金刚石布里渊激光器实现 4 倍线宽窄化

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摘　要：布里渊激光器是实现高相干、低噪声激光输出的重要技术路径，其中空间结构布里渊激光器被证实可以产生高功率的单频激光辐射。然而，不同于被广泛研究的导波结构布里渊激光器，目前针对自由空间运转布里渊激光器的线宽特性还尚无报道。笔者课题组在国家和省级自然科学基金和国防预研基金资助下，以金刚石晶体作为增益介质，围绕自由空间结构布里渊激光的产生、参数调控和性能优化开展了系列的研究，并在近日成功验证了其实现线宽窄化输出的可行性。该研究对推动高功率高相干激光光源的发展具有重要的指导意义。

关键词：布里渊激光；　金刚石；　线宽窄化；　高功率；　单频

中图分类号：TN248　　　**文献标志码：**A　　　**DOI：**10.3788/IRLA20230295

高功率窄线宽单频激光器由于其在引力波探测、量子信息光学、原子物理和非线性频率转换等领域的优越特性而受到广泛关注[1−2]。然而，目前常用的获得高功率窄线宽激光器的方法存在一些问题，如激光放大器中的光束质量恶化、模式不稳定、线宽增宽以及难以抑制的非线性光学效应等[3−4]。为了解决这些问题，近年来研究人员提出了一种利用自由空间运行的布里渊激光器来实现高功率和窄线宽输出的新方法，其相对于导波结构的优点在于空间腔中分离腔体和增益介质有助于热管理和相位匹配条件的控制，以及布里渊增益材料的多样性使其能够实现特殊波长下的高功率窄线宽激光输出[5−7]。尽管自由空间运行的布里渊激光器具有许多优点，且已经分别在可见光和近红外波段获得了功率高达 11 W[6] 和 22.5 W[5] 的单频激光输出，但是针对空间结构布里渊激光器线宽窄化尚无报道，这使得人们对自由空间运转布里渊振荡器是否能够如其他导波结构一样获得极窄线宽、极高信噪比的激光输出存有一定的疑问。

为了更好地理解自由空间运行的布里渊激光器的工作原理，并探究其在实现高功率窄线宽激光输出方面的优势和局限，近日笔者课题组从理论上和实验上对空间布里渊激光器的线宽行为进行了分析，验证了不同振荡器参数下的线宽输出特性，成功实现了线宽窄化布里渊激光输出[8]。

图 1(a) 和 (b) 分别为空间布里渊激光器的结构和相应的线宽测量装置。布里渊激光器以金刚石晶体作为布里渊增益介质，金刚石介质具有已知的最高的热导率和透过范围[9−11]。实验采用直接泵浦的环形腔结构，其中泵浦光的线宽为 7.36 kHz。实验上通过选择三组不同的耦合镜反射率：R_1 = 96%, R_1 = 97% 和 R_1 = 98.5% 进行实验对 Stokes 光的线宽行为进行了对比研究。图 2 中的测量结果表明，随着耦合镜反射率的增加，Stokes 光输出线宽逐渐变窄。三组耦合镜反射率对应的 Stokes 线宽分别为 3.2 kHz、2.43 kHz 和 1.77 kHz, 与泵浦相比都实现了线宽压缩，最高压缩比为 4.1。理论上通过减少腔内元件的插入损失可

收稿日期:2023−05−18;　**修订日期:**2023−06−19

基金项目:国家自然科学基金项目 (61927815); 天津市自然科学基金项目 (22JCYBJC01100); 量子光学与光量子器件国家重点实验室开放课题 (KF202201); 河北工业大学基本科研业务费 (JBKYTD2201); 河北省教育厅在读研究生创新能力培养资助项目 (CXZZBS2021030, CXZZSS2023029)

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以同时提高输出效率和线宽压缩效果，分析表明，在泵浦功率为 60 W 且耦合镜反射率为 96% 时，通过减少腔内元件的插入损失可以实现 1.6 kHz 的线宽和高达 80% 光学转换效率的 Stokes 光输出。未来在实现超窄线宽激光辐射时，系统中引入的技术噪声将成为限制基础线宽进一步缩小的主要障碍[8]。

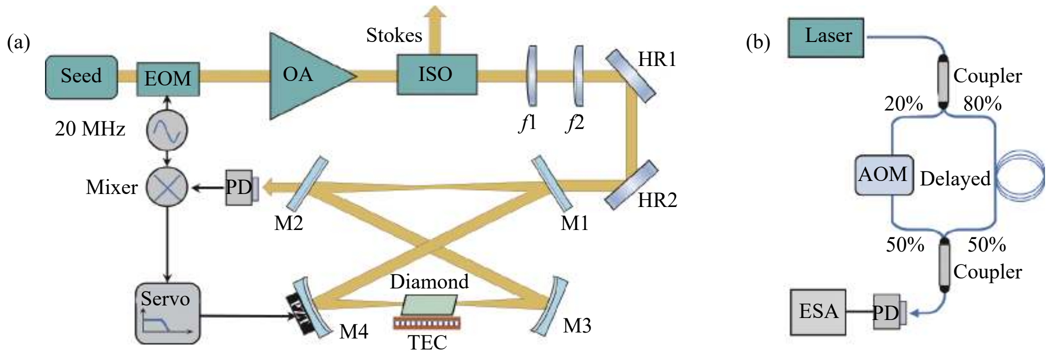

图 1 (a) 金刚石布里渊激光器结构示意图：(EOM：电光调制器，OA：光放大器，ISO：光隔离器；(b) 布里渊激光器 Stokes 光线宽测量结构)

Fig.1 (a) Diagram of diamond Brillouin laser structure:(EOM: electronical optical modulator, OA: optical amplifier, ISO: isolator; (b) Stokes linewidth measurement structure for Brillouin laser)

