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ABSTRACT

This paper reviews our latest achievements in the field of 2.1 µm ultrafast Ho:fiber-based laser sources, including tunable all-fiber oscillators, diode-pumped optical preamplifier (booster), and high power fiber-based amplifiers. Pulse energy up to 1 mJ at the wavelength around 2.1 µm was demonstrated out of picosecond ultrashort-pulse oscillator-amplifier system. On the application side, we report the volume modification of silicon using picosecond 2.1 µm laser system. We present both modelling and experimental results for the 2.1 µm ultrashort laser pulse interaction with silicon.

Keywords: holmium, fiber laser, fiber amplifier, silicon, multiphoton absorption, optical nonlinearity

INTRODUCTION

Fiber-based lasers emitting beyond 2 µm have been extensively developed in the last few years by the researchers in academia and industry. The interest to 2 µm fiber laser technology is triggered by a number of advanced applications in environmental sensing, material processing, high-field physics, and medicine. Lasers manufactured in the fiber form are advantageous over its solid-state competitors because of their compactness, reliability, and efficiency. The most common active ion to achieve lasing around 2 µm is trivalent thulium (Tm<sup>3+</sup>). A number of different systems based on Tm:fiber have been reported so far [1-4]. Many Tm:fiber laser systems, both cw and pulsed, are already available commercially. However, the emission wavelength of thulium lasers is generally limited at 2097 nm for continuous-wave systems [5] and 2050 nm for mode-locked lasers [6]. Implementation of holmium fiber opens the way to longer wavelengths, for example, 2210 nm was demonstrated in continuous-wave system [7] and 2138 nm in the mode-locked regime [8].

Holmium doped fiber lasers have achieved increased attention last years. Among the most interesting results one can mention the hybrid-cavity laser mode-locked by the nonlinear polarization evolution with pulse duration of <180 fs from [9], ultrabroadband graphene-mode-locked all-fiber laser [10], and original two-stage thulium-holmium amplifier MOPA approach [11]. Our group at NTNU has obtained several important results, demonstrating the first graphene-mode-locked holmium doped fiber laser [12], the first dispersion-managed diode-pumped holmium doped fiber laser [13], the record-long emission wavelength of 2138 nm from the mode-locked holmium doped fiber laser [8] and finally, the first all-polarization-maintaining all-diopte-pumped all-fiber holmium MOPA with pulse energies up to 5 nJ [14].

At the first sight the emission wavelength shift of 100 nm as a result of transition from Tm:fiber to Ho:fiber can be considered as incremental. However, it required considerable technological advancement from the side of the optical fiber manufacturing. This shift is important for several applications. For example, for the needs of molecular sensing with holmium fiber laser one can reach the absorption lines of N<sub>2</sub>O, one of the “greenhouse” gases with dramatic impact on Earth’s climate, and thus develop the monitoring system in the spectral region of 2.1 µm, where the detectors are much more sensitive and fibers have considerably less losses than in the alternative 3-5 µm spectral region relevant for measurement of N<sub>2</sub>O. For the needs of distance measurement systems, the wavelength shift from 2 to 2.1 um decreases the water absorption about 2 times, and will also reduce the scattering losses, thus contributing to increase of the maximal measurement distance especially in bad atmospheric conditions (rain, fog, snow, etc). Clear interest arises from high-field scientific applications, which are searching for the light sources in the mid-IR spectral range. Dielectric Laser
Accelerator is a novel concept paving the way towards the compact source of high-energy particles and, finally, the X-ray lasers. The accelerator requires high-energy ultrashort laser pulses as a pump source, and has been initially driven by traditional Ti:sapphire laser. As stated by the authors of the concept, silicon accelerators driven by longer-wavelength lasers at 2 μm could handle significantly higher average powers [15].

This paper overviews our developments in fiber-based laser systems emitting around 2.1 μm, and also describes the first results of the applications of those systems for volume microstructuring of silicon.

