HIGH RESOLUTION OPTICAL COHERENCE TOMOGRAPHY USING CHIRPED PULSE AND HIGHLY NONLINEAR OPTICAL FIBER

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ABSTRACT
OCT is an emerging noninvasive optical diagnostic imaging method with medium penetration and high resolution primarily used in medicine. A method to increase OCT resolution is proposed in this paper using up-chirped optical pulse which then propagates in HNLF coil designed for this goal. The spectrum of the pulse is broadened by the SPM and as a result imaging resolution is increased. The performance of the light broadened with initially up-chirped and un-chirped pulse is compared for use in OCT imaging.

Keywords: *Optical coherence tomography (OCT), Self phase modulation (SPM), Highly nonlinear fiber (HNLF), grating pair*

INTRODUCTION
Optical coherence tomography (OCT) is a real time imaging approach for micron-resolution cross-sectional imaging of biological tissues that can be used in ophthalmology, dentistry, and for treating cardio-vascular diseases [1, 2, 12]. The combination of OCT with endoscopy allows to study internal tissues without removing parts of them. OCT has also some other applications in art and industry.

The function of this approach is based on reflection and interference of optical beams which can be used in 1D, 2D, and 3D imaging [1, 2, 12, 13]. In OCT imaging, the axial resolution can be expressed as [13]:

$$\Delta l = \frac{2\ln 2}{\pi\Delta_\lambda}\lambda_0^2 \qquad (1)$$

Where, λ0 and Δλ are the central wavelength and FWHM of the source spectrum bandwidth, respectively. Therefore, to improve the OCT resolution in a certain central wavelength, the source bandwidth needs to be increased. Primary considerations for evaluating optical sources of OCT imaging are wavelength, bandwidth, single-transverse mode power, stability and Gaussian shape of the source power spectrum [2]. Superluminescent diodes (SLDs) which are also used in OCT supply a resolution of about 10-15µm[3] but due to their limited bandwidth are not suitable for more accurate works. A broadband Kerr-lens mode-locked Ti:sapphire laser is another source that is used for OCT imaging and supplies an axial resolution of about 2µm [4]. The structure complexity is one of the limitations of this kind of source, another problem is that their central wavelength is different from the wavelength required for OCT which is in the range of 800-1550 nm. Recently, optical sources that are based on nonlinear fibers have found wide applications, including in OCT[5]. Highly nonlinear micro- structure fibers(MSFs) can generate an extremely broadband spectrum from 800nm up to 1600 nm [6], and a resolution of 2.5µm has been reported for OCT systems with MSF source [7]. One of the problems of MSF sources is their poor SNR [8-14]. Highly nonlinear single mode fiber with an un-chirped Gaussian input pulse is another source that has been used in OCT and have provided better SNR than MSF [9-15]. One of the problems of optical sources with optical fibers is creating a Gaussian spectrum because the SPM in the nonlinear region creates ripples in the optical spectrum and causes it to lose it Gaussian shape [2].

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In the approach proposed in this paper, it will be shown that if the optical pulse is initially up-chirped before entering the fiber coil, in addition to increasing the bandwidth in the same fiber length, it will have a better spectrum shape compared to the case that the pulse is un-chirped.

OCT systems fundamentals

OCT is an imaging method with medium penetration and high resolution which is between microscopic and ultrasound methods. It is used for imaging with a penetration depth of 3-10 mm [1, 2, 13]. Fig. 1 shows a comparison made between OCT and other imaging approaches from the penetration depth and resolution points of view.

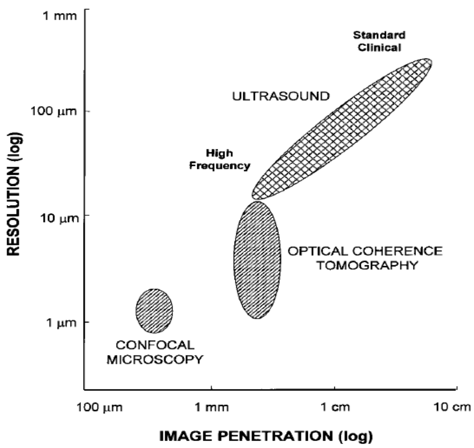

Fig. 1. A comparison between OCT and other imaging methods from resolution and penetration depth points of view.

