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# 长波红外量子级联激光器的高效率光纤合束

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**摘要** 长波红外量子级联激光器（QCL）具有波长设计灵活、体积小、寿命长等优点。目前单横模QCL较低的输出功率（1～3 W）是限制其应用的主要因素。光纤功率合束技术是提升输出功率的有效手段。然而由于长波红外波段缺少低传输损耗的玻璃光纤，使得高效率长波红外光纤功率合束的实现难度很大。本文研究了基于低损耗单模空芯光纤的长波红外激光功率合束技术。针对基横模长波红外QCL有源区尺寸大、发散角大的特点，设计了大数值孔径扩展光源双非球面准直镜，有效提高了单模光纤耦合效率。设计制备了无端面损耗的长波红外单模光纤束，光纤传输效率高达91.2%，实现了7.6～7.8 μm波段QCL的高效率合束。当4个长波红外QCL的输出总功率为2.27 W时，采用所设计的光纤耦合光学系统及制备的4×1单模空芯光纤合束器获得了1.5 W的连续输出，总合束效率为66%。此外，测量得到单根单模长波红外光纤耦合输出光的光束质量因子$M^2$为1.2，光强分布和光束质量因子均优于QCL的直接输出激光，说明空芯单模光纤具有一定的非高斯光束模式净化作用。合束光束的传输质量因子为2.6，依然具有较好的光束质量。本文所研究的光纤合束方式对QCL的输出波长、偏振态均不敏感，且具有良好的可扩展性。实验结果表明，此方式可有效解决长波红外QCL单元器件输出功率偏低的问题。

**关键词** 长波红外；量子级联激光器；光纤合束；耦合效率；空芯光纤

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## 1 引 言

量子级联激光器（QCL）是一种基于子带间电子跃迁的半导体激光器，可以直接发射3～300 μm的红外光，使用方法简单、光电转换效率高、体积小，是气体传感、环境监测、医疗诊断和光电对抗等领域的理想光源[1-2]。近年来，中长波红外波段QCL在设计原理和制备工艺上均获得了长足进步[3-5]，基横模长波红外QCL在室温下连续运转时的最高输出功率可达到3.4 W[6]。然而，在很多些应用中，为了提高测量范围和测量精度，对QCL的输出功率、光束质量和稳定性提出了更高的要求[7]。激光合束技术是光源输出功率扩展的最常用手段。

半导体激光器的功率合束主要采用非相干技术，包括光谱合束、偏振合束和空间合束[8-11]。对于中长波QCL功率合束，2022年，Zhang等[12]利用金属平面闪耀光栅实现了两路中波红外QCL的光谱合束，合束效率约为54%。该合束方法对QCL的发射中心波长与光谱宽度都有较严格的要求。此外，与近红外半导体激光器相比，QCL较长的波长使得光栅刻线的线对数较小，所导致的低色散要求参与合束的QCL光谱间隔较大。这意味着在一定波段内能参与合束的QCL数量有限。2022年，王珂等[13]使用偏振合束技术实现了两路4.05 μm波段QCL的合束，合束后光束质量较好。但偏振合束只能实现两路正交偏振激光的功率合束。2019年，Major等[14]制备了7×1硫系光纤合束器，实现了4个不同波段QCL的合束，获得了波长范围为6.02～11.3 μm的宽波段激光输出。受限于硫系光纤的传输带宽，在11.3 μm处传输损耗为12.4 dB/m，使得总体合束效率不高。2023年，黄梓轩等[15]制备了7×1硫系光纤合束器，在不计入光纤耦合损耗和光纤端面反射损耗的情况下，测试得到3 μm和4.5 μm波长处的光纤端口传输效率优于85%，但尚未使用制备的光纤进行合束实验。由以上研究结果可知，中长波红外QCL的功率合束，尤其是在长波红外波段，受限于低损耗光学材料和元件制备工艺，报道的结果较少，仍存在传输损耗高、合束效率低的问题。

为实现高效率、高光束质量长波红外QCL多路合束，本文针对QCL发光面大、发散角大的特点，对大数值孔径、扩展光源双非球面准直镜进行了优化设计，降

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低了由于光源与单模光纤模式不匹配导致的耦合损耗。通过使用无端面损耗、低传输损耗的长波单模空芯光纤，提高了光纤端口传输效率。实验制备了4合1单模空芯光纤合束器，开展了7.6~7.8 μm波段长波红外QCL的光纤合束研究。当单路QCL平均输出功率为0.57 W时，合束获得了1.5 W的连续激光输出，总体合束效率达到66%；在实验上获得了较高效率的多路长波红外光纤合束。本文所研究的方法对QCL的中心波长、光谱宽度、偏振态均无严格要求，且使用的光学元件少、结构紧凑、易扩展。

## 2　设计与制备

### 2.1　高效率光纤耦合光学系统设计

为了实现QCL输出激光到单模光纤的高效率耦合，需要通过光束变换使激光束腰和发散角与光纤芯径和数值孔径匹配。中心波长为$\lambda$、束腰为$\omega_0$、距离透镜为$l$的基模高斯光束经过焦距为$F$的单透镜时，光束发散角$\theta_0'$、束腰大小$\omega_0'$及束腰位置$l'$[16]可表示为

$$\theta_0'=\frac{2\lambda}{\pi}\sqrt{\frac{1}{\omega_0^2}\left(1-\frac{l}{F}\right)^2+\frac{1}{F^2}\left(\frac{\pi\omega_0}{\lambda}\right)^2},\tag{1}$$

$$\omega_0'^2=\frac{F^2\omega_0^2}{(F-l)^2+\left(\frac{\pi\omega_0^2}{\lambda}\right)^2},\tag{2}$$

$$l'=F+\frac{(l-F)^2F^2}{(l-F)^2+\left(\frac{\pi\omega_0^2}{\lambda}\right)^2}。\tag{3}$$

为尽量降低光纤耦合光学系统的复杂度和元件的失调灵敏度，本文所设计的光纤耦合光学系统由一片QCL准直镜和一片光纤耦合镜组成，如图1所示，QCL的快轴出光面位于QCL准直镜后焦点处，单模光纤端面位于光纤耦合镜后焦面。

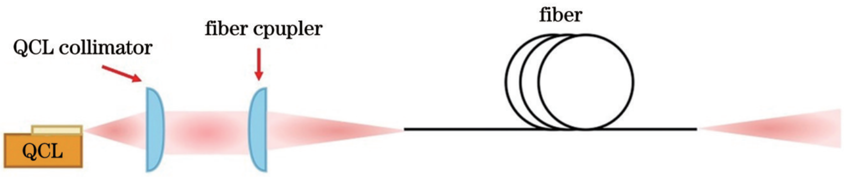

图1　光纤耦合光学系统示意图

Fig. 1　Schematic diagram of fiber-coupled optical system

区别于传统的单模玻璃或晶体光纤，单模空芯光纤具有较大的芯径和很小的数值孔径，因此，光纤耦合光学系统采用扩束系统。当选用的单模空芯光纤芯径为300 μm时，根据如表1所示的长波红外基横模QCL参数，可计算得到扩束系统的放大倍数为37.5。由此，本文选择QCL准直镜的焦距为4.5 mm，而光纤耦合镜焦距为150 mm。相比于可见光与近红外单模半导体激光器的快轴束腰（通常小于1.5 μm），长波红外QCL的束腰较大，因此本文将其看作扩展光源。

