Watt-level, kHz pulsed ASE source with pulse-width close to round-trip time based on Nd:GdVO₄ bounce geometry

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We demonstrate a watt-level, kHz nanosecond-pulse ASE source with its pulse-width being close to its round-trip time. The ASE uses a Nd:GdVO₄, high gain bounce geometry structure without an output coupler. Using an EOQ (electro-optics Q-switch) device with high extinction-ratio, the pulse-width reaches 2.28, 1.73 and 1.17 ns under three effective cavity lengths, respectively. All these pulse-widths are close to the round-trip time of the corresponding effective cavity lengths. With the pulse-width being 1.17 ns, maximum output energy of 120 μJ and peak power of 100 kW are achieved. This study offers a convenient method to obtain high-peak-power short pulses, comparing with cavity-dumping method.

OCIS codes: (140.3580) Lasers, solid-state; (140.3538) Lasers, pulsed; (140.3540) Lasers, Q-switched; (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium

http://dx.doi.org/10.1364/OL.99.099999

For decades, growing interests were paid to the research of ASE sources in various media, including dye [1, 2], gas [3, 4], fibers [5] and solid-state media [6-8]. ASE sources have continuous spectra rather than discrete longitudinal modes since there are no feedbacks provided by cavities. This feature has very important applications in a vast range of fields. For example, in high power fiber lasers, ASE is widely applied as seed sources to suppress the nonlinear effects[5]. In dye media, Pique et al. demonstrated an ASE with 3 GHz continuous bandwidth which can excite D₂-sodium star six time brighter than that of a single-mode laser [2]. In solid-state lasers, Chen et al. reported a narrow linewidth ASE around 1064 nm, which is promising for applications of adaptive optics. Therein, the pulse-width of the ASE source reached a level of 100 μs by quasi-continuous wave pumping of 100 Hz[6]. However, an ASE output with high repetition rate and pulse duration of nanoseconds in solid-state medium was rarely investigated.

Light pulses generated in solid-state laser media with nanosecond durations are widely applied in industrial applications such as machining, remote sensing and imaging. Q-switching technique is commonly used to generate pulses with durations of nanoseconds[9-11]. Since several round-trips in the cavity are needed to form oscillations, the pulse-widths are at least several times of round-trip time with respect to the cavity length in this technique. Cavity dumping is proposed to further shorten the pulse duration under a given cavity length[12]. Using a Q-switching device, the photons stored in the cavity is possible to be released in only one round-trip time of the cavity. However, this method relies on high speed Q-switching devices with rise/fall time close to round-trip time of the cavity[12-14].

In this letter, we present a watt-level ASE source with kHz repetition rate and nanoseconds pulse duration. The pulse-widths can reach the round-trip time of the effective cavity lengths without using high-speed Q-switch devices. A high gain Nd:GdVO₄ bounce geometry without an output coupler is adopted. An AOQ (acousto-optics Q-switch) device and an EOQ (electro-optics Q-switch) device are successively used to switch on/off the ASE laser periodically. The AOQ and the EOQ make the ASE operates at the repetition of 50 kHz-500 kHz and 1 kHz-50 kHz, respectively. The relationship between the pulse-width and the repetition rate is experimentally investigated in three effective cavity lengths for both AOQ and EOQ setups. Particularly, the pulse-width in our EOQ experiment can approach to the round-trip time in all three effective cavity lengths. The output energy and the spectrum characteristics of the ASE output are also investigated. To our best knowledge, this is the first watt-level ASE in solid-state media with narrow pulse-width close to round-trip time.

We firstly realize a CW operating ASE output without Q-switch devices. The distance between M₀ and the exiting end face of the crystal d is ~220 mm. The output beam is divided by a beam splitter (BS), where most of the power enters into the power meter. The output power against pump power emitted from LD is shown in Fig. 2. At the pump power of 30 W, the output power is 3.7 W,
corresponding to an optical efficiency of 12.3%. The output power fluctuates by about ±0.1 W for d=120 mm~300 mm. The far field beam profile is elliptical, as is illustrated in the inset.

We use an AOQ device and an EOQ device to perform pulsed ASE output, separately. The pulsed ASE is first realized by using the AOQ device. Figure 3 (a) shows the measured pulse-width against pulse repetition rate under three different $L_{\text{eff}}$. The performance of pulsed ASE of AOQ is of interest for repetition rate in 50-500 kHz. The FWHM (Full Width at Half Maximum) of pulses is monitored by an InGaAs detector (bandwidth of 5 GHz) and an oscilloscope (Tektronix MDO3104, bandwidth of 1 GHz). With the increase of the repetition rate, the pulses become broadened for three $L_{\text{eff}}$. For the $L_{\text{eff}}=310, 240$ and 170 mm, the pulse-width changes from 17.2, 14.5 and 7.3 ns to 28.2, 27.0 and 20.7 ns. When the repetition rate is lower than 50 kHz, the pulse shape becomes unstable and sub-pulses start to emerge. This behavior is caused by high gain at lower repetition rate and the AOQ cannot hold off the sub-pulses. For repetition rate higher than 500 kHz, the amplitudes of different pulse periods become inconsistent because the gain cannot recover promptly. The waveforms of the pulses at 50 kHz under different $L_{\text{eff}}$ are shown in Fig. 3 (b). The average power of $L_{\text{eff}}=310, 240$ and 170 mm varies from 3.16, 3.28 and 3.34 W to 3.60, 3.78 and 3.81 W when the repetition rate increases from 50 to 500 kHz.

