Fiber-optically integrated cost-effective spectrometer for optical coherence tomography

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ABSTRACT

A tilted fiber Bragg grating (TFBG) was integrated as the dispersive element in a high performance biomedical imaging system. The spectrum emitted by the 23 mm long active region of the fiber is projected through custom designed optics consisting of a cylindrical lens for vertical beam collimation and successively by an achromatic doublet onto a linear detector array. High resolution tomograms of biomedical samples were successfully acquired by the frequency domain OCT-system. Tomograms of ophthalmic and dermal samples obtained by the frequency domain OCT-system were obtained achieving 2.84 μm axial and 10.2 μm lateral resolution. The miniaturization reduces costs and has the potential to further extend the field of application for OCT-systems in biology, medicine and technology.

Keywords: TFBG spectrometer, tilted fiber Bragg grating, optical coherence tomography, miniaturized spectrometer, OCT spectrometer, spectrometer approach, cost-effective spectrometer

1. INTRODUCTION

Spectrometers based on bulk diffraction gratings are common practice, albeit such spectrometers show high performance, the miniaturization of these devices is limited by the diffraction limit that necessitates expansion and focusing of the beam. Furthermore, the number of components and their long term alignment drives the costs for low maintenance, high resolution instruments. An approach to miniaturize devices and thereby increase their stability is to combine functionalities of different optical components into one, such as with classic concave gratings that integrate the grating with the focusing element [1] or arrayed wave guide gratings that found examples of application in spectrometers for biomedical imaging [2]. These approaches suffer from high complexity of the manufacturing process. A tilted Bragg grating as the dispersive element can be integrated via an automated inscription process directly into the optical fiber, which already is an intrinsic component of the optical set-up. The principle realization of a high resolution tilted fiber Bragg-grating (TFBG) Optical Spectrum Analyzer (OSA) was demonstrated [3], [4]. Its simplicity and high potential for efficient light collection makes it appealing for low cost high resolution spectrometry, and spectral imaging techniques like Spectral Domain Optical Coherence Tomography SD-OCT. OCT is a well-established technology to generate noninvasive cross-sectional depth resolved 2-dimensional and 3-dimensional tomograms of biological tissue be measuring the backscattered and back-reflected light [5]–[7] that encodes depth information in a spectral interference signal.

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Integration of the spectrometers dispersive element into the fiber eliminates the need for an external diffraction grating and the collimation optics. The reduced number of bulk optical elements increases stability, while direct fiber integration favors efficiency. Together with simple broadband light sources the miniaturization and simplification results in lowered costs for OCT-devices as they are demanded by the market. In contrast to fully integrated photonic designs this approach avoids the high losses of fiber-waveguide coupling [2], [8]. This opens new fields of potential applications such as portable OCT devices for flexible and long term monitoring of disease or technical applications.

1.1 Tilted Bragg grating fiber

A tilted Bragg grating fiber (TBG fiber) is an optical fiber with an inscribed fiber Bragg Grating titled at a specific facet angle. The TFBG structure was first demonstrated by Meltz et al. [8] and the theoretical analysis on mode coupling mechanism was given by Erdogan and Sipe [9]. The TFBG alters the propagation direction and causes partial coupling out of the fiber by reflection. The angle of the out-coupled light is determined by the well-known grating equation. The angular dispersion of the first order diffraction is given by:

$$D = \frac{\delta\theta}{\delta\lambda} = \frac{1}{\Lambda} \tag{1}$$

Here, Λ is the grating period. The refraction in the axial direction leads to a diverging light bundle coupling out at angle α in the radial direction, according to the numerical aperture $N_A = n\sin(\alpha)$ as displayed in Figure 1.

