

掺镱光纤激光器中的自脉冲效应

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摘要 高功率光纤激光器多选用掺镱双包层光纤作为增益介质。掺镱双包层光纤与普通非掺杂光纤相似, 由于纤芯尺寸非常小, 一般为几微米至几十微米量级, 极易产生自脉冲效应。进行了大功率条件下掺镱光纤激光器自脉冲效应的研究, 观察到不同的自脉冲现象。研究表明, 在大功率激光作用下, 尽管镱离子不存在浓度淬灭, 但是对于大芯径掺镱双包层光纤, 与其他三能级系统相同, 均存在弛豫振荡引发的饱和吸收自脉冲效应。掺镱光纤激光器中的饱和吸收效应、受激布里渊散射、受激拉曼散射等自脉冲效应不容忽视。

关键词 激光器; 光纤激光器; 自脉冲效应; 饱和吸收; 受激拉曼散射; 受激布里渊散射

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Self-Pulsing Behaviors of Yb-Doped Fiber Lasers

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Abstract It is common to use Yb-doped double-clad fibers as gain material for high power fiber lasers. It is found that these fibers are similar to the general un-doped telecommunication fiber. Because of small core size, only from several microns to tens of microns, it is much easier to cause self-pulsing effects in the fiber lasers. It is presented the experimental study of self-pulsing behavior of Yb-doped fiber lasers. The result shows that under the high power condition without concentration effect, large core Yb-doped double-clad fiber are the same to three-level ion systems that self-pulsing behavior is the result of relaxed oscillation. To Yb-doped fiber laser, saturated absorption effect, stimulated Brillouin scattering and stimulated Raman scattering cannot be ignored.

Key words lasers; fiber laser; self-pulsing effect; saturated absorption; stimulated Raman scattering; stimulated Brillouin scattering

1 引言

大功率光纤激光器容易产生自脉冲效应和热效应, 甚至造成光纤损坏^[1~4]。针对掺铒、掺镱光纤激光器进行的研究认为三能级系统产生自脉冲是由于饱和吸收作用, 进而导致离子对相互作用^[5]。增益介质的宿主引入的非线性以及色散效应是导致激光器不稳定的根本原因^[6]。大功率掺镱光纤激光器中的自脉冲效应的产生主要有三个方面的原因: 弛豫振荡^[7,8]、饱和吸收^[9~11]以及受激散射^[12~23]的影响。由于所采用的不同的增益光纤具有不同的模场特性, 因而各种效应影响的作用程度不同。进行了

不同功率水平、不同谐振腔条件下的实验研究, 将大功率条件下的实验结果与文献报道进行了分析比较, 结果发现在大功率激光作用下, 掺镱光纤激光器中的饱和吸收效应、受激布里渊散射、受激拉曼散射引发的自脉冲效应不容忽视。

2 实验研究

利用单端抽运的线性腔结构, 分别采用纤芯直径为 7 μm 和 30.5 μm 的掺镱大芯光纤进行实验, 结果发现随着抽运功率的增加, 掺镱大功率光纤激光器的自脉冲效应呈现不同的特点。

采用纤芯直径 $7\ \mu\text{m}$ 的掺镱双包层光纤的实验,其中受激布里渊散射和受激拉曼散射的影响比较大。

一般情况下,受激布里渊散射的阈值较低,比较容易发生。在抽运功率达到激光器阈值附近时,观察到了激光器的弛豫振荡,继续增大抽运功率,则在弛豫振荡脉冲开始变成一系列的脉冲串,如图 1 所示(此时的抽运功率为 $0.3\ \text{W}$)。

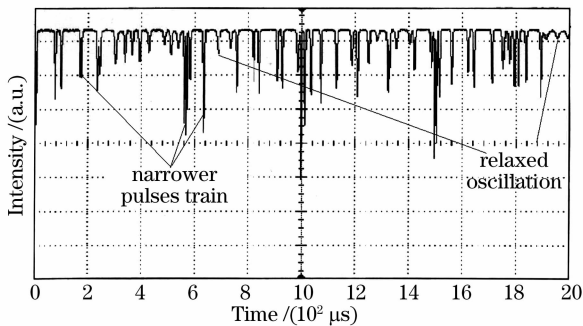


图 1 弛豫振荡脉冲向一系列脉冲串的变化

Fig. 1 Relaxed oscillation pulses change into series of narrower pulses train

将一个脉冲串展开如图 2(a)所示,可以看清受激布里渊散射纳秒量级的弛豫振荡。利用不同的输出反馈使谐振腔形成高低输出损耗两种状态。继续增加抽运功率,高输出损耗状态下发现受激布里渊散射形成的自脉冲在达到一定的峰值以后,随着抽运功

