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高平均功率光纤激光技术基础:模式*

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摘 要: 从具有不同模式特性的光纤激光研究现状出发,指出模式是光纤激光特性的核心参数之一。通过算例给出模式与光束质量之间的关系,引出模式分解技术是准确知晓模式组分和光束质量的关键,介绍常见的模式分解技术。针对模式不稳定效应这一限制光纤激光功率提升的新现象,归纳总结了不同因素对模式不稳定效应产生阈值的影响,梳理了提高阈值的物理原理和实现方法。从高阶模抑制、特定高阶模式和结构光场输出等三个方面介绍了光纤激光模式控制的最新进展。

关键词: 光纤激光; 单模; 多模; 模式分解; 模式不稳定; 模式控制

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2009 年之前光纤激光的输出功率就突破了 50 kW[1],2013 年突破了 100 kW [2],笔者在 2016 年底访问 IPG Photonics 公司主页时发现已有 500 kW 输出功率的报道(目前仍能查询)[3]。实际上,上述激光器都是多模激光器,都是采用多个单模光纤激光器一级或两级功率合成实现的,最终将多束单模激光耦合进一根多模光纤输出。单模激光与多模激光的区别可以用光束质量因子加以表征,表 1 所示为公开报道的单模和多模光纤激光器的特性参数。

表 1 公开报道的具有代表性的单模和多模光纤激光器的特性参数

Table 1 Characteristic parameters of representative single-mode and multi-mode fiber lasers

	output power/kW	M^2	beam parameter product(BPP)	references	备注
single-mode laser	9.6	~1.2		[4]	for the diffraction limited beam in 1 μm wavelength band, M^2 = 1, BPP=0.33 mm·mrad[6]
single-mode laser	10	<1.5		[5]	
multi-mode laser	20	15	15 mm·mrad	[6]	
multi-mode laser	50	30	10 mm·mrad	[6]	
multi-mode laser	100		16 mm·mrad	[7]	

可以看出,虽然多模光纤激光器的输出功率已经超过单模光纤激光器 1 个量级,但光束质量较差,对相同的光学系统而言,聚焦光斑尺寸较大,作用到目标上的功率密度较低。因此,模式是影响光纤激光输出特性的核心指标之一。本文旨在介绍高光束质量光纤激光的输出模式方面的研究动态。后文阅读需要读者掌握光纤本征模和光束质量因子的相关知识[8-10],比如 LP 模式、归一化频率 V 值等。另外,模式有纵模和横模之分,本文特指横模。

1 模式与光束质量

文献[11-12]研究了不同 LP 模式的 M^2 因子,图 1 所示为文献[11]中给出的 V 值在 1~12 之间时不同本征模式的 M^2 因子。LP_{01} 模的 M^2 因子在 $V<1.5$ 时较大,且随着 V 的减小迅速增加。这是因为在该范围内,波导结构没有形成足够的束缚作用,导致 LP_{01} 模大部分光场分布在包层中,从而偏离了高斯分布;高阶模在 V 值处于截止状态时也存在类似的情况[12]。当 $V>1.5$ 时,LP_{01} 模的 M^2 因子接近于 1。随着 V 值的增加,光纤中能够支持的高阶模的数量逐渐增加,并且高阶模的阶数越高,M^2 因子越大。因此,若以 M^2 因子的大小判定

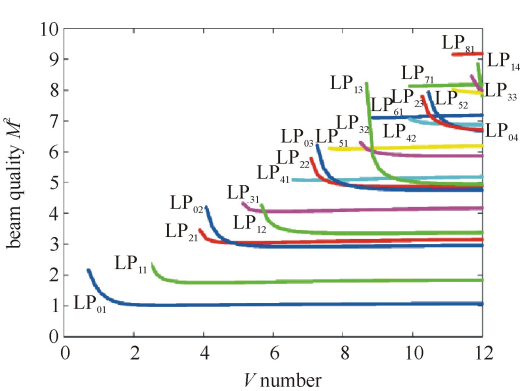

Fig. 1 The M^2 factor of different eigenmode in case of different V number[11]

图 1 不同 V 值下不同本征模式的 M^2 因子[11]

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光束质量的好坏，一般认为模式与光束质量之间存在直观的对应关系：即单模激光光束质量好、多模激光光束质量差，低阶模式越多（高阶模式越少）光束质量越好。

然而，M^2 因子本质是高斯光束的偏离程度的表现[13-15]，对于非高斯光束而言，运用 M^2 因子描述光束质量不一定是最佳选择，近年来科研人员也提出了其他方法来描述光纤激光的光束质量[16-17]。需要特别注意的是，当光纤输出光束为基模和高阶模相干叠加时，M^2 因子越小并不意味着 LP_{01} 模的模式比例越高。2007 年，Wielandy 等计算结果表明[18]，即使 $M^2<1.1$，也不意味着高阶模式少，实际上高阶模的成分可能高达 30%。文献[11]计算了 LP_{11e} 模与 LP_{01} 模的相位差 ψ 在 $0\sim\pi$ 之间，不同的 LP_{11e} 模比例 α 下 LP_{01} 与 LP_{11e} 相干叠加形成的光束的 M^2 因子，如图 2 所示。当 α 固定时，M^2 因子随 ψ 的变化而变化，ψ 为 0.5π 时 M^2 因子最大，而当 ψ 为 0 或 π 时 M^2 因子最小。当 ψ 为 $\pi/6\sim5\pi/6$ 之间以及 ψ 为 0 或 π 且 $\alpha>0.3$ 时，M^2 因子随着 α 的增加逐渐增加。当 ψ 为 0 和 π 时，α 由 0 增加至 0.3 对应的 M^2 因子几乎没有变化，甚至略有下降。以上结果表明，通过 M^2 因子无法直接判断出光束中高阶模的具体含量，M^2 因子的数值小并不代表基模含量高，而只能说明光束在真空中的传输特性更接近于基模高斯光束。若考虑到在实际环境（如湍流大气）中的传输，情形则更加复杂[19]。上述结论属理论计算结果，基模和高阶模之间存在稳定的相位差；实际情况中，由于外界因素扰动，模间相位会产生变化，上述情形是否存在尚待检验。

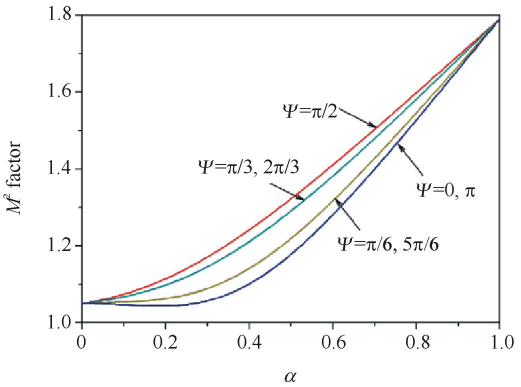


Fig. 2　The M^2 factor of the beam coherently combined by LP_{01} mode and LP_{11e} mode in case of different mode weight α and relative phase difference ψ [11]

图 2　不同 LP_{11e} 模比例 α 以及不同 LP_{11e} 模与 LP_{01} 模的相位差 ψ 下 LP_{01} 与 LP_{11e} 相干叠加光束的 M^2 因子[11]

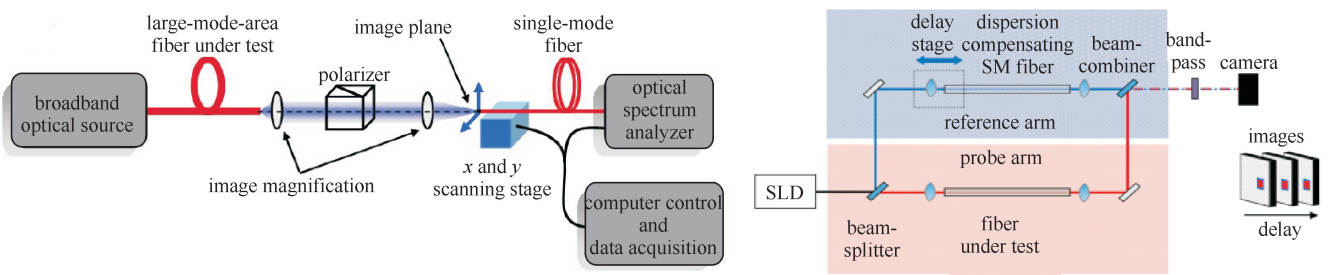
综上，要正确分析光纤激光的光束质量，准确知晓输出光束的模式组成就十分重要了，这需要运用模式分解技术[11]。

