光学学报

高峰值功率掺Yb^{3+}石英光纤脉冲单频MOPA

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摘要 报道了基于掺Yb^{3+}石英有源光纤的高峰值功率脉冲单频激光主振荡功率放大器(MOPA)。实验研究了主放大器中有源光纤长度对脉冲单频激光峰值功率、受激布里渊散射(SBS)阈值和光-光转换效率的影响，为优化激光器的转换效率和抑制SBS效应提供了依据。当使用的有源光纤长度为0.9 m时，21 W泵浦功率下脉冲宽度为2.4 ns、重复频率为20 kHz的1064.4 nm脉冲单频激光的平均输出功率为4.37 W，且没有明显的连续波放大自发辐射(ASE)成分，对应的单脉冲能量为0.22 mJ，峰值功率可达91 kW。最大输出功率时脉冲单频激光光谱线宽为279 MHz，光信噪比为45 dB，光束质量因子M^2为1.44。

关键词 光纤光学；脉冲单频激光；光纤激光器；主振荡功率放大器；受激布里渊散射

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1 引言

高峰值功率的脉冲单频光纤激光在激光雷达、非线性光学频率变换、遥感和激光相干合成等领域中具有广泛的应用前景，是激光技术领域的研究热点[1-5]。尤其是，基于全光纤主振荡功率放大器(MOPA)结构的脉冲光纤激光器具有良好的系统集成性、稳定性和环境适应性，是实现高峰值功率脉冲单频激光输出的主要方法之一。其中，由强度调制器调制连续波(CW)单频激光而产生的脉冲序列作为MOPA系统的种子源，相比于调Q脉冲激光[6-10]，在脉冲宽度、重复频率和脉冲波形控制方面更为灵活。然而，由于脉冲单频激光的窄光谱线宽和高峰值功率，以及光纤对光场的限制作用产生的高功率密度和非线性效应作用长度的积累，脉冲单频光纤MOPA在功率放大过程中容易发生严重的受激布里渊散射(SBS)效应，这成为了限制脉冲单频激光峰值功率提升的主要因素[11-14]。

为实现高峰值功率的脉冲单频激光输出，通常可采用小于光纤材料声子寿命(石英光纤约为10 ns)的脉冲宽度来抑制SBS效应[15]。结合软玻璃光纤提高激光增益、锥形光纤增加模场面积和施加温度或应力梯度控制SBS有效增益等方法可以进一步提高SBS阈值[16-27]。2012年，Petersen等[16]采用长度仅为12 cm、纤芯直径为25 μm、包层直径为400 μm的高掺Er^{3+}/Yb^{3+}磷酸盐光纤，在3 ns脉冲宽度和10 kHz重复频率下实现了最高峰值功率为128 kW的1550 nm脉冲单频激光输出。同年，Fang等[18]采用长度为41 cm、纤芯直径为30 μm、包层直径为300 μm的高掺杂锗酸盐光纤对脉冲宽度为2 ns的1918 nm单频种子光进行放大，获得了最高峰值功率为78.1 kW的输出。与高增益软玻璃光纤相比，石英光纤具有更好的机械性能、与光纤器件的兼容性，有助于系统的全光纤化和实用化。2016年，Ran等[20]采用一段9 m长、纤芯直径为20 μm、内包层直径为400 μm的保偏掺Yb^{3+}石英有源光纤，对脉冲宽度为3 ns、重复频率为5 MHz的脉冲单频激光进行放大，获得了峰值功率为8.5 kW的脉冲单频激光输出。石英基质对稀土离子的溶解度较低，采用较长的有源光纤才能提供足够的激光增益，故不利于SBS效应的抑制。为解决此问题，研究人员尝试用大模场的锥形有源光纤控制SBS增益[22,24]。2021年，Huang等[22]采用了一段总长度为1.27 m的保偏大模场锥形光纤，在3.8 ns脉冲宽度和80 kHz重复频率下获得了峰值功率为30 kW、线宽为283.8 MHz的1064 nm脉冲单频激光输出，光束质量因子为$M^2=1.2$。虽然使用锥形有源光纤能够达到数十千瓦峰值功率水平，但是其成本因素在一定程度上限制了该技术的广泛应用。近年来，随着石英有源光纤制备工艺的进步，商用掺Yb^{3+}石英光纤也能够实现较高的泵浦吸收和激光增益，从而可在缩短光纤长度和提高SBS阈值的同时保证脉冲单频激光的有效放大，为高峰值

