中国激光

0.59 mJ 单频掺 Yb^{3+} 百纳秒脉冲全光纤激光器

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摘要 报道了基于混合增益光纤实现的 1064 nm 高能量单频掺 Yb^{3+} 百纳秒脉冲全光纤激光器。当主放大级的泵浦功率为 13 W 时，获得了最大 0.59 mJ 的脉冲能量，重复频率为 5 kHz，脉冲宽度为 104 ns。主放大级采用芯径分别为 35 μm 和 50 μm 的掺 Yb^{3+} 光纤级联作为增益介质，以此来提高受激布里渊散射阈值和激光信噪比。为了保证转换效率，对有源光纤长度和盘绕方式进行了优化，实现了较好的光束质量，最大脉冲能量时光束质量为 1.50，光谱线宽为 40 MHz。

关键词 激光器；光纤激光器；脉冲激光器；激光放大器；受激布里渊散射

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1 引 言

高能量单频纳秒脉冲光纤激光器在相干雷达、遥感和非线性频率变换等领域具有广阔的应用前景，受到了广泛的关注[1-5]。尤其是雷达探测领域，大脉冲能量可以极大提升系统的探测距离，而窄线宽可以提高系统的探测精度，因此百纳秒量级的单频激光是理想的激光光源。全光纤主振荡功率放大器（MOPA）结构的脉冲光纤激光系统具有时间特性灵活、系统结构紧凑等优点，是获取较高能量脉冲单频激光输出的有效工具。然而，系统较长的光纤长度以及光纤介质较小的模场面积降低了受激布里渊散射（SBS）效应[6-10]阈值，尤其是单频脉冲激光的较高峰值功率使得 SBS 极易发生，反向 Stokes 光会劣化激光系统的稳定性，甚至会造成系统损伤。特别是百纳秒长脉冲激光的脉宽远大于声子寿命（～10 ns），较大的脉宽显著增强了信号光与声场的相互作用，为反向 Stokes 光提供了更高的增益，SBS 阈值较低。因此，寻求有效的 SBS 抑制方法以实现更高能量的单频百纳秒脉冲激光输出具有重要的意义。

在高能量单频光纤 MOPA 中，多采用长度较短的高掺杂大模场软玻璃光纤[11-16]来抑制 SBS 效应。大模场降低了激光功率密度，而高掺杂的软玻璃光纤能够以相对较短的光纤长度提供足够的激光增益，二者均有助于降低 SBS 的增益。2012 年，Fang 等[13]使用长度为 41 cm、芯径为 30 μm 的高掺铥锗酸盐光纤，在中心波长为 1918.4 nm 时获得了 0.97 mJ 的高能量脉冲激光输出。2018 年，Lee 等[15]报道了脉冲宽度为 510 ns 的铒镱共掺硅酸盐光纤 MOPA，长度为 55 cm、芯径为 45 μm 的 Er^{3+}（质量分数为 1%）和 Yb^{3+}（质量分数为 5%）共掺硅酸盐光纤有效提高了 SBS 阈值，获得了 1.8 mJ 的脉冲能量输出。同年，本课题组使用长度为 34 cm、芯径为 25 μm 的高增益掺 Yb^{3+} 磷酸盐光纤获得了百纳秒 0.47 mJ 的 1064 nm 脉冲激光，由于光纤具有较小的数值孔径（0.04），因此获得了较好的光束质量，光束质量（M^2）为 1.4[16]。虽然使用较短的高增益软玻璃光纤可以有效提高 SBS 阈值，从而获取高能量的激光输出，但是其较高的稀土离子掺杂造成上能级粒子数剩余，导致激光器的输出中可能会存在较多的放大自发辐射（ASE）成分，降低了激光转换效率和脉冲激光的信噪比[17]。近年来，锥形光纤开始被用于获取高峰值功率/高能量的脉冲激光输出，一方面锥形光纤沿纵向逐渐增大的纤芯提高了光纤的模场面积，另一方面逐渐增加的纤芯尺寸可展宽布里渊增益带宽[18-22]。2019 年，Patokoski 等[19]基于锥形掺 Yb^{3+} 有源光纤在 1053 nm 处实现了脉冲宽度为 130 ns、单脉冲能量为 0.524 mJ 的单频脉冲激光输出。

