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Measurement of amplified spontaneous emission noise in high power pulsed fiber laser*

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Abstract: High power pulsed fiber lasers are attractive for light detection and ranging (lidar) systems. However, the amplified spontaneous emission (ASE) noise of the high power pulsed fiber laser degrades the system performance. A method to measure the ASE noise inherited in the high power pulsed laser is proposed. Using this new method, the high power laser is attenuated firstly, and then the relative energies of the ASE noise and the laser pulse are measured and calculated separately in time domain. The attenuated ASE noise profiles as well as the ratios of the ASE noise energy to the laser pulse energy are presented at different pump conditions.

Key words: high power pulsed fiber laser; amplified spontaneous emission; ASE ratio; ASE profile; lidar

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Outstanding performance of high power pulsed fiber lasers have been demonstrated in atmospheric light detection and ranging (lidar) systems, attracting considerable attentions to atmospheric wind measurements (including wake vortices, wind shear, clear air turbulence[1-4]), density and temperature measurements[5-6], as well as the gas concentration measurements[7-8]. Furthermore, the increasing power, excellent beam quality, compact packaging, stable narrow linewidth and high overall efficiency, make high power pulsed fiber lasers popular for atmospheric remote sensing from ground-based to airborne-based systems[9-10].

The high power pulsed fiber laser usually employs the master oscillator power amplifier (MOPA) scheme[11]. For a typical pulsed power amplifier, the gain fibers are pumped continuously and seeded by an optical pulse. In principle, stored energy would build up in the gain fiber as population inversion and then release when stimulated by the seeder. In fact, the power amplifier will emit photons spontaneously within the optical gain bandwidth even without seed pulse. In addition, the emitted photons are amplified by stimulating the emission of more photons while travelling through the gain fiber. Consequently, these photons, generally known as the amplified spontaneous emission (ASE) noise, leak out between seed pulses, which produce background noise adding to the laser pulse and reduce the efficiency of the power amplifier[12]. In the application of lidar systems, for example, the system measurement accuracy is degraded due to the ASE noise of the pulsed fiber laser. In such systems, the suppression of the ASE noise is crucial to accurate measurements[1-7]. Therefore, measuring the ASE noise accurately is of great importance to evaluate pulsed fiber lasers as well as enhance their applications in lidar systems.

The ASE noise of the pulsed fiber laser has been studied theoretically and experimentally by several research groups[12-18]. The internal gain and the spontaneous emission factor of the power amplifier were deduced with no seed signal applied[13]. A measurement using an optical spectral analyzer and a polarizer was

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introduced based on the assumption that the laser signal was polarized and the degree of polarization was 100%[14]. In this case, for a pulsed fiber laser with a peak power of about 405 W and a polarization extinction ratio (PER) of 20 dB[15], a corresponding ASE noise measurement of 4.05 W will be introduced. Some other measurement setups, which use a laser source modulation or a chopper to discriminate the laser pulse from the ASE noise, are only practicable on low power conditions up to hundreds of milliwatt[17-18]. To measure the ASE noise of high power pulsed fiber lasers, a method based on the separation of the ASE noise and the laser pulse in time domain is proposed in this paper.

1 Experimental setup

The experimental setup of a typical pulsed fiber laser is shown in Fig. 1. The continuous-wave (CW) laser from a seed laser is split by a polarization-maintaining fiber splitter (PMFS) into two beams. One beam is usually used as a local oscillator for coherent detection, and the other is modulated to a quasi-Gaussian shaped pulse using an acousto-optic modulator (AOM) and then amplified by a two- (or even more) stage fiber power amplifier. The first pulse signal from the Arbitrary Function Generator (AFG) is linked to the driver of the AOM, and the second one is fed to the electro-optic intensity modulator (EOM, Thorlabs LN56S-FC). The pulsed fiber laser emits a high power linear polarized laser through the large mode area polarization-maintaining fiber which is connected to a large beam fiber collimator (LBFC), expanding the laser beam into free space. After attenuated by an iris and a neutral density filter (NDF, Newport 5241) in sequence, the laser is coupled into a single-mode fiber (SMF) by an achromatic doublet. The attenuation of the iris can be adjusted continuously by turning its diaphragm and the NDF can be removed from the laser beam path conveniently. The polarization state of the laser in the SMF is aligned to the slow-axis of the input PM fiber pigtail of the EOM by using a polarization controller (PC). Driven by the AFG, the EOM modulates the intensity of the laser in time domain. The modulated laser is detected by a photodetector (PD, Thorlabs PDB130C), and the output voltages are recorded on a digital storage oscilloscope (DSO).

As illustrated in Fig. 2, the measurement can be carried out in the following two steps.

