U.P.B. Sci. Bull., Series A Vol. 71, Iss. 1, 2009 ISSN 1223-7027

TWO SPECTRAL SHAPING METHODS OF A BROADBAND FIBRE SOURCE FOR BIOMEDICAL OCT IMAGING

Ramona CERNAT[1], George M. DOBRE[2], Adrian Gh. PODOLEANU[3]

Autorii raportează două metode de investigare pentru modelarea spectrului unei surse optice de bandă largă (BBS) spre a fi folosită în Tomografia prin Coerenta Optica (OCT). BBS emite intre 450 si 1750 nm şi este folosită selectiv în multiple benzi spectrale. Modelarea spectrului este realizată cu (i) filtre optice (combinaţie de filtre dicroic şi trece banda poziţionate la diverse unghiuri de incidenta) şi (ii) dubla trecere a fasciculului printr-o secventa de 2 prisme (un cub divizor, două prisme echilaterale şi o oglinda metalică) ce oferă posibilitatea de a selecta unele caracteristici ale spectrului (lungimea de undă centrală, largimea de banda spectrală). BBS permite obţinerea de imagini OCT cu o rezoluţie în adancime de 2 µm sau mai bună. Rezoluţia în adâncime face din BBS o sursă optică potrivită pentru obţinerea de imagini OCT în embriologie, cultura celulelor şi imagistica ochiului, investigaţii ce vor completa tradiţionalele investigaţii de imagistică prin fluorescenţă şi cea confocală

The authors report two investigation methods into the spectral shaping of an optical broadband source (BBS) to be used in Optical Coherence Tomography (OCT). The BBS spectrum extends from 450 nm to 1750 nm and is selectively used in multiple spectral wavebands. Spectral shaping is performed with: (i) an optical filter unit (a combination of dichroic and bandpass filters at different incident angles) and (ii) a double-pass prism sequence (a cube beam splitter, two equilateral prisms and a metallic mirror) which allow the freedom to select the characteristics of the spectrum (central wavelength, spectral bandwidth). BBS can allow imaging with a depth resolution of 2 µm or better. Such a high depth resolution makes BBS suitable for OCT imaging in embryology, cells culture and eye imaging, investigations which will complement the more traditional fluorescence labelling and confocal imaging.

Keywords: Optical coherence tomography, spectral shaping, multiple spectral wavebands, depth resolved imaging

[1] Drd. Researcher, School of Physical Sciences, Applied Optics Group, University of Kent, Canterbury, UK, email:R.Cernat@kent.ac.uk, National Institute for Lasers, Plasma and Radiation Physics (NILPRP), 409 Atomistilor, P.O. Box: MG-36, 077125, Bucharest, Romania
[2] School of Physical Sciences, Applied Optics Group, University of Kent, Canterbury, UK
[3] Prof., School of Physical Sciences, Applied Optics Group, University of Kent, Canterbury, UK

1. Introduction

Optical coherence tomography (OCT) is an established non-invasive technique which has proved its utility in a variety of imaging applications from clinical to multilayered structures of paintings and highly scattering materials such as ceramics and plastics [1-3]. Greater emphasis is now being placed on functional imaging at a variety of wavelengths, which calls for the ability to use sources with adequate outputs in a variety of spectral windows. The most commonly used sources in OCT are superluminescent diodes (SLDs), which operate predominantly in the 800 nm and 1300 nm windows. Only devices of comparatively smaller power exist yet in the blue, yellow and red ranges. Other sources have been reported for these wavelengths such as the Kerr lens mode locked laser, but these tend to be expensive, bulky and relatively costly to maintain, although research continues to advance in this respect. Recently, research in fibre lasers made possible the introduction to the market of broadband turnkey systems [4, 5].

This paper reports investigations into the spectral shaping of an optical broadband source (BBS) which provides through a combination of highly nonlinear components, a supercontinuum of light from 450 nm to 1750 nm in an all fibre configuration. BBS (Fianium SC450, Fianium Ltd., Southampton). The source operates at 1064 nm central wavelength and consists of a Yb-doped fibre laser, a high power fibre amplifier and a highly nonlinear photonic crystal fibre (PCF). The output of the BBS is delivered into a 3.3 mm wide collimated beam with a power spectral density of greater than 2 mW/nm.

In this work we evaluate the process of spectral shaping of the BBS output into several spectral windows using two methods: an optical filter unit (a combination of dichroic and bandpass filters at different incident angles) and a double-pass prism sequence (a cube beam splitter (BS), two equilateral prisms and a metallic mirror).