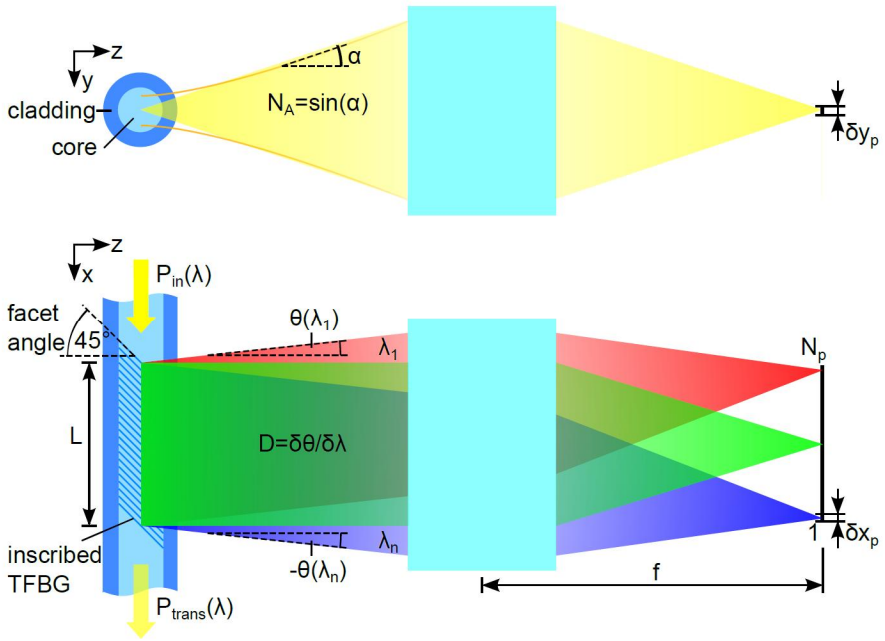

Figure 1. Simplified sketch of a TFBG displaying the emission geometry. Left: Divergence output characteristics in the radial plane of the fiber. Right: Wavelength dependent refraction of the tilted Bragg grating in the axio-lateral plane.

The light emission depends strongly on polarization. [10], [11] and therefore limits the overall throughput efficiency of the spectrometer. The TFBG can be used as polarization separator, with two successive TFBG gratings with different orientation, polarization sensitive OCT is potentially possible. As expected the emitted intensity profile in the axial direction follows an exponential decay in propagation direction [12]. This intensity distribution will affect the shape of the point spread function PSF in the image plane.

2. SYSTEM DESIGN

2.1 Simple two stage spectrometer

We start this section with some general considerations about the spectrometer used in SD-OCT systems. The whole spectral bandwidth of the SLED source $\Delta\lambda$ (Full Width Half Maximum FWHM) has to be imaged onto the pixel array of the line camera with length $N_p \delta x_P$. Here N_p is the number of pixels and δx_P the pixel pitch. The spectral resolution of the spectrometer is therefore $\delta_p \lambda = \Delta\lambda / N_p$. Together with the angular dispersion (1) of the TFBG, the focal length of the spectrometer objective can be determined provided that the light at central wavelength λ_c exit perpendicular to the fiber axis.

$$f = \frac{N_p \delta x_p}{D \Delta\lambda} \tag{2}$$

The active length of the TFBG grating can be estimated by considering a Gaussian intensity profile in the x-axis of the emitted light. Although this distribution is different for the TFBG used in this study, it gives at least a coarse estimation. If we define the length of the TFB as twice the 1/e^2 radius of the light intensity, the waist w_0 of the point spread function PSF in the plain of the CD array is:

$$w_0 = 2\frac{\lambda_c f}{\pi L} \tag{3}$$

A reasonable choice of the PSF is to define $\delta x_p = 2w_0$. In this case the length of the TFBG is:

$$L = \frac{4}{\pi}\frac{\lambda_c N_p \Lambda}{\Delta\lambda} \tag{4}$$

After quantifying the spectral and intensity characteristics of the TFBG in a first stage a simple two-element imaging system was realized, consisting of a cylindrical and a spherical lens of suitable focal lengths. Connected to a high resolution 2D-camera with standard data acquisition and a Michelson interferometer with a motor-driven sample arm, the spectral resolution and the corresponding depth dependent fringe loss could be specified as -16 dB/0.4 mm. Since the sensitivity of this device was limited by the chromatic error of the cylindrical lens, the size of the focusing lens and the instability of the fiber mount, a second spectrometer with a USB line-camera (3648 pixels, 8 µm pixel pitch) was devised to span a 6.4 mm depth scan range in air. To optimize the performance of this low-cost configuration the optical concept was revised based on the specifications of the TFBG.