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功率的全光纤脉冲单频激光输出提供了有利条件。

本文采用商用掺 Yb^{3+}石英光纤作为脉冲单频光纤激光 MOPA 主放大器的增益介质，对脉冲宽度为 2.4 ns、重复频率为 20 kHz 的 1064.4 nm 脉冲单频激光进行放大。研究了所能实现的脉冲单频激光峰值功率、SBS 阈值和光-光转换效率随有源光纤长度的变化关系，通过优化有源光纤长度来平衡泵浦吸收和 SBS 阈值，使用长度为 0.9 m 的有源光纤时实现了最大单脉冲能量为 0.22 mJ、峰值功率为 91 kW 的 1064.4 nm 脉冲单频激光输出。

2　实验装置

图 1 为脉冲单频光纤 MOPA 实验装置示意图。中心波长为 1064.4 nm、输出功率为 30 mW、线宽为 1 kHz 的单频掺 Yb^{3+}光纤（YDF）激光器（NP Photonics，RFLS-25-3-1064）结合一级纤芯预放大器后可得到 70 mW 的连续波激光输出，激光输出经任意波形发生器（AWG）控制的电光强度调制器（EOIM，iXblue，NIR-MX-LN-10，带宽为 12 GHz）调制后产生脉冲序列，一个和 EOIM 时域同步的声光强度调制器（AOM）用来进一步滤除脉冲序列中的连续波成分和带内放大自发辐射（ASE）。在 EOIM 和 AOM 之间配置两级掺 Yb^{3+}纤芯预放大器对其峰值功率进行预放大以补偿 EOIM 和 AOM 的插入损耗。在 AOM 后可得到脉冲宽度为 2.4 ns、重复频率为 20 kHz、平均功率为 0.16 mW 的脉冲单频激光输出，将其作为脉冲单频激光种子源，再利用两级包层预放大器和一级包层主放大器对种子源进行功率放大。两级包层预放大器分别采用长度为 1.5 m、纤芯直径为 10 μm 、包层直径为 130 μm 的掺 Yb^{3+}有源光纤（Nufern，LMA-YDF-10/130-M，在 975 nm 处的包层泵浦吸收系数为 4.1 dB/m）和长度为 2 m、纤芯直径为 20 μm、包层直径为 130 μm 的掺 Yb^{3+}有源光纤（Nufern，LMA-YDF-20/130-VIII，在 976 nm 处的包层泵浦吸收系数为 8.7 dB/m）作为增益介质，泵浦源均为 976 nm 稳波长半导体激光器（LD）。脉冲单频激光种子源在两级包层预放大器中 4.6 W 和 2.6 W 泵浦功率下平均功率分别被放大至 45 mW 和 120 mW。经两级包层预放大后单脉冲能量被放大至 6 μJ，脉冲宽度仍保持为 2.4 ns，相应的峰值功率为 2.5 kW。主放大器采用纤芯直径和包层直径分别为 30 μm 和 250 μm 的掺 Yb^{3+}石英光纤（Liekki，Yb-1200-30/250）作为增益介质，该光纤在 976 nm 处的包层泵浦光吸收系数为 14 dB/m。将主放大器有源光纤盘绕成直径为 14 cm 的圆形光路，并固定在水冷散热器上。实验中在各级放大器之前均加入隔离器（ISO）以滤除反向的 ASE，在级间加入带通滤波器（BPF）以滤除带内 ASE。主放大器之后放置包层模式剥除器（CMS）以滤除剩余泵浦光。主放大器输出端采用 8°角斜切方式来避免端面反射。