2　模式分解

目前高平均功率高光束质量光纤激光器所采用的光纤一般不是严格的单模光纤，而是支持一定模式数量的少模光纤，输出光束中的基模与高阶模的组分决定了光束质量。利用模式分解技术获取各个本征模式的含量和相位关系以准确知晓输出光束的组成，已成为光纤激光技术领域的热点[11,20]，目前研究较多的方法有成像法[21-24]、直接测量法[25-28]和数值分析法[29-31]。其余方法在测量结果方面存在不足之处，如环行腔法[32]无法得出各个模式的相位。

2.1　成像法

成像法主要包括空间-光谱分辨成像（spatially and spectrally resolved imaging，简称 S^2）法和交叉相关成像（cross-correlated imaging，简称 C^2）法。如图 3(a)所示，S^2 法基于光纤中的模间干涉效应，测量光纤输出端不同位置处的光谱并进行逆傅里叶变换，变换图中存在由于模式间群延时差异不同导致的若干尖峰，由此可以初步判定模式数量，再通过数值计算方法得出高阶模与基模之间的相对功率比。这种方法对光源的线宽、光谱



(a) spatially and spectrally resolved imaging[21]　　(b) cross-correlated imaging[23]

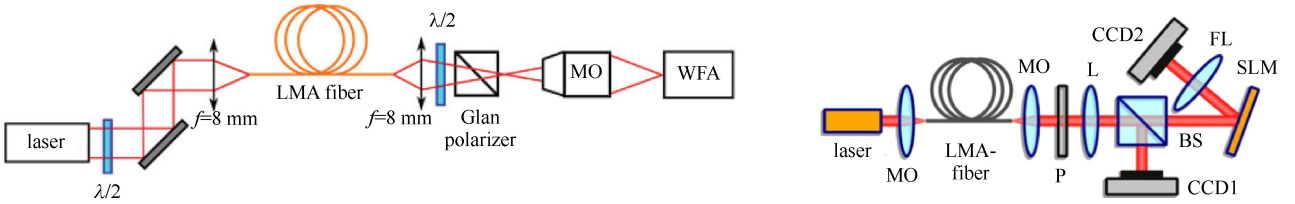
Fig. 3　Experimental setup for imaging method

图 3　成像法实验结构示意图

仪的分辨率等参数都有要求，其中宽线宽（如大于 10 nm[20]）的要求使得这种方法不能直接应用于很多 kW 级（以上）高平均功率光纤激光的测量。C^2 法采用色散补偿光纤作为参考臂，如图 3(b)所示，通过 CCD 记录每一个像素点的时域干涉特性并据此重建参与干涉的模式。这种方法可以确定模式分布、权重、相对群延时以及模间色散，并已实现高速测量[24]。

2.2　直接测量法

直接测量主要包括波前测量法和相关分析法。如图 4(a)所示，波前测量法采用波前干涉仪，同时测得光强分布和波前分布[26]。如果将波前测量结果视作相位分布，那么结合光强分布就得出了完整的光场信息。由于本征模式之间的正交关系，模式权重可以通过测得的光场与理想本征模场的共轭乘积得出。相关分析法需要实现根据待测光纤的特性通过计算机生成光学滤波器，如图 4(b)所示，它的透过率函数为光纤本征模场分布的共轭，光纤激光光束通过该滤波器后，透射光远场光强的强弱与对应的模式权重成正比[28]。通过角分复用的方法可以将所有本征模式的权重和相位对应的透过率函数都写入滤波器中，以实现“全光”模式分解。



(a) wavefront measurement(Paurisse M, et al, 2012)　　(a) correlation analysis(Flanm D, et al, 2012)

Fig. 4　Experimental setup for direct measuring method

图 4　直接测量法实验结构示意图

2.3　数值分析法

数值分析法首先测量光纤输出光束的近场或/和远场光强分布，通过数值分析使得重构的光强分布与实测的光强分布相同。数值算法是这种分解方法的关键所在，其基本过程是枚举不同模式系数的组合找到使得重构的光强分布与测量的光强分布差别最小的模式系数[29-31]。与其他几种方法相比，数值分析法具有实验设置简单易行、对实验仪器要求相对较低的优点。

3　模式不稳定

模式不稳定现象是近年来才被发现和逐渐认知的新现象，它指输出功率超过某个阈值功率后，光纤激光的输出模式由稳定的基模变为基模和高阶模相对成分随时间迅速变化的非稳态模式[33]。

3.1　产生机制与物理表征

研究人员认为高功率光纤激光模式不稳定发生的根源在于增益光纤中的热效应[34-38]：由于大模场面积光纤纤芯支持多个模式，当信号光注入主放光纤时，虽然主要能量集中在基模，但是不可避免会激发少量的高阶模式。基模和高阶模干涉会在光纤中形成周期性光强分布。当泵浦光注入、信号光开始被放大后，纤芯掺杂区会形成周期性的泵浦光提取，而量子亏损产热与泵浦光吸收相关，因此会形成准周期性振荡的热负荷分布，最终形成周期性的温度分布。由于热光效应，纤芯中准周期性温度分布调制纤芯中的折射率分布，形成长周期折射率光栅。热致折射率光栅满足相位匹配条件，可以实现基模和高阶模的动态能量耦合。需要指出的是，其他物理效应也会导致光纤激光在低平均功率出现动态模式不稳定现象，如前向 SBS 中声场[39-41]、低功率光纤激光中粒子数反转分布[42]等。

大量实验研究表明，光纤激光中的模式不稳定有以下典型特点[43-44]：(1) 具有“阈值性”，阈值仅与平均功率有关，与峰值功率无关；(2)模式不稳定现象发生后，能量在基模和高阶模之间动态耦合，耦合的时间尺度在 ms 量级；(3)输出激光的时域特性在阈值附近具有“周期性”，特征耦合频率在 kHz 量级；随着输出功率升高，模式不稳定时域特性的频谱会展宽并失去周期性而趋于“混沌”。

3.2　影响因素

从光纤激光系统组成而言，几乎每一个组件的性能都会对模式不稳定现象的阈值产生影响。依据公开发表的文献，我们从光纤本身和系统设计两个方面对影响因素予以归纳总结，详见表 2。

表 2 模式不稳定阈值的影响因素

Table 2 Factors of influencing mode instability(MI) threshold

first level	second level	third level	conclusions	references
optical fiber	fiber core/cladding diameter		lower core-cladding ratio, higher MI threshold	[45-47]
	numerical aperture of fiber core		numerical aperture decreases, MI threshold increases	[48-49]
	fiber doping	doping concentration	independent of longitudinal distribution of doping concentration	[50]
		doping radius	partially doped area decreases and MI threshold increases	[51-54]
	photodarkening		photodarkening increased, MI threshold decreases	[55-58]
	characteristics of polarization maintaining		MI threshold is irrelevant with polarization maintaining; polarization control causes amplitude modulation, which is relevant	[59-62]
	fiber material		optimization of fiber materials can improve the MI threshold	[63-65]
system	signal light	power of signal light	increasing the signal light power can improve the MI threshold.	[66-67]
		signal noise	relative intensity noise increases, MI threshold decreases	[45]
		initial high-order mode ratio	initial high-order mode components increases, MI threshold decreases	[51,68]
		wavelength of signal light	MI threshold is related to the signal light wavelength	[69-72]
		linewidth of signal light	MI threshold is affected by relatively wide linewidth	[42,73-74]
		amplitude modulation of signal light	suppressing signal amplitude modulation helps increasing MI threshold	[61-62]
	cooling capacity		MI threshold is independent of symmetric cooling	[43,62]
	pump source	pump wavelength	reducing pump absorption cross section can increase MI threshold	[75]
		hybrid pump	increasing the wavelength component deviating absorpting peak can increase MI threshold	[43]
		pump modulation	suppression of pump power/spectrum modulation can increase MI threshold	[61]
	pump modes	pump direction	bidirectional pump and backward pump can increase MI threshold	[43,76-77]
		side pump	multi-point side pumping can increase MI threshold	[43, 77]
	higher-order mode loss		increasing higher-order mode loss can increase MI threshold	[55,78-81]

3.3 抑制方法

从表 2 不难发现,系统组件对模式不稳定效应产生阈值的影响可分为内部和外部两个方面。内部主要是影响光纤中的增益饱和、量子亏损、额外热源等,外部主要是系统的高阶模抑制能力。因此,我们可以采取相应的一系列优化设计方法提高模式不稳定效应的产生阈值,如表 3 所示。

