

6 kW 超荧光光纤光源

李瑞显¹, 王崇伟^{1,2}, 叶俊^{1,2,3}, 肖虎^{1,2,3*}, 许将明¹, 冷进勇^{1,2,3}, 周朴^{1**}¹国防科技大学前沿交叉学科学院, 湖南 长沙 410073;²国防科技大学南湖之光实验室, 湖南 长沙 410073;³国防科技大学高能激光技术湖南省重点实验室, 湖南 长沙 410073

摘要 由于自激振荡的限制, 单级超荧光光纤光源的功率提升十分困难, 目前仅达到百瓦量级。基于主振荡功率放大(MOPA)方案, 使用 1018 nm 光纤激光级联泵浦 1080 nm 波段的超荧光, 实现了 6.2 kW 高功率输出。最高功率下的光光转换效率为 81.5%, 没有出现横模不稳定(TMI), 功率提升受限于受激拉曼散射(SRS)。

关键词 光纤光学; 超荧光光源; 高功率; 级联泵浦; 受激拉曼散射; 横模不稳定

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高功率超荧光光源因其结构简单、时间相干性低、时域稳定性好、无弛豫振荡和无自锁模脉冲等优势^[1], 在拉曼光纤激光泵浦^[2-3]、光学相干成像^[4]、光谱合束^[5]等领域中有着广泛的应用。超荧光既要求增益光纤中的反转粒子数满足自发辐射条件, 又要求自发辐射光子能够受泵浦光激励实现功率放大, 其工作功率具有阈值性。泵浦功率过高将触发自激振荡, 极易形成高峰值功率的偶发脉冲, 造成光纤损伤^[6]。因此, 单级超荧光光源的功率提升十分困难, 目前输出功率仅为百瓦量级^[7]。

利用主振荡功率放大(MOPA)结构对低功率超荧光种子进行放大是提升输出功率的有效方式。2007年, 英国南安普敦大学研究人员首次采用空间MOPA结构, 将宽谱超荧光种子放大至百瓦量级(122 W), 但由于掺镱光纤重吸收和增益窄化等原因, 宽谱超荧光在功率提升过程中线宽自发变窄, 中心波长自发红移。为实现对中心波长、线宽等光谱参数的有效调控, 研究人员对宽谱超荧光先进行窄谱滤波处理, 再利用MOPA

结构放大^[8]。2011年, 德国Fraunhofer应用光学与精密工程研究所课题组将窄谱滤波超荧光作为种子源, 通过空间MOPA结构的两级放大, 实现了697 W输出功率^[9]。2015年, 国防科技大学课题组首次将全光纤MOPA结构的超荧光功率提升至千瓦量级(1.01 kW)^[10]。随后, 清华大学^[11]、中国科学院上海光学精密机械研究所^[12]、中国科学院西安光学精密机械研究所^[13]、中国电子科技集团公司第二十三研究所^[14]等单位相继实现了千瓦量级超荧光输出。目前, 基于掺镱光纤的1 μm超荧光公开报道的最高功率达到了3 kW量级^[15-16], 远高于其他波段。MOPA结构超荧光光源的功率提升主要受限于受激拉曼散射(SRS)和横模不稳定(TMI)。

近期, 国防科技大学课题组利用后向级联泵浦技术有效提升了MOPA结构超荧光光源的SRS和TMI阈值, 实现了大于6 kW的高功率超荧光输出。系统由种子级和放大级构成, 如图1所示。超荧光种子源的增益介质为10 μm/130 μm双包层掺镱光纤1(YDF 1), 长度约为20 m。超荧光被带通滤波器(BPF)滤波后,

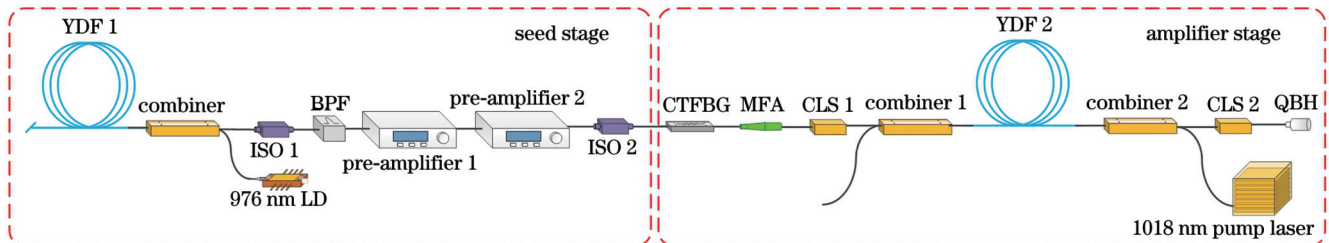


图1 超荧光光纤光源系统结构图

Fig. 1 Structural diagram of superfluorescent fiber light source system

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通信作者: *xhwise@163.com; **zhoupu203@163.com

