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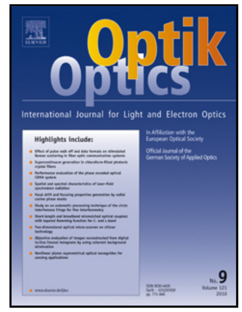

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PII: S0030-4026(20)31219-5

DOI: https://doi.org/10.1016/j.ijleo.2020.165383

Reference: IJLEO 165383

To appear in: *Optik*

Received Date: 2 June 2020

Revised Date: 13 July 2020

Accepted Date: 2 August 2020

Pump-controlled wavelength switchable dissipative soliton mode-locked Yb-doped fiber laser using a 45° tilted fiber grating

Yanlv Lin[a], Zinan Huang[a], Qianqian Huang[a], Lilong Dai[a], Qingguo Song[b], Zhijun Yan[b], Chengbo Mou[a,*] ,Kaiming Zhou[c] and Lin Zhang[c]

[a]*Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, China*

[b]*School of Optical and Electronic Information, National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science and Technology, Wuhan, China*

[c]*Aston Institute of Photonic Technologies, Aston University, Aston Triangle, Birmingham, B4 7ET, United Kingdom*

E-MAIL ADDRESS: mouc1@shu.edu.cn (Chengbo Mou)

Abstract

We demonstrate a pump-controlled wavelength switchable Yb-doped fiber laser (YDFL) by nonlinear polarization rotation (NPR) for the first time. The polarizer replaced by a 45° tilted fiber grating (45°-TFG) combines with a section of polarization maintaining fiber (PMF) to form a fiber-based birefringent filter. Stable dissipative soliton (DS) with center wavelength of 1068.39 nm is generated under the mode-locked threshold of 277 mW. The operating wavelength switching between 1046.51 nm and 1067.90 nm can be realized via increasing the pump power simply while keeping the polarization controllers (PCs) in a fixed state. The laser maintains stable mode-locking operation at each wavelength, which can be regarded as a type of multi-wavelength ultrafast light source with precise control and integration potential.

Keywords: Yb-doped fiber laser, pump-controlled, dissipative soliton, wavelength switching, tilted fiber grating.

1. Introduction

Recently, due to the urgent requirements in photonic signal processing, biomedical detection and wavelength division multiplexed system [1], more and more researchers are investing their interest in the topic of wavelength switchable ultrafast fiber lasers. Especially in the field of biomedicine, the high pulse energy is an indispensable indicator of wavelength switchable fiber lasers. As we know, Yb-doped fiber lasers (YDFL) have been proved to be ideal candidates in competition with high power solid-state lasers [2]. The broad gain bandwidth and large gain saturation power [3] make YDFL less susceptible to gain limitation. In addition, since the normal dispersion of single-mode fiber (Corning HI1060) as well as fiber-based components in the working waveband of 1 μm [4], the YDFL generally operating in all-normal-dispersion (ANDi) region, which leads to the generation of dissipative soliton (DS) normally [5]. Fortunately, DS exhibits higher pulse energy compared with other types of soliton particularly the conventional soliton (CS).

