Visible light optical coherence tomography

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ABSTRACT

We demonstrate for the first time optical coherence tomography (OCT) in the visible wavelength range with unprecedented sub-micrometer axial resolution, achieved by employing a photonic crystal fiber in combination with a sub-15fs Ti:sapphire laser (FEMTOLASERS). The shaped emission spectrum produced by the photonic crystal fiber ranges from 535 nm to 700 nm (centered at ~600 nm) resulting in ~0.9 µm axial OCT resolution in air corresponding to ~0.6 µm in biological tissue. Preliminary demonstration of the sub-micrometer resolution achieved with this visible light OCT setup is demonstrated on a 2.2 µm thick nitrocellulose membrane. The visible wavelength range not only enables extremely high axial resolution for OCT imaging, but also offers an attractive region for spectroscopic OCT.

Keywords: Optical coherence tomography, sub-micrometer axial resolution, photonic crystal fiber, Ti:sapphire laser

1. INTRODUCTION

Optical coherence tomography (OCT) is an emerging medical diagnostic imaging technique which can perform two or three dimensional cross sectional visualization of microstructural morphology of biological tissue *in situ*[1,2,3]. OCT is somewhat analogous to ultrasound B mode imaging, except that OCT imaging is performed by measuring the intensity of reflected or backscattered light rather than acoustical waves. Tomographic images are generated by scanning an optical beam across the tissue and measuring the echo time delay and intensity of light that is reflected or backscattered from internal tissue microstructures. OCT is based on a classic optical measurement technique known as low coherence or white light interferometry. Therefore, axial OCT resolution is mainly limited by the temporal coherence properties of the light source, usually a superluminescent diode, to typically 10-15 µm.

Broad bandwidth light sources are required for enhanced axial resolution OCT imaging. The first sub-10-µm-resolution was achieved by using broadband fluorescence from organic dye and from Ti:sapphire[4]. Biological imaging could not be performed with these light sources due to their low brightness. Although incandescent light sources have broad emission bandwidths and can result in high axial resolutions, they do not possess sufficient intensity in a single spatial mode for high speed imaging. Nevertheless, as recently demonstrated, thermal light sources could be used for a novel OCT technique[5]. The development of femtosecond Kerr lens mode locking of solid state-lasers enabled the generation of ultrabroad bandwidth, low-coherent light. Because of their broad emission bandwidth and high output power, modelocked femtosecond lasers have become attractive OCT light sources and have already been used for *in vitro* and *in vivo* imaging where axial resolutions of 3.7 µm and 6 µm has been achieved[6,7]. Recently, a state of the art, broadband Ti:Al_2O_3 (Ti:sapphire) has been developed for ultrahigh 1 µm axial resolution, spectroscopic OCT imaging at center wavelength of 800 nm[8,9]. Highly optically nonlinear air-silica microstructure fibers[10] or tapered fibers[11] can be used to generate an extremely broadband continuum using low energy femtosecond pulses. As recently demonstrated, the utilization of a pumped photonic crystal fiber as a light source in an OCT system can result in ~2 µm axial image resolution for emission spectra located in the 1300 nm range[12].

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In this paper we demonstrate, according to our knowledge, for the first time OCT in the visible wavelength range, enabling unprecedented sub-micrometer axial resolution in this new field. This is achieved by using a photonic crystal fiber pumped with light from a compact sub-15 fs Ti:sapphire laser.

2. METHODS

Spectra spanning more than one optical octave can be produced via non-linear propagation of laser pulses in micro-structured fibers (photonic crystal fibers, PCF) or tapered fibers[10,11]. Due to the geometry of these fibers, the cross-section of the fundamental mode is unusually small, which enhances the peak power and thus the non-linear effects. At the same time, the fiber dispersion can be engineered to avoid fast temporal spreading. As a result, spectra covering more than one optical octave can be produced even with pulses having moderated energies of few nanojoules. Such a spectral width can never be generated directly from a Ti:sapphire laser oscillator, because it exceeds the gain bandwidth of the crystal.