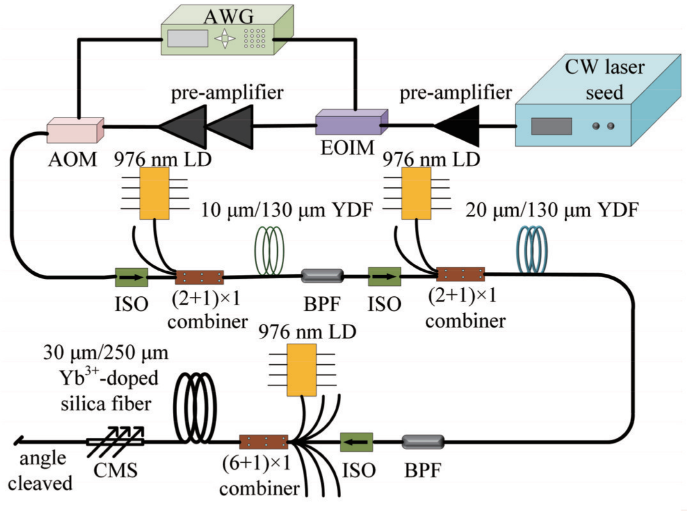

图 1　脉冲单频光纤 MOPA 实验装置示意图

Fig. 1　Schematic diagram of pulsed single-frequency fiber MOPA

3　结果与讨论

为实现高峰值功率的脉冲单频激光输出，需尽量缩短种子光的脉冲宽度以抑制 SBS 效应，种子源脉冲宽度（半峰全宽，FWHM）为 2.4 ns，其为受 AWG 带宽所限的最小脉冲宽度。实验中除了用能量计探头 Ophir PE10-C 直接测量激光输出的单脉冲能量外，还采用功率计探头 Ophir 12A 测量激光输出的平均功率，以验证脉冲单频光纤激光 MOPA 的输出中是否存在连续波 ASE 成分。

当主放大器使用不同长度的有源光纤时，注入的最大泵浦功率、获得的峰值功率和光-光转换效率分别如图 2（a）～（c）所示。需要说明的是，当有源光纤长度为 0.5 m 和 0.7 m 时，在注入泵浦功率分别达到 18 W

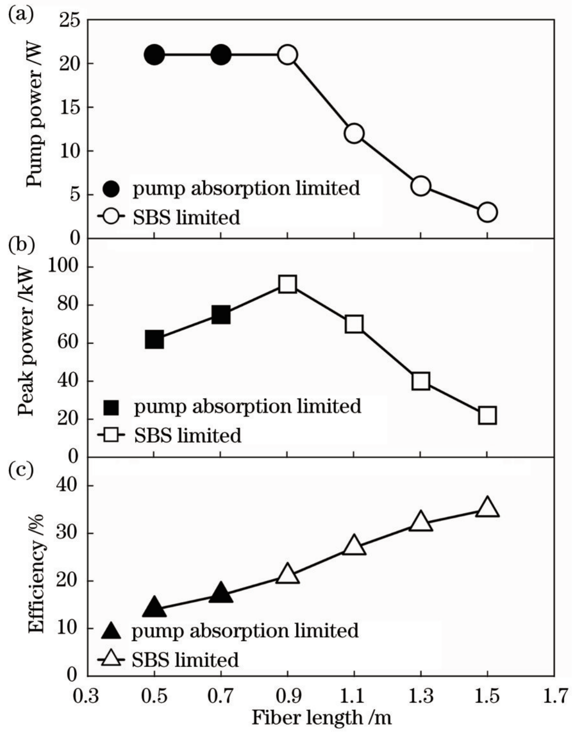

图2 脉冲宽度为2.4 ns、重复频率为20 kHz时光纤激光MOPA的输出功率特性随主放大器中有源光纤长度的变化曲线。(a)最大注入泵浦功率；(b)最大输出峰值功率；(c)光-光转换效率

Fig. 2 Output power characteristics of fiber MOPA varying with active fiber length in main amplifier for pulse width of 2.4 ns and repetition rate of 20 kHz. (a) Maximum launched pump power; (b) maximum output peak power; (c) optical-to-optical efficiency

