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Silver nanorods absorbers for Q-switched Nd:YAG ceramic laser

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The silver nanorods (Ag-NRs) with a longitudinal surface plasmon resonance (SPR) absorption peak at 1.06 μm band was synthesized through a seed-mediated growth method, and performance was investigated in a passively Q-switched Nd:$Y_3Al_5O_{12}$ (YAG) ceramic laser for the first time. Under an absorbed pump power of 2.75 W, stable pulse trains with a pulse width of 197 ns were obtained. For the case of passively Q-switched operation, the maximum average output power of 114 mW was generated with a repetition rate of 223.7 kHz.

1. Introduction

Q-switched pulsed laser sources operating in 1.06 μm region are powerful research tools for many scientific research fields. Passively Q-switched technique is a main method to achieve Q-switched pulsed laser [1–6]. Recalling the history of passively Q-switched technique development, it is not difficult to find that the progress of materials used as saturable absorbers (SAs) has promoted the advancement of the applications of pulse lasers. Due to the unique zero-band gap structure of wide absorption spectrum range characteristics and significant saturable absorption capacity, the discoveries of two-dimensional materials represented by graphene [6–9], transition-metal dichalcogenides (TMDs) [10–12] and black phosphorus (BP) [13–16] have aroused widespread concern and research boom.

Recently, metal nano-materials have aroused increasing attention due to their superior optical properties and application prospects. In particular, the discoveries of near-infrared absorption properties of metal nano-materials with controlled morphology allows many researchers to engage in the study of precious metal nano-materials in laser applications. There were some reports on applying gold nanobipyramids or silver nanoparticles as SAs to build mode-locked and Q-switched lasers [1,17–21]. In one of the Q-switched Nd:YVO_4 laser containing gold nanobipyramids based SAs, 396 ns pulse width was obtained [1], which was narrower than the outputs of BP, MoS_2 and Bi_2Se_3-based Q-switched lasers at 1.06 μm. Excellent optical properties of metal nano-particles are from the localized surface plasmon resonance (LSPR). One-dimensional silver nano-materials (representing by silver nanowires or silver nanorods) hold a transverse surface plasmon resonance (SPRT) absorption peak and a longitudinal surface plasmon resonance (SPR) absorption peak. The SPRT absorption peak stabilized at about 400 nm, and the SPR absorption peak occurred a red shift over a wide range near infrared as the diameter ratio of nanorods was raised. Therefore, the longitudinal absorption peak of the metal nano-materials used as saturable absorbers can be aligned with the laser emission wavelength by controlling the aspect ratio. Prepared a nanorod silver colloid with different aspect ratios by chemical reduction method, X. Liu et al. observed two surface plasmon resonance absorption peaks. One of the absorption peaks was stable at about 420 nm and the other was red shifted from 550 to around 800 nm, corresponding to the theory on computing [22]. Moreover, in a passively Q-switched erbium-doped fiber laser, 2.4 μs pulses were generated containing silver nanoparticles based SAs [17]. These results indicate the potential of silver nanorods in the field of lasers. However, so far, no passively Q-switched laser at 1.06 μm wavelength based on Ag-NRs SA has been reported, the saturable absorption of Ag-NRs is not fully exploited.

As a promising gain media, Nd:YAG ceramic [2,5,23–25] is an efficient diode-pumped 1.06 μm laser material. It could be grown in large volume with homogeneous doping concentration, which is superior to single crystal. However, it was not until recently that passively Q-switched Nd:YAG ceramic laser with Ag-NRs absorber were reported. In this paper, we report the performance of a diode-pumped passively Q-switched Nd:YAG ceramic laser using Ag-NRs as saturable absorber. The pulses with a shortest pulse width of

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197 ns corresponding to a repetition rate of 223.7 kHz and a peak power of 2.59 W were generated. To our best knowledge, this is the first time that Ag-NRs as saturable absorber was applied to an all solid-state pulsed laser at 1.06 μm.

2. Fabrication and characterization of the Ag-NRs

The Ag-NRs used in our experiment was synthesized through a seed-mediated growth method. At first, it was necessary to prepare a small-sized gold nanobipyramids solution as a growth solution. For the preparation of growth solution, 2 ml of 0.1 M $HAuCl_4$ solution and 400 μL of 0.01 M $AgNO_3$ solution and 800 μL of 0.1 M HCl solution were added to 40 ml of 0.1 M cetyltrimethylammonium bromide (CTAB) solution. And then a 200 μL of seed solution was injected into the growth solution and placed in an oven heated to 65 °C for 10 h. The second step was the preparation of the Ag-NRs solution. A 5mL of the small-sized gold nanobipyramids solution was removed and centrifuged at a rate of 6000 rpm for 10 min. After that, it was placed in 15 mL of 0.08 M cetyltrimethylammonium Chloride (CTAC) (384 mg). Then 300 μL of 0.01 M $AgNO_3$ solution and 150 μL of 0.1 M ascorbic acid solution were added to the mixed solution. Finally, the solution was placed in an oven heated to 65 °C for 4 h. After that, The final Ag-NRs SA film was formed by transferring the solution to quartz carrier substrate with a spin coating method and then followed by slow drying at room temperature. Then, in the experiment, the substrate was inserted into the laser cavity. The transmission electron microscopy (TEM) image of the Ag-NRs SA film is shown in Fig. 1(a). As is shown in Fig. 1(b), at about 400 nm, there is a absorption high value corresponds to the SPRT absorption, and the SPR absorption peak is near 1040 nm. The absorption intensity coefficient of Ag-NRs SA at 1064 nm is about 0.814, which is consistent with the theoretical calculation based on the aspect ratio of the nanoparticles. This indicates the possibility of the Ag-NRs as SA used in pulsed lasers.