The ultrasound technique is one of the imaging methods used in medicine. This technique is based on ultrasound waves and is used to examine subcutaneous tissues such as muscles, joints, and internal organs and their damages. In this method, sound waves with high frequencies are transmitted inside the tissue by an ultrasound transducer, and the sound waves are reflected or scattered by the inner structures of the tissue that have different sonic features. The reflected sound waves are detected and then, the dimensions and structure of the tissue are obtained, and the basis of this detection is the echo time which can be directly detected by electronic detection techniques due to the low speed of sound waves compared with that of light waves. However, in OCT imaging, electronic detectors are not capable of directly detecting the echo time because of the high speed of light waves [13]. Therefore, in OCT method, as it is shown in Fig. 2, in addition to transmitting the light to the sampling arm, a certain percentage of it is also transmitted to the reference arm and the interference of the reflected light from these two arms is detected by a detector. In ultrasound approach, the sonic transducer must be directly in contact with the tissue but since the light waves are used in OCT, a direct contact with the tissue is not necessary and this is one of the main advantages of OCT imaging. For example, the device which is used in ophthalmology for observing the retina uses OCT imaging and the device does not need to be directly in contact with the eye tissues while, if this device have used the ultrasound technology, it would have been necessary for the device to be directly in contact with the eye which is very painful for the patients.

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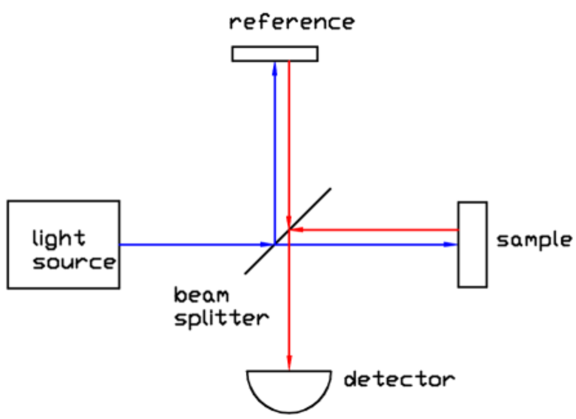

Fig. 2. The OCT approach based on interferometry

In the interferometer, beam splitter and mirrors are represented by [1]:

50/50 beam splitter: $\begin{bmatrix} -\frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix}$ reference arm mirror: $\begin{bmatrix} -r_r & 0 \\ 0 & -r_r \end{bmatrix}$

And sample arm in the simplest form : $\begin{bmatrix} -r_s & 0 \\ 0 & -r_s \end{bmatrix}$ (2)

The two light beams entering each arm are represented by:

$$E_{reference} = -\frac{1}{\sqrt{2}} E_{source} \quad (3) \qquad E_{sample} = \frac{i}{\sqrt{2}} E_{source} \quad (4)$$

After reflecting off the mirrors and entering the beam splitter the fields become:

$$E_{reference2} = r_r \left(\frac{1}{\sqrt{2}}\right) E_{source} e^{-i2kl_r} \quad (5) \qquad E_{sample2} = -r_s \left(\frac{i}{\sqrt{2}}\right) E_{source} e^{-i2kl_s} \quad (6)$$

In which, the path length in both arms is represented by $2kl_r$ and $2kl_s$.
Repassing through the beam splitter, the field in the detector arm becomes:

$$E_D = \left(\frac{i}{\sqrt{2}}\right) E_{reference2} + \left(\frac{-1}{\sqrt{2}}\right) E_{source2} = r_r \left(\frac{i}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right) E_{source} e^{-i2kl_r} + r_s \left(\frac{i}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right) E_{source} e^{-i2kl_s} \quad (7)$$

OCT techniques are divided into two groups; *time domain* (TD) approach and *spectral domain* (SD) method. The SD approach itself is divided into two methods known as *Fourier domain* (FD) and *swept source* (SS) [1, 2, 13]. The diagram of TD_OCT is shown in Fig. 3. As it can be observed in this figure 3, in order to obtain the depth data, a movable mirror is used in the reference arm and it is responsible for scanning.