和20 W后均观察到吸收泵浦功率和输出功率不再随泵浦功率的增加而线性上升，发生了明显的饱和现象，故在泵浦功率达到21 W后不再继续增加泵浦功率，即图2中实心部分所示的泵浦功率、峰值功率和转换效率均受到了较短长度的有源光纤的泵浦吸收限制，相应的最高峰值功率分别为62 kW和75 kW，光-光转换效率为14%和17%。增加有源光纤长度能够起到改善泵浦吸收、提高转换效率的作用，当有源光纤长度为0.9 m时，在21 W泵浦功率和20 kHz重复频率下激光单脉冲能量可达到0.22 mJ，对应的脉冲峰值功率为91 kW，此时激光平均输出功率为4.37 W，对应的光-光转换效率为21%。然而，在此有源光纤长度下进一步增加泵浦功率会出现显著的SBS现象，即在主放大器的信号/泵浦合束器的空闲泵浦端口处监测的反向光光谱中会产生明显的SBS斯托克斯光成分。继续增加有源光纤长度，由于泵浦吸收得到改善，故光纤激光MOPA的光-光转换效率得到了进一步提升，使用1.5 m长的有源光纤时光-光转换效率可以达到35%。然而，光纤激光MOPA的SBS阈值和相应受SBS效应所限的最大脉冲峰值功率逐渐降低，有源光纤长1.5 m时泵浦功率超过3 W即发生SBS，所得到的最大脉冲峰值功率仅为22 kW。在上述过程中，用能量计记录的单脉冲能量与用功率计记录的平均功率和脉冲重复频率换算得到的单脉冲能量始终保持一致，说明没有产生明显的连续波ASE成分。同时，在不同光纤长度下激光输出功率在30 min的观测中不稳定度均小于2%。

图3给出了有源光纤长度为0.5、0.9、1.5 m时光纤激光MOPA输出的平均功率和峰值功率随注入泵浦功率的变化关系。可以看出：虽然增加有源光纤长度能够显著改善转换效率，但是SBS效应严重限制了激光器的功率；当光纤长度为0.5 m时，在泵浦功率达到18 W之后激光输出功率随泵浦功率的增长十分缓慢。因此，优化有源光纤长度并综合考虑泵浦吸收和SBS效应的影响是实现高峰值功率脉冲单频激光输出的关键。本实验后续激光输出性能的测量均基于0.9 m长的有源光纤，在该光纤长度下，20～80 kHz重复频率下脉冲单频激光系统的SBS阈值未表现出明显差异。

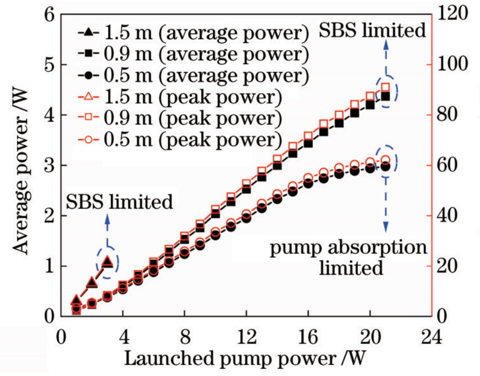

图3 在不同主放大器有源光纤长度下，脉冲宽度为2.4 ns、重复频率为20 kHz时光纤激光MOPA输出的平均功率和峰值功率随泵浦功率的变化曲线

Fig. 3 Average power and peak power of fiber MOPA varying with launched pump power for pulse width of 2.4 ns and repetition rate of 20 kHz under different active fiber lengths in main amplifier

图4(a)、(b)分别为使用高速光电探测器(Thorlabs，DET08CFC，上升沿约为70 ps)和示波器(Tektronix，TDS3052C，带宽为500 MHz，采样率为5 GSa/s)记录的经AOM输出的脉冲单频激光种子源和主放大器91 kW峰值功率输出时的时域波形。二者的FWHM均为2.4 ns，激光脉冲波形在放大过程中没有发生明显的形变。

使用法珀扫描干涉仪(FPI，Thorlabs，SA200-8B，分辨率为7.5 MHz，自由光谱范围为1.5 GHz)测量了脉冲单频激光种子源和主放大器91 kW峰值功率输出时的光谱线宽。同时，也给出了对图4中的脉冲波形进行傅里叶变换后得到的频域包络。测得的激光种子

