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Femtosecond Mode-locked Yb:KYW Laser Based on InP Nanowire Saturable Absorber

Junting Liu, Shuai Ye, Feifei Wang, Xiaohui Sun, Vladislav Khayrudinov, Harri Lipsanen, Hongkun Nie, He Yang, Kejian Yang, Baitao Zhang and Jingliang He

***Abstract*—In this paper, indium phosphide (InP) nanowires (NWs) are fabricated by Au-nanoparticle assisted vapor-liquid-solid method and applied as a saturable absorber (SA) for continuous-wave (CW) mode-locked femtosecond Yb:KYW bulk laser. I-scan method was used to characterize the saturable absorption properties of the prepared InP NWs SA. Pulses as short as 394 fs with repetition rate of 41.5 MHz and maximum average output power of 315 mW are achieved. To the best of our knowledge, this is the first demonstration of InP NWs working as SA for the femtosecond generation of solid-state bulk laser. The results indicate that InP NWs is a promising SA candidate for applications in ultrafast nanophotonic devices.**

***Index Terms*—InP NWs, Mode-locked laser, Solid-state lasers.**

I. INTRODUCTION

Due to the advantages of ultrashort pulse width, high peak power and broadband wavelength, ultrafast lasers have aroused much attention and are widely used in various fields including industry, medical and scientific research. With the continuous innovation of laser technology, passive mode-locking has proved to be one of the most efficient and effective technique for generating ultrafast laser source [1]. As the key element for the passively mode-locked lasers, saturable absorber (SA), whose absorption of light increases with increasing of the incident light intensity, plays a significant role and determines the output laser performance [2, 3]. Semiconductor saturable absorber mirrors (SESAMs) is a mature industrialized technology, but its application is still limited by its complicated manufacturing process, high price and narrow response bandwidth. Therefore, investigating novel SAs with low loss, wide response band, suitable modulation depth and saturation intensity, and simple preparation process is always a hot-topic in laser technology research and material science. Over the last few years various novel low-dimensional materials, such as carbon nanotubes (CNT) [4, 5], graphene [6, 7], black phosphorus (BP) [8, 9], topological insulator (TI) [10, 11], and transition metal dichalcogenides (TMDs) [12-17], have been widely studied and used for generating ultrafast lasers, providing a new platform for design and fabrication of novel SA devices.

III−V semiconductor NWs have attracted much attention and have been used for various optoelectronic devices because of their unique optical and electronic properties [18-20]. Indium phosphide (InP) nanowires (NWs), a member of the III-V NW family, have large electron g-factors and small electron effective mass [21, 22], which makes them a promising candidate for photonic and integrated electronic devices. InP NWs also possess strong saturable absorption response with an effective nonlinear absorption coefficient of ~ -10^5 cm/GW [23], which is much larger than that of graphene (~ -10^{-2} cm/GW) [24] and BP (~ -10^{-3} cm/GW) [25]. We recently demonstrated a passively Q-switched $Nd:YVO_4$ laser by using InP NWs as SA, generating a pulse width of 462 ns and single pulse energy of 1.32 μJ [23]. Ultrafast intra- and inter-band relaxation time was measured to be 8.1 and 63.8 ps, respectively, indicating the great potential for ultrafast optical signal processing [23]. However, up to date there have been no reports of InP NWs SA based mode-locked solid-state bulk laser.

In this work, high-quality InP NWs SA were prepared and successfully employed to generate femtosecond pulses from a mode-locked Yb:KYW laser. A stable continuous-wave (CW) mode-locking laser operation was achieved with the pulse width of 394 fs, pulse repetition rate of 41.5 MHz and maximum average output power of 315 mW. These results indicate that InP NWs are promising SA candidates for mode-locking laser generation.

