta p} e^{\frac{-2(r-\Delta p)^2}{R_P^2}} dr \quad (2.2)$$

and the photodiode signal can be mathematically represented using the error function (erf):

$$I_{PD} = 2I_0 \left\{ \operatorname{erf} \left(\sqrt{\frac{2}{R_P^2}} \frac{R_{PD} + \Delta p}{4} \right) + \operatorname{erf} \left(\sqrt{\frac{2}{R_P^2}} \frac{R_{PD} - \Delta p}{4} \right) \right\} \quad (2.3)$$

The normalized optical power is illustrated in Figure 2.4 as a function of the displacement of the pillar tip, for different photodetector dimensions. It has been concluded that matching the diameter of the photodetector with the diameter of the micropillar provides the most optimal result in order to observe detection sensitivity and accuracy. Calculations show that a photodetector detection area size that is the same as the pillar diameter, $R_{PD} = R_P$, is optimal. In the analyses; If a detector area smaller than the micropillar diameter is used, the entire output light power will not be captured, and a detector area larger than the micropillar diameter will lead to undesirable detection of adjacent objects. It has been demonstrated that there must be a balance between the two situations. The complex interplay between the beam size larger than the detector and the detector's ability to capture varying intensities as the beam enters and exits its field has been a major factor in determining the optimum detector size.

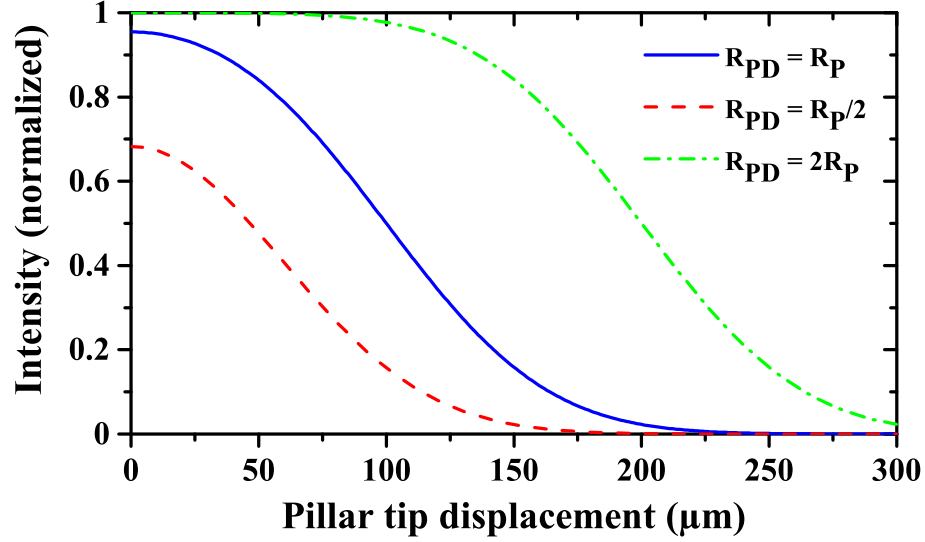


Figure 2.4 : For different photodiode dimensions, the normalized light intensity was calculated as a function of the pillar's bending [1].

The micropillars serve as waveguides, and the Numerical Aperture (NA) of the waveguide is determined by calculating the refractive indices of the materials used. The NA can be represented or articulated as:

$$NA = \sqrt{n_p^2 - n_s^2} \quad (2.4)$$

n_p is refractive index of the PDMS micropillars ($n_p = 1.42$ [85]). n_s represents the refractive index of tested liquid samples ($n_s = 1.33$ for water).

The micropillar waveguide configuration results in a NA of 0.49, which corresponds to a half exit angle of 22 degrees. The parameter in question is of utmost importance as it directly influences the range of light that may be efficiently caught or released by the waveguide, thereby affecting the effectiveness of optical transmission. It is crucial to comprehend and account for this NA in order to optimize the spatial alignment between the micropillar exit and the photodetector, thereby guaranteeing accurate and effective light detection.

2.4 Ray Tracing Simulations

All ray tracing simulations were performed in Ansys Zemax OpticStudio software, which stand out as a practical tool for optical design. By utilizing advanced ray tracing and analysis features, engineers and researchers can simulate and enhance optical systems. One of the questions at the beginning of the project was whether the light would be coupled to a single micropillar with a diameter of $200\mu\text{m}$. Before the experimental setup, the operability of the system was verified by simulation and two stages proceeded simultaneously.

This chapter covers detailed simulation of light propagation through micropillar-based microfluidic viscometry, focusing on how micropillar tip bending affects light output. Figure 2.5 in the thesis shows the ray tracing model results and highlights how the output light model changes depending on the bending of the micropillar tip. Note that in Figure 2.5.a the ray colors illustrated in simulation results are altered by the software with segment coloring command, when the rays experience reflection or refraction. This color change is important to help dissolve in the systems where light performance deviates from expected patterns due to optical phenomena such as scattering or total internal reflection.

The ray tracing model was designed in non-sequential mode to reflect the real experimental setup as closely as possible. It is worth mentioning that a very basic setup was established to perform the evaluation. The mechanism consists of a light source, a lens (100mm focal length) to focus the light on the pillar inlet, a microfluidic chip and a detector (Figure 2.6). Key parameters include light source characteristics such as wavelength (630 nm was chosen) and beam profile, which are set to replicate a laser emitting a near-Gaussian beam.