2.2 TFBG spectrometer with low cost CCD Line Camera

A PS750 fiber with an UV-inscribed TBG providing a dispersion of 2.06 radiant/µm, a grating length of 23 mm and a numerical aperture of 0.1 was used to build the spectrometer. For horizontal beam collimation a cylindrical lens (69-747 from Edmund Optics) with a focal length of 20 mm was inserted. The spectral focusing was achieved by an objective consisting of two achromatic doublets (AC508-150-B from Thorlabs) with focal lengths of 150 mm using an additional field flattening lens (f=86 mm) for reducing internal reflections to a low cost USB CCD Line form Mightex with 3648 pixels (8 µm pitch and 200 µm height). The field flattening lens was not optimized for this spectrometer design, however, it was inserted to reduce the reflection on the uncoated camera glass. The spectrometer was designed for a super luminescence diode laser source (SLED, EBS8000 from Exalos) with a central wavelength of 800 nm the spectral bandwitdh of 120 nm at FWHM (full width at half maximum), which was mapped on approximately 2000 pixels. Since the orthogonally emitted wavelength of the TFBG was 776 nm, the TFBG and the cylindrical lens had to be tilted with respect to the CCD line array. The arrangement of the elements was optimized with the ray trace software Zemax. Figure 2 shows the two different planes as 2D Layout printouts. The element positions were numerically optimized for broadband operation to maximize throughput and minimize chromatic error. The 280×80×70 mm³ set-up (including the camera) was realized as a cage system supporting the necessary degrees of freedom for the alignment.

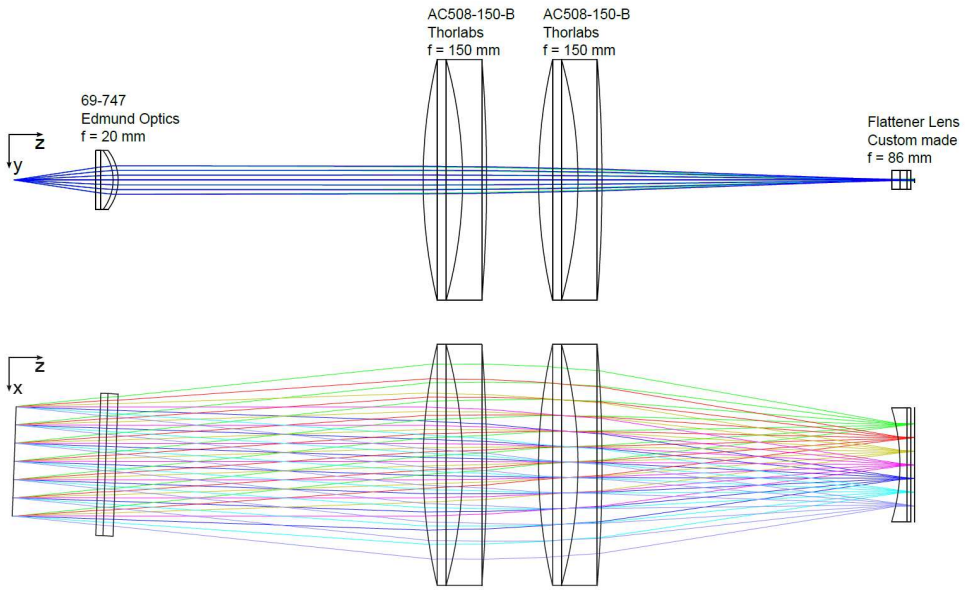

Figure 2. Optical design with refractive elements: illustrated in different planes as a printout of the Zemax simulation.