II. PREPARATION AND CHARACTERIZATION OF INP NWS

InP NWs were fabricated using Au-nanoparticle assisted vapor-liquid-solid method (see the details in our previous work

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[23]). As shown in Fig.1(a) and (b), atomic force microscopy (AFM) was used to identify the diameter of the prepared InP NWs, which was determined to be ~80 nm (consistent with the Au particle diameter). Raman scattering spectrum was measured under the backscattering geometry by using a HR 800 system from Horiba Jobin Yvon and excited by a 532 nm laser. As shown in Fig. 1(c), two peaks were observed at 305.6 cm^{-1} and 344.7 cm^{-1}, corresponding to the transverse optical and longitudinal optical phonon mode, respectively, which is consistent with a previous report [26]. Fig. 1(d) demonstrates a scanning electron microscopy (SEM) micrograph of the InP NWs, indicating that the prepared InP NWs were uniformly distributed on a quartz substrate. To characterize the nonlinear optical absorption response of InP NWs SA, I-scan measurements were performed using a homemade mode-locked Yb-fiber laser (center wavelength at 1064 nm, repetition rate of 100 kHz-1 MHz, pulse duration of ~13 ps).

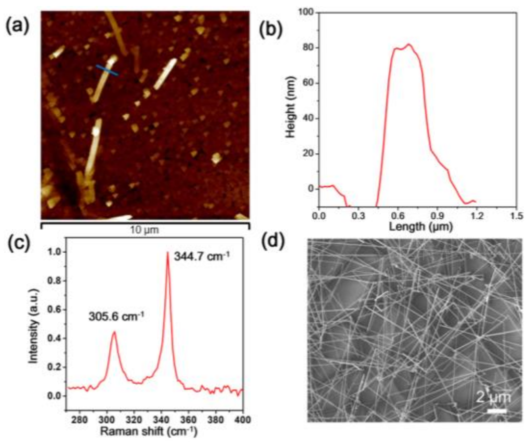

Fig. 1. (a) AFM image of InP NWs and (b) the corresponding height profile of the section marked in AFM. (c) Raman spectrum of as-grown InP NWs. (d) SEM image of InP NWs.

The measured nonlinear transmission curve is shown in fig. 2. The prepared InP NWs show a typical characteristic of saturable absorption, in which the transmission increases as the input pulse fluence increases. The nonlinear transmittance curve can be fitted by the following equation [27]:

$$T = 1-\frac{\Delta R}{1+\frac{F}{F_S}}-\Delta R_{ns}. \qquad (1)$$

where F_S is the saturable fluence, ΔR is the modulation depth, and ΔR_{ns} is the non-saturable loss. By using a two-level SA model to fit the data, the saturable fluence (F_S), the modulation depth (ΔR) and the non-saturable loss (ΔR_{ns}) were calculated to be 80.1 μJ/cm^2, 10% and 8%, respectively.

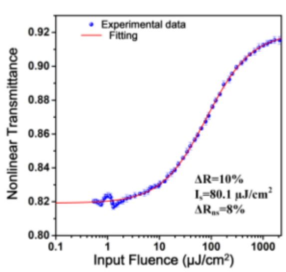

Fig. 2. Nonlinear transmission of the InP NWs SA at the wavelength of 1.0 μm.

III. CW MODE-LOCKED LASER OPERATION WITH INP NWS SA

To further investigate the saturable absorption phenomenon in InP NWs and its ability of femtosecond laser generation in bulk laser, we chose the Yb:KYW crystal as a gain medium due to its excellent properties, such as wide emission spectra (FWHM ~24 nm) and large emission cross section (~10^{-20} cm^2) [28]. The stable continuous-wave mode-locking operation can be achieved when the mode-locking pulse energy E_p is larger than the minimum intracavity pulse energy $E_{p,c}$, which can be expressed as [29]:

$$E_p^2 > E_{p,c}^2 = F_{sat,A}A_{eff,A}F_{sat,L}A_{eff,L}\Delta R. \qquad (2)$$

where $F_{sat,A}$ and $F_{sat,L}$ are the saturation fluences of the InP NWs SA and laser crystal, respectively, $A_{eff,L}$ and $A_{eff,A}$ are the effective laser mode areas at the position of the gain medium and InP NWs SA. Considering the SA parameters, it can be expressed as the following equation:

