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中国激光

基于半导体激光合束技术的高效点火光源研究

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摘要 随着半导体激光技术的快速发展，以半导体激光为核心光源的激光点火技术得到越来越广泛的应用。本文开展了高效激光点火光源的研究，设计出一种单光纤双波长输出的光学结构，将高功率 976 nm 点火激光和低功率 1310 nm 检测激光通过空间合束以及波长合束技术耦合到芯径为 105 μm，数值孔径（*NA*）为 0.22 的光纤中，获得了输出功率大于 10 W 的 976 nm 点火激光以及输出功率大于 1 mW 的 1310 nm 检测激光，其中高功率点火激光的耦合效率超过 90%；通过自聚焦透镜对出纤激光进行光束整形，与自由输出光束相比，整形后出射光斑发散角减小了，入射到点火药剂上的光功率密度增大了，点火效率提高了。实验结果表明，所设计的分光镜膜系以及光路结构可实现光路自检以及高功率点火激光的输出功率同步自检，满足该领域对于点火光源高效率、高可靠性的应用要求。

关键词 激光器；半导体激光器；激光点火；空间合束；波长合束；光路自检

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1 引 言

近些年来，半导体激光器快速发展，已被广泛应用于工业加工、航空航天、军事等领域，特别是在点火起爆领域越来越受青睐[1-5]。传统电点火技术是通过热阻丝产生热量引爆药剂，该方案存在静电放电、电磁辐射等潜在风险，难以适应现代战场复杂的环境变化[6-7]。激光点火技术可以很好地解决上述问题，该技术是将激光产生的能量转化为热能从而引爆药剂[8]，相比于传统技术具有更好的抗静电干扰、抗电磁干扰能力，从而保证火工品的可靠性以及安全性。

国外对激光点火技术的研究开展较早。1995 年，NASA 在运载火箭上开展了激光点火相关实验，该项目成功证明了以半导体激光器为光源的点火系统具有高可靠性，可以设计并用于空间运载火箭[9]；2002 年，Quantic 公司开发出可同步实现激光点火以及光路连续性的检测系统，其中点火光源以及检测光源通过电路系统控制从相同的激光器输出[10]；2003 年，Benner 等[11]为了获得高可靠性、高点火效率的半导体激光光源，设计了一种密封腔结构，通过 100 μm 芯径光纤输出激光。目前，国外已经掌握了激光点火技术，并且在不同型号设备上实现了工程化的应用。

国内对激光点火技术的研究起步较晚，但是近些年来发展迅速。2010 年，中国科学院长春光学精密机械与物理研究所的曹军胜等[12]利用高功率半导体激光器作为点火光源，对传统激光点火系统中的光路自检功能进行改进，提高了检测的有效性；2013 年，北京航天自动控制研究所的张磊等[13]采用双光纤检测技术对激光点火控制系统进行分析，并给出检测合格判断依据；2020 年，中北大学的王端等[14]设计了一种半导体激光点火系统，通过对点火延迟时间和点火能量进行研究，确定了药剂、药量以及装药密度，提高了系统的可靠性。

虽然激光点火技术和传统电点火技术相比有很大的应用优势，但是激光点火系统对于激光的功率和功率密度有严格的要求。此外，点火激光光源中

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需要采用一系列光学元件如准直透镜、聚焦镜、光纤等，一旦在应用过程中出现透镜微形变、光纤松动弯折等情况，会导致光功率降低甚至损坏设备，因此激光点火系统需要具备光路自检功能，在系统工作之前进行通路自检，以便于排除故障。由于工作时不能将光功率计放入结构中直接测量光功率，因此需要采用光电探测器(PD)将光信号转换为电信号，通过 PD 的反馈数值来判断光路系统的连续性。PD 采用半导体材料铟镓砷(InGaAs)，其有效探测波段为 800～1700 nm，可以满足设计需求。