Microfluidic chip designs were drawn in the Solidworks CAD program and then uploaded to Zemax as a CAD file. Each microfluidic chip drawing represents 11 different pillar bending distances that will correspond to a different pillar tip displacement (there is a $15\mu\text{m}$ pillar tip displacement difference between each drawing). As can be seen in Figure 2.5.c, simulations were carried out in the total

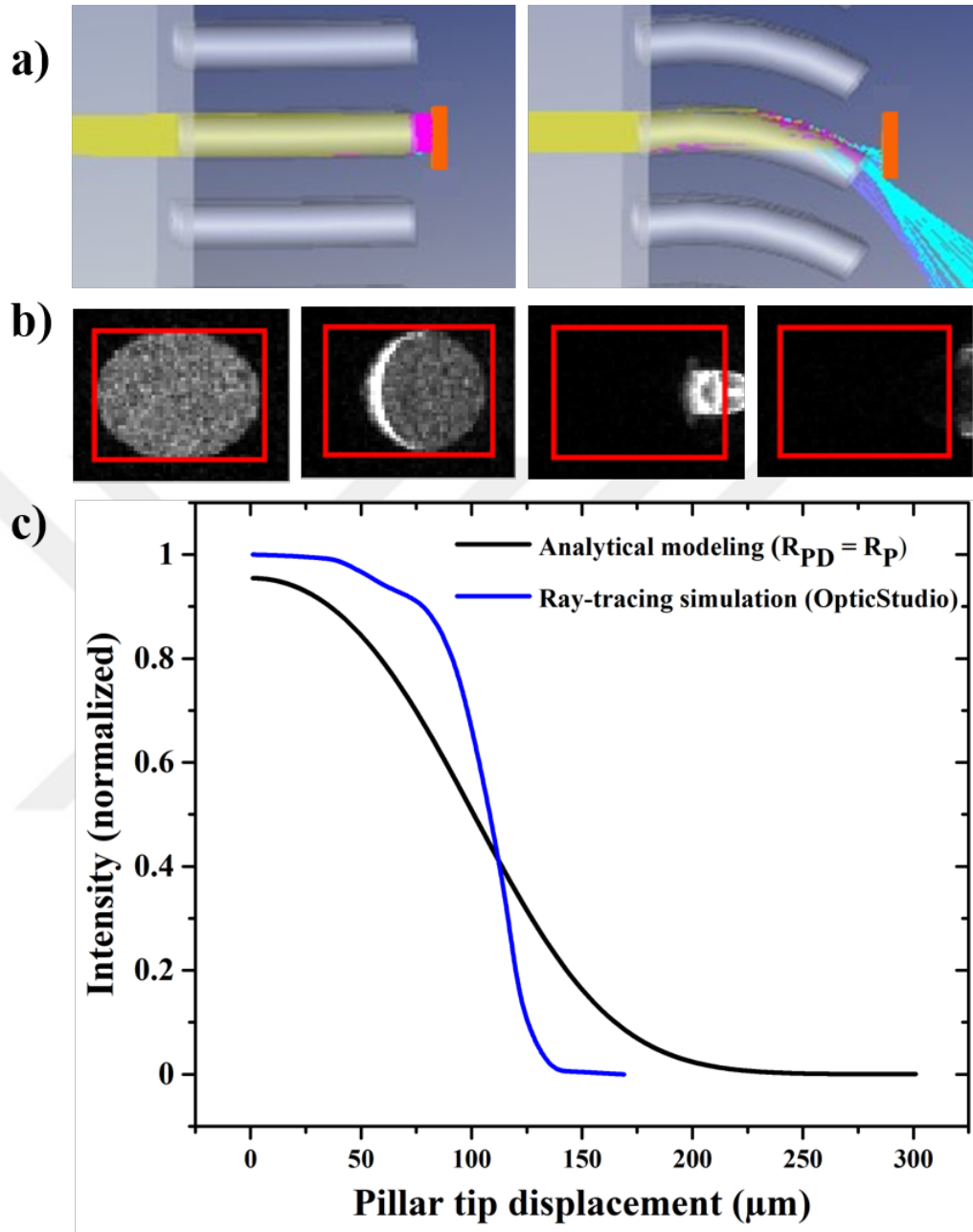


Figure 2.5 : Ray tracing simulation of the microfluidic chip; a) coupling of light into a rest and bent pillar, b) detector data (light output profile) taken from the simulation was processed, the detector area is shown with a rectangle drawn in red, c) normalized output light intensity vs. pillar displacement and comparison to analytical findings (ideal detector size according to pillar diameter) [1].

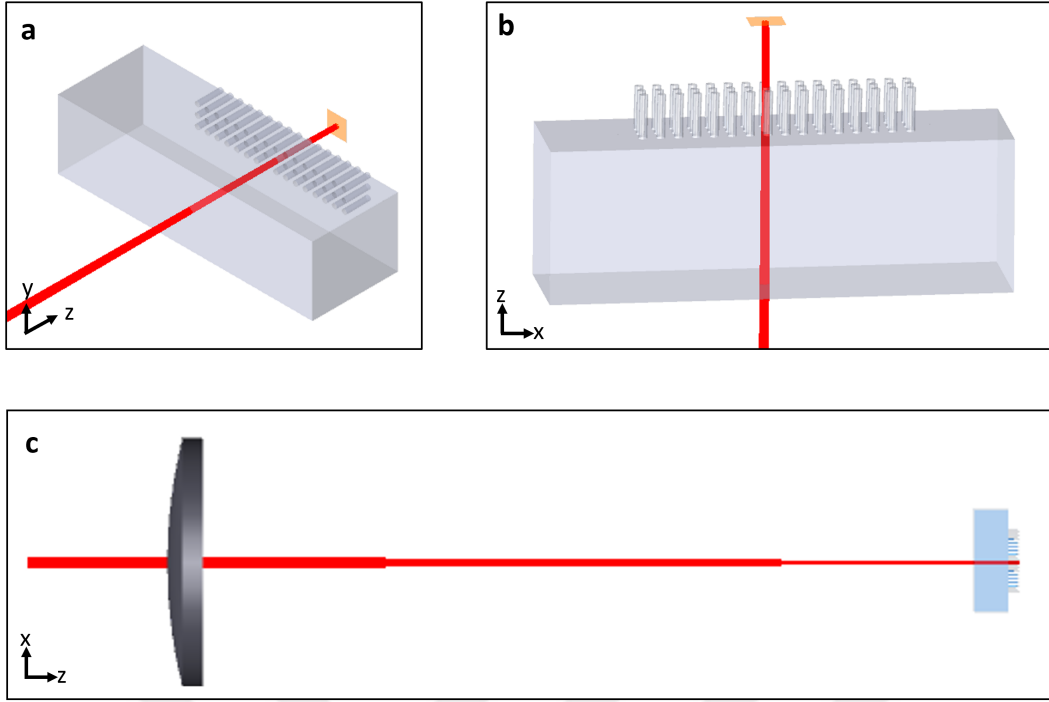


Figure 2.6 : The optical setup in the simulation; a,b) the microfluidic chip and detector from different directions, c) from left to right: the light source, lens to focus, micropillar-based microfluidic chip, and detector.