Due to the demand for strong spectral filtering effects [6], the optical filters including Mach-Zehnder interferometer (MZI) [7-9], Fabry-Perot interferometer (FPI) [9-10], chirped fiber gratings [11], Sagnac loop filter [12-13] and fiber-based birefringent filter [14], have become the priority for the achievement of wavelength switching in YDFL. Among them, the fiber-based birefringent filter is highly appreciable in wavelength switchable lasers due to its simple structure and flexibility without adding complexity to the laser cavity. Since the comb filtering of such filter is highly correlated with the polarization orientation in the cavity, most wavelength switchable lasers are realized by tuning the intracavity polarization controllers (PCs) [15]. In 2013, dual-wavelength switchable and tunable DS operation was demonstrated in YDFL by adjusting the polarization orientation [16]. Xu *et al.* reported a wavelength switchable DS YDFL through the rotation of PCs [17]. However, it contains strong randomness and unpredictability during the adjustment of the PCs, which can not achieve precise control of wavelength switching. It is quite desirable to improve the switchable controllability by finding a method to replace the polarization state adjustment and achieve wavelength switching, for example, the pump power [18-20]. A switchable ANDi YDFL was realized by increasing the pump power [21]. Comprising of several bulk components in this laser undoubtedly weakened the advantages of the compact structure of fiber laser. Li *et al*. experimentally demonstrated a wavelength switchable DS mode-locked YDFL by integrating weak birefringent filter and single-walled carbon nanotube (SWCNT) by solely increasing the pump power [22]. However, the weak birefringent filter is generally introduced by a long bending fiber, and the low thermal damage threshold of SWCNT becomes the main barrier to high power operation. Alternatively, due to the strong birefringence in polarization maintaining fiber (PMF), the long bending fiber can be replaced by a short section of PMF, while keeping the filter at a designated bandwidth [23]. In addition, nonlinear polarization rotation (NPR) is characterized by large modulation depth, high thermal damage threshold and simple structure, which greatly improves the average power of the laser output compared to materials-based saturable absorbers [24-25]. Meanwhile, NPR structure comes with a polarizer, only a section of PMF needs to be added to the laser to form a birefringent filter, which undoubtedly simplifies the structure of the laser cavity.

Here a pump-controlled wavelength switchable mode-locked YDFL incorporating a birefringent filter based on a 45° tilted fiber grating (45°-TFG) is proposed and demonstrated. Although it has been reported that 45°-TFG is used in YDFL [26], it is still meaningful to discover new features of these 45°-TFG-based lasers. The 45°-TFG combining with a section of PMF and PCs acts as both the birefringent filter and the artificial saturable absorber. The wavelength of the obtained dissipative soliton is originally centered at 1068.39 nm. Specifically, observed by solely increasing the pump power, wavelength switching between 1046.51 nm and 1067.90 nm can be without tuning the PCs. Such switchable method avoids disturbance of polarization and achieves more precise control because of the absence of PCs adjustment. Moreover, as far as we know, the all-fiber pump-controlled wavelength switchable mode-locked YDFL by using NPR is reported for the first time.

2. Experimental setup

45°-TFG, as a novel fiber-based polarizer, has the characteristics of superior fiber compatibility, robustness and low insertion loss. They have been widely used in various types of fiber lasers [27-29]. The inscription details of the 45°-TFG are described in ref

[30]. Because of the high polarization dependent loss (PDL) in wide wavelength range, such tilted grating can act as a broadband fiber-based polarizer. The PDL measurement of the specific TFG used in the experiment was carried out by a home-made Yb broadband light source, a 1μm fiber polarizer, a PC and an optical spectrum analyzer (OSA, YOKOGAWA AQ6370B), which is clear shown in Fig. 1(a). The maximum/minimum transmission of TFG can be obtained by adjusting the PC, thereby calculating the corresponding PDL [31]. The measured PDL response of the grating is shown in Fig. 1(b). It clearly indicates that a maximum value of PDL reaches 32 dB at 1014 nm, and the PDL exceeds an average of 20 dB within the entire operating wavelength region (1040 nm - 1070 nm) of the laser.

The configuration of the proposed wavelength switchable YDFL is shown in Fig. 2. The pump light delivered from a commercial 980 nm bench-top pump source is absorbed by a 35.6 cm Yb-doped fiber (YDF, LIEKKI Yb1200-4/125) through a wavelength division multiplexer (WDM). After the gain medium, a 10:90 coupler is placed to draw 10% light out of the cavity. A 45°-TFG sandwiched between PC1 and PC2 forms an artificial saturable absorber. The unidirectional transmission of light in the oscillator is ensured by a polarization-independent isolator (ISO). A 10 cm PMF is applied as the birefringent medium, and the corresponding filtering bandwidth can be calculated as 22.1 nm [23]. The pigtails are HI1060 with a whole length of ~10 m. All the fiber-based components in the cavity have normal dispersion. An OSA (YOKOGAWA AQ6370B) is used to display the laser spectrum. A 12.5 GHz photodetector (PD, Newport 818-BB-51F) is applied to convert the output light and combines with a high speed oscilloscope (OSC, KEYSIGHT DSO90804A) to observe the temporal waveform. The radio frequency (RF) response is monitored by a 3.2 GHz spectrum analyzer (SA, SIGLENT SSA3032X).