本文提出了一种基于级联有源光纤结构的光纤放大器，在一段较小芯径的掺 Yb^{3+} 石英光纤后熔接了一

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段大芯径高掺 Yb^{3+} 磷硅酸盐光纤，这是利用了与锥形光纤类似的结构优势，即芯径的差异给反向 Stokes 光引入了较大的损耗，从而提高了 SBS 阈值，同时避免了复杂的光纤制备工艺，还可以通过调节级联光纤结构中增益光纤的掺杂浓度与长度配比实现放大器性能的优化，提高了系统的灵活性。另一方面，常规掺杂浓度的有源光纤在泵浦功率较高而信号光功率较低的输入端附近不会产生明显的 ASE，经石英光纤放大的信号光可以更充分地提取高掺杂磷硅酸盐光纤中的上能级粒子数，起到了提高光-光转换效率和抑制 ASE 的作用。本文使用芯径为 35 μm 的石英光纤和芯径为 50 μm 的磷硅酸盐光纤构成级联结构的主放大级有源光纤，在脉冲重复频率为 5 kHz 和脉冲宽度为 104 ns 时获得了最大单脉冲能量为 0.59 mJ、激光光谱线宽为 40 MHz 的单频脉冲激光输出。

2 实验装置

图 1 为脉冲单频光纤激光 MOPA 光路示意图。任意信号发生器（AFG）控制的电光强度调制器（EOIM）将单频掺 Yb^{3+} 光纤激光振荡器提供的功率为 76 mW 的 1064.44 nm 连续波（CW）种子光调制为脉宽为 100 ns 的脉冲种子光。先经过 2 级纤芯泵浦源为 976 nm 单模半导体激光器（LD）的掺 Yb^{3+} 光纤预放大级后，再经过与 EOIM 时域同步的声光调制器（AOM）以滤除连续波成分的 ASE，最终获得了脉冲重复频率为 5 kHz、平均功率为 1 mW 的单频脉冲种子源。脉冲种子光经两级掺 Yb^{3+} 增益光纤（YDF）尺寸分为 10 μm/ 130 μm 和 20 μm/ 130 μm 的 976 nm 包层泵浦预放大级后，其平均功率提升至 120 mW，即脉冲能量为 0.024 mJ。

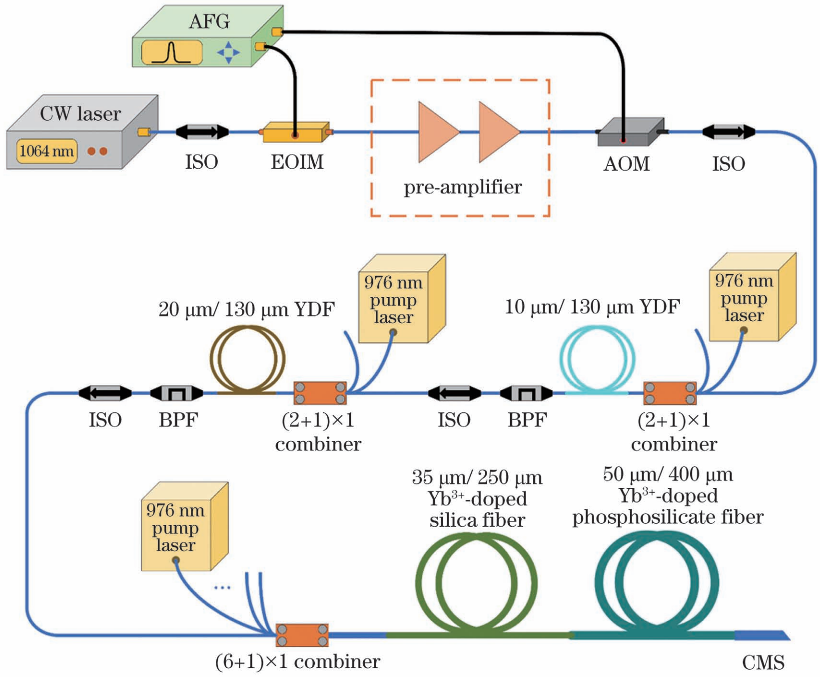

图 1 脉冲单频光纤 MOPA 示意图

Fig. 1 Diagram of pulsed single-frequency fiber MOPA

主放大级采用级联的 35 μm/ 250 μm（12 dB/m 泵浦吸收@976 nm）掺 Yb^{3+} 石英增益光纤和 50 μm/ 400 μm（27 dB/m 泵浦吸收@976 nm）掺 Yb^{3+} 的磷硅酸盐增益光纤来提供增益，同时优化光纤盘绕方式来优化光束质量。在各级放大器之后均加入带通滤波器（BPF）和隔离器（ISO）以分别滤除本级带内 ASE 和后级反向 ASE。主放大级采用包层模式剥除器（CMS）来滤除剩余泵浦光，同时输出端斜切 8°角以避免反射光损坏激光系统。