2.3 TFBG spectrometer with reflective elements

An opto-mechanically simpler solution is achieved by introducing an astigmatic mirror. The TFBG fiber is in the same plane of the CCD array, due to the folded optical path a smaller form factor of the whole device is possible. The design shown in fig. 3 was optimized for a SLED source with its emission centered at 780nm, a spectral width of 120 nm and the same TFBG as in the design with the refractive lenses. The shape of the mirror is an aspheric surface in the xz-plane and elliptical in yz-plane. Beside the advantages of reducing the needed space and the number of elements, the mirror is purely achromatic. Fig. 3 indicates the performance of this three element design.

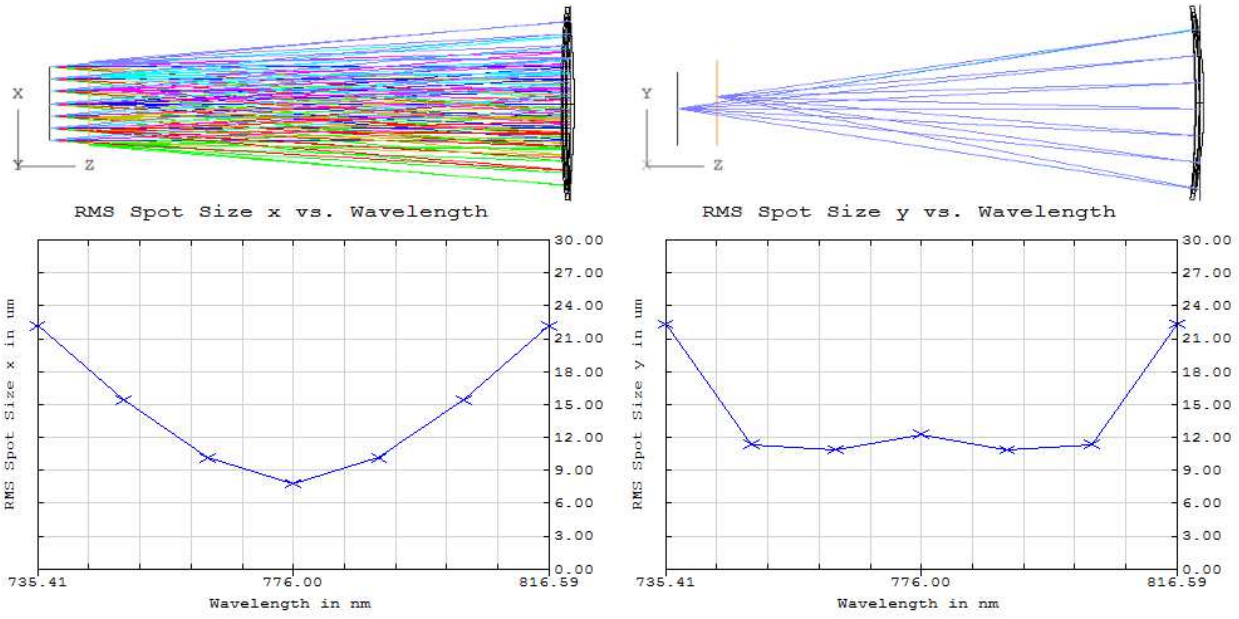

Figure 3. Optical design with a single reflective element: illustrated in different planes as a result of the Zemax simulation. Top left: fiber top view, top right: radial plane view with the displaced camera array, allowing for mounting the fiber on the camera, Bottom: respective calculations for the spot sizes

2.4 OCT system

The spectrometer with the TFBG was connected with a common fiber optical Michelson Interferometer OCT setup as schematically shown in Figure 4. The broadband laser light of the SLED (λ_C = 800 nm, $\Delta\lambda$ = 120 nm) is guided in a single mode fiber trough a FC/APC connector to a 50:50 fiber coupler where the light is split into reference- and sample arm. The backscattered and reflected light interferes in the fiber coupler before it is analyzed by the TFBG spectrometer. Since the coupling efficiency of the TFBG is highly polarization sensitive, in the reference arm, the sample arm and bin front of the spectrometer, polarization controllers (PC) were inserted to adjust and optimize the polarization.