3. Results and discussion

As the pump power exceeds 277 mW, stable mode locking can be realized by rotating the PCs appropriately. DS operation centered at 1069.39 nm with a 3-dB bandwidth of ~13.58 nm is characterized by its typical steep-edge spectrum, which is consistent with the characteristic of ANDi lasers (in Fig. 3(a)). Fig. 3(b) is the output pulse trains with a 25.74 MHz fundamental repetition rate. As shown in Fig. 3(c), the corresponding RF spectrum indicates a signal-to-noise ratio (SNR) of 47 dB, which means that the pulse train is in a nearly undisturbed state.

In general, the rotation of the PC can shift the transmission peak/valley position of the birefringent comb filter, thus leading to laser operation wavelength switching [22]. However, in our experiment, in order to replace the adjustment of PCs, the wavelength-switching can be achieved by raising the pump power only. When the pump power raised to 301 mW, the operating wavelength switched to short wavelength, which is depicted in Fig. 4(a). The center wavelength at this moment is 1046.51 nm. The RF spectrum with a SNR of 48 dB in Fig. 4(b), meaning that the laser can also maintain stable mode-locking state at this wavelength. Continuously raising the pump power, mode-locking operation is disturbed. But when the increased pump power reaches 422 mW, the laser returns to mode-locking state and the operating wavelength is switched back to the original long wavelength. As it is plotted in Fig. 4(c) and Fig. 4(d), the wavelength is centered at 1067.90 nm and the corresponding SNR is 53 dB, which means the mode-locking is more stable. Without changing any experimental conditions, the mode-locking can be maintained for a few hours. At this pump power, the average power reaches the maximum value of ~ 25 mW, and the single pulse energy is ~ 1nJ. The increase in pump power from 277 mW to 422 mW is accompanied by a slight increase in spectral bandwidth from 13.58 nm to 15.54 nm because of the enhancement of self-phase modulation. This spectral width increase is also a typical feature of DS. The difference between the two switching wavelengths is about 22 nm, which matches the bandwidth of the self-constructed birefringent filter. The obvious sidebands in Fig. 4(c) are caused by the periodicity of the birefringent filter [32]. While the pump power surpasses 422 mW, the laser starts to lose stability as well as the output tends to be multi-pulses operation. It is worth mentioning that this is the first time to realize all-fiber pump-controlled wavelength switching in NPR mode-locked YDFL.

The wavelength switching behavior can be attributed to the variation of transmission peak position of the birefringent filter. The increase of pump power leads to the enhancement of the intracavity pulse peak power. As the instantaneous input signal of the filter, the intracavity pulse greatly influences the nonlinear phase delay which is the main factors of the filter's transmission. After that, the peak/valley position of spectral modulation can be shifted to other wavelengths, resulting in the lasing wavelength switching.

The transmission function of the comb filtering introduced by PMF can be expressed as [33-35]:

$$T = \cos^2\theta_1\cos^2\theta_2 + \sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}\sin(2\theta_1)\sin(2\theta_2)\cos(\Delta\varphi_L + \Delta\varphi_{NL}) \quad (1)$$

where, θ_1 and θ_2 are the included angles of the two ends of 45°-TFG relative to the fast axis of PMF, respectively. $\Delta\varphi_L = 2\pi L\Delta n/\lambda$ on behalf of the linear phase delay and $\Delta\varphi_{NL} = 2\pi n_2 PL\cos(2\theta_1)/(\lambda A_{eff})$ is the nonlinear phase delay. In Eq. (1), L is the length of PMF and Δn is the corresponding birefringence n_2 is the nonlinear coefficient, , λ is the center wavelength, P stands for the instantaneous input power and A_{eff} represents the effective fiber core area. In order to make the parameters close to the experiment, we set $L = 10$ cm and $\Delta n = 0.00048$. Since the PCs are fixed when wavelength switchable operation occurs in our experiment, θ_1 and θ_2 are set as constants. Because of the pump power elevation, the peak pulse power, which is the instantaneous input power P, is greatly enhanced. The increase of P causes displacement of the transmission peak position. These results are shown in Fig. 5. Under different pulse peak power ($P1$ and $P2$), the transmission peak position shift to other wavelengths, thus affecting the operating wavelength of the laser. It is worth mentioning that the change in pulse peak power has no obvious effect on the birefringent filter bandwidth and modulation depth. The filtering bandwidth, which is described as [23]:

$$\Delta\lambda = \frac{\lambda^2}{L\Delta n}, \quad (2)$$

is mainly determined by the length of PMF. And the modulation depth is mainly determined by θ_1 and θ_2 in Eq. (1). Furthermore, both the 45°-TFG and the birefringent filter have a wide operating wavelength, so the laser can obtain stable mode locking in a wide wavelength range. One may note the lack of autocorrelation trace measurement across our experiments. We would like to emphasize that the unavailability of a 1.06 μm autocorrelator in our lab is the main reason. However, this does not affect the main conclusions of our experiments.

4. Conclusions

In short, we propose and demonstrate an all-fiber pump-controlled wavelength switchable passively mode-locked YDFL using 45°-TFG. The 45°-TFG forms an artificial saturable absorber with PCs, and combines a section of PMF to form an integrated birefringent filter to realize wavelength switching. When pump power exceeds the mode-locking threshold, stable DS pulse trains at 1068.39 nm with a repetition rate of 25.74 MHz are generated. The spectral bandwidth is 13.58 nm and the SNR is 47 dB. Increasing pump power without adjusting PCs, the operating wavelength is switched to 1046.51 nm. And increasing pump power further can make the operating wavelength switched back to 1067.90 nm. The interval of wavelength is ~22 nm, which matches the filtering bandwidth of the birefringent filter. Compared with polarization-controlled wavelength switchable fiber lasers, the pump-controlled mechanism avoids unnecessary polarization state changes and can achieve more precisely controlled laser systems, which may have potential in applications such as optical integration system and biomedical detection *etc*. Furthermore, the 45°-TFG inscribed in PMF may feature more functionality than in standard single-mode fiber 45°-TFG. With its excellent polarization-maintaining and polarization characteristics, a more compact fiber laser can be designed in future research.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (NSFC) (grant number 61975107，61605107) and the 111 project (D20031).

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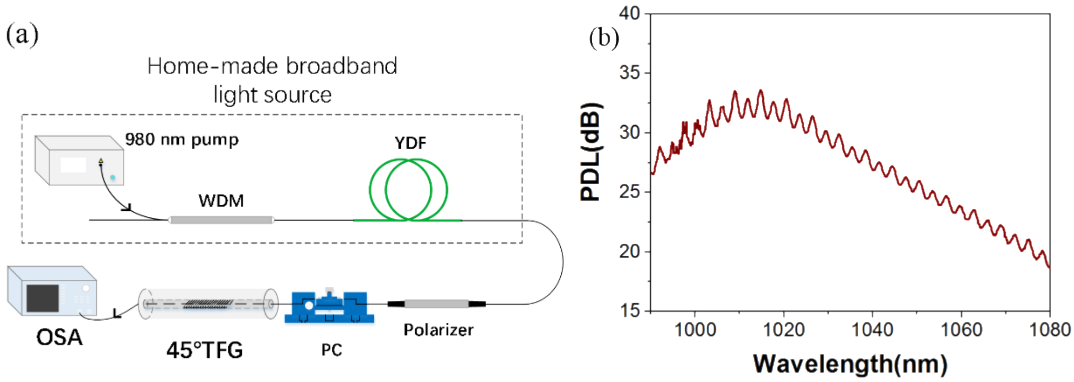

Fig. 1. PDL measurement system and the corresponding response (a) Measurement system setup. (b) PDL response of a typical 45°-TFG at 1μm region.