经过两级预放大器,功率被放大至 40 W,中心波长为 1080.08 nm,3 dB 线宽约为 2.08 nm。隔离器(ISO)用于减小回光对超荧光种子源的影响。在放大级中,超荧光经过倾斜光栅(CTFBG)、模场适配器(MFA)、包层光滤除器 1(CLS 1)、前向合束器 1(combiner 1)后进入双包层掺镱光纤 2(YDF 2)。1018 nm 泵浦光通过后向合束器 2(combiner 2)注入 YDF 2。YDF 2 的长度约为 50 m,纤芯/包层直径为 25 μm /250 μm ,泵浦光吸收系数约为 0.3 dB/m@1018 nm。放大后的超荧光经包层光滤除器 2(CLS 2)、端帽(QBH)输出。

图 2 所示为超荧光输出特性的测试结果。从图 2(a)可以看出,输出功率随泵浦功率的增加呈近似线性增加,当注入泵浦功率为 7554 W 时,输出功率为 6200 W,

光光转换效率为 81.5%。图 2(b)为不同功率下的输出光谱,随着功率的增加,光谱逐渐展宽,3 dB 线宽由种子光的 2.08 nm@40 W 展宽至 7.72 nm@6200 W。当功率为 6000 W 时,光谱在 1135 nm 附近出现较明显的一阶拉曼光。当功率为 6200 W 时,拉曼光强度迅速增加,拉曼抑制比仅为 ~ 25 dB,同时观察到了 1190 nm 附近的二阶拉曼光,表明系统出现了较为严重的 SRS。图 2(c)为不同功率下的光束质量因子(M^2),随着功率的提升, M^2 先增大然后趋于稳定。种子光的 M^2 为 1.71,当输出功率为 2071 W 时 M^2 提升至 1.93,最高功率 6200 W 下的 $M^2 = 1.98$ 。图 2(d)所示为输出荧光的时序及频谱特性,可以看出,时序信号稳定,频谱中未观察到 kHz 特征峰,表明系统未出现 TMI 效应。

