Broadband blue light for Optical Coherence Microscopy

Sylwia Maliszewska, Maciej Wojtkowski,*

Institute of Physics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun

Received November 15, 2011; accepted December 16, 2011; published December 31, 2011

Abstract−Optical coherence microscopy (OCM) is relatively new, noninvasive method of biomedical imaging. It uses Michelson interferometer to locate successive layers in tissue and enables reconstructing cross-sectional images that can be useful for medical diagnosis. In this work, we propose to develop new light sources for OCM to increase the resolution of images by introducing blue light. To achieve this goal, we decided to test a method known as achromatic second harmonic generation in our own, new configuration.

Current advancements of laser technology are drawing more and more attention of scientists and engineers to the possibility of using high-energy and spectrally broadband light in many regions of science and technology. The range of applications spreads from telecommunications through materials engineering, near-infrared spectroscopy even to applications of optics in biology and medicine. A new class of imaging and functional analysis techniques has emerged in biomedical optics, which is called Optical Coherence Imaging (OCI) [1, 2]. The useful information in OCI is closely related to statistical properties of light. In this group, there can be discerned various methods such as Optical Coherence Tomography (OCT) [3, 4], Optical Coherence Microscopy (OCM) [5], interferometric phase-contrast microscopy [6], optical coherence elastography [7-9], phototermal imaging [10], magnetomotive imaging [11]. The greatest advantages of these methods are their non-invasiveness and non-contact operation while applied to imaging of semi-transparent biological structures. Spectral windows of light used in OCT and OCM are usually in near infrared region – the central wavelengths here are usually 1300nm, 1050nm and 800nm.

One of the most important features of Optical Coherence Imaging is the ability of performing axial sectioning. From many perspectives, this method can be treated as an extended version of confocal microscopy with extra coherence gating [2, 12]. The ability of axial sectioning in OCT and OCM determines the transverse resolution of these techniques, which depends directly on the central wavelength (λ_0) of applied light and its full width at half-maximum, FWHM, ($\Delta\lambda$):

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

with the assumption that the incoming beam has a Gaussian spectral shape and it travels through the air. The immediate conclusion regarding Eq. (1) is that the axial resolution, or the resolution in the direction of beam propagation in a sample, of an image improves linearly while using broader spectra (assuming that the central wavelength does't change) and, what is more important, quadratically while using shorter wavelengths (assuming here that the wavelength span doesn't change). That's why to obtain the same resolution for two times shorter central wavelength, one needs to get four times narrower wavelength span. Using four times narrower wavelength span is especially convenient in Fourier domain OCT due to the fact that the construction of the spectrometer becomes less sophisticated in contrast to the ones currently utilized in OCT setups which need to disperse 300-nm wide wavelength span with decent resolution and image it by 10μm pixel of a line scan sensor. However, the price that has to be paid while using shorter wavelengths is limited penetration depth in a sample and limited applicability of these methods to regular corneal and retinal eye imaging. On the other hand, absorption of visible light in water is much lower in comparison to the absorption of NIR light. Apart from that, using shorter wavelengths improves lateral resolution of OCT images due to the smaller size of the beam in the focal point of a lens. Lateral resolution (δx) depends on numerical aperture of the lens used for imaging (NA) and the central wavelength of the light:

$$\delta x \propto \frac{\lambda_0}{NA} \qquad (2)$$

Thus, utilization of light in the visible region in Optical Coherence Microscopy measurements would enable imaging with high sensitivity and better lateral resolution at lower optical power of light illuminating the object.

Light used for Optical Coherence Imaging is usually characterized by broad spectral width (50-300nm) and high power density. One of possible ways to get to the visible radiation with such properties (especially for shorter optical wavelengths – blue and violet) is by using second harmonic generation (SHG). SHG is a nonlinear optical process that occurs most abundantly in anisotropic crystals while illuminated by high power laser radiation. The intensity of second harmonic generation (I_2) is proportional to l – the length of the crystal, n_1 and n_2 – refractive indices of the fundamental beam (characterized by the frequency ω_1 and intensity I_1) and second harmonic beam (characterized by the frequency $2\omega_1$ and intensity I_2), respectively, as follows:

* max@fizyka.umk.pl

$$I_2 \propto l^2 I_1^2 \left[\sin c\left(\frac{\omega_1}{c}(n_2 - n_1) l \right) \right]^2, \qquad (3)$$

where c is the velocity of light in vacuum.

The intensity of the second harmonic has its maximum value when $n_1=n_2$ and from there rapidly decays when this condition, known as a phase-matching condition, is not met. It means that, in a dispersive medium, the phase-matching condition can be fulfilled only for small window of optical frequencies – fwhm of emitted radiation should be small. To compensate for this condition, thinner crystals (which implies smaller l in *sinc* argument) can be used. Theoretical simulations show that to get satisfying 40nm of FWHM of the spectral span, very thin crystal should be utilized – its thickness should not exceed a few tens of micrometers, which causes a practical problem with manufacturing and substantial expenses. However, it is easily noticed in formula (3) that intensity of the second harmonic component depends on the thickness l of the nonlinear crystal, so the conversion efficiency would dramatically decrease making generated SH light very hard to employ in OCT.