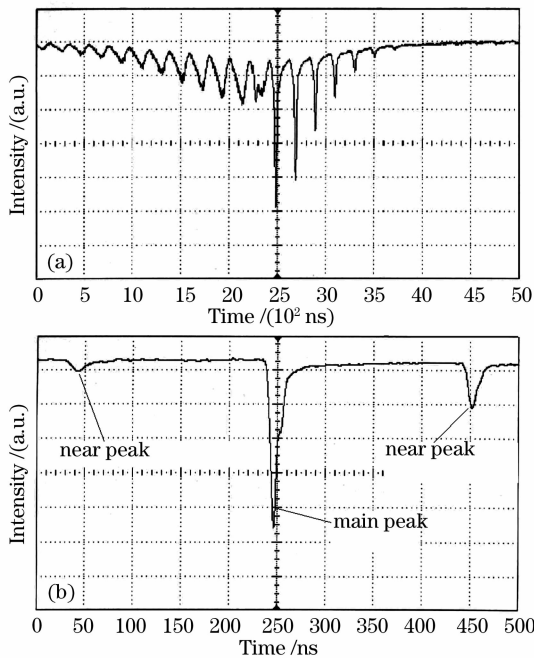


图 2 单个脉冲串(a)主峰时(b)的脉冲展开图

Fig. 2 Expanded scheme of single pulse train (a) single main peak (b)

率的增加仅有一个主峰的峰值功率不断增加,而临近的其他脉冲峰值功率逐渐减小,如图 2(b)所示(抽运功率约为 $0.5\ \text{W}$)。

继续增加抽运功率($1\ \text{W}$ 左右),发现激光信号再次变为无周期性的不规则脉冲串[见图 3(a)],展开可以得到如图 3(b)所示的激光输出。图 3(c)给出相应的光谱图,在激光谱线 $\lambda = 1086\ \text{nm}$ 的长波方向出现了一中心波长为 $1136\ \text{nm}$ 的新谱线,两谱线的波长差为 $50\ \text{nm}$,与在石英光纤由受激拉曼散射效应引起的频移量一致,可以认定光纤中产生了受激拉曼效应。因此可以确定,图 3(b)是在一串布里渊脉冲后出现的峰值较高的拉曼脉冲。

在低输出损耗状态下,随着抽运功率的增加,形

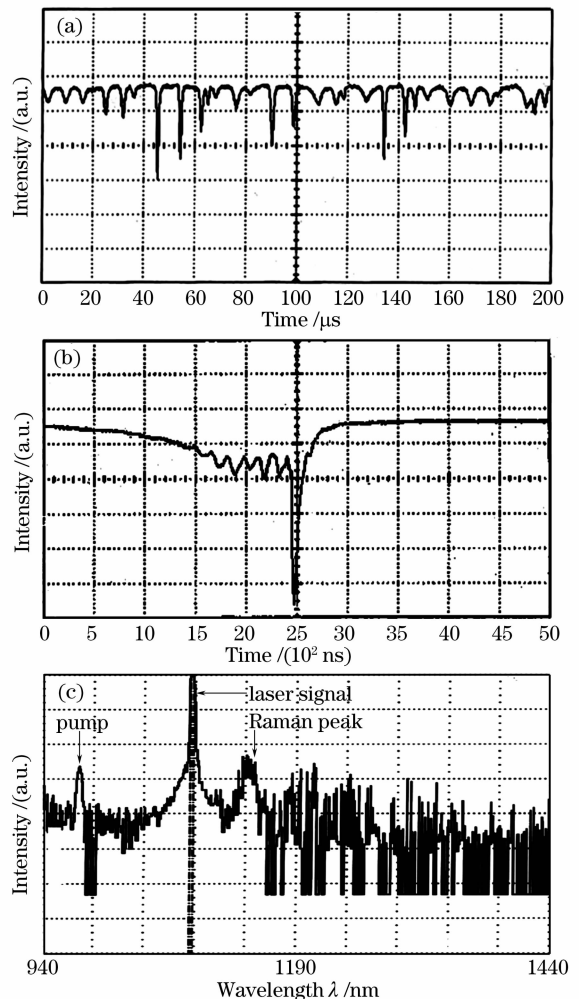


图 3 连续抽运功率接近 $1\ \text{W}$ 时光纤激光输出的动态特性。(a)时域特性整体图,(b)单个脉冲展开图,(c)光谱特性

Fig. 3 Dynamics of single mode double-clad laser output near $1\ \text{W}$ CW pumping. (a) Whole dynamic character, (b) expanded single pulse, (c) spectral character