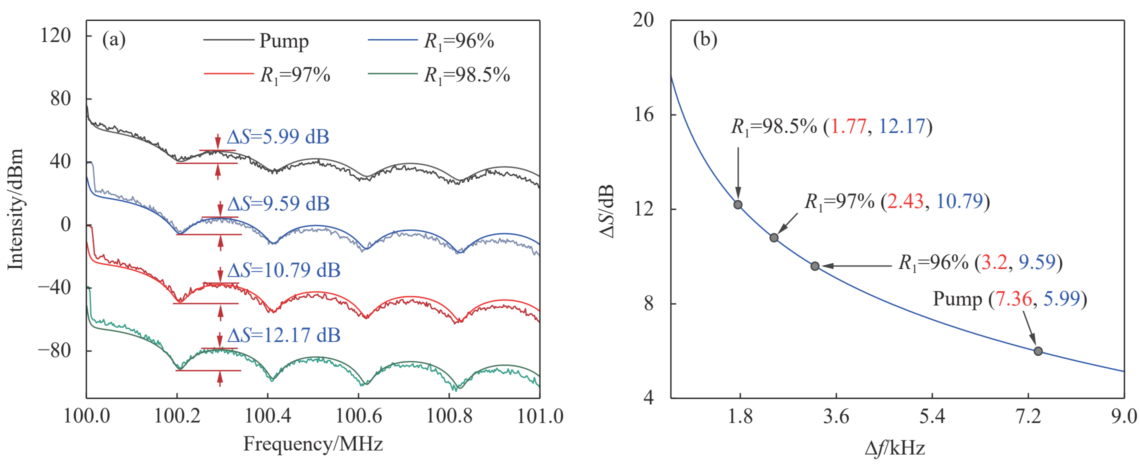

图 2 三组耦合镜反射率对应的 Stokes 线宽。(a) 延迟自外差测量得到的功率谱的幅度差；(b) 通过相干包络法计算的线宽和包络幅度差曲线

Fig.2 Stokes linewidth corresponding to the reflectivity of the three sets of coupling mirrors. (a) Power spectrum of the corresponding delayed self-heterodyne amplitude difference; (b) Linewidth and envelope amplitude difference curves calculated by the coherent envelope method

这里，首次验证了自由空间光传输结构中实现线宽窄化布里渊激光输出的可行性。项目成果为获得高功率、窄线宽特殊波长的激光提供了一种可行的技术方案，对促进金刚石激光技术的发展和推动高相干光源的应用具有重要意义。

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Four times linewidth narrowing has been achieved in diamond Brillouin laser

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Abstract:

Objective Brillouin laser is an important technological approach for achieving high coherence and low noise lasing, among which Brillouin lasers in free space have been proven to generate high-power single-frequency laser radiation. However, unlike the widely studied guided-wave-based Brillouin lasers, no studies on the linewidth properties have been reported for Brillouin lasers in free space. In this paper, a series of research works have been conducted on the generation, parameter regulation, and performance optimization of the Brillouin lasers in free space using diamond as gain media. We experimentally studied the feasibility of realizing linewidth narrowing of the Brillouin laser in free space.

Methods The structure of the spatial Brillouin laser and the corresponding linewidth measurement device is shown respectively (Fig.1(a), (b)). The Brillouin laser uses a diamond crystal as the Brillouin gain medium, which has the highest known thermal conductivity and transmission range. A directly pumped ring cavity structure is used for the experiments, where the linewidth of the pumped light is 7.36 kHz. The linewidth behavior of the Stokes light is comparatively investigated by choosing three different sets of coupled mirror reflectivity: R_1 = 96%, R_1 = 97% and R_1 = 98.5% for the experiments.

Results and Discussions The measurement results (Fig.2) show that the Stokes linewidth becomes narrower as the coupler reflectivity increases. The Stokes linewidths corresponding to three sets of coupler reflectivity are 3.2 kHz, 2.43 kHz and 1.77 kHz, respectively, and all of them realize linewidth compression compared with the pump, with the highest compression ratio of 4.1. Theoretically, the output efficiency and linewidth compression can be improved at the same time by decreasing the insertion loss of the intracavity element, and the analysis shows that, at the pump power of 60 W and coupled-mirror reflectivity of 96%, the linewidth of 1.6 kHz and up to 80% can be achieved by decreasing the insertion loss of the intracavity element. The analysis shows that at a pump power

of 60 W and a coupling mirror reflectivity of 96%, a linewidth of 1.6 kHz and a Stokes output with an optical conversion efficiency of up to 80% can be realized by reducing the insertion loss of the intracavity components. In the future, when realizing ultra-narrow linewidth laser radiation, the technical noise introduced in the system will be the main obstacle limiting the further reduction of the fundamental linewidth.

Conclusions For the first time, we have verified the feasibility of realizing linewidth-narrowed Brillouin laser output in a free-space optical transport structure. The study provides a feasible technical solution for obtaining high-power, narrow-linewidth lasing with a wide wavelength range. The result is of great significance for promoting the development of diamond laser technology and advancing the application of highly coherent light sources.

Key words: Brillouin laser; diamond; linewidth narrowing; high power; single-frequency

Funding projects: National Natural Science Foundation of China (61927815); Natural Science Foundation of Tianjin (22JCYBJC01100, 20JCZDJC00430); Program of State Key Laboratory of Quantum Optics and Quantum Optics Devices (KF202201); Funds for Basic Scientific Research of Hebei University of Technology (JBKYTD2201); Postgraduate Innovation Ability Training Program of Hebei Province (CXZZBS2021030, CXZZSS2023029)