980 nm大功率垂直腔面发射激光器偏振特性

彭　彪[1,2]，宁永强[1*]，秦　莉[1]，孙艳芳[1,2]，李　特[1,2]，崔锦江[1,2]，
刘光裕[1,2]，张　岩[1,2]，顾媛媛[1,2]，彭航宇[1,2]，王立军[1]
(1. 中国科学院 长春光学精密机械与物理研究所，吉林 长春　130033；2 中国科学院 研究生院，北京　100049)

摘要：大功率垂直腔面发射激光器单管器件出光口径大、横向模式多。随着注入电流和工作温度的改变出射光偏振态在两个正交偏振基态上转换。为分析输出光偏振特性，采用 500 μm出光口径 980 nm底发射器件，通过控制器件热沉温度，利用偏振分光镜分离正交偏振基态为透射波和反射波，半导体综合参数测试仪测量其功率、中心波长等参量。分析得出：两个偏振态的光功率温度特性与未加偏振分光镜时的总输出光的温度特性基本一致，中心波长差随温度升高缓慢增加。在温度低于 328 K时，随着注入电流的增大，反射波首先达到阈值，形成激射。但透射光波形成激射后其斜效率大于反射波。因此在达到某个电流后两个偏振态的功率变化曲线出现交替。当温度升高到 328 K以上时两个偏振态的功率曲线却没有明显的交替。根据对大尺寸 VCSEL器件偏振特性的研究，提出通过外腔选频的方法来控制偏振的方案，分析计算后得出外腔腔长大约为 0 45 mm。

关　键　词：垂直腔面发射激光器；偏振分光镜；偏振基态
中图分类号：O482 31　　**PACC**：3250F；7860　　文献标识码：A

1　引　　言

垂直腔面发射激光器(VCSEL)具有低成本、低阈值[1,2]、单纵模输出[3]、光束近圆[4~6]等优点。但由于其增益分布和谐振腔结构上的柱对称性，理论上可以输出任意方向上的偏振光，所以其输出光很难有一个稳定的偏振方向[7]。根据增益与晶体晶向的关系[8,9]，对于沿 GaAs衬底[001]方向的标准器件而言，具有两个相互正交的偏振基态，其电矢量沿着$[110]$和$[\bar{1}10]$晶轴方向，并且随着注入电流和温度的改变偏振方向在这两个正交方向上转换[10,11]。同时，由于半导体材料的电光效应两个偏振基态上的光具有微小的波长差[12]。

VCSEL不稳定的偏振光输出对于一些光偏振敏感的应用是很致命的，例如光传输上将会加大误码率，在激光倍频上也很难获得稳定的二次谐波，降低倍频效率[13]。用于通信上的单管VCSEL器件要求功率低，出光口径小，单横模输出偏振态便于控制，但用于激光倍频中的 VCSEL器件要求功率比较大，对于单管器件则出光口径大，横向模式多，难于控制。为此设计了如下实验来研究了大口径高功率 VCSEL的偏振特性。并提出了获得稳定偏振的设想。

2　实验原理和方案

2 1　实验装置

实验装置示意图如图 1所示。实验中将封装完毕的 VCSEL器件固定在一个铜加热器上，加热器通过热偶和温控仪连接，温控仪通过接受到的温度反馈控制变压器的供电时间从而实现控温。由于直接检测和控制器件的温度比较困难，这里通过监测热沉的温度来表示器件的热效应。VCSEL由半导体激光器综合参数测试仪提供 0~ 6 A直流驱动，出射光射到偏振分光棱镜 (PBS)上，分离为电矢量相互正交的透射波和反射波，调整系统使透射波和反射波分别对应 VCSEL的两个偏振基态，输出光通过综合参数测试仪自带的积分球接收信号，分别测试出两个方向上的光功率、中心波长等。

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作者简介：彭彪(1982-)，男，四川眉山人，主要从事垂直腔面发射激光器的研究。
E-mail：pbciomp0728@hotmail.com

*：通讯联系人；E-mail：ningyq@ciomp.ac.cn，Tel：(0431)86176348

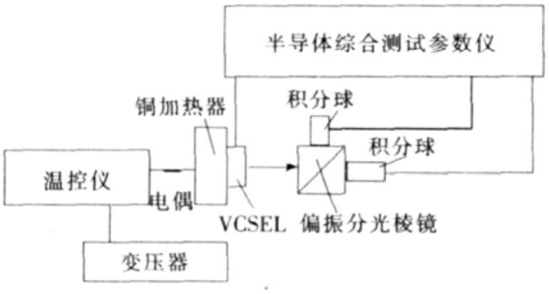

图 1 实验装置示意图

Fig. 1 Scheme of experimental setup.