表1　长波红外QCL性能参数表

Table 1　Performance parameters of long-wave infrared QCL

| QCL center wavelength /μm | Fast axis waist radius /μm | Slow axis waist radius /μm | Fast axis divergence half-angle /(°)(1/$e^2$) | Slow axis divergence half-angle /(°)(1/$e^2$) |
|---|---|---|---|---|
| 7.8 | 4 | 4.5 | 34.73 | 30.64 |

作为对比，分别设计了焦距为4.5 mm、直径为9 mm的点光源QCL准直镜与扩展光源QCL准直镜，设计结果如表2和表3所示，材料选用ZnSe，通过表面镀增透膜降低反射损耗；点光源QCL准直镜为单非球面，而扩展光源QCL准直镜的两个面均为非球面。

表2　点光源QCL准直镜参数

Table 2　Lens data of point-source QCL collimator

| Surface | Radius of curvature | Semi-diameter / mm | Thickness /mm | Material | Conical coefficient | 4th order term | 6th order term | 8th order term |
|---|---|---|---|---|---|---|---|---|
| 1 | −17.866 | 4.5 | 2.3 | ZnSe | 0 | 0 | 0 | 0 |
| 2 | −5.060 | 4.5 | — | — | −0.531 | $2.130\times10^{-5}$ | $2.181\times10^{-6}$ | $1.144\times10^{-9}$ |

图2为两个QCL准直镜的发散角仿真结果，图2(a)为按照点光源设计的准直镜的准直光束均方根(RMS)发散角，为0.001 mrad，图2(b)~(d)为按照扩展光源设计的准直镜的发散角，三个视场的RMS发散角分别为0.007、0.031、0.031 mrad。

在ZEMAX物理光学传播中对两个QCL准直镜

表3 扩展光源QCL准直镜参数

Table 3 Lens data of extended-source QCL collimator

| Surface | Radius of curvature | Semi-diameter /mm | Thickness /mm | Material | Conical coefficient | 4th order term | 6th order term |
|---|---|---|---|---|---|---|---|
| 1 | 55.333 | 4.5 | 3 | ZnSe | $-1.616\times10^{36}$ | $1.329\times10^{-4}$ | $7.005\times10^{-7}$ |
| 2 | $-6.990$ | 4.5 | — | — | $-0.276$ | $4.593\times10^{-4}$ | $8.702\times10^{-6}$ |

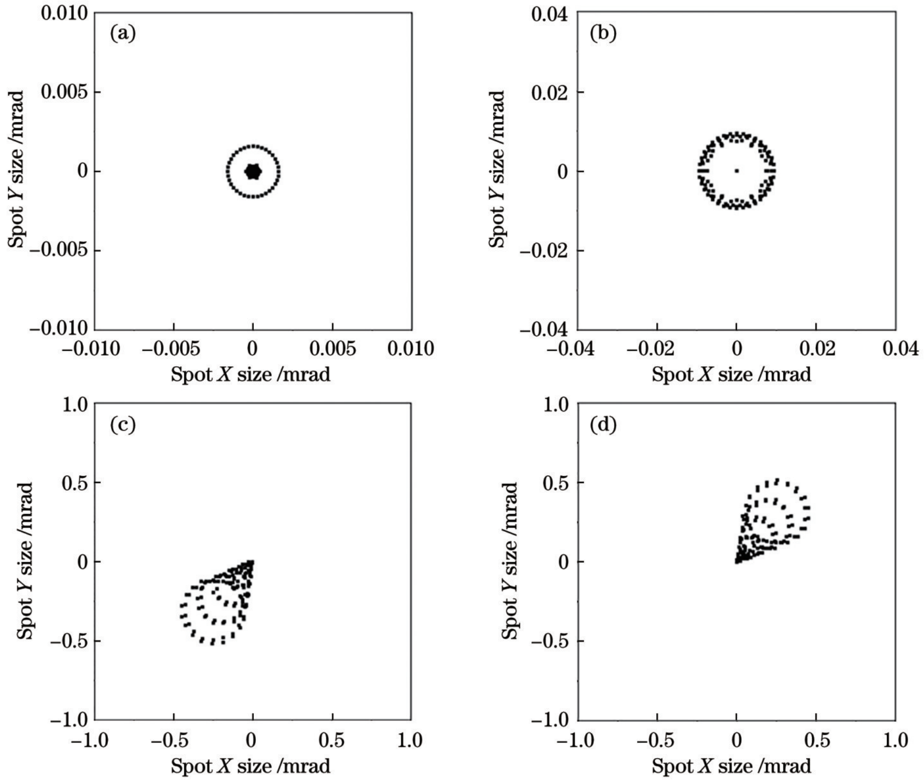

图2 准直光束发散角仿真结果。(a)点光源QCL准直镜发散角;(b)扩展光源QCL准直镜(0 mm,0 mm)视场的发散角;(c)扩展光源QCL准直镜(−0.004 mm,−0.005 mm)视场的发散角;(d)扩展光源QCL准直镜(0.004 mm,0.005 mm)视场的发散角

Fig. 2 Simulation results of divergent angles of collimated beams. (a) Divergent angle of point-source QCL collimator; (b) divergent angle of extended-source QCL collimator with (0 mm, 0 mm) field of view; (c) divergent angle of extended-source QCL collimator with (−0.004 mm, −0.005 mm) field of view; (d) divergent angle of extended-source QCL collimator with (0.004 mm, 0.005 mm) field of view

的准直效果进行仿真，准直光斑的快轴方向强度分布如图3所示，准直后的光斑均为基模高斯分布。但点光源准直光束的实际发散角为0.8 mrad，而按扩展光源设计的准直镜的准直后光束发散角为0.7 mard。因

