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Broadband Passively Mode-Locked Fiber Laser with DNA Aqueous Solution as Saturable Absorber

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Abstract: We demonstrate a passively mode-locked fiber laser using aqueous DNA solution as a saturable absorber (SA), with broadband pulse laser emission from 1 to 1.5 µm. The mode-locked laser with erbium-doped fiber as the gain material has a center wavelength of 1563 nm, a 3 dB bandwidth of 3.9 nm, and a pulse width of 822 fs, whereas the laser with ytterbium-doped fiber as the gain material and an identical DNA aqueous SA has a center wavelength of 1037 nm, a 3 dB bandwidth of 5.04 nm, and a pulse width of 250 ps. The proposed laser, which is simple and cost effective to fabricate, exhibits excellent long-term stability as well as thermal stability during high-power operation. This mode-locked laser scheme with a liquid-phase DNA component has the potential to provide in-depth understanding of the optical nonlinearity and usefulness of DNA.

Keywords: DNA; ultrafast laser; mode-locking; saturable absorber; liquid phase

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1. Introduction

Ultrafast pulse lasers are suitable for thermal damage- and particle-free micromachining/fabrication, as well as being precise enough for optical measurement and surgical treatment in the biomedical field [1–6]. Such pulses are frequently generated through passive mode locking using a passive nonlinear optical component, such as a saturable absorber (SA), in a fiber laser system [7–10]. Semiconductors are extensively used as the SA material in ultrafast fiber lasers, which is already a mature and commercialized technology. However, semiconductor saturable absorption mirrors (SESAMs) are expensive and complicated to fabricate and have a low damage threshold [11–15]. Of late, carbon-based materials, such as graphene and carbon nanotubes, have also been widely investigated as SA materials [16–20]; however, reliable and optimized mode-locked ultrafast laser pulse generation with these unconventional materials is yet to be realized.

Besides providing crucial genetic information, DNA is of great interest among researchers even outside the biomedical field because of its numerous interesting properties that can be exploited in various fields. Moreover, DNA is cheap and abundant in nature; hence, its optical/electronic properties render it a promising optical material replacement for organic light-emitting diodes (OLEDs), lasers, and optofluidic systems [21,22]. Recently, the high optical nonlinearity and lyotropic chirality of DNA have been discovered [23–25], and Khazaeinezhad et al. reported an ultrafast laser pulse using a solid-state DNA SA [26]. The ultrafast DNA fiber laser was realized with a D-shaped fiber, also known as a side-polished fiber, which is advantageous in handling 2D materials and fabricating solution-based thin films interacting with fiber-coupled light. However, DNA in aqueous solution is unsuitable for generating ultrafast pulses in such platforms because of the limited interaction, relatively high intrinsic optical loss, and thermal stability issues.

In this study, we demonstrate a broadband ultrafast fiber laser with a pulse laser wavelength of 1–1.5 µm, utilizing an identical aqueous DNA solution SA. The passively

mode-locked laser is made of etched fiber, which has an elongated light–SA interaction length and relatively low intrinsic optical loss. The proposed system exhibits reliable mode-locking laser operation under high pump power because of the large specific heat of water, as well as great long-term stability. As control over the molecular orientations of the DNA lyotropic chiral nematics is possible [25], this liquid-phase DNA solution-based ultrafast laser opens new possibilities for the in-depth understanding of the optical properties of DNA and optimized applications of DNA material in optoelectronic devices in the near future.

2. Materials and Methods

The liquid DNA solution used in this study was prepared using commercially purchased crude DNA powder extracted from salmon testes (Sigma-Aldrich, single-stranded, molecular mass = 1.3 × 106 Da, approximately 200 bases, %G-C content = 41.2%) mixed in DI water at a concentration of 1.2 wt%. After sonification of the DNA solution at 60 °C for an hour, the solution exhibited a clear and slightly yellowish color without precipitation.

Figure 1 illustrates the manufacturing process and cross-section of the DNA SA fabricated using etched fiber. Initially, the polymer protection of the single-mode optical fiber (SMF-28®, Corning®) was removed from a 1 cm section in the middle of the fiber. The cladding of this section was subsequently wet etched by immersing in 30% hydrofluoric acid solution, which selectively etched the fiber cladding for 2 h until the total diameter of the fiber observed by a microscope was 15 microns. For the 1 μm wavelength mode-locked laser with Yb-doped fiber laser gain material, the fiber diameter was etched down to 8.5 microns because evanescent field interaction between the DNA solution and shorter-wavelength light can be obtained with a thinner cladding configuration. The etched part was sealed with a capillary tube containing aqueous DNA solution, where the DNA was used as the SA. Unlike D-shaped fibers (or side-polished fibers), the etched fiber has a relatively low intrinsic optical loss of 12% due to an intact fiber core.