除了表 3 介绍的内容之外,有效抑制光子暗化、采用具有良好热光特性的新光纤材料也是行之有效的方

法。近年来，研究人员还发现了输出激光从基模单向耦合至高阶模的模式退化现象[96-97]，但理论研究和实验研究亟需深入[98-99]。

表 3　提高模式不稳定阈值的技术手段

Table 3　Technical measures to increase the mode instability threshold

physical mechanism	implementation method	technical measure	notes	references
increase high-order mode loss	increase high-order mode bending loss	reduce bending radius	bending can lead to changes in the area of the optical fiber module	
		reduce numerical aperture of fiber core		[49, 82]
		reduce core diameter	small fiber core is easy to stimulate Raman scattering and other effects	
		optimize fiber coiling		[83]
		increase signal wavelength	increasing the wavelength of signal light will lead to increase of quantum loss	
	optimize optical fiber design	gain-cut fiber	fiber bending easily leads to more overlap of higher-order modes with doped regions	[84]
		large air hole spacing fiber	increase the threshold by 3 times	[36]
		distributed mode filter fiber	increase the threshold by 1.5 times	[56]
		chirp coupled core fiber	increase the threshold by 2 times	[85-86]
		all-solid photonic band gap fiber		[87-88]
		conical fiber		[89]
increase gain saturation	reduce the core cladding ratio		absorption coefficient decreases, long fibers are required, and nonlinear effects are common	[47]
	change the wavelength of the semiconductor pump		absorption coefficient decreases, long fibers are required, and nonlinear effects are common	
	change the pump light injection direction		for large-core fiber, the effect is limited	[76, 90]
	increase injection signal power		the stimulated Raman scattering threshold decreases	[56 ,91-92]
	change signal wavelength		unconventional bands need to effectively inhibit ASE	[72, 93-95]
reduce quantum loss	in-band pumping		absorption coefficient decreases, long fibers are required, and nonlinear effects are common	

4　模式控制

传统意义上的模式控制一般指抑制高阶模保证基模输出以获得近衍射极限的光束质量，主要包括外部模式控制和特殊光纤设计两种方法。近年来，随着光场调控等新兴学科领域的快速发展，基于光纤激光实现特定高阶模式和具有复杂相位(偏振)分布的结构光场输出也成为了研究热点。另外，基于长周期光纤光栅可以实现模式转换，这方面已有详细的报道，本文不再赘述。

4.1　外部模式控制

外部模式控制是指对已经拉制完成的光纤实施模式控制，比较常见的有光纤拉锥和弯曲盘绕两种方法。

光纤拉锥法对光纤进行拉锥处理，从而增加高阶模的损耗，实现对高阶模振荡的抑制[100-101]。该方法能实现较高光束质量输出，但激光器的效率一般不高，大量纤芯中的激光在拉锥区泄漏到内包层中。在实际应用中，需要将包层光倾泻掉，在高功率运行时，拉锥区倾泻的包层光功率较高，会导致该区域局部过热，可能会触发光学放电现象[102-103]，限制了该方法的应用范围。值得注意的是，基于锥度光纤的高功率光纤激光近年来引起了多国研究人员的关注[104]，利用该光纤已经实现了 kW 级高平均功率、高光束质量输出。

2000 年，Koplow 等通过将纤芯直径为 25 μm，NA 为 0.1 的阶跃折射率分布掺镱光纤盘绕弯曲至直径仅为 1.58 cm 时得到近衍射极限输出[105]。对于常规的阶跃折射率光纤而言，盘绕弯曲光纤能够使各个模式产生损耗，并且在弯曲半径一定的情况下，模式的阶数越高损耗越大[106-107]。总体而言，这是最简单有效的模式控制方法[108]，已被大量应用[109-111]。实际应用中需要考虑，随着光纤纤芯直径的增加，基模与高阶模的弯曲损耗差异逐渐减小。过小的弯曲半径还会引起基模模场变形，进一步导致基模等效模场面积的减小，影响非线性效应的抑制效果。此外，过小的弯曲半径还会对光纤的机械可靠性产生影响，降低光纤激光系统长时间运行的可靠性[112]。

4.2 特殊光纤设计

4.2.1 改进阶跃折射率光纤

阶跃折射率光纤(Step Index Fiber, SIF)结构简单、容易拉制，基于 SIF 的光纤器件制备很成熟，目前绝大多数近衍射极限大功率光纤激光器均是基于 SIF 实现的，改进 SIF 以实现模式控制已成为光纤设计领域的研究热点。

传统的 MCVD 工艺能够实现的 NA 最低为 0.05[113]。然而，若能进一步降低 NA，则可以在更大直径的光纤中实现近衍射极限。近三年来，科研工作者们通过改进工艺，在制备超低 NA 光纤上取得了突飞猛进的进展[113-117]。目前掺镱光纤的 NA 已经可以做到 0.025 甚至 0.02[113,116]，在纤芯直径 52 μm 的情况下也获得了很好的光束质量。另外，改进的 MCVD 工艺得到的超低 NA 掺镱光纤也实现了 kW 量级的输出，最高功率达到了 4.3 kW[114, 118]。

单沟壑光纤(Single-Trench Fiber, STF)是一种有效的改进型 SIF。其结构特点是纤芯周围还依次包覆折射率与内包层相同的沟壑层，以及折射率和纤芯一致的环形层[119]，结构示意图如图 5(a)所示。环形层使得基模模场面积增大，并且在弯曲光纤的情况下环形层能够引起高阶模与包层模的共振耦合，从而实现高阶模的高损耗。STF 的结构简单，且为圆对称，对拉制工艺要求较低，同时基模模场面积和高阶模损耗比 SIF 都有了很大的提高。2015 年，Jain 等人拉制了纤芯直径 30 μm 的 STF，通过实验证明了该光纤获得基模输出的有效性，并最终实现了平均功率 52 W、峰值功率 160 kW 的 ps 脉冲输出，M^2 因子<1.15[120]。

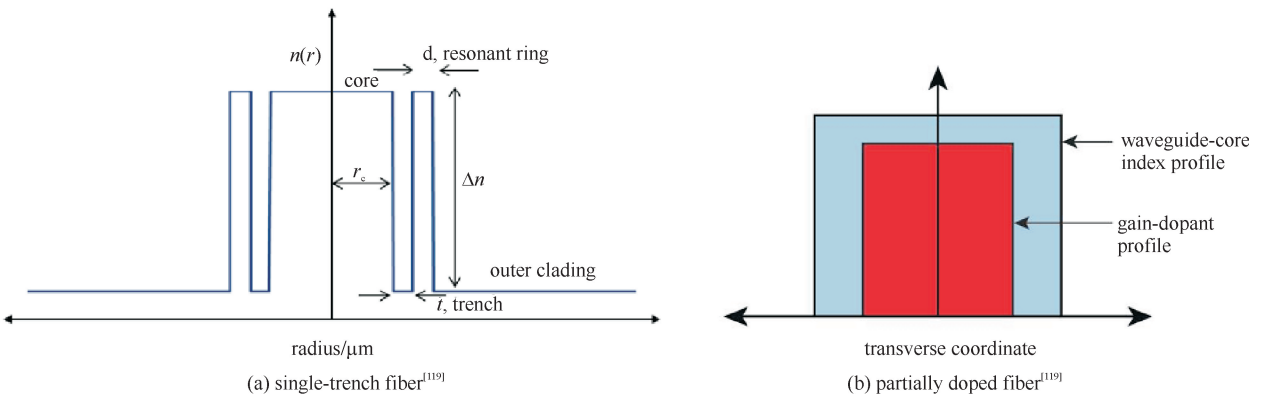


Fig. 5 Illumination of improved step-index fiber

图 5 改进型阶跃折射率光纤示意图

传统掺稀土光纤在整个纤芯区域进行均匀掺杂，由于基模的光强分布接近高斯分布以及基模占优引起的中心区域的增益饱和效应，纤芯边缘可能存在很高的增益，导致高阶模放大，且在纤芯边缘存在较强的光子暗化[121]。如图 5(b)所示，若将纤芯掺稀土的区域仅控制在纤芯中心的部分区域，在保持基模与掺杂区域高度重叠的同时，减小高阶模与掺杂区域的重叠，就能够减小高阶模的增益，从而实现基模输出[122-123]。Marciante 通过仿真证明了在输出功率数 kW 量级的光纤放大器中，部分掺杂可以使芯径达 100 μm 时仍能得到基模输出，

并在相对低功率条件下实验验证了部分掺杂光纤的优势[123]。当然，部分掺杂光纤的制备比 SIF 复杂，常规的制备方法难以实现对掺杂的高精度控制，可能需要采用纳米粒子直接沉积法[124]。另外，弯曲光纤导致的模场变形也可能影响高阶模抑制水平[124-125]，部分掺杂导致泵浦吸收降低也是需要考虑的问题。

