Custom chromatic confocal microscope for surface profilometry

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Summary

In this work, a surface profiling system is introduced, employing a custom-designed chromatic confocal (CC) distance sensor. Today's commercial sensors based on the CC principle have a major drawback of effectively coupling light from the illumination source into the optical imaging system, mainly due to etendue mismatch. Consequently, a substantial amount of light is lost, significantly reducing the overall SNR of the system. This limitation restricts its applicability primarily to highly reflective surfaces. To address this issue, an etendue-matched optical system is proposed, that incorporates an innovative superluminescent light source. Through this approach, the system achieves 4 orders of magnitudes higher illumination intensity concentrated within the focus spot compared to existing devices in the current market.

Keywords: chromatic confocal microscope, surface profiling, etendue, superluminescent diode (SLD)

Egyedi kromatikus konfokális mikroszkóp felületi profilometriához

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Összefoglalás

Korunk egyik legmeghatározóbb fejlődését a mikroelektronikai és nanotechnológia terén értük el. Könnyedén hozunk létre mikronos tartományban ellenőrzött struktúrákat, melyek segítségével javíthatjuk felületek fizikai tulajdonságait, mint például érdesség, nedvesíthetőség, vagy akár a Fresnel-reflexió csökkentése optikai felületeken. Mint minden gyártási folyamat, a mikronos tartományban történő technológiai lépések során is elengedhetetlen a minőség-ellenőrzés, a folyamat monitorozása. Erre a célra olyan precíz mérőberendezésekre van szükség, melyek gyorsan, roncsolásmentesen képesek információt szolgáltatni a munkadarab kérdéses tulajdonságairól, mint például felületi érdesség, 3D-topográfia vagy a felvitt rétegek vastagsága.

A dolgozat célkitűzéseként szerepel egy olyan új, optikai elven működő felületprofil-mérő rendszer kidolgozása, mely lefedheti az ipar imént említett területeit, és akár új, hasonló módszerekkel eddig nem kezelhető problémákra is megoldást nyújthat. Eredményként bebizonyítjuk, hogy szuperlumineszcens fényforrás alkalmazásával jelentősen növelhető egy ilyen típusú mérőrendszer érzékenysége és jel-zaj viszonya, ezáltal felhasználható alacsony reflektivitású, erősen diffúz felületek vizsgálatára is, melyre a jelenlegi berendezések csak limitáltan alkalmasak.

A kéziratban bemutatjuk egy egyedi szuperlumineszcens forráson alapuló kromatikus konfokális mikroszkóp tervezési és megvalósítási fázisait. A kutatás első fejezetében több koncepciót hasonlítunk össze, melyek között szerepel gyári berendezések lehetséges átalakításának vizsgálata, valamint több elképzelhető optikai rendszer tervezése és elemzése számítógépes környezet segítségével. A legjobbnak ítélt koncepciót később részletesen kidolgozzuk, mely magában foglalja egy egyedi, nagy kromatikus diszperziójú, diffrakciólimitált mérőobjektív, valamint egy, a választott fényforrás hullámhossztartományán működő, egyedi felépítésű spektrométer megtervezését és legyártását. A bemutatott berendezés újdonságereje abban rejlik, hogy a teljes optikai rendszer az új típusú fényforrás méreteire és teljesítménysűrűségére optimalizált, így az iparban jelenleg alkalmazott technológiához képest négy nagyságrenddel nagyobb fényhasznosítást ér el. Ezáltal jelentősen növelhető a mintavételi sebesség, valamint olyan felületek is vizsgálhatóvá válnak, melyekről csak nagyon kis mértékben verődik vissza hasznos jel. A készülék teljes mértékben száloptikai felépítésű, mely robusztussá és flexibilissé teszi, növelve a hordozhatóságot és az egyéb kiegészítő optikai elemek, mint például az elektrooptikai teljesítményszabályozó vagy a szálcsatolók könnyű cseréjét vagy beépítését. A fejlesztett eszköz munkatávolsága meghaladja a 30 mm-t, s ez lehetővé teszi akár egy nyalábfordító tükör felrögzítését is az objektívre, ezáltal belső felületek is vizsgálhatóvá válnak. Mérési tartománya 350 µm, ezáltal a legtöbb mikronos tartományba eső felület vizsgálhatóvá válik az újrapozicionálás szükségessége nélkül, így növelhető a mérési sebesség. A laterális (térbeli) felbontás a diffrakciólimitált objektívnek köszönhetően a fényforrás 820-tól 920 nm-ig terjedő hullámhossztartományán 2 µm körül alakul, s ez elegendő a legtöbb felületi morfológia letapogatására. Axiális felbontása mikrométer alatti, valamint nagy numerikus apertúrája meredek oldalfalak (akár 60° feletti) vizsgálatát is lehetővé teszi. A mérési sebességet jelenleg az egyedi felépítésű spektrométer 12 bites CCD vonalszenzorának kiolvasási frekvenciája korlátozza, mely 51 kHz.

Kulcsszavak: kromatikus konfokális mikroszkóp, felületi profilalkotás, etendue, szuperlumineszcens dióda (SLD)

Forewords

The scientific publication of Lóránt Tibor Csőke KDP scholarship PhD student reflects the main focus of his research. In cooperation with Optimal Optik Ltd., Lóránt has developed innovative technology in the field of chromatic confocal microscopy (CCM). He developed a prototype for the next generation of future CCM requirements. The device that has been built is a complex machine combining knowledge of optical measurement, signal processing, and hardware design. His ideas led to novel discoveries and many modifications that helped to improve the precision of the CCM device. I truly recommend the publication to the attention of all professionals interested in surface measurements using chromatic confocal microscopes.

Dr. Zsolt Kollár
Associate Professor
Budapest University of Technology and Economics
Scientific Supervisor

In this paper, Lóránt Tibor Csőke PhD student introduced a novel chromatic confocal microscope (CCM) tailored for enhanced surface profilometry. This custom development focuses on overcoming the limitations of commercial CCMs, notably improving light coupling efficiency. The integration of a cutting-edge superluminescent light source with an etendue-matched optical system results in a significant increase in illumination intensity at the focus spot. This advancement not only boosts the Signal-to-Noise Ratio and measurement speed but also enables the analysis of highly absorbing, complex objects due to the microscope's extended working distance and illumination intensity. These research achievements, realized within the Budapest University of Technology and Economics (BME) Cooperative Doctoral Program, foster a more effective collaboration between academia and the competitive sector. The findings are being utilized at Optimal Optik Ltd., enhancing the company's market competitiveness in optical profilometry, and representing a significant leap in precision measurement.