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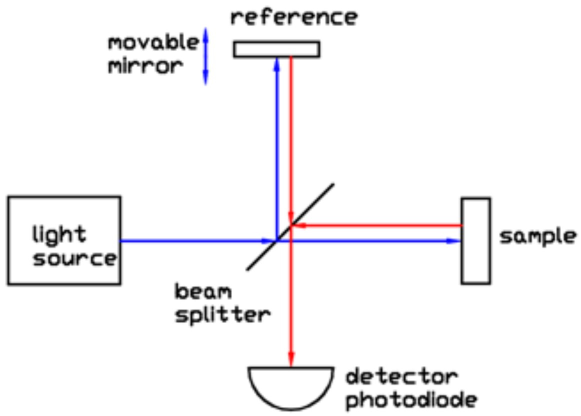
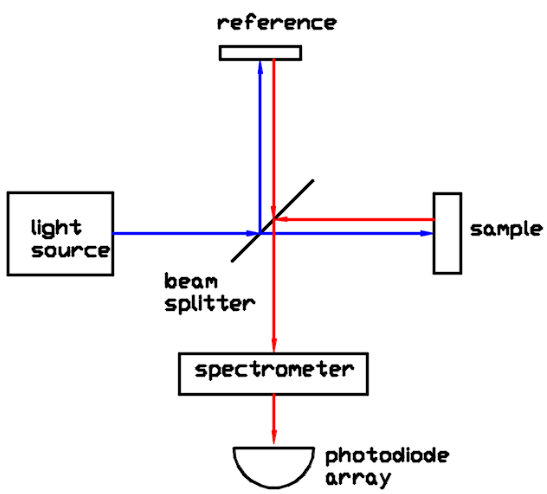


Fig. 3. The diagram of TD_OCT.

Also, Fig. 4 shows the diagram of Fourier domain OCT (FD_OCT). As it can be seen in this figure, the moving mirror of the reference arm is removed and a spectrometer and a photodiode array are used in the detector arm, and the depth data is obtained by analyzing the beam spectrum created by the interference of two arms.



1.
Fig. 4. The diagram of FD_OCT.
The diagram of swept source OCT (SS_OCT) is shown in Fig. 5. As it can be seen in this figure, instead of using a spectrometer and a photodiode array, a single photodiode is used in the detector arm also, a light source of swept type is used.

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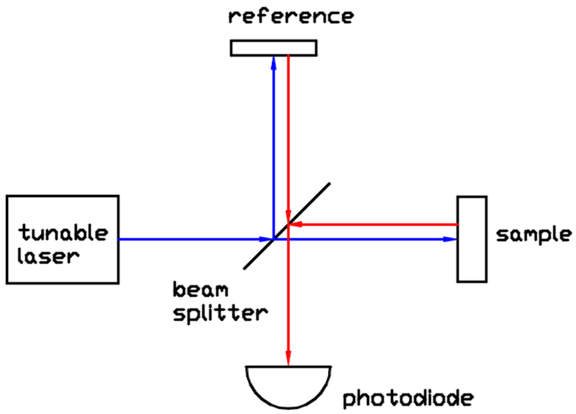

Fig. 5. The diagram of SS_OCT.