传统方式中，检测系统首先输出 1310 nm 的激光，出纤后通过 PD 探测到 1310 nm 反馈光。确定光路系统连续后再开启 976 nm 激光点火，点火光源同样利用光纤输出，直接照射到药剂上实现激光点火。需要指出的是，上述方案的光学结构虽然相对简单，但是存在两个缺点：1)通过探测 1310 nm 的反馈光，如指标一致性出现偏差，除了光纤因素外，检测激光参数也是影响因素，如芯片散热性差或者自身缺陷可能导致出光功率降低，因此需要同步探测未通过光纤时的检测激光功率；同理，对于 976 nm 的点火激光也需要测试其耦合进入光纤前的光功率。2)点火激光从光纤输出后存在一定的发散角，激光通过光窗口镜后辐射面积增大，功率密度减小，导致点火阈值功率提高和点火可靠性降低；该结构不利于光路连续性检测，即在这种结构中，点火激光由于出纤后发散角较大，照射到 PD 后接收随机性很大，导致难以制定光路连续性检测的定量判据。

本文针对激光点火领域对点火光源的需求，先通过光束准直、空间合束、波长合束技术以及光纤耦合技术相结合的方法[15-16]，研制了出纤功率不小于 10 W 的点火光源，点火光源的波长为 976 nm，检测光源波长为 1310 nm，光纤芯径为 105 μm；再通过合理地设计分光镜的膜系以及光学结构，实现了光通路以及点火光源的输出功率自检，确保系统的可靠性以及稳定性。

2 实验原理及设计

激光点火系统的主要特点是激光照射到药剂上被药剂吸收，激光能量转化为热能，从而达到引爆效果。采用掺碳的 BNCP 作为系统的点火药剂，该材料在 500～2000 nm 范围内均有较高的吸收强度[17]。针对半导体激光点火光源，在药剂吸收波段内，976 nm 波长的光具有较高的电光转换效率以及较小的发光区条宽，因此适合作为大功率点火光源；针对半导体激光检测光源，考虑到光纤的传输损耗以及高功率点火光源的点火激光和检测激光的波长间隔，波长间隔太大会影响光纤以及镜片增透膜的透过率，本文选择 1310 nm 波长的光作为检测光源，两种光源均采用单管激光器，具体参数见表 1。

表 1 976 nm 点火激光器和 1310 nm 检测激光器的主要参数

Table 1 Typical parameters of 976 nm igniting laser and 1310 nm detection laser

Parameter	Specification	
	976 nm igniting laser	1310 nm detection laser
Output power /W	12	3.5×10^{-3}
Operating current /A	12	15×10^{-3}
Operating voltage /V	1.8	1.0
Fast axis divergence angle /(°)	58	45
Slow axis divergence angle /(°)	10.5	25
Emitter width /μm	94	2

将 976 nm 和 1310 nm 单管半导体激光芯片封装成 COS 结构，两个波长的单管激光器阶梯式固定进行空间合束[18]，阶梯高度为 0.55 mm。由于半导体激光器的初始快慢轴发散角较大，因此需要准直后才能实现光纤耦合[19-21]。1310 nm 激光芯片的发光区条宽以及快轴发散角相对较小，因此采用单片非球面准直镜可实现快慢轴方向的双向准直；976 nm 的激光芯片需要采用快轴准直镜＋慢轴准直镜(FAC＋SAC)组合结构分别对快慢轴方向的激光进行准直[22]，最终通过非球面聚焦镜将两波长激光耦合到光纤芯径为 105 μm、数值孔径(*NA*)为 0.22 的光纤中。通过 Zemax 软件对该结构进行模拟仿真，结构如图 1 所示。

基于目前点火激光器存在的问题，对现有结构进行了优化设计，光路结构如图 2 所示。准直后的 1310 nm 和 976 nm 两束激光通过两片分光镜改变两种波长激光的传播方向，其中分光镜 1(S_1)的 *A* 面和 *B* 面以及分光镜 2(S_2)的 *D* 面均镀有 976 nm/1310 nm 增透膜，透过率≥99.5%，分光镜 2 的 *C* 面镀有 976 nm 增透/1310 nm 半反半透膜，通过分光镜 1 对部分 976 nm 光实现 45°反射，通过 976 nm PD 进行探测反馈；同理，分光镜 2 对 1310 nm 光进行 45°反射，理论上约有 50%的探测光被 1310 nm PD 接收，额外的光束通过聚焦镜耦合进入光纤。

