熔融石英中实现高效率的百毫焦受激布里渊散射

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摘 要：固体布里渊增益介质是目前实现高稳定、高重复频率受激布里渊散射 (SBS) 的重要光学元件，能够产生高光束质量的相位共轭光。然而，不同于被广泛研究的液体布里渊增益介质，目前针对固体布里渊增益介质如何产生高效率高能量的 SBS 尚无成熟的研究。近日，笔者团队以块状熔融石英作为布里渊增益介质，在高强度纳秒激光脉冲泵浦下，围绕熔融石英中的 SBS 能量转换效率和损伤阈值与泵浦光纵模的关系开展了研究，实现了最高单脉冲能量 183.1 mJ、反射率为 81.0%、斜效率高达 85.8% 的相位共轭光输出。该研究结果对于实现高功率全固态的 SBS 相位共轭镜，进而提升脉冲激光器的输出功率水平、获得高稳定高效率的 SBS 运转具有重要的指导意义。

关键词：受激布里渊散射； 熔融石英； 高效率； 损伤阈值； 纵模

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大能量全固态短脉冲激光器由于其优越特性在激光清洗、加工、测距等领域受到广泛关注[1−3]。目前，高强度激光的获取需要采用高功率泵浦源结合多级放大器，但往往伴随而来的是热透镜、热致双折射等效应引起的波前畸变，显著影响产生激光的光束质量，因此如何提高激光输出强度并改善光束质量是需要解决的关键难题[4]。研究表明，基于受激布里渊散射 (SBS) 的相位共轭镜 (PCM) 是补偿波前畸变的有效方式，且 SBS 固有的高增益和小频移特性，使之成为获取高能量转换效率 PCM 的重要手段[4−5]。虽然液体的 SBS 已经成熟应用于脉冲压缩及相位共轭等方面，但是为了获得结构紧凑的高稳定性 SBS-PCM，固体是具有巨大潜力的 SBS 介质种类[6]。原因在于固体布里渊增益介质由于高导热率、低吸收系数和方便处理的结构为其在高重复频率激光放大系统中应用提供了机会。目前，在低重复频率运转的单纵模激光泵浦条件下，熔融石英可承受高达 2.3 J 的入射能量[7]；在高重复频率泵浦条件下，已经实现了重复频率 1 kHz、泵浦能量 50 mJ 的 SBS 稳定运转[8]。但是针对不同泵浦模式下的固体布里渊增益介质的斜率效率尚无报道，这使得人们对多纵模激光器是否能够如单纵模激光器一样通过固体 SBS-PCM 高效的获得高功率激光输出存有一定的疑问。

为了探究固体布里渊增益介质在实现大能量窄脉宽激光输出方面的优势和局限，笔者团队近期利用稳定输出单纵模和多纵模的纳秒激光作为泵浦源，对基于熔融石英的 SBS 产生器进行了实验研究，通过改变泵浦模式和泵浦光强度，研究了不同泵浦纵模模式下的 SBS 产生阈值、斜率效率、损伤阈值及光束轮廓等输出特性。

图 1 所示为 SBS 实验装置示意图，泵浦源使用环形腔结构，控制标准具的插入来调节输出的纵模数量，输出脉宽为 10 ns[9]；SBS 产生装置中采用熔融石英作为布里渊增益介质，长度为 200 mm。利用透镜

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组 L_1 和 L_2 将光斑直径由 3.2 mm 扩束至 5.6 mm, L_3 焦距为 250 mm。如图 2(a) 所示, 单纵模泵浦的 SBS 阈值为 10.1 mJ, 受泵浦能量限制, 在最大泵浦能量 226 mJ 时未见损伤, 在有限的泵浦能量情况下获得的斜率效率高达 85.8%。其中, 在能量反射率为 15% 时获得最窄脉宽 5.5 ns。与单纵模泵浦相比, 通过多纵模泵浦产生 SBS 的阈值功率高 14%, 多纵模泵浦时损伤阈值仅为 34 mJ。实验结果证明了多纵模脉冲尖峰是造成 SBS 过程中光学击穿的关键因素, 单纵模泵浦可以有效地避免固体介质的光学击穿。图 2(b) 展示了泵浦光能量为 226 mJ 时, 泵浦光和产生 Stokes 光波形, 可见其具有很好的波形保真度。图 2(c) 所示为低能量泵浦条件下产生的 SBS 光束实现了良好的净化效果, 随着能量的增加, SBS 光束轮廓逐渐向泵浦轮廓演变, 因此理论上存在最佳的能量密度以获得高光束质量的 SBS 激发。目前, 块状固体介质的有限尺寸是制约其内部增益强度进一步提升的关键所在, 但通过对增益介质进行串联或设计成折返结构能够有效突破现阶段的能量瓶颈。

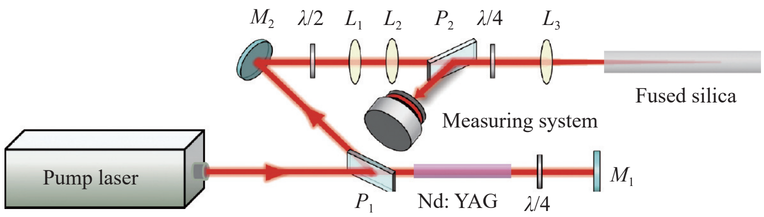

图 1 基于熔融石英的 SBS 实验装置示意图 (P_1~P_2: 偏振片; M_1~M_2: 反射镜; λ/4: 四分之一波片; λ/2: 半波片; L_1~L_3: 透镜)