Pulse propagation in optical fiber in nonlinear conditions

If the fiber loss is ignored nonlinear Schrodinger equation takes the following form [10]:

$$\frac{\partial B}{\partial z} - j\frac{\mathrm{sgn}(\beta_2)}{2L_D}\frac{\partial^2 B}{\partial T^2} + j\frac{1}{L_{NL}}|B|^2 B = 0 \quad (8) \qquad A(z,T) = \sqrt{P}B(z,T) \quad (9)$$

$$L_D = \frac{\tau_0^2}{|\beta_2|} \ \text{:dispersion length} \quad (10) \qquad L_{NL} = \frac{1}{\gamma P} \ \text{:nonlinear length} \quad (11)$$

Where, $B(z,T)$ is the normalized pulse, β_2 is GVD factor, γ is nonlinearity coefficient and P is peak power of pulse. Now if the fiber length L is selected in a way that $L \ll L_D$ and $L \geq L_{NL}$, under such conditions the effective factor on propagation is the nonlinearity and thus, the dispersion could be neglected. Therefore, equation (8) takes the following form [10]:

$$\frac{\partial B}{\partial z} = -j\frac{1}{L_{NL}}|B|^2 B \quad (12)$$

By solving the equation of (12), following equations are obtained:

$$B(z,T) = B(0,T)e^{j\varphi_{NL}(z,T)} \quad (13) \qquad \varphi_{NL}(z,T) = |B(0,T)|^2 \frac{z}{L_{NL}} \quad (14)$$

If we consider a Gaussian input pulse :

$$B(0,T) = \exp\left(-(1+iC)\frac{T^2}{2T_0^2}\right) \quad (15)$$

Where, C is the chirp parameter and if it is equal to zero, the pulse is not initial chirped, if it has a positive value, the pulse is up-chirped, and if it has a negative value, the pulse is down-chirped. If the input pulse is an unchirped or an upchirped pulse, SPM causes its bandwith to increase while in the case of a downchirped pulse, the bandwidth decreases [10].

Problem statement and the proposed solution

As it was mentioned in introduction section, to increase the image resolution in OCT system, according to equation (1), the bandwidth of the light wave must be increased.

In the proposed approach, the pulse first is up-chirped with the help of a grating pair before propagating in the fiber. It will be shown that under such conditions, in comparison with the case of an un-chirped pulse, in addition to increasing the bandwidth, a better pulse shape is obtained. The diagram of the proposed approach is shown in Figure 6.

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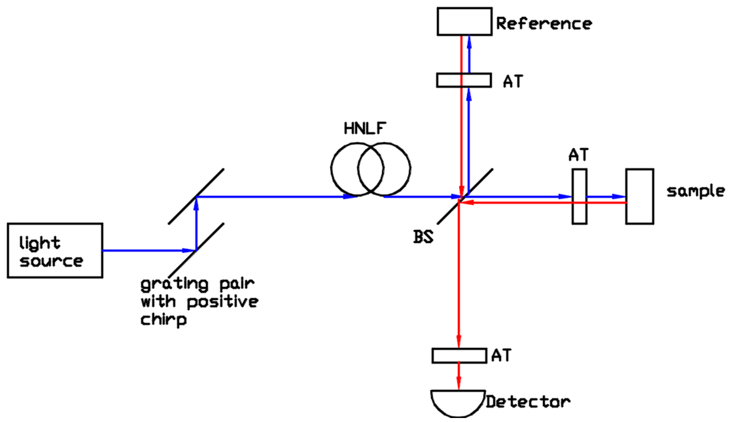

Figure 6. The proposed approach for increasing the resolution and SNR of OCT system

RESULTS AND DISCUSSION

In the approach proposed in this paper, a light source with a pulse width of $0.5ps$, central wavelength of 1550 nm, an average optical power of 20 mw and a repetition rate of 20 MHz is used. After being up-chirped by a grating pair, it enters the fiber coil of the source arm with a peak power of about 200 Watts. Although, to make sure that the sampled tissue and the detector would not be damaged also, to establish a balance between the pulses of the reference and the sample arms, attenuators (AT) are used in all three OCT arms so that their optical power is limited to about 20 mW.

