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论 文

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光纤激光器中包层功率剥离器的热效应

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摘要 为了将光纤激光器输出光纤包层中未完全被增益光纤吸收的残余泵浦光及非线性因素产生的高阶激光高效率剥离，提高剥离功率和得到较为均匀的热分布，采用优化的高折胶法制作包层功率剥离器，通过实验和有限元仿真模拟对包层功率剥离器的热效应进行了研究．实验表明包层功率剥离器剥离功率为132 W时，稳定工作温度最高为50.0℃，在此剥离条件下仿真模拟的结果与实验基本吻合，证明了仿真模型及参数的正确性，并证明了该种结构包层功率剥离器的实用可靠性．

关键词 光纤激光器，包层功率剥离器，高折胶法，热效应

与其他激光器相比，光纤激光器具有光束质量好、转换效率高、使用成本低、可靠性高和体积小等优势．已经被广泛应用于工业加工、光学传感、医疗器械和军事装备等领域[1~4]．随着双包层光纤技术和半导体激光器泵浦技术的不断发展，光纤激光器能够输出的功率迅速提高．由于全光纤激光器的特殊结构，其输出的激光中必然会含有无用的残余泵浦光及高阶激光．随着光纤激光器输出的功率不断提升，残余泵浦光和高阶激光的功率也随之提升，它们的存在不但恶化了激光的光束质量，更对整个激光器系统的可靠性产生了极大的威胁，所以必须使用包层功率剥离器将无用的包层光剥离出去[5~7]．

自光纤激光器诞生以来，研究者们对于包层功率剥离器(CPS)的探索从未停止．如今包层功率剥离器制作方法主要有3种：高折射率胶法、氢氟酸腐蚀法以及高折射率基质法．Wetter等人[8]首先使用高折射率胶替代原光纤外包层涂覆在内包层上的方法剥离包层功率，发现包层功率在光纤前端几个毫米范围内大量剥离，从而导致光纤局部温度陡升．为了改善剥离器热集中效应，Wang等人[9]采用三段不同折射率胶由低至高依次涂覆于光纤内包层上将包层功率逐段剥离，Guo等人[10]采用级联式功率剥离器将内包层功率分级剥离．此外，Poozesh等人[11]在2012年提出了氢氟酸腐蚀法制作包层功率剥离器．Klrner和Tucker在[12]2011年发表的专利中详细描述了高折射率基质法制作包层功率剥离器的原理．虽然氢氟酸腐蚀法与高折射率基质法逐渐被研究者们所关注，但是由于这两种方法的制作工艺较为复杂，对制作的设备环境要求较高，目前还无法用于规模化生产．所以，高折胶法仍是制作包层功率剥离器的主流方法．

虽然研究者们对高折胶法进行了优化与改良，但其发热集中的问题仍无法很好的解决，或是需要微通道水冷及其他特殊结构予以辅助冷却，影响其实用性．所以，本文采用一种实用简单的方式优化了高折胶法，并制造出包层功率剥离器样品，通过实验及仿真模拟对其工作时的热效应进行了研究，证明了其实用可靠性．

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1 实验测量

1.1 包层功率剥离器原理及结构

双包层光纤中光的传输依靠光在折射率不同的两界面上发生全反射实现[13]，全反射条件由以下公式可得

$$\Psi > \Psi_0 = \arcsin(n_2/n_1), \tag{1}$$

其中Ψ为入射角，n_1和n_2分别为入射介质和折射介质的折射率.

包层折射率的大小排列为纤芯>内包层>外包层. 故增益光纤产生的受激辐射激光在纤芯中传播；泵浦光及高阶激光则在内包层和纤芯中传播. 所以可以通过破坏泵浦光及高阶激光在内包层中的全反射效应制成包层功率剥离器，包层光从内包层泄露到高折胶中，随之在高折胶与热沉金属的界面处转化为热能并通过热传导导出剥离器.