**OVERVIEW OF THE DEVELOPED LASER SYSTEMS**

**Picosecond fiber oscillators**

Rare-earth ions (Tm³⁺, Ho³⁺) doped into fused silica glass exhibit broad emission bands, typically much broader than the bandwidth of a picosecond pulse. Thus, the emission wavelength of an ultrafast fiber laser is not fully determined by the choice of an active ion, but is possible to achieve in the certain wavelength range, depending on the laser cavity design. If no special measures are taken, this wavelength is not defined well enough, can be dependent on the operation conditions, and might even slowly drift with time. For many applications, however, it is important to keep the emission wavelength within the certain, sometimes rather narrow spectral range. For some applications one might even need to have the possibility to adjust or fine tune the emission wavelength. Thus, in our development of ultrafast fiber oscillator we have focused on the stability and wavelength control.

For the first system we built [8], the challenge was to shift the emission wavelength as far as possible to the infrared. In order to achieve that, we implemented the specially designed fused fiber coupler into the cavity to work as a wavelength filter. The active fiber length was increased accordingly to support the long-wavelength operation. The linear cavity was implemented with a fiber loop serving as an output coupler, and SESAM as a mode-locking element. The laser was pumped by a pair of single-mode diodes emitting at 1150 nm. The cavity setup is shown on Fig. 1 [8].

![Figure 1](https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie)
The laser operated in a fundamental soliton mode-locking regime at a pulse repetition rate of 15 MHz with a pulse energy up to 0.4 nJ. The wavelength filter implemented into the cavity efficiently suppressed laser emission below 2.12 µm, shifting it to the region 2120 – 2150 nm. The longest emission wavelength was demonstrated at 2141 nm. Emission bandwidth of 3.2 nm (Fig. 1b) and pulse duration of 1.56 ps (Fig. 1c) resulted in a time-bandwidth product of 0.326 showing that the pulses are nearly transform-limited. To the best of our knowledge, this is the longest operation wavelength for 2.1 µm laser transition in an ultrafast holmium fiber laser.

In order to further improve the stability of the laser (both the long-term stability of the emission wavelength and the sensitivity of the laser parameters to the environmental fluctuations) we have rebuilt the laser using the polarization maintaining (PM) fibers [14]. The emission wavelength was locked by implementing the chirped fiber Bragg grating (FBG) as the output coupler. FBGs are usually rather narrowband, being mostly used as sensors, but the bandwidth of our FBG was designed to be around 5 nm centered around 2089 nm. The substantial GDD of the FBG had to be compensated by the respective length of the passive fiber to keep the laser in the fundamental soliton operation regime. The cavity setup of the FBG-based laser is shown in Fig. 2.

![Cavity Setup Diagram](image)

**a)** Laser output
- PM Isolator
- FBG
- PM WDM
- SESAM
- PM Ho fiber
- Pm1550
- LD 1150 nm 0.3 W

**b)**
- Wavelength (nm)
- Power (dBm)

![Optical Spectrum](image)

Figure 2. The experimental setup (a) and the optical spectrum (b) for the ultrafast holmium fiber laser wavelength-stabilized by fiber Bragg grating.

The laser emitted at 2089 nm. The emission bandwidth of 2.1 nm (Fig. 2b) corresponded to a transform-limited pulse duration of 2.4 ps. The pulse repetition rate of 3.76 MHz resulted in an average output power below 0.3 mW and pulse energy below 0.1 nJ. The pulse energy was below the sensitivity of our autocorrelator. The system showed outstanding emission wavelength stability ensured by the Fiber Bragg Grating. Further optimization of the cavity GDD might lead to shorter pulses with the emission bandwidth limited by the bandwidth of FBG.

Finally, the ultrafast fiber oscillator with a tunable emission wavelength was developed. To support the tunable operation we switched back to the broadband output coupler configuration (fiber loop mirror). The typical emission wavelength of the laser depends on the cavity- and output coupling parameters, being around 2080 nm in our particular case. However,
due to the wavelength tuning mechanism, the emission can be tuned by user in about 30 nm range around the central wavelength, while the laser remains in the mode-locked regime. The active electronic wavelength-locking system eliminates wavelength drift and ensures stable operation at the desired wavelength. The laser in the current configuration exhibits average output power around 0.5 mW at a repetition rate around 17 MHz. The details about this system will be published in the separate paper [16].