To obtain broad bandwidth, the group of methods known as achromatic second harmonic generation is introduced. Its main concept is to direct laser light in many different, but appropriate, directions simultaneously onto the crystal so that the phase-matching condition is met for different wavelengths at the same time [13].

Our approach, however, is to divide Ti:Sapphire laser beam in several separate beams of the same statistical properties (and of energy several times smaller, of course) and focus those clone-beams with appropriate lens on the nonlinear crystal to generate different regions of blue light by SHG process in the crystal. We are not focusing here on pulse properties of the beam. The most important feature of light that is planned to be used in Fourier domain OCM measurements is the spectral bandwidth which spectrometer has to disperse and analyze. Such synthesized spectrum may be obtained by superposition of light generated in independent SHG processes. In this work we proposed using a diffraction element to split our initial beam into multiple beams illuminating the SHG crystal. Our choice was dictated by the fact that such solution would enable some flexibility in the shaping of the blue spectrum in the setup, especially when we don't have to care about the shape of the pulse. On the other hand, using diffractive element will always cause some chromatic effects, but it was shown earlier that those effects can be compensated by a careful design of diffractive and refractive elements [14].

To generate broadband blue light, the experimental setup presented in Fig. 1 was constructed. Light coming from Ti:Sapphire laser (central wavelength: 778nm, FWHM: 100nm, power during mode-locked operation: 230mW) passes through half-wave plate which orients accordingly the polarization of light in crystal and then illuminates the diffractive element D8 (the *1x8 spot array generator* from Tessera, formerly Digital Optics Corp.) that generates 8 beams with similar optical powers and properties. Each beam is focused by the lens (f=19mm) on the crystal (BBO, 0.5 mm thick, cut angle: Θ=28.9°).

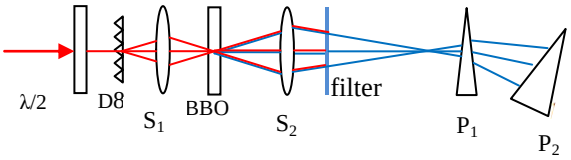

Fig. 1. Schematic of the setup for achromatic SHG. S_1, S_2 – lenses of focal lengths equal to 19mm, 50mm, respectively, λ/2 – half-wave plate, D8 – diffractive element dividing laser light in 8 energetically equal clone-beams, BBO – nonlinear anisotropic crystal, P_1, P_2 – prisms of apex angles 16° and 36°.

Afterwards, a color filter blocks the fundamental beam and lens (f=50mm) collimates each blue beam. Unfortunately, focused beams are not parallel to each other. In order to create one collimated beam two extra prisms P_1, P_2 were introduced. Collimated blue light is then focused onto the pinhole of 5μm aperture.

To test the performance of proposed device, the spectrum of each component of blue light was detected separately (before it was merged to one collimated beam) on the spectrometer (Fig. 2).

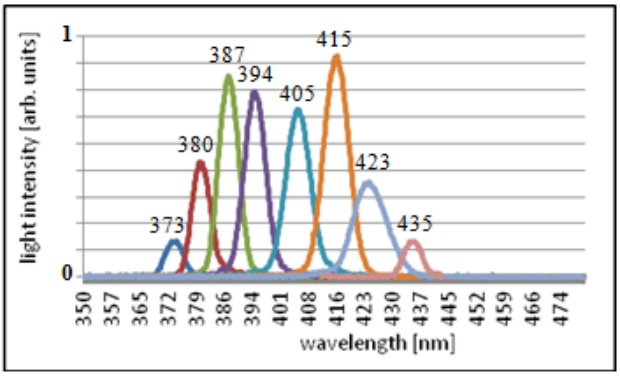

Fig. 2. Spectra of SHG beams generated by diffractive element D8. Central wavelength of each component is indicated as a number above the spectra.

We came across some severe difficulties while trying to gather generated blue beams together. The theoretical simulation based on earlier measurements of spectra of 8 blue beams and their geometry after leaving the filter indicated that putting two 16° and 36° prisms with proper orientation with respect to each other and with respect to incoming light would make those beams collimated and parallel to each other. Unfortunately, in the experiment we had to compromise the collimation of each component and collimation of all components. The closest we got to

the goal was when the prisms where illuminated under very steep angles. To check the parallelism of the blue beams, a lens f=75mm was put, and the focal plane was imaged by a ccd camera (Figs. 3 and 4). In the ideal situation the focal points of each beam would be in the same spot.