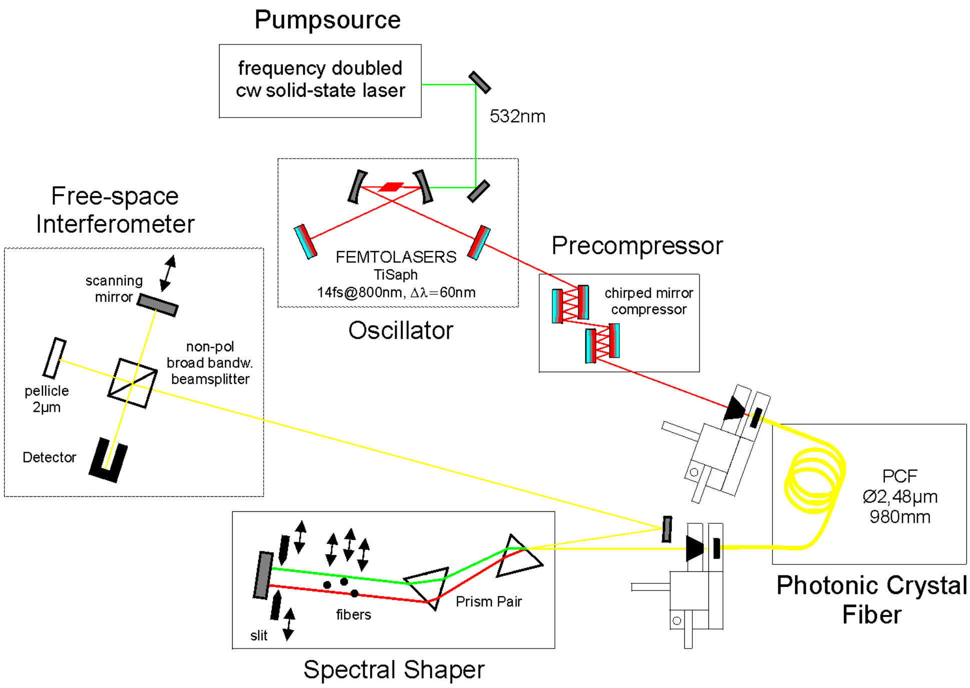

Figure 1 Schematics of the photonic crystal fiber light source based OCT setup. The oscillator and fiber parameters are optimized for visible light emission. An external prism sequence is used to spectrally shape the pulses. A free space interferometer is designed for ultrabroad bandwidths in the visible wavelength range to achieve sub-micrometer axial resolution.

Until now photonic crystal fibers have only been used in combination with conventional 100 fs Ti:sapphire oscillators[12]. In this paper, a solid state laser pumped, commercially available Ti:sapphire laser (FEMTOLASERS) emitting 14 fs pulses with 66.4 MHz repetition rate and power output of up to 400 mW, was used to pump a PCF with 2.48 µm diameter and 980 mm length that was fabricated at the University of Bath, UK (cf. Figure 1). The oscillator pulses were pre-compressed before coupling into the PCF and the setup was optimized for emitting mainly laser light in the visible wavelength range. An external prism sequence in combination with thin absorbers was used to spectrally shape the emission spectrum. A free space interferometer, optimized to support broad bandwidth visible laser light was used for preliminary demonstration of ultrahigh axial OCT resolution.

3. RESULTS AND DISCUSSION

Figure 2 depicts a comparison between the emission spectra and interference signals of a compact, commercially available sub-10 fs Ti:sapphire laser (Femtosource Pro, FEMTOLASERS) and the PCF based light source. This Ti:sapphire laser is different from the one used in the PCF setup. Its emission spectrum is centered around 800 nm, has a bandwidth of up to 165 nm (cf. Figure 2 top left) and up to 400 mW output power. It enables 2.0 µm axial resolution in free space, corresponding to about 1.4 µm in biological tissue (cf. Figure 2 bottom left), when interfaced to a high speed, fiber-optical based, broad bandwidth OCT.