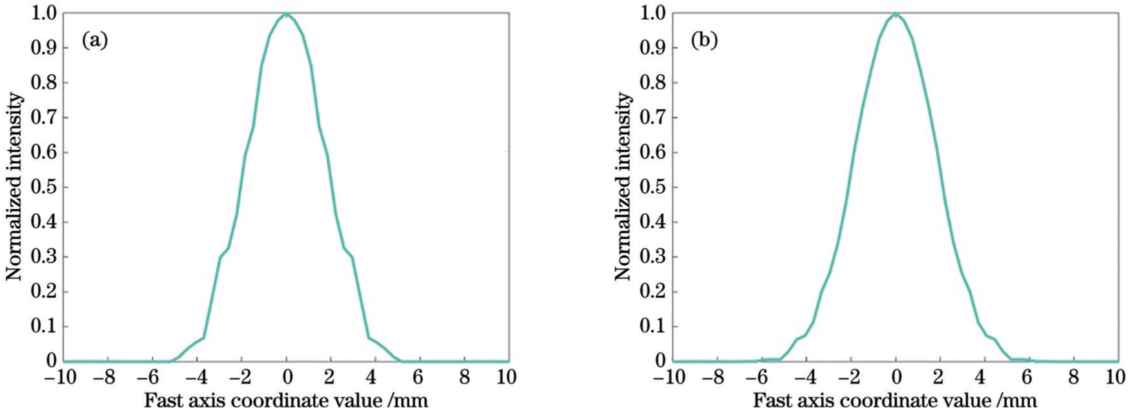

图3 两种准直镜的光束发散角仿真结果。(a)点光源QCL准直镜;(b)扩展光源QCL准直镜

Fig. 3 Simulation results of divergent angles of two collimators. (a) Point-source QCL collimator; (b) extended-source QCL collimator

此本文将QCL视为扩展光源，对QCL准直镜进行设计和优化。

由于基横模长波红外QCL发散角较大，因此必须设计大数值孔径准直镜，才能获得高透过率、低边缘衍射，从而提高光纤耦合效率。将QCL视为扩展光源，分别设计了焦距为4.5 mm、数值孔径（NA）为0.68及焦距为4.5 mm、NA为0.83的QCL准直镜；设计结果如表4和表5所示，材料仍然选用ZnSe。

表4　NA为0.68的QCL准直镜参数

Table 4　Lens data of QCL collimator with NA of 0.68

| Surface | Radius of curvature | Semi-diameter /mm | Thickness /mm | Material | Conical coefficient | 4th order term | 6th order term |
|---|---|---|---|---|---|---|---|
| 1 | 55.333 | 4.5 | 3 | ZnSe | $-1.616\times10^{36}$ | $1.329\times10^{-4}$ | $7.005\times10^{-7}$ |
| 2 | −6.990 | 4.5 | — | — | −0.276 | $4.593\times10^{-4}$ | $8.702\times10^{-6}$ |

表5　NA为0.83的QCL准直镜参数

Table 5　Lens data of QCL collimator with NA of 0.83

| Surface | Radius of curvature | Semi-diameter /mm | Thickness /mm | Material | Conical coefficient | 4th order term | 6th order term |
|---|---|---|---|---|---|---|---|
| 1 | 55.333 | 6 | 3 | ZnSe | $-1.994\times10^{36}$ | $-1.743\times10^{-5}$ | $-4.421\times10^{-7}$ |
| 2 | −6.990 | 6 | — | — | −0.276 | $4.480\times10^{-4}$ | $3.157\times10^{-6}$ |

基横模长波红外QCL的输出光经过两个不同数值孔径准直镜准直后，距离准直镜后表面10 mm处的光斑分布仿真结果如图4所示。NA为0.68的QCL准直镜透过率为86%，而NA为0.83的QCL准直镜透过率为94%。由图可见，经过较低数值孔径QCL准直镜准直后的光斑具有明显的与口径相同的尺寸边缘，说明部分光束未通过透镜，且会在边缘发生衍射。准直后的快轴光斑直径为7.2 mm，发散角为0.67 mrad；与设计值0.7 mrad相符合。

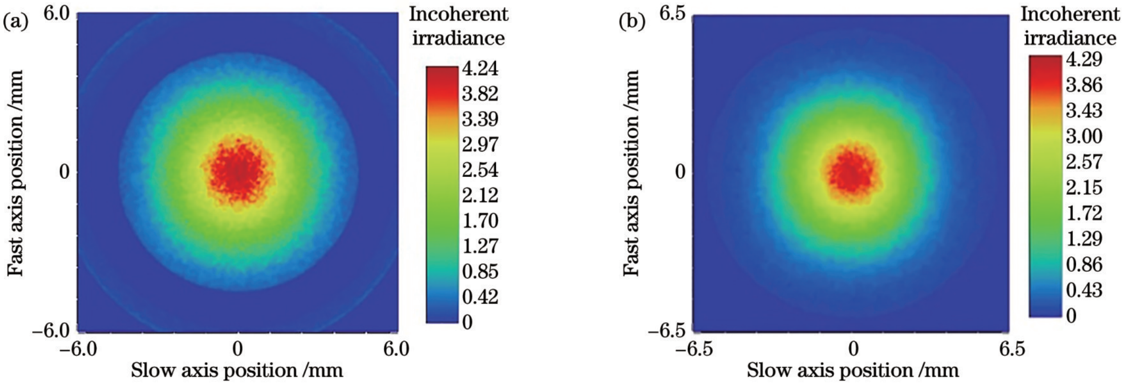

图4　准直后光斑的强度分布仿真结果。(a)NA为0.68的QCL准直镜；(b)NA为0.83的QCL准直镜

Fig. 4　Simulated intensity distributions of collimated beams. (a) QCL collimator with NA of 0.68; (b) QCL collimator with NA of 0.83

因此，经过优化设计后，本文选用基于扩展光源设计的、焦距为4.5 mm、NA为0.83的QCL准直镜。光纤耦合镜的焦距为150 mm，材料选用ZnSe，设计结果如表6所示。

表6　光纤耦合镜参数

Table 6　Lens data of fiber coupler

| Surface | Radius of curvature | Semi-diameter /mm | Thickness /mm | Material | Conical coefficient |
|---|---|---|---|---|---|
| 1 | 209.0 | 12.7 | 4 | ZnSe | 0 |
| 2 | Infinite | 12.7 | — | — | 0 |

在Zemax非序列模式中设置QCL光源、QCL准直镜与光纤耦合镜，建立光纤耦合模型对单路光纤耦合系统进行了仿真。仿真得到光纤入射端面处的光斑分布如图5(a)所示，光斑直径为270 μm，小于光纤芯径。仿真得到的光纤耦合效率为88.9%。耦合效率仿真未计入光纤传输损耗。距离光纤输出端面0.1 mm处的光斑分布如图5(b)所示，光斑直径为303 μm，与光纤芯径设置值300 μm相符合。

