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Published in:
Optics Communications

Link to article, DOI:
10.1016/j.optcom.2014.11.078

Publication date:
2015

Document Version
Peer reviewed version

Efficient generation of 509 nm light by sum-frequency mixing between two tapered diode lasers

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Abstract.

We demonstrate a concept for visible laser sources based on sum-frequency generation of beam combined tapered diode lasers. In this specific case, a 1.7 W sum-frequency generated green laser at 509 nm is obtained, by frequency adding of 6.17 W from a 978 nm tapered diode laser with 8.06 W from a 1063 nm tapered diode laser, inside a periodically poled MgO doped lithium niobate crystal. This corresponds to an optical to optical conversion efficiency of 12.1 %. As an example of potential applications, the generated nearly diffraction-limited green light is used for pumping a Ti:sapphire laser, thus demonstrating good beam quality and power stability. The maximum output powers achieved when pumping the Ti:sapphire laser are 226 mW (CW) and 185 mW (mode-locked) at 1.7 W green pump power. The optical spectrum emitted by the mode-locked Ti:sapphire laser shows a spectral width of about 54 nm (FWHM), indicating less than 20 fs pulse width.

Keywords: Diode lasers, sum frequency generation, tapered lasers, visible lasers.

1. Introduction

Many applications within the field of biomedicine, material processing or display technology require compact, effective and robust laser light sources in the visible region. Diode lasers have the advantages of being very versatile in wavelength and capable of high power operation as well as being highly compact and having high wall-plug efficiency [1].

The generation of light in the red spectral region is covered by direct emission from diode lasers, and the blue region is usually covered by nitride-based diode lasers. At higher power levels the green spectral region however, is not easily accessible by direct diode lasers, but several other methods exist for generation of green light. Perhaps the most well-known process is second harmonic generation (SHG) where the infrared emission from diode-pumped solid state-, fiber lasers, or diode lasers is converted into green light by the non-linear process. By this method, many watts of green light may be generated and with very good spectral and spatial quality [2,3].

One important application using green lasers is pumping of Ti:sapphire lasers, which emits in a large spectral region covering the spectral range from 600 nm to 1100 nm [4]. This wide emission band enables the generation of very short pulses and Ti:sapphire lasers are therefore preferred for biophotonics imaging [5], spectroscopy [6] or materials processing [7]. Ti:sapphire has its absorption peak located around 490 nm. Most commercial Ti:sapphire lasers are pumped by green lasers emitting at 532 nm and the absorption in Ti:sapphire is thus not optimum. A laser source closer to the absorption peak could potentially optimize the efficiency of Ti:sapphire lasers.

An efficient method to generate high power visible light is SHG of high power tapered diode lasers. These lasers have very good properties for non-linear frequency conversion i.e. high power, good beam quality and narrow spectral linewidth [8–11]. Frequency doubling of such lasers has been demonstrated at different wavelength regions [12–15]. Recently, single-pass SHG of tapered diode lasers with an embedded distributed Bragg reflector (DBR) has resulted in more than 1.5 W of visible light at 488 nm and 532 nm and in a cascade of two nonlinear crystals as much as 3.5 W was demonstrated [16].

Sum frequency generation (SFG) is an alternative, yet efficient, way to generate light by mixing the output from two laser sources. SFG between two similar DBR tapered diode lasers was recently demonstrated to generate up to 3.9 W of nearly diffraction limited light at 531 nm [17]. In that work a volume Bragg grating was used to combine the light from the two spectrally closely spaced lasers.
In this work, we demonstrate the concept of combining two tapered diode lasers at much larger wavelength separation (978 nm and 1063 nm), and thereby generate up to 1.7 W of 509 nm green light by SFG, closer to the absorption peak of Ti:sapphire. This is done using a periodically poled MgO doped lithium niobate (PPMgLN) crystal. The 509 nm light is nearly diffraction limited with narrow spectral linewidth. We used this laser to pump a Ti:sapphire laser and generated up to 226 mW in CW operation and 185 mW in mode-locked operation with 54 nm spectral width corresponding to less than 20 fs pulse duration. This versatile concept can be expanded to cover almost any wavelength of interest by a different choice of diode laser wavelengths.