**Single-mode fiber preamplifier (booster)**

The average output power and pulse energy of the developed ultrafast fiber oscillators could be boosted by a compact diode-pumped preamplifier. The setup of the preamplifier is shown in the Fig. 3 [14]. It is counter-pumped by a pair of single-mode laser diodes emitting at 1150 nm. The preamplifier can provide up to 40 dB gain, depending on the level of the input signal. Particularly for the laser shown in the Fig. 2 above, the preamplifier allowed to boost the average output power of the fiber laser up to 38 mW (Fig. 3b) resulting in 10 nJ pulse energy. However, because of the tiny-core single-mode fiber used in the amplifier, the self-phase modulation distorted the spectral and temporal profile of the amplified pulse (Fig. 3c), thus limiting the pulse energy at around 4.5 nJ, depending on the degree of distortions the particular application can afford. For example, the autocorrelation trace corresponding to the pulse energy of 2.2 nJ, where the pulse experience rather low degree of distortions, is shown in Fig. 3d.

![Figure 3](https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie/1135713-4)

Figure 3. The schematics of the holmium single-mode fiber preamplifier (a), and its performance in combination with the single-mode fiber oscillator described in paragraph 2.1: output characteristics (b), optical spectrum development depending on the amplification (c), and fringe-resolved autocorrelation at the output pulse energy of 2.2 nJ (d)
**Picosecond high-power amplifier**

The combination of wavelength-stabilized fiber oscillator described in paragraph 2.1 and booster described in paragraph 2.2 can serve as the seed source to the 2-micron high-power amplifier, for example, as described in [17].

The high-power MOPA system of this type emitting at 2090 nm was built. With 100W Tm:fiber laser as a pump source, it provided up to 1 mJ of output pulse energy at 10 kHz repetition rate. Pulse duration around 5.1 ps (Fig. 4b) could be achieved, and we are currently working towards further shortening of the pulses.

![Graph showing Amplifier output versus Wavelength and Autocorrelation intensity versus Delay](attachment:figure4.png)

**Figure 4.** Emission spectrum (a) and intensity autocorrelation trace (b) of the high-power amplifier which delivers pulse energy of 1 mJ at 2.1 µm.

**Raman-shifted fiber laser systems**

The wavelength of 2.1 um could also be obtained by Raman soliton self-frequency shift of the ultrashort pulse generated at shorter wavelength. Thus, one can benefit from the lower price and better availability of the fiber components designed for shorter wavelengths. Here we refer to a Thulium fiber MOPA system developed by our group a few years ago [18-20] and commercialized by ATLA Lasers AS. The ultrashort pulse is generated around 1960 nm in single-mode Thulium fiber oscillator and is seeded into a single-mode double-clad Thulium fiber amplifier. If the parameters of the pulse generated in the seed laser are properly matched with the parameters of the amplifier, the Raman soliton can be formed. During the amplification process this soliton can be self-frequency shifted to a longer wavelength. For example, Fig. 5 shows the spectrum and the autocorrelation trace of the Thulium fiber MOPA system [20] generating Raman soliton at the wavelength of 2100 nm. The central wavelength of the soliton can be controlled by varying the amplifier pump power, and the spectral bandwidth of the generated soliton is about 60 nm FWHM (Fig. 5a). The duration of such pulse was measured to be around 180 fs (Fig. 5b).

It should be noted that the pulse energy of a Raman-shifted pulse is limited by the parameters of the fiber used in the amplifier. For the single-mode fiber laser system described above the pulse energy is limited to a few tens of nanoJoule level [19,20]. We are working towards the energy scaling of such a fiber laser system by implementing the large mode area thulium fiber, which according to numerical simulations should result in the micro-Joule level pulse energies. First experimental results have already been reported [21].
Sub-nanosecond fiber MOPA

For some applications such as range finding picosecond pulse duration is not so critical, and nanosecond (sub-nanosecond) pulses can easily be used instead. Furthermore, longer pulse duration helps to mitigate nonlinear optical effects occurring during the pulse amplification, giving reasons to design high power amplifier in the all-fiber format. Nanosecond pulses do not necessarily require a mode-locked oscillator but can be efficiently generated by a gain-switched laser diode.

For our experiment we implemented the 2091 nm gain-switched laser diode and the two amplification stages [22]. For the first amplification stage we used the preamplifier described in paragraph 2.2. The second amplification stage was built using LMA holmium fiber and was pumped by 100 W thulium fiber laser.