### 2.2　低损耗光纤合束器的制备

目前可用于中长波红外波段激光低损耗传输的光纤主要有玻璃基质光纤、晶体基质光纤和空芯光纤。使用最广泛的是卤化物和硫卤玻璃光纤。对于中长波

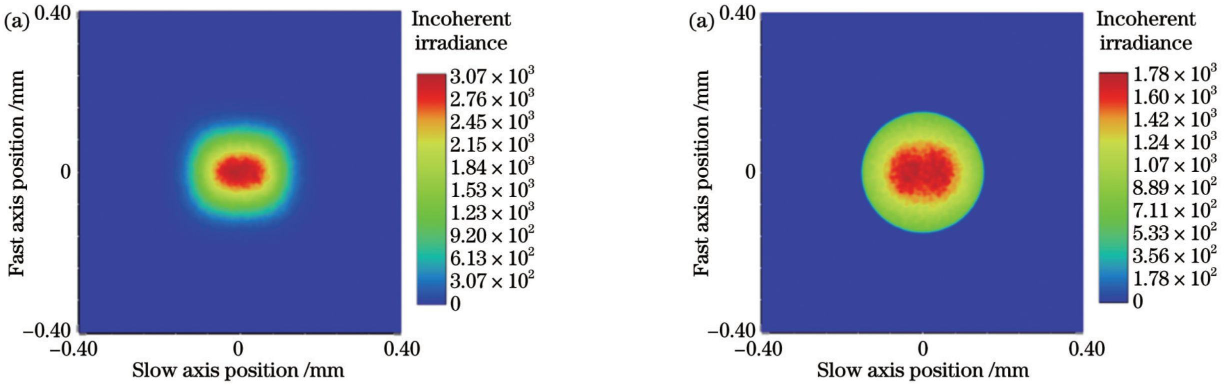

图5 单路光纤耦合系统仿真结果。(a)光纤入射端面处的光斑分布；(b)距光纤出射端光0.1 mm处的光斑分布

Fig. 5 Simulation result of single-channel fiber-tcoupling system. (a) Laser spot on input surface of fiber; (b) laser spot at 0.1 mm away from output surface of fiber

红外波段的单模光纤而言，玻璃光纤的芯径在10 μm量级，高功率激光输入将会造成过大的功率密度，极易造成光纤端面损伤，通常可承受的输出功率在百毫瓦至瓦量级。与之相比，单模空芯光纤的传输介质为空气，无端面反射损耗，在长波红外波段的损伤阈值高达10～30 W[17]。碘化银/银(AgI/Ag)泄漏型空芯光纤是典型的中长波空芯光纤，其结构如图6(a)所示，最外层为玻璃基管，基管上为Ag薄膜，Ag层上为AgI介质层，通过高效率的全反射实现光信号的低损耗传输。

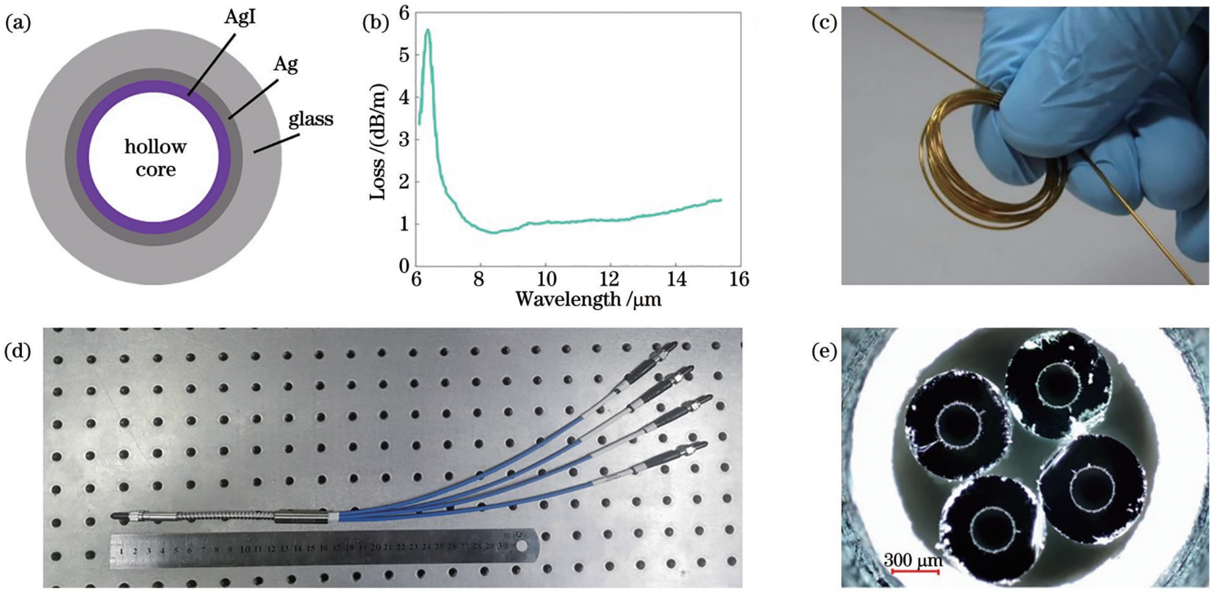

图6 单模空芯光纤合束器。(a)空芯光纤结构示意图；(b)单模空芯光纤的传输损耗；(c)单模空芯光纤实物图；(d)单模空芯光纤4合1光纤合束器实物图；(e)单模空芯4合1光纤合束器端出射端面在显微镜下的照片

Fig. 6 Single-mode hollow core fiber combiner. (a) Structure diagram of hollow core fiber; (b) transmission loss of single-mode hollow core fiber; (c) picture of single-mode hollow core fiber; (d) picture of single-mode 4×1 hollow core fiber combiner; (e) picture of output surface of single-mode hollow core 4 in 1 fiber combiner under microscope

空芯光纤的损耗与纤芯半径$a$有关，数值上与$1/a^3$成正比，因此在实际应用中往往使用大芯径的空芯光纤来获得较低的传输损耗，但过大的芯径将会导致光纤内多模传输，降低输出光的光束质量。实验使用的AgI/Ag单模空芯光纤的芯径为300 μm，可保证长波红外波段的单模传输。当弯折半径小于0.5 m时弯折损耗仅为0.2 dB/m，可承受的最大输入功率为10 W。AgI/Ag单模空芯光纤在长波红外波段的传输损耗如图6(b)所示，该单模空芯光纤在7～15.5 μm波段的传输损耗均值为1 dB/m。具有聚合物保护层的AgI/Ag单模空芯光纤实物图如图6(c)所示，该光纤较为柔软，最小可弯折半径为50 mm，有利于光纤合束装置的小型化。该光纤为非保偏光纤，对输入激光的偏振态不敏感。

为进行光纤合束实验，使用该低损耗单模空芯光纤制备了4合1光纤合束器。制备时剥除了光纤外层

保护层，使4根光纤紧密排列在套管中并固定，最终使用金属铠甲保护合束光纤。光纤输入端为4个独立的SMA905光纤接头，而在输出端制作了统一的SMA905接头。制作的4合1光纤合束器实物如图6(d)所示，合束器长度为0.5 m，制备的合束器在7～15.5 μm的传输损耗与单根单模空芯光纤的传输损耗相同。光纤束出射端面在显微镜下的照片如图6(e)所示，4根光纤外部的玻璃套管相切，相邻光纤的中心距为750 μm。