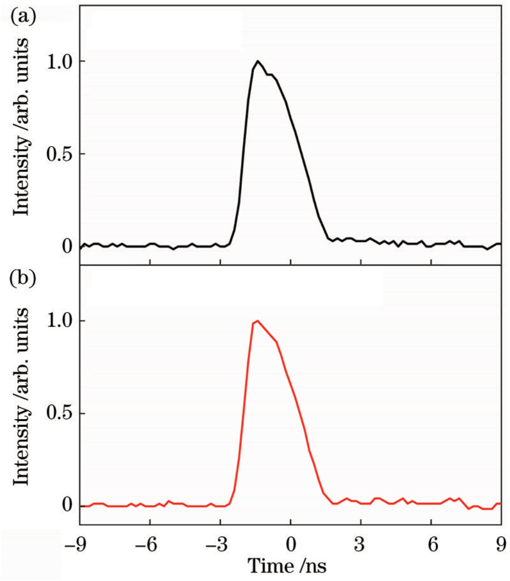

图 4　脉冲波形。(a)脉冲单频激光种子源;(b)主放大器 91 kW 峰值功率输出

Fig. 4　Pulse waveforms. (a) Pulsed single-frequency laser seed; (b) main amplifier output at peak power of 91 kW

源的光谱线宽(FWHM)为 201 MHz,与其理论变换极限水平一致。然而,在 91 kW 峰值功率输出时激光光谱发生了一定展宽,线宽为 279 MHz,这是由自相位调制(SPM)效应引起的[28]。在 30 min 的观测中,激光线宽未发生明显变化。

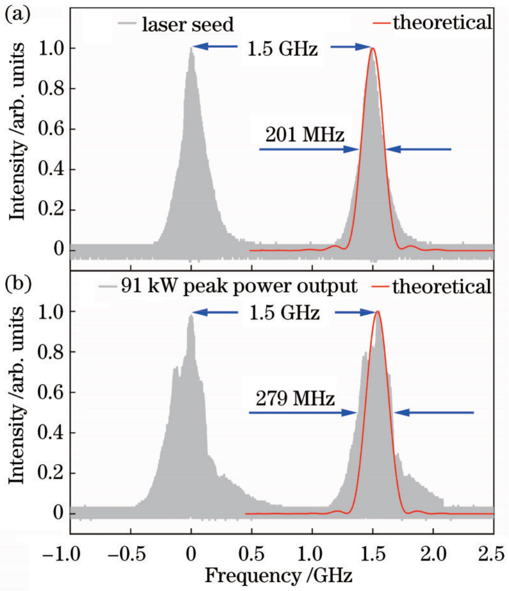

图 5　光谱线宽。(a)脉冲单频激光种子源;(b)主放大器 91 kW 峰值功率输出

Fig. 5　Spectral linewidths. (a) Pulsed single-frequency laser seed; (b) main amplifier output at peak power of 91 kW

用光谱仪 Yokogawa 6370D(分辨率为 0.02 nm)测量主放大器最大输出功率时的激光光谱,如图 6(a)所示,此时激光的信噪比为 45 dB,激光中心波长为 1064.4 nm。得益于带通滤波器对带内 ASE 的滤除作用,在实验中并未观察到明显的 ASE。用电荷耦合器件(CCD)相机 Spiricon SP907 测量了脉冲单频激光在主放大器放大前后的光束质量,结果如图 6(b)、(c)所示。可以发现,在主放大器放大前 x 方向和 y 方向的光束质量因子 M_x^2 和 M_y^2 分别为 1.31 和 1.33,而主放大器 91 kW 峰值功率激光输出时 x 方向和 y 方向的光束质量因子 M_x^2 和 M_y^2 均为 1.44,即脉冲单频激光在主放大器放大前后没有发生明显的光束质量劣化,仍保持了近衍射极限的激光输出。图 6(b)、(c)中的插图为相应的激光光斑能量分布。