The PCF based light source emits a spectrum spanning from ~535 nm to ~700 nm, centered around 600 nm (cf. Figure 2 top right) at up to 23 mW before and 7.5 mW after spectral shaping. An axial resolution of about 0.9 µm in free air, corresponding to about 0.6 µm in biologic tissue (cf. Figure 2 bottom right) could be achieved when interfaced to a free space interferometer. Although spectrally shaped, the residual strong modulations in the emission spectrum causes reduced sensitivity in the interference signal.

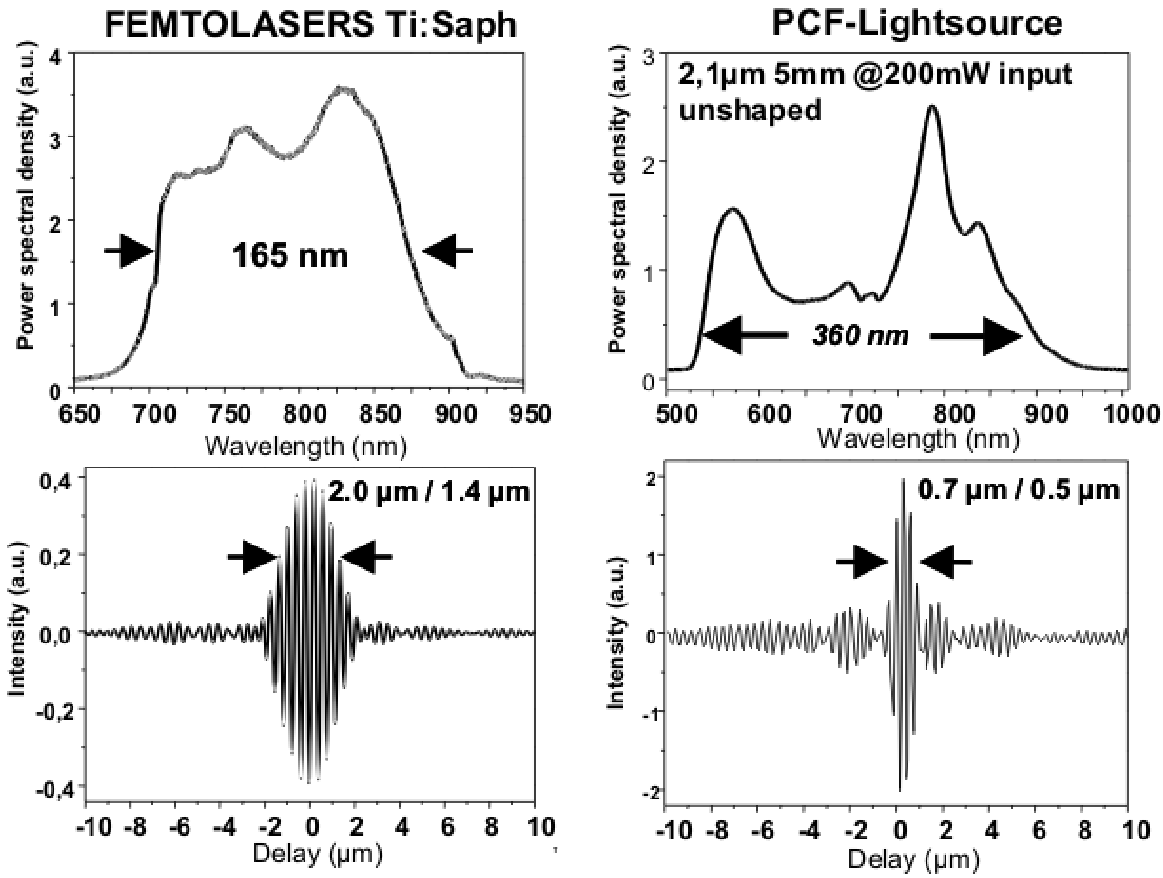

Figure 2 Optical spectra (top) and interference signals (bottom) of a commercially available Ti:sapphire laser (Femtosource Compact Pro, FEMTOLASERS; left) and a photonic crystal fiber based light source (right). An axial resolution of 2.0 µm and 0.9 µm in free space, corresponding to about 1.4 µm and 0.6 µm in biological tissues can be achieved with the Ti:sapphire and the photonic crystal fiber optically based light source, respectively.