所测样品制作方式为：将一段双包层光纤的外包层用机械旋转剥离法剥离，即分为4段，每段各20 mm，每段剥离面积占该段包层总面积30%，并且每段之间旋转90°，在其外部涂抹折射率为1.68的高折胶，将这段光纤放入热沉中，最后将热沉固定在激光器的水冷板上.

具体结构如图1所示，包层功率剥除器的尺寸为：长120 mm，宽20 mm，涂胶孔直径为10 mm，外包层剥离长度为80 mm. 定位螺孔直径为3 mm，热沉材料为铝材.

1.2 实验测量

采用单只160 W开普林半导体激光模块作为泵源. 将其尾纤与7×1合束器的其中一根输入光纤熔接，再将合束器的输出光纤用切刀切出一个水平端面，以提高输出激光光束质量. 测得泵源在不同电流下产生泵浦光的功率$P1$，之后将包层功率剥除器输入光纤与合束器输出光纤熔接，同样用切刀在包层功率剥除器的输出纤上切一个水平端面，再在相同环境条件下测得输出光功率$P2$，水冷板水温设定为26℃. 通过改变输入泵源的电流大小改变其输出功率，在不同电流下稳定工作5 min后记录此时功率计的示数以及红外热像仪中CPS的温度T. 实验装置实物图如图2所示.

图3为实验中，在各电流下包层功率剥离器稳定工作5 min时的红外热像仪图. 可以看出，随着电源功率增大，泵浦源输出光功率随之增大，包层功率剥离器剥离的包层功率逐渐增大，导致其温度逐渐升高，并且，各图中均无明显热点，热分布较为均匀，说明包层功率的剥离沿剥除器方向有序进行.

将测得各电流下泵浦功率与经包层功率剥离器后功率进行对比得到图4，经计算可得平均剥除效率为88%，并且剥除功率随泵浦功率呈近似线性关系.

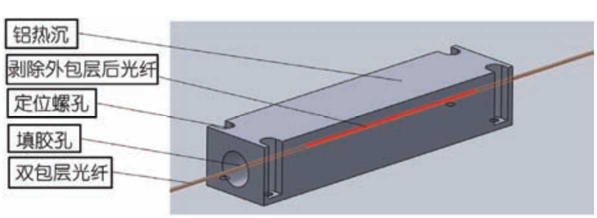

图 1 (网络版彩色)包层功率剥除器示意图
Figure 1 (Color online) Schematic diagram of CPS

2 有限元仿真模拟

2.1 仿真原理

使用comsol软件中的固体传热模块进行模拟，对包层光功率剥除器工作时的热效应研究主要是对其胶-热沉界面光热转换以及不同固体间和相同固体中热传导的研究. 其中固体间及固体内部热传导满足泊松方程[14]

$$\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}+\frac{\partial^2 T}{\partial Z^2}+\frac{q}{\lambda}=0, \tag{2}$$