Dr. László Domján
CEO at Optimal Optik Ltd.
Industrial Supervisor

Introduction

Since the invention of the confocal imaging principle in 1961 by Marvin Minsky, numerous applications have been developed based on the patented approach *(Marvin 1961)*. The method involves the use of a spatial filter to eliminate out-of-focus light reaching the detector, resulting in improved resolution and contrast in optical imaging *(Elliott 2020)*. Under this methodology, a novel detection method has been developed during the last decades, namely the chromatic confocal distance sensing. This way, the axial scanning motion can be omitted and replaced by wavelength encoding the distance along the optical axis *(Blateyron 2011)*.

The primary components of a Chromatic Confocal Microscope (CCM) consist of a broadband light source, a pinhole aperture, a confocal objective with high chromatic aberration, and a spectrometer *(Merchant et al. 2005)*. In simple monochromatic confocal systems, obtaining a 3D surface profile requires axial and lateral scanning *(Elliott 2020)*. For high-resolution quality data and precision actuator stages are required that have a low self-vibration, non-linearity, and hysteresis *(Chen–Chen 2023)* This method is therefore time-consuming, and only applicable for fixed samples containing expensive moving parts. A significant improvement of this principle was achieved by utilizing the effect of chromatic aberration and using a broadband light source instead of monochromatic illumination. In this configuration, the chromatic aberration of the objective lens disperses the broadband light of the illumination source, forming an axially extended focus point per wavelength along the optical axis *(Blateyron 2011)*. This way, the axial scanning process can be omitted and replaced by focus-wavelength encoding of the distance. The principle is depicted in *Figure 1*.

A key component of a CCM is the broadband light source. Given that most of these devices are constructed with fiber optics for their robustness and flexibility, it is imperative to effectively couple the emitter to the fiber optic system. A commonly used light source is a white Light Emitting Diode (LED), which is a desirable choice considering the price, accessibility, lifetime, and ease of

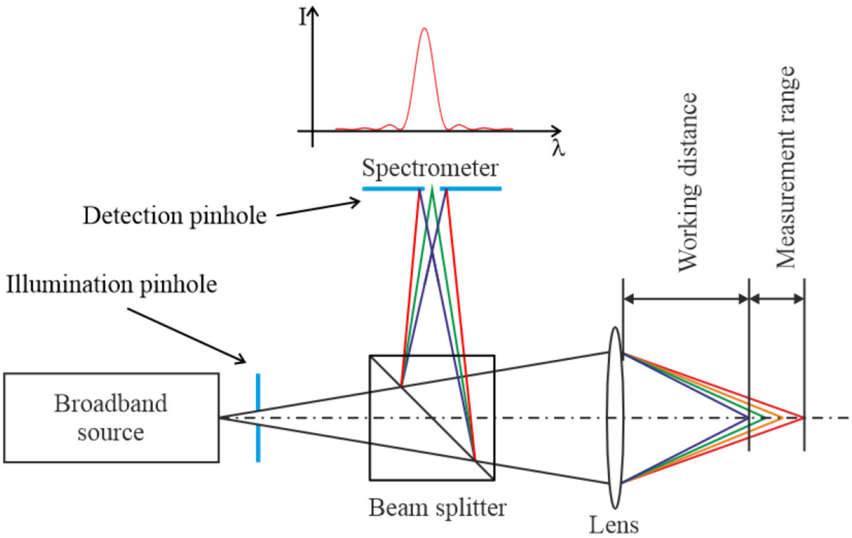

Figure 1 Focus-wavelength encoding principle of a chromatic confocal microscope

Source: Own work

handling. However, taking the average emitter size of an LED into consideration compared to the entrance pupil size of such an optical system, we can experience differences of several orders of magnitude. (Presuming that the emitter size of an LED falls within the square millimeter (mm^2) range, whereas the entrance pupil size of such high-aperture focusing systems is in the micrometer (µm) range *(Polytec GmbH. 2016)*.) Quantified, the irradiance in the focal spot of a commercial CCM is expected to be in the microwatt domain. Losses on optical interfaces, internal reflections, and losses caused by the reflectivity and tilt of the examined surface are also added to the already low light output. If the sample is highly reflective and the probe orientation is close to perpendicular, the reflected light is gathered by the objective lens with minimal losses, resulting in a high Signal-to-Noise Ratio (SNR). The SNR is defined as a ratio of the intensity of the reflected peak wavelength signal and the variance of the noise present in the full spectral bandwidth of the measured signal. If any of these parameters are deterred from the optimal conditions, the signal will decrease notably. This scenario can often occur in the case of samples with high surface roughness, where the light is absorbed or scattered *away (Hillenbrand et al. 2014)*.

To address this issue either the power density of the source or the light-gathering capability of the optical system must be increased. Since the boundaries of the design parameters of the optical system are quite narrow, if a high lateral resolution is expected (small, diffraction-limited focus spot) then the only solution is to match the emitter size to the optical systems etendue. There are some notable research efforts put into finding a solution for this problem, however, as of now, none of them are ready on the market. A novel method for detecting wavelengths, as described by *Taejoong et al. (2013)* allows for instantaneously acquiring depth information. This is achieved by analyzing the ratio of intensity signals, which are separated by a color filter and detected by two photomultiplier tubes. While the concept is innovative, the system's performance, boasting a 100 µm measurement range and over 1 µm axial accuracy, does not measure up to our solution. It is important to note that the reflected signal intensity can fluctuate rapidly during scanning due to surface roughness and variations in reflectivity. Despite the photomultiplier tubes having a dynamic range capable of spanning several orders of magnitudes, adjusting the control voltage is essential to prevent detector saturation, which would otherwise lead to extended recovery times. Settling times are prolonged due to slow changes in acceleration voltage, often taking many hundreds of milliseconds or even seconds, which would significantly reduce the measurement speed *(Hamamatsu – PMTs 2023)*. Unfortunately, the work does not provide specific data regarding the achieved scanning speed.