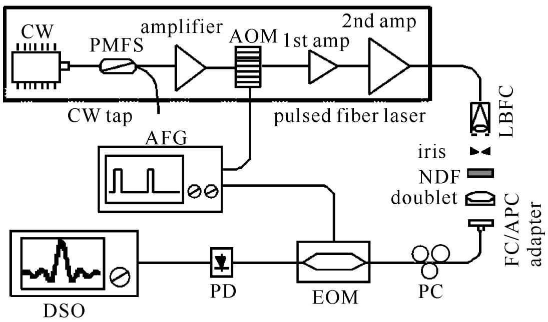

Fig. 1 Experiment setup of a typical pulsed fiber laser

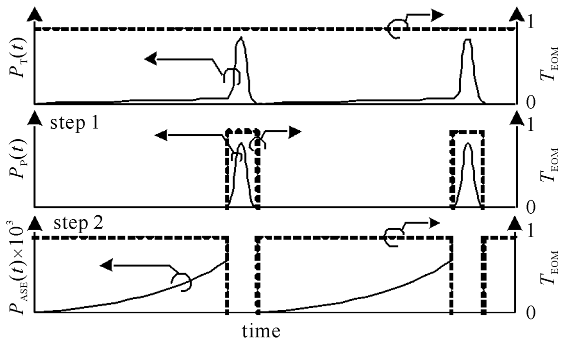

Fig. 2 Timing sequence of measurement. $P_T(t)$ is the total laser power. $P_P(t)$ is the laser pulse power. $P_{ASE}(t)$ is the ASE noise power. T_{EOM} is the transmittance by the modulation of the EOM.

Step 1. Insert the NDF between the iris and the doublet. By adjusting the pulse width and time delay of the driving signal, the EOM produces a transmission profile, allowing the transmission of the laser pulse whereas blocking the ASE noise.

Step 2. Remove the NDF from the laser beam path. By adjusting the driving signal, the EOM produces a transmission profile, allowing the transmission of the ASE noise whereas eliminating the optical pulse.

The total power of the pulsed fiber laser is supposed to be $P_T(t)$, including the laser pulse power $P_P(t)$ and the ASE noise power $P_{ASE}(t)$. In step 1, the laser pulse power detected by the PD is written as

$$P_{P\_D}(t) = \eta_T T_{NDF} P_P(t) \qquad (1)$$

where η_T is the total optical efficiency including the transmittance of the LFBC, iris, achromatic doublet, EOM and the coupling efficiency of the achromatic doublet, $T_{NDF}=3.02\%$ stands for the transmittance of the

NDF, which is calibrated in advance. In step 2, due to the absence of the NDF and the elimination of the laser pulse by virtue of the EOM, the ASE noise power detected by the PD is written as

$$P_{\mathrm{ASE\_D}}(t)=\eta_{\mathrm{T}} P_{\mathrm{ASE}}(t) \tag{2}$$

The voltages induced by the laser pulse and the ASE noise are given by

$$V_{\mathrm{P\_D}}(t)=G\Re P_{\mathrm{P\_D}}(t) \tag{3}$$

and

$$V_{\mathrm{ASE\_D}}(t)=G\Re P_{\mathrm{ASE\_D}}(t) \tag{4}$$

respectively, where G is the transimpedance gain, and $\Re$ is the photodetector responsivity. From equations (1)-(4), the relationships between the voltage and the power of laser pulse and the ASE noise is deduced as

$$P_{\mathrm{P\_D}}(t)=\frac{V_{\mathrm{P\_D}}(t)}{G\Re\eta_{\mathrm{T}} T_{\mathrm{NDF}}} \tag{5}$$

and

$$P_{\mathrm{ASE\_D}}(t)=\frac{V_{\mathrm{ASE\_D}}(t)}{G\Re\eta_{\mathrm{T}}} \tag{6}$$

respectively.

The ASE ratio, defined as the ratio of the ASE noise energy E_{ASE} to the total laser energy E_{T}, can be expressed as

$$R_{\mathrm{ASE}}=\frac{E_{\mathrm{ASE}}}{E_{\mathrm{T}}}=\frac{E_{\mathrm{ASE}}}{E_{\mathrm{P}}+E_{\mathrm{ASE}}}=\frac{\int_T P_{\mathrm{ASE}}(t)\,\mathrm{d}t}{\int_T [P_{\mathrm{P}}(t)+P_{\mathrm{ASE}}(t)]\,\mathrm{d}t}=\frac{\int_T V_{\mathrm{ASE\_D}}(t)\,\mathrm{d}t}{\int_T [V_{\mathrm{P\_D}}(t)/T_{\mathrm{NDF}}+V_{\mathrm{ASE\_D}}]\,\mathrm{d}t} \tag{7}$$

where T is the pulse repetition interval. The total laser energy E_{T} can be determined by an energy meter, thus the total ASE noise energy can be calculated by $E_{\mathrm{T}}\times R_{\mathrm{ASE}}$.

2 Measurement results

The experimental configuration is shown in Fig. 1. The fiber laser employs the MOPA scheme, emitting a peak power of 360 W with a pulse width of 300 ns and a pulse repetition frequency (PRF) of 20 kHz. The pump current of the first amplifier is fixed at 1.7 A. The pump current of the second amplifier is adjustable and the maximum is recommended to be 8.0 A. In the first step, with the attenuation of the NDF and the elimination of the ASE noise, the voltages resulting from the attenuated laser pulse at the pump currents of 6.0 A, 7.0 A and 8.0 A are plotted in Fig. 3. In the second step, due to the removal of the NDF and the elimination of the laser pulse, voltages resulting from the attenuated ASE noise in multiple pulse repetition periods (PRD) at the same pump currents are plotted in Fig. 4. As one can see from this figure, curves where voltages prick above 0.7 mV are related to the leakage of the laser pulse passing through the EOM. Such voltages will be deleted when calculating the attenuated ASE noise energy in the following step.