4.2.2　全新机制光纤

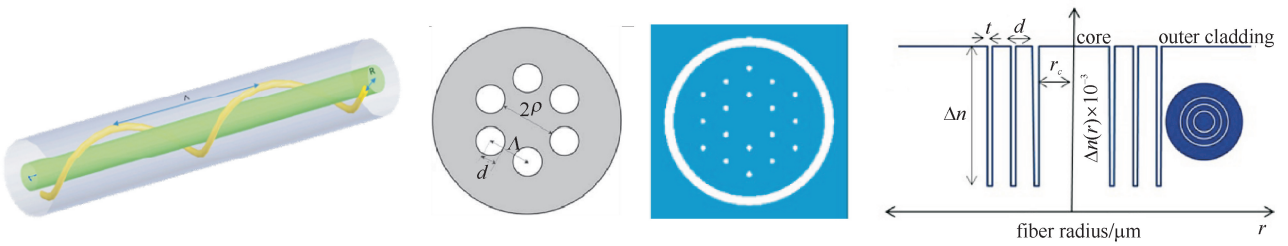
为了能够进一步地提升光纤激光器的性能，突破 SIF 的限制，引入全新的导光机制或抑制高阶模的机制是一条重要途径。全新机制光纤种类繁多，本文介绍几种比较有代表性的设计思想。

螺旋芯（Chirally Coupled Core，简称 3C）光纤的结构如图 6(a) 所示，在主掺杂纤芯外螺旋缠绕一根或多根侧芯形成螺旋芯[126-127]。通过合理的设计，可以实现侧芯中的基模与主芯中的高阶模达到相位匹配或准相位匹配，从而将主芯中的高阶模能量耦合至侧芯中。因此，在纤芯很粗的光纤中也能够实现接近严格单模输出。3C 光纤可以实现很大的模场面积以及良好的高阶模抑制。

泄漏通道光纤（Leakage Channel Fiber，LCF）的结构示意图如图 6(b)所示[128]。LCF 抑制高阶模的基本原理是保证纤芯与包层折射率相同的情况下，通过在纤芯与包层边界处引入低折射率孔形成不闭合的纤芯边界，使得全反射仅发生在纤芯与低折射率孔重叠的区域，而各低折射率孔之间的区域则成为模式泄露的通道[129]。通过合理的设计可以实现高阶模的泄漏损耗远大于基模，从而实现高阶模的抑制。在 LCF 发展的早期阶段，一般由空气孔构成低折射率孔[129-130]，这样的光纤拉制比较困难，而且切割和熔接等处理可能会造成空气孔的变形从而影响光纤的性能。为了克服这些缺陷，空气孔已经由掺有低折射率材料的玻璃棒取代[131]。

大节距光子晶体光纤（Large-pitch Photonic-crystal Fiber，LPF）的结构示意图如图 6(c)所示，空气孔之间的距离（pitch，节距）大于 10 个波长，大于普通的光子晶体光纤。这种结构能够产生较强的高阶模离域效应（HOM delocalization）[132-133]，使得高阶模与纤芯的重叠因子很小。图 6(c)所示的 LPF 中，节距为 30 μm，空气孔的直径为 6 μm，纤芯直径为 54 μm，当激光波长为 1 μm 时，计算得到：高阶模中最高的重叠因子仅为 35%，而基模的重叠因子高达 75%。高阶模离域效应将使得高阶模获得的增益很小，从而实现有效的高阶模抑制。需要指出的是，为了避免弯曲 LPF 对高阶模离域效应的影响，LPF 均为棒状。

多沟壑光纤（Multi-Trench Fiber，MTF）的折射率分布示意图如图 6(d)所示，纤芯的折射率与包层一致，并且在纤芯外有多个低折射率环（可以看做是折射率沟壑）。这种结构不仅能够使高阶模和包层模产生强烈的共振耦合，导致高阶模的损耗很大，而且能够导致高阶模产生很强的离域效应[134]。相对于 3C 光纤、LCF 和 LPF，MTF 的优势在于可以采用成熟的 MCVD 法进行大规模生产。需要指出的是，弯曲 MTF 会影响高阶模抑制能力，可弯曲的 MTF 仅在纤芯直径<30 μm 的情况下才能实现基模输出[135]。



(a) 3C fiber[126]　(b) LCF[128]　(c) LPF[132]　(d) MTF[135]

Fig. 6　Schematic dravings of fibers based on new mechanisms

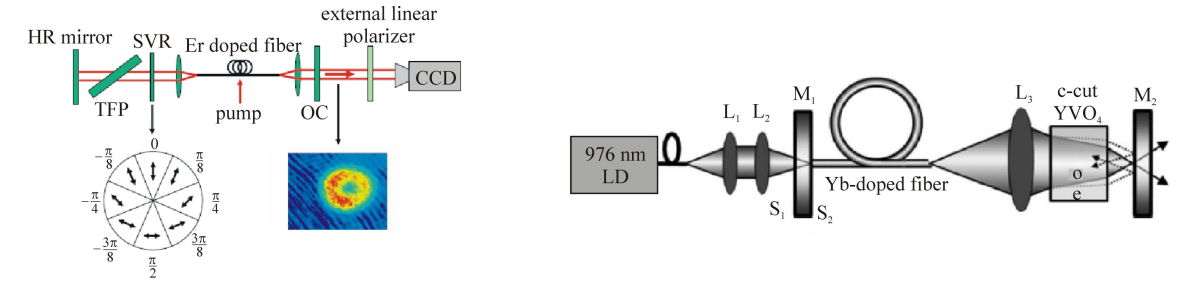
图 6　全新机制光纤示意图

4.3　特定高阶模式与结构光场输出

在本系列综述的上一篇论文中，我们介绍了基于光纤光栅产生特殊模式分布。实际上，运用偏振相关光学元件（双折射晶体、波片等）在空间结构的光纤激光器中进行选模，也是产生矢量光或涡旋光等结构光场的常用方法[136-139]。图 7(a)所示为 Fridman 等通过在光纤激光腔内插入空间可变延迟片（SVR）的方式同时产生径向偏振光和角向偏振光实验系统结构示意[136]；图 7(b)所示为 Zou 通过在光纤激光腔内插入 YVO_4 双折射晶体的方式产生高功率、高效率径向偏振光实验系统结构示意[137]。

运用掺杂光纤作为功率放大介质，还可以实现对结构光场的功率放大[140-144]。文献[140]设计了基于应力长周期光栅的大模场双包层光纤模式转换器，运用图 8(a)所示的功率放大结构，在高功率皮秒脉冲主振荡功率放大器中实现了基模与高阶模的高效转换，输出的基模和高阶模平均功率均达到 117 W。文献[142]运用图

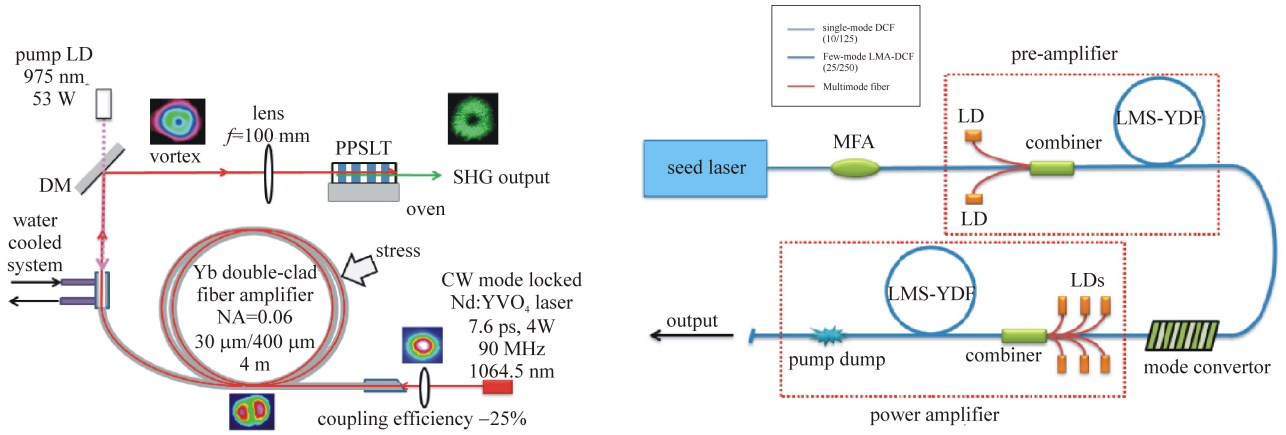
8(b)所示的功率放大结构实现了平均功率 25 W 的皮秒脉冲涡旋激光。文献[143]实现了径向偏振光纤激光功率放大，在泵浦功率 30 W 时，激光功率为 21 W。



(a) by inserting space variable retarder(SVR) into the cavity[136]　　(b) by inserting YVO_4 crystal[137]