## 3　实验结果与分析

采用设计的光纤耦合光学系统和制备的长波单模空芯光纤合束器搭建了光纤合束实验装置，如图7所示。4个输出中心波长为7.6～7.8 μm的QCL的输出光先经由QCL准直镜分别准直后，由光纤耦合镜耦合至4合1光纤束的4个输入端，4路合束后的输出光从统一的光纤输出端输出。

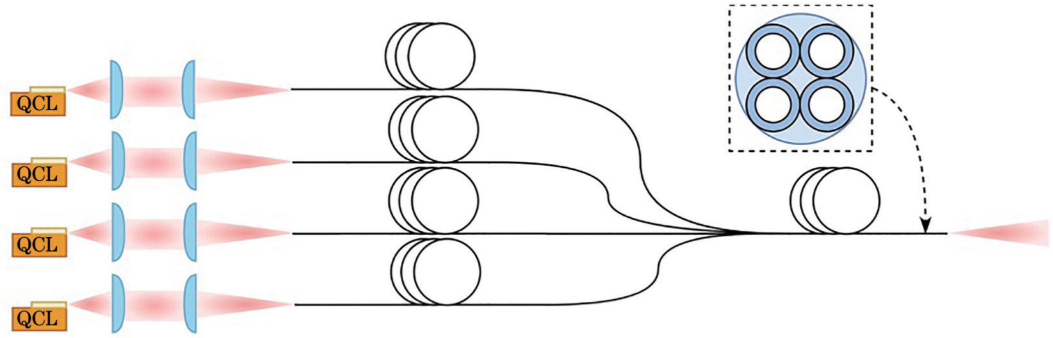

图7　光纤合束实验系统示意图

Fig. 7　Schematic diagram of fiber combining experimental system

### 3.1　QCL输出特性

首先对4个QCL的输出特性进行了实验测量。QCL光电转换效率小于15%，85%的电能会转换为热能，因此实验使用热电制冷器(TEC)配合风冷装置将QCL的工作温度控制在20 ℃。输出功率使用Thorlabs S470C光功率计测量，而输出光谱使用卓立汉光omni-λ300光栅光谱仪测量。本文所使用的4个基横模长波红外QCL的输出特性测量结果汇总于表7。

表7　QCL输出特性测量结果

Table 7　Measurement results of QCL output properties

| QCL ID | Output power /mW | Central wavelength /nm | Spectral linewidth /nm | Slow axis beam quality $M^2$ | Fast axis beam quality $M^2$ |
|---|---|---|---|---|---|
| 1 | 472(@1.4 A) | 7800 | 40 | 1.20 | 1.56 |
| 2 | 642(@0.8 A) | 7830 | 85 | 1.22 | 1.55 |
| 3 | 621(@0.8 A) | 7659 | 161 | 1.25 | 1.60 |
| 4 | 535(@1.4 A) | 7728 | 226 | 1.23 | 1.50 |

### 3.2　单模光纤耦合与合束

为了验证光纤耦合效率，搭建了如图8所示的单根光纤耦合实验装置。QCL准直镜及光纤耦合镜参数如表5和表6所示，实物照片如图9所示。QCL与QCL准直镜之间距离为3.7 mm，QCL准直镜与光纤耦合镜间隔为35 mm，光纤耦合镜距离光纤端面为150 mm。

长波红外QCL单路光纤耦合实验结果如图10所示，图10(a)为光纤耦合输出功率，10(b)为光纤耦合效率。当QCL的输出功率为642 mW时，光纤输出端测量到的激光功率为438 mW，QCL的光纤耦合效率为68%。

从图10中可以看出，当QCL的输出功率为58 mW时，光纤耦合效率为76%；随着输出功率的升高光纤

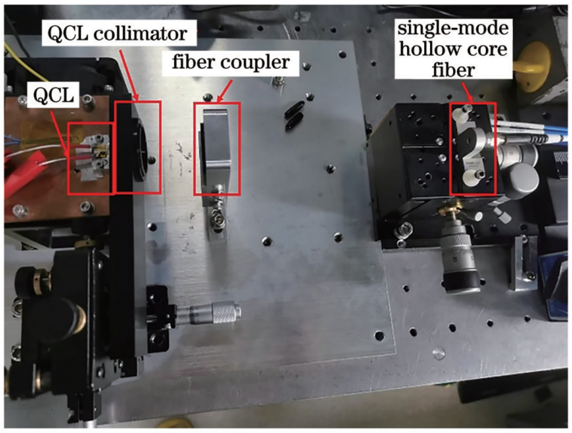

图8　单模光纤耦合实验装置图

Fig. 8　Experimental setup of single-mode fiber coupling system

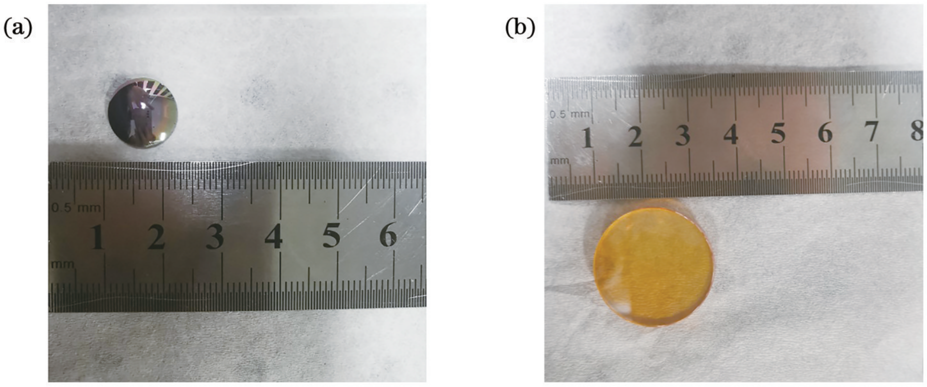

图 9　QCL 准直镜与光纤耦合镜实物图。(a)NA 为 0.83 的 QCL 准直镜；(b)光纤耦合镜

Fig. 9　Picture of QCL collimator and fiber coupler. (a) QCL collimator with NA of 0.83; (b) fiber coupler

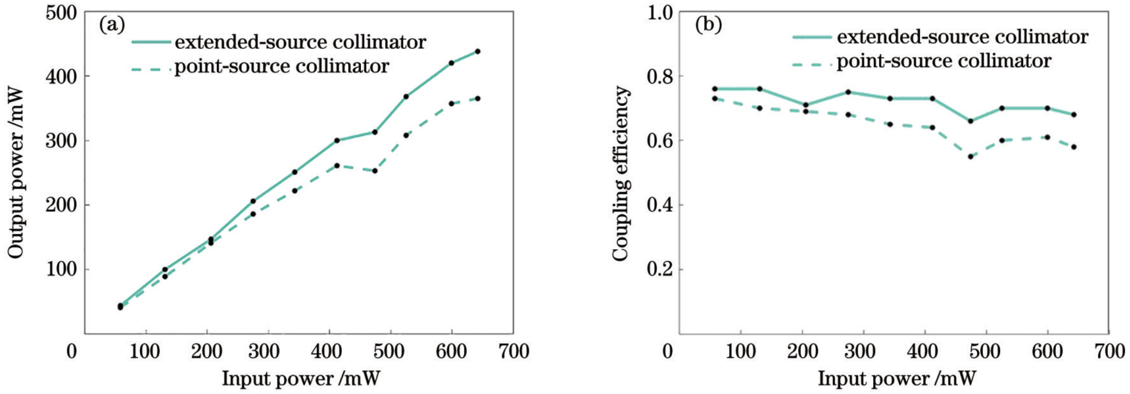

图 10　单模长波红外空芯光纤耦合实验结果。(a)光纤输出功率；(b)光纤耦合效率

Fig. 10　Experimental results of coupling of single-mode long wave infrared hollow core fiber. (a) Fiber output power; (b) fiber coupling efficiency