pillar tip displacement range of $0\text{ }\mu\text{m}$ (rest) - $150\text{ }\mu\text{m}$ (bent). Micropillars are modeled with precise geometric and material properties, including their refractive index, size, and orientation relative to the light source and detector. Micropillars are drawn with a width of 10.4mm and a thickness of 3.5mm (pillar entrance, the point where the light should focus). Micropillar heights are drawn realistically as 1mm , with a diameter $200\mu\text{m}$.

A detector with an area comparable to the cross-sectional area of the micropillar is strategically positioned to capture the full optical power when the micropillars are at rest. As a result of this placement, any deviation in the light path due to bend directly affects the detector's readings, giving precise measurements of pillar deformation. Afterwards, the intensity data taken from the detector for each different bending distance was recorded and processed in Matlab. A comparison was made with the analytical modeling explained in the previous chapter (Figure 2.5.c).

Elucidated the differences in the bending vs. output optical power behavior, also shown in Figure 2.5.b, to the deviation of the output laser distribution from a Gaussian beam

profile. As seen in Figure 2.5.b, the light output resembles that of a waxing crescent phase of the moon. It should also be said that this is also due to the square detector as opposed to the circular detector shape that is utilized in the derived analytical formulation above.

2.5 Experimental Process

As shown in Figure 2.7, the experimental setup was designed to observe the bending of a single micropillar within a microfluidic device using optical components when the flow was given to the microfluidic chip. This setup features a comprehensive assembly of optical and electronic components. Focusing the laser on a single micropillar within the micropillar-based viscometer, enabling precise control and measurement of light interactions.

To illuminate the chip, there is a laser diode source (CPS635, Thorlabs Inc.) (Figure 2.7.a) chosen for its stability and wavelength suitable for optical measurements. Laser light is directed to a selected micropillar that acts as a waveguide using a plano-convex lens (Figure 2.7.b) with a focal length of 100 mm. This lens focuses the laser beam onto the micropillar, ensuring efficient light coupling and minimal loss. This is crucial to maintaining consistent light intensity throughout experiments.

After the light passes the micropillar, it exits from the far end. Thanks to a 10x magnification objective lens (Figure 2.7.d) placed here, the image is enlarged, and a lens (Figure 2.7.e) placed right behind it parallelizes the incoming light to prevent deviation. This collimated light beam is then split using a reflective Neutral Density (ND) filter (ND10A, Thorlabs Inc.) (Figure 2.7.f) to be directed to two detection systems: a photodetection unit (PDA36A, Thorlabs Inc.) (Figure 2.7.i) and a CMOS camera (DCC1545M, Thorlabs Inc.) (Figure 2.7.g). As stated before, this stage was done to compare the data received from the CMOS camera and photodiode and to prove the functionality of the photodiode in this measurement. On the side of the split light goes to the photodiode. Another plano-convex lens (Figure 2.7.h) with a focal length of 50 mm is used to further manipulate the light, which is further magnified by a factor of 10 using the plano-convex lens. With this magnification, the laser spot

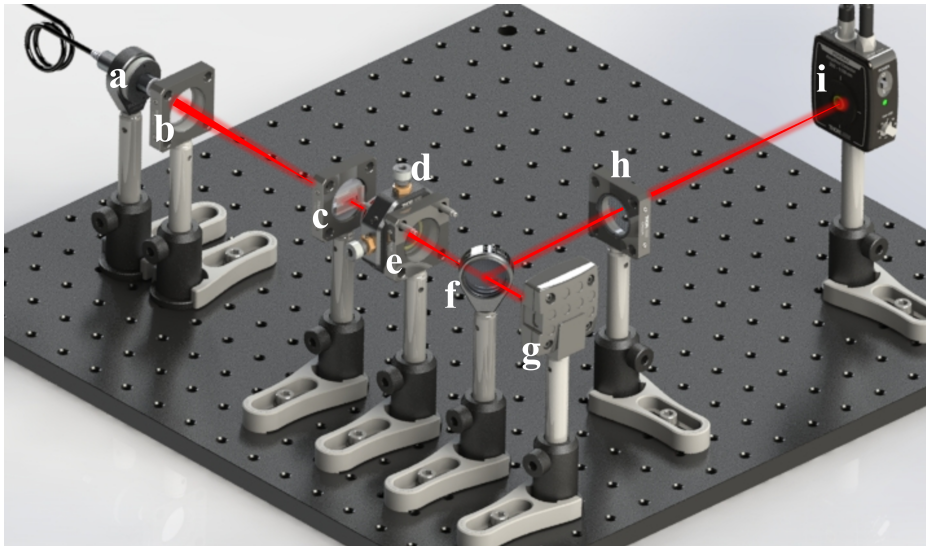


Figure 2.7 : Illustration of optical setup [1].

diameter is specifically matched to the area of the photodiode detector (3.2 mm x 3.2 mm), which ensures that the entire beam is captured and measured.