Fig. 7　Structured light field generation based on fiber laser

图 7　基于光纤激光的结构光场产生

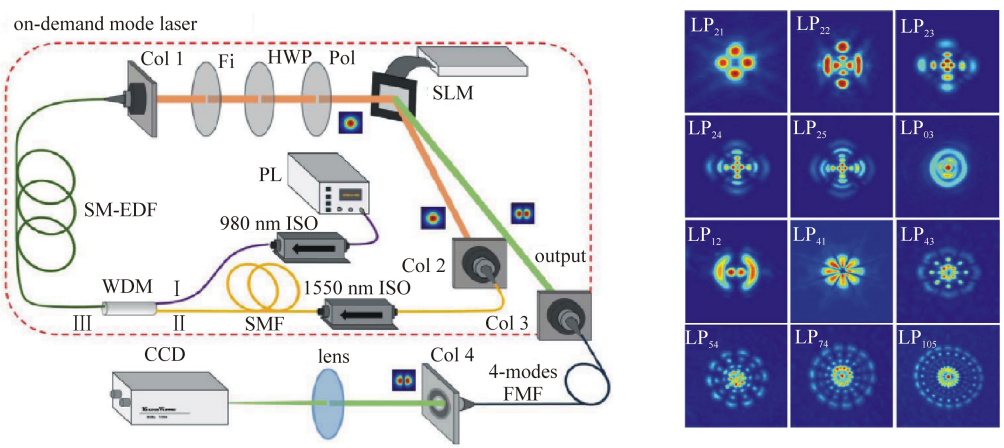


(a) vortex beam generation[141]　　(b) radially polarized beam generation[143]

Fig. 8　Structured light field generation based on fiber amplifier

图 8　基于光纤放大器的结构光场产生

从前文可以看出，无论是基于光纤光栅还是偏振相关光学元件，无论是振荡器结构还是放大器结构，都可以实现特定高阶模式或结构光场的激光输出，但对光场调控的自由度不够。近年来，随着空间光调制器等光场调控器件的引入[145,146]，光纤激光器也可以实现可定制光场输出[147]。文献[147]基于如图 9(a)所示的实验结构，通过在空间光调制器上载入不同的相位分布，可实现 LP_{01} 至 LP_{05} 模式的可定制输出，模式之间可实时切换。



(a) system setup　　(b) typical results

Fig. 9　Fiber Laser with on-demand output property[147]

图 9　可定制光场输出的光纤激光器[147]

5 结　论

与其他类型的激光器一样，光纤激光器本质上是一个亮度提升器，通过激光产生或功率放大的过程完成能量从多模泵浦光到低阶模（或特定模式）信号光的转移。尽管由于量子亏损等因素导致功率下降，但模式的改变实现了亮度成量级的提升。尽管光纤激光的产生和传输都在封闭的波导结构中，实际应用时，还需要使用“波导到自由空间”的光学元件（系统），如光纤端帽、准直器[148-149]等将激光导入自由空间，这有可能会再次对输出模式产生影响[150]。诚如文献[20]的作者所言，“系统掌握激光模场相关的基础知识和研究方法，并应用这些知识来指导激光器的设计及应用，对激光科学家和工程师都是十分必要的”，对模式的关注应当贯穿光纤激光器（放大器）设计、研制和应用的全过程。

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参考文献：

[1] Shiner B. Recent progress in high power fiber lasers[R]. Laser Applications Workshop, 2009.

[2] Shcherbakov E, Fomin V, Abramov A, et al. Industrial grade 100 kW power CW fiber laser[C]//Advanced Solid State Laser. 2013: ATh4A. 2.

[3] http://www.ipgphotonics.com

[4] Gapontsev V, Fomin V, Ferin A, et al. Diffraction limited ultra-high-power fibre lasers[C]//Advanced Solid State Laser. 2010: AWA1.

[5] Protz R, Zoz J, Geidek F, et al. High-power beam combining—a step to a future laser weapon system[C]//Proc of SPIE. 2012: 854708.

[6] Injeyan H, Pflug G C, Vespucci M T. High power laser handbook[M]. New York: McGraw-Hill, 2011.

[7] YLS series 10-100 kW datasheet [DB/OL]. http://www.ipgphotonics.com

[8] Paschotta R. Field guide to optical fiber technology[M]. New York: SPIE Press, 2010.

[9] Okamoto K. Fundamentals of optical waveguides[M]. New York: Academic Press, 2010.

[10] 廖延彪，金慧明. 光纤光学[M]. 北京：清华大学出版社，1992.（Liao Yanbiao, Jin Huiming. Fiber optics. Beijing: Tsinghua University Press, 1992）

[11] 黄良金. 大功率光纤激光器的模式分解及模式控制[D]. 长沙：国防科学技术大学，2016.（Huang Liangjin. Mode decomposition and mode control of high-power fiber lasers. Changsha: National University of Defense Technology, 2016）

[12] Yoda H, Polynkin P, Mansuripur M. Beam quality factor of higher order modes in a step-index fiber[J]. Journal of Lightwave Technology, 2006, 24(3): 1350-1355.

[13] Siegman A E. How to (maybe) measure laser beam quality[C]//Diode Pumped Solid State Lasers: Applications and Issues. 1998: MQ1.

[14] Siegman A E. Defining and measuring laser beam quality[M]//Solid State Lasers. 1993: 13-28.

[15] Zhou Pu, Liu Zejin, Xu Xiaojun, et al. Numerical analysis of the effects of aberrations on coherently combined fiber laser beams[J]. Applied Optics, 2008, 47(18): 3350-3359.

[16] Zhou Pu, Liu Zejin, Xu Xiaojun, et al. Beam quality factor for coherently combined fiber laser beams[J]. Optics & Laser Technology, 2009, 41(3): 268-271.

[17] Yan Ping, Wang Xuejiao, Gong Mali, et al. Evaluating the beam quality of double-cladding fiber lasers in applications[J]. Applied Optics, 2016, 55(23): 6145-6150.

[18] Wielandy S. Implications of higher-order mode content in large mode area fibers with good beam quality[J]. Optics Express, 2007, 15(23): 15402-15409.

[19] Tao Rumao, Huang Long, Zhou Pu, et al. Propagation of high-power fiber laser with high-order-mode content[J]. Photonics Research, 2015, 3(4): 192-199.

[20] 冯国英，周寿桓，高春清. 激光模场及光束质量表征[M]. 北京：国防工业出版社，2016.（Feng Guoying, Zhou Shouhuan, Gao Chunqing. Laser mode field and beam quality characterization. Beijing: National Defense Industry Press, 2016）

[21] Nicholson J W, Yablon A D, Ramachandran S, et al. Spatially and spectrally resolved imaging of modal content in large-mode-area fibers[J]. Optics Express, 2008, 16(10): 11.

[22] 胡丽荔，冯国英，董哲良. 基于空间和频谱分辨的光纤模式测量方法[J]. 红外与激光工程，2015，44(8)：2517-2522.（Hu Lili, Feng Guoying, Dong Zheliang. Spatially and spectrally resolved fiber mode measurement method. Infrared and Laser Engineering, 2015, 44(8): 2517-2522）

[23] Schimpf D N, Barankov R A, Ramachandran S. Cross-correlated (C^2) imaging of fiber and waveguide modes[J]. Optics Express, 2011, 19(14): 13008-13019.

[24] Demas J, Ramachandran S. Sub-second mode measurement of fibers using C^2 imaging[J]. Optics Express, 2014, 22(19): 23043-23056.

[25] Schmidt O A, Schulze C, Flamm D, et al. Real-time determination of laser beam quality by modal decomposition[J]. Optics Express, 2011, 19(7): 6741-6748.

[26] Paurisse M, Lévèque L, Hanna M, et al. Complete measurement of fiber modal content by wavefront analysis[J]. Optics Express, 2012, 20(4): 4074-4084.

[27] Brüning R, Gelszinnis P, Schulze C, et al. Comparative analysis of numerical methods for the mode analysis of laser beams[J]. Applied Optics, 2013, 52(32): 7769-7777.

[28] Flamm D, Naidoo D, Schulze C, et al. Mode analysis with a spatial light modulator as a correlation filter[J]. Optics Letters, 2012, 37(13):2478-2480.

[29] Lü Haibin, Zhou Pu, Wang Xiaolin, et al. Fast and accurate modal decomposition of multimode fiber based on stochastic parallel gradient descent algorithm[J]. Applied Optics, 2013, 52(12): 2905-2908.

[30] Huang Liangjin, Guo Shaofeng, Leng Jinyong, et al. Real-time mode decomposition for few-mode fiber based on numerical method[J]. Optics Express, 2015, 23(4): 4620-4629.