Kebin et al. (2004) present a closely related solution to our work by using supercontinuum light as illumination. In the setup, a femtosecond laser pulse is coupled to a photonic crystal fiber, resulting in supercontinuum radiation. This extremely broadband light is then used in a chromatic confocal system composed of off-the-shelf components. While this work does not specify the exact measurement speeds, the conclusion drawn is that the illumination efficiency is improved by 1000 times compared to a conventional light source-based system. Despite the promising concept, the generation of supercontinuum radiation remains highly expensive (30–50,000 USD), even with recent technological advancements, primarily due to the requirement for a femtosecond laser system *(RP Photonics 2023)*. Additionally, various parameters, such as the 7 µm effective depth scanning range, fall significantly below the performance of our system. Most recent research advancements primarily concentrate on one-step 3D acquisition employing multi-point techniques *(Chen–Chen 2023; Fuerst et al. 2020; Hillenbrand et al. 2015)*. In contrast, there is less focus on increasing illumination efficiency, even though this remains a pressing issue, especially for sensors operating at multiple points.

In this study, we explore potential methods for enhancing the light efficiency of a commercial system. Subsequently, we introduce a customized optical configuration, specifically optimized for a novel type light source, a SuperLuminescent Diode (SLD). This way, we intend to improve light efficiency of a CCM system by orders of magnitudes to extend its application areas where low light intensity is not eligible. The primary objective was to achieve a broad measurement range of at least 300 µm and a spot size limited by diffraction through the design of a customized optical system, while also ensuring measurement speeds above 10 kHz. Although the cost of a SLD is comparable to the total expense of the remaining optical system, it remains significantly more affordable than a supercontinuum source with the price around 5,000 USD *(Thorlabs - SLD880)*. Despite the promising advancements, a drawback remains: currently available broadband SLDs are only accessible in the near-infrared (NIR) wavelength range. This limitation constrains the diffraction-limited spot size, in accordance with the Rayleigh criteria, to approximately 2.5 µm. Another drawback of utilizing an SLD as a light source is its high sensitivity to back reflections. This sensitivity arises from the high gain in the active region, leading to instability and the sudden appearance of resonance peaks in its spectrum, which leads to measurement errors. In the next phase of the research, we are focusing on addressing this issue by inserting a polarization independent optical isolator to prevent back reflections from optical elements reaching the SLD. An alternative approach involves constructing a reference path, where a spectrometer simultaneously measures the intrinsic spectra of the light source alongside the signal path. This enables real-time compensation of the measurement data reducing error caused by sudden fluctuations of the reference spectrum.

The paper is divided into two main sections as follows: The first section comprises two subsections. In the first subsection we investigate a commercial CCM device for improving its light efficiency and the main aspects of selecting a suitable external light source will be explained. In the second subsection the design steps of a custom optical system are described. Experiments presented in the second paragraph aim to prove the capabilities of the proposed system. Conclusively, we draw final remarks and discuss potential implications for future research.

Research on enhancing light efficiency

In this study, the enhancement of light efficiency in a chromatic confocal microscope will be examined. The section aims to identify the best-suited light source that

Figure 2 The Polytec CCS Prima commercial confocal sensor, equipped with an optical fiber for external supply of illumination

Source: Own work

can optimize the performance of the microscope hoping for clearer and more efficient imaging results. In the theoretical study, the light utilization and resulting signal strength of a commercial CCM (Polytec CCS Prima, Polytec GmbH.) are calculated analytically and compared with measurement data. The actual system undertaken in measurements is depicted in *Figure 2*.

A crucial aspect of an optical illumination system is its capacity for collecting or emitting light, known as etendue. The etendue describes mathematically, that the product of the emitter size (A) and the emitting solid angle (Ω) is conserved throughout the optical system *(Lerner–Dahlgrenn 2006)*:

$$A\Omega \leq A'\Omega' \quad (1)$$

The etendue G can be expressed with the numerical aperture as follows:

$$G = \pi * S * NA^2 \quad (2)$$

where S is the size of the emitting surface and NA is the numerical aperture of an optical system defined as:

$$NA = n * \sin(\theta) \quad (3)$$

immersed in a medium with refractive index n and an acceptance or emitting cone half-angle of θ. Taking this into consideration, it is easy to see that if there are orders of magnitudes in difference of the emitter size while the angle is limited at maximal 90° incidence, then according to (1) and (2) the etendue must significantly decrease as well *(Markvart 2007)*. As a result, the coupling efficiency deteriorates dramatically.

Based on the equations above, we estimated the resulting light output power in the focus spot of the Polytec sensor equipped with the CL2 optical pen and the MG210 magnifier adapter *(Polytec GmbH. 2016)*. The key optical parameters of the commercial system are summarized in *Table 1*.

Table 1 | Key optical parameters of the Polytec CCS Prima

Measuring range [µm]	400
Working distance [mm]	10.8
Max. sample slope [deg]	±28
Spot size [µm]	.0
Lateral resolution [µm]	1.7
Numerical aperture	0.46
Static noise [nm]	17
Fiber optic cable	50/125 µm

Source: Polytec Datasheet

The coupling efficiency (η) can be estimated based on the etendue ratio of the emitter (G_e) and the optical pen (G_{op}) as follows *(Shatz et al. 2010)*:

$$\eta \approx G_{op}/G_e \tag{4}$$

If we assume that a typical high-power white LED is used as the built-in light source of the device, with an emitter size of 1×1 mm² and a typical total included angle of 90°, then the coupling efficiency is approximated to be around 10^{-6} *(Lumileds 2021)*. This results in an expected optical power of 0.1µW confined into the focus spot.

To assess whether the signal strength of the commercial system could be enhanced using external sources, two fiber-coupled emitters were chosen for the test configurations:

- Albalux FM: A laser excited phosphor, white light module from Laser Components, with a luminous output of 150 lm (~1.5 W) out of 1 mm, 0.63 NA fiber *(Laser Components GmbH. 2021)*.
- MCWHF2: A high-power fiber-coupled LED from Thorlabs, with a nominal output power of 27 mW for a multimode fiber of Ø400 µm core and 0.39 NA *(Thorlabs – MCWHF2 Datasheet 2016)*

The expected coupling efficiencies and intensity improvements were calculated as described earlier and compared with measured values in *Table 2* and *Table 3*. The measurements were made with a Coherent FieldMaxII-TO power meter having a calibration uncertainty of ±1% and a display accuracy of ±2% *(Edmund Optics 2023)*. All measurements were performed in an optical

Table 2 | Estimated output optical power of the commercial system

Configuration	Estimated coupling efficiency [*E-6]	Estimated optical power output [µW]	Calculated power improvement
Built-in LED	0.79	0.79	1x
Thorlabs MCWHF2	141	3.82	4.8x
Albalux FM	8	12.04	15.2x

Source: Own work

Table 3 | Measured optical power output of the commercial system

Configuration	Measured optical power input [mW]	Measured output optical power output [µW]	Resulting coupling efficiency [*E-6]	Resulting power improvement
Built-in LED	40	0.07	1.75	1x
Thorlabs MCWHF2	25	0.116	8.92	1.65x
Albalux FM	24	0.33	13.8	4.7x

Source: Own work

dark room at 22 °C and 35% RH. The input optical power is defined as the optical power measured at the input fiber end with 400 µm core diameter and 0.39 NA.