We measured the nonlinear saturable absorption properties of the Ag-NRs by a homemade 12 ps pulsed Yb:KGW laser which delivered a repetition rate of 86.6 MHz at 1047 nm. The transmittance was detected by varying intensity of the laser seed source power. We quoted a model of $T(I) = 1 - \varphi_0 \times \exp(-I/I_{sat}) - \varphi_{ns}$ [11] to characterize nonlinear optical parameters. ($T(I)$, φ_0, I, I_{sat} and φ_{ns} correspond to transmission, modulation depth, input optical intensity, saturation optical intensity, and non-saturable loss, respectively.) The modulation depth of the Ag-NRs SA was measured to be about 41.1% as shown in Fig. 1(d). Non-saturable loss and relatively low saturation optical intensity were calculated to be around 12.4% and 25.46 mW/cm^2 respectively.

3. Experimental setup

The experimental arrangement is shown schematically in Fig. 2. A 30 W, 808 nm commercial fiber-coupled CW diode laser was

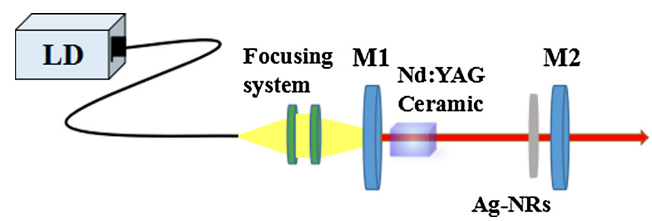

Fig. 2. Schematic of the Nd: YAG ceramic laser passively Q-switched with Ag-NRs as saturable absorber.

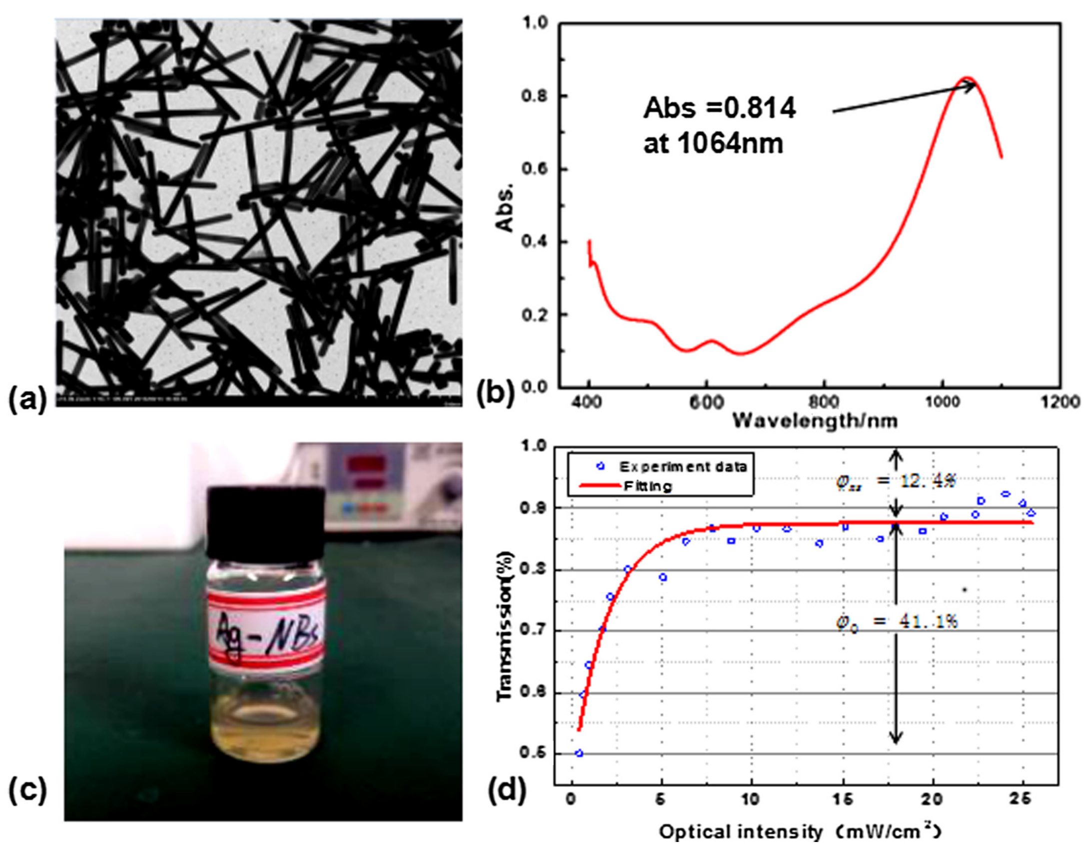

Fig. 1. (a) TEM image of the Ag-NRs SA with a scale bar of 500 nm; (b) Absorption intensity coefficient of the Ag-NRs SA; (c) Photograph of Ag-NRs solution; (d) Nonlinear transmission curve of the Ag-NRs SA.