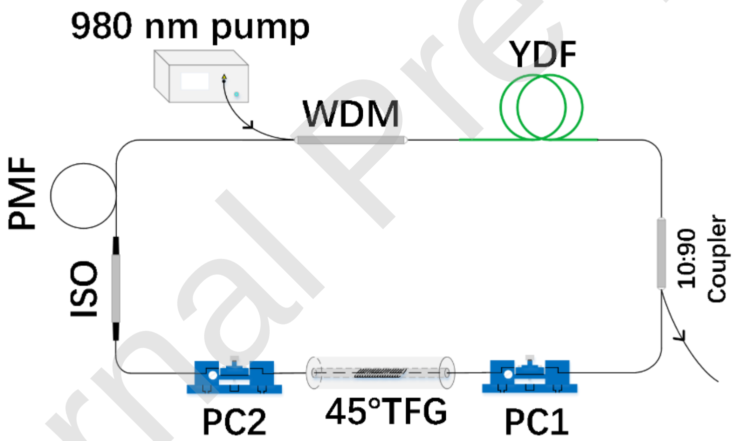

Fig. 2. Experimental setup of the wavelength switchable YDFL.

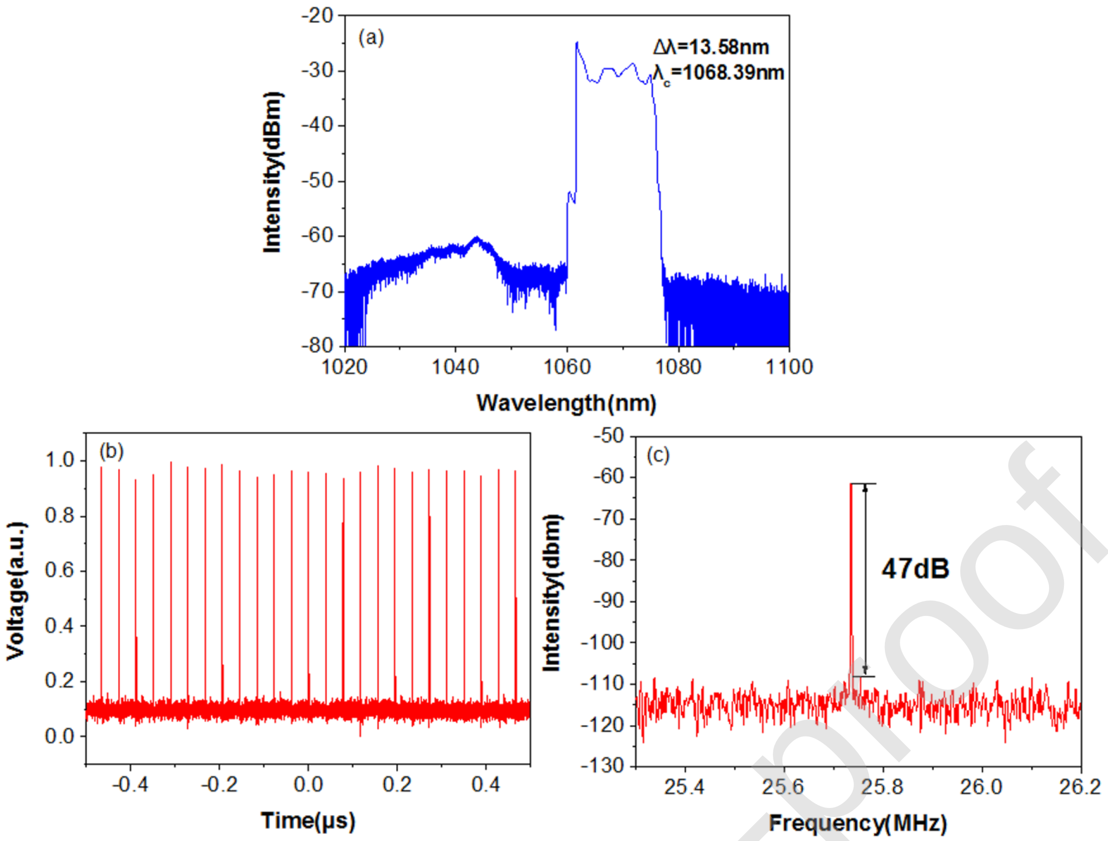

Fig. 3. Measurement results of the laser under the pump power of 277 mW (a) Output spectrum with the resolution of 0.02 nm. (b) Pulse trains. (c) RF spectrum.