2. The experimental setup

The scheme of the experimental setup for sum frequency generation between two DBR tapered lasers is shown in Fig. 1. For the generation of light close to the absorption peak of Ti:sapphire, we chose to combine two DBR-tapered diode lasers, emitting at 978 nm and 1063 nm, respectively. The emission wavelength of both lasers can be shifted by adjusting the current in the taper section or by adjusting the laser temperature. A detailed description of similar diode structures and layout can be found in[10,11]. Each of the 6 mm long tapered diode lasers was mounted p-side up on a CuW heat spreader, which itself was mounted on a 25 × 25 mm^2 conduction cooled package mount allowing efficient cooling. Both lasers consists of an unpumped 1 mm long 6^{th} order surface grating followed by a 1 mm ridge waveguide and a 4 mm long tapered section. The current to the ridge waveguide and the tapered section were controlled individually.

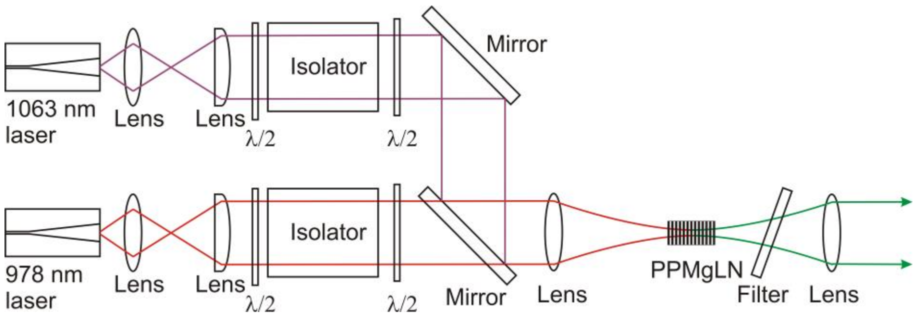

Fig. 1. Setup for spectral beam combining of DBR-tapered diode lasers with subsequent sum-frequency generation.

The output from each laser was collimated in the fast axis using an aspherical lens with a focal length of 3.1 mm and a numerical aperture of 0.68. Due to astigmatism of tapered diode lasers, two cylindrical lenses each with a focal length of 15 mm were used to collimate the beams in the slow axis, and generate an approximately circular beam. Then, each beam passed through a half-wave plate and an optical isolator in order to avoid feedback to the lasers. By turning the half-wave plate in front of the optical isolator, the power level could be adjusted without changing the laser current, which will change the astigmatism and wavelength of the laser, thus reducing the SFG efficiency. A half-wave plate was used after each isolator to correct the polarization of each beam to align to the optimum polarization state for SFG. The two beams were then spatially combined by using two mirrors, both highly reflective at 1063 nm, while the second mirror also allow transmission for the 978 nm beam. A focusing lens with a focal length of 60 mm proved to be optimum for the SFG process, and was used to generate a beam waist in the non-linear crystal with a radius of approximately 35 µm. The crystal was a PPMgLN (Covesion) containing 5 poling channels with different poling periods ranging from 5.927 – 6.061 µm. Each poling channel was 500 µm wide. We used a poling period of 6.03 µm in the experiments. Its dimensions were 20 × 10 × 0.5 mm^3 ($L \times W \times H$), and both facets were AR-coated at 509 nm, 978 nm and 1063 nm. The crystal was temperature stabilized using an oven in order to achieve phase matching at the laser wavelengths. Behind the nonlinear crystal an optical filter was used to separate the sum frequency generated beam from the two fundamental beams.

The 1063 nm diode laser was operated at 25.72°C, injection current to the ridge waveguide section was set to 330 mA and the tapered section was operated at 15 A, resulting in a maximum available infrared power of 8.06 W.

The 978 nm diode laser was operated at 20°C, the injection current to the ridge waveguide was set to 413 mA and the tapered section was operated at 12 A, resulting in a maximum available infrared power of 6.17 W. The PPMgLN crystal generated a maximum conversion when operated at 62.95°C, when pumped with the maximum combined power of the two tapered diode lasers.