A single mode optical fibre (SMF) was used at the output of the optical filter unit for ease of light routing and high spatial coherence. However, an all fibre implementation cannot cover the entire spectrum from blue to IR, since the fibre introduces its own filtering and limits the optical waveband that could be transferred to the input of the scan head in an OCT system. Depending on the wave-guiding properties of the SM used, only certain spectral windows can be transmitted to the arms of the interferometer. Due to this limitation, the double-pass prism sequence was considered as an alternative way to enable a finer control of the spectral shaping. Furthermore, in order to avoid SMF filtering effects, the interferometer is entirely in bulk. This enables better control of the spectral characteristics of the light in both arms of the OCT interferometer set-up (two key parameters being the central wavelength (λ_c) and the spectral bandwidth ($\Delta\lambda$)).

A recent report of coherence imaging presents two separate spectral bands using a similar PCF based broadband supercontinuum generation for ultrahigh resolution OCT [6]. A double-pass prism sequence was considered and reported to have been used to simultaneously separate two wavelength bands at 840 and 1230 nm for ultrahigh resolution OCT.

Our two proposed methods for the spectral shaping of the broad emission spectrum of the 1200 nm wide BBS allow the freedom to select a suitable spectral window for any wavelength in bands where OCT had been previously demonstrated, i.e. 700-900 nm, 1000-1100 nm and 1200-1500 nm.

Future work will concentrate on the use of the shaped spectra in different configurations for OCT imaging in embryology, cell culture, artificial tissue scaffoldings and eye imaging.

2. Experimental setup

In the following sections (2.1 and 2.2) the experimental arrangements for the spectral shaping of the BBS will be described, using an optical filter unit (a combination of dichroic and bandpass filters at different incident angles) and a double-pass prism sequence (a cube beam splitter (BS), two equilateral prisms and a metallic mirror). Spectrally shaped spectra will be used as input to the OCT systems based on a configuration of balanced detection, usually a balanced detection interferometer, whose schematic diagram will be presented in section 4.

2.1. Method A: Optical filter unit

Spectral shaping of the BBS was first carried out with an optical filter unit which contains a combination of dichroic and bandpass filters at different incident angles. A schematic diagram of the experimental arrangement is presented in Fig. 1.

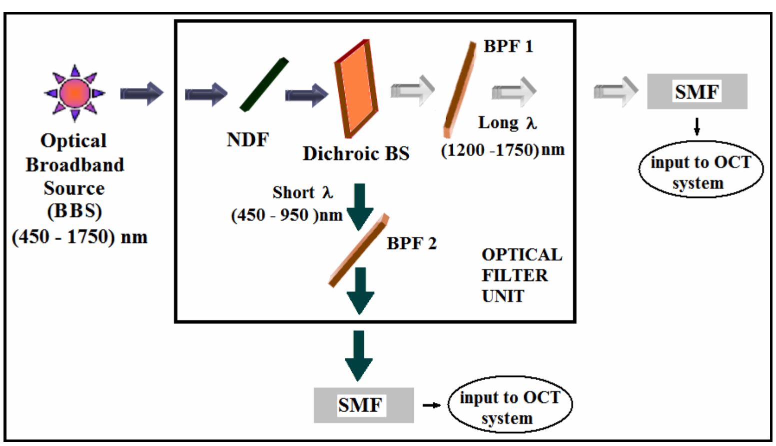


Fig. 1. Schematic diagram of the experimental arrangement for the spectral shaping using the optical filter unit which consists of: neutral density filter -NDF, dichroic beam splitter - BS, BPF 1 and BPF 2 - bandpass filters. SMF – single mode fibre

The optical filter unit consists of a neutral density filter (NDF), a dichroic beam splitter BS (875dcxr, Chroma Tech. Corp.) and two bandpass filters BPF 1 (812 nm, Iridian Spectral Tech.) and BPF 2 (1235 nm, Omega Optical). The dichroic BS with a transition wavelength at 850 nm is used to split the entire broad spectrum of the BBS in two wavelength bands: short wavelengths band [(450-950) nm] and long wavelength band [(950 – 1800) nm], so they can be used simultaneously in two different OCT systems.

BPF 1 transmits light between 790 nm and 950 nm while BPF 2 between 1200 nm and 1800 nm. BPF2 was used to block the residual pump laser emission at 1064 nm which is not converted into supercontinuum radiation within the PCF. After propagating through the optical filter unit, the light in selected spectral windows is launched into SMFs which are used to transfer light towards the OCT systems.