式中(X,Y,Z)为固体中一点的坐标，T为该点温度，q为该点热源密度，λ为该点所属材料的导热系数，式中热源密度q满足下式：

$$q=\frac{P}{\pi r^2 x}, \tag{3}$$

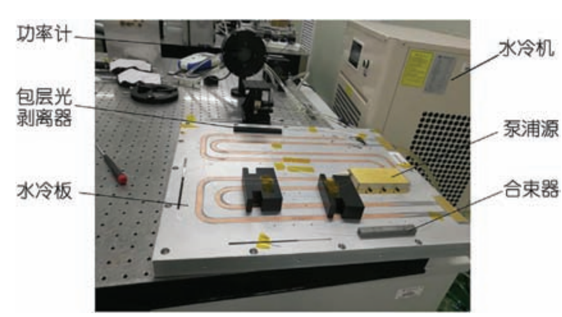

图 2 (网络版彩色)实验装置图
Figure 2 (Color online) Set-up diagram of experiment

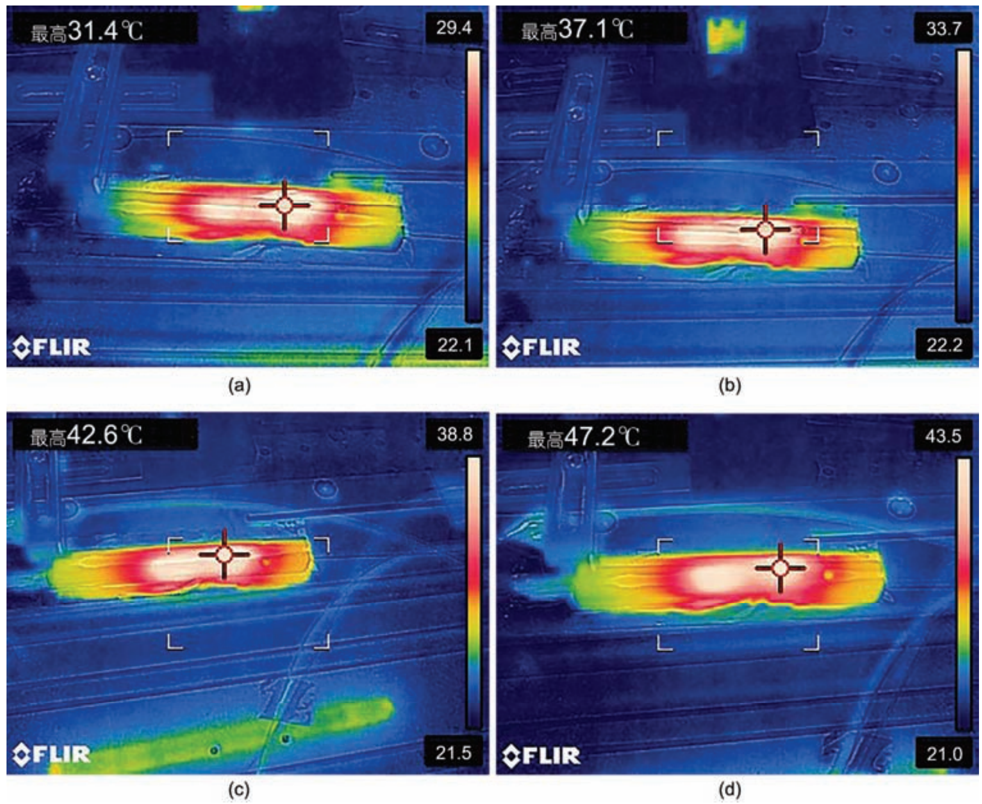

图 3 (网络版彩色)在各电流下CPS的温度分布. (a)~(d)为 3, 5, 7 和 9 A下的CPS温度

Figure 3 (Color online) Temperature distribution of CPS at each current. (a)–(d) The temperatures of CPS at 3, 5, 7 and 9 A

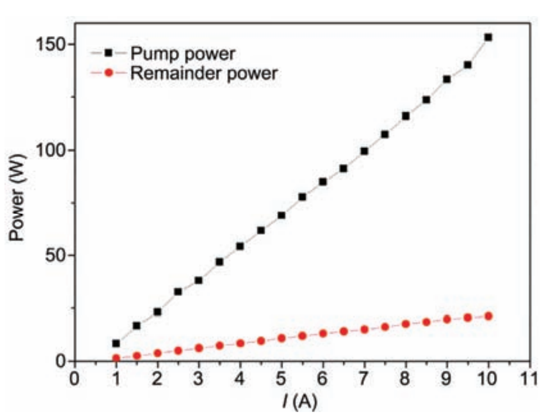

图 4 (网络版彩色)各电流下泵浦功率与剥离后功率关系

Figure 4 (Color online) Relationship between pump power and after stripping power at each current

其中P为剥离器剥离功率, r为剥离器的填胶孔半径, x为剥离器的长度.