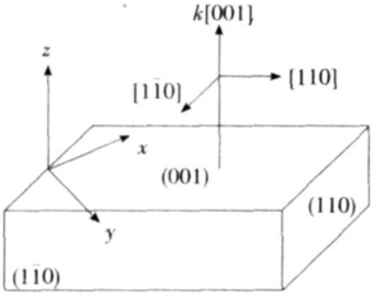

图 2 管芯解理方向和偏振基态示意图

Fig. 2 Schematic diagram of the crystal orientation of the VCSEL chip and basic polarization state orientations.

在这里要注意的是器件偏振基态方向和 PBS的 ***p*** 矢量和 ***s*** 矢量方向的重合问题。如图 2所示 *o-xyz*为原胞坐标, (110)为 VCSEL管芯解理面, ***k*** 为光传播方向, [110]和 [$\bar{1}10$] 分别对应两偏振基态方向[14], 所以在器件制作过程中选定沿解理面切割芯片, 使解理方向为管芯的一直边, 封装完成后虽无法辨别解理方向但可以通过调整管芯直角边位置保证其和 PBS的 ***p*** 矢量和 ***s*** 矢量方向平行。

此外, 由于外界条件影响, 基态方向将发生微小角度的偏差, 并不是严格的在晶轴方向, 但由于器件功率瓦级以上且偏差角度很小, 发生的功率偏差也很小, 所以我们忽略了这种影响。

2.2 实验方案

通过温控仪, 控制热沉温度从 298 K 稳定变化到 368 K。每个测试点温度间隔为 5 K(控温过程中要注意的是, 在每一个热沉温度下, 器件内部温度仍然随电流变化, 只不过随着热沉温度的升高器件热效应越加严重, 器件性能变差)。利用半导体激光器综合参数测试仪, 分别测量每一个温度下, 通过 PBS后反射光波和透射光波的光功率和中心波长。

3 结果与讨论

实验中采用自行制作的 980 nm 底发射 VCSEL, 衬底为 n-GaAs, 有源层由 3个 8 nm 的 $\mathrm{In_{0.2}Ga_{0.8}As/GaAs}$量子阱构成, n-DBR 为 $\mathrm{In_{0.9}Ga_{0.1}As/GaAs}$(掺 Si), p-DBR 为 $\mathrm{In_{10.9}Ga_{0.1}As/GaAs}$(掺 C), 器件采用湿法氧化工艺制作, 出光口径为 500 μm。

以 T表示经过 PBS后的透射波, F代表反射波, 如图 3所示, 为透射波和反射波中心波长随热沉温度的变化曲线。从图 3中可以得出反射方向的波长在 298~ 363 K 范围内都比透射方向的要大, 这主要是由于阱材料的双折射效应, 导致二者对应的实际折射率不同, 根据谐振条件必然输出波长不一样[15]。但 368 K时候急剧下降, 这主要因为此时反射方向已经为多纵模工作 (如图 4所示), 已不属于正常工作范围, 也正因为如此, 在图 3中对波长变化曲线进行线性拟合时, 去掉了 368 K处的值, 进而得到: 二者在正常工作范围内波长随温度变化幅度反射波略大于透射波。

如图 5所示为透射波和反射波在不同温度下的 *P*-*I* 曲线。

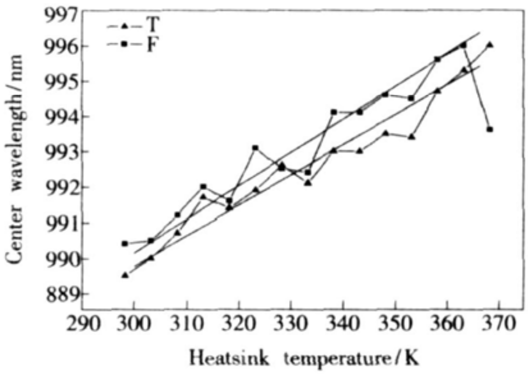

图 3 透射和反射波长随热沉温度变化曲线

Fig. 3 Temperature dependences of the transmission wavelength and reflection wavelength.

