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Morphological and functional retina imaging with ultrahigh resolution optical coherence tomography at the 1060 nm wavelength region

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Presentation: Oral (preferred) or Poster

Abstract: An ultrahigh resolution Fourier domain optical coherence tomography (UHR FDOCT) system was designed and built for simultaneous imaging of retinal morphology and function. Two broad bandwidth light sources – an SLD (Superlum, $\lambda_c = 1020$ nm, $\Delta\lambda = 108$ nm and $P_{out} = 9$ mW) and a fiber based ASE source (NP Photonics, $\lambda_c = 1036$ nm, $\Delta\lambda = 61$ nm and $P_{out} = 15$ mW) were interfaced to the system to achieve $3 \mu\text{m} \times 6.5 \mu\text{m}$ (SLD) and $6.9 \mu\text{m} \times 6.5 \mu\text{m}$ (ASE) imaging resolution (axial x lateral) in biological tissue. The system provides time resolution of $240 \mu\text{s}$ and sensitivity of 110 dB (SLD) and 120 dB (ASE) and will be used for simultaneous imaging of retinal morphology and function.

Keywords: Optical coherence tomography, retina imaging, functional imaging, optical biopsy

Biography:

Kostadinka Bizheva has received her Diploma in Semiconductor Physics from Plovdiv University, Bulgaria in 1993, and MS and PhD degrees in Physics from Tufts University, USA in 1997 and 2001 respectively. Between 2001 and 2004 she was a Postdoctoral Fellow at Dr. W. Drexler's group in the Institute of Medical Physics, University of Vienna, Austria. Currently she is an Assistant Professor at University of Waterloo, Department of Physics and Astronomy, Waterloo, Canada. Her major research interests are focused on development of novel biomedical applications of OCT.

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ABSTRACT

An ultrahigh resolution Fourier domain optical coherence tomography (UHR FDOCT) system was designed and built for simultaneous imaging of retinal morphology and function. Two broad bandwidth light sources – an SLD (Superlum, $\lambda_c = 1020$ nm, $\Delta\lambda = 108$ nm and $P_{out} = 9$ mW) and a fiber based ASE source (NP Photonics, $\lambda_c = 1036$ nm, $\Delta\lambda = 61$ nm and $P_{out} = 15$ mW) were interfaced to the system to achieve $3 \mu\text{m} \times 6.5 \mu\text{m}$ (SLD) and $6.9 \mu\text{m} \times 6.5 \mu\text{m}$ (ASE) imaging resolution (axial x lateral) in biological tissue. The system provides time resolution of $240 \mu\text{s}$ and sensitivity of 110 dB (SLD) and 120 dB (ASE) and will be used for simultaneous imaging of retinal morphology and function.

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INTRODUCTION

It was recently demonstrated that retinal imaging performed at wavelengths $> 900\text{nm}$ has the dual advantage of allowing improved image penetration in the choroid^{1,2} for better visualization of sub-retinal vasculature, as well as permitting non-invasive probing of the functional response of the retina to visual stimulation³. Here we present a novel FDOCT system with improved image resolution and acquisition speed that can be used for simultaneous imaging of retinal morphology and function.

METHODS

The outputs of two broad bandwidth light sources – an SLD (Superlum, $\lambda_c = 1020$ nm, $\Delta\lambda = 108$ nm and $P_{out} = 9$ mW) and a fiber based ASE source (NP Photonics, $\lambda_c = 1036$ nm, $\Delta\lambda = 61$ nm and $P_{out} = 15$ mW) were interfaced to a compact, fiber-based FDOCT system designed to operate in the 900-1200nm wavelength range. A microscope and an eye imaging interface were built for *ex-vivo* / *in-vitro* and *in-vivo* imaging of retina samples. Both the microscope and the visual interface allow for fast 3D imaging by using a pair of scanners (Cambridge Technology). All optical and fiber optic components of the FDOCT system were selected to support the propagation of broadband light through the systems with minimal spectral and power losses. The interference signal is detected by a high efficiency custom built spectrometer, which utilizes a linear 1024 pixel array CCD camera with 4.3 kHz readout rate. The spectrometer is designed for the spectral range 940 - 1120nm and provides efficiency of 80% and spectral resolution of $\delta\lambda = 0.15\text{nm}$ in the case of the SLD and $\delta\lambda = 0.3\text{nm}$ in the case of the fiber based ASE light source. Data is acquired with a framegrabber and is processed and displayed by a computer (Intel Xion, 3.6 GHz, 2GB RAM).