2.2 边界条件设定

环境温度及水冷板初始温度均为26℃, 被包层功率剥离器剥离的包层功率在胶与热沉金属界面转化为热功率, 由于高折胶固化后的光透过率很高[15], 界面光热转换功率近似为包层光剥离功率. 使用状态下, 包层功率剥离器封装在光纤激光器中, 故不考虑其热沉表面对流散热. 热沉与水冷板接触表面由黏性石墨垫片连结, 可近似完全排除接触面的空气. 剥离器中所用材料的热物理参数如表1所示.

3 模拟结果与实验对比

按所设计模型进行模拟, 得到剥除功率为132 W时的温度分布垂直截面图, 此时的剥除功率与实验

表 1 所用材料的热物理参数

Table 1 Thermal physical parameters of used materials

材料	比热容 (J kg^{-1} K^{-1})	导热系数 (W m^{-1} K^{-1})	导温系数 (W m^2 J^{-1})
铝	877	238	9.45×10^{-5}
光纤(SiO_2)	966	27	1.20×10^{-7}
高折胶(丙烯酸环氧树脂)	1700	50	1.47×10^{-7}
石墨片	710	1500	–

所得最高剥除功率相同，对比图如图5所示. 此时模拟模型中最高点温度为48.9℃，实验中最高温度为50.0℃，并且仿真模拟中包层功率剥离器的温度分布均匀，符合实验结果，由仿真垂直截面图可以看出，剥离器中的热主要集中在剥离器的上端，其高温区域为涂胶区与热沉接触界面，故在实际实验中所测得表面最高温度需要增加1~2℃才能得到剥离器最高温区域的实际温度. 除此之外，可以看出剥离器纵向温度分布比较均匀，该结构不会产生局部热集中效应.

图6是实验与仿真中剥离功率与最高温度关系对比图，由图可知，实验与仿真中剥离器表面最高温度随剥离功率增大满足近似线性增长的关系，并且，剥离功率平均每提高7 W，剥离器的温度上升1.3℃，两条折线基本吻合，在试验段最大温差为4.1℃，说明仿真与实际情况较为接近. 故此仿真模型能够较好地还原实验过程中剥离器工作状态下的热分布情况，对该结构包层功率剥离器的高功率模拟具有一定的参考价值.

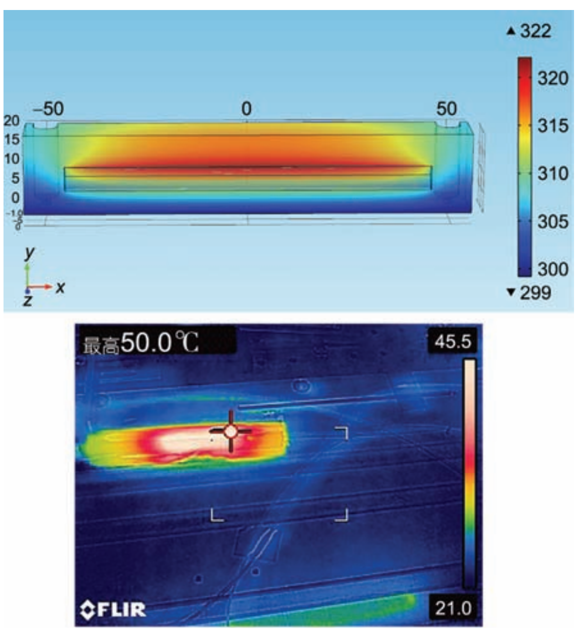

图 5 (网络版彩色)剥离功率为 132 W包层功率剥离器温度分布. (a) 模拟截面图; (b) 实验热像图

Figure 5 (Color online) Temperature distribution of CPS under 132 W stripping power. (a) Simulation section; (b) experiment thermography