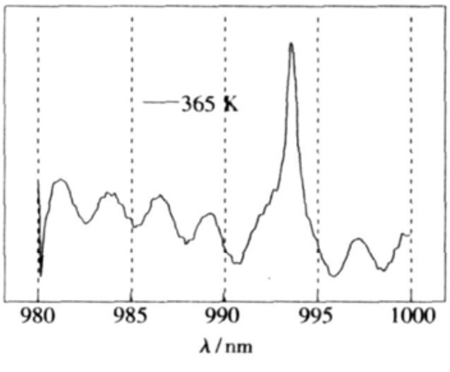

图 4 368 K 时反射波光谱

Fig. 4 Reflection spectrum at 368 K.

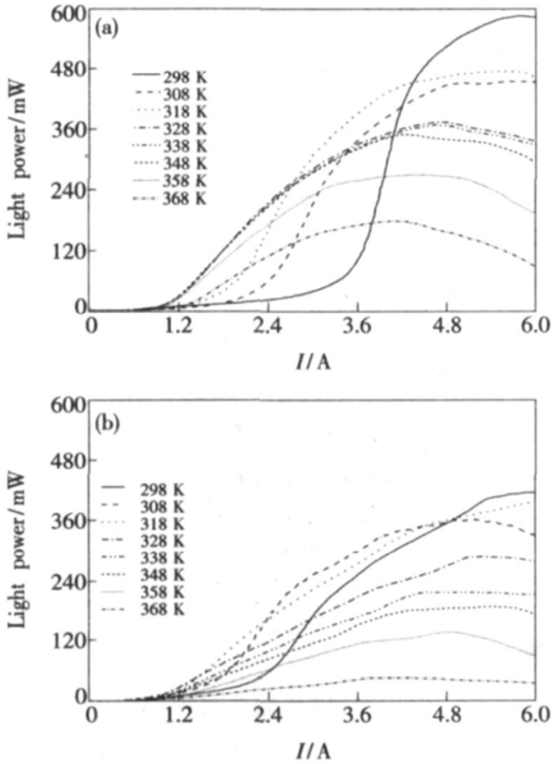

图 5　不同温度下, (a)透射波 (T)和 (b)反射波 (F)光功率随注入电流的变化

Fig. 5　Power-current curves of the transmission wave and reflection wave at different temperatures (a) Transmission wave; (b) Reflection wave

由图 5中可见, 透射波和反射波光功率总体趋势都随着温度的升高而降低, 这和器件总输出光的温度特性是一致的[16], 但在 318 K的透射波和反射波功率反而比 308 K时要高, 这可能因为此温度下有源层内部激射波长和 DBR反射谱最为匹配。

通过比较相同热沉温度下的透射波、反射波光功率可以得到图 6。由图 6可知 298, 308, 318 K分别在 3.978, 3.233, 2.397 A处发生偏振态转换, 但热沉温度继续升高到 328 K时, 就已经观察不到明显的偏振态交替了。图 6(a)中可见在热沉温度较低时 (328 K以下), 低电流注入下反射波的光功率总是比透射波大, 这主要是因为热沉温度较低, 热效应不是很严重, 内部温升小, 透射波和反射波红移小, 但反射波长大于透射波长所以更加接近 DBR反射谱中心波长, 所以反射波占优势; 当电流注入较高时, 器件内部自身温升大, 透射波和反射波红移较大, 所以波长较小的透射波波长更加接近 DBR反射谱中心波长, 因此透射波占优势。图 6(b)中可见, 在热沉温度较高时 (328 K以上), 透射波始终占优势, 这主要是因为热沉温度高, 热效应大, 器件内部温度很高, 载流子向高能带激发, 所以波长较短的透射波占优势。