[31] Huang Liangjin, Lü Haibin, Zhou Pu, et al. Modal analysis of fiber laser beam by using stochastic parallel gradient descent algorithm[J]. Photonics Technology Letters, 2015, 27(21): 2280-2283.

[32] Andermahr N, Theeg T, Fallnich C. Novel approach for polarization-sensitive measurements of transverse modes in few-mode optical fibers [J]. Applied Physics B, 2008, 91(2): 353-357.

[33] Eidam T, Wirth C, Jauregui C, et al. Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers[J]. Optics Express, 2011, 19(14): 13218-13224.

[34] Smith A V, Smith J J. Mode instability in high power fiber amplifiers[J]. Optics Express, 2011, 19(11): 10180-10192.

[35] Hansen K R, Alkeskjold T T, Broeng J, et al. Thermally induced mode coupling in rare-earth doped fiber amplifiers[J]. Optics Letter, 2012, 37(12): 2382-2384.

[36] Jauregui C, Eidam T, Otto H-J, et al. Physical origin of mode instabilities in high-power fiber laser systems[J]. Optics Express, 2012, 20(12): 12912-12925.

[37] Dong Liang. Stimulated thermal Rayleigh scattering in optical fibers[J]. Optics Express, 2013, 21(3): 2642-2656.

[38] Hu I-Ning, Zhu Cheng, Zhang Chao, et al. Analytical time-dependent theory of thermally-induced modal instabilities in high power fiber amplifiers[C]//Proc of SPIE. 2013: 860109.

[39] Zervas M N. High power ytterbium-doped fiber lasers—fundamentals and applications [J]. Int J Mod Phys B, 2014, 28(12): 1442009.

[40] Russell P S t J, Culverhouse D, Farahi F. Theory of forward stimulated Brillouin scattering in dual-mode single-core fibers [J]. IEEE J Quantum Electron, 1991, 27(3): 836-842.

[41] Russell P St J, Culverhouse D, Farahi F. Experimental observation of FSBS in dual-mode single-core fibre [J]. Electron Lett, 1990, 26(15): 1195-1196.

[42] Kuznetsov M, Vershinin O, Tyrtyshnyy V, et al. Low-threshold mode instability in Yb^{3+}-doped few-mode fiber amplifiers [J]. Opt Express, 2014, 22(24): 29714-29725.

[43] 陶汝茂. 高功率窄线宽近衍射极限光纤激光放大器热致模式不稳定研究[D]. 长沙: 国防科学技术大学研究生院,2015. (Tao Rumao. Study of thermal-induced modal instabilities in high power narrow-linewidth fiber amplifiers with near diffraction-limited beam quality. Changsha: National University of Defense Technology, 2015)

[44] 陶汝茂, 周朴, 肖虎, 等. 高功率光纤激光中模式不稳定性现象研究进展[J]. 激光与光电子学进展, 2014, 51(2): 1-8. (Tao Rumao, Zhou Pu, Xiao Hu, et al. Progress of study on mode instability in high power fiber amplifiers. Laser & Optoelectronics Progress, 2014, 51(2): 1-8)

[45] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. 1.3 kW monolithic linearly polarized single-mode master oscillator power amplifier and strategies for mitigating mode instabilities[J]. Photonics Research, 2015, 3(3): 86-93.

[46] Jansen F, Stutzki F, Otto H J, et al. Thermally induced waveguide changes in active fibers[J]. Optics Express, 2012, 20(4): 3997-4008.

[47] Smith A V, Smith J J. Increasing mode instability thresholds of fiber amplifiers by gain saturation[J]. Optics Express, 2013, 21(13): 15168-15182

[48] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. Influence of core NA on thermal-induced mode instabilities in high power fiber amplifiers [J]. Laser Physics Letter, 2015, 12: 085101.

[49] Beier F, Hupel C, Nold J, et al. Narrow linewidth, single mode 3 kW average power from a directly diode pumped ytterbium doped low NA fiber amplifier[J]. Optics Express, 2016, 24(6): 6011-6020.

[50] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. Study of dopant concentrations on thermally induced mode instability in high-power fiber amplifiers[J]. Laser Physics, 2016, 26: 065103.

[51] 陶汝茂, 王小林, 肖虎, 等. 高功率光纤放大器中模式不稳定阈值功率的理论研究[J]. 光学学报, 2014, 34: 114002. (Tao Rumao, Wang Xiaolin, Xiao Hu, et al. Theoretical study of the threshold power of mode instability in high-power fiber amplifiers. Acta Optica Sinica, 2014, 34: 114002)

[52] Eidam T, Hädrich S, Jansen F, et al. Preferential gain photonic-crystal fiber for mode stabilization at high average powers[J]. Optics Express, 2011, 19(9): 8656-8661.

[53] Engin D, Lu W, Verdun H, et al. High power modal instability measurements of very large mode area (VLMA) step index fibers[C]//Proc of SPIE. 2013: 87330J.

[54] Naderi S, Dajani I, Madden T, et al. Investigations of modal instabilities in fiber amplifiers through detailed numerical simulations[J]. Optics Express, 2013, 21(13): 16111-16129.

[55] Smith A V, Smith J J. Mode instability thresholds of fiber amplifiers[C]//Proc of SPIE. 2013: 860108.

[56] Laurila M, Jørgensen M M, Hansen K R, et al. Distributed mode filtering rod fiber amplifier delivering 292 W with improved mode stability[J]. Optics Express, 2012, 20(5): 5742-5753.

[57] Johansen M M, Laurila M, Maack M D, et al. Frequency resolved transverse mode instability in rod fiber amplifiers[J]. Optics Express, 2013, 21(19): 21847-21856.

[58] Otto H-J, Modsching N, Jauregui C, et al. Impact of photo darkening on the mode instability threshold[J]. Optics Express, 2015, 23(12): 15265-15277.

[59] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. Comparison of the threshold of thermal-induced mode instabilities in polarization-maintaining and non-polarization-maintaining active fibers[J]. Journal of Optics, 2016, 18: 065501.

[60] Goodno G D, McNaught S, Thielen P, et al. Polarization control with mode stability: US8922877B1[P]. 2014-12-30.

[61] Smith A V, Smith J J. Influence of pump and seed modulation on the mode instability thresholds of fiber amplifiers[J]. Optics Express, 2012, 20(22): 24545-24558.

[62] Hansen K R, Alkeskjold T T, Broeng J, et al. Theoretical analysis of mode instability in high-power fiber amplifiers[J]. Optics Express, 2013, 21(2): 1944-1971.

[63] Jauregui C, Limpert J, Tünnermann A. High-power fibre lasers [J]. Nat Photon, 2012, 7: 861-867.

[64] Ballato J, Dragic P. Materials development for next generation optical fiber[J]. Materials, 2014, 7(6): 4411-4430.

[65] Shaw L B, Askins C, Kim W, et al. Cladding pumped single crystal Yb: YAG fiber amplifier[C]//Advanced Solid State Laser, 2015: AM4A. 4.

[66] Tao Rumao, Wang Xiaolin, Zhou Pu, et al. Seed power dependence of mode instabilities in high power fiber amplifiers[J]. Journal of Optics, 2017, 19: 065202.

[67] Otto H-J, Jauregui C, Stutzki F, et al. Dependence of mode instabilities on the extracted power of fiber laser systems[C]//Advanced Solid State Laser, 2013: ATu3A. 02.

[68] Haarlammert N, Sattler B, Liem A, et al. Optimizing mode instability in low-NA fibers by passive strategies[J]. Optics Letter, 2015, 40(10): 2317-2320.

[69] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. Study of wavelength dependence of mode instability based on a semi-analytical model[J]. IEEE Journal of Quantum Electronics, 2015, 51(8): 1-6.

[70] Otto H-J, Modsching N, Jauregui C, et al. Wavelength dependence of maximal diffraction-limited output power of fiber lasers[C]//Proc of SPIE. 2015: 93441Y.

[71] Brar K, Leuchs M S, Henric J, et al. Threshold power and fiber degradation induced modal instabilities in high power fiber amplifiers based on large mode area fibers[C]//Proc of SPIE. 2014: 89611R.

[72] Yagodkin R, Platonov N, Yusim A, et al. >1.5 kW narrow linewidth CW diffraction-limited fiber amplifier with 40nm bandwidth[C]//Proc of SPIE. 2015: 972807.

[73] Smith A V, Smith J J. Steady-periodic method for modeling mode instability in fiber amplifiers[J]. Optics Express, 2013, 21(3): 2606-2623.

[74] Smith J J, Smith A V. Influence of signal bandwidth on mode instability thresholds of fiber amplifiers[C]//Proc of SPIE. 2015: 93440L.