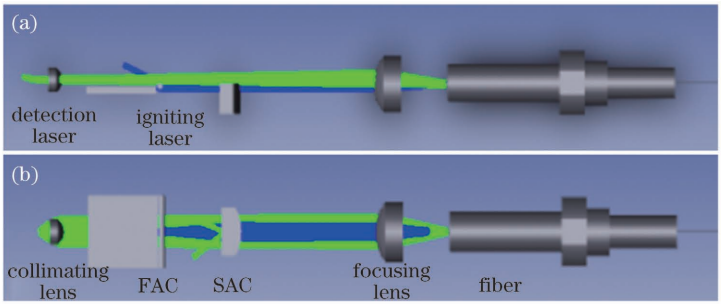

图 1 沿不同方向的光路结构仿真结果。(a)快轴方向;(b)慢轴方向

Fig. 1 Simulation results of optical path structure along different directions. (a) Fast axis direction; (b) slow axis direction

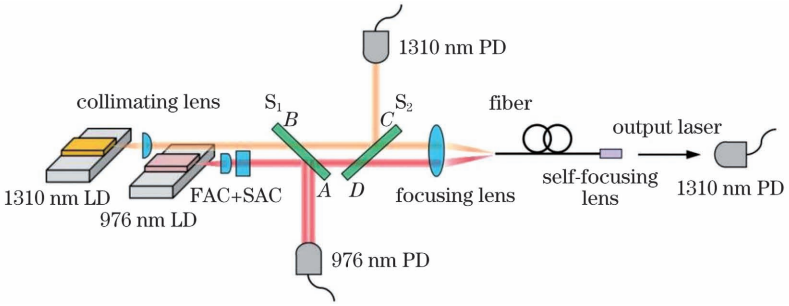

图 2 光路结构示意图

Fig. 2 Schematic of light path structure

由于出纤激光的发散角过大会影响点火可靠性,在点火光纤与药剂之间加入自聚焦透镜,如图 3 所示。通过自聚焦透镜减小出纤光斑发散角[23],从而增大入射到药剂上的光功率密度,提高点火效率。此外,减小发散角后的检测光更有利于通过 PD 进行探测,从而减小检测光的接收随机性,使得检测结果更为准确。通过 Zemax 软件分别对光纤输出后自由运转的激光以及通过自聚焦透镜整形后的激光进行仿真,模拟得到两种情况下激光的发散角,如图 4 所示。与自由输出的激光束相比,通过自聚焦镜后激光发散角约缩小为原来的一半,模拟结果也证明了自聚焦透镜对出纤激光发散角的优化作用。

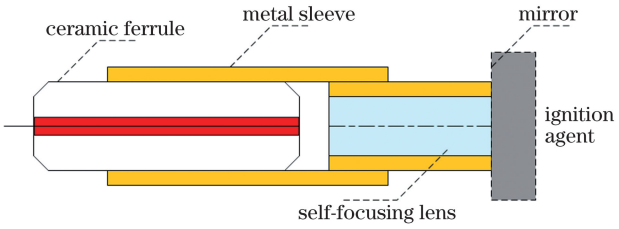

图 3 基于自聚焦透镜结构的激光点火光窗口

Fig. 3 Laser ignition window based on grin lens

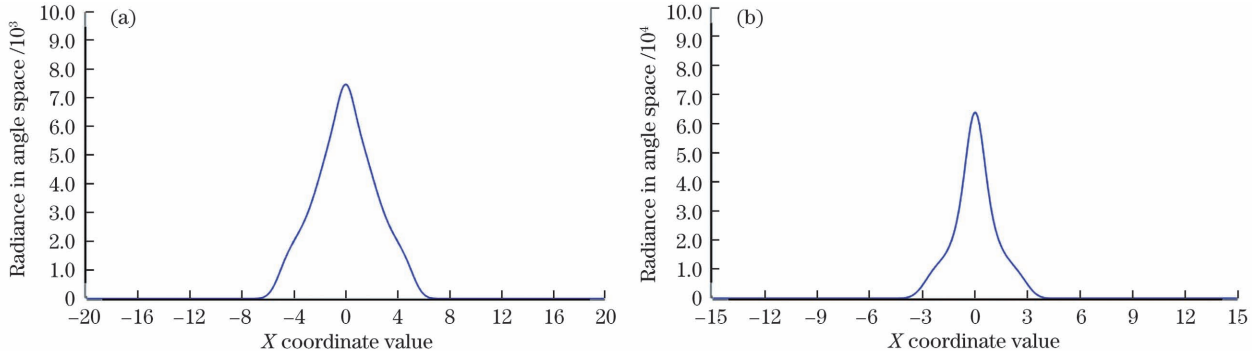

图 4 不同输出条件下的光纤光斑发散角。(a)自由输出;(b)经自聚焦透镜整形后输出

Fig. 4 Divergence angles of optical fiber spot under different output conditions. (a) Free running; (b) by self-focusing lens collimating