Since the calculations are coarse and do not take other optical losses into account, the measured values slightly differ from the theoretical ones. Nevertheless, the magnitude and proportions align well with the theory. Even under optimal conditions, the observed increase in intensity was only 4.7 times compared to the scenario with the built-in LED. The reflected signal strength was measured and compared in various scenarios. In this

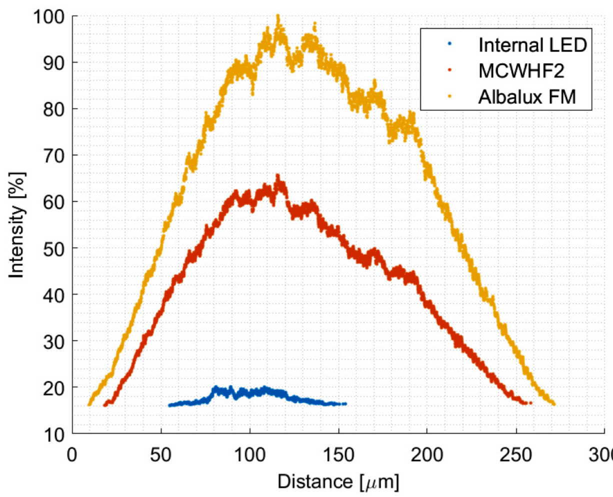

Figure 3 | Measured signal strength of the commercial probe using external light sources. The curve for the internal LED does not extend across the entire measurement range, as the reflected signal strength was insufficient for evaluation

Source: Own work

configuration, the confocal probe was placed above a glass block, that was moved axially throughout the entire focus range of the device. The measured relative intensity was logged and plotted against the corresponding measured distance in *Figure 3*. The ratio of the maximum of the signals in each case aligns well with the theory.

Based on the calculations and measurement results we can conclude that the SNR of a commercial CCM system cannot be increased significantly by driving it from higher power external light sources. The power density of the emitter must be increased significantly by reducing the size of the emitting surface by orders of magnitudes compared to that of the conventional illuminators. This results in reducing the etendue and thereby significantly improving the coupling efficiency.

Design of a custom optical system

Fundamental considerations in the optical design of chromatic confocal objectives for infrared light sources

The primary finding from the experiments and calculations outlined in the preceding section is that the sole viable approach to enhance the system's light efficiency is by increasing the power density of the emitter by reducing its emission surface. A novel superluminescent source identified for addressing these issues in the system presents a cutting-edge solution with several notable advantages. Unlike conventional light sources, SLDs combine the broad spectral bandwidth of LEDs with the coherence properties approaching those of lasers, making them ideal for applications requiring both high brightness and spectral versatility *(Perlin et al. 2019)*. One key feature of SLDs is their extreme power density, a crucial factor in improving the overall light efficiency of the system. Furthermore, the broad spectral characteristics are advantageous for applications like chromatic confocal microscopy *(Thorlabs – NIR-SLDs 2023)*. The section will describe the design process of an optical configuration designed especially for an SLD and compare its parameters against those of the commercial device.

To increase the SNR of a CCM by several orders of magnitudes, a broadband fiber coupled light source is required, with an emission power in the range of 10 mW. The optimal fiber diameter should be below 50 μm and the fiber numerical aperture must be less than 0.2 NA. Unfortunately, light sources found satisfactory for these criteria usually emit radiation in the Near-InfraRed (NIR) domain, especially in the 700–1200 nm spectral region. This makes it impossible to use in CCMs designed for visible wavelengths. As a result of comprehensive research on the market for SLDs, a suitable device has been found for our requirements: the SLD880S from Thorlabs Inc. *(Thorlabs – SLD880 Datasheet 2018)*. To use it in the chromatic confocal system, we must emphasize two significant issues:

- The radiation spectra of this device predominantly resided in the NIR region, making it unsuitable for use in existing systems designed for visible wavelengths.
- The practical bandwidth of the emission spectra is narrower compared to conventional emitters in the visible range, resulting in a reduced measurement range.

To address these issues, we decided to design new optical systems and objective lenses, that are optimized for the emission properties of the chosen SLD model. The main objectives of designing custom optics for a novel SLD based CCM can be summarized as follows:

- Ensuring proper working distance (30–40 mm)
- Ensuring a measuring range of 300–400 μm
- Delivered optical power output into the focus spot must be in the mW range.
- Diffraction limited Point Spread Function (PSF) in the selected wavelength range.
- Adaptations to the specifications of the selected higher brightness light source (wavelength range, optical fiber coupling, etc.).

Designing of novel optical lenses for use with SLDs

This chapter outlines the design process for innovative objectives tailored to SLD light sources. The wavelength range used in the designs is approximately the 20 dB bandwidth of the SLD880S, which extends from 830 nm to 940nm according to the datasheet. The rationale behind this choice is that a standard Charge-Coupled Device (CCD) detector employed in the spectrometer typically possesses a dynamic range of 40–50 dB. This range comfortably accommodates the bandwidth without necessitating adjustments to the exposure time or gain. The emission power of the selected device in this spectral range is 25 mW out of a single-mode optical fiber with a diameter of 4.4 μm numerical aperture of 0.13 NA. During the optical design, we separated our methods according to two significant aspects:

- Design with stock lenses
- Design with custom lenses

In the case of designing with stock lenses, the time to market can be reduced and the manufacturing costs of custom optical elements are avoided, therefore we first considered this approach. The spectral bandwidth of SLDs is usually narrower than that of the broadband visible emitters, which results in a shorter measurement range. We had to implement a strategy to increase the working range of the objectives. One approach for resolving this issue involves introducing additional internal image planes into the optical system. Between the fiber coupling lens group and focusing objectives, we form one or two inner image surfaces (inner focal point). This internal image can in principle be easily realized with two identical lenses facing each other. The wavelength-de-

Table 4 Resulting parameters of the designed objectives from stock lenses

Configuration	Img. space NA	Strehl ratio	Theoretical coupling efficiency	Working distance [mm]	Measurement range [µm]
Single int. img. plane	0.39	0.996	1	17.31	188
Dual int. img. plane	0.41	0.995	1	18.27	350

Source: Own work

pendent focus shift of the stock aspheric lenses facing each other adds up (see curves a and b in *Figure 5*). With two consecutive inverted systems, two internal image planes can be realized. In this case, the focus shift is about the fourth time that of the single lens group. The 2D layout of the proposed multi-image plane objectives is depicted in *Figure 4*. Both suggested designs were evaluated to meet the previously listed criteria in their respective parameters. The value of the Strehl ratio listed in Table 4 indicates that the system can be considered diffraction-limited. The Strehl ratio is defined as the ratio of the peak intensity of the PSF of an optical system to the peak intensity of an ideal diffraction-limited optical system under the same conditions *(Ottevaere–Thienpont 2005)*. In simpler terms, it represents how close the actual optical system comes to achieving the theoretical limit of perfect focus.