3 结果与分析

MOPA 系统主放大级的输出脉冲能量随泵浦功率的变化曲线如图 2（a）所示。需要特别指出的是，当在主放大级合束器的空闲泵浦端口处监测到信号光长波方向的 Stokes 光成分时，我们停止增加泵浦功率。当增益光纤为级联的长度均为 30 cm 的 35 μm/ 250 μm 和 50 μm/ 400 μm 掺 Yb^{3+} 光纤时，如图 2（a）中带方形的曲线所示，在脉冲重复频率为 5 kHz 的情况下，泵浦功率为 13 W 时获得了 0.59 mJ 的单脉冲能量，对应的平均功率为 2.95 W，光-光转换效率为 22.7%。此时在反向检测端观察到 Stokes 光成分，如图 2（b）所示。使用型号为 Ophir 12A 的功率计测得的脉冲激光的平均功率为 3.05 W，信号光中仅有 0.1 W 的连续光成分。为了研究级联增益光纤结构对 SBS 阈值的提升作用，我们采用长度为 60 cm（与级联有源光纤方案的总长度相同）的 35 μm/ 250 μm 掺 Yb^{3+} 光纤作为主放大级的增益介质对脉冲激光进行放大，如图2（a）中带圆形的曲线所示，泵浦功率为

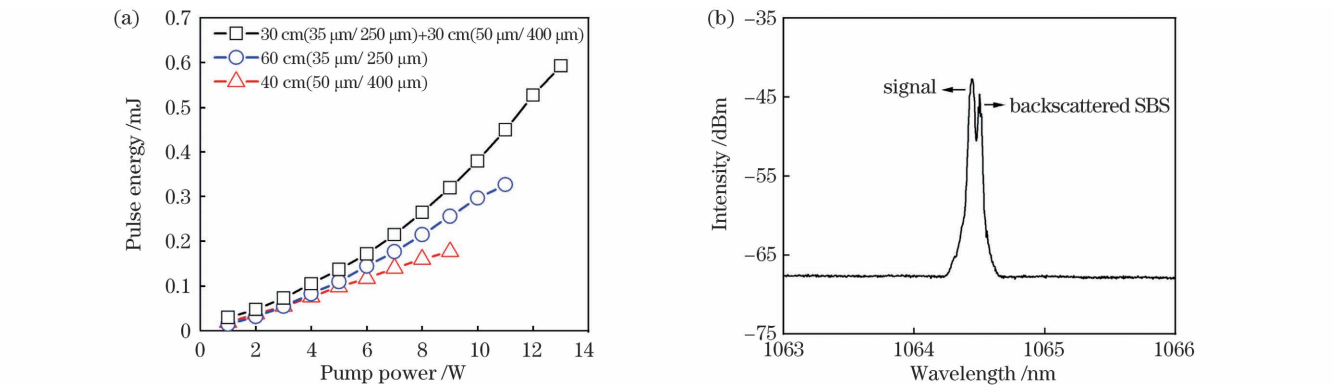

图 2 实验结果。(a) 主放大器中不同有源光纤配置对应的单脉冲能量曲线;(b) 单脉冲能量为 0.59 mJ、脉冲重复频率为 5 kHz 时的反向激光光谱

Fig. 2 Experiment results. (a) Single pulse energy profiles corresponding to different active fiber configurations in main amplifier; (b) backward laser spectrum at single pulse energy of 0.59 mJ and PRF of 5 kHz

11 W 时得到的最大单脉冲能量仅为 0.327 mJ。由此可见,级联方案通过增加增益光纤模场面积并引入反向光损耗,有效提高了系统的 SBS 阈值。此外,我们还采用长度为 40 cm 的 50 μm/ 400 μm 掺 Yb^{3+} 磷硅酸盐光纤进行放大,使其与级联有源光纤保持几乎相同的泵浦吸收,结果如图 2(a)中带三角的曲线所示。当最大泵浦功率为 9 W 时,使用能量计测得 0.187 mJ 的单脉冲能量,当重复频率为 5 kHz 时对应的平均功率应为 0.935 W,光-光转换效率仅为 10.4%。而在最大脉冲能量时功率计测量到的平均功率为 1.67 W,表明其中混有大量的 ASE 及连续光成分,这是由于较弱的信号光无法完全提取高掺杂光纤在泵浦光注入端产生的大量的上能级粒子数,上能级粒子数的剩余导致了 ASE 及连续光成分的存在。由此可见,级联方案不仅可以有效提升 SBS 阈值,同时,在放大过程中,被石英光纤放大后的信号光可以更充分地提取高掺杂磷硅酸盐光纤中的上能级粒子数,从而提高光-光转换效率。