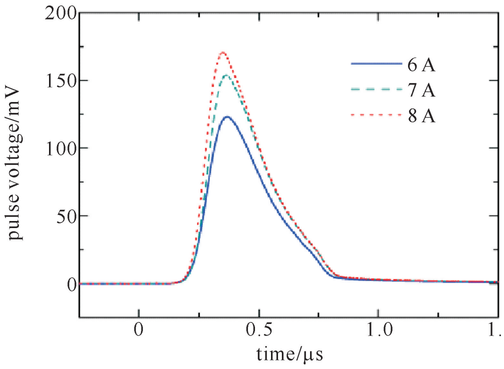

Fig. 3 Voltages resulting from the attenuated laser pulse at pump currents of 6.0, 7.0, and 8.0 A

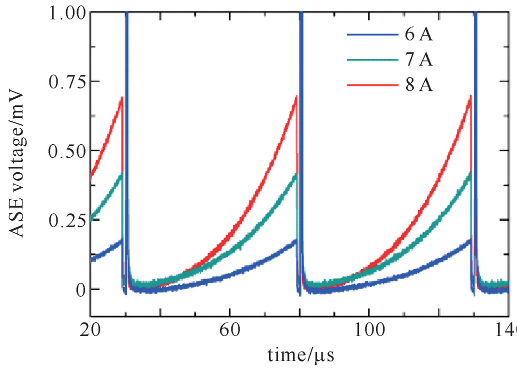

Fig. 4 Voltages resulting from the attenuated ASE noise in multiple PRDs at pump currents of 6.0, 7.0, and 8.0 A. Curves above 0.7 mV are residual laser pulses which are not perfectly eliminated by the modulation of the EOM

Instead of the ASE noise energy E_{ASE} and the laser energy E_P in (7), we define two relative quantities, E'_{ASE} and E'_P, by integrating the attenuated ASE noise voltages $V_{ASE\_D}(t)$ and laser pulse voltages $V_{P\_D}(t)$, respectively,

$$E'_{ASE} = \int_T V_{ASE\_D}(t)\,dt \quad \text{and} \quad E'_P = \int_T V_{P\_D}(t)\,dt \tag{8}$$

Calculated from Fig. 3 and Fig. 4, according to (7) and (8), the measurement results of the ASE noise at pump currents of 6.0 A, 7.0 A and 8.0 A are listed in Table 1.

Table 1 Measurement results of ASE noise

pump current/A	attenuated laser pulse energy */a. u.	attenuated ASE noise energy */a. u.	ASE ratio/%
6.0	3.707×10^{-8}	2.356×10^{-9}	0.19
7.0	4.557×10^{-8}	6.459×10^{-9}	0.43
8.0	4.984×10^{-8}	9.613×10^{-9}	0.58

*: The laser pulse energy and the ASE noise energy are attenuated at the same factor except the transmittance T_{NDF} of the NDF, so both are calculated in relative quantities.

3 Conclusion

A method for measuring the ASE noise of the high power pulsed fiber laser by separating the ASE noise from the laser pulse in time domain is proposed and demonstrated. Because the EOM device is polarization dependent, the polarization state of the fiber laser under test is assumed to be linear. Otherwise, a polarizer should be added between the iris and the achromatic doublet. It is worth mentioning that the laser power after the attenuation by the iris and the NDF should be in the linear responsivity range of the PD when measuring the laser pulse. The measurement accuracy of our method relies on the accuracy of the NDF transmittance T_{NDF}. Therefore the T_{NDF} must be calibrated accurately in advance. Obviously, for lasers with very high PRF, the EOM is better than the mechanical chopper to discriminate the laser pulse from the ASE noise. With the proposed method, the ASE noise of a high power pulsed fiber laser is analyzed at different pump currents. Such measurement results are important for engineers to inspect the high power pulsed fiber laser as sell as research the impact of the ASE noise on the performance of lidar systems.

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高功率光纤激光器中 ASE 噪声的测量方法

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摘　要： 高峰值功率脉冲光纤激光器在激光雷达系统中有着广泛的应用。然而，光纤激光器中放大自发辐射噪声（ASE）严重影响了系统的探测性能。提出一种测量高峰值功率脉冲光纤激光器中 ASE 噪声的方法。在该方法中，首先对高峰值功率的激光脉冲衰减，然后在时域分别测量和计算 ASE 噪声和激光脉冲的相对能量。给出了光纤激光器在驱动电流分别为6 A，7 A 和 8 A 时衰减后的 ASE 噪声廓线以及 ASE 噪声占激光脉冲能量的比例。

关键词： 高功率光纤激光器； 放大自发辐射； ASE 比例； ASE 廓线； 激光雷达