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Self-Starting Passively Mode-Locking All-Solid-State Laser with GaAs Absorber Grown at Low Temperature *

JIA Yu-Lei(贾玉磊)[1], LING Wei-Jun(令维军)[1], WEI Zhi-Yi(魏志义)[1**], WANG Yong-Gang(王勇刚)[2], MA Xiao-Yu(马骁宇)[2]

[1] *Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080*
[2] *Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083*

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We realize a stable self-starting passively mode-locking all-solid-state laser by using novel GaAs mirrors as the absorber and output coupler. The GaAs mirror is grown by the technology of metal organic chemical vapour deposition at low temperature. With such an absorber as the output coupler in the laser resonator, laser pulses with duration of 42 ps were generated at a repetition rate of 400 MHz, corresponding to the average power of 590 mW.

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Compact ultra-short pulse lasers with high stability have widespread applications in many fields. Over the past decade, diode laser pumped passively mode-locked all-solid-state lasers using semiconductor saturable absorption mirrors (SESAMs) have shown an attractive interest because of the characteristics of compact configuration and shorter pulse duration. Reliable self-starting all-solid-state picosecond and femtosecond lasers based on the SESAM were well developed with many kinds of gain media,[1−4] which lead to great improvements in efficiency, size, lifetime and robustness for ultrafast laser technology. In general, the manufacture of SESAM is a complicated process, which involves many techniques such as material growing, polishing, etching and optical coating. In particular, for the SESAMs with the type of saturable Bragg reflectors (SBR), they are composed by multiple pairs of layers with different semiconductor materials. As a typical example, the SESAMs used at 1 μm wavelength compose of several GaAs/$In_{0.25}Ga_{0.75}As$ quantum well absorbers. Because of the mismatch between GaAs and $In_{0.25}Ga_{0.75}As$, it leads to the generation of interior strain of the absorber and may shorten the working life. Although a thick absorber layer can support a large modulation depth and is easily operated for laser mode-locking, the strain will increase with the thickness.

A high-quality solid state saturable absorber can play an important role in the progress of all-solid-state ultrafast lasers. Obviously, it is a significant work to develop new kinds of absorbers for mode-locking lasers. Compared to the complicated composition of SESAM, GaAs wafer shows a simpler configuration as the absorber. The working procedure for fabricating the absorber is an easier technique except for the coating, and this will decrease the cost. In some aspects, GaAs wafer is even superior to SESAMs for mode-locking lasers. Because of these characters, GaAs substrate (or GaAs wafer) was used in passively Q-switched solid-state lasers as early as the late 1990s.[5] More recently, the cw mode locking pulses with the duration as short as 18.9 ps were obtained with a GaAs saturable absorber mirror.[6] However, due to some weak points, GaAs wafer is far away from real application. First, the modulation depth of GaAs wafer is limited, because the GaAs single crystal wafer is generally fabricated by the methods of liquid encapsulated Czochralski (LEC) or vertical gradient freezing (VGF). Therefore, the operation of the Q-switch or mode locking with GaAs absorber is usually unstable. Second, some parameters of the GaAs wafer, such as recovery time and modulation depth, cannot be modulated freely as those of SESAM.

In recent years, use of the semiconductor absorber as the output coupler has led to a new interest on the research of passively mode-locking all-solid-state lasers; it will enable us to further simplify the laser configuration. With the output coupling absorber, Spühler *et al.*[7] reported a passive Q-switched Nd:YVO_4 laser with pulse width of 143 ps. Wang *et al.*[8] further realized a 10-ps mode-locking Nd:YAG laser by using an SESAM as the output coupler. A similar experiment in Nd:$GdYVO_4$ lasers was also demonstrated and pulse duration of shorter than 4 ps was generated.[2] Our experiment with a Nd:YVO_4 crystal showed the pulse width of as short as 2.3 ps.[9] In this Letter, we report a novel passively mode-locking solid-state laser by using a new GaAs mirror as the absorber, which was grown at low temperature (LTGAM) by metal organic chemical vapour

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** To whom correspondence should be addressed. Email: zywei@aphy.iphy.ac.cn

deposition (MOCVD). Different from the conventional technique, the absorber not only has a simple structure, but also can be used as the output coupler. In addition, the growing process at low temperature has greatly ameliorated the shortcomings of the modulation depth and the recovery time. Using one piece of such a mirror in the laser resonator, we can realize stable mode-locking laser running with the pulses width of 42 ps, corresponding to the average powers of 590 mW. These results show a new technology for realizing all-solid-state picosecond laser with even the simplest way.