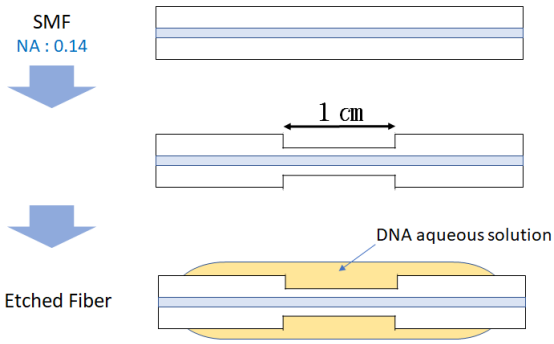

Figure 1. Fabrication process and cross-section of the DNA SA.

The transmittance change in the fabricated DNA SA was measured with an 80 fs pulse laser (Spectra-Physics, repetition rate = 80 MHz, wavelength = 1550 nm) input source directed to the SA through a variable optical attenuator and a polarization controller, and a power meter. The measured nonlinear transmission of the DNA SA is depicted in Figure 2. The nonsaturable transmission is 87.73% when the intensity of light is 1500 MW/cm^2 or less. The low intrinsic loss is not only due to the intact fiber core as mentioned above, but also the DNA aqueous solution. While a light scattering from the dried DNA film on D-shaped fiber is inevitable, our aqueous solution is free from the scattering issue. This is a significant improvement over existing technologies based on D-shaped fibers. The transmission of the DNA SA component increases to 92.73% as the input light intensity increases. Based on this transmission measurement, the modulation depth of the DNA SA is estimated to be approximately 5%, which is higher than that previously reported, and this is mainly due to the lower optical loss and elongated light–SA interaction of the etched fiber configuration. The modulation depth can be somewhat modified, controlling

the final diameter of the etched fiber. The larger modulation depth with the thinner etched fiber gives a higher optical loss, resulting in a loss of the mode locked laser. The most reliable mode-locked laser was obtained in the optimal conditions described previously. Even though the modulation depth of 5% is slightly higher than the typical numbers from most mode-locked lasers, it is still far from the Q-switching regime, thus this result derived from trial and error is reasonable.

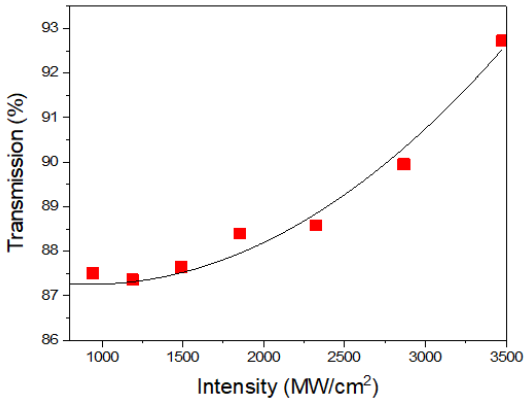

Figure 2. Nonlinear transmission measurement of the DNA SA at a wavelength of 1550 nm.

The experimental setup of the fiber laser system, including the liquid DNA SA, is shown in Figure 3. The ring cavity of the 1.5 µm laser with a 4.5 m erbium-doped fiber (EDF) as the gain medium is pumped using a 980 nm laser diode (LD) through a 980/1550 nm wavelength division multiplexing (WDM) coupler; replacement of the gain medium with a 5 m ytterbium-doped fiber (YDF) and the corresponding components (dimensions of the ring cavity/components were optimized for each of the 1.5 µm and 1 µm laser schemes) switches the entire system to a 1 µm laser. Note that the DNA solutions utilized in both systems are identical, even though the etched fiber dimensions are tailored to optimize light–DNA interaction. A polarization-independent isolator is located downstream to render the cavity unidirectional. A polarization controller is placed in front of the SA for mode locking by controlling the polarization of light. The laser is out-coupled through the 5% port of a 95/5 optical coupler (20% port of the 80/20 optical coupler for the 1 µm laser). Further, the output laser is analyzed using an optical spectrum analyzer (OSA), oscilloscope, autocorrelator, and radiofrequency (RF) spectrum analyzer.