我们使用 Tektronix TDS3052C 型号的示波器和 Thorlabs DET01CFC 型号的高速光电探测器测量了脉冲激光的时域特性。通过给 EOIM 施加 100 ns 的高斯脉冲信号,在单脉冲能量为 0.024 mJ 时测量到的脉冲种子波形如图 3 所示,脉冲宽度为 100 ns,由于 EOIM 的响应特性,输出脉冲波形与高斯脉冲相比稍有形变。图 3 同时展示了单脉冲能量被放大至 0.59 mJ 时的脉冲波形,脉冲上升沿提取了较多的激光增益,与脉冲种子的波形相比,明显变得陡峭,脉冲宽度发生了轻微展宽,脉冲的半峰全宽从 100 ns 展宽至 104 ns,对应的激光最大峰值功率为~5.33 kW。

使用型号为 Thorlabs SA200-8B 的法布里-珀罗扫描干涉仪 (FPI) 测量了输出激光的光谱线宽。在 AOM 后测量到的百纳秒脉冲种子激光的光谱线宽为 15 MHz,这主要受限于 FPI 的分辨率 (7.5 MHz)。自相位调制 (SPM) 会引入非线性频移,且当脉冲时域上的光强对时间的导数不断变化时,时域上脉冲内

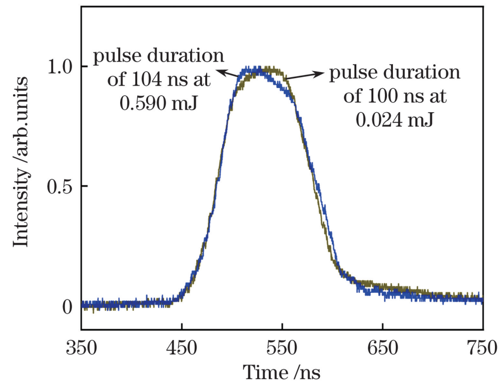

图 3 进入主放大器之前脉冲能量为 0.024 mJ 时的波形与主放大器输出最高能量为 0.59 mJ 时的波形

Fig. 3 Waveform at pulse energy of 0.024 mJ before entering main amplifier and waveform at maximum output energy of 0.59 mJ from main amplifier

不同时刻的频移量不同[23],在 0.59 mJ 最大脉冲能量时测量到的激光光谱线宽如图 4 所示,此时在 SPM 作用下激光光谱线宽轻微展宽至 40 MHz。

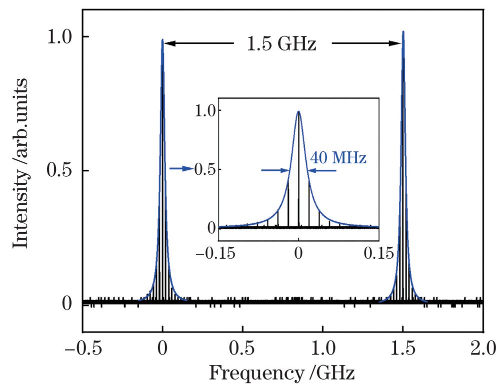

图 4 主放大器最高输出能量为 0.59 mJ 时的激光光谱线宽

Fig. 4 Laser spectral linewidth at maximum output energy of 0.59 mJ from main amplifier

使用光谱仪(分辨率为 0.02 nm)测量得到的激光单脉冲能量为 0.59 mJ 时的输出光谱如图 5 所示,激光的中心波长为 1064.44 nm。得益于主放大级中芯径为 35 μm 的增益光纤对激光信号的预放大作用,紧