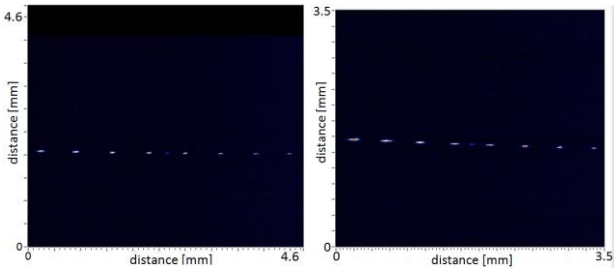

Fig. 3. Location of the focal points of multiplexed blue SHG light using the lens of f=75mm (left) without a prism – the distance between most right and most left beam is about 4.42mm (right) with the prism of apex angle 36°, the angle of incidence of light is taken from the simulation (the distance – about 3.26mm).

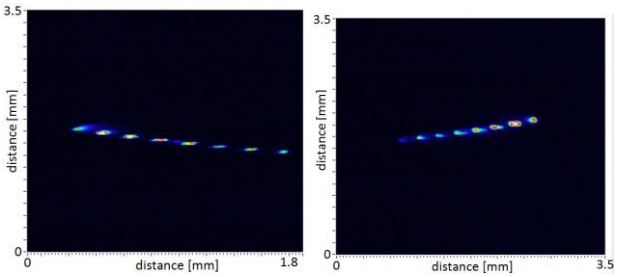

Fig. 4. Location of the focal points of multiplexed blue SHG (left) when the beams illuminate the prism of apex angle 36° under very acute angles (right) the beams illuminate the prisms of apex angle 36° and 16° under very acute angles.

Optimal orientation of prisms, however, caused broadening of the spatial cross-section of the blue beams. In this case the focusing on the pinhole decreased optical power of the transmitted beam so the beam could not have been spectrally analyzed.

In presented paper we made the first attempt to achieve a broadband blue and violet radiation for use in OCT and OCM. We proposed using a multibeam method of second harmonic generation. The first proposed configuration enabled to achieve broadband blue radiation split into 8 separate beams. However, this method turned out to be hard to implement due to power-inefficient combination of all blue light sub-beams into one collimated parallel beam.

The safety limits are much more demanding while operating in a shorter wavelength region. Also, the requirements for optical power, which illuminates the sample in OCT or OCM, are significantly lower due to safety limits. Therefore, the idea of dividing laser light into eight energetically equal clone-beams, which decreases the efficiency of a single second harmonic generation sixty-four times, was not critical for these studies, where the pumping laser can reach 400mW for 160nm FWHM of spectral bandwidth. Additionally, to assure no "holes" in the output broadband spectrum, we had to use very thin crystal that produces relatively broad single second harmonic light and simultaneously caused worse conversion efficiency. However, in the future these serious limitations should be also taken into consideration.

This work was supported by EuroHORCs-European Science Foundation and Foundation for Polish Science EURYI Award EURYI-01/2008-PL (M.W.) Sylwia Maliszewska acknowledges European Social Fund and Polish Government within Operational Programme "Human resources Development", project POKL.04.01.01-00-081/10 called "Wzrost".

Authors would like to thank anonymous Reviewer B for insightful comments that helped to improve the quality of this paper.

References

[1] A.M. Zysk *et al.*, J Biomed Opt **12**, 051403 (2007).
[2] M. Wojtkowski, Appl Opt **49**, D30 (2010).
[3] D. Huang *et al.*, Science **254**, 1178 (1991).
[4] A.F. Fercher *et al.*, Reports on Progress in Physics **66**, 239 (2003).
[5] A.D. Aguirre *et al.*, Opt. Lett. **28**, 2064 (2003).
[6] M.V. Sarunic, S. Weinberg, J.A. Izatt, Opt. Lett. **31**, 1462 (2006).
[7] S.J. Kirkpatrick, R.K. Wang, D.D. Duncan, Opt. Exp. **14**, 11585 (2006).
[8] J.M. Schmitt, Opt. Exp. **3**, 199 (1998).
[9] B.F. Kennedy *et al.*, Opt Exp. **19**, 6623 (2011).
[10] D.C. Adler *et al.*, Opt. Exp. **16**, 4376 (2008).
[11] A.L. Oldenburg *et al.*, Opt. Exp. **16**, 11525 (2008).
[12] M. Wojtkowski, *Obrazowanie za pomocą tomografii optycznej OCT z detekcją fourierowską* (Wydawnictwo Naukowe UMK, Toruń 2009).
[13] P. Wnuk, Y. Stepanenko, and C. Radzewicz, Opt. Exp. **18**, 7911 (2010).
[14] G.J. Swanson, *Binary Optics Technology: The Theory and Design of Multi-level Diffractive Optical Elements* (Massachusetts Institute of Technology, Lincoln Laboratory 1989)