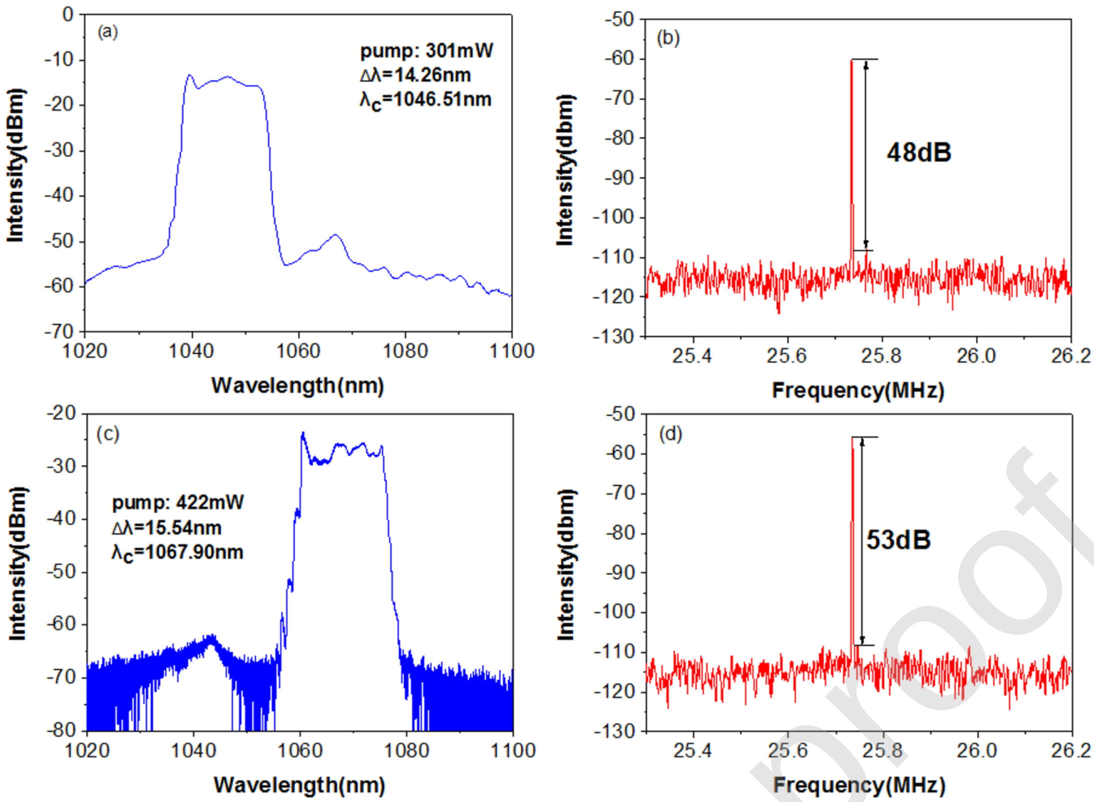

Fig. 4. Measurement results at different pump powers (a) Optical spectrum under the pump power of 301 mW with the resolution of 1 nm. (b) The RF spectrum at 1046.51 nm. (c) Optical spectrum under the pump power of 422 mW with the resolution of 0.02 nm. (d) The RF spectrum at 1067.80 nm.

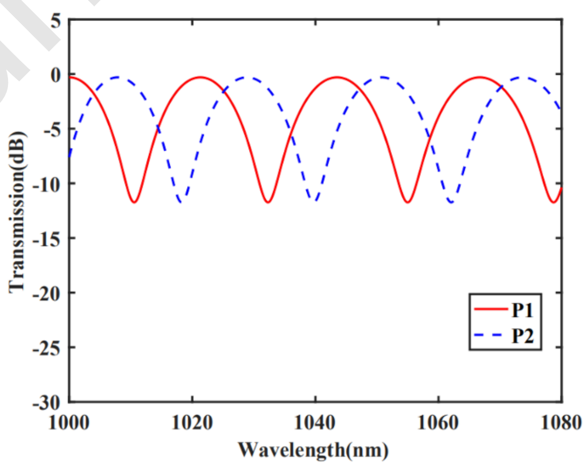

Fig. 5. Comb filtering spectrum of birefringent filter with different pulse peak power.