所采用的 976 nm 芯片的初始功率为 12 W,1310 nm 芯片的初始功率为 3.5 mW,考虑到镀膜损耗、光场分布、光纤耦合损耗,得到的模拟结果如图 5 所示。理论上 976 nm 波长的点火激光通过光纤后,耦合效率可以达到 99%以上,较高的耦合效率有利于保障点火工作效率以及系统的安全可靠

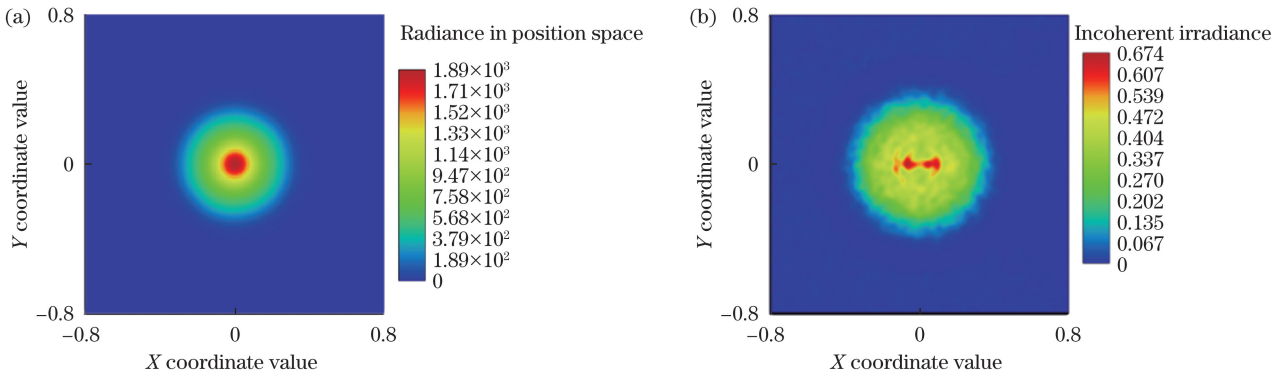

图 5　光束整形及光纤耦合后的激光功率。(a) 976 nm 激光;(b) 1310 nm 激光

Fig. 5　Laser power after beam shaping and fibre coupling. (a) 976 nm laser; (b) 1310 nm laser

性,1310 nm 波长的检测激光输出功率大于 1 mW 即可满足应用需求。

3　分析与讨论

所设计的半导体激光点火光源实物见图 6,976 nm 点火激光的驱动电流在 0～12 A 范围内调节,记录电流(I)、电压(V)、功率(P),绘制成 P-I-V 曲线,如图 7 所示。当电流为 12 A 时,工作电压为 2 V,976 nm 点火激光的自由输出功率为 12.05 W,通过光束整形以及光纤耦合后,出纤功率为 10.92 W,整形以及耦合效率达到90.62%。需要指出的是,实际耦合效率和理论模拟效率相比有一定的差距,主要是因为实际合束效率、镜片镀膜透过率、光纤耦合效率以及光纤传输损耗等参数低于理论模拟值。