Although the ASE is capable of working at high repetition rates up to 500 kHz in AOQ experiment, we discover that the power mainly distributes in the continuous light component. This is because diffraction efficiency of AOQ is only about 80%, while ~20% of ASE would not be diffracted, and still be amplified in double-passes, independent of varying AOQ state. To measure the power of continuous component, a signal of low duty cycle (high voltage time ~10ns) is applied to the AOQ, and the Q-pulses are restrained. Under this condition, the output power is about 3.1W, which indicates that the power in the pulse component is mainly about 0.5, 0.68, and 0.71 W at 500 kHz under three $L_{\text{eff}}$. This indicates the maximum single pulse energy in AOQ experiment is below 5 μJ, and the maximum peak power is less than 700W.

![Image](image_url)

Fig. 2. Output power against pump power (inset: the far field beam profile).

![Image](image_url)

Fig. 3. Experimental results in AOQ experiment under three different $L_{\text{eff}}$: (a) Pulse-width against repetition rate, (b) Pulse profile at 50kHz

To obtain a high-peak-power pulsed ASE, we replace the AOQ device with an EOQ device. Comparing with the AOQ, the EOQ has a better extinction-ratio, which means better performance in producing pulses with short duration and high-peak-power. The EOQ is composed of a polarized beam splitter (PBS) and a pair of RTP crystals. Under the quarter-wave voltage, the RTP crystal pairs rotate the vertical polarization state to the horizontal polarization state, thus the ASE cannot be amplified for the second time. The EOQ device provide a high extinction-ratio of 23dB at 1064nm. Hence, the output power is only about 0.15 W when the EOQ is working at high loss state. The EOQ experiment is also investigated under three $L_{\text{eff}}$: 340, 250, and 170 mm. The corresponding round-trip time of the three $L_{\text{eff}}$ are 2.26, 1.68 and 1.13 ns, respectively (shown with dotted line in Fig. 4(a)). The relationship between the pulse-width and the repetition rate is illustrated in Fig. 4 (a). When the repetition rate is below 15 kHz, the pulse-widths of all three $L_{\text{eff}}$ approach to the corresponding round-trip time. With the increase of repetition rate, the pulse-widths broaden to 3.00, 2.39 and 1.53 ns at 50 kHz.

![Image](image_url)

Fig. 4. Experimental results in EOQ experiment under three different $L_{\text{eff}}$: (a) Pulse-width against repetition rate, (b) Pulse profile at 10kHz, (c) Average power and (d) pulse energy against repetition rate

The pulse profiles at 10 kHz for the three $L_{\text{eff}}$ are shown in Fig. 4 (b). The pulse-widths are 2.28, 1.73 and 1.17 ns for $L_{\text{eff}}=340, 250$, and 170 mm, respectively. It means that the pulse-widths reach 1.01, 1.03, and 1.04 times of round-trip time corresponding to the three $L_{\text{eff}}$ above. This is hard to be realized in Q-switch oscillators. According to Zayhowski’s theory, the minimum pulse-width that can be reached in a Q-switched laser is [11, 17]:

$$t_{w, \text{min}} = \frac{8.1 \tau_p}{\ln(G_{rt})}$$

(2)

where $t_p$ is the round-trip time, and $G_{rt}$ is the small-signal gain of one round-trip. The optimal output coupling is:

$$G_{o} = 1 - e^{-0.32 \ln(G_{rt}) + \gamma_p}$$

(3)

where $\gamma_p$ is the round-trip parasitic loss constant. Eq. (2)-(3) indicate that the optimal output coupling approaches to 100% when there is sufficiently high gain. In our experiment, high gain level of $G_{rt, i} \sim 10^{11}$ is reached. Hence, the optimal output coupling to achieve minimum pulse-width is satisfied under the cavility
configuration. In this way, a short pulse close to \( t_r \) is achieved. Although cavity dumping technique is capable to produce pulse-width that approach to \( t_r \), drivers with corresponding short rise/fall time are needed [12-14]. For the shortest \( L_{\text{eff}}=170 \) mm, a driver with rise/fall time of \( \approx 1.17 \) ns is needed in cavity dumping method. However, in our EOQ setup, the fall time of the driver is larger than 14 ns. This long fall time still results in the pulse-width of 1.17 ns, which is nearly the round-trip time for \( L_{\text{eff}}=170 \) mm. This fact indicates that high gain cavityless configuration can provide sufficient tolerance to the speed of the Q-switch driver.