If a highly nonlinear fiber with $|\beta_2| = 2\frac{\mathrm{ps}^2}{\mathrm{km}}$ and $\gamma = 14(1/\mathrm{kmw})$ [11] is used, considering Eq. (10) and (11), the following values are obtained for dispersion length and nonlinearity length in the source arm:

$$L_D = \frac{0.5^2\, ps^2}{2\frac{\mathrm{ps}^2}{\mathrm{km}}} = 125 \text{ m} \qquad (16) \qquad\qquad L_{NL} = \frac{1}{(14*200)1/km} = 0.35 \text{ m} \qquad (17)$$

As it was mentioned before, in order to put the pulse in the SPM range, the conditions of $L \geq L_{NL}$ and $L \ll L_D$ must be satisfied. Therefore, the fiber length is selected within the following range:

$$L_{NL} < L < \frac{1}{10}L_D \rightarrow 0.35m < L < 12.5m \qquad (18)$$

For the case that the pulse is up-chirped with $c = +8$ simulation results for different fiber lengths are shown in Figure 7. The FWHM is 34 nm at fiber input (z=0) and reaches 70 nm at $z = 2.1$ meters fiber length, and according to equation (1), resolution is doubled.

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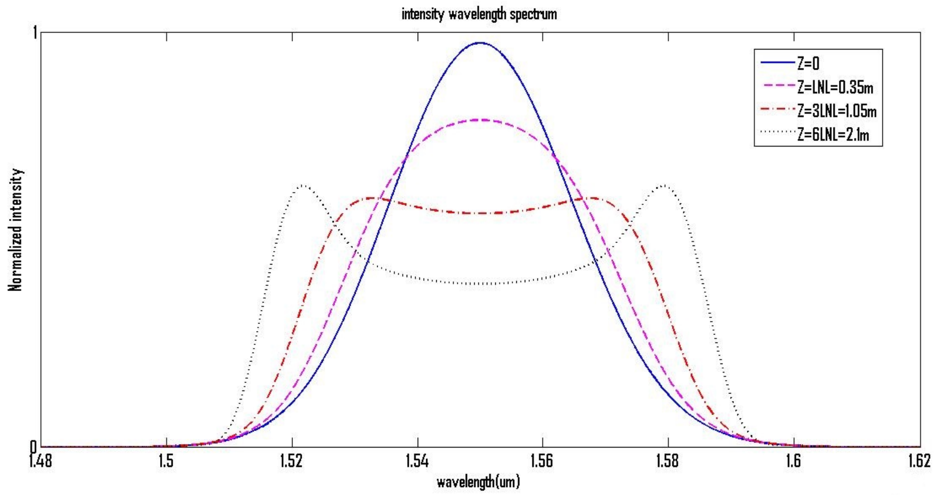

Figure 7. Increasing the spectrum bandwidth of an initially up-chirped pulse

For the case that the pulse is not chirped before propagating in the fiber, simulation results for different fiber lengths are shown in Figure 8. Spectrum shape and bandwidth in the up-chirped case is better than that of the un-chirped case therefore, the image quality will be better when the pulse is initially up-chirped.

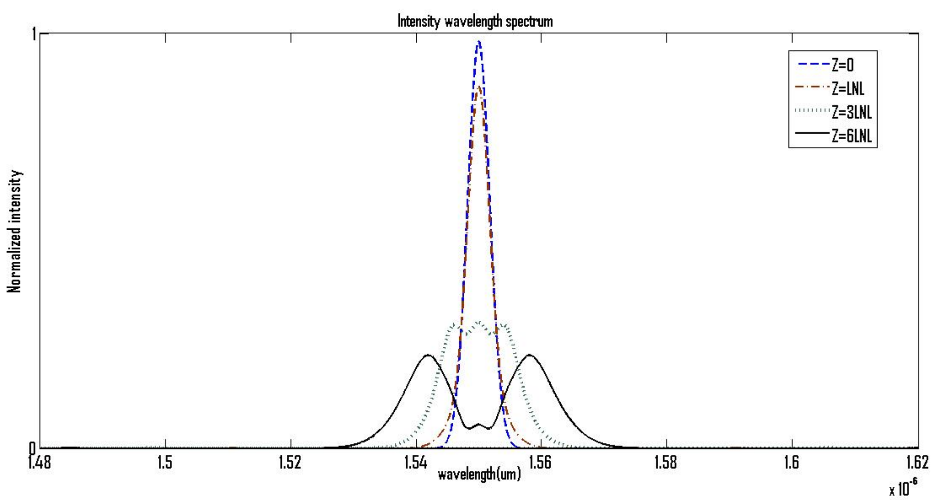

Figure 8. Increasing the spectrum bandwidth of an un-chirped pulse in the source arm