3. Experimental results and discussion

The achieved green laser output power with respect to the combined pump power is shown in Fig. 2(a). At the described settings, a maximum green power of 1.73 W was achieved. This corresponds to an optical to optical conversion efficiency of η = 12.1 % from infrared to green light. The conversion efficiency for SFG with pump depletion is obtained using the relation [17]

$$P_{SFG} = \frac{P_1 + P_2}{2} \tanh^2 \sqrt{\eta_{SFG} \frac{P_1 + P_2}{2}}$$

where P_1 and P_2 are the individual pump laser powers, P_{SFG} is the power of the sum frequency generation and η_{SFG} is the nonlinear conversion efficiency. From the numerical fitting of our results in Fig 2(A), we obtain a nonlinear conversion efficiency of $\eta_{\mathrm{SFG}} = 4.3\%/\mathrm{W}$, comparable to previously obtained values [17,18]. The lower generated power compared to [17] can partly be explained by lower total input power, a shorter nonlinear crystal and possibly a worse overlap of the two fundamental beams due to the difference in optical properties of the two lasers. The output power was stable to within +/-1% limited by the open setup and no degradation was observed for any components during the experiments.

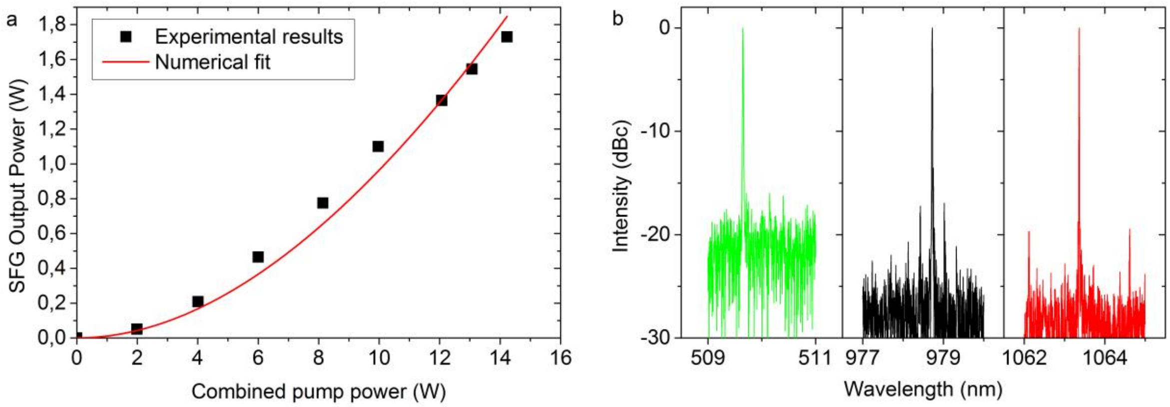

Fig. 2. (a) SFG output power vs. combined input power using a 60 mm focusing lens. The red curve is a numerical fit of the non-linear process, resulting in a nonlinear conversion efficiency of 4.3 %/W. (b) Optical spectra of the SFG beam and the two individual beams.

Fig. 2(b) shows the emission spectrum of the SFG beam, which shows a center wavelength of 509.64 nm. The spectral width of the 509 nm light was below 2 pm limited by the resolution of the optical spectrum analyzer (Advantest Q8347). The side mode suppression was larger than 15 dB limited by the dynamic range of the optical spectrum analyzer. The emission spectra of the two tapered diode pump lasers are also shown, where a side mode suppression of >15 dB is seen.

The beam propagation parameters of the SFG are calculated by measuring the beam profiles along the beam waist of the focused beam with a beam scanner (Photon, Inc) and fitting the measured $1/e^2$ beam widths, see Fig. 3(a). At 1.7 W green light, the achieved M^2 values shows that the green laser light was nearly diffraction-limited, with M^2_{509nm} = 1.1 in the fast and in the slow axis, respectively. These M^2_{509nm} values were also measured at different SFG output powers (1 W and 50 mW) and proved to be very similar. The beam profiles at focus for the two axes are shown in Fig. 3(b).