成较为稳定的振荡,脉冲峰值功率的稳定度为 $\pm 5\%$,如图4所示。这与脉冲抽运条件下得到的结果十分相似,二者的区别在于脉冲抽运时得到的激光脉冲的间隔大,多为微秒量级,且相邻的两个脉冲之间没有噪声的干扰。

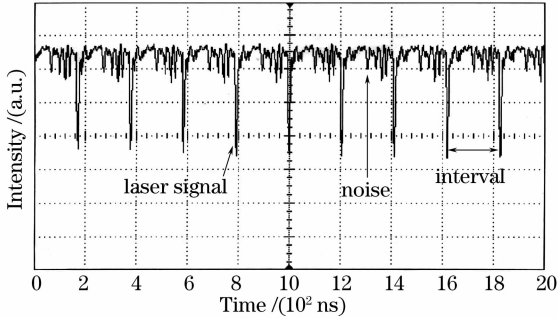


图4 低输出损耗状态下受激布里渊散射自脉冲效应
Fig. 4 Low loss condition the self-pulsing behavior of stimulated Brillouin scattering

采用纤芯直径 $31.5\ \mu\text{m}$ 的掺镱双包层光纤进行实验,观察到弛豫振荡引起的饱和吸收效应。随着抽运功率的增加,饱和吸收效应越来越明显。在抽运功率为 $15\ \text{W}$ 时就观察到了饱和吸收效应,如图5(a)所示,并且强度随着抽运功率的增加也逐步得到增强。在低输出损耗时继续增大抽运功率,如图5(b)所示,当抽运光功率增加到 $20\ \text{W}$ 时,观察到了 $10\ \text{ns}$ 以下

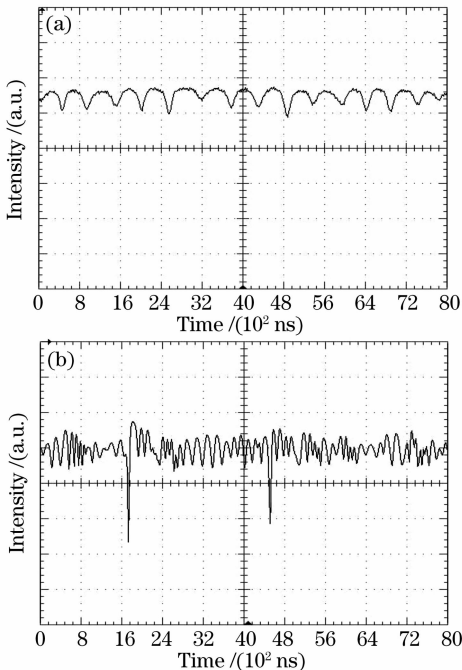


图5 高输出损耗、抽运功率为 $15\ \text{W}$ (a)低输出损耗抽运功率为 $20\ \text{W}$ (b)时的饱和吸收自脉冲

Fig. 5 Saturated absorber self-pulsing behavior when pump power reaches $15\ \text{W}$ (a) pump power reaches $20\ \text{W}$ (b)

脉冲。

当抽运光增大到一定的功率后,靠近抽运光入射端的部分光纤中,抽运功率较大,增益系数大于损耗系数,产生了激光。抽运光继续沿光纤向前传输时,由于损耗,抽运功率迅速减小,增益系数也随之下降,小于损耗系数时,这部分光纤就不再产生激光。它还会吸收前一部分光纤激光的激光光子,成为一段可饱和吸收体。随着抽运功率的继续增大,产生激光的光纤长度也不断增加,但仍有部分光纤以吸收体的形式存在。这种过程表现为光纤的输出功率不稳定,且抽运功率增加时,输出功率增加缓慢。进一步增加抽运功率,使得在整根光纤上都有净增益,于是输出功率再次随入纤功率线性增加。饱和吸收产生的自脉冲的峰值功率较高,当其峰值功率满足受激布里渊散射或者受激拉曼散射的阈值时,相应的受激散射产生。

3 结 论

大功率光纤激光器中的自脉冲效应对激光器的质量影响极大。产生自脉冲效应的原因有很多,对于单模掺镱双包层光纤,受激布里渊散射和受激拉曼散射的影响最大。对于大芯径掺镱双包层光纤,饱和吸收效应对于自脉冲效应的影响更大。此外,谐振腔输出损耗的影响十分关键,输出损耗越高,自脉冲效应越不稳定,输出损耗越低,不仅能够产生更窄的脉冲,还可以起到稳定激光器输出的目的。但是在千瓦量级的水平下,更窄的脉冲意味着峰值功率的大幅度增加,会引发光纤的损坏等问题的出现。

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