$$F_{sat,A}\Delta R < \frac{(PT_R)^2 \times m\sigma_{em,L}\lambda}{hc\times\pi\omega_{eff,L}^2\times\pi\omega_{eff,A}^2} \qquad (3)$$

where h is the Planck constant, c is the speed of light in vacuum, T_R is the round-trip time, $\sigma_{em,L}$ is the emission cross-section of the laser crystal, P is the intracavity pulsed laser power, λ is the laser wavelength, $\omega_{eff,L}$ and $\omega_{eff,A}$ are the effective laser radii at the gain medium and SA, and m is a cavity constant: m=1 for a ring cavity, and m=2 for a linear cavity. The emission cross-section $\sigma_{em,L}$ of the laser crystal is 3×10^{-20} cm^2. Therefore, to realize a stable CW mode-locked operation, one should optimally design a laser resonator to satisfy (3).

In our experiment, we transferred the as-grown InAsP NWs grown on quartz onto mirror with high-reflection (HR) coating at 1020–1100 nm via a PMMA-mediated method[30]. A z-type resonator with the cavity length of 3.61 m was applied, as shown in fig. 3(a). A 3×3×2 mm^3 N_p-cut Yb:KYW crystal with Yb^{3+} concentration of 10% was used and directly pumped by a 976 nm fiber-coupled diode laser with a core diameter of 105 μm and a numerical aperture of 0.22. With a 1.8:1 optical collimation system, the pump beam radius inside the crystal was ~29 μm. With the ABCD propagation matrix, the oscillation laser mode radii were 31 μm and 49 μm on Yb: KYW and InP NWs, respectively. The dichroic mirrors M1 (R=∞), M2 (R=0.8 m), and M3 (R=0.1 m) were antireflection (AR) coated at 976 nm and high-reflection (HR) coated at 1020—1100 nm. The flat output coupler (OC) had the transmission of T=1% coating for the spectral range of 1020-1100 nm. To compensate the dispersion introduced by the gain medium, mirrors, and InP NWs, two Gires-Tournois interferometers (GTI) with group delay dispersion (GDD) of -500 fs^2 and -375 fs^2 per round were used.

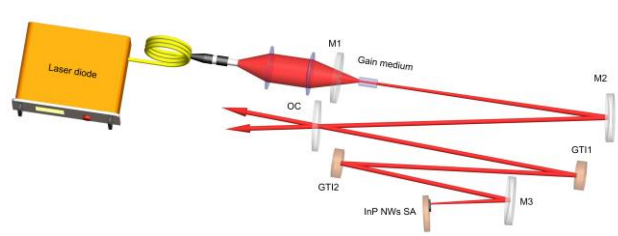

Fig. 3. Experimental setup of the mode-locked laser with InP NWs SA.