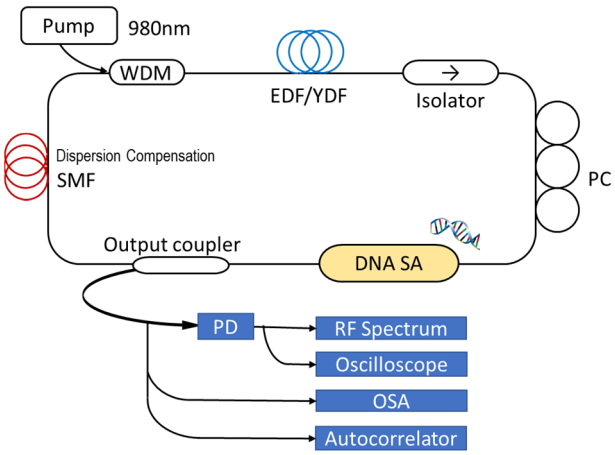

Figure 3. Experimental setup of the passively mode-locked fiber laser using liquid DNA as the SA.

The laser pulses of the passively mode-locked fiber laser with a liquid DNA SA were observed by controlling the polarization of the incident light on the DNA SA. By adjusting the polarization controller, the repeatedly added polarization components were made to

coincide with the optimal direction of the SA. In addition, with this method, we obtained a stable soliton pulse using a polarization controller within the ring cavity. The average output intensity is approximately 7.5 mW for a pump LD power of 280 mW.

3. Results

The optical spectrum and oscilloscope trace of the output pulses are displayed in Figure 4. The spectrum measured by the OSA has a central wavelength of 1563 nm with a 3 dB bandwidth of 3.9 nm (Figure 4a). The oscilloscope trace (Figure 4b) shows a fundamental repetition rate of 14.11 MHz and a pulse train of 70.87 ns corresponding to a total cavity length of 14.3 m.

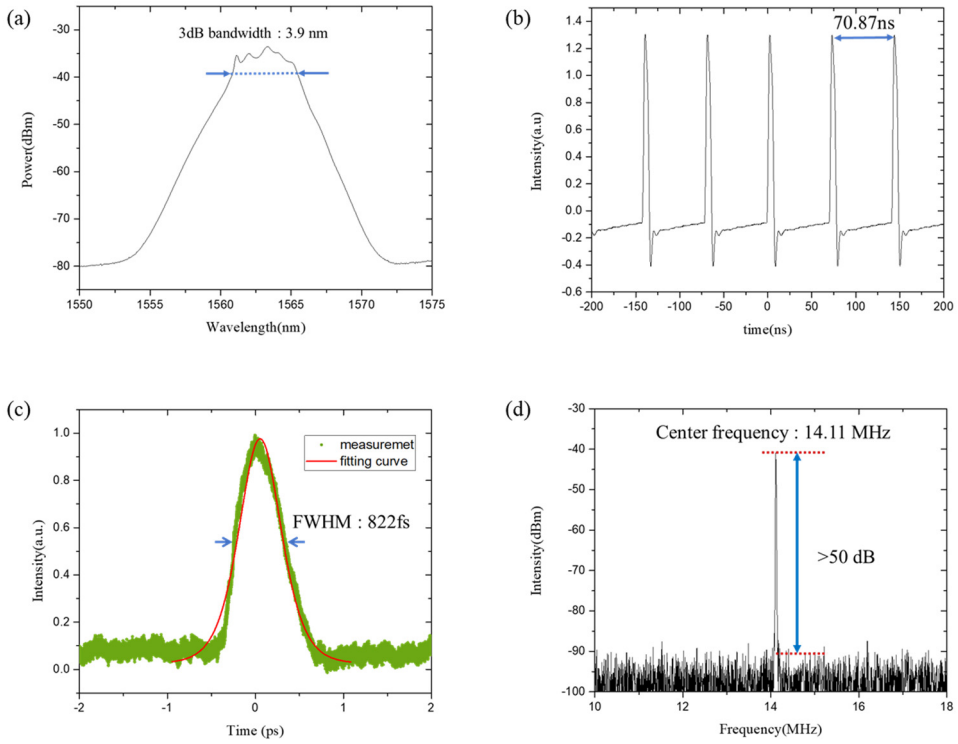

Figure 4. Soliton pulse train of the 1.5 μm passively mode-locked fiber laser: (**a**) optical spectrum; (**b**) oscilloscope trace; (**c**) autocorrelation trace; (**d**) RF spectrum.