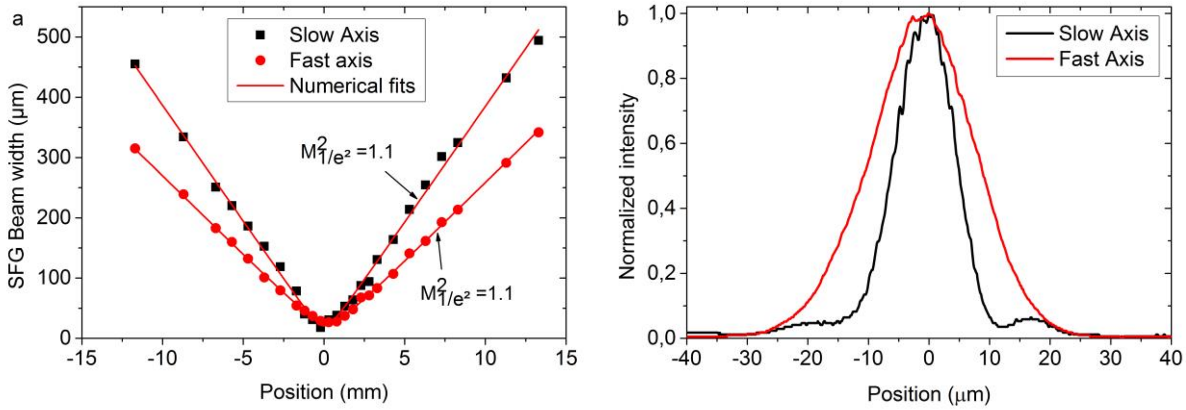

Fig. 3. (a) M^2 measurements $(1/e^2)$ of the SFG beam. The squares show measurements of the slow axis, the circles show the fast axis and the red curves represent the numerical fittings of the beam profiles. (b) Beam profiles of the slow- and the fast axis for the SFG laser beam.

These beam propagation parameters originate from two different tapered diode lasers each with different beam propagation parameters. The 978 nm diode laser had the values M^2_{978nm} = 1.29 in the slow axis and M^2_{978nm} = 1.38 in the fast axis, respectively, measured at the $1/e^2$ level. For the 1063 nm laser, M^2_{1063nm} = 2.46 in the slow axis and M^2_{1063nm} = 1.29 in the fast axis was measured. The large improvement in beam propagation parameter for the generated beam at 509 nm is due to nonlinear beam clean-up [19]. To demonstrate the high quality of the 509 nm light source, the 509 nm beam was used to pump a Ti:sapphire laser (Femtosource Scientific, Femtolasers Productions GmbH). The total length of the cavity was about 1.75 m resulting in a repetition rate of approximately 80 MHz. An output coupler with 95% reflectivity is used. Similar compact and low-cost oscillators are described in [20–22] showing high potential for e.g. clinical applications while offering user friendliness, high stability and reproducibility. The Ti:sapphire laser was pumped with the 509 nm SFG diode laser, which resulted in a maximum output power of 226 mW (CW) and 185 mW (mode-locked) with 1.7 W pump power, see Fig. 4. We observed a threshold value around 0.4 W (CW) and 0.7 W (mode-locked). This compares favorably with values obtained in [21] and indicates that 509 nm is better suited for pumping of Ti:sapphire lasers. A direct comparison is, however, difficult as the beam properties of the two pump sources were slightly different

and the Ti:sapphire oscillators were not identical. Furthermore, we measured the absorption coefficient in the Ti:sapphire crystal at 509 nm and 532 nm and found it to be 15% higher at 509 nm in good agreement with [4]. From [4] we estimate the absorption coefficient at 509 nm to be 94% of the maximum value at 490 nm, while at 532 nm the absorption coefficient is estimated to be 80% of the maximum value.
Fig. 5 shows the emission spectrum of the mode-locked Ti:sapphire laser, pumped by the 509 nm laser beam. We observed a broad spectral width FWHM $= 54$ nm, indicating a pulse width below 20 fs.

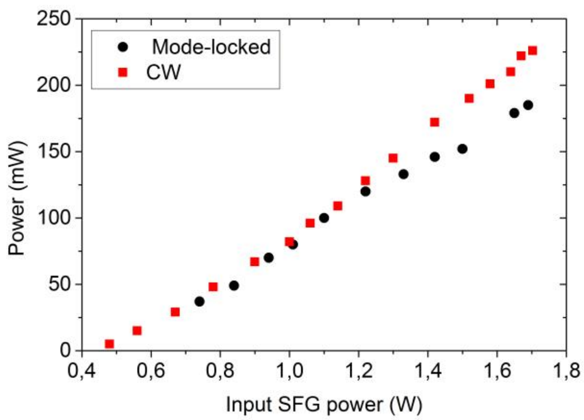

Fig. 4. Ti:sapphire characteristics of CW emission (squares) and mode-locked emission (dots), pumped by the 509 nm SFG laser.