Flow experiments were carried out in basically two different ways. Air flow experiments and fluid tests. Fluid tests will be detailed in the Results and Discussion section. An air compressor is used to create controlled air flow around the micropillar, simulating various flow conditions within the microfluidic device. There are a number of advantages to using the setup described here, including being able to observe the response of micropillars to different flow rates, which is necessary in order to determine the viscometric properties of the liquid under investigation. As the light intensity is continuously monitored, the light detection unit provides real-time data on the flow-induced deflection of the micropillars. Simultaneously, the CMOS camera serves a dual purpose: by monitoring the corresponding optical power on a group of pixels aligned with the photodetector and visually observing the position of the pillars, it verifies measurements from the photodetector. To analyze CMOS camera images captured by the device, image processing techniques are employed, specifically Hough Transform-based circle detection following image binarization, to analyze the images captured by the device. This technique, executed via the `imfindcircles` command in MATLAB, provides a robust reference measurement that complements the data obtained from the photodetector.

3. RESULTS AND DISCUSSION

There are a number of findings documented in this section of the thesis. The results of experiments were presented that were conducted using an optical knife-edge detection method applied to a micropillar-based microfluidic viscometer. The purpose of the experiments was to validate the effectiveness of this new optical approach to measure the bending of micropillars due to flow, a metric that is indicative of the viscosity of the fluid, by measuring the bending of micropillars. The precision and promise of this technology in real-world applications are demonstrated through the analysis of comprehensive data obtained using both photodetectors and CMOS cameras. Using a mathematical model to describe the bending limitations of micropillars under varying fluid conditions, we present a comprehensive analysis of the results of the experiment, focusing on the complexities of optical power measurements and their limitations. For this comprehensive analysis of the results, a proposed mathematical model is explained in detail.

3.1 Optical Power Measurement and Analysis

Experimental results focused on capturing optical power delivered through micropillars, which were meticulously recorded over time as various air flow rates were applied. There is a clear and consistent relationship between the optical power detected by the photodetector and the area determined by the CMOS camera. This relationship is directly related to micropillar bending as a function of the optical power detected by the photodetector. This variation is drawn and shown in Figure 3.1. To ensure the accuracy of these measurements, the region on the CMOS camera was carefully selected to best match the readings from the photodetector. This alignment, i.e., area determination, was crucial to verifying the sensitivity and accuracy of the knife-edge detection method. For providing a secondary point of validation, the circle fitting

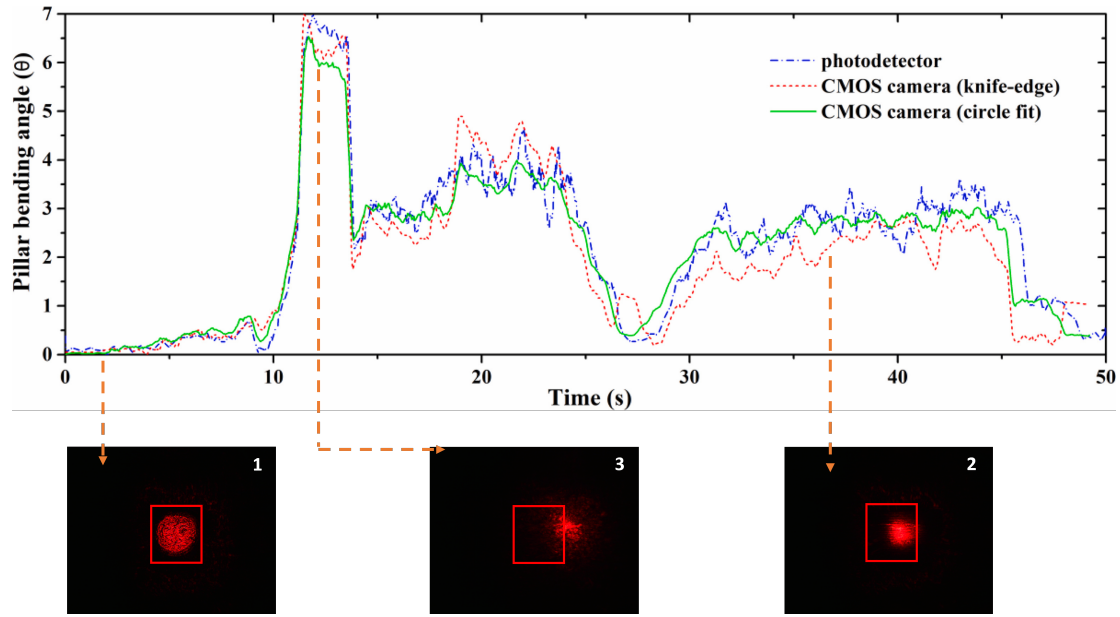


Figure 3.1 : The bending of micropillar as a function of time as observed by the photodetector and CMOS camera (knife-edge and circle-fit) [1]. Insets represents CMOS camera images, no flow state (1) and when air flow was given into the pillar (2, 3).

method with the 'imfindcircle' command on MATLAB software, used to measure the tip bending angle of the micropillars.

Throughout the duration of experiment, the microfluidic chip was continuously photographed to capture the movement of the micropillar tips in response to air flow. We aimed to measure density values across the entire area of the pillar to see if comprehensive data could be obtained without the traditional knife-edge technique. More than 900 photographs were taken from the CMOS camera and then analyzed with image processing tools using MATLAB. These obtained data were used in synchronization with photodiode data. This allowed us to meticulously measure the intensity of each pixel within a specially selected rectangular region, as seen in Figure 3.1, approximately equivalent to the detector area covering the entire pillar tip.

When airflow was introduced into the microchip, the micropillar, which was initially in a steady state (Figure 3.1.1), began to bend (Figure 3.1.2), leading to changes in the light intensity captured by both the camera and the photodetector. Camera data normalized for comparison revealed that intensity values were higher when no air was

introduced and decreased as air pressure caused the bright areas to narrow (Figure 3.1.3), indicating bending of the micropillars.

The experimental setup did not initially contain a sharp-edge 'knife', an obstacle; Instead, the desired obstacle was created when the micropillar tip bent under the flow moved out of the detector detection area. The photodiode, an imaging device containing a single pixel simultaneously, provided numerical values ranging from 0 to 1 depending on the light intensity hitting this pixel. Voltage values were recorded from the photodetector during the approximately 50-second experiment (air flow experiment). Data read through an oscilloscope reflected the on-off response mechanism of the photodetector, with values normalized between 0 and 1.