接着用软玻璃光纤进一步提升脉冲能量，光谱图中无明显 ASE 产生，信噪比为 41 dB。图 6 插图为型号为 Spiricon SP907 的光束质量分析仪测量到的 0.59 mJ 最高脉冲能量时的光斑，级联方案中的前后半段增益光纤的盘绕直径分别控制在～12 cm 和～20 cm，由于光纤盘绕方式得到优化，光斑呈现出几乎对称的高斯分布，测得 x 方向与 y 方向的光束质量 M_x^2 和 M_y^2 分别为 1.48 和 1.50。使用长度为 40 cm 的盘绕直径为～20 cm 的 50 μm/ 400 μm 掺 Yb^{3+} 磷硅酸盐光纤进行放大时，在单脉冲能量为 0.187 mJ 时测得 M^2 大于 1.60。

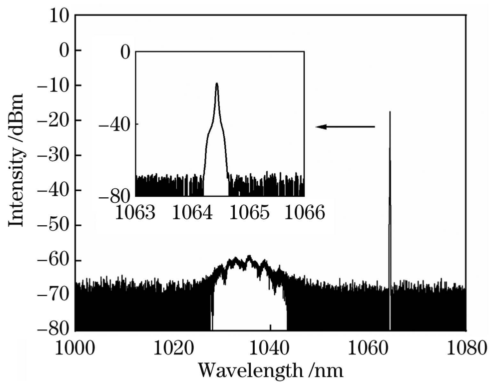

图 5 单脉冲能量为 0.59 mJ、脉冲重复频率为 5 kHz 时的激光光谱

Fig. 5 Laser spectrum at single pulse energy of 0.59 mJ and PRF of 5 kHz

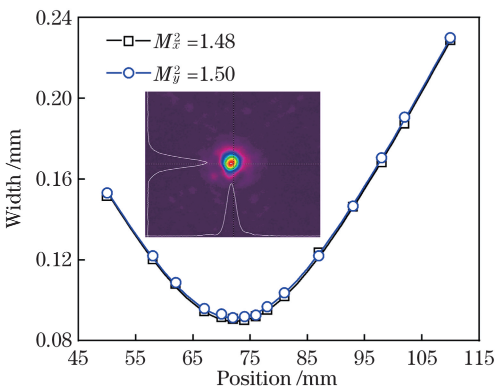

图 6 单脉冲能量为 0.59 mJ 时测量得到的光束质量

Fig. 6 Beam quality measured at single pulse energy of 0.59 mJ

4 结　　论

研究了通过级联不同尺寸的增益光纤来提高单频高能量脉冲光纤激光放大器中 SBS 阈值的方法。实验实现了 1064.44 nm 脉冲掺 Yb^{3+} 光纤激光 MOPA 的高能量单频输出，获得了脉冲能量为 0.59 mJ、脉冲宽度为 104 ns、脉冲重复频率为 5 kHz、对应峰值功率为～5.33 kW 的高能量脉冲单频激光输出，测得最高输出能量时的激光光谱线宽为 40 MHz，光-光转换效率为 22.7%。而对照实验结果显示，当采用与级联光纤结构相同长度而整体芯径较小的增益光纤时，在单脉冲能量被放大至 0.327 mJ 时已出现强度较高的反向 Stokes 光；当采用与级联光纤结构总泵浦吸收相同的高增益光纤时，能量转换效率却明显下降至 10.4%，说明级联不同尺寸的增益光纤是实现高能量单频纳秒脉冲光纤激光输出的有效方法。后续工作方向是优化级联方案中不同增益光纤的掺杂浓度与长度配比以达到最佳的 SBS 抑制效果，同时在级联增益光纤的基础上引入温度梯度或者应力梯度，进一步提高 SBS 阈值以获得更高能量的脉冲激光。

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0.59-mJ Single-Frequency Yb^{3+}-Doped Hundred-Nanosecond Pulsed All-Fiber Laser

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Abstract

Objective Progress on high-energy hundreds-ns all-fiber single-frequency fiber master-oscillator-power-amplifier (MOPA) is mainly constrained by the stimulated Brillouin scattering (SBS) effect. The SBS can be generally suppressed by using large-mode-area active fibers with high dopant concentration so that short fiber length is allowed for power scaling. Whereas the insufficient extraction of population inversion due to the limited seed power induces a significant part of amplified spontaneous emission (ASE), which degrades the spectral purity. To avoid this when increasing the SBS threshold of the pulsed single-frequency laser, a fiber amplification scheme based on a hybrid active fiber structure is proposed here to achieve a high energy output. A piece of heavily Yb^{3+}-doped phosphosilicate fiber with a large core diameter is spliced after a piece of Yb^{3+}-doped silica fiber with a smaller core diameter. The difference in active fiber size introduces the loss to the reversed Stokes light, which is similar to the operating principle of an outstanding tapered fiber, thereby increasing the threshold of SBS while avoiding the complicated fabrication process. The signal which is pre-amplified by the low Yb^{3+}-doped silica fiber can effectively extract the population inversion in the phosphosilicate fiber, which exhibits the benefits on ASE suppression and efficiency improvement.