RESULTS AND DISCUSSION

To evaluate the optical transfer function of the FDOCT system for each light source, the spectra of the SLD and the fiber based ASE source direct outputs (Fig.1A and C, black line) were measured with the custom built spectrometer and compared with the spectrum acquired at the detection end of the FDOCT system (Fig.1 A and C, red line) for a highly reflective sample (Au mirror). Comparison of the spectra shows that both the SLD and the ASE spectra are transmitted through the FDOCT system with minimal spectral changes and total power loss. The small changes observed at shorter wavelengths are most likely due to chromatic aberrations in the optics and / or polarization sensitive losses in the fiber optics.

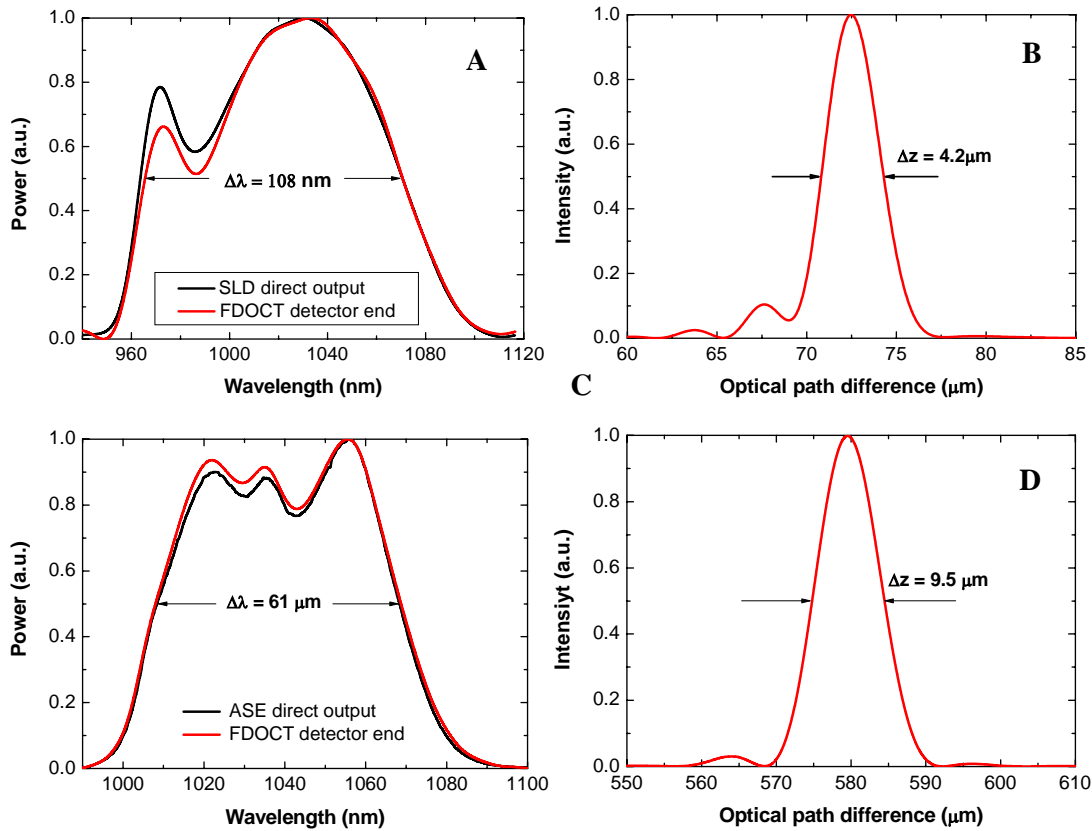


Fig.1 Spectrum of the SLD measure directly from the fiber output (black line) and at the detector end of the FDOCT system (red line) with the same custom built high efficiency spectrometer (A). The axial point-spread function of the FDOCT system + SLD measured from an Au mirror. Spectrum of the ASE light source measure directly from the fiber output (black line) and at the detector end of the FDOCT system (red line) with the same custom built high efficiency spectrometer (C). The axial point-spread function of the FDOCT system + ASE light source measured from an Au mirror.