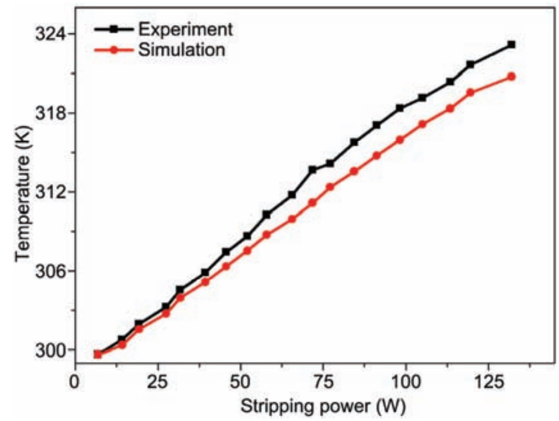

图 6 (网络版彩色)不同剥除功率下包层剥离器的实验与仿真温度

Figure 6 (Color online) Experiment and simulation temperature of CPS under different stripping power

4 结论

利用优化后的高折胶法制作了包层功率剥离器，并按此结构进行了有限元仿真模拟. 通过实验证明了该结构剥离器在剥离功率为132 W及以下时能够稳定工作，最高工作温度为50.0℃，并且通过对照有限元模拟的温度变化及截面温度分布，证明了仿真模型结构及参数的准确性，该热效应分布完全满足高折胶包层功率剥离器的可靠工作条件. 此方法为千瓦级光纤激光器包层功率剥除提供了易于大规模生产的解决方案，并为高折胶法包层功率剥离器的优化提供了一些参考.

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Summary for “光纤激光器中包层功率剥离器的热效应”

The thermal effect of cladding power stripper for high power fiber lasers

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Lasers have been widely used in many fields such as machinery, medicine, and military. With the development of fiber lasers, high power lasers become more and more desirable. Although lasers with power level of kilowatt or even million watt have been fabricated, there could be many problems associated with the increased power. The most important problem needed to be solved is how to strip unnecessary pump light before laser emit out from the devices. With the progresses in the past years, people have developed some methods to overcome this problem. However, these methods also have some disadvantages, such as too small stripping area to achieve high power light emission, and unsuitability of the technology for mass production.

Glue method is the earliest proposed way for stripping the unnecessary light. Its biggest advantage is the simple process. But it also has a big disadvantage that glue cannot endure underhigh temperature in the range of 60°C to 70°C. To solve this problem, people have made attempts for years by either forced cooling or rasing the bearing temperature of glue, however, there is still no good solution. In fiber lasers, the superfluous pump light is dense, which has contributions from the pump light that is not fully absorbed by gain fiber and from high order laser due to misalignment elements. To efficiently strip the inner cladding light, and to get higher stripping power and more uniform heat distribution, we have used an optimized high index glue to fabricate the cladding power stripper. The basic idea is to improve the heat distribution in cladding power stripper by handle the structure of double clad fiber. The specific method is to rotate the cutting area at outsourcing, so the pump light can emit out uniformly, and the glue will have a low working temperature. Experiments and FE simulation are conducted to study the thermal effect of cladding power stripper. The results show that the highest stable operating temperature is 50.0°C when the cladding power is 132 W, and the temperature of cladding power stripper increases linearly with the increase of the stripping power. There is no overheating point in the stripper in the test indicating that the proposed method is applicable for kilowatt level fiber lasers. The experimental results are consistent with FE simulations, which verifies the correctness of simulation model and parameters. As the working temperature is much lower than 60°C, the results demonstrate that such stripper structure is reliable and its properties can be well described by simulations. Such a cladding power stripper only changes the structure of the double clad fiber to optimization the heat distribution, and the result shows this method are useful. The cooling effect of heat source was not perfect, which is the reason why the stripper temperature is 50.0°C when stripping power are only 132 W. So there is an opportunity to change the structure of heat source or use water-cooling or air-cooling to auxiliary heat dissipation for heat source. If both the structures of double clad fiber and heat source are optomized, this cladding power stripper can be used for million watts level lasers without problem. In addition, the simple structure of glue method cladding power stripper, enables its mass production, therefore, this stripper has a great application potential.

fiber lasers, cladding power stripper, glue method, thermal effect

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