2.2. Method B: Double-pass prism sequence

Method A (using an optical filter unit and a connectorised SMF with an important alignment simplicity advantage) required a suitable spectral window selection to be carried out on the light in accordance with the fibre wave-guiding properties, and also required replacing the SMF every time a new waveband was investigated. Method B on the other hand, consisting of a double-pass prism sequence with no fibre elements, was considered in order to exert a better control over the central wavelength and the spectral bandwidth of light. This method is also better suited to explore a variety of spectral windows. A schematic diagram of the experimental arrangement is depicted in Fig. 2.

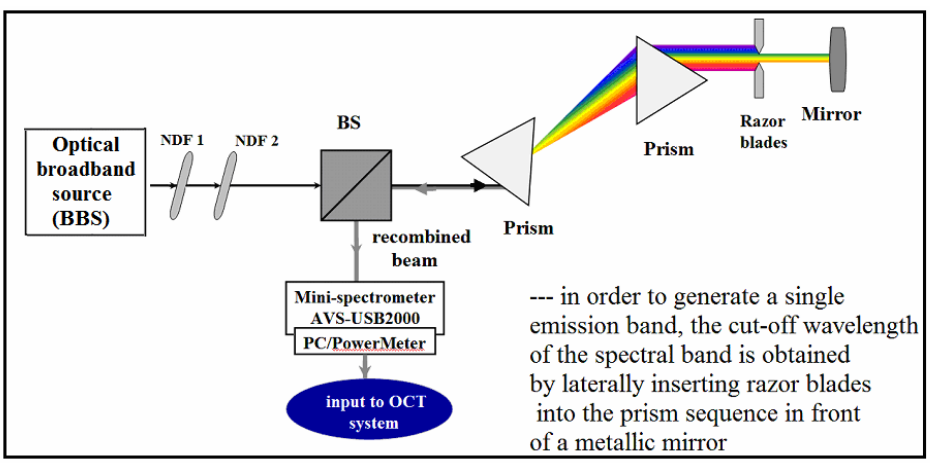


Fig. 2. Schematic diagrams of the experimental arrangement for the spectral shaping using a double-pass prism sequence: NDF 1 and NDF 2 - neutral density filters, BS - cube beam splitter

Light from the BBS attenuated with two neutral density filters (NDF 1 and NDF 2) is launched into the double-pass prism sequence which consists in a cube beam splitter BS (50/50 ratio), two equilateral prims and a metallic mirror. In order to generate a controlable emission band, the lower and upper cut-off wavelength are determined by inserting razor blades into the beam path. Spectrally shaped light reflected from the mirror returns through the BS whose outputs are coupled (i) into a mini-spectrometer/power meter (in order to monitor and control its characteristics) and (ii) to the OCT system input.

3. Experimental results

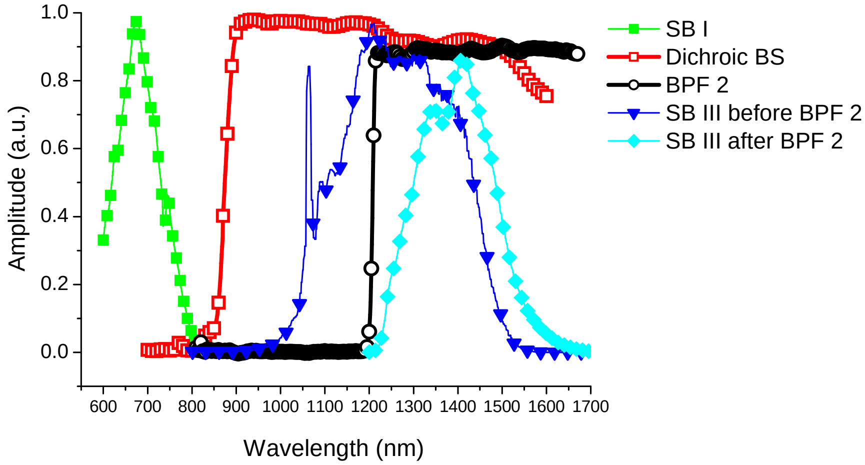
3.1 Optical filter unit

Figures 3 a and b display examples of the resulting spectra in the regions of interest for our study which show how the optical filter unit splits the entire spectrum of the BBS. The dichroic BS was used to isolate the short wavelength band [(450-950) nm] from the long wavelength band [(950 – 1800) nm], so they can be used simultaneously in two different OCT systems.

