Sub-40 fs, 1060-nm Yb-fiber laser enhances penetration depth in nonlinear optical microscopy of human skin

Mihaela Balu
Ilyas Saytashev
Jue Hou
Marcos Dantus
Bruce J. Tromberg
Sub-40 fs, 1060-nm Yb-fiber laser enhances penetration depth in nonlinear optical microscopy of human skin

Mihaela Balu,‡,† Ilyas Saytashev,‡,† Jue Hou,* Marcos Danus,§ and Bruce J. Tromberg‡

‡University of California, Irvine, Beckman Laser Institute, Laser Microbeam and Medical Program, 1002 Health Sciences Road, Irvine, California 92612, United States
§Michigan State University, Department of Chemistry, 578 South Shaw Lane, East Lansing, Michigan 48824, United States

Abstract. Advancing the practical utility of nonlinear optical microscopy requires continued improvement in imaging depth and contrast. We evaluated second-harmonic generation (SHG) and third-harmonic generation images from ex vivo human skin and showed that a sub-40 fs, 1060-nm Yb-fiber laser can enhance SHG penetration depth by up to 80% compared to a >100 fs, 800 nm Ti:sapphire source. These results demonstrate the potential of fiber-based laser systems to address a key performance limitation related to nonlinear optical microscopy (NLOM) technology while providing a low-barrier-to-access alternative to Ti:sapphire sources that could help accelerate the movement of NLOM into clinical practice. © The Authors.

Keywords: nonlinear optical microscopy human skin; third-harmonic generation microscopy; multiphoton microscopy; multimodal microscopy; optical biopsy; depth resolved imaging; Yb-fiber laser; adaptive phase-amplitude pulse shaper.

Paper 150438LRR received Jun. 29, 2015; accepted for publication Oct. 30, 2015; published online Dec. 7, 2015.

In vivo, label-free nonlinear optical microscopy (NLOM) of human skin is under investigation for a broad range of clinical applications spanning from skin cancer detection and diagnosis to characterizing and understanding keratinocyte metabolism, skin aging, pigment biology, and extracellular matrix proteins. Although exceptionally rich in both anatomic and functional contrast, NLOM has relatively limited penetration depth in turbid materials. This is due to the fact that multiple light scattering diminishes the instantaneous excitation intensity and nonlinear signal generation in the focused laser beam. As a result, there is considerable interest in exploring how light source performance can be optimized to improve imaging depth. Ti:sapphire lasers, commonly used in NLOM imaging, are generally able to access the superficial dermis of human skin to depths of 150 to 200 μm. Penetration depth primarily depends on the material scattering length at the excitation wavelength, the efficiency of the nonlinear excitation process, the excitation average power, repetition rate, pulse width, and the detection geometry. Adjusting these parameters in order to improve the penetration depth has been explored in several studies using Ti:sapphire and optical parametric oscillator-based femtosecond lasers as excitation light sources. Sun et al. have shown that reduced light scattering using a Cr:Forsterite 1230 to 1250 nm source can increase penetration depth up to 300 μm for harmonic generation imaging of human skin. Improvements in penetration depth can also be achieved when using shorter laser pulse widths. Depth resolved imaging studies require higher average laser powers and thermal damage to tissue becomes an issue of concern. Photothermal absorption of tissue is wavelength dependent, and so is the damage threshold. Heating following laser exposure at 800 nm is five times greater than at 1060 nm, and the damage threshold at 800 nm is three times lower than at 1060 nm. With the development of next-generation fiber lasers, it is possible to imagine combining these technical features with more compact, portable, and inexpensive light sources that could facilitate clinical translation of NLOM technology.

Fiber-based laser sources have been used for NLOM imaging of thin tissue cross-sections, mouse brain, and human skin tissue using fluorescence labeling. In this work, we evaluate the performance of a sub-40 fs, 1060-nm Yb-fiber laser for label-free NLOM imaging of human skin. The effect of excitation wavelength and pulse width on penetration depth in thick, turbid tissues is determined by comparing the fiber laser to an 800 nm Ti:sapphire laser source. We employ the depth-dependent decay of second-harmonic generation (SHG) signals as a standard metric for evaluating performance.

The excitation laser sources used were a Ti:sapphire oscillator (MIRA 900; Coherent Inc.; 220 fs, 76 MHz, 600 mW output power, tuning wavelength 720 to 980 nm) tuned to 800 nm for this study and a Yb-fiber laser (BioPhotonic Solutions Inc., 1060 nm, sub-40 fs, 39.2 MHz, 200 mW compressed output power). The prototype Yb-fiber laser, with self-similar pulse evolution, has an integrated adaptive phase-amplitude pulse shaper (MIIPS-HD, BioPhotonic Solutions Inc.) based on a 4f configuration with a two-dimensional spatial light modulator. The purpose of the pulse shaper was to control high-order phase distortions introduced by the high numerical-aperture (NA) objective and other dispersive elements in the beam path. The 1060-nm pulses were compressed to nearly transform limited duration using multiphoton intrapulse interference phase scan (MIIPS), and their full-width half maximum duration was measured by interferometric autocorrelation using the microscope detection unit (BioPhotonic Solutions Inc.) at the focal plane. Each of the two excitation beams (800 and 1060 nm) was directed toward our home-built scanning microscope and focused into the sample by an Olympus objective (XLPL25XWMP, 25x/1.05 NA water). The nonlinear signals from the sample were epi-collected and directed toward two photomultiplier tubes (R3896, Hamamatsu) by a dichroic...
Fig. 1 Multimodal nonlinear optical microscopy (NLOM) images of human skin acquired with 800- and 1060-nm excitation wavelengths at the same depth. (a) Epidermal-dermal junction in human skin imaged by third-harmonic generation (THG) (blue) and second-harmonic generation (SHG) (red) using 1060 nm and by two-photon excited fluorescence (TPEF) (green) using 800 nm as excitation wavelengths (z = 35 μm). TPEF signal originates from keratin in the epidermal keratinocytes and from elastin fibers (arrows) in the superficial papillary dermis, while THG signal highlights the keratinocytes only: SHG signal originates from collagen fibers. (b) Multimodal NLOM image corresponding to the inset in (a) representing contribution from three channels: (c) TPEF signal from keratinocytes and elastin fibers (arrows), (d) THG signal from keratinocytes, and (e) SHG signal from collagen fibers. Scale bar is 50 μm.

In summary, these results demonstrate the potential of fiber-based laser systems to be used as excitation light sources for NLOM imaging of highly turbid media. Despite their current lack of tunability, short-pulse, >1 μm wavelength fiber lasers can provide a low-barrier-to-access alternative to conventional Ti:sapphire lasers. They are of particular interest in applications...
related to *in vivo* imaging of human skin as they can deliver up to 80% improvement in SHG imaging depth compared to conventionally used Ti:sapphire lasers. An additional benefit for *in vivo* human skin imaging is related to the THG contrast mechanism which, unlike TPEF, does not involve absorption and might allow for the use of higher excitation powers. With continued development of expanded wavelengths, powers, and pulse characteristics, these systems are expected to increase in use, particularly in skin studies where assessment of 3-D morphology is important.

**Acknowledgments**

We would like to thank BioPhotonic Solutions Inc. for making their laser prototype available for these measurements and, in particular, Dr. Bingwei Xu for installing the laser system at UC Irvine. This research was supported partially by the...
National Institutes of Health (NIH) NIBIB Laser Microbeam and Medical Program (LAMMP, P41-EB015890), Air Force Research Laboratory Agreement No. FA9550-04-1-0101, and the Arnold and Mabel Beckman Foundation.

References