The average power and pulse energy (at the pump power of 30 W) that related to repetition rate under three different \( L_{\text{eff}} \) is illustrated in Fig. 4 (c) and (d), respectively. The average powers increase from 0.30, 0.24 and 0.19 W to 2.88, 2.65, and 2.64 W with the increase of repetition rates from 1 kHz to 50 kHz for \( L_{\text{eff}}=340, 250, \) and 170 mm, respectively. The Q-switched efficiency is 78%, 74%, and 73% at 50 kHz, accordingly. At 1 kHz, the pulse energy reaches 120 \( \mu \)J for all the three \( L_{\text{eff}} \). For the shortest \( L_{\text{eff}} \) of 170 mm, the maximum peak power exceeds 100 kW. The average output power is above 1 W at 15 kHz, while the pulse-widths remain close to round-trip time under the three effective cavity lengths. These results validate that watt-level, kHz ASE with round-trip time pulse-width can be achieved by a combination of high gain cavityless configurations and high extinction-ratio Q-switch devices. This combination offers a convenient method to obtain pulsed ASE source with high-peak-powers and short pulses.

The spectra of the ASE are monitored by an optical spectrum analyzer (Agilent 86142B, minimum resolution of 0.06nm) for CW mode at the pump power of 30 W. Without \( M_0 \), the single pass ASE has a bandwidth (10dB) of 1.29 nm (3dB bandwidth 0.12 nm). With the insertion of \( M_0 \), the bandwidth (10dB) decreases to 0.22 nm (3dB bandwidth< 0.06nm).

As the resolution of 0.06nm cannot offer more detailed spectra information, the spectrum content is further investigated by a scanning Fabry-Perot (FP) interferometer with the free spectral range (FSR) of 3 GHz. After divided by \( BS \), a small portion of power about 30mW enters into FP interferometer. To prevent feedbacks and parasitic oscillators, an optical isolator (OI) is inserted between BS and FP interferometer. When the ASE works at CW mode (still at a pump power of 30 W), the scanning output is the continuous spectrum accompanied by several disordered pulses: both the amplitudes and the spacing of these pulses are random, as shown in Single Frame 1-4 of Fig. 6 (a). If multiple frames are averaged (64 frames in Fig. 6(a)), the scanning output becomes flatter, which implies that the spectrum is continuous in the range of 3 GHz for time-averaged observation, no steady longitudinal modes and longitudinal intervals are discovered. To verify that the CW light obtained here is ASE, we implement a comparative experiment. An output coupler (T = 80%) is inserted after VCSEL. The output power increases to 62 W, which means oscillation is formed. At this moment, 4 peaks with fixed interval are observed, which implies at least 4 steady longitudinal modes are generated. The measured longitudinal mode interval is consistent with the cavity length of the oscillator. This phenomenon proves the random emerging pulses in the scanning output for the CW light is not caused by multiple longitudinal modes, but the random fluctuations of ASE.

The spectra of pulsed operating ASE are also analyzed in FP interferometer. When the ASE is working at pulsed state, the scanning output of FP interferometer has equal repetition rate with the ASE pulses, as illustrated in Fig. 6(b). This is different to that in frequency-shifted feedback laser [18], which also owns a continuous spectrum. Considering the results in Fig 6 (a) and (b), a conclusion can be reached that the output of the cavityless configuration in our experiment has a continuous spectrum, and parasitic oscillations are avoided in our experiments. The characteristics of continuous spectrum and less coherence may be helpful in applications such as nonlinear interactions [19, 20].

In conclusion, a watt-level average power ASE source with kHz repetition rate and nanosecond pulse-width is demonstrated. The pulse-widths reach the round-trip time of the effective cavity lengths. Based on a high gain bounce geometry without an output coupler, the pulsed ASE experiments are performed with the insertion of an AOQ and an EOQ device, respectively. In AOQ experiment, lower extinction-ratio restricts the pulse-width and the peak power. Using an EOQ with much higher extinction-ratio, the minimum pulse-widths of the ASE reach 228, 1.73, and 1.17 ns under three effective cavity lengths. The pulse energy of the ASE reaches 120\( \mu \)J for three effective cavity lengths. For the shortest effective cavity length, the peakpower exceeds 100 kW. To our best knowledge, this is the first watt-level ASE source with pulse-width close to round-trip time in solid-state media. Comparing with cavity dumping method, this work does not rely on a high speed Q-switch device to generate light pulse of round-trip time. It is a convenient method to produce ASE pulses with short durations and high-peakpower, which has potentials in many cost-effective applications.
Funding. National Key Research and Development Program of China (2017YFB1104500)

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