Comparison between camera data and photodetector readings showed a high degree of agreement, confirming the reliability of our measurement approach. Additionally, data was recorded from the camera at a rate of 20 frames per second (fps), and a total of 985 frames were recorded. This means that the recorded (experimental) time under air flow was 49.25 s. During the same period, 2488 data points were recorded from the photodiode. From this it is deduced that there is approximately 0.0198 sec between each data point recorded from the detector. Discrepancies in data overlap were attributed to the region selected for analysis; this suggested that adjustments in coverage could improve data alignment in future experiments.

The selected knife edge region in CMOS camera images is adapted to obtain the best match with the photodetector and circle-fit measurements (as shown in Figure 3.1. The micropillar tip deflection observed at the pillar tip based on circle fitting algorithm in MATLAB was also plotted for verification purposes. Pillar displacement is simply converted to bending angle by calculating the arc tangent of pillar displacement over effective pillar length [86]. Thus, all results largely match, once again highlighting the cost and form factor advantages of using a single photodetector on a camera.

3.2 Analysis of Optical Detection in Glycerol-Water Mixtures

In a subsequent series of experiments in our study, we performed experiments with a glycerol-water mixture using the photodetector-based optical knife-edge detection method and focused on evaluating the behavior of micropillars in liquid conditions. Research was conducted to assess the sensitivity and accuracy of our sensing system under varied fluid conditions that are close to those encountered in real-life applications. For these experiments, a glycerol-water mixture mixed at a weight ratio of 32:68 with a viscosity of 2.637 cP and a refractive index of 1.373 was used [87]. This specific mixture was chosen because its refractive index by weight ratio can be varied very easily, thus representing many biological fluids and thus providing a relevant test scenario for potential medical diagnostic applications. Experiments were carried out by monitoring the output signal of this mixture at various flow rates to investigate how different flow rates affected the bending of the micropillar and the corresponding changes in light intensity.

To verify and compare the photodetector data, similar readings were taken using a CMOS camera positioned to capture the same area covered by the photodetector and in the same position as in the experiments with air flow (Figure 3.2). Images recorded with the camera were analyzed by measuring the intensity of each pixel within a specially selected rectangular region. Images acquired from the CMOS camera were also analyzed using the circle-fitting algorithm designed to detect and measure micropillar deflection angles in liquid media. Nevertheless, the method was less effective in the glycerol–water mixture due to reduced optical contrast and minimal bending (typically less than a degree). These factors showed that the image processing algorithm was inadequate for experiments with liquid, limited in its ability to accurately track the subtle movements of micropillars. In spite of these challenges, the photodetector provided consistent and repeatable measurements consistent with expected changes due to fluid dynamics.

With the mixture of glycerol and water, optical knife-edge detection systems were demonstrated to be durable in different test scenarios, as well as areas for improvement

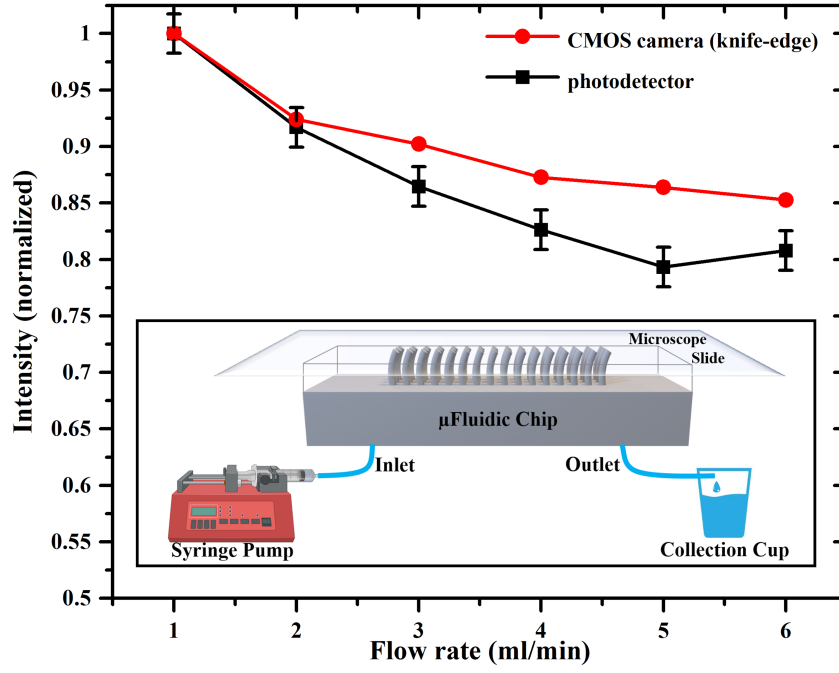


Figure 3.2 : The knife-edge reading for the glycerol-water mixture liquid experiments, recorded with both the photodetector and the CMOS camera (with the selected area). Normalized intensity results are shown comparatively for flow rates ranging from 1 to 6 ml/min. An illustration of the conducted experiment is shown in the inset [1].

in low-contrast image processing. It will be crucial to develop algorithmic strategies to deal with these situations in the future. Additionally, the information gained from these experiments will be used to improve microfluidic design, making it more suitable for a wider variety of fluid states. This will increase the utility of the system in biomedical applications.

3.3 Mathematical Modeling of Bending Limitations

Key advance considered by the research is the development of a mathematical model to understand the bending limitations of micropillars in response to fluid-induced forces. Material properties and geometric configuration of micropillars under changing fluid conditions are addressed in this model. Proposed model was used to determine the maximum bending angles that the pillars could withstand before the integrity of the total internal reflection (TIR) was compromised due to the changing refractive index of liquids.