耦合效率有所下降，这是由于QCL输出功率增加时光束质量会发生恶化。实验结果低于仿真结果的原因是QCL输出光不是完全的基横模，且仿真中未计入透镜的透过率和光纤的传输损耗。当两个透镜的表面镀膜后计透过率为0.97、0.5 m光纤传输损耗为0.97时，计算得到的光纤耦合效率为0.76，与QCL处于较低输出功率时一致。

此外，本文还实验对比了采用表2和表5所示的两个不同QCL准直镜时的单模空芯光纤耦合效率，如图10中的实线和虚线所示。使用将QCL视为扩展光源且数值孔径较大的QCL准直镜时，确实可获得更优的光纤耦合效率，印证了QCL光纤耦合系统优化的正确性。

本文使用BeamGage Pyrocam Ⅲ光束质量分析仪分别测量了QCL在输入电流为0.8 A、输出功率为642 mW时的准直光斑，及单模空芯光纤耦合后的输出光斑，测量结果如图11所示。图11(a)为准直后的QCL输出光斑，图11(b)为经过单模空芯光纤耦合后的输出光斑。经过单模光纤传输后，输出光束腰为386 μm、远场发散角为30 mrad，可计算得到光束传输质量因子$M^2$为1.2，光束质量优于表7中QCL直接输出时的光束质量。

在单路光纤耦合实验的基础上，搭建了4路长波红外QCL光纤耦合实验装置，如图12所示。采用表7所示的4个长波红外QCL，当其分别工作于最高输出功率时，经过4合1单模空芯光纤合束器后的输出功率分别为323、438、400、347 mW，耦合效率分别为68%、68%、64%、65%，实验结果如图13(a)所示。不同QCL耦合效率相近，其微小差异主要源于4个QCL略微不同的光束质量及装调误差。该合束系统总输出功率与合束效率如图13(b)所示，当4个长波红外QCL同时工作于最高输出功率时，总功率为2.27 W，此时光纤合束器出射端输出功率为1.5 W，4合1光纤合束效率为66%。实验所使用的4个QCL的中心波长相差约170 nm，光谱线宽从40 nm到226 nm不等，而实验测得四路的耦合效率基本一致，说明该合束装置对入射光波长及光谱特性不敏感。为评估合束输出光的光束质量，使用透镜对输出光聚焦，并在2倍瑞利距离内测量了合束器输出光斑的强度分布，结果如图14和图15所示，计算得到合束光束的传输质量因子$M_X^2=2.67$，$M_Y^2=2.56$；仍然具有较好的光束质量。

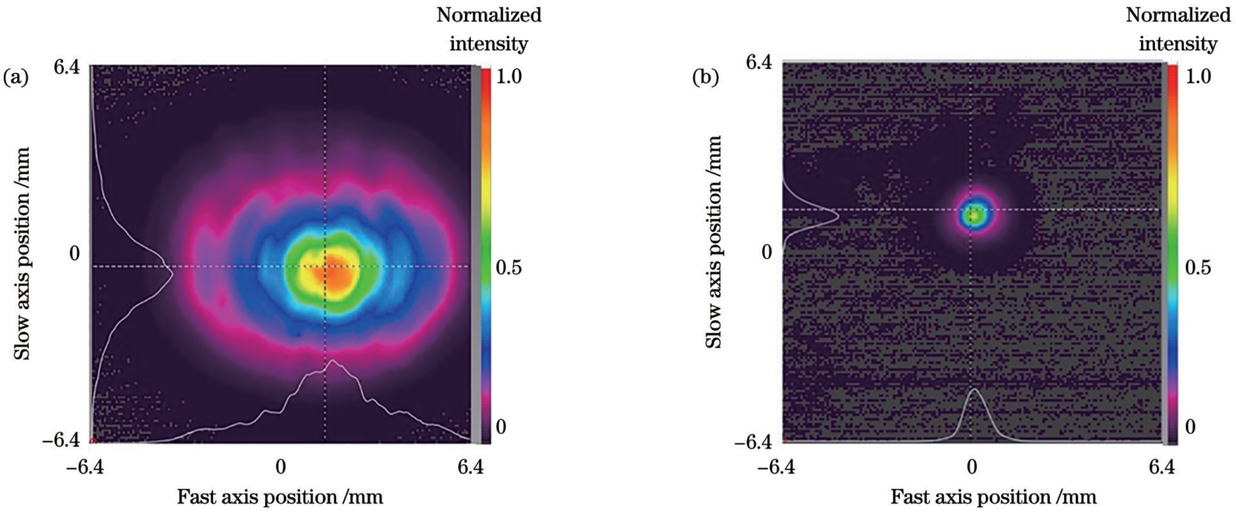

图 11　QCL 准直光斑与光纤耦合输出光斑。(a)QCL 准直光斑；(b)光纤耦合输出光斑

Fig. 11　QCL collimating spot and fiber coupling output spot. (a) QCL collimating spot; (b) fiber coupling output spot