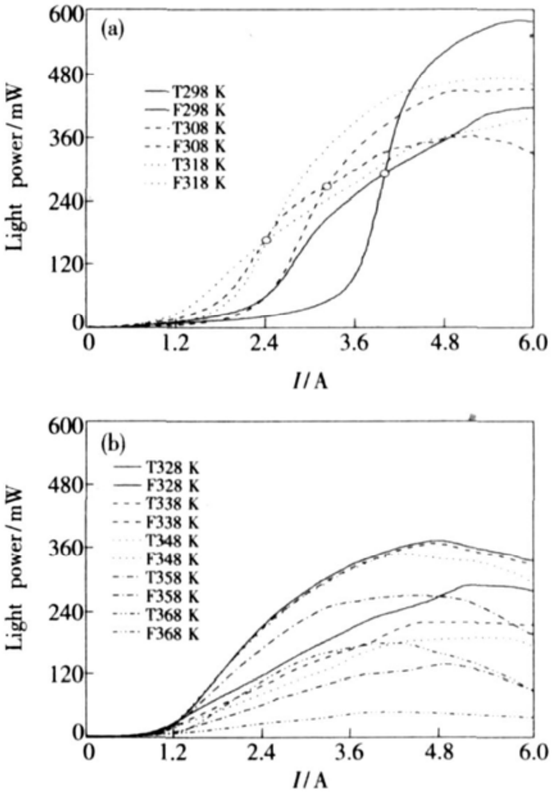

图 6　不同热沉温度下偏振态转换示意图

Fig. 6　Polarization state alternate at different substrate temperature (a) below 328 K; (b) above 328 K.

由于不同热沉温度下两偏振基态峰值功率基本在同一电流处, 所以取透射和反射的峰值功率来计算偏振度 $p = 10\lg\left|\frac{P_T}{P_F}\right|$, P_T, P_F 表示透射波和反射波的峰值功率。他们分别对应 VCSEL出射光的两个偏振基态。由偏振度曲线可以看出, 沿透射波方向的峰值高于反射波, 但偏振度都较小,

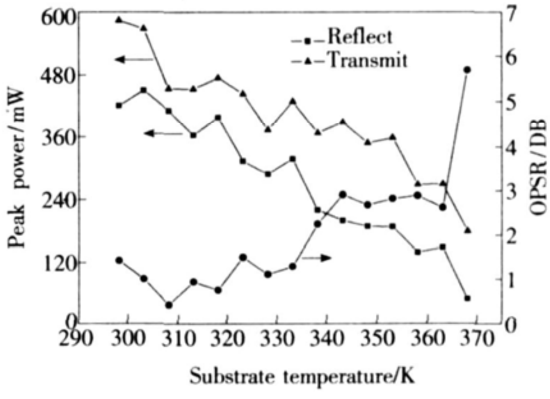

图 7　透射波和反射波峰值功率随衬底温度的变化以及正交偏振比曲线

Fig. 7　Transmission wave and reflect wave's peak power and orthogonal polarization suppression ratio (OPSR) changing with substrate temperature

所以总的输出光为椭圆偏振。

通过以上分析得出利用下面的外腔结构来控制高功率大口径器件的偏振态[17,18]。

外腔偏振控制系统结构示意图如图 8所示。界面 1和界面 2构成了一个 F-B腔结构，腔长为 L，根据其选频公式

$$\Delta\nu = \frac{c(1-\sqrt{R_1R_2})}{2\pi nL(R_1R_2)^{1/4}}$$

对于适当的外腔镜，调整的距离 L，使 $\Delta\nu$与测量出的波长差吻合，即可达到一定程度的稳偏效果。

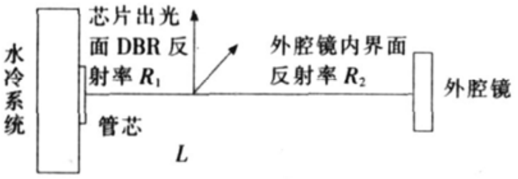

图 8　外腔偏振控制系统结构示意图

Fig. 8　External resonance polarization control system structure.

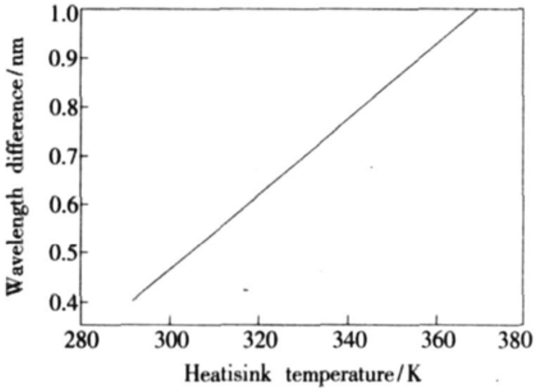

图 9　透射波和反射波峰值波长差随热沉温度的变化曲线

Fig. 9　Transmission wave and reflect wave's center wavelength difference changing with substrate temperature.