[75] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. Mitigating of modal instabilities in linearly-polarized fiber amplifiers by shifting pump wavelength[J]. Journal of Optics, 2015, 17: 045504.

[76] Tao R, Ma P, Wang X, et al. Theoretical study of pump power distribution on modal instabilities in high power fiber amplifiers [J]. Laser Phys Lett, 2017, 14: 025002.

[77] Yu C X, Shatrovoy O, Fan T Y. All-glass fiber amplifier pumped by ultra-high brightness pumps[C]//Proc of SPIE. 2015: 972806.

[78] Tao Rumao, Ma Pengfei, Wang Xiaolin, et al. 1.4 kW all-fiber narrow-linewidth polarization-maintained fiber amplifier[C]//Proc of SPIE. 2014: 92550B.

[79] Lei Min, Qi Yunfeng, Liu Chi, et al. Mode controlling study on narrow-linewidth and high power all-fiber amplifier[C]//Proc of SPIE. 2015: 95431L.

[80] 雷敏,漆云凤,刘驰,等. 高功率全光纤放大器的高阶模激发阈值特性研究[J]. 中国激光, 2015, 42: 0605002. (Lei Min, Qi Yunfeng, Liu Chi, et al. High-order modes threshold study on high power all-fiber amplifier. Chinese Journal of Lasers, 2015, 42: 0605002)

[81] Ma Pengfei, Tao Rumao, Su Rongtao, et al. 1.89 kW all-fiberized and polarization-maintained fiber amplifiers with narrow linewidth and

near-diffraction-limited beam quality[J]. Optics Express, 2016, 24(4): 4187-4195.

[82] 陶汝茂，周朴，王小林，等. 高功率全光纤结构主振荡功率放大器中模式不稳定现象的实验研究[J]. 物理学报，2014，63：085202.（Tao Rumao, Zhou Pu, Wang Xiaolin, et al. Experimental study on mode instability in high power all-fiber master oscillator power amplifier fiber lasers. Acta Physica Sinica, 2014, 63: 085202）

[83] Tao Rumao, Su Rongtao, Ma Pengfei, et al. Suppressing mode instabilities by optimizing the fiber coiling methods[J]. Laser Physics Letter, 2017, 14: 025101.

[84] Robin C, Dajani I, Zeringue C, et al. Gain-tailored SBS suppressing photonic crystal fibers for high power applications[C]//Proc of SPIE. 2012: 82371D.

[85] Liu C H, Chang G, Litchinitser N, et al. Chirally coupled core fibers at 1550-nm and 1064-nm for effectively single-mode core size scaling [C]//Proc CLEO/QELS 2007. CTuBB3.

[86] Kanskar M, Zhang J, McComb T S, et al. Traverse-modal-instability (TMI)-free Yb-doped 35 μm core and 250 μm clad chirally coupled core (3C) fiber MOPA with 475 W output power[C]// Laser Technology for Defense and Security XII. 2016.

[87] Dong L, Saitoh K, Kong F, et al. All-solid photonic bandgap fibers for high power lasers [C]// Proc of SPIE. 2012: 85470J,.

[88] Kong F, Gu G, Hawkins T, et al. ～1 kilowatt ytterbium-doped all-solid photonic bandgap fiber laser[C]//Proc of SPIE. 2017: 1008311.

[89] Filippov V, Ustimchik V, Chamorovskii Yu, et al. Impact of axial profile of the gain medium on the mode instability in lasers: regular versus tapered fibers[C]//European Conference on Laser and Electro-Optics and the European Quantum Electronics Conference. 2015.

[90] Eznaveh Z S, Lopez-Galmiche G, Antonio-Lopez E, et al. Bi-directional pump configuration for increasing thermal modal instabilities threshold in high power fiber amplifiers[C]//Proc of SPIE. 2015: 93442G.

[91] Stihler C, Jauregui C, Otto H J, et al. Controlling mode instabilities at 628 W average output power in an Yb-doped rod-type fiber amplifier by active modulation of the pump power [C]// Proc of SPIE. 2017: 100830P.

[92] Liu Wei, Ma Pengfei, Lü Haibin, et al. General analysis of SRS-limited high-power fiber lasers and design strategy[J]. Optics Express, 2016, 24(23): 26715-26721.

[93] Xiao Hu, Zhou Pu, Wang Xiaolin, et al. Experimental investigation on 1018-nm high-power ytterbium-doped fiber amplifier[J]. IEEE Photonics Technology Letters, 2012, 24(13): 1088-1090.

[94] Xiao Hu, Zhou Pu, Wang Xiaolin, et al. High power 1018 nm monolithic Yb^{3+}-doped fiber laser and amplifier[J]. Laser Physics Letters, 2012, 9(10): 748.

[95] Huang Y, Edgecumbe J, Ding J, et al. Performance of kW class fiber amplifiers spanning a broad range of wavelengths: 1028～1100 nm [C]//Proc of SPIE. 2014: 89612K.

[96] 于海龙，王小林，张汉伟，等. 300 W 线偏振飞秒全光纤啁啾脉冲放大系[J]. 强激光与粒子束，2016，28：050101.（Yu Hailong, Wang Xiaolin, Zhang Hanwei, et al. 300 W linearly polarized femtosecond all-fiber chirped pulse amplification system. High Power Laser and Particle Beams, 2016, 28: 050101）

[97] Bobkov K K, Bubnov M M, Aleshkina S S, et al. Long-term mode shape degradation in large mode area Yb-doped pulsed fiber amplifiers [J]. Laser Physics Letter, 2017, 14: 015102.

[98] Ward B, Theory and modeling of photodarkeninginduced quasi static degradation in fiber amplifiers[J]. Optics Express, 2016, 24(4): 3488-3501.

[99] 史尘，陶汝茂，王小林，等. 光纤激光模式不稳定的新现象与新进展[J]. 中国激光，2017，44:0201004.（Shi Chen, Tao Rumao, Wang Xiaolin, et al. New progress and phenomena of modal instability in fiber lasers. Chinese Journal of Lasers, 2017, 44:0201004）

[100] Alvarez-Chavez J A, Grudinin A B, Nilsson J, et al. Mode selection in high power cladding pumped fibre lasers with tapered section[C]// Conference on Lasers and Electro-Optics. 1999: 247-248.

[101] Li Libo, Lou Qihong, Zhou Jun, et al. High power single transverse mode operation of a tapered large-mode-area fiber laser[J]. Optics Communications, 2008, 281(4): 655-657.

[102] 张汉伟，周朴，王小林，等. 双包层光纤光学放电现象的建模仿真分析[J]. 光学学报，2013，33：706015.（Zhang Hanwei, Zhou Pu, Wang Xiaolin, et al. Simulation of fiber optical discharge effect of double cladding fiber. Acta Optica Sinica, 2013, 33: 0706015）

[103] Zhang Hanwei, Zhou Pu, Wang Xiaolin, et al. Fiber fuse effect in high-power double-clad fiber laser[C]//Conference on Lasers and Electro-Optics. 2013: WPD_4.

[104] 史尘，王小林，粟荣涛，等. 长拉锥双包层光纤在光纤激光领域的应用研究进展[J]. 激光与光电子学进展，2015，52(12)：1-8.（Shi Chen, Wang Xiaolin, Su Rongtao, et al. Progress of study on long tapered double-clad fiber in fiber laser application. Laser & Optoelectronics Progress, 2015, 52(12): 1-8）

[105] Koplow J P, Kliner D A V, Goldberg L. Single-mode operation of a coiled multimode fiber amplifier[J]. Optics Letters, 2000, 25(7): 442-444.

[106] Schermer R T, Cole J H. Improved bend loss formula verified for optical fiber by simulation and experiment[J]. IEEE Journal of Quantum Electronics, 2007, 43(10): 11.

[107] Marcuse D. Influence of curvature on the losses of doubly clad fibers[J]. Applied Optics, 1982, 21(23): 4208-4213.

[108] Li Mingjun, Chen Xin, Liu Anping, et al. Limit of effective area for single-mode operation in step-index large mode area laser fibers[J]. Journal of Lightwave Technology, 2009, 27(15): 3010-3016.

[109] Jeong Y, Sahu J K, Payne D N, et al. Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power[J]. Optics Express, 2004, 12(25): 6088-6092.

[110] Huang Liangjin, Wang Wenliang, Leng Jinyong, et al. Experimental investigation on evolution of the beam quality in a 2-kW high power fiber amplifier[J]. IEEE Photonics Technology Letters, 2014, 26(1): 33-36.

[111] Xu Jiangming, Liu Wei, Leng Jinyong, et al. Power scaling of narrowband high-power all-fiber superfluorescent fiber source to 1.87 kW [J]. Optics Letters, 2015, 40(13): 2973-2976.