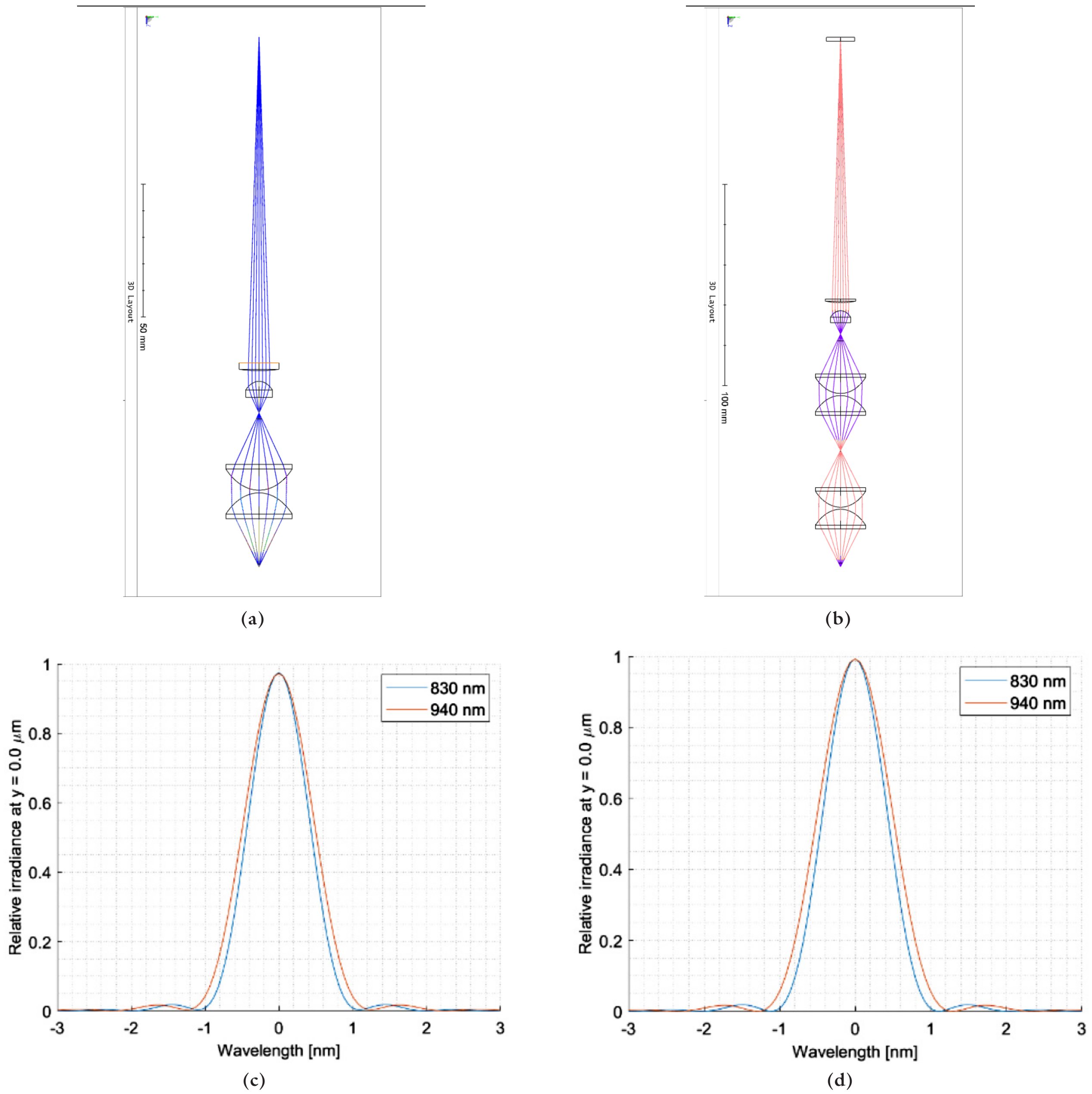

Figure 4 2D layout of custom optical designs with (a) single and (b) dual internal image planes with the corresponding PSFs (c) single, (d) dual

Source: Own work

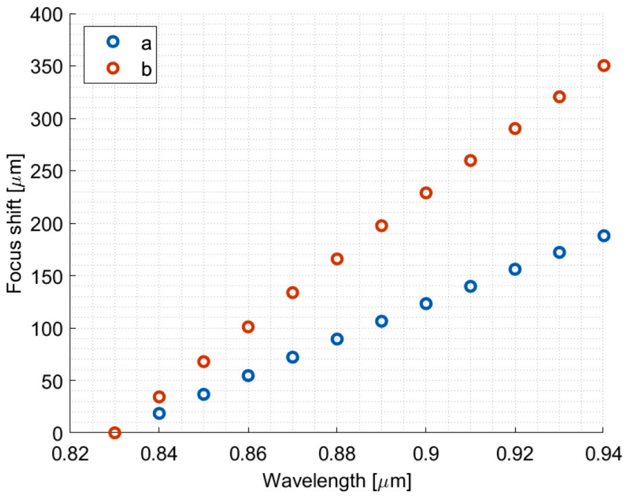

Figure 5 Dispersion curves of the designed objectives from stock lenses with (a) single and (b) dual internal image planes. The achieved measurement ranges are 188 µm and 350 µm, respectively

Source: Own work

Unfortunately, a major drawback of these concepts has been found during the design period. Despite all the advantages of using stock lenses, the tolerance analysis showed that the largest challenge for the realization of confocal objectives with internal image planes is the tight fabrication and assembling tolerances. The most critical permissible variances are highlighted in *Figure 6:*

- ±0.01 mm distance tolerances at the two side of the internal image planes
- ±0.02 mm decenters and tilt tolerances of the aspherical surfaces

Consequently, we had to redesign the system with another approach by using custom lenses. This way, the control over the system parameters is more flexible, allowing easier optimization of the design to fit the listed requirements. In this scenario, no internal image plane is formed, the required focus range is set among the optimization criteria. The object space field and numerical aperture are constrained to match the parameters of the light source's optical fiber. The system designed and finally manufactured this way consists of three custom spherical lenses and a catalog asphere. Its schematic depicted in *Figure 7.* shows the arrangement of the custom spherical lenses.