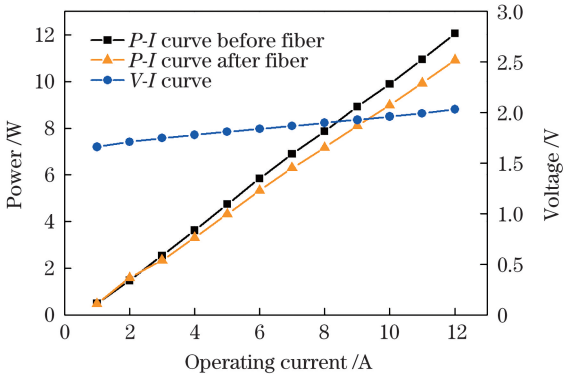

图 7　976 nm 激光 P-I-V 曲线图

Fig. 7　P-I -V curves of 976 nm laser

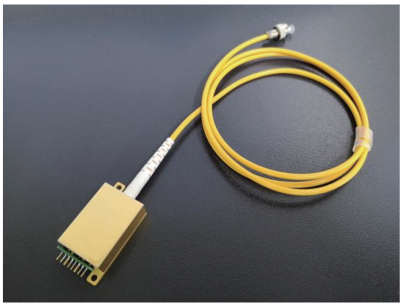

图 6　激光点火光源实物图

Fig. 6　Photograph of laser ignition light source

从光纤出射的激光通过自聚焦透镜整形前、后在距离出光面 80 mm 处的实测光斑如图 8 所示,可以明显看到,经过自聚焦镜整形后光斑发散角变小,传输到相同距离处的光斑尺寸更小,因此在相同功率下光功率密度显著提高。

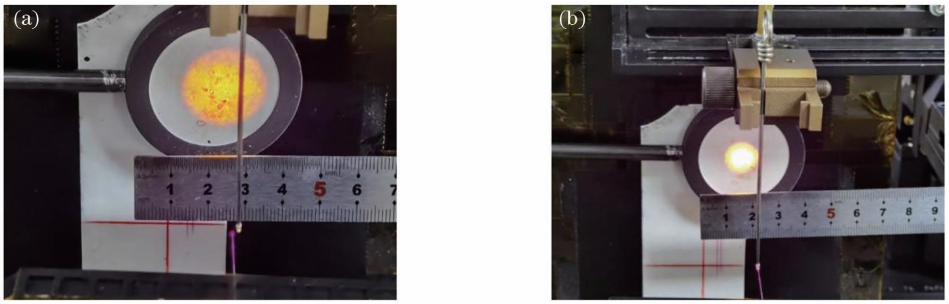

图 8　通过自聚焦透镜整形前、后的光斑。(a)整形前光斑;(b)整形后光斑

Fig. 8　Light spots before and after shaping via self-focusing lens. (a) Before shaping; (b) after shaping

通过实验测量在不同驱动电流条件下 1310 nm 检测光的功率以及 PD 响应度,测试的 P-I-V 曲线如图 9(a)所示。当驱动电流为 15 mA 时,光纤耦合后测量得到的输出功率为 1.08 mW,电压保持在 1 V,满足出纤功率高于 1 mW 的应用需求。此外,实验测量了 1310 nm检测光耦合前通过分光镜反

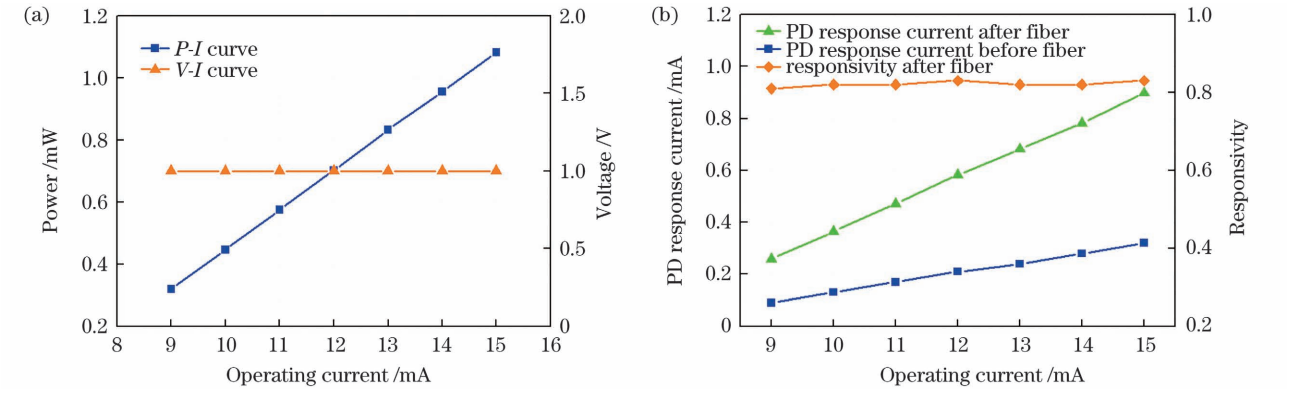

图 9 实验所获得的曲线。(a) 1310 nm 激光 *P-I-V* 曲线图;(b)检测光响应电流和响应度

Fig. 9 Curves obtained in this experiment. (a) *P-I -V* curves of 1310 nm laser; (b) response current and responsivity of detection light