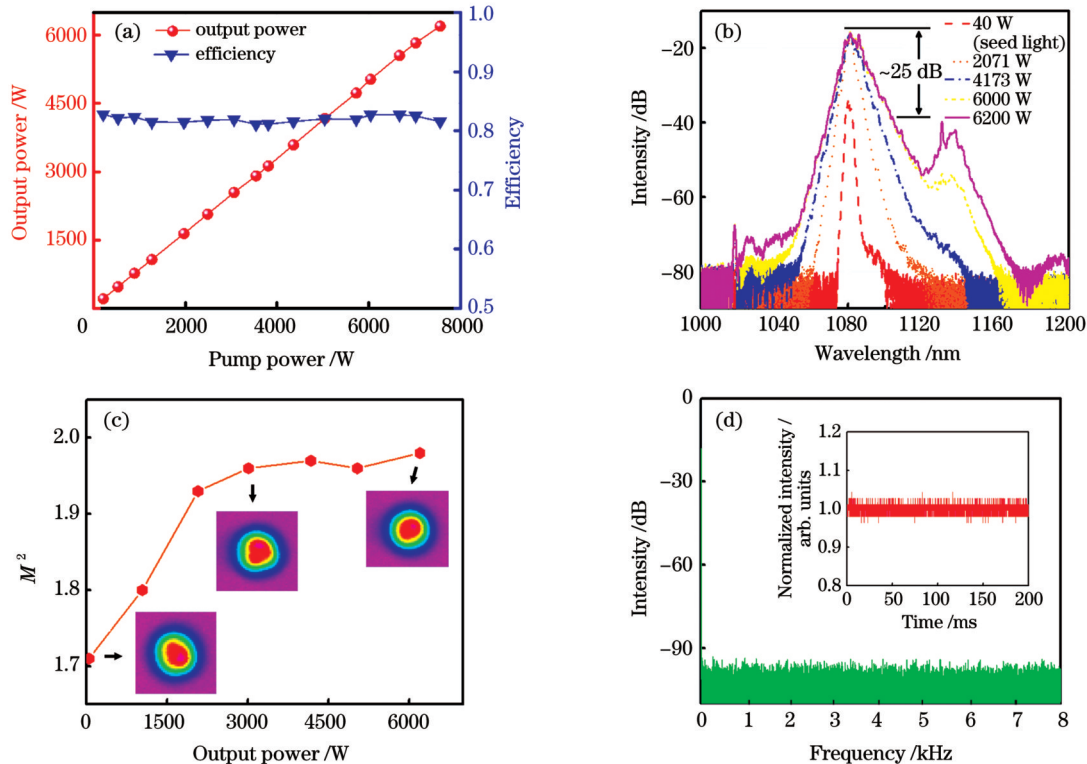


图 2 超荧光的输出特性。(a)输出功率和效率随泵浦功率的变化;(b)不同功率下的光谱;(c)不同功率下的 M^2 ;(d)最高功率 6200 W 下的输出时序(插图)和对应频谱

Fig. 2 Output characteristics of superfluorescent light. (a) Output power and efficiency versus pump power; (b) spectra under different powers; (c) M^2 under different powers; (d) output time sequence (insert) and its corresponding spectrum at highest power of 6200 W

本文为高功率超荧光光源的设计提供了可行的技术方案,实现了较高功率的超荧光输出,但进一步的功率提升受限于 SRS。下一步将对光纤参数进行优化,通过提高镱离子掺杂浓度、缩短光纤长度、优化光纤弯曲直径等方式进一步提高输出功率和光束质量。

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参 考 文 献

[1] Martin-Lopez S, Gonzalez-Herrera M, Carrasco-Sanz A, et al. Broadband spectrally flat and high power density light source for

fibre sensing purposes[J]. Measurement Science and Technology, 2006, 17(5): 1014-1019.

[2] Pan W W, Zhang L, Zhou J Q, et al. Raman dissipative soliton fiber laser pumped by an ASE source[J]. Optics Letters, 2017, 42(24): 5162-5165.

[3] Xu J M, Ye J, Liu W, et al. Passively spatiotemporal gain-modulation-induced stable pulsing operation of a random fiber laser[J]. Photonics Research, 2017, 5(6): 598-603.

[4] Redding B, Ahmadi P, Mook V, et al. Low-spatial-coherence high-radiance broadband fiber source for speckle free imaging[J]. Optics Letters, 2015, 40(20): 4607-4610.

[5] Zheng Y, Yang Y F, Wang J H, et al. 10.8 kW spectral beam combination of eight all-fiber superfluorescent sources and their dispersion compensation[J]. Optics Express, 2016, 24(11): 12063-12071.

- [6] Xiao Q R, Tian J D, Yan P, et al. Exploring the initiation of fiber fuse[J]. *Scientific Reports*, 2019, 9: 11655.
- [7] An Y Y, Yu Y, Cao J Q, et al. Power scalability of a single-stage Yb-doped superfluorescent fiber source[J]. *Laser Physics Letters*, 2016, 13(2): 025105.
- [8] Wang P, Sahu J K, Clarkson W A. Power scaling of ytterbium-doped fiber superfluorescent sources[J]. *IEEE Journal of Selected Topics in Quantum Electronics*, 2007, 13(3): 580-587.
- [9] Schmidt O, Rekas M, Wirth C, et al. High power narrow-band fiber-based ASE source[J]. *Optics Express*, 2011, 19(5): 4421-4427.
- [10] Xu J M, Huang L J, Leng J Y, et al. 1.01 kW superfluorescent source in all-fiberized MOPA configuration[J]. *Optics Express*, 2015, 23(5): 5485-5490.
- [11] Yan P, Sun J Y, Li D, et al. 933 W Yb-doped fiber ASE amplifier with 50.4 nm bandwidth[J]. *Optics Express*, 2016, 24(17): 19940-19948.
- [12] 刘广柏, 杨依枫, 雷敏, 等. 1.5 kW 近衍射极限全光纤窄带超荧光光源[J]. *中国激光*, 2015, 42(12): 1202009.
- [13] Liu G B, Yang Y F, Lei M, et al. 1.5 kW near-diffraction-limited narrowband all-fiber superfluorescent source[J]. *Chinese Journal of Lasers*, 2015, 42(12): 1202009.
- [14] Li Z, Li G, Gao Q, et al. Kilowatt-level tunable all-fiber narrowband superfluorescent fiber source with 40 nm tuning range[J]. *Optics Express*, 2020, 28(7): 10378-10385.
- [15] 张璟璞, 丁亚茜, 赵翔, 等. 光谱不展宽的 1.08 kW 窄线宽全光纤超荧光光源[J]. *中国激光*, 2021, 48(23): 2301001.
- [16] Zhang J P, Ding Y Q, Zhao X, et al. 1.08 kW narrowband all-fiber super-fluorescent source with spectral-broadening-free property[J]. *Chinese Journal of Lasers*, 2021, 48(23): 2301001.
- [17] Ren S, Wang G J, Li W, et al. 3 kW power-level all-fiberized superfluorescent fiber source with linear polarization and near-diffraction-limited beam quality[J]. *Applied Optics*, 2022, 61(14): 3952-3956.
- [18] Xu J M, Ye J, Xiao H, et al. In-band pumping avenue based high power superfluorescent fiber source with record power and near-diffraction-limited beam quality[J]. *High Power Laser Science and Engineering*, 2018, 6: e46.