Table 5 Achieved parameters with the custom lens design

Object space NA	Img. space NA	Theoretical coupling efficiency	Working distance [mm]	Measurement range [µm]
0.13	0.39	1	32.64	356

Source: Own work

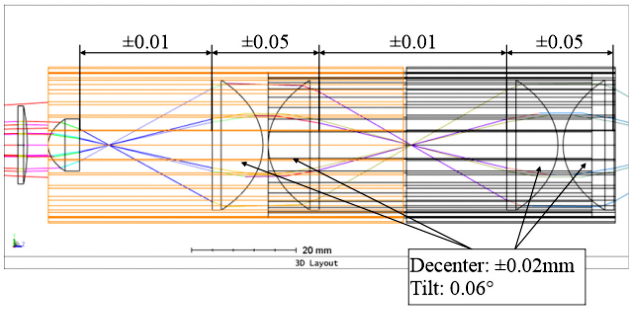

Figure 6 Critical tolerances in the dual image plane confocal objective design

Source: Own work

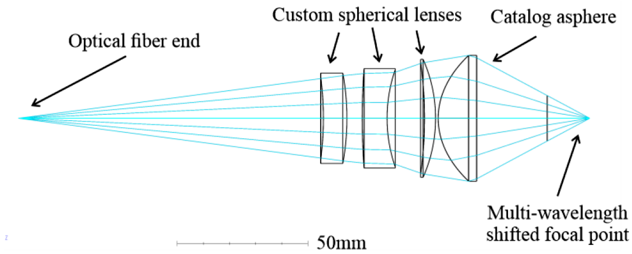

Figure 7 The structure of the completed custom objective lens system

Source: Own work

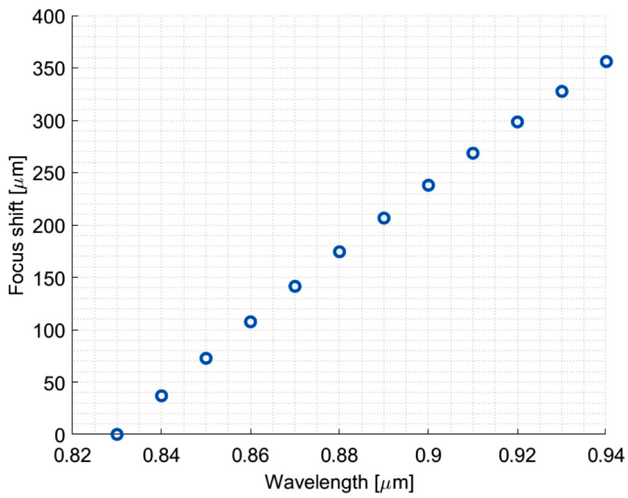

Figure 8 Calculated dispersion curve of the objective with custom lenses

Source: Own work

The resulting parameters are listed in *Table 5.* As with the previous designs, this arrangement also satisfies the criteria for diffraction limit with a Strehl ratio of 0.97. The achieved dispersion curve is depicted in *Figure 8.*

The design was deemed suitable for production. Under the experimental section its parameters are verified with actual measurements. In the next paragraph, one of the key elements of the apparatus, the spectrometer designed for the infrared wavelength range, will be presented. Due to the constraints of the current manu-

Table 6 | Parameter table of 3 possible line scan camera models

Model	Resolution	Pixel size	Line rate	Interface	Pixel depth
Basler raL2048-48gm	2048 x 1	7 μm x 7 μm	51kHz	GigE	8/12 bits
Teledyne DalsaLA-GM-02K08A-00-R	2048 x 1	7.04 μm x 7.04 μm	52kHz	GigE	8/12 bits
ContrasTech Mars2048-L51gm	2048 x 1	10 μm x 10 μm	51kHz	GigE	8/10 bits

Source: Basler, Teledyne, Contrastech

script's length, we will not delve into the necessary signal processing steps; however, they are essential for the operation of the system.

Designing of a custom spectrometer

The sampling speed and the wavelength range of the commercial system's spectrometer are not designed to operate with the parameters of the SLD. The measuring speed limit of the purchased POLYTEC spectrometer and evaluation electronic is only 2000Hz *(Polytec GmbH. 2016)*. This speed is like the other spectrometers on the market. For much faster measurements (shorter exposure time) we must develop a custom spectrometer with custom optics and electronics. In this chapter, we show the optical system of the custom spectrometer. During the design, we use "Off the Shelf" lenses. *Figure 9* shows the draft drawing of the optical system. The image plane spot diagram of the F = 100 mm focusing lens system is depicted in *Figure 10.*

From a resolution standpoint, we compared two optical systems. In the first configuration, the focusing lens has a focal length (F) of 42 mm, while in the second case, the focal length is 100 mm. Although the spot size for F = 42 mm is smaller, the proximity of different wavelengths is more pronounced. Assuming rectangular detector pixels of size 7 μm × 7 μm, we investigated which lens separates spots better with two closely spaced wavelengths on the detector's surface. Extended Sources Enclosed Energy curves were computed for both systems to compare their performance. Based on the simu-

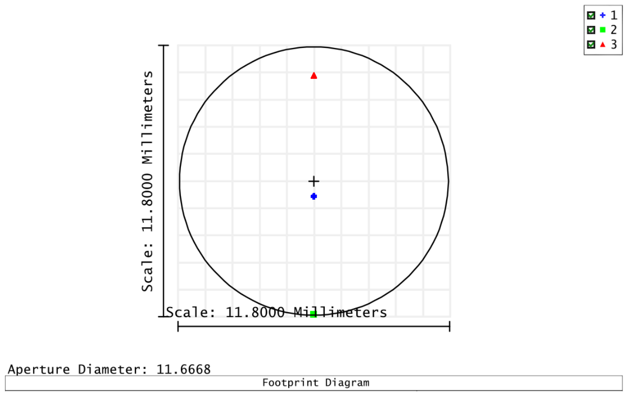

Figure 10 | Image surface of the custom spectrometer with F = 100 mm achromat Wavelengths: 0.92 μm green dots, 0.88 μm blue dots, 0.84 μm red dots

