High resolution, spectroscopic optical coherence tomography in the 900 - 1100 nm wavelength range

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ABSTRACT

We demonstrate for the first time optical coherence tomography (OCT) in the 900-1100 nm wavelength range. A photonic crystal fiber (PCF) in combination with a sub-15fs Ti:sapphire laser is used to produce an emission spectrum with an optical bandwidth of 35 nm centered at ~1070 nm. Coupling the light from the PCF based source to an optimized free space OCT system results in ~15 µm axial resolution in air, corresponding to ~10 µm in biological tissue. The near infrared wavelength range around 1100 nm is very attractive for high resolution ophthalmologic OCT imaging of the anterior and posterior eye segment with enhanced penetration. The emission spectrum of the PCF based light source can also be reshaped and tuned to cover the wavelength region around 950-970 nm, where water absorption has a local peak. Therefore, the OCT system described in this paper can also be used for spatially resolved water absorption measurements in non-transparent biological tissue. A preliminary qualitative spectroscopic OCT measurement in D_2O and H_2O phantoms is described in this paper.

Keywords: Optical coherence tomography, photonic crystal fiber, Ti:sapphire laser, ophthalmologic OCT, water absorption, spectroscopy

1. INTRODUCTION

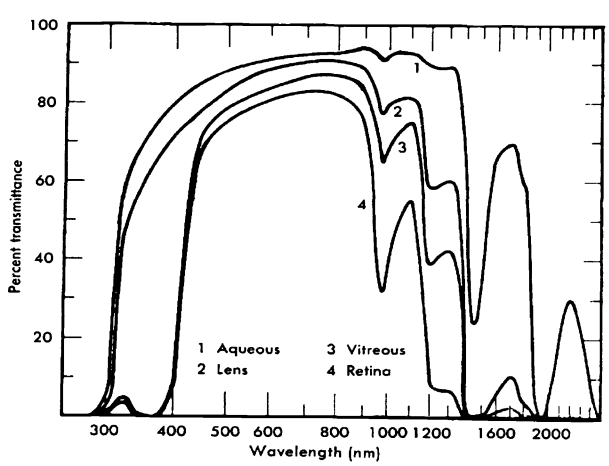


Figure 1. Total transmittance of the human eye. (R.A. Moses and W.H. Hart, "Radiometry and photometry", in *Adler's Physiology of the Eye, Clinical Application*, Mosby, St.Louis, Mo., pp. 346 (1987)).

In the last decade, optical coherence tomography (OCT) has emerged as a promising new technique for high resolution, cross sectional imaging[1,2,3,4]. OCT is analogous to conventional ultrasonic pulse-echo imaging (ultrasound B-mode) except that it uses light rather than sound[1]. Since the eye is essentially transparent in the wavelength region around 800 nm, transmitting light with only minimal optical attenuation and scattering and also provides easy optical access to the anterior segment as well as the retina, OCT was first investigated in ophthalmology[2]. Recently, a third generation of ophthalmic OCT system has been developed, enabling optical biopsy of the human eye, i.e. *in vivo* imaging of internal retinal and corneal structure with unprecedented axial resolution, which previously had only been possible with histopathology[5]. This novel OCT system employs a broad bandwidth Ti:sapphire laser that emits laser light centered at 800 nm. In combination with image processing and segmentation techniques, ultrahigh resdution OCT permits quantitative measurements of internal retinal architectural morphology for the first time[5]. In the present paper we demonstrate, according to our knowledge, for the first time OCT in the 900-1100 nm wavelength range. This is achieved by employing a photonic crystal fiber pumped with light from a compact sub-15 fs Ti:sapphire laser. Ophthalmologic OCT in the 800 nm region has limited penetration depth, thus resulting in mainly visualizing the retina down to the choriocappilaris/choroid interface. Employing light sources for ophthalmologic OCT centered at the 1100 nm wavelength range, might further extend the penetration depth of OCT imaging beyond the retina, considering the fact that the transparency of the ocular media in this region is still good (fig.1). Moreover, using laser light in the 1100 nm wavelength range, should give less attenuation in opaque eye media, that might occur in older patients due to cataract and haze in the cornea. Ophthalmologic OCT imaging in the 1100 nm region may find important applications such as visualizing the chroiocappillaris and choroid, essential for early diagnostics of diabetic macular edema and for detection of angiogenetic processes in AMD. With this novel OCT system it may also be possible to image the anterior chamber angle of the human eye, which may have great impact in glaucoma diagnosis.

2. METHODS

A commercially available Ti:sapphire oscillator (FEMTOLASERS) emitting 14 fs pulses with 66.4 MHz repetition rate and output power of up to 650 mW, was used to pump a PCF with 1.9 μm diameter and 980 mm length, fabricated at the University of Bath, UK (fig.2). The emission spectrum of the fiber based light source was shaped to produce a Gaussian peak centered at 1070 nm with output power of ~1.2 mW. The light was coupled to a free space interferometer, optimized to support broad bandwidth laser light in the 400-1700 nm region.