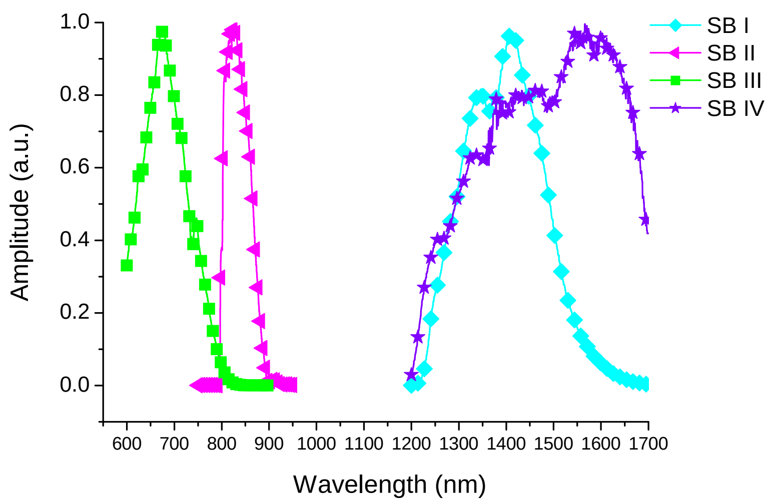
The short wavelength band is separated into two regions: spectral band (SB) I [(550 – 800) nm] and SB II [(800 – 950) nm]. SB I was obtained by launching the light into a SMF (Thorlabs FS-SN-3224, operating wavelength λ_{op} = 630 nm and the second mode cutoff wavelength λ_{cutoff} < 620 nm). SB II was selected by using BPF 1 which has a transmission between 790 nm and 950 nm and launching light into a SMF (Thorlabs FS-SN-4224, λ_{op} = 820 nm and λ_{cutoff} < 780 nm).

The long wavelength band is separated into SB III [(1200 -1500) nm], and SB IV [(1200 -1800) nm] by simply launching light into a SMF (Thorlabs FS-SC-6324, λ_{op} = 1300 nm and λ_{cutoff} < 1270 nm) and SMF (Thorlabs FS-SC-7324, λ_{op} = 1550 nm and λ_{cutoff} < 1500 nm) respectively. BPF 2 with a transmission between 1200 nm and 1800 nm was used in order to block the pumping peak at 1064 nm.

The spectral characteristics of the dichroic BS and BPF 2, and the spectra in SB I as well as SB III before and after using BPF 2 are presented in Figure 3 a. Figure 3 b shows the resulting spectra in each of the four spectral bands after using the optical filter unit.



a)



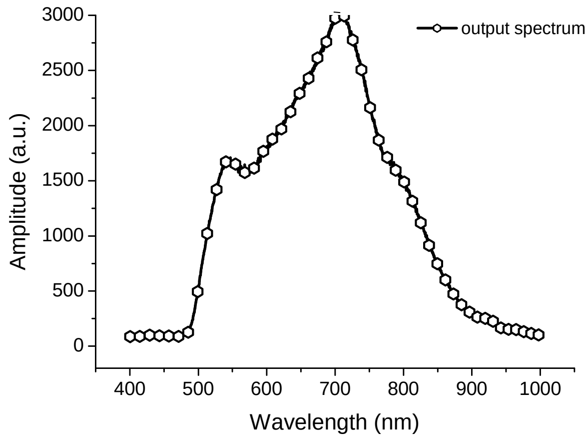
b)

Fig. 3 a) Normalized spectra at the BBS output using the dichroic BS and the BPF 2 to obtain SB I and SB III;
b) Normalized spectra obtained after separation of the BBS output into SB I, II, III and IV after using the optical filter unit.