Methods The 1064.44 nm continuous-wave (CW) laser with a power of 76 mW is modulated by an electro-optic intensity modulator (EOIM) to become a pulsed laser source with a pulse duration of 100 ns. A single-frequency pulsed laser source with an average power of 1 mW is obtained after two-stage Yb^{3+}-doped fiber core-pumped pre-amplification and an acousto-optic modulator (AOM) synchronized with the EOIM. The average power of the pulsed laser source is increased to 120 mW corresponding to the pulse energy of 0.024 mJ after two-stage Yb^{3+}-doped fiber cladding-pumped pre-amplification. In the power amplifier, a hybrid active fiber structure, consisting of a 30 cm long piece of Yb^{3+}-doped silica fiber with a core/cladding diameter of 35 μm/250 μm (pump absorption of 12 dB/m @ 976 nm) and a 30 cm long piece of heavily Yb^{3+}-doped phosphosilicate fiber with a core/cladding diameter of 50 μm/400 μm (pump absorption of 27 dB/m @ 976 nm) spliced after it, is employed as the gain medium. Meanwhile, the coil diameters of the hybrid active fibers are controlled to ~12 cm and ~20 cm, respectively, in order to optimize the beam quality. For comparison, a 60-cm silica fiber with the same fiber length as that of the hybrid active fiber structure and the 40-cm phosphosilicate fiber which maintains almost the same pump absorption as that of the hybrid active fiber, are also employed as the gain medium in the power amplifier, respectively. The pump power in different cases is increased until the reversed Stokes light appears.

Results and Discussions The maximum pulse energy of 0.59 mJ is obtained with the hybrid active fiber structure at

the pump power of 13 W and the PRF of 5 kHz [Fig. 2 (a)], and the corresponding average power is 2.95 W with the conversion efficiency of 22.7%. The measured average power of the pulsed laser is 3.05 W, indicating that there is only 0.1 W CW component in the laser output. However, the maximum pulse energy of only 0.327 mJ is obtained at the pump power of 11 W [Fig. 2 (a)] when a 60-cm silica fiber is employed as the gain medium, which indicates that in the hybrid active fiber structure, the SBS threshold is effectively raised by increasing the mode field area of the active fiber and introducing the loss to the reversed Stokes light. When a 40-cm phosphosilicate fiber is employed as the gain medium, the maximum pulse energy is 0.187 mJ, which is corresponding to the average power of 0.935 W and the conversion efficiency of only 10.4% [Fig. 2 (a)]. The measured average power is 1.67 W, which indicates that plenty of ASE and CW components exist, which decreases the signal-to-noise ratio (SNR) and the conversion efficiency. Therefore, in the hybrid active fiber structure, with the benefit of the pre-amplification of the signal by the silica fiber, the population inversion in the phosphosilicate fiber is effectively extracted and the conversion efficiency is enhanced. The pulse shape is measured at the pulse energy of 0.59 mJ, and the pulse duration is broadened to 104 ns from 100 ns (the pulse duration of the seed laser) (Fig. 3). The corresponding maximum peak laser power is ~5.33 kW, the measured spectral linewidth is 40 MHz (Fig. 4), the center wavelength is 1064.44 nm, the SNR is 41 dB (Fig. 5), and the measured beam quality in the x and y directions are 1.48 and 1.50, respectively (Fig. 6).

Conclusions A 1064-nm single-frequency Yb^{3+}-doped pulsed all-fiber laser based on a hybrid active fiber structure is demonstrated. It can achieve a 0.59-mJ laser output with spectral linewidth of 40 MHz and beam quality of 1.50. The hybrid Yb^{3+}-doped active fibers with different core diameters are served as the gain media of the power amplifier to enhance the threshold of the SBS and inhibit the ASE. The calculated conversion efficiency is 22.7% and the measured SNR is 41 dB at the highest pulse energy. The hybrid active fiber structure provides a beneficial reference for further pulsed fiber amplifiers.

Key words lasers; fiber lasers; pulsed lasers; laser amplifier; stimulated Brillouin scattering