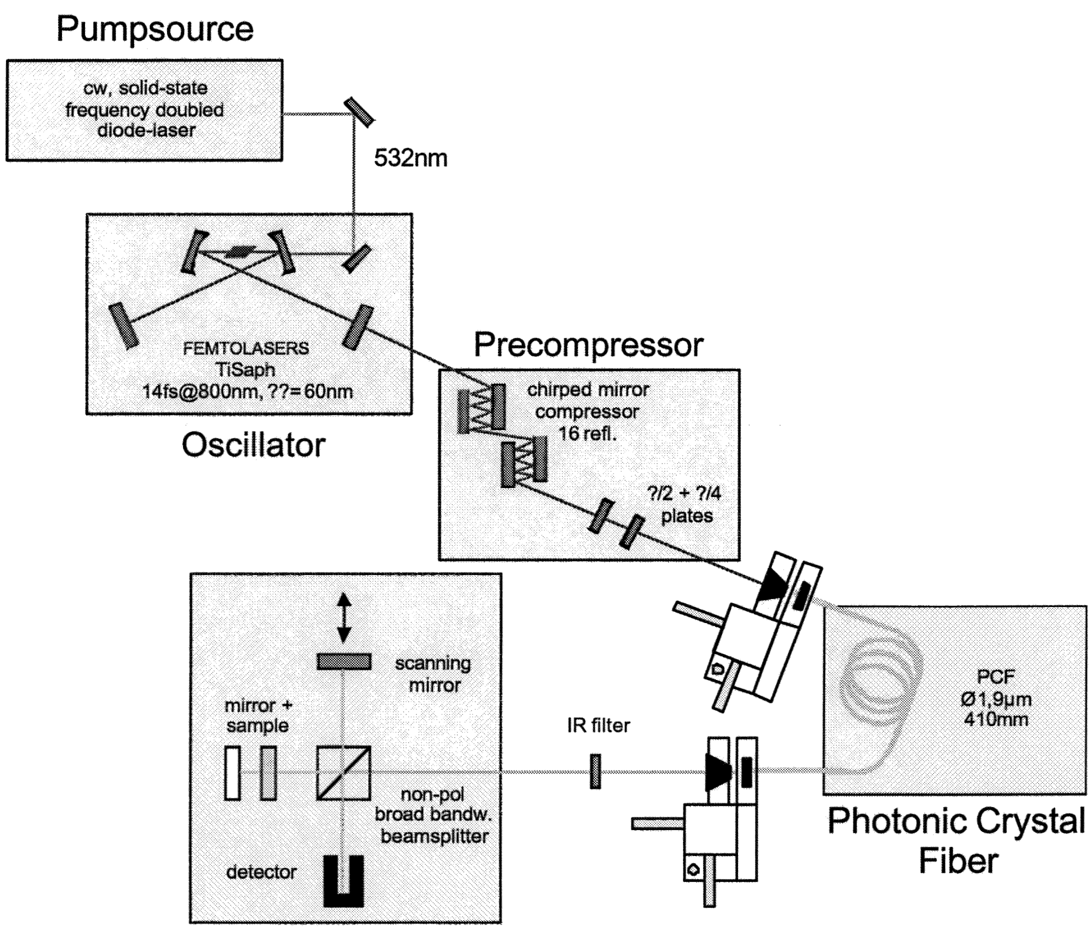
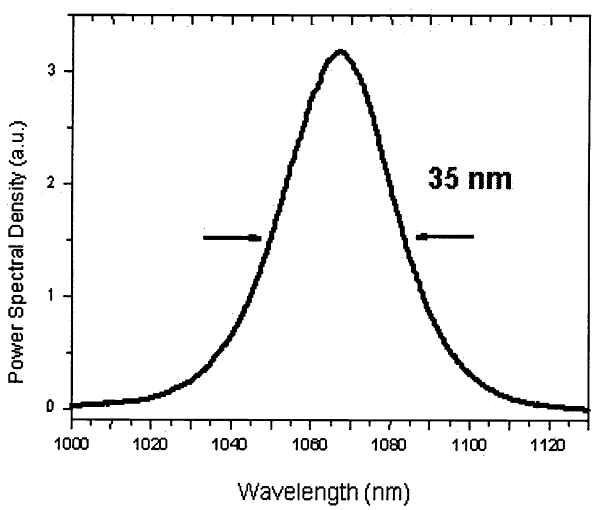


Figure 2. Schematics of the photonic crystal fiber light source based OCT set-up. The oscillator and fiber parameters are optimized for emission in the 800-1300nm wavelength region. A free space interferometer optimized for the NIR wavelength region is coupled to the PCF based source.

For spectroscopic OCT of water absorption, the emission spectrum of the PCF based light source was tuned and reshaped to a Gaussian centered at 970 nm with an output power of ~275 μW. Custom designed phantoms comprised of two 130 μm thick cover slip glass slides spaced at 1.5mm distance were used for the water spectroscopy experiments. Considering the low power output of the light source at 970 nm, the lack of dual balanced detection in the current OCT setup, and the weak reflection produced by a water-glass interface, it was necessary to place a mirror behind the phantom in order to detect these preliminary full interferometric OCT data instead of using the reflection of the water/glass interface of the phantom. The acquired fringe data was processed with a Morlet wavelet transform in order to obtain spectroscopic information of the measured phantom. Information about the measured DC level when using H_2O and D_2O was utilized in the post-processing of the data in order to accomplish proper normalization of the data. The absorption spectra of H_2O and D_2O were also acquired with a commercially available spectrophotometer and were used for comparison with the spectroscopic information derived from the OCT measurements.