The new GaAs mirror used in this experiment was grown at low temperature by an MOCVD device with the fabrication as shown in the inset of Fig. 1. To manufacture the LTGAM, a GaAs buffer layer with thickness about 500 nm was firstly deposited on a semi-insulating GaAs substrate. Then, about 3 μm GaAs material was further grown on the buffer layer with rate of 40 nm/min at a lower temperature of 550°C. In order to decrease the non-saturable loss, an annealing procedure of about three minutes is also necessary after the growth. Finally, by polishing the other side of the GaAs substrate and coating seven pairs of Al_2O_3/SiO_2 films, it will supply us an absorber with a partial transmissivity around the wavelength of 1 μm. In this case, the fabricated GaAs absorber can also be used for mode-locking laser as an output coupler. Because of the single material for both the absorption layer and substrate, there is no strain arising from the mismatch problem between the closed layers, and the LTGAM has a lifetime longer than the conventional SESAMs. In addition, the fabricating technique is easier than the SESAM to make it in a lower cost. Figure 1 shows the measured transmission spectrum of the LTGAM, the transmissivity is about 9% at 1064 nm. By decreasing the growth temperature or increasing the thickness of the GaAs absorption layer, the modulation depth of the LTGAM will be increased, and the recovery time will decrease with the decreasing growth temperature. This means that the key parameters of LTGAM for mode-locking are adjustable.

The experimental layout is shown in Fig. 2, which is a typical three-mirror cavity. A piece of LTGAM was used to replace the SESAM as the output coupler. The gain medium is a 12-mm-long Nd:YVO_4 crystal with 1.5% Nd^{3+} doping. A 10 W cw diode laser (Apollo Instruments Inc.) was coupled into the gain crystal through a dichroic flat mirror (M1) coated with 99.8% reflectivity at the laser wavelength of 1064 nm and 98% transmissivity at the pump wavelength of 808 nm. To compact the laser device, we inserted a plane folding mirror M2 after the laser gain crystal, the mirror M2 is coated with 99.8% reflectivity at the laser wavelength of 1064 nm. A concave mirror M3 with the radius of curvature (ROC) of 100 mm was used as the second folding mirror to focus the 1064 nm laser beam on the LTGAM, and the LTGAM play two roles as the absorber and output coupler at the same time. Fine adjusting the position of the LTGAM will enable us to observe the laser running. Our calculation shows that the focused beam spot on the LTGAM is about 50 μm. To cool the absorber for optimizing the mode-locked pulses, we fixed the LTGAM on a hollow copper heat sink.

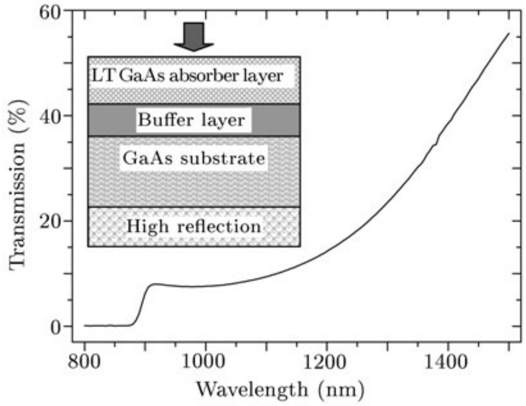

Fig. 1. Measured transmission spectrum of the LTGAM. The inset shows the schematic structure of the LTGAM, and the incident laser is vertical to the LT GaAs absorber layer, as shown by the arrowhead.

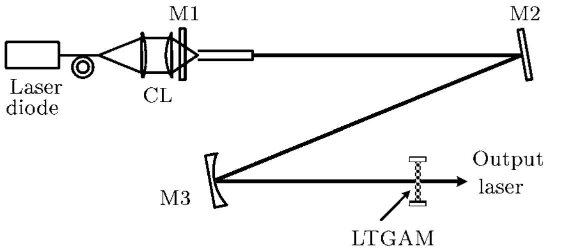

Fig. 2. The schematic of the mode-locking laser. CL: the collimating and focusing system; M1: input mirror; M2: folding mirror; M3: focusing mirror; LTGAM: low temperature GaAs mirror (OC = 9%).