射后的 PD 响应光电流,如图 9(b)所示。通过该合束结构,PD 对 1310 nm 激光的响应电流呈线性增长且一致性较好。实验还测量了 1310 nm 检测光的 PD 响应光电流,得到的响应度约为 0.82 且一致性较好。结合耦合前 PD 响应结果,可以判定 1310 nm 检测光的自身光功率以及点火系统光纤通路是否存在问题。

此外,利用 PD 反馈经分光镜反射的 976 nm 激光,通过分析 PD 响应光电流和激光注入电流的对应关系,可以判断将点火激光放入系统后的激光功率。如图 10 所示,随着驱动电流的增大,PD 对 976 nm 点火激光的响应电流呈线性增长。对于 976 nm 点火激光的检测,原则上要保证反射进入 PD 的反馈光功率尽可能小,避免光功率过高导致 PD 对该激光探测出现饱和的情况,导致响应度下降。

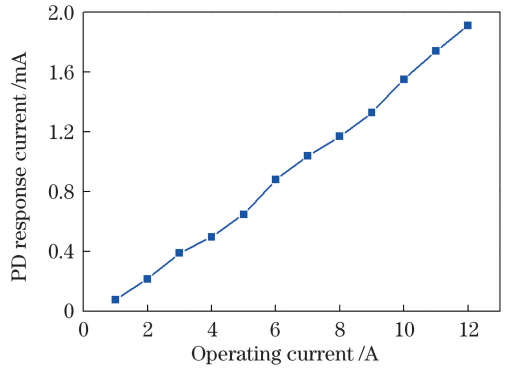

图 10 976 nm 激光的检测光响应电流

Fig. 10 Response current of detection light for 976 nm laser

4 结 论

结合空间合束、波长合束以及光束整形技术,设计出一种可实现单光纤双波长输出、具备自检功能的光学结构,获得了出纤功率大于 10 W 的 976 nm 点火激光以及大于 1 mW 的 1310 nm 检测激光,该结构可同步实现 976 nm 点火激光和 1310 nm 检测激光的功率自检以及光路自检。使用自聚焦透镜对出纤激光进行整形,减小了输出激光的发散角并获得了更高功率密度的激光输出,有效降低了出纤后检测光发散角过大导致 PD 探测光束的随机性较大的问题,有利于实现检测系统反馈光的定量检测,提高光路连续性检测的有效性。

参 考 文 献

[1] Bruggeman D, Huttl C. State of development of laser ignition[J]. MTZ Worldwide, 2009, 70(3): 28-30.

[2] Brieschenk S, Kleine H, O'Byrne S. Laser ignition of hypersonic air-hydrogen flow[J]. Shock Waves, 2013, 23(5): 439-452.

[3] Pletnev N V, Ponomarev N B, Motalin G A, et al. Development and testing of the laser system of ignition of rocket engines[J]. Combustion, Explosion, and Shock Waves, 2020, 56(2): 181-187.

[4] Andronov A A, Gurin V A, Marugin A V, et al. Laser ignition in internal-combustion engines: sparkless initiation[J]. Technical Physics Letters, 2014, 40(8): 662-664.

[5] Han J L, Zhang J, Shan X N, et al. High power heating light source based on semiconductor laser beam combintion technology[J]. Acta Optica Sinica, 2021, 41(22): 2214001.
韩金楑, 张俊, 单肖楠, 等. 基于半导体激光合束技术的高功率加热光源[J]. 光学学报, 2021, 41(22): 2214001.

[6] Wang Y Y, Ma Y P, Cheng W M, et al. Key technology and development of laser multi-initiation system[J]. Initiators & Pyrotechnics, 2010(1): 53-56.
王悦勇, 麻永平, 程伟民, 等. 激光点火多路起爆关

键技术及发展[J]. 火工品, 2010(1): 53-56.

[7] Hu Y, Shen R Q, Ye Y H. Development of laser ignition[J]. Energetic Materials, 2000, 8(3): 141-144.
胡艳, 沈瑞琪, 叶迎华. 激光点火技术的发展[J]. 含能材料, 2000, 8(3): 141-144.

[8] Dang R R, Li J L. A laser firing and initiating system [J]. Journal of Detection & Control, 1999, 21(3): 3-6,18.
党瑞荣, 李甲连. 激光点火与起爆系统[J]. 探测与控制学报, 1999, 21(3): 3-6,18.