The gain-switched diode provided 5 ns pulses with 2 mW peak power (Fig. 6b), and the optical pulse duration was limited by the electrical pulse duration of pulse generator (sub-nanosecond pulse should be achievable with a faster electrical pulse generator). After the first amplification stage pulse peak power was increased up to 0.4 W. These pulses were free-space coupled to the LMA fiber amplifier in the backward-pumped configuration. After the second amplification stage we currently obtained about 400 W peak power, which equals to about 2 uJ pulse energy. Total amplification of our amplifier system thus exceeds 50 dB [22].
The first experimental results were strongly affected by the thermal effects in the LMA active fiber. We were limited to operate at pump power level about half of the total available pump power. Since the amplifier was designed to operate at high gain and high threshold; thus we can expect much higher amplification at higher pump powers. According to our model, more then 100 µJ pulse energy could be achieved at the output of our MOPA system. The experimental work is ongoing.

**APPLICATION EXAMPLE: SUB-SURFACE MODIFICATION OF SILICON BY ULTRAFAST LASER PULSES AROUND 2.1 µM**

One of the potential applications for the ultrafast lasers emitting around 2.1 µm is the subsurface modification of silicon as silicon becomes transparent at this wavelength.

Silicon wafers are currently largely separated from the bulk mono-crystalline Si-block using thin diamond saws, which introduces a loss of material of up to 50% [23]. For extremely thin wafers with a thickness ≤ 100µm the loss increases up to 70% [23]. Thus, alternative methods for wafer separation are in development, such as epitaxial Si lift-off, stress-induced spalling, and smart-cut [24, 25]. This latter technique employs the fact that by the introduction of defects in a target layer below the Si wafer surface this layer will be weakened, allowing the wafer itself to be removed. There are multiple techniques for introducing such defects into bulk Si. The expansion coefficient difference for two materials can be used [26], without adding modifications inside the crystal. However, the crystal itself can be modified internally by the use of a layer of porous Si [27], the use of high-energy protons [25] or the use of two-photon absorption of laser pulses at 1550nm [28].

Even though much work has been conducted at common wavelengths such as 1064nm and 1550nm, both experimentally and numerically [29-36] only a small amount of works have been published at longer wavelengths, including 1965nm [32], 1970nm [37] and 2300nm [32, 38]. Chambonneau et al. [37] used a Tm-fiber laser for generating pulses with a duration of 400ps, which then were compressed outside of the fiber laser. Furthermore, they investigated the number of pulses necessary to modify silicon, depending on the pulse energy. In the latter work a femtosecond OPO (optical parametric oscillator) was used to produce modifications below a SiO₂ layer, but not within bulk Si.

It is well known that nonlinear optical phenomena in silicon such as self-focusing and multi-photon absorption are strongly dependent on the wavelength, energy and duration of the exciting pulse. In Ref. [32] we noticed that due to a dip in the nonlinear absorption spectrum and a peak in the spectrum of the third-order non-linearity, the wavelengths between 2000-2200nm are more favourable for creating sub-surface modifications in silicon. This is the case even though those wavelengths do not allow as tight a focusing as those at 1550nm. This is compensated by an increased self-focusing due to the nonlinear Kerr-effect around 2100nm.

**Numerical simulations**

The numerical model of ultrashort pulse interaction with silicon wafer based on non-linear Schrodinger equations was built. The details of the modelling will be reported separately [39], and here we will give an insight on the modelling results.

The energy transported towards the focal spot for the wavelengths 1550nm to 2350nm with a pulse energy of 1µJ and 10 µJ for two different values of n2 reported in literature [40, 41] are shown in Figure 7. While the pulse with the shortest wavelength is absorbed quite significantly already on the way to the focal spot, the other wavelengths can retain more energy, before depositing it closer to the focal spot. In addition, the absorption close to the focal spot depends on the value of the third-order non-linearity, as shown e.g. when comparing Figure 7a and Figure 7b. Here one also can see the ripples, originating from the strong self-focusing within the material, followed by local absorption and collapse, which show up in Figure 8 too.

Figure 7 shows that the most of the pulse energy is absorbed already in the first millimeter of the material, leading to a loss of 50-99% of the pulse energy, depending on the initial pulse energy and wavelength.
When considering the achieved intensities, one can refer to Figure 8. It shows that the self-focusing of the pulse at a wavelength of 1950nm and 2150nm starts at a significantly smaller depth than for the other two wavelengths.