Figure 3 depicts the output characteristic with the incident laser power for the GaAs absorber. Corresponding to the cavity length, we observed a stable pulses train on the oscilloscope at a repetition rate of 400 MHz, as shown in Fig. 4. To measure the exact pulse duration, we set up a nonlinear autocorrelator driven by a computer. The measured profile of autocorrelation trace is shown in Fig. 5. Given the Gaussian-shaped assumption, it reveals typical pulse duration of 42 ps. We measured the average output power of mode-locked pulses that was achieved at the maximum value as high as 590 mW when the incident pump power was increased to 13.3 W, which corresponds to the conversion efficiency of 4%. Considering the repetition rate of 400 MHz, this laser is capable of delivery picosecond laser with the single pulse energy of about 1.5 nJ and the peak power is estimated to be 35 W for the maximum average output power. Moreover, any optical damage on the LTGAM has not been observed in the experiment. Although the gain bandwidth of about 0.8 nm for Nd:YVO_4 is relatively narrow, the 42-ps pulse duration is still too wider and far from the Fourier transform limit. The possible reason we thought for the wider pulse duration was the etalon effects caused by the residual back from the LTGAM. It is understandable because there is only a part high reflection film on the back of the GaAs substrate and without any antireflection film coated on the inner side of the 3-mm GaAs layer. The low optical conversion efficiency can also be regarded as the absence of the antireflection film and the poor coating on the absorber which brought large intracavity loss.

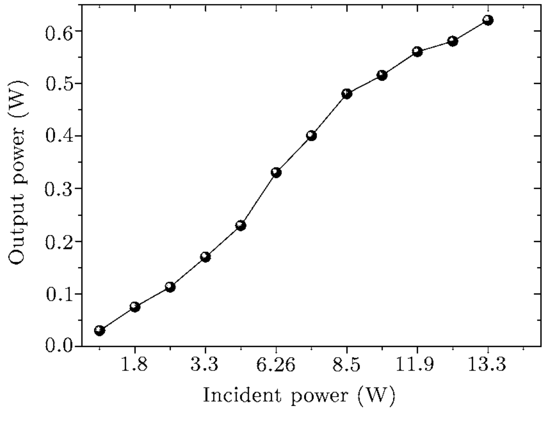

Fig. 3. Dependence of the mode-locked average output versus incident power for the laser.

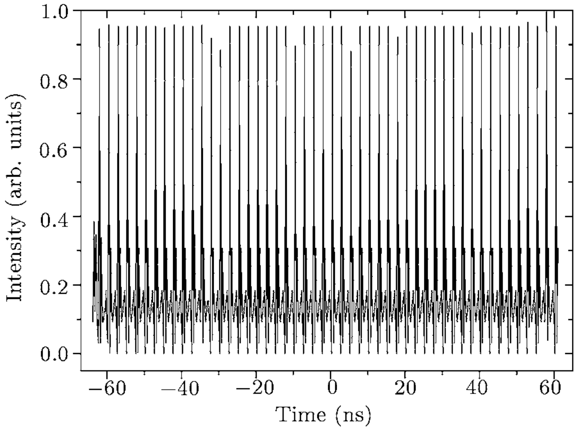

Fig. 4. The trace of mode-locking laser pulses.

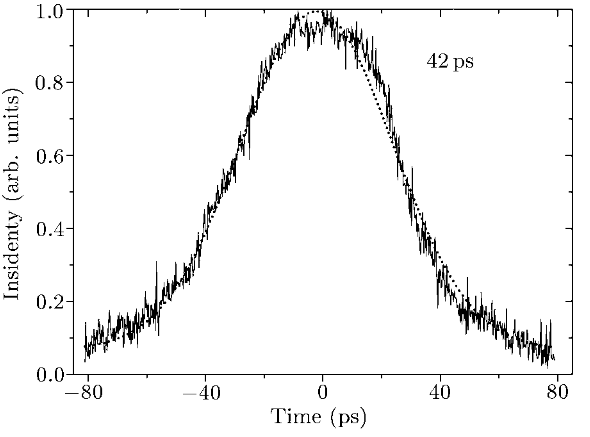

Fig. 5. The measured profile of autocorrelation trace, corresponding to the pulse width of 42 ps, and the dotted line shows the Gaussian assumption.

In summary, we have demonstrated a stable passively mode-locked all-solid-stated laser with a novel output coupling saturable absorber grown at low temperature. Clean mode-locked laser pulses with average output power of 590 mW was achieved at the pump power 13.3 W. Because of the possible rear reflection from the GaAs layer, the output pulse shows a wider duration of 42 ps. With the compact and simple configuration, this laser will supply a new feasible picosecond laser source for many applications, and it will open a new picosecond laser source with even compact and simple configuration.

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