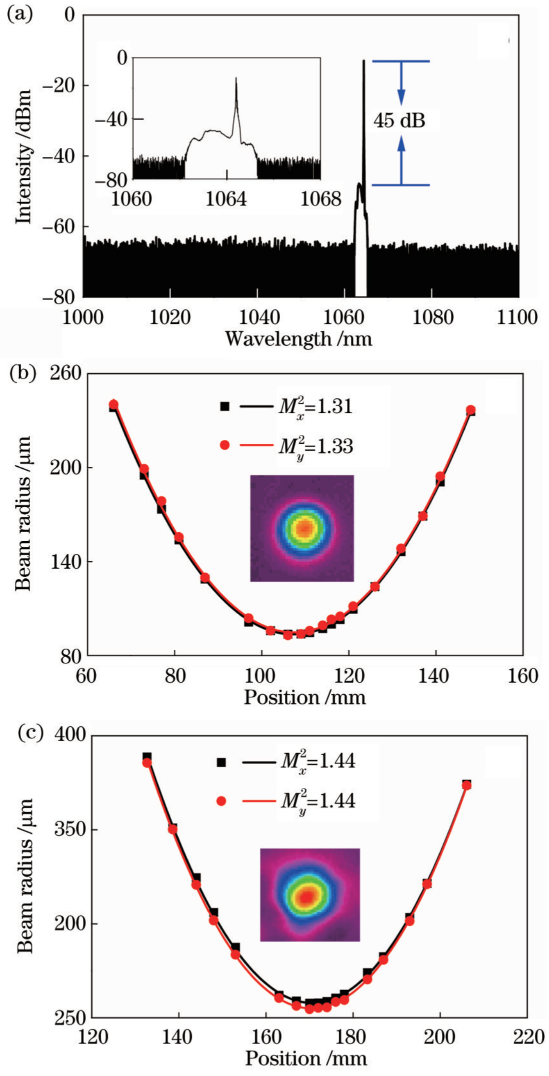

图 6　主放大器 91 kW 峰值功率输出时的光谱和脉冲单频激光种子源放大前后的光束质量。(a)激光光谱;(b)二级包层预放大器输出激光的光束质量;(c)主放大器 91 kW 峰值功率输出时的光束质量

Fig. 6　Spectrum of main amplifier output at peak power of 91 kW and beam quality of pulsed single-frequency laser seed before and after amplification. (a) Laser spectrum; (b) beam quality of laser output after second cladding pre-amplifier; (c) beam quality of main amplifier output at peak power of 91 kW

4 结论

研究了百千瓦量级高峰值功率的脉冲单频石英光纤MOPA。采用高泵浦吸收的掺Yb^{3+}石英光纤作为主放大器的增益介质，研究了脉冲单频激光峰值功率、SBS阈值和光-光转化效率随主放大器有源光纤长度的变化关系。同时，使用0.9 m长的掺Yb^{3+}石英光纤对中心波长为1064.4 nm、脉冲宽度为2.4 ns、重复频率为20 kHz的脉冲单频种子源进行放大，放大后激光的平均功率为4.37 W、单脉冲能量为0.22 mJ、光-光转换效率为21%，相应的脉冲峰值功率可达到91 kW，最大输出功率时的光谱线宽为279 MHz，此时光束质量因子M^2为1.44。

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High-Peak-Power Pulsed Single-Frequency Fiber MOPA Based on Yb^{3+}-Doped Silica Fiber

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Abstract

Objective In the pulsed single-frequency fiber master oscillator power amplifier (MOPA), the stimulated Brillouin scattering (SBS) effect severely limits the increase of peak power. Although both soft glass large-mode-area fibers and tapered fibers can effectively suppress SBS, the complex manufacturing process and the relatively high requirements for use restrict their applications to some extent. Actually, large-mode-area silica fibers have been widely used in the preparation of fiber lasers due to their excellent compatibility. However, in previous work, the low doping concentration of rare-earth ions in silica fibers leads to low SBS thresholds of laser systems. In this work, a commercial silica fiber with high doping concentration is used as the gain medium, and the trade-off between SBS threshold and laser efficiency is investigated by optimizing fiber length. As a result, a single-frequency laser output with a peak power of 91 kW at 1064.4 nm is realized.