Source: Own work

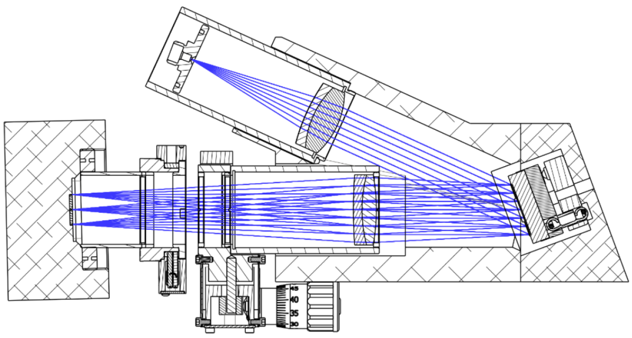

Figure 11 | Mechanical cross section of the proposed IR-spectrometer

Source: Own work

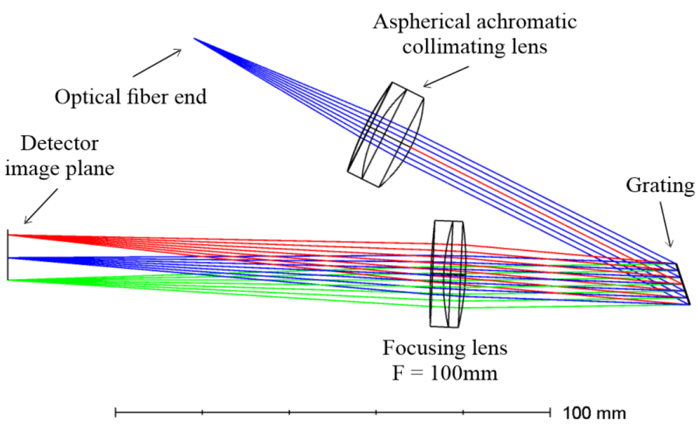

Figure 9 | Schematic of the optical system with F = 100 mm achromatic lens. Wavelengths: 0.92 μm green lines, 0.88 μm blue lines, 0.84 μm red lines

Source: Own work

Figure 12 | ContrasTechMars2048-L51gm camera model

Source: Contrastech

lations, the lens system with a longer focal length appeared to be more suitable for realization.

The mechanical design of the spectrometer body can be seen in *Figure 11*. The body holding the optical elements is 3D printed, which allows rapid prototyping and evaluation. All the other optical elements like the lens holder tubes, the grating, and the focusing mechanism are stock items from Thorlabs Inc. The fully assembled spectrometer is depicted in *Figure 16*.

A line scan camera is used as the detector in the custom spectrometer design. We compared 3 models available on the market based on the parameters listed in *Table 6*.

The choice was on the ContrasTech camera, because a higher percentage of light can be focused on a 10 µm × 10 µm pixel than on a 7 µm × 7 µm and adjusting the optical system is also easier with a larger pixel size.

The image of the chosen model is depicted in *Fig. 12*.

Experiments and evaluation

Utilizing the designed optical arrangements, a prototype system was constructed as depicted in *Figure 15*. Subsequently, the characterization of this system is undertaken. The optical scanning head is mounted on the vertical stage (Newport M-IMS100V), which could move the scanning head vertically above a sample holder. The practical measurement range of the proposed objective was evaluated by moving the lens assembly above a mirror along the optical axis, covering the entire focus range. The recorded dispersion curve (a) and the fitting error of a parabolic curve (b) is depicted in *Figure 13*. The results confirm a measurement range of almost 350 µm, which aligns well with the target value of 356 µm. *Figure 14* illustrates the spectral response curves obtained during the calibration of the measurement range for the custom system.

The output power was measured in the focus spot with the same optical power meter used in the measurement of the commercial system. The irradiance in the

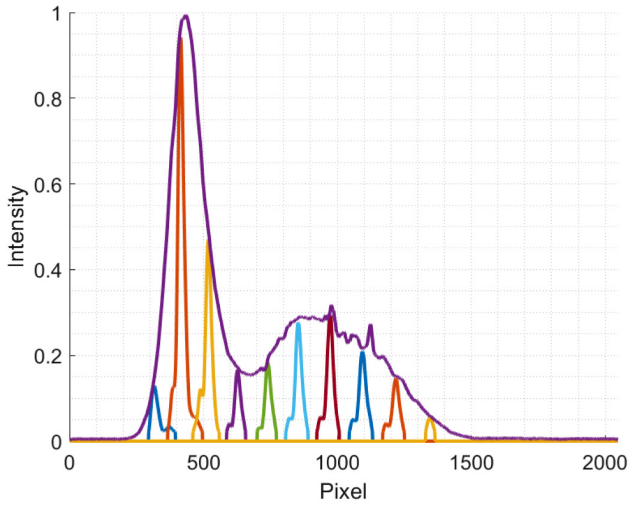

Figure 14 | Spectral response curves of the design system acquired at different focusing distances. The spectrum envelope of the SLD is also plotted for reference