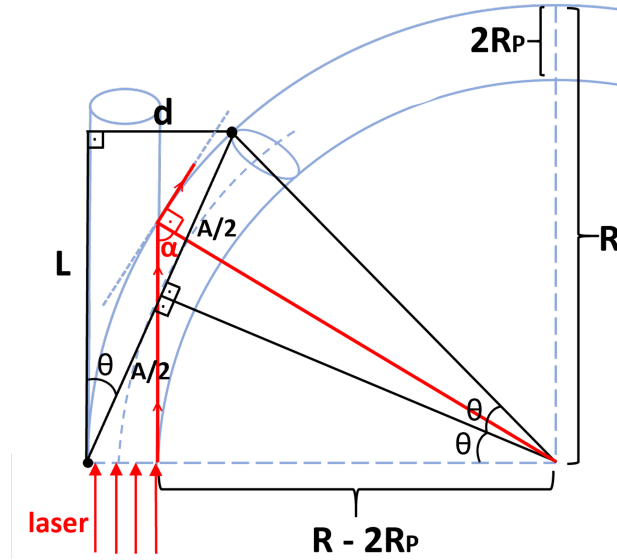


Figure 3.3 : Mathematical modeling of micropillar's circular bending profile [1].

TIR is the situation in which light passes from a more dense medium to a less dense medium, and when the light hits the boundary surface at an angle greater than the critical angle, all of the light is reflected back to the first medium and cannot pass to the second medium. The critical angle is the angle at which light cannot pass into another medium. If the angle of incidence is greater than the critical angle, the light is reflected from the first medium; if it is small, the light can pass to another medium and refraction occurs. For this study, as bending increased the angle of incidence of light decreased, began to escape from the waveguide structure, marking the critical bending limit at which micropillars could no longer function effectively as optical waveguides.

To understand the limitations of bending behavior for our design, a simplified mathematical model is proposed, which is validated through simulation for water and some other biological environments. The light is coupled to the micropillar along its axis, as shown in Figure 3.3. The radius of curvature was calculated by measuring the degree of bending of the micropillar and, from the known length of the overhanging micropillar, modeling the bending to be circular in profile. The model starts by assuming a circular bending profile of the micropillars; this simplifies the complex interactions between the micropillar structure and fluid dynamics. The smallest allowable radius of curvature that the micropillar can bend without light escaping is represented by R . Considering that a ray coming along the inner edge will

have the largest angle of incidence (α), this incoming ray has a higher probability of escaping to the outside. With the geometric inference obtained from the model given in the Figure 3.3, the angle of incidence of the ray to the micropillar is defined as follows:

$$\sin\alpha = \frac{R - 2R_p}{R} \quad (3.1)$$

Applying Snell's law for the critical angle, we can write as follows:

$$n_{PDMS}\sin\alpha = n_{water} \quad (3.2)$$

where the micropillar diameter is 200 μm ($2R_p$) and the PDMS refractive index is 1.42 [88] and the water (or corresponding biological fluid, i.e., blood, cerebrospinal fluid) refractive index is 1.33. The minimum allowable radius of curvature R can be derived using the above equations. We now model the micropillar with overhang length L and lateral deflection d of the micropillar. The mathematical model used the arc length formula to relate the bending angle to the displacement of the micropillar, taking into account the physical dimensions and material properties of the pillars. Since pillars are 1 mm long, we can calculate the pillar bending angle θ using a simple arc length formula:

$$2\pi R \frac{2\theta}{360} \quad (3.3)$$

After subtracting the bend angle, we can use the following formulas to determine pillar tip deflection.

$$\sin\theta = \frac{A/2}{R} \quad (3.4)$$

$$\sin\theta = \frac{d}{A} \quad (3.5)$$

Assuming that water flows in the microfluidic channel, according to the calculations made for the water environment, the light will travel through the micropillar without escaping to the outside until a bend of about 9 degrees, and as the degree of bending

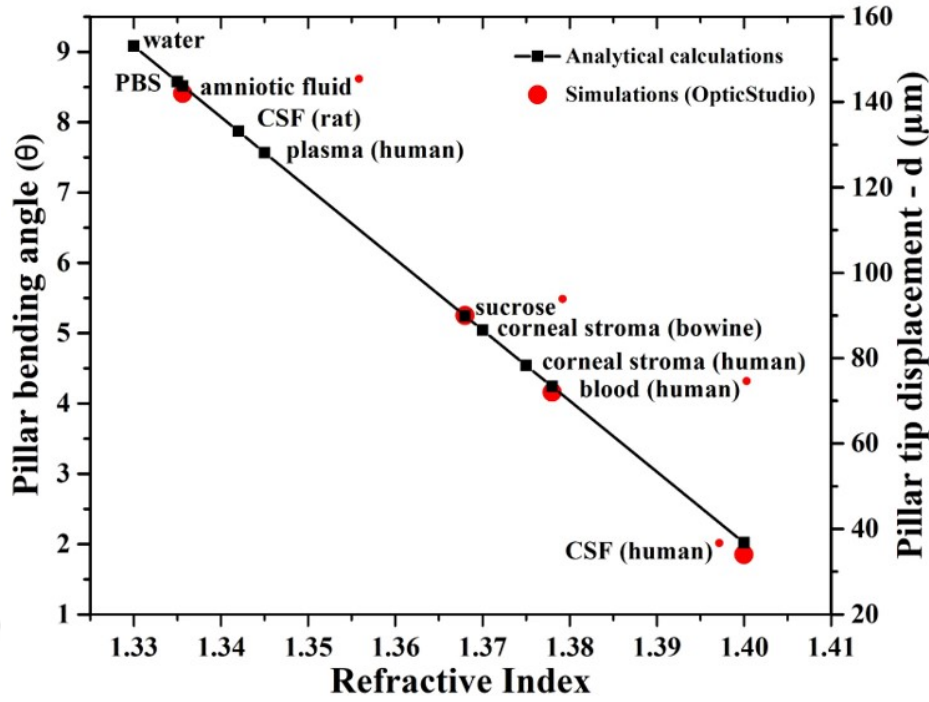


Figure 3.4 : Analytically calculated micropillar bending and micropillar tip displacement based on the refractive index, compared with simulation results. Figure presents the comparative analysis between the calculated values and simulated outcomes [1].

increases, the light will begin to escape from the inside of the pillar. According to the calculation, the tip deflection of the pillar is approximately 157 μm .