[112] Walorny M, Abramczyk J, Jacobson N, et al. Mechanical reliability of double clad fibers in typical fiber laser deploy[C]//Proc of SPIE. 2016: 97283A.

[113] Petit V, Tumminelli R P, Minelly J D, et al. Extremely low NA Yb doped preforms (<0.03) fabricated by MCVD[C] //Proc of SPIE. 2016: 97282R.

[114] Kuhn S, Hein S, Hupel C, et al. Towards monolithic single-mode Yb-doped fiber amplifiers with >4 kW average power[C]//Advanced Solid State Laser. 2016: ATu4A.2.

[115] Jain D, Jung Y, Barua P S, et al. Demonstration of ultra-low Na rare-earth doped step index fiber for applications in high power fiber lasers[J]. Optics Express, 2015, 23(6): 7407-7415.

[116] Xu Wenbin, Lin Zhiquan, Wang Meng, et al. 50 μm core diameter $Yb^{3+}/Al^{3+}/F^{-}$ codoped silica fiber with $M^2<1.1$ beam quality[J]. Optics Letters, 2016, 41(3): 504-507.

[117] Hupel C, Kuhn S, Hein S, et al. MCVD based fabrication of low-NA fibers for high power fiber laser application[C]//Advanced Solid State Laser. 2015: AM4A.2.

[118] Beier F, Hupel C, Kuhn S, et al. Single mode 4.3 kW output power from a diode-pumped Yb-doped fiber amplifier[J]. Opt Express, 2017, 25: 14892-14899.

[119] Jain D, Jung Y, Nunez-Velazquez M, et al. Extending single mode performance of all-solid large-mode-area single trench fiber[J]. Optics Express, 2014, 22(25): 31078-31091.

[120] Jain D, Alam S, Codemard C, et al. High power, compact, picosecond MOPA based on single trench fiber with single polarized diffraction-limited output [J]. Optics Letters, 2015, 40(17): 4150-4153.

[121] Söderlund M J, Ponsoda M J J, Tammela S K T , et al. Mode-induced transverse photodarkening loss variations in large-mode-area ytterbium doped silica fibers [J]. Opt Express, 2008, 16(14): 10633-10640.

[122] Marciante J R. Gain filtering for single-spatial-mode operation of large-mode-area fiber amplifiers[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2009, 15(1): 30-36.

[123] Marciante J R, Roides R G, Shkunov V V, et al. Near-diffraction-limited operation of step-index large-mode-area fiber lasers via gain filtering[J]. Optics Letters, 2010, 35(11): 1828-1830.

[124] Ye C, Koponen J, Kokki T, et al. Confined-doped ytterbium fibers for beam quality improvement: fabrication and performance[C]// SPIE LASE. 2012: 823737.

[125] Fini J M. Bend distortion in large-mode-area amplifier fiber design [C]//Proc of SPIE. 2007: 67810E.

[126] Ma Xiuquan, Liu Chi-Hung, Chang Guoqing, et al. Angular-momentum coupled optical waves in chirally-coupled-core fibers[J]. Optics Express, 2011, 19(27): 26515-26528.

[127] Ma Xiuquan, Zhu Cheng, Hu I-Ning, et al. Single-mode chirally-coupled-core fibers with larger than 50μm diameter cores[J]. Optics Express, 2014, 22(8): 9206-9219.

[128] Dong L, McKay H A, Marcinkevicius A, et al. Extending effective area of fundamental mode in optical fibers[J]. Journal of Lightwave Technology, 2009, 27(11): 1565-1570.

[129] Dong Liang, Peng Xiang, Li Jun. Leakage channel optical fibers with large effective area[J]. Journal of the Optical Society of America B, 2007, 24(8): 1689-1697.

[130] Wong W S, Peng X, McLaughlin J M, et al. Breaking the limit of maximum effective area for robust single-mode propagation in optical fibers[J]. Optics Letters, 2005, 30(21): 2855-2857.

[131] Dong L, McKay H A, Fu L, et al. Ytterbium-doped all glass leakage channel fibers with highly fluorine-doped silica pump cladding[J]. Optics Express, 2009, 17(11): 8962-8969.

[132] Limpert J, Stutzki F, Jansen F, et al. Yb-doped large-pitch fibres: effective single-mode operation based on higher-order mode delocalisation[J]. Light: Science & Applications, 2012,1: e8.

[133] Stutzki F, Jansen F, Otto H-J, et al. Designing advanced very-large-mode-area fibers for power scaling of fiber-laser systems[J]. Optica, 2014, 1(4): 233-242.

[134] Jain D, Baskiotis C, May-Smith T C, et al. Large mode area multi-trench fiber with delocalization of higher order modes[J]. IEEE Jour-

nal of Selected Topics in Quantum Electronics, 2014, 20(5): 242-250.

[135] Jain D, Jung Y, Kim J, et al. Robust Single-mode all-solid multi-trench fiber with large effective mode area[J]. Optics Letters, 2014, 39(17): 5200-5203.

[136] Fridman M, Machavariani G, Davidson N, et al. Fiber lasers generating radially and azimuthally polarized light[J]. Applied Physics Letters, 2008, 93:191104.

[137] Zou Lin, Yao Yao, Li Jianlang. High-power, efficient and azimuthally polarized ytterbium-doped fiber laser[J]. Optics Letters, 2015, 40(2):229-232.

[138] Lin D, Daniel J M, Gecevičius M, et al. Cladding-pumped ytterbium-doped fiber laser with radially polarized output[J]. Optics Letters, 2014, 39(18):5359-5361.

[139] Lin D, Clarkson W A. Polarization-dependent transverse mode selection in an Yb-doped fiber laser[J]. Optics Letters, 2015, 40(4):498-501.

[140] Liu Tong, Chen Shengping, Qi Xue, et al. High-power transverse-mode-switchable all-fiber picosecond MOPA[J]. Optics Express, 2016, 24(24): 27821-27827.

[141] Tanaka Y, Okida M, Miyamoto K, et al. High power picosecond vortex laser based on a large-mode-area fiber amplifier[J]. Optics Express, 2009, 17(16): 14362-14366.

[142] Koyama M, Hirose T, Okida M, et al. Power scaling of a picosecond vortex laser based on a stressed Yb-doped fiber amplifier[J]. Optics Express, 2011, 19(2):994-999.

[143] Kanazawa S, Kozawa Y, Sato S. High-power and highly efficient amplification of a radially polarized beam using an Yb-doped double-clad fiber[J]. Optics Letters, 2014, 39(10):2857-2859.

[144] Kim D J, Kim J W, Clarkson W A. High-power master-oscillator power-amplifier with optical vortex output[J]. Applied Physics B, 2014, 117(1):459-464.

[145] Ngcobo S, Litvin I, Burger L, et al. A digital laser for on-demand laser modes [J]. Nat Commun,2013, 4: 2289.

[146] Huang Liangjin, Leng Jinyong, Zhou Pu, et al. Adaptive mode control of a few-mode fiber by real-time mode decomposition [J]. Optics Express, 2015, 23(21): 28082-28090.

[147] Tian Chenghui, Yu Song, Cai Shanyong, et al. Fiber laser for on-demand mode generation in 1550 nm band[J]. Photonics Research, 2017,5(3) :256.

[148] Zhou Xuanfeng, Chen Zilun, Wang Zefeng, et al. Monolithic fiber end cap collimator for high power free-space fiber-fiber coupling[J]. Applied Optics, 2016, 55(15):4001-4003.

[149] Zhi Dong, Ma Yanxing, Chen Zilun, et al. Large deflection angle, high-power adaptive fiber optics collimator with preserved near-diffraction-limited beam quality[J]. Optics Letters, 2016, 41(10): 2217-2220.

[150] Tao Rumao, Si Lei, Ma Yanxing, et al. Optical quality of high-power fiber laser beams propagating through collimating systems[J]. Acta Physica Sinica, 2011, 60: 104208.

Fundamentals of high-average-power fiber laser technology: Mode

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Abstract: Mode (transverse mode) is one of the key parameters, which could be deduced from the status of the fiber lasers with different mode properties. The relationship between mode and beam quality is analyzed by numerical calculations, based on which it is pointed out that mode decomposition is the key to well understand the mode constitution and beam quality, then the common mode decomposition techniques are introduced. Aimed at mode instability (MI), which is a new phenomenon that prohibits power scaling of fiber laser, various parameters affecting the threshold of MI are summarized, then the physical mechanism and technique to increase the threshold are concluded. The recent progress on mode control of fiber laser is introduced from the viewpoint of high-order-mode suppression and structured light field generation.

Key words: fiber laser; single mode; multimode; mode decomposition; mode instability; mode control

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