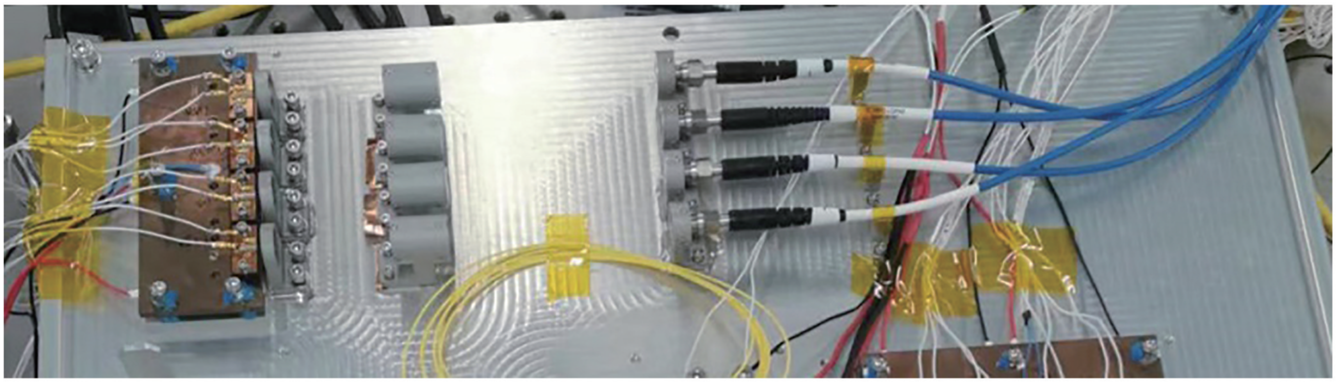

图 12　4×1 光纤合束系统实验装置图

Fig. 12　Experimental setup of 4×1 fiber combining system

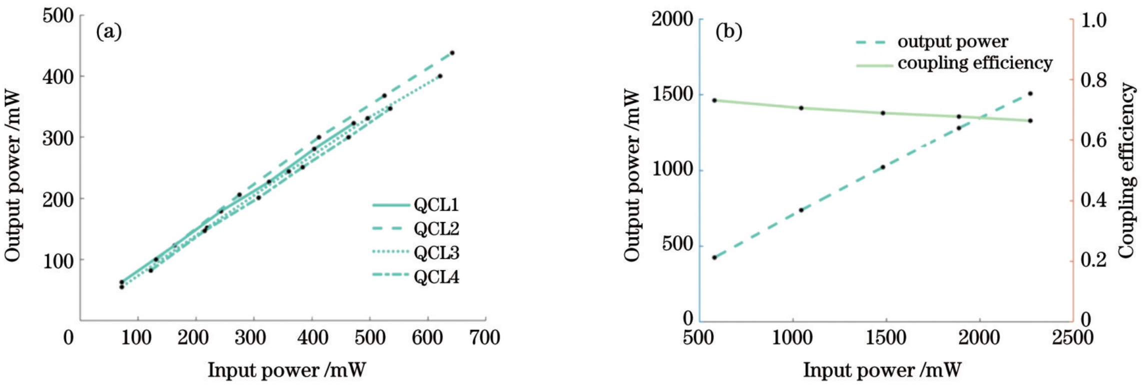

图 13　QCL 4×1 光纤合束实验结果。(a)光纤耦合输出功率；(b)光纤总输出功率与系统总耦合效率

Fig. 13　Experimental results of QCL 4×1 fiber combining. (a) Fiber coupling output power; (b) total fiber output efficiency and total system coupling efficiency

## 4　结　论

本文从理论和实验上研究了基于长波红外单模空芯光纤的长波红外 QCL 功率合束技术。针对基横模长波红外 QCL 的发光特性，设计了扩展光源、大数值孔径双非球面 QCL 准直镜，有效提高了单模光纤的耦合效率。使用无端面损耗、低传输损耗的 AgI/Ag 单模空芯光纤制作了 4 合 1 光纤合束器，实现了 4 路 7.6～7.8 μm 波段 QCL 的功率合束。实验结果表明，单根单模空芯光纤的耦合效率为 68%，输出光的光束传输质量因子 $M^2$ 为 1.2；4 路 QCL 合束后输出功率为 1.5 W，合束效率为 66%，合束光束的

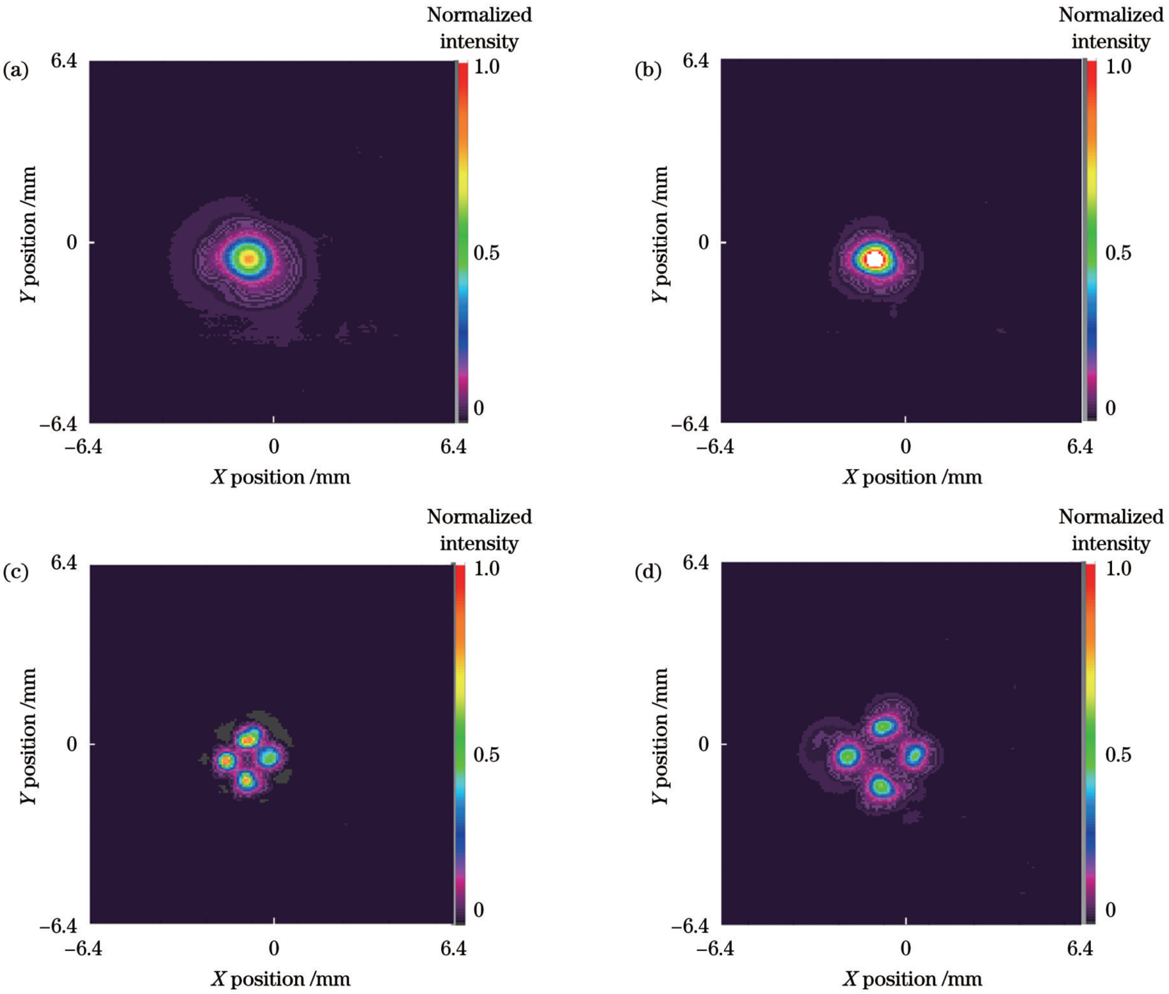

图 14　距离束腰不同距离处的QCL合束光束光斑。(a) −50 mm;(b) 0 mm;(c) 100 mm;(d) 150 mm

Fig. 14　Combined QCL beam spots at different positions along beam propagation direction. (a) −50 mm; (b) 0 mm; (c) 100 mm; (d) 150 mm