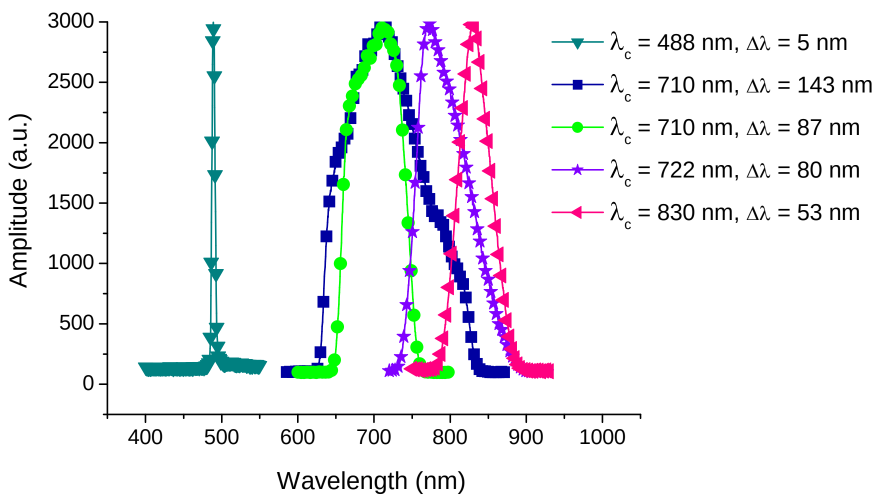
The measured spectral curves are limited to the (600 – 1700) nm spectral window imposed by the optical spectrum analyzer used for these measurements.

3.2 Double-pass prism sequence

Figure 4 a) displays the output spectrum of the BBS measured with a MiniSpectrometer (AVS-USB2000) and b) the normalized resulting spectra for different λ_c and $\Delta\lambda$ values after spectral shaping using the double-pass prism sequence.



a)



b)

Fig. 4 a) Normalized output spectrum of the BBS measured with a MiniSpectrometer (AVS-USB2000) and b) Normalised shaped spectra using the double-pass prism sequence for different central wavelength (λ_c) and spectral bandwidth values ($\Delta\lambda$)

The lower and upper cut-off wavelengths of the shaped spectra are controllable using razor blades. By shifting these laterally, λ_c and $\Delta\lambda$ can be finely selected (from $\Delta\lambda$ = 5 nm at λ_c = 488 nm up to $\Delta\lambda$ >140 nm at λ_c = 710 nm or more). The experimental results are presented into the [400 - 1000] nm spectral window due to the range limitation of the spectrometer used (AVS-USB2000).

4. Experimental OCT setup

The time-domain OCT systems to be driven by the spectrally shaped spectra are based on a configuration of balanced detection, usually a balanced detection interferometer which requires two optical splitters [7].

The OCT configuration contains an object-reference splitter (optical fibre or bulk beam splitter) and a single-mode directional coupler which leads to the balanced photo-receiver. The operating wavelength of each OCT system dictates the wavelength band of choice in each case. Shaped spectra obtained from the BBS (using either method A or B) are amplitude-divided into a reference beam and an object beam. In the object arm, a pair of galvanometer scanners (MX, MY) is used to scan the beam across the target via interface optics. A generic schematic diagram of the OCT configuration is presented in Figure 5.

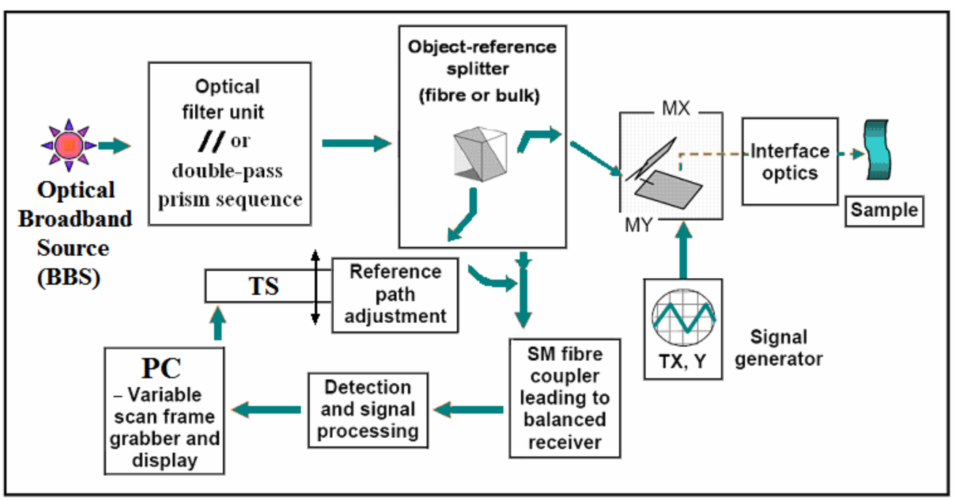


Fig 5. Schematic diagram of the OCT configurations: TS – translation stage; MX, MY - galvanometer scanners; PC – personal computer

The reference path is adjusted by a micrometer precision PC-controlled translation stage (TS). The reference beam and the beam that returns from the sample via the interface optics and the galvanometer scanners interfere in the

50/50 single-mode directional coupler. The outputs of the single-mode directional coupler are balance-detected, and the photo-currents are further processed through rectification, envelope finding and grayscale encoding to provide the OCT signals. A variable-scan frame grabber is used to display the OCT images.