In the frequency domain, the RF spectrum (Figure 4d) indicates the stability of the laser; the signal-to-noise ratio of the mode-locked pulses is approximately 50 dB. The autocorrelation trace (Figure 4c) shows a measured pulse trace that is well fitted with the Seth profile. The pulse width estimated using the fitting curve is approximately 822 fs. These results successfully demonstrate the ultrafast mode-locked laser with the proposed etched fiber-based liquid DNA SA. As mentioned earlier, the average output power of our ultrafast laser is 7.5 mW when the pump 980 nm LD power is 280 mW, which can be improved by optimizing the optical gain (i.e., EDF/YDF configurations) and out-coupling ratio (through optical coupler and/or isolator).

The lasing characteristics of the 1 μm laser with an ytterbium-doped fiber are illustrated in Figure 5. Mode-locking behavior is observed at a pump LD power ranging from 185 to 247 mW. In this regime, with the increase in the pump power, the pulse duration decreases, and a more stable mode-locked laser is obtained. At a pump power of 247 mW, the center wavelength of the laser is 1037 nm and the 3 dB bandwidth is approximately 5 nm. The optical spectrum (Figure 5a) presents a typical dissipative soliton, and the fundamental repetition rate of 20.16 MHz derived from the pulse train in Figure 5b matches well with the entire cavity length of 10 m. The pulse duration estimated using an 80 GHz high-speed oscilloscope and 12.5 GHz high-speed photodetector is 250 ps (Figure 5c).

This is comparable with the other dissipative solitons in 1 μm wavelength pulsed lasers demonstrated with various solid-state SAs [27–29], and 250 ps pulse duration is clearly in a mode-locked laser range rather than Q-switching. The RF spectrum (Figure 5d) shows a signal-to-noise ratio of 55 dB, which directly proves the obtainment of stable mode-locked pulses at a high pump power.

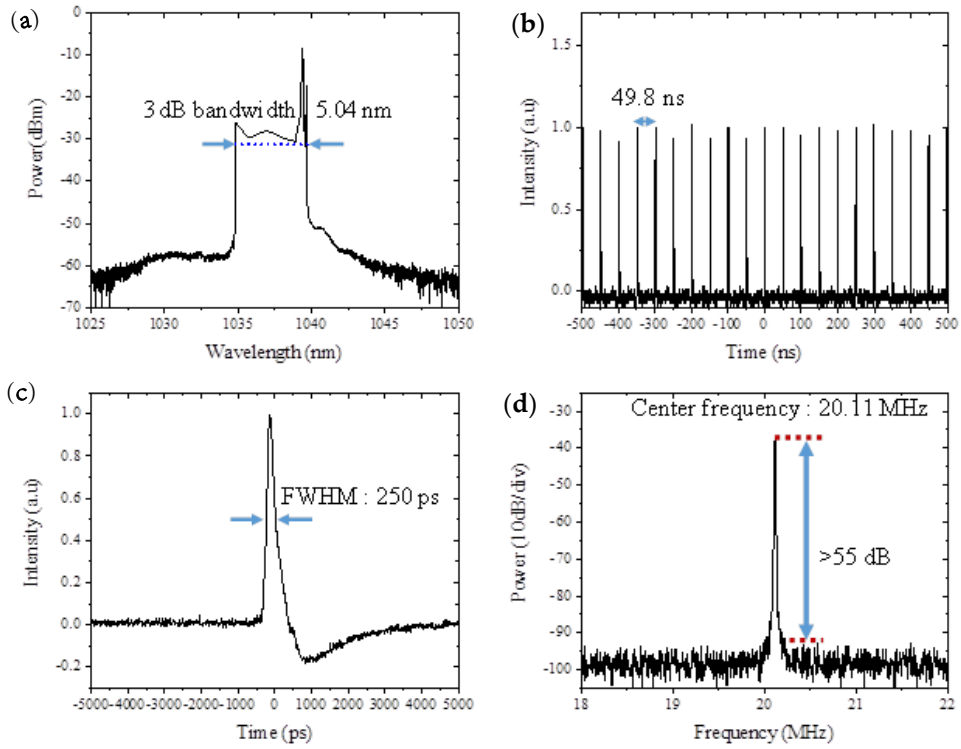

Figure 5. Characteristics of the 1 μm mode-locked pulse laser at a pump power of 247 mW: (**a**) optical spectrum; (**b**) oscilloscope trace; (**c**) high-speed oscilloscope trace and estimated pulse duration; (**d**) RF spectrum.