Fig.1 (a) Diagram of SBS experimental device using fused silica (P_1-P_2: Polarizer; M_1-M_2: Mirror; λ/4: Quarter-wave plate; λ/2: Half-wave plate; L_1-L_3: Lens)

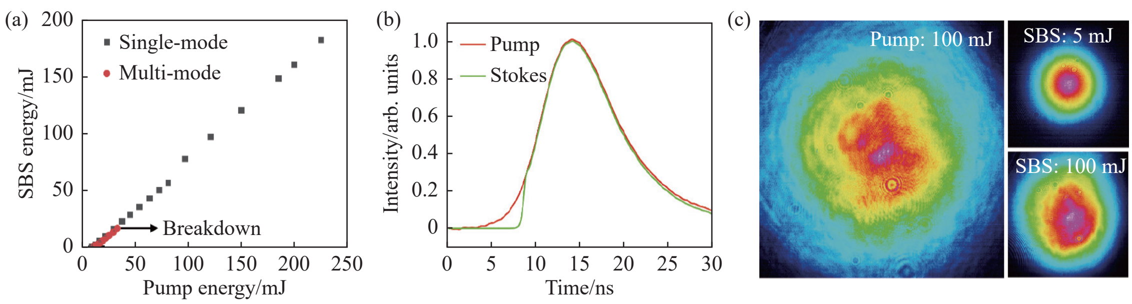

图 2 (a) SBS 反射能量随泵浦能量的变化; (b) 泵浦能量最大时泵浦光和 Stokes 光波形; (c) 不同能量下的泵浦光及 SBS 光束轮廓

Fig.2 (a) Variation of SBS reflected energy with pump energy; (b) Waveforms of pump and Stokes at maximum pump energy; (c) Pump and SBS beam profiles at different energies

笔者验证了在熔融石英中获得高效率高能量 SBS 输出可行性, 该研究成果为基于固体布里渊增益介质的 SBS 的相位共轭光的优化, 以及拓展其在脉冲压缩、布里渊放大和光束合成奠定了基础, 对实现高功率全固态的 SBS 激光具有重要的指导意义。

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Generation of high-efficiency hundred-millijoule stimulated Brillouin scattering in fused silica

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Abstract:

Objective Stimulated Brillouin scattering (SBS) is a powerful tool for serving as a phase conjugation mirror (PCM) due to its inherent properties of high gain, small frequency shift, and phase conjugation. Solid-state gain media offer the advantages of high stability and high repetition rate SBS, compared to liquid and gas gain media. However, solid gain media face the challenge of recovery once breakdown occurs. Currently, there is limited research on achieving high-efficiency and high-energy SBS generation in solid media, which restricts the application of solid gain media in high-energy SBS. In this study, we experimentally investigate an SBS generator based on bulk fused silica to provide guidance for the development and application of all solid-state SBS systems with high efficiency.

Methods The experimental setup is illustrated (Fig.1). A passively Q-switched nanosecond laser, based on a ring cavity, is used as the pump source, delivering a pulse width of 10 ns. A Fabry-Perot etalon is inserted into the cavity to control the number of longitudinal modes. Lenses L_1 and L_2 are utilized to adjust the beam diameter from 3.2 mm to 5.6 mm, while the focal length of L_3 is 250 mm. Fused silica, with a length of 200 mm, serves as the Brillouin gain medium. The output characteristics of SBS generation, including threshold, slope efficiency, damage threshold, and beam profile, are studied by varying the pump mode and pump intensity.

Results and Discussions Compared to a single longitudinal-mode (SLM) pump, the SBS threshold for a multi-longitudinal-mode (MLM) pump is 14% higher, and the damage threshold is only 34 mJ (Fig.2(a)). A phase-conjugate reflectivity of up to 81.0%, with a slope efficiency of 85.8%, is achieved when the pump single pulse energy is 183.1 mJ. The results indicate that MLM pulse spikes are the key factor causing optical breakdown in the SBS process, while SLM pumping can effectively prevent the optical breakdown in solid media. The narrowest Stokes pulse width of 5.5 ns is obtained at an energy reflectivity of 15%; While the waveform maintains good fidelity at the highest input pump energy (Fig.2(b)). The Stokes beam profile exhibits a good cleanup effect under low-energy pumping conditions (Fig.2(c)). However, it gradually evolves towards the pumping profile as the energy increases. This suggests that high reflectivity also leads to high beam quality fidelity of Stokes.

Conclusions In this study, we have demonstrated the feasibility of achieving high-efficiency and high-energy SBS output in fused silica. A Stokes energy of 183.1 mJ with a slope efficiency of 85.8% was obtained when the pump energy was 226 mJ. This research lays the foundation for optimizing the characteristics of SBS-PCM based on solid Brillouin gain media, as well as its expansion in pulse compression, Brillouin amplification, and beam combination. It has important implications for achieving high-power all-solid-state SBS lasers.

Key words: stimulated Brillouin scattering (SBS); fused silica; high efficiency; damage threshold; longitudinal mode

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