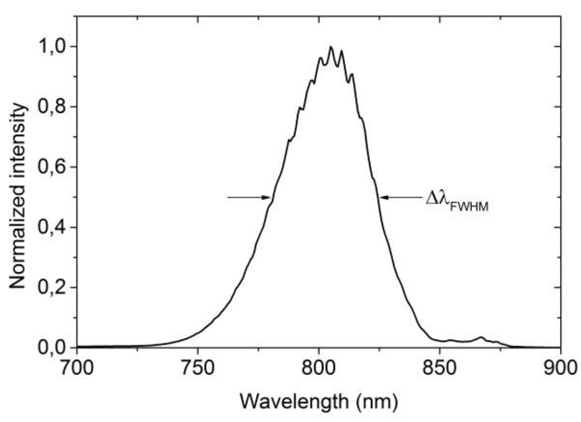

Fig. 5. Optical spectrum of the mode-locked Ti:sapphire laser, directly pumped by the 509 nm SFG laser.

4. Conclusion

In this study, we demonstrated a versatile 1.7 W, narrow linewidth green 509 nm light source based on sum frequency generation between two DBR tapered diode lasers with different wavelengths. This light source was nearly diffraction limited with beam propagation parameters of M^2_{1/e^2} = 1.1 in both the fast and the slow axis.

As an example of potential applications, the generated green light was used to pump a Ti:sapphire oscillator, which resulted in in a maximum output power of 226 mW (CW) and 185 mW (mode-locked), thus demonstrating the good beam quality of the pump source. The optical spectrum emitted by the mode-locked Ti:sapphire laser showed a spectral width of about 54 nm (FWHM), corresponding to less than 20 fs pulse width. The absorption coefficient of Ti:sapphire is larger at 509 nm than at 532 nm resulting in higher efficiency when using the 509 nm pump source.

Our study shows a concept for generation of laser light based on sum frequency generation between tapered diode lasers with different wavelengths. The advantage of this concept is the capability of efficiently producing diffraction limited light at a desired wavelength and with relatively high emission power. Such light sources could advantageously be introduced in different optical systems where either high power at a specific wavelength is needed or in systems where the reduction of cost and footprint would be advantageous.

Acknowledgements

This research was supported by the European project FAMOS (FP7 ICT 317744). The authors gratefully acknowledge Femtolasers Produktions GmbH for providing the Ti:sapphire laser.

References

[1] A. Müller, S. Marschall, O.B. Jensen, J. Fricke, H. Wenzel, B. Sumpf, P.E. Andersen, Diode laser based light sources for biomedical applications, Laser Photon. Rev. 7 (2013) 605–627.

[2] L. McDonagh, R. Wallenstein, Low-noise 62 W CW intracavity-doubled TEM_{00} $Nd:YVO_4$ green laser pumped at 888 nm, Opt. Lett. 32 (2007) 802–804.

[3] V. Gapontsev, A. Avdokhin, P. Kadwani, I. Samartsev, N. Platonov, R. Yagodkin, SM green fiber laser operating in CW and QCW regimes and producing over 550W of average output power, in: K.L. Vodopyanov (Ed.), Proc. SPIE, 2014: p. 896407.

[4] P.F. Moulton, Spectroscopic and laser characteristics of Ti:$A1_20_3$, J. Opt. Soc. Am. B. 3 (1986) 125–133.

[5] A. Unterhuber, B. Považay, K. Bizheva, B. Hermann, H. Sattmann, A. Stingl, T. Le, M. Seefeld, R. Menzel, M. Preusser, H. Budka, C. Schubert, H. Reitsamer, P.K. Ahnelt, J.E. Morgan, A. Cowey, W. Drexler, Advances in broad bandwidth light sources for ultrahigh resolution optical coherence tomography, Phys. Med. Biol. 49 (2004) 1235–1246.

[6] O. Katz, A. Natan, Y. Silberberg, S. Rosenwaks, Standoff detection of trace amounts of solids by nonlinear Raman spectroscopy using shaped femtosecond pulses, Appl. Phys. Lett. 92 (2008) 171116.

[7] J. Koch, E. Fadeeva, M. Engelbrecht, C. Ruffert, H.H. Gatzen, A. Ostendorf, B.N. Chichkov, Maskless nonlinear lithography with femtosecond laser pulses, Appl. Phys. A. 82 (2005) 23–26.

[8] J.N. Walpole, Semiconductor amplifiers and lasers with tapered gain regions, Opt. Quantum Electron. 28 (1996) 623–645.

[9] B. Sumpf, K.-H. Hasler, P. Adamiec, F. Bugge, F. Dittmar, J. Fricke, H. Wenzel, M. Zorn, G. Erbert, G. Tränkle, High-Brightness Quantum Well Tapered Lasers, IEEE J. Sel. Top. Quantum Electron. 15 (2009) 1009–1020.