The light behavior inside the micropillars was further investigated using detailed ZEMAX ray-tracing simulations. As a result of these simulations, we were able to support our mathematical models by showing that light is capable of maintaining total internal reflection within micropillars up to a certain level of bending.

In the Figure 3.5 of the thesis, these findings are presented by comparing simulation results with analytical predictions, thus proving the accuracy and reliability of the developed models. It should be noted that color changes occur when rays are reflected or refracted by the simulation software. In ray tracing simulations for the water environment, light was confirmed to travel fully within the micropillar at bending up to 150 μm (Figure 3.5 a), which matches our analytical calculation mentioned above.

To overcome the challenge posed by different refractive indices of different fluids, we extended our calculations by using different refractive indices of different fluids

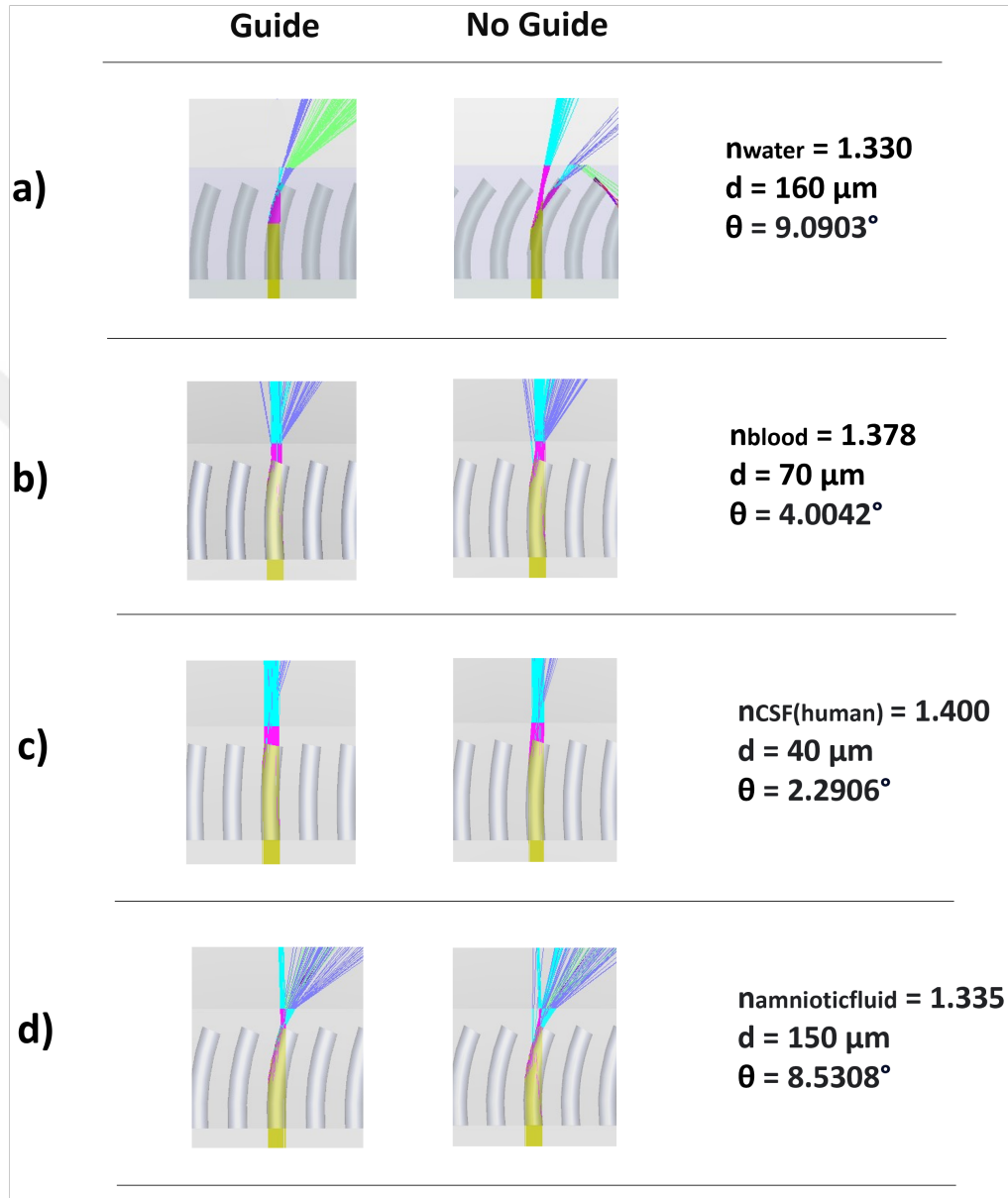


Figure 3.5 : Ray tracing simulation screenshots.

obtained from the literature to calculate the critical angles for total internal reflection. In Figure 3.4 we plot analytical calculation results compared with ray tracing simulations for the maximum bending, i.e., maximum pillar tip displacement, possible with a list of biological fluids with different refractive indices; samples belong to water, PBS (phosphate-buffered saline) [89], amniotic fluid [90], CSF (cerebrospinal fluid) (rat and human) [91], plasma (human) [92], sucrose [93], corneal stroma (bovine and human) [94], blood (human) [95]. Additionally, screenshots of what the pillar inflection point at the total internal reflection limit looks like in the ray tracing simulation for selected biological liquids are also shared in Figure 3.5.

3.4 Discussion on Computational Efficiency

One issue of concern is evaluating the computational efficiency of the optical knife-edge micropillar tip bending reading system, especially when compared to CMOS camera-based methods more commonly used in microfluidic devices. This comparison is critical as it directly impacts the practical deployment of these technologies in real-world applications, especially in point-of-care (POC) environments where speed, accuracy, and equipment cost are important factors.