For preliminary demonstration of this unprecedented sub-micrometer axial resolution, the thickness of a nitrocellulose membrane was measured (cf. Fig. 3 right) and compared to the results obtained with the Ti:sapphire laser (cf. Fig. 3 left). Using the Ti:sapphire laser a clear separation of the signals reflected from the front and the back surface of the membrane can be achieved. This separation is even further enhanced using the PCF based light source. With both light sources an optical thickness of 3.3 µm corresponding to 2.2 µm geometrical thickness, assuming a group refractive index of 1.5, was measured.

4. CONCLUSION

Using a compact commercially available sub-15 fs Ti:sapphire laser, a photonic crystal fiber based light source has been developed and optimized to enable visible light OCT. For the first time unprecedented sub-micrometer axial resolution has been demonstrated in the visible wavelength range using a PCF based light source. Future research will focus on optimization of the oscillator pulse width, energy and polarization state, as well as the photonic crystal fiber parameters for a smoother and more stable emission spectrum in order to improve OCT sensitivity. In addition, a free space interferometer specifically designed for fast two dimensional scanning and able to support broad emission bandwidth of the PCF light source will be designed. In accordance with the preliminary results presented in this paper, it is expected that this visible light OCT system will provide sub-micrometer axial resolution OCT imaging in biological tissue.

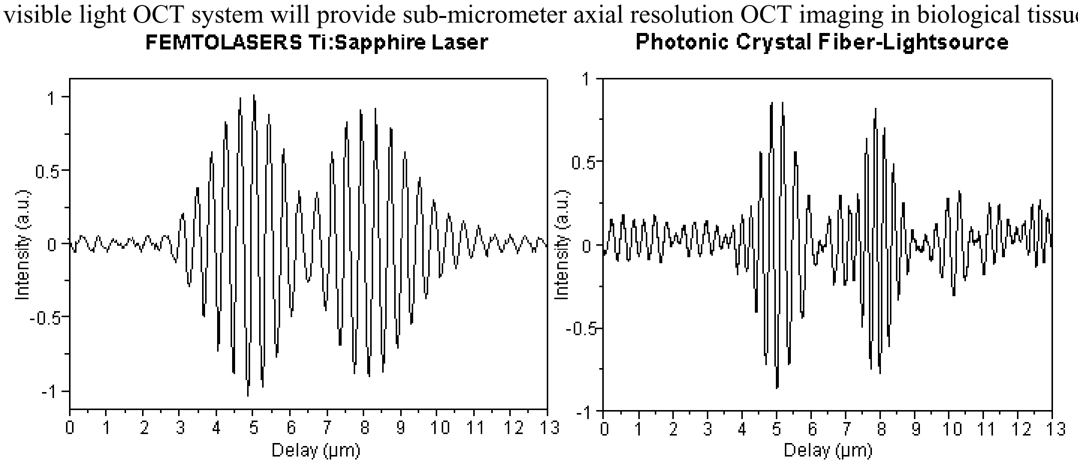

Figure 3 . Measurement of nitrocellulose membrane thickness with a Ti:sapphire laser (Femtosource Compact PRO, FEMTOLASERS; left) and a photonic crystal fiber based light source (right) demonstrating the potential for ultrahigh resolution OCT imaging. An optical thickness of 3.3 µm, i.e. a geometrical thickness of 2.2 µm ($n_g \sim 1.5$) has been achieved.

Considering that the emission bandwidth of the PCF light source overlaps with the so called therapeutic window, covering absorption features of several biological chromophores, like melanin, oxy- and deoxyhemoglobin, the visible light OCT system also offers the potential for enhanced non-invasive spatially resolved spectroscopy. Preliminary research in this direction is already on the way.

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