3. RESULTS AND DISCUSSION

Figure 3 demonstrates the shaped emission spectrum of the PCF based light source centered at 1070 nm (left) and the corresponding OCT axial resolution measured in air obtained with this light source (right). The spatial resolution of this OCT system is comparable to the resolution offered by conventional superluminescent diodes (SLD) in the 800 nm range, though the penetration depth in biological tissue in the 1070 nm wavelength range should be significantly enhanced due to less scattering. As mentioned in the introduction of this paper, imaging in the 1100 nm region provides attractive possibilities for ophthalmologic OCT as well as other novel biomedical OCT applications.



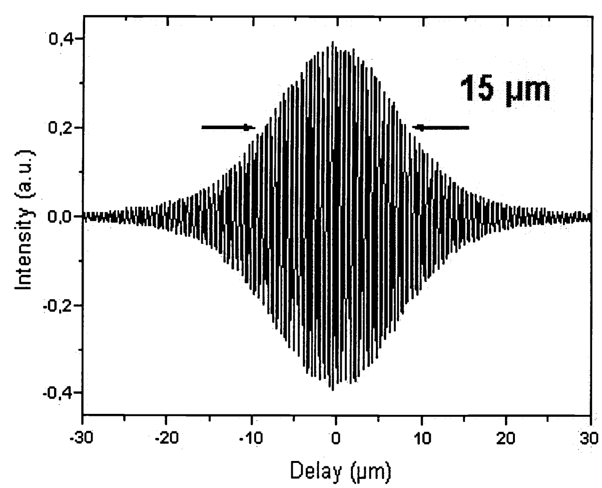


Figure 3. Optical output spectrum (left) and interference signal (right) of the PCF based light source in the 1100 nm range. An optical bandwidth of 35 nm enables a free space resolution of ~15μm, corresponding to ~ 10 μm in biological tissue.

The possibility of shaping the emission spectrum of the PCF based source presents an unique opportunity to perform water spectroscopy in the 950 nm region. Figure 4 presents the preliminary spectroscopic data acquired with the PCF based OCT system. Heavy water (D_2O) has negligible absorption in the 970 nm range, while water has a μ_a of ~0.4 cm^{-1}. The difference in the peak intensities of H_2O and D_2O observed in the figure is due to water absorption in the 1.5 mm thick phantom. From the data presented in fig. 4 we were able to calculate the water absorption coefficient (μ_a = 0.39 cm^{-1}) which agreed fairly well with the expected value for this wavelength range (μ_a ~0.4-0.46 cm^{-1}).

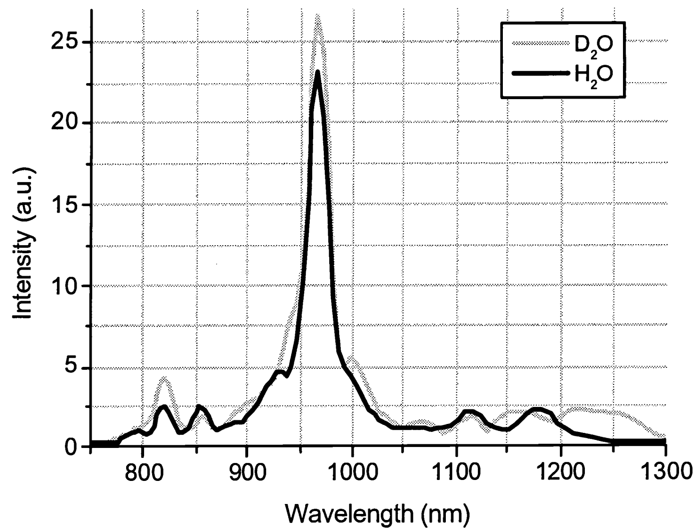


Figure 4. Water (H_2O) and heavy water (D_2O) spectra acquired with the PCF based OCT system

4. CONCLUSION

In this study we have used a unique PCF based light source with an OCT setup optimized for this wavelength range and have demonstrated high resolution OCT in the 900-1100 nm wavelength range. We have also demonstrated the possibility of reshaping and tuning the light source spectrum to emit a Gaussian shaped spectrum at 970 nm, which enabled preliminary spectroscopic OCT measurements on H_2O and D_2O phantoms. In the near future dual balancing detection in combination with a dynamic focusing and high speed, interferometric triggering will be implemented into the OCT system. Effort will also be focused on stabilizing and optimizing the PCF based light source output and to extend it to even broader bandwidths in the 1070 nm wavelength range. A bandwidth of 100 nm centered at 1070 nm should enable sub-5μm axial resolution ophthalmologic OCT imaging with enhanced penetration. In addition experimental work will be also focused on developing a spectroscopic OCT system designed for differential water absorption measurements in the 900-1100nm wavelength region.

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