[10] C. Fiebig, G. Blume, M. Uebernickel, D. Feise, C. Kaspari, K. Paschke, J. Fricke, H. Wenzel, G. Erbert, High-Power DBR-Tapered Laser at 980 nm for Single-Path Second Harmonic Generation, IEEE J. Sel. Top. Quantum Electron. 15 (2009) 978–983.

[11] K.-H. Hasler, B. Sumpf, P. Adamiec, F. Bugge, J. Fricke, P. Ressel, H. Wenzel, G. Erbert, G. Tränkle, 5-W DBR Tapered Lasers Emitting at 1060 nm With a Narrow Spectral Linewidth and a Nearly Diffraction-Limited Beam Quality, IEEE Photonics Technol. Lett. 20 (2008) 1648–1650.

[12] R. Le Targat, J.-J. Zondy, P. Lemonde, 75%-Efficiency blue generation from an intracavity PPKTP frequency doubler, Opt. Commun. 247 (2005) 471–481.

[13] B. Beier, D. Woll, M. Scheidt, K. Boller, R. Wallenstein, Second harmonic generation of the output of an AlGaAs diode oscillator amplifier system in critically phase matched LiB_3O_5 and β-BaB_2O_4, Appl. Phys. Lett. 71 (1997) 315–317.

[14] D. Fluck, T. Pliska, P. Günter, Compact 10 mW all solid state 491 nm laser based on frequency doubling a MOPA laser diode, Opt. Commun. 123 (1996) 624–628.

[15] K. Sakai, Y. Koyata, N. Shimada, K. Shibata, Y. Hanamaki, S. Itakura, T. Yaki, Y. Hirano, Master-oscillator power-amplifier scheme for efficient green-light generation in a planar MgO:PPLN waveguide, Opt. Lett. 33 (2008) 431–433.

[16] O.B. Jensen, A.K. Hansen, A. Müller, B. Sumpf, A. Unterhuber, W. Drexler, P.M. Petersen, P.E. Andersen, Power scaling of nonlinear frequency converted tapered diode lasers for biophotonics, IEEE J. Sel. Top. Quantum Electron. 20 (2014) 7100515.

[17] A. Müller, O.B. Jensen, K.-H. Hasler, B. Sumpf, G. Erbert, P.E. Andersen, P.M. Petersen, Efficient concept for generation of diffraction-limited green light by sum-frequency generation of spectrally combined tapered diode lasers, Opt. Lett. 37 (2012) 3753–3755.

[18] Y.F. Chen, S.W. Tsai, S.C. Wang, Y.C. Huang, T.C. Lin, B.C. Wong, Efficient generation of continuous-wave yellow light by single-pass sum-frequency mixing of a diode-pumped Nd:YVO(4) dual-wavelength laser with periodically poled lithium niobate, Opt. Lett. 27 (2002) 1809–11.

[19] E. Karamehmedović, C. Pedersen, O.B. Jensen, P. Tidemand-Lichtenberg, Nonlinear beam clean-up using resonantly enhanced sum-frequency mixing, Appl. Phys. B. 96 (2009) 409–413.

[20] A. Unterhuber, B. Považay, B. Hermann, H. Sattmann, W. Drexler, V. Yakovlev, G. Tempea, C. Schubert, E.M. Anger, P.K. Ahnelt, M. Stur, J.E. Morgan, A. Cowey, G. Jung, T. Le, A. Stingl, Compact, low-cost Ti:Al_2O_3 laser for in vivo ultrahigh-resolution optical coherence tomography, Opt. Lett. 28 (2003) 905–907.

[21] A. Müller, O.B. Jensen, A. Unterhuber, T. Le, A. Stingl, K.-H. Hasler, B. Sumpf, G. Erbert, P.E. Andersen, P.M. Petersen, Frequency-doubled DBR-tapered diode laser for direct pumping of Ti:sapphire lasers generating sub-20 fs pulses, Opt. Express. 19 (2011) 12156–12163.

[22] A. Unterhuber, B. Považay, A. Müller, O.B. Jensen, M. Duelk, T. Le, P.M.Petersen, C. Velez, M. Esmaeelpour, P.E. Andersen, W. Drexler, Simultaneous dual wavelength eye-tracked ultrahigh resolution retinal and choroidal optical coherence tomography, Opt. Lett. 38 (2013) 4312–4315.

Figure captions

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