In order to evaluate the axial resolution of the BBS in the OCT imaging configuration described above, the auto-correlation function was measured (Fig. 6).

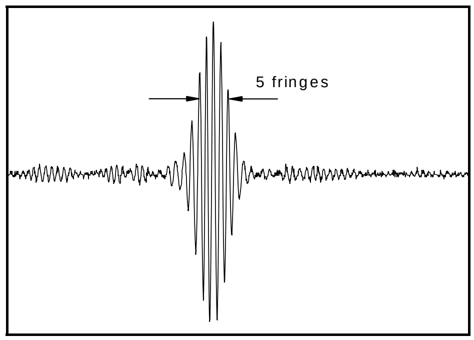


Fig. 6. Auto-correlation function measured for a fibre-based OCT system for an input spectrum shaped with the optical filter unit method (λ_c = 1350 nm and $\Delta\lambda$ = 268 nm)

To measure the autocorrelation function, a fibre-based OCT system was considered [8]. The auto-correlation trace was obtained for a spectrally shaped input spectrum with the optical filter unit method (λ_c = 1350 nm and $\Delta\lambda$ = 268 nm). The data shown in Figure 6 indicates a depth resolution value of ~ 3.4 µm corresponding to 5 fringes (compared with the theoretical prediction of 3 µm).

5. Conclusions

We demonstrate the suitability of a commercial optical broadband source (BBS) for use in OCT. The BBS spectrum covers a wide range of wavelengths, from 450 nm to 1750 nm. Spectral windows at various wavelengths were spectrally shaped using two methods: an optical filter unit and a double-pass prism sequence. The optical filter unit consists in a combination of optical filters at different incident angles which provide several selectable spectral wavebands such as {SB I [(550 – 800) nm], SB II [(800 – 950) nm], SB III [(1200 – 1500) nm], and SB IV [(1200 -1800) nm]}.The second implemented method based on a double-pass prism sequence allows a better control of the spectral shaping of the BBS output to be used in different OCT systems where the central wavelength (λ_c) and spectral bandwidth values ($\Delta\lambda$) are finely selected from 5 nm at 488 nm up to 268 nm at 1350 nm or more. This shows that a great variety of light delivery options are possible for coherence imaging, based on the principles presented here. Systems using such tailored light at the input are anticipated to be very versatile, particularly if adapted for extended band operation (>250 nm), and hold the promise of very specialised wavelength-specific coherence imaging as well as being capable of ultra-high resolution (better than 1 micron) made possible by the wide spectra that have been obtained.

Future work in OCT requires spectrally shaped spectra in different configurations which demand different spectral windows: embryology, cell culture, artificial tissue scaffoldings, art conservation and eye imaging.

REFERENCES

[1] *Brett E. Bouma, G. J. Tearney,* "Clinical Imaging with Optical Coherence Tomography" Academic Radiology, Vol **9**, No 8, August 2002, pp. 942-953

[2] *H. Liang, M. Gomez Cid, R.G .Cucu, G. M. Dobre, A. Gh. Podoleanu, J. Pedro, D. Saunders*, "En-face optical coherence tomography – a novel application of non-invasive imaging to art conservation" Opt. Express **13***,* 2005, pp. 6133 - 6144

[3] *M. Bashkansky, M. D. Duncan and J. Reintjes,* "Detection of near-surface microscopic defects in ceramics and other materials using Optical Coherence Tomography" CP509, Review of Progress in Quantitative Nondestructive Evaluation, edited by D. 0. Thompson and D. E. Chimenti American Institute of Physics l-56396-930-0, 2000

[4] Fianium: http://www.fianium.com

[5] Koheras: http://www.koheras.com

[6] *F. Spoler, S. Kray, P. Grychtol, B. Hermes, J. Bornemann, M. Forst, and H. Kurz*, "Ultrahigh resolution OCT at two infrared wavelength regions using a single light source", Proc. of SPIE-OSA Biomedical Optics, Vol. **6627**, 2007, pp. 662704-1—662704-8

[7] *D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto,* Science **254,** 1178, 1991.

[8] *A. Bradu, L. Ma, J.Bloor and A. Podoleanu,* "Versatile confocal/optical coherence tomography system for embryonic developmental imaging", Proc. of SPIE, Vol. **6847**, 2008, pp. 68471W-1—68471W-6.