Methods A pulsed single-frequency MOPA system based on a silica fiber is built. Firstly, an electro-optic intensity modulator (EOIM) is used to modulate a continuous-wave (CW) single-frequency Yb^{3+}-doped fiber laser, so as to generate a pulse train with a pulse width of 2.4 ns and a pulse repetition frequency of 20 kHz. The CW single-frequency fiber laser with a central wavelength of 1064.4 nm consists of a single-frequency laser seed with an output power of 30 mW and a core-pumped pre-amplifier which can boost the power of the CW laser seed to 70 mW. Due to the insertion loss of the EOIM and the low duty cycle of the modulated laser, the weak signal pulses are pre-amplified using two stage core-pumped Yb^{3+}-doped pre-amplifiers with a 0.5-m Yb^{3+}-doped fiber and a 0.6-m Yb^{3+}-doped fiber (LIEKKI, Yb-300-6/125) as the gain medium, respectively. The pre-amplified laser is then modulated by an acousto-optic modulator (AOM) which is synchronized to the EOIM to remove the amplified spontaneous emission (ASE) component for higher signal-to-noise ratio (SNR) in the time domain. The laser output with an average power of 0.16 mW, corresponding to 3.3 kW peak power, is obtained after the AOM, which is further amplified by two stage cladding-pumped pre-amplifiers. The first stage cladding-pumped pre-amplifier and the second stage cladding-pumped pre-amplifier use a piece of 1.5-m Yb^{3+}-doped fiber (Nufern, LMA-YDF-10/130-M) and a piece of 2-m Yb^{3+}-doped fiber (Nufern, LMA-YDF-20/130-VIII) as the gain medium, respectively. The average power of the pulsed single-frequency laser seed is boosted to 45 mW and 120 mW under a pump power of 4.6 W and 2.6 W in these two stage cladding-pumped pre-amplifiers, respectively. Before being injected into the main amplifier, the single-frequency laser reaches a pulse energy of 6 μJ, with the pulse width remaining 2.4 ns and the peak power being 2.5 kW. In the main amplifier, a piece of Yb^{3+}-doped silica fiber (Liekki, Yb-1200-30/250) with a core diameter of 30 μm, a cladding diameter of 250 μm, and an absorption coefficient of 14 dB/m at 976 nm is used as the gain medium. The coiling diameter of the active fiber is controlled to 14 cm in order to optimize the beam quality.

Results and Discussions With a 0.9-m active fiber used in the main amplifier, an average power of 4.37 W (Fig. 3) is obtained under a pump power of 21 W, which corresponds to an optical-to-optical efficiency of 21% [Fig. 2(c)]. The maximum pulse energy of 0.22 mJ is achieved with a pulse repetition frequency of 20 kHz, which corresponds to a pulse peak power of 91 kW (Fig. 3). The pulse width of the pulsed single-frequency laser seed modulated by the AOM and the main amplifier output with a peak power of 91 kW are both 2.4 ns, which manifests that there is no obvious distortion of the pulse waveform during the amplification process [Figs. 4(a) and 4(b)]. The measured spectral linewidth of the laser seed, namely, the full width at half maximum (FWHM), is 201 MHz [Fig. 5(a)], which is consistent with its theoretical transform-limited level. However, the spectral linewidth after amplification broadens to 279 MHz due to the self-phase modulation (SPM) effect [Fig. 5(b)]. The SNR of the laser at the maximum output power is 45 dB, and the central wavelength of the signal is 1064.4 nm [Fig. 6(a)]. Before the main amplification, the beam quality factors M_x^2 and M_y^2 in the x and y directions are 1.31 and 1.33 [Fig. 6(b)], respectively, while the beam quality factors M_x^2 and M_y^2 in the x and y directions are both 1.44 at a 91-kW peak power laser output of the main amplifier [Fig. 6(c)], which indicates that the pulsed single-frequency laser undergoes no obvious degradation in beam quality and maintains the near-diffraction-limited laser output.

Conclusions In this work, a high-peak-power pulsed single-frequency fiber MOPA based on Yb^{3+}-doped silica fiber is demonstrated. The influence of the active fiber length in the main amplifier on the peak power, the threshold of SBS, and the optical-to-optical efficiency of the pulsed single-frequency fiber laser is investigated experimentally. With a 0.9-m Yb^{3+}-doped silica fiber used in the main amplifier, the pulsed single-frequency laser with an average power of 4.37 W is obtained at a central wavelength of 1064.4 nm under a launched pump power of 21 W with a pulse width of 2.4 ns and a pulse repetition frequency of 20 kHz. The maximum pulse energy is 0.22 mJ, which manifests that there is no obvious CW ASE component, and the corresponding peak power is 91 kW. The spectral linewidth is 279 MHz, and the SNR is 45 dB, with the beam quality factor M^2 being 1.44 at the maximum output power.

Key words fiber optics; pulsed single-frequency laser; fiber laser; master oscillator power amplifier; stimulated Brillouin scattering