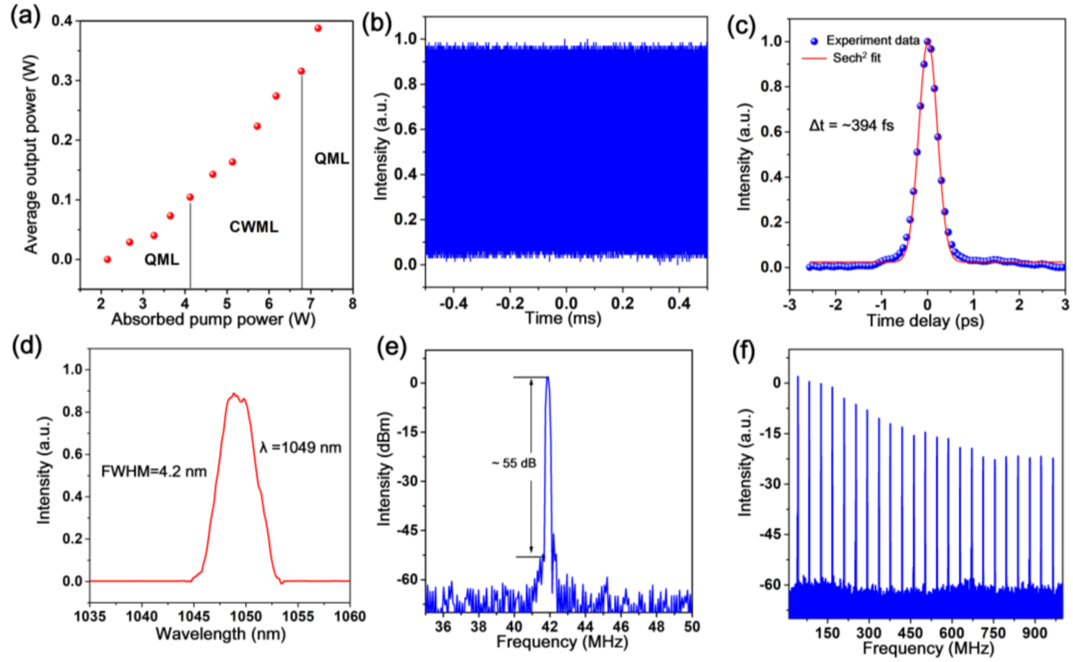

Fig.4. (a) Average output power versus absorbed pump power. (b) Recorded CWML pulse trains under the maximum pump power. (c) Autocorrelation trace for 394 fs duration, and (d) the corresponding spectrum centered at 1049 nm. (e) Recorded frequency spectrum of the mode-locked laser (f) Frequency spectrum over the 1.0 GHz wide span.

Considering the corresponding parameters in (3), the right-hand side was calculated to be 65 μJ/cm ^{2}, while the $F_{sat,A}\,\Delta R$ was 8 μJ/cm^2. Therefore, stable CW mode-locked (CWML) operation could be obtained with the as-prepared InP NWs SA and as-designed laser cavity. By careful adjustment, CWML operation was obtained. Fig. 4(a) shows the dependence of average output power versus absorbed pump power. The laser operation regime varied from Q-switched mode-locking (QML) to stable CW mode-locking (CWML) as the pump power increased. A stable CWML laser was achieved when the absorbed pump power increased to 4.1 W. Then it was sustained until the absorbed pump power increased up to 6.8 W, corresponding to a maximum average output power of 315 mW. If the pump power further increased, the CWML operation became unstable and eventually disappeared. The output power instability (rms) was measured to be less than 2% at 2 h. As shown in Fig. 4(b), the CWML pulse trains were recorded in millisecond time span at the maximum output power, indicating the good stability of the mode-locked laser.

Fig. 4(c) shows the autocorrelation trace of the mode-locked pulses, which were measured by a commercial noncollinear autocorrelator (APE, Pulse Check 150). With sech^2 pulse shape fitting, the pulse duration was determined to be 394 fs. As shown in Fig. 4(d), the spectrum of a CWML laser was centered at 1049 nm with the full-width at half-maximum (FWHM) of 4.2 nm, corresponding to the time-bandwidth product of 0.451. This value was larger than the Fourier-transform-limited value (0.315), indicating the pulse was slightly chirped. Fig. 4(e) shows the recorded radio frequency (RF) spectrum of the mode-locked laser, with a fundamental beat note near 41.5 MHz and corresponding signal-to-noise ratio of ~55 dB, which was measured by a spectrum analyzer (Agilent N9000A) with resolution bandwidth (RBW) of 75 kHz. In addition, there were no spurious frequency components or modulations over the entire 1.0 GHz span, as illustrated in Fig. 4(f). The clean RF signals implies the single pulse operation of the InP NWs-based mode-locked femtosecond laser. In our experiment, no sparks were observed even at the highest intracavity fluence. These results indicated that the InP NWs is an excellent SA for ultrafast laser generation.

IV. Conclusions

In conclusion, a high-quality InP NWs SA was fabricated and successfully employed to achieve a femtosecond ultrafast bulk laser for the first time, to the best of our knowledge. By using a Yb:KYW crystal as the gain medium and InP NWs as the SA, a stable CW mode-locking laser operation was demonstrated with a maximum average output power of 315 mW and pulse width as short as 394 fs. The results validate that InP NWs is a novel kind of promising SA candidate for ultrafast mode-locked laser generation and paves a new platform for designing novel photonic devices.

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