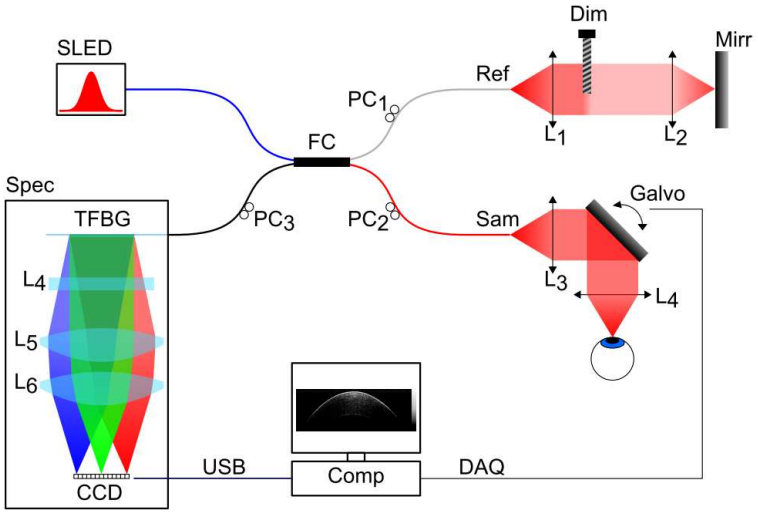

Figure 4. Schematic overview of the OCT system with the implemented TFBG spectrometer: SLED - superluminescence diode, FC – 50:50 fiber coupler, PC_1-PC_3 – Polarization controller, Ref – reference arm, L_1-L_6 – lenses, Dim – screw to dim the reference signal, Mirr – silver mirror, Sam – Sample arm, Galvo – galvanometric scanner, Spec – TFBG Spectrometer, TFBG – tilted fiber Bragg grating, CCD – CCD line camera, USB – USB interface, Comp – computer, DAQ – data acquisition cart.

3. MEASUREMENTS

The performance of the spectrometer was specified with the OCT system described in section 2.2. In a first step a sensitivity characterization of the spectrometer was performed. In a second step B-Scans of different biological samples were acquired. All measurements were performed with an integration time for the CCD line camera of 100 µs and show single tomograms without averaging.

3.1 OCT Measurements

To evaluate imaging quality of the TFBG spectrometer 2-dimensional OCT imaging on a lemon slice shown in Figure 5 was performed. The low scattering and high contrast of the samples cellular structures demonstrates the high axial resolution of the device.

Human in-vivo measurements of dermal tissue were obtained by a telecentric 2-D galvonometric scanhead with an effective focal length of 47 mm and a minimal spot waist of 10.2 µm. Figure 6 shows a 2-dimensional OCT image of a fingertip. Figure 6 right was acquired with an optimized configuration. Furthermore ophthalmological cross-sectional OCT images from an anterior segment of a pig eye were acquired (Figure 7). All measurements were performed at an optical power of 0.98 mW on the sample.

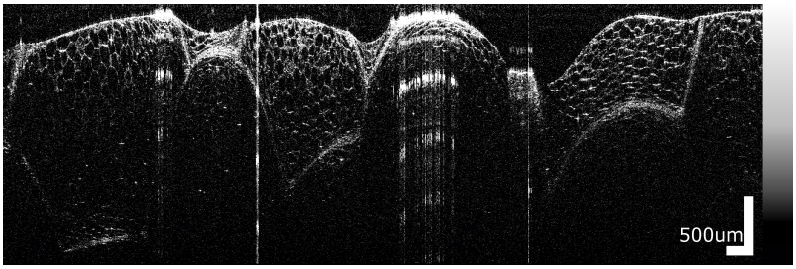

Figure 5. Single tomogram of lemon pulp: lateral scan range of 18 mm, acquired at 100 µs integration time sampled at 1024x4096 pixels.