By its nature, the optical knife-edge reading method uses a photodiode as the primary detection element, capable of operating at very high frequencies with bandwidths of megahertz or higher. High speed operation allows the system to provide output data in sub-microsecond time intervals, making it extremely suitable for applications where rapid viscosity measurement is required. Photodetector provides fast response time, allowing liquid properties to be monitored and analyzed in real-time. In dynamic environments, such as biomedical applications or chemical reactions, this is advantageous.

In contrast, CMOS cameras often used in similar applications operate at significantly lower speeds, typically ranging from 30 to 60 frames per second (fps). This lower speed results in a much slower data collection rate; this can be a limiting factor in rapid experimental setups or clinical settings where rapid decision making is important. Additionally, CMOS cameras require complex image processing algorithms, such as the Hough Transform for circle-fitting, to analyze captured images. These algorithms

are computationally intensive and require significant processing power that is not readily available in compact, portable POC devices.

CMOS cameras generate a lot of computational demands in order to operate and process their data, which is significantly higher than the computational requirements of photodetector systems. Due to the time required to process and analyze the data, relying on advanced image processing algorithms can provide a second stage of temporal resolution. The delay can be critical and possibly affect the outcome and reliability of experiments or diagnostic tests in the process of being conducted. Based on the above characteristics, the use of a photodiode-based technique not only enhances operating efficiency but also greatly decreases the complexity and expense of hardware installation. By streamlining the process of collecting and analyzing data for various applications, such as healthcare diagnostics, environmental monitoring, and quality control in industrial processes, we can provide a more efficient and cost-effective solution for measuring viscosity. This will lead to a solution that is both more economical and efficient. It is a good idea to include the system in portable diagnostic devices used in point-of-care medical applications because it can make quick and accurate measurements with little computing and power needs.



4. CONCLUSIONS

4.1 Concluding Remarks

The purpose of this thesis has been to explore the application and efficacy of optical knife-edge detection technology within a micropillar-based microfluidic viscometer. Viscosity measurements are crucial to a multitude of scientific and industrial applications, which are made possible by this innovative approach that utilizes precision optical manipulations and measurements.

Our research introduced a method that uses laser light coupled to a single micropillar within a microfluidic chip, where the displaced (caused by flow) light output at the far end of the pillar causing flow is captured by a single photodetector. Optical setup not only increases the sensitivity of detection but also simplifies the overall system design by eliminating the need for more complex and bulky imaging equipment. Detailed analytical discussions are presented on optimal positioning of the photodetector and sizing of the light beam to maximize sensitivity and minimize cross-coupling effects between adjacent pillars. Presented analytical models supported by detailed ray tracing simulations; these simulations provided deeper insights into the effectiveness of knife-edge detection in capturing subtle changes in light behavior resulting from pillar bending. These simulations helped identify and reduce potential discrepancies between expected and observed results resulting from deviations in the light intensity profile, particularly when the pillars are bent. Our experimental validations, performed under both air and fluid flow conditions, tightly supported the theoretical and simulation-based predictions. Optical knife-edge measurements obtained from the photodiode system have consistently demonstrated its reliability and the robustness of the method across different conditions.

A comparison between proposed method and CMOS camera-based detection systems revealed that the optical knife-edge method has many important advantages over

CMOS-based methods. Particularly, the use of single pixel photodiode, which cost much less than CMOS cameras, not only reduces the financial burden but also offers a compact form factor of mm^3 rather than cm^3 , which is ideal for integration into POC devices. Adopting a single photodiode has the advantage in terms of cost, being \$ 1-10 compared to hundreds of \$ for a CMOS camera. Another advantage of photodiode is reduced computational overhead; enabling microsecond-level data acquisition steps as opposed to 1 s duration required to compute the pillar positions based on CMOS camera frames. This is a significant improvement over the lengthy calculations required by CMOS-based systems.

4.2 Future Works

The presented research proposes a new method for viscosity detection. It is based on solving the challenges of optical detection of viscosity. The proposed method provides a new perspective on the effectiveness of the optical knife edge method in microfluidic applications while also highlighting its broader application potential in industries requiring precise liquid analysis.

There are multiple ideas proposed for the next phase of optical detection for micropillar bending detection; 1- A study for which we have a patent application, by connecting the light beam to more than one micropillar separately and simultaneously, with a complex lens system, the optical power coming out of all the pillars can be read, similar to the proposed method (the applied patent involves mounting a fiber cable to each pillar separately and (It also includes different studies such as changing the light source), 2- In addition to the micropillars that are monitored vertically with the camera in the current method, images of the micropillars will be taken in a synchronized time interval in order to calculate the pillar bending angles, with a camera system that will be added to the optical setup and whose pillars will be monitored horizontally. While circle detection and region tracking algorithms will be used to analyze top view images, Fast Fourier Transform (FFT) will be used to analyze side view images and it will be shown that the FFT-based approach reduces the calculation time for the same frames.

Future work should enable the conversion of a microfluidic system into a micro-viscometer by miniaturizing the design, increasing its sensitivity, and expanding

its applicability to a wider range of liquids. In the line with these goals, they provide more compact, cost-effective, and versatile solutions for real-time liquid property analysis.





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- **E. Şentürk**, C. Köksal, A. C. Erten, O. Ferhanoğlu, “A PDMS Micropillar Waveguide-based Microfluidic Viscosity Sensor” *International Conference on Optical MEMS and Nanophotonics, 2024 (OMN 2024)*
- **E. Şentürk**, C. Köksal, A. C. Erten, O. Ferhanoğlu, “Optical Knife-Edge Detection for Micropillar-based Microfluidic Viscometer” *Sensors and Actuators A: Physical*, doi: 10.1016/j.sna.2024.115226, 2024

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- I. Jafari, **E. Şentürk**, C. Köksal, O. Ferhanoğlu, A. C. Erten, “FFT-Based Viscosity Sensing for a Micropillar-Based Microfluidic Chip” *International Conference on Sensor, Detector, Materials Science and Technologies, 2023 (SensTech 2023)*
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