6 kW Superfluorescent Fiber Light Source

Li Ruixian¹, Wang Chongwei^{1,2}, Ye Jun^{1,2,3}, Xiao Hu^{1,2,3*}, Xu Jiangming¹, Leng Jinyong^{1,2,3}, Zhou Pu^{1**}

¹*College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, Hunan, China;*

²*Nanhu Laser Laboratory, National University of Defense Technology, Changsha 410073, Hunan, China;*

³*Hunan Provincial Key Laboratory of High Energy Laser Technology, National University of Defense Technology, Changsha 410073, Hunan, China*

Abstract

Objective High-power superfluorescent fiber light sources have a wide range of applications, including Raman fiber laser pumping, optical coherence imaging, and spectral beam combining. They are favored for their simple structure, low temporal coherence, high temporal stability, absence of relaxation oscillation, and lack of self-locking mode pulses. However, because of the limitation of parasitic lasing, it is challenging to increase the power of a single-stage superfluorescent fiber light source. Currently, its power only reaches a few hundred watts. A master oscillator power amplification (MOPA) structure provides a solution to achieve high power output by amplifying a low-power superfluorescent seed. The highest reported power of 1- μm superfluorescence based on a Yb-doped fiber MOPA structure is 3 kW. Further power scaling is limited by stimulated Raman scattering (SRS) and transverse mode instability (TMI). In this study, we implement backward cascaded pumping to suppress TMI and SRS and boost the superfluorescent output to more than 6 kW.

Methods First, the superfluorescent source is filtered out by a bandpass filter and amplified to 40 W by two pre-amplifiers. In the seed stage, it is important to use isolators to reduce the negative impact of backscattering on the superfluorescent seed source. In the amplification stage, the superfluorescent light is launched into the double-clad ytterbium-doped fiber (YDF) through a mode field adapter, a cladding light stripper, and a combiner. A 1018-nm pump laser is injected into YDF through a backward combiner. Finally, the amplified superfluorescent light is emitted through a cladding light stripper and a beam collimator.

Results and Discussions The output power increases almost linearly with the injected pump power. At a pump power of 7554 W, the output power reaches 6200 W with a corresponding optical-to-optical conversion efficiency of 81.5%. As the power increases, the spectral width gradually broadens, and the 3-dB linewidth increases from 2.08 nm at 40 W to 7.72 nm at 6200 W. At an output power of 6200 W, the system experiences severe SRS, and the Raman suppression ratio is only approximately 25 dB. Beam quality factor (M^2) first increases and then stabilizes as the power is increased. The seed has an M^2 value of 1.71, while $M^2=1.98$ at the maximum power of 6200 W. The temporal and spectral superfluorescence characteristics indicate that the system does not exhibit the TMI phenomenon.

Conclusions A practical technical approach to designing high-power superfluorescent light sources is proposed. To the best of our knowledge, the 6.2-kW superfluorescent output achieved is the higher power level reported publicly.

Key words fiber optics; superfluorescent light source; high power; cascaded pumping; stimulated Raman scattering; transverse mode instability