CONCLUSION

In this paper, a method has been presented for increasing the image resolution and SNR in OCT imaging. To do so, the nonlinear feature of light propagation has been used. To increase the image resolution, by up-chirping the pulse and propagating it in an optical fiber, SPM increased the light bandwidth in the source arm, and it was shown that in addition to increasing the bandwidth, a better spectrum shape is obtained in comparison with the un-chirped case.

REFERENCES

[1] Brezinski ME. Optical Coherence Tomography principles and Applications. 1nd ed. USA: Academic Press, 2006.
[2] Aljasem KH. Research in Micro-optics. Ph.D, IMTEK University of Freiburg, Germany, 2010

Submit Date: 12.09.2016, Acceptance Date: 05.10.2016, DOI NO: 10.7456/1060NVSE/080

[3] Youngquist RC, Carr S, Davies DEN. Optical Coherence-Domain Reflectometry: A New Optical Evaluation Technique. Opt. Lett. 1987;12:158-160.

[4] Drexler W, Morgner U, Kartner FX, Pitris C, Boppart SA, Li XD, Ippen EP, Fujimoto JG. In vivo ultrahigh-resolution optical coherence tomography. Opt. Lett. 1999;24:1221-1223.

[5] Bourquin S, Aguirre AD, Hartl I, Hsiung P, Ko TH, Fujimoto JG, Birks TA, Wadsworth W, Bunting U, Kopf D. Ultra high resolution real time OCT imaging using a compact femtosecond Nd:Glass laser and nonlinear fiber. Opt. Express 2003;11: 3290-3297.

[6] Ranka J. K, Windeler RS, Stentz AJ. Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm. Opt. Lett. 2000; 25:25-27.

[7] Hartl I, Li XD, Chudoba C, Ghanta RK, Ko TH, Fujimoto JG. Ultrahigh-resolution optical coherence tomography using continuum generation in an air–silica microstructure optical fiber. Opt. Lett. 2001;26: 608-610.

[8] Gaeta AL. Nonlinear propagation and continuum generation in microstructured optical fibers. Opt. Lett.2002; 27: 924-926.

[9] Wang Y, Tomov I, Nelson JS, Chen Z. Low-noise broadband light generation from optical fibers for use in high-resolution optical coherence tomography. Opt. Soc. Am. A 2005;22:1492-1499

[10] Agrawal GP. Nonlinear Fiber Optics 3nd ed. USA: Academic Press, 2001

[11] Okuno T, Hirano M, Nakanishi T, Onishi M. Highly-nonlinear Optical Fibers and Their Applications. SEI TECHNICAL REVIEW. 2006;62:34-40

[12] Bouma BE & Tearney GT, Handbook of Optical Coherence Tomography, 1nd ed. Marcel Dekker Inc.,2002

[13] Drexler W & Fujimoto JG, *Optical Coherence Tomography Technology & Applications* , Springer Inc,2008

[14] Newbury NR, Washburn BR, Corwin KL, and Windeler RS. Noise amplification during supercontinuum generation in microstructure fibers," Opt. Lett. 2003; 28: 944–946.

[15] Sorin WV and Baney DM, "A simple intensity noise reduction technique for optical low-coherence reflectometry," IEEE Photonics Technol. Lett. 1992; 4; 1404–1406.

Submit Date: 12.09.2016, Acceptance Date: 05.10.2016, DOI NO: 10.7456/1060NVSE/080