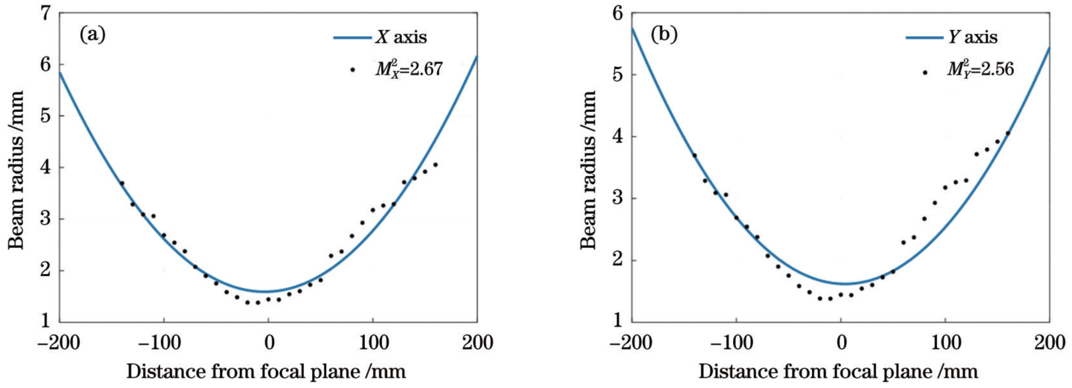

图 15　合束QCL光束传输质量因子$M^2$。(a)X方向;(b)Y方向

Fig. 15　Beam propagation quality factor $M^2$ of combined QCL. (a) X axis; (b) Y axis

传输质量因子$M_X^2=2.67$,$M_Y^2=2.56$。该合束技术有效提高了长波红外QCL的输出功率,光纤合束器的低损耗工作波段很宽,为7～15.5 μm,且通过增加合束器中的光纤数量可进一步提高输出光功率,为实现高功率、宽波段长波红外激光输出提供了有效的技术途径。

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# High-Efficiency Fiber Combining of Long-Wave Infrared Quantum Cascade Lasers

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## Abstract

**Objective** Quantum cascade laser (QCL) is a semiconductor laser based on sub-band electronic transition, which results in a broad emitting wavelength covering from 3 to 300 μm. QCL is an ideal light source in the fields of gas sensing, environmental monitoring, medical diagnosis, and photoelectric countermeasures. However, the relatively low output power (1–3 W) of the single transverse mode QCL is a major limitation for its applications. Laser beam combining technology is an effective way to enhance the output power. At present, the power beam combining of mid-infrared and long-wave infrared QCLs is heavily limited by the low-loss optical materials and component preparations. Beam combining with high efficiency and low loss is challenging, and few research results have been reported. Therefore, the fiber combining of long-wave infrared QCLs in the 7.6–7.8 μm wavelength band was studied in this paper. The laser power was combined with a 4-in-1 single-mode hollow-core fiber bundle.

**Methods** In order to realize the high-efficiency single-mode fiber coupling of QCLs, the optical fiber coupling system was designed. The optical fiber system was composed of a QCL collimator and a fiber coupler. Due to the large QCL emitting area and large divergence angle, an aspheric collimator with a large numerical aperture was designed and fabricated. During the optical design and optimization, the QCL was assumed to be an extended light source. Using the optimized collimator, a fiber coupling efficiency of 88.9% was obtained. To combine the laser beams from individual QCL, a 4-in-1 fiber combiner was fabricated using AgI/Ag single-mode hollow-core fiber, which had a high damage threshold and low transmission loss. During the preparation, the outer protective layer of the fiber was stripped away, and the four fibers were tightly arranged in the sleeve and fixed. Finally, the fiber was protected by metal armor. The input terminals of the fiber combiner were four independent SMA905 fiber connectors, and a unified SMA905 connector was made at the output end.

**Results and Discussions** The optical fiber coupling experiments are conducted using the designed optical fiber coupling system and the prepared long-wave single-mode hollow-core fiber combiner. When the QCL output power is 642 mW, the laser power throughout the single-mode fiber is 438 mW. The corresponding fiber coupling efficiency is 68%. In addition, we experimentally compare the coupling efficiency using a point-source collimator and an extended-source collimator. Using the extended-source collimator with a large numerical aperture, the fiber coupling efficiency is increased from 59% to 68%, as shown in Fig. 10. An infrared camera is used to observe the collimated QCL spot and the beam spot out of the single-mode fiber. In addition, the beam propagation quality factor $M^2$ after the fiber coupling is calculated. After the fiber coupling, a symmetric Gaussian distribution is observed, and the beam quality is improved to 1.2, compared to the $M^2$ in Table 7. On the basis of the single-channel optical fiber coupling experiment, the optical fiber combining experimental setup of a four-channel long-wave infrared QCL is built. When the total input power from four QCLs is 2.27 W, the fiber combining power is 1.5 W. The corresponding combining efficiency is 66%. In order to evaluate the beam quality of the combined beam, the lens is used to focus the output light, and the intensity distribution of the output spot of the beam combiner is measured within two times Rayleigh distance. The results are shown in Figs. 14 and 15. The transmission quality factors of the combined beam are calculated as $M_X^2=2.67$ and $M_Y^2=2.56$, which meant a good beam quality.

**Conclusions** In this paper, the long-wave infrared QCL beam combining technology based on single-mode hollow-core fiber is studied. Considering the large emitting area and big divergent angle of the fundamental transverse mode long-wave infrared QCL, a QCL collimator with a large numerical aperture is used. During the design, the QCL is treated as an extended light source. To obtain the optimized collimation result, both surfaces of the collimator are aspheric. A 4-in-1 fiber combiner is fabricated using the AgI/Ag single-mode hollow-core fiber. The fiber has no end face reflection loss and low transmission loss. The experimental results show that the single-mode fiber coupling efficiency is 68%. After the fiber coupling, the beam propagation quality factor $M^2$ is 1.2. In addition, the power combining of four QCLs in the wavelength band of 7.6–7.8 μm is realized. When the input power is 2.27 W, the combined output power is 1.5 W. The beam combining efficiency is 66%. The transmission quality factors of the combined beams are $M_X^2=2.67$ and $M_Y^2=2.56$. The low-loss working band of the fiber combiner ranges from 7 to 15.5 μm. The output optical power can be further increased by increasing the number of QCLs in the beam combining, which provides an effective way to expand the output power and wavelength range in the long-wave infrared wavelength band.

**Key words** long-wave infrared; quantum cascade laser; fiber combining; coupling efficiency; hollow-core fiber