Our numerical simulations confirm the initial assumption, that the wavelengths in the range of 2000 to 2200nm are more efficient for modifying Si compared to wavelengths above 2200nm and below 1900nm.

**Experiments on subsurface modification of silicon**

The mJ-class ultrashort-pulse fiber-based MOPA laser system described in Paragraph 2.3 was used for the experimental demonstration of the subsurface silicon modification. The sample (monocrystalline silicon wafer with polished front surface) was mounted onto a four-axis stage, with two axes controlled by an electronic controller. Electronic control allowed precise movement with a fixed speed, variable between several µm s⁻¹ and several mm s⁻¹. The laser light was focused using an aspheric lens with typical focal distance of f = 4mm either onto or under the surface or a silicon wafer.

The processed samples were investigated using three different techniques, including optical microscopy, transmission IR microscopy and scanning electron microscopy (SEM). The first two techniques are non-destructive, while the cross-sectional imaging using the SEM required splitting of the sample. Optical microscopy alone is applicable to study of the surface, while transmission IR microscopy was used to look through the sample and investigate subsurface modifications without damaging the sample.

In the first experimental configuration the silicon sample was moved perpendicular to its surface and along the laser beam direction. Effectively it was equal to the focal spot moving from the bottom of the sample towards the top surface with a speed between 0.2 – 20µm s⁻¹. This movement resulted in the local modifications of silicon structure following the trace of a focal spot visible through the whole thickness of the silicon wafer. The top and cross-section images of the sample obtained by transmission IR microscopy are shown on Fig. 9a and 9b, respectively. The characteristic size of the subsurface modifications is between 40 µm and 100 µm.
High $n_2$-values, 1µJ pulse energy

Low $n_2$-values, 1µJ pulse energy

High $n_2$-values, 10µJ pulse energy

Low $n_2$-values, 10µJ pulse energy

Figure 8: Intensity of a pulse with different wavelengths and energies, depending on the position within the material. The focal length of the used lens is $f = 8$ mm, with the focal point at $f_i = 4$ mm inside the material. The pulse duration is of 5 ps, and the pulse energy is varied between 1 µJ and 10 µJ.

Figure 9. Subsurface modifications of the monocrystalline silicon by the ultrafast laser emitting at 2090 nm, viewed using a transmission IR microscope from the top of the sample (a) and the side of the sample (b) for different processing speeds.

In the second experimental configuration the sample was translated perpendicular to the laser beam direction and along the sample surface. Effectively it was equal to the focal spot moving at a certain constant depth under the surface of the silicon wafer parallel to that surface. Several modification lines were created, which are shown on the Fig. 10. As seen on the Fig. 10 a, certain lines are visible on the surface of a sample (M1 to M4, and M6). At the same time Fig. 10b shows that there are several modifications in the region M5, which are not visible on the surface, but can be visualized in the transmission. Some of the subsurface lines are not continuous though. Imaging the cross-section of the sample (Fig. 10c) confirms the existence of the subsurface modifications M4, M5, and M6. It should be noted that lines M4, M5 and
M6 are stacked lines, i.e., several lines were drawn on top of each other. The size of the modified regions is in the range of hundreds of micrometers, showing that optimization of the laser and focusing parameters are necessary.

![Stacked lines](image1)

(a) Top view using the optical microscope  
(b) Top View using the infrared transmission microscope

![Infrared transmission microscopy](image2)

(c) Cross-section view using the infrared transmission microscope

Figure 10. Subsurface modifications of the monocrystalline silicon by the ultrafast laser emitting at 2090 nm: top view from a visible microscope (a) and an infrared transmission microscope (b), and cross-section view from an infrared transmission microscope (c).

After confirming that modifications below the surface were made, the sample was cleaved, polished, and the cross section of the sample was investigated by SEM. The sample cross-section was observed from both sides, due to the spottiness of the lines. The SEM images of sample cross-sections from both sides are shown in Figure 11. Several modification regions can be clearly seen and corresponded to the transmission microscopy images from the Fig. 11. The modifications have a characteristic elongated shape.
CONCLUSION

Ultrashort pulse lasers emitting at 2.1 µm are being extensively developed. The wavelength shift from 2 µm to 2.1 µm is important for a number of applications, namely remote sensing, laser distance measurements, high-field physics (particularly laser particle accelerator), and volume modification of silicon wafers. Some results on the latter application are reported in the article.

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