A standard USAF resolution target was used to evaluate the performance of the FDOCT system with the two light sources. The system can provide $4.2 \mu\text{m} \times 9 \mu\text{m}$ (axial x lateral) resolution in free space, corresponding to $3 \mu\text{m} \times 6.5 \mu\text{m}$ resolution in biological tissue for the case of the SLD. In the case of the ASE light source the imaging resolution was measured to be $9.5 \mu\text{m} \times 9 \mu\text{m}$ in air, corresponding to $6.9 \mu\text{m} \times 6.5 \mu\text{m}$ in biological tissue. Theoretically, interfacing the ASE light source to an FDOCT specifically optimized for its spectrum should result in axial resolution of $7.8 \mu\text{m}$. However, in our case the full spectrum of the ASE source covers less than 50% of the pixels in CCD linear array, which results in lower effective resolution of the spectrometer – a factor that can contribute to the observed difference between the measured and theoretically calculated axial resolution for the ASE source. Fig. 1B and 1D show the axial point-spread functions of the FDOCT system determined from an Au mirror reflection for the SLD and ASE light sources respectively. The sensitivity of the system was measured to be 110 dB in the case of the SLD and 120 dB for the fiber based ASE source for 2 mW power incident on the reflective mirror. The power in the sample arm of the system used for the sensitivity measurements is well below the ANSI standard limit for 10s exposure of the eye to light in the wavelength region 940 nm to 1120 nm.

The presence of a local peak at 980nm in the water absorption profile can have a deteriorating effect on the FDOCT axial resolution, considering the fact that both the SLD and the fiber based ASE source emission spectra partially overlap with it. This effect was modeled theoretically for a water layer of variable thickness and the results from the model are presented in fig.2. The water absorption profile is shown in gray while the colored curves show the altered spectra of the SLD (fig.2 A) and the fiber based ASE source (fig.2 B) as the imaging beam passes through a water layer of certain thickness. The calculations were made for a double pass through the water layer and assuming an average refractive index of retinal tissue $n = 1.38$. Fig.2 shows that a water layer of $\sim 1\text{mm}$ thickness has no significant effect on the emission spectra of the SLD and ASE light source and

the corresponding OCT axial resolution, therefore, *ex-vivo* or *in-vitro* imaging retinal imaging can be performed with the FDOCT system with the highest possible image resolution. Fig.2 also shows that in the case of *in-vivo* retinal imaging in adult patients, water absorption will cause a reduction in the OCT image resolution from $3\mu\text{m}$ to $5.7\mu\text{m}$ in the case of the SLD and from $5.6\mu\text{m}$ to $7\mu\text{m}$ in the case of the ASE light source.

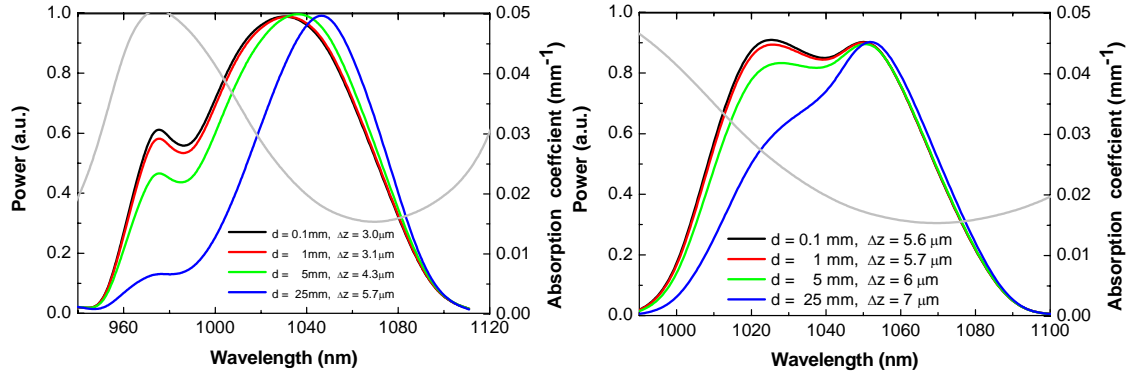


Fig.2 The effect of water absorption on the spectral shape of the detected imaging beam for a double pass through a layer of water with specified thickness. The gray line shows the absorption profile of water. The changes in the FDOCT axial resolution shown in the figure were calculated assuming an average refractive index $n = 1.38$ of retinal tissue.

Comparison between the two light sources shows that the SLD can permit imaging of retina morphology and function with about 2 times better axial resolution in *ex-vivo* or /and *in-vitro* preparations. However, in the case of *in-vivo* clinical retina imaging, the axial OCT resolution achieved with the two light sources is comparable. The ASE light source has some additional advantages in terms of more compact design and better noise level and power stability and a built-in optical isolator.

CONCLUSION

We have demonstrated a high speed, ultrahigh resolution FDOCT system that can be used for simultaneous *in-vitro* and *in-vivo* imaging of retinal morphology and function. Results from a theoretical model developed to account for the effect of water absorption on the OCT axial resolution provide some insights on development of an ‘ideal’ light source for high resolution retina imaging with OCT in the 1060nm wavelength region.

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