Source: Own work

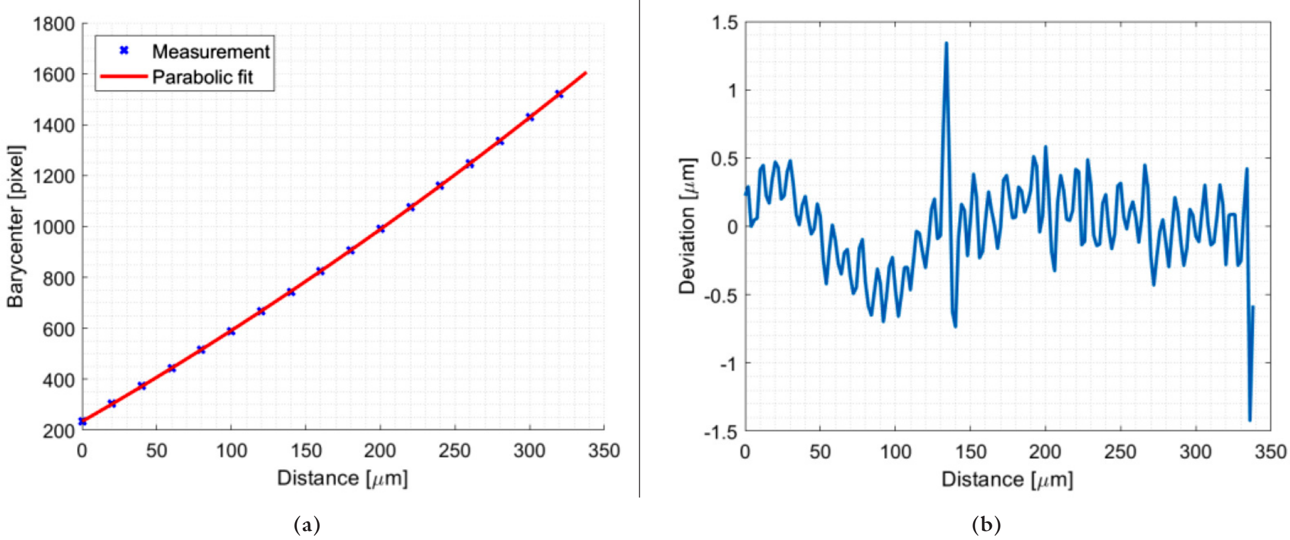

Figure 13 | Measured dispersion curve (a) and fitting error (b)

Source: Own work

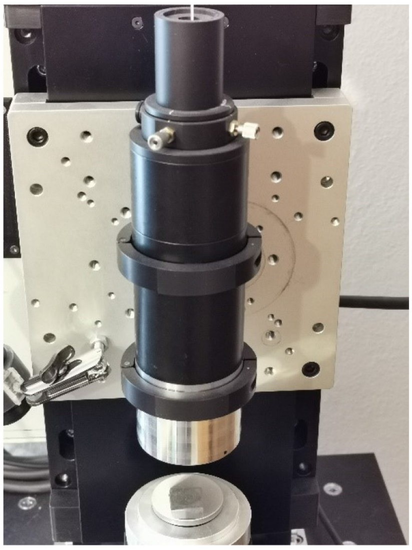

Figure 15 The manufactured optical head, attached to the vertical actuator stage. Below the confocal probe the test mirror on the sample holder can be seen

Source: Own work

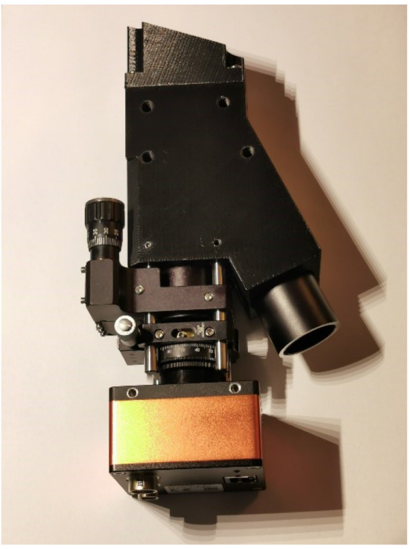

Figure 16 The realized custom spectrometer. The line scan camera can be recognized easily in the bottom of the image

Source: Own work

focus spot of the actual system was measured as 5 mW. The output optical power at the SLD's fiber end was measured as 16 mW. Considering that a 50–50% beam splitter is used, the results prove that the radiant power of the light source can be coupled into the custom optical system with minimal losses, compared to that of the commercial system. The difference can be explained by the insertion loss on the connectors of the fiber optic cables, which is typically around 0.3dB. The manufactured custom objective attached to the high-precision actuator stage and the custom spectrometer can be seen in images 1 and 2.

Conclusions and outlook

In this manuscript, we showed that current commercial chromatic confocal sensors cannot utilize efficiently the output radiant power of a conventional light source, which results in low optical power output in the focus spot. This leads to slow sampling rates, and reduced signal to noise ratio in the case of samples from highly absorbing materials or with diffuse, rough surfaces. This hinders the application of the technology in significant industrial sectors such as rubber and plastic manufacturing, ceramic production, and in situations where non-metallic and antireflective coatings are employed. To identify the underlying reason for this inefficiency, we performed calculations and assessed the coupling losses using the optical etendue theory for a standard device available in the market. In the case of a purchased instrument, we concluded that due to etendue mismatch, roughly 6 orders of magnitude of light is lost along the optical path from the emitter to the focal spot of the confocal objective. The predicted values were validated with actual measurements in three different scenarios according to the light source used:

- Internal LED
- High-power fiber coupled LED from Throlabs Inc.
- Laser-driven phosphorus ultrabright source from Laser Components GmbH.

The experimental outcomes closely corresponded to the expectations set by the theoretical background, thereby supporting our theory, that the only way to effectively improve the coupling efficiency is by increasing the optical power density (decreasing the etendue) of the light source used. Since conventional light sources like LEDs, halogen, or incandescent lamps are unable to fulfill these requirements due to their large emitter size, we had to find a special technology, that possesses an emission surface in the µm range with a small numeric aperture and has an output power in the mW range.

We conducted comprehensive research on light source technologies and found out that superluminescent sources can be appropriate for the task. These devices feature a laser-like waveguide that facilitates the emission of highly spatially coherent radiation, allowing for easy coupling into optical fibers. Simultaneously, due to suppressed feedback, they maintain low temporal coherence and moderate output power in the mW range. Upon thorough examination of the possible utilization of an SLD as an illumination source in a chromatic confocal system, we identified two significant issues:

- The radiation spectra of these devices predominantly resided in the NIR region, making them unsuitable for existing commercial systems designed for visible wavelengths.
- The practical bandwidth of the emission spectra is narrower compared to conventional emitters in the visible range, resulting in a reduced measurement range.

To resolve these issues, we decided to design a new optical system and objective lens, that is optimized for the emission properties of the chosen SLD model. The paper then presents the design steps and optimization criteria of such a system. Three different optical configurations are shown and compared based on the achievable measurement range, working distance, and complexity. The most vital construction was selected to build an actual prototype system. In the experimental section of the report, we demonstrate that the device's actual performance aligns with the design requirements, attaining a measurement range of at least 350 µm at a working distance of approximately 33 mm and exhibiting an output power of approximately 4 orders of magnitude higher than that of a commercial device.

As a potential extension of the study, we intend to explore the utilization of SLDs with shorter wavelengths possibly in the ultraviolet band. This exploration aims to reduce the diffraction-limited spot size, thereby enhancing spatial resolution. Another prospective avenue involves evaluating the applicability of the current device to materials transparent in the NIR spectra. This could enable the measurement of concealed features, such as defects within the subsurface volume of adhesives transmissive at these wavelengths, for instance.

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