[9] Craig J B, Norman R S. Flight demonstration of MSER diode initiated ordnance [C]// 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 10-12, 1995, San Diego, CA. Reston: AIAA, 1995.

[10] Fahey W D, Carvalho J E. Optical built-in-test (BIT) for laser initiation systems[C]//38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana. Reston: AIAA, 2002.

[11] Benner D E, Haas J, Massey R J, et al. Development of a lasers ignited actuator[C]// 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 20-23, 2003, Huntsville, Alabama. Reston: AIAA, 2003.

[12] Cao J S, Wang L J, Shan X N, et al. Design of laser ignitio system[J]. Applied Laser, 2010, 30(2): 83-85.
曹军胜, 王立军, 单肖楠, 等. 激光二极管点火系统的设计[J]. 应用激光, 2010, 30(2): 83-85.

[13] Zhang L, Ling Z, Xiang Z Y. Design of laser initiation control system based on dual-fiber detection technology [J]. Aerospace Control, 2013, 31(4): 84-87.
张磊, 凌震, 项宗友. 基于双光纤检测技术的激光点火控制系统设计[J]. 航天控制, 2013, 31(4): 84-87.

[14] Wang D, Gao Y L, Li S, et al. Research on the design of a semiconductor laser ignition system[J]. Initiators & Pyrotechnics, 2020(2): 5-8.
王端, 高一隆, 李帅, 等. 某半导体激光点火系统设计研究[J]. 火工品, 2020(2): 5-8.

[15] Ning Y Q, Chen Y Y, Zhang J, et al. Brief review of development and techniques for high power semiconductor lasers[J]. Acta Optica Sinica, 2021, 41(1): 0114001.
宁永强, 陈泳屹, 张俊, 等. 大功率半导体激光器发展及相关技术概述[J]. 光学学报, 2021, 41(1): 0114001.

[16] Zhang J, Peng H Y, Fu X H, et al. High-brightness 800-nm semiconductor laser source based on spectral beam combining [J]. Chinese Journal of Lasers, 2020, 47(7): 0701021.
张俊, 彭航宇, 付喜宏, 等. 基于光谱合束的 800 nm 高亮度半导体激光源[J]. 中国激光, 2020, 47(7): 0701021.

[17] Cao J S. Experimental study on the initiation of semiconductor laser [J]. Laser Journal, 2014, 35(10): 29-32.
曹军胜. 半导体激光起爆试验研究[J]. 激光杂志, 2014, 35(10): 29-32.

[18] Price K, Karlsen S, Leisher P, et al. High-brightness fiber-coupled pump laser development[J]. Proceedings of SPIE, 2010, 7583: 758308.

[19] Liu R, Jiang X C, Yang T, et al. High-brightness 9×× nm fiber coupled diode lasers[J]. Proceedings of SPIE, 2015, 9348: 93480V.

[20] Pierer J, Lützelschwab M, Grossmann S, et al. Automated assembly processes of high power single emitter diode lasers for 100 W in 105 μm / *NA* 0.15 fiber module[J]. Proceedings of SPIE, 2011, 7918: 79180I.

[21] Kanskar M, Bai C, Bao L, et al. High brightness diodes and 600 W 62% efficient low SWaP fiber-coupled package [J]. Proceedings of SPIE, 2020, 11262: 112620A.

[22] Heinemann S, Fritsche H, Kruschke B, et al. Compact high brightness diode laser emitting 500 W from a 100 μm fiber[J]. Proceedings of SPIE, 2013, 8605: 86050Q.

[23] Zhang B Y, Wang G J, He J L, et al. Passively mode locking of Nd∶YVO_4 laser with grin lens as optical coupler[J]. Acta Optica Sinica, 2011, 31(7): 0714001.
张丙元, 王国菊, 何京良, 等. 自聚焦透镜耦合激光二极管抽运 Nd∶YVO_4 锁模激光器的研究[J]. 光学学报, 2011, 31(7): 0714001.