对于该器件其波长差曲线如图 9所示，所以为器件加上一个水冷系统控制器件工作温度，控制其波长差变化，便于腔长调节，实际上根据文献[18]所述，由于波长的红移，腔长精度要求并不需要很高。取波长为 980 nm 波长差平均值为 0.7 nm，$R_1 = 0.993$，$R_2 = 0.8$，$n = 1$，根据 $\Delta\nu = c/\lambda^2 \cdot \Delta\lambda$，初步计算腔长$L = 0.45$ mm。

4　结　论

通过以上分析可知，对于高功率大口径单管器件，由于其出光孔径大，横向模式多，受外界影响复杂，所以他的偏振特性不同于低功率小口径单模器件。热效应较小时，随着电流的变化偏振态发生交替，但当热效应较大时，将不再发生交替，但此时两偏振态各自的功率显著降低，所以不能达到大功率稳定偏振的效果。此外无论热效应如何，大口径器件偏振比都不高，所以其输出光为椭圆偏振光。但出射光两正交方向的波长差随温度值缓慢增大，所以通过控制器件工作温度，利用外腔系统达到稳偏效果。

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Polarization Characteristics of 980 nm High Power Vertical Cavity Surface Emitting Laser

PENG Biao[1,2], NING Yong-qiang[1], QIN Li[1], SUN Yan-fang[1,2],
LI Te[1,2], CUI Jin-jiang[1,2], LIU Guang-yu[1,2], ZHANG Yan[1,2],
GU Yuan-yuan[1,2], PENG Hang-yu[1,2], WANG Li-jun[1]

(1. *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun* 130033, *China*;
2. *Graduate School of the Chinese Academy of Sciences, Beijing* 100049, *China*)

Abstract Vertical-cavity surface-emitting lasers (VCSEL) have many advantages such as low threshold current and single mode operation, as well as easy to be fabricated in high-density arrays and low cost in manufacturing. VCSELs are used in many areas, for example, optical communications, optical interconnections, and optical signal processing. But in some applications, the polarization orientation is sensitive, such as optic recording and laser frequency doubling. It is necessary to control the polarization characteristics of VCSEL effectively. In fact, the reliable control of the polarization orientation of single devices with small emission window is realized through many methods, in which the most popular one is the sub-wavelength surface grating technique. But due to the existence of multi-transverse modes in high power VCSEL devices with large emission window, the polarization orientation changes from one basic state to the other orthogonal one depending on the input current and temperature. The temperature dependence of the polarization characteristics of a 980 nm bottom-emitting laser with 500 μm emitting aperture is investigated. The temperature changes from 298 K to 368 K with a increasing step of 5 K. It is not easy to directly measure the temperature of the active region, so the temperature of the heatsink is used to characterize the temperature of the active region. A polarization beam splitter (PBS) element is used to split the two orthogonal polarization states into transmission wave and reflection wave, respectively. The output powers and center-wavelengths of these two orthogonal polarizations states are measured by using a semiconductor laser parameters test system. The temperature dependence of the output power of each polarization state is the same as that of the total output power of the device without the PBS. The center-wavelength difference between the two polarization states increases slowly with increasing temperature. When comparing the polarization behavior of both states, we find that the reflection state reaches threshold of lasing before the transmission state when the device is kept at a temperature below 328 K. But the output power in the transmission state rises quickly than that in the reflection state. At every temperature, there is a certain current where the powers in the two states are equal with increasing the current. With increasing the current further, the power in the transmission state is higher than that in the reflection state. And when the device is kept at a temperature above 328 K, there is no obvious alternation point between the two states, and the power in the transmission state is higher than that in the reflection state all the time. The reason may be that at low temperature and low current, the heat effect is not serious, the red shifts of the reflection wave and transmission wave are both small, but reflection one is a little more, so the reflection wave is closer to the center-wavelength of DBR. With increasing the current, the internal temperature of the device increases seriously, the red shift of reflection state increase faster than that of transmission state, so the transmission wave is closer to the center-wavelength of DBR. At high temperature the heat effect is serious, whatever at low current and high current, both of the red shifts are big, so the transmission wave is closer to DBR center-wavelength all the time. According to the detailed investigation on the polarization characteristics of large diameter VCSEL device, a method with an external resonator was proposed to realize a stable polarization orientation with a resonance length of about 0.45 mm.

Key words: vertical cavity surface emitting laser (VCSEL); PBS; polarization basic state

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