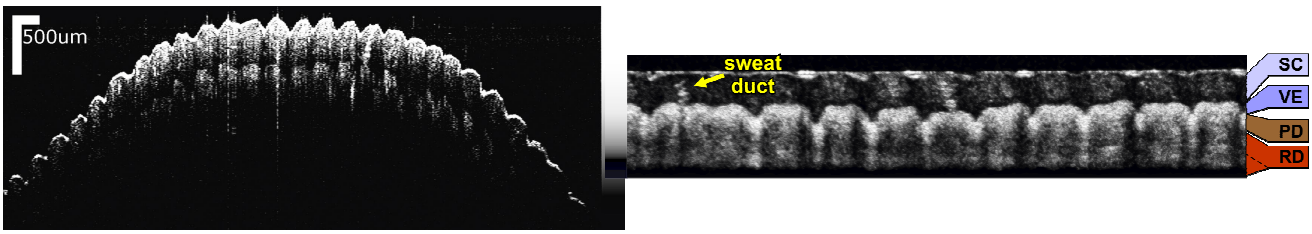

Figure 6. In-vivo OCT image of a fingertip with 400x1200 pixels from a volunteer acquired on an integration time of 100 µs over a scan range of 11 mm. Right: Cross section acquired with a direct contact to a tilted cover glass utilizing index matching gel to reduce specular surface reflections.

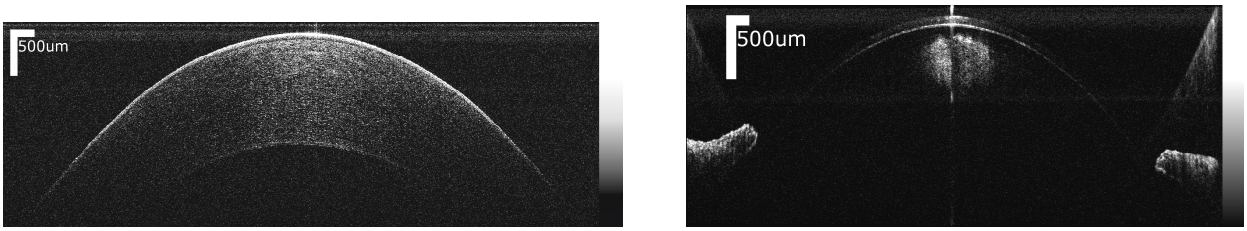

Figure 7. Anterior segment images of a pig-eye made with an integration time of 100 µs (a) cross-sectional OCT image of the cornea, scan range of 12.5 mm, 1024x1400 pixels (b) averaging of 18 frames shows lens and the iris, scan range 11.5 mm, 667x1096 pixels.

4. CONCLUSION

The feasibility of a TFBG-spectrometer for SD-OCT was successfully demonstrated. The spectrometers maximum sensitivity for the optimized state of polarization reaches 108 dB at 100 µs integration time and an overall sensitivity fall-off of 34 dB across 6.4 mm measurement range. Cross-sectional 2-D OCT images of a fruit, a human fingertip and the anterior segment of a pig-eye were demonstrated. A reasonable image quality was achieved with this preliminary low cost system.

Further improvement of the optical design and the TFBG fabrication process have potential to optimize the TFBG spectrometer towards smaller size and higher efficiency to achieve better optical performance and higher imaging speed. In the current setup the detection probe is the limiting component rather than the detection side. Even without further optical optimization the device can be fitted into a 200×60×10 mm³ format after removal of unnecessary optical surfaces using only standard components. To reduce the depth dependent signal loss which is caused by the limited spectral resolution an increase of the numerical aperture is necessary. This is usually associated with enlarged optics. A growth of the device can be counteracted by a more efficient grating with shorter emission length, but higher coupling ratio, so that the radii of curvature can be reduced. Similar to concave gratings also fully reflective designs are possible. Here, however, the integration of the dispersive component into the fiber instead of the reflector does not necessitate complex manufacturing processes for blazed surface gratings to achieve high efficiency. The relatively simple design and dense integration as a fiber-optic adapter to an existing cheap optical-electronic infrastructure overcomes mechanic limitations

of bulk systems, enables miniaturization at reduced costs and has the potential to extend the field of application for OCT-systems in biology, medicine and technology.

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