High-Efficiency Ignition Laser Source Based on Diode Laser Beam Combination Technology

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Abstract

Objective Recently, with the rapid development of diode lasers, it has been widely used in industrial processing, aerospace, military, and other fields, especially in ignition and detonation fields because of its unique advantages, such as small size, high efficiency, wide wavelength range, and high reliability. The traditional electric ignition technology generates heat to detonate the gunpowder through the thermal resistance wire. However, this method has potential risks, such as electrostatic discharge and electromagnetic radiation. Additionally, it is difficult to apply to the complex environmental changes of the modern battlefield. Laser ignition technology has been proved to be a proper solution to the above problems. This technology transforms the energy generated by the laser into heat energy to detonate the gunpowder. It has better antistatic interference and antielectromagnetic interference ability to ensure the reliability and safety of the explosive device than traditional technologies. Although laser ignition technology has great application advantages, it has strict requirements for power and power density of laser beams. Additionally, the ignition light source needs to adopt a series of optical components, such as a collimating lens, focusing lens, and optical fiber. Once the microlens deforms or the optical fiber bends, it will influence the laser power; thereby, damaging the equipment. Therefore, the laser ignition system must be equipped with the optical path self-inspection function, and the operation of self-inspection must be performed before working to ensure the system's reliability and stability.

Methods This paper proposes a high-efficiency laser ignition source. First, we design an optical structure of single fiber and dual-wavelength output. A high-power 976 nm ignition and low-power of 1310 nm detection lasers are simultaneously coupled into a 105 μm/*NA* 0.22 optical fiber using space and wavelength combining techniques. Simulation results of the ZEMAX optical design software verify the feasibility of the solution. Second, the laser beam divergence angle and beam size are reduced effectively using a self-focusing lens. The laser power density and ignition efficiency improve significantly under the same distance condition. Additionally, the reduction of the laser divergence angle effectively avoids the problem that the reflectivity of the laser is random when it is irradiated to the window mirror of the gunpowder. Thus, the quantitative criterion of the continuity detection of the optical path is more accurate. Finally, aiming at the critical detection function of the ignition laser system, the optical path self-inspection and synchronous output power self-inspection of high-power ignition laser can be achieved using spectroscope coating film and optical path structure. This can meet the application requirements of high efficiency and reliability of ignition laser source in this field.

Results and Discussions The photo of the diode laser ignition light source is shown in Fig. 5. When the operating current is set to 12 A, and the operating voltage is 2 V, the free-running output power of the 976 nm ignition laser is 12.05 W. After the beam shaping and fiber coupling, the output power from the fiber is 10.92 W, and the fiber coupling efficiency reaches 90.62%. A laser beam is measured at a distance of 80 mm from the luminous surface before and after self-focusing lens shaping (Fig. 7). After self-focusing lens shaping, the divergence angle of the laser becomes smaller, and the beam size of the laser transmitted at the same distance also becomes smaller. Consequently, the optical power density increases significantly at the same power. We measure the power of 1310 nm detection light and PD responsiveness under different operating current conditions. When the operating current is set to 15 mA, the output power measured after fiber coupling is 1.08 mW, and the voltage is maintained at 1 V, which meets the application requirements of output power from fiber higher than 1 mW. The response photocurrent of PD through the spectroscope is shown in Fig. 9(b). The response current of PD to 1310 nm laser increases linearly with good consistency through this beam combination structure. We also measure the photocurrent

response of 1310 nm laser after fiber coupling. According to the curve, the responsivity is about 0.82, and it has a good consistency. Combining with the PD response results before coupling, we can judge whether there is a problem with the optical power of detecting laser and the optical path of the ignition system. The 976 nm laser reflected by the spectroscope is fed back by PD, and the operating ignition laser power is put into the system. This can be determined from the corresponding relationship between the photocurrent of PD response and the laser injection current. The response current of PD to the 976 nm ignition laser increases linearly (Fig. 10).

Conclusions An optical structure with a single fiber dual-wavelength output and self-inspection function is designed using spatial combining, wavelength beaming, and beam shaping techniques. We obtain a 976 nm ignition laser with an output power greater than 10 W and a 1310 nm detection laser with an output power greater than 1 mW. The structure can simultaneously realize the power and optical path self-inspection of 976 nm ignition and 1310 nm detection laser. The divergence angle and beam size of the laser are effectively reduced using a self-focusing lens. This can improve laser power density and solve the randomness problem of the PD detector. It is crucial to realize the quantitative detection of optical detection system feedback and improve the effectiveness of the optical path continuity testing.

Key words lasers; diode lasers; laser ignition; spatial combining; wavelength combining; optical path self-inspection