The mode-locked laser emission of the 1 μm laser was measured over time, and the optical spectrum change is presented in Figure 6. In addition, the pulse duration and 3 dB bandwidth are depicted as a function of time. These results establish that our mode-locked laser exhibits virtually identical lasing characteristics over time, even at high pump power operation, due to the thermal stability of the aqueous DNA SA. The laser maintains its characteristics not only at a time scale of a few hundred hours but also over several weeks, as long as the liquid-phase DNA SA is perfectly passivated such that the solution does not suffer from evaporation. Our system exhibits stable mode locking and is free from thermal damage and/or evaporation of the SA component at a relatively high operating power because the DNA SA is an aqueous solution with large specific heat. As a result, both our 1 μm and 1.5 μm laser exhibit virtually identical laser characteristics after six weeks under ambient conditions, proving that the liquid DNA SA mode-locked laser has superior long-term stability as long as the liquid DNA SA is perfectly sealed and intact.

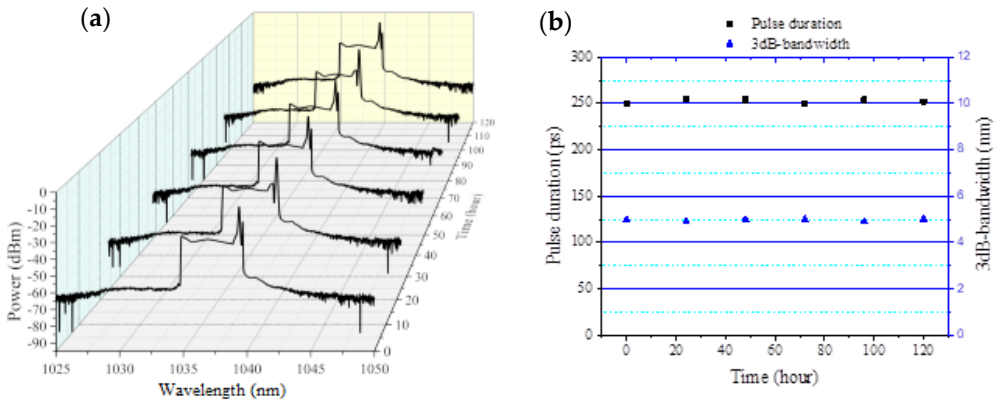

Figure 6. (**a**) Optical spectrum and pulse duration; (**b**) 3 dB bandwidth as a function of time.

The experimental results using liquid DNA as the SA indicate disadvantages such as a wide pulse width in terms of the beam quality compared to a previously reported solid- film SA [26]. However, the pulse width is narrower than 1 ps for a 1.5 μm mode-locked laser and a stable pulse laser with a signal-to-noise ratio of more than 50 dB can be achieved. For a 1 μm laser, the 250 ps pulse duration is still in mode-locking range rather than Q-switch. The mode locking is clearly attributed to the DNA SA, neither water nor nonlinear polarization rotation, because the mode-locked laser cannot be obtained with water alone, no matter how the PC is optimized. It is confirmed that DNA, which shows nonlinearity even in a liquid state, can be applied as an SA with the appropriate optical configurations and light–SA interactions.

4. Discussion

A passively mode-locked fiber laser with liquid DNA as the SA was demonstrated in the 1–1.5 μm broad band. An etched fiber, with low optical loss and better light–SA interaction, immersed in the DNA aqueous solution, functioned successfully as an SA. Pulse laser with a central wavelength of 1563 nm and pulse width of 822 fs was achieved using erbium-doped fiber as the gain medium, whereas a 1034 nm wavelength/250 ps pulse was obtained using ytterbium-doped fiber as the gain medium and an identical DNA SA. The broadband mode-locked laser with DNA SA exhibits excellent thermal stability under high-pump power conditions as well as long-term stability because of the large specific heat of the aqueous solution and the natural stability of DNA. The liquid phase DNA SA is also free from bubble/scattering issues thanks to relatively low optical loss from the etched fiber/DNA solution configuration. We confirmed the optical nonlinearity of the aqueous DNA solution in this study, and improved the usability of the material using liquid DNA and etched optical fiber. In particular, because the concentration of liquid-state DNA can be readily manipulated and the DNA molecular orientation can be controlled in the lyotropic chiral nematic state, it can be utilized as a platform for the in-depth study of the optical properties of DNA as well as in various optoelectronic and fiberoptic applications.

Author Contributions: Conceptualization, W.L.; methodology, W.L.; investigation, M.K. and J.J.K.; writing—original draft preparation, M.K. and J.J.K.; writing—review and editing, W.L.; visualization, W.L.; supervision, S.B.L. and D.-Y.K.; project administration, K.L. All authors have read and agreed to the published version of the manuscript.

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