高光束质量闲频光谐振中红外 MgO:PPLN 光参量振荡器

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摘　要：报道了采用纳秒脉冲激光器泵浦基于掺杂氧化镁周期极化铌酸锂 (MgO:PPLN) 晶体的高光束质量、闲频光谐振中红外光参量振荡器。通过选取曲率半径为 200 mm 的凹面输入镜和平面输出镜来建立平凹腔，实现了高光束质量的近-中红外激光输出。当输入的最大泵浦能量为 21 mJ 时，输出信号光和闲频光的最大能量分别为 3.2 mJ 和 1.12 mJ，对应信号光和闲频光的斜效率分别为 24% 和 9%。通过在 25~200 ℃ 范围内改变 MgO:PPLN 晶体温度，实现信号光波长 1.505~1.566 μm 和闲频光波长 3.318~3.628 μm 的激光调谐输出。由于闲频光单谐振的光参量振荡器具有较大的衍射损耗和光束发散角，可以提高输出闲频光的光束质量。采用刀口法测量得到中红外激光在两个正交方向的光束质量因子分别为$M_x^2 \approx 1.2$和$M_y^2 \approx 1.2$。

关键词：非线性光学；　高光束质量；　光参量振荡器；　中红外激光

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0　引　言

中红外 3~5 μm 激光为红外波段的大气窗口，在大气传输过程中损耗较少，且此波段存在很多痕量气体吸收峰。随着光电技术的不断发展，中红外激光具有十分广泛的应用，如大气环境监测、光谱分析、医疗诊断、自由空间光通信等诸多领域[1−3]。鉴于 3~5 μm 中红外激光极大的应用前景和战略需求，已成为国防和民用竞相研究开发的重点领域，其中 3.2~3.6 μm 波段在激光制导、通信、雷达等军事方面有着更重要的应用价值和研究意义[4−6]。

目前，国内外实现中红外激光输出的主要有光纤激光器、量子级联激光器、半导体激光器、过渡金属或稀土离子掺杂的固体激光器以及光参量振荡器等方法[7−8]。其中，基于非线性变频技术的光参量振荡器 (Optical Parametric Oscillator, OPO) 具有结构紧凑、调谐范围宽、转换效率和输出功率高等优点，已经成为产生中红外激光的主要技术手段[9]。

用于产生中红外激光的非线性光学晶体材料主要包括砷酸钛氧钾 ($KTiOAsO_4$, KTA)、磷酸钛氧钾 ($KTiOPO_4$, KTP)、铌酸锂 ($LiNbO_3$, LN) 和周期极化铌酸锂 (PPLN) 等[10]。相较于传统型生长的双折射 KTA、KTP 晶体，基于准相位匹配的 PPLN 晶体可以在二阶非线性极化方向进行周期性反转来补偿相位失配，有效避免空间走离效应，并且在传输过程中可利用最大的非线性系数 (d_{33}= 27.2 pm/V)。PPLN 晶体损伤阈值较低，容易在应用中产生光折变损伤，故实验中所使用 5 mol% MgO 掺杂的 PPLN 晶体可以有效提高晶体的损伤阈值[11]。

信号光单谐振 OPO 在实验中具有起振阈值低、输出能量和转换效率较高等优点[12]，是利用 OPO 产生中红外激光的主要方式。2020 年，Niu Sujian 等人采用 1.064 μm 的全固态激光器泵浦多周期 MgO:PPLN 晶体，结合极化周期和温度调谐实现了中红外闲频光在 2.28~4.8 μm 范围内的连续可调谐中红外激光输出，在 3.4 μm 处的最大能量为 2.15 mJ，对应的光-光

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转换效率超过 10%[13]。2021 年，南京大学祝世宁院士团队采用 808 nm 半导体激光器泵浦基于信号光单谐振的 MgO:PPLN-OPO，在 2.25~4.79 μm 波段实现了连续可调谐中红外激光输出。当泵浦功率为 9.1 W 时，在 3.189 μm 处获得最大功率为 1.08 W 的激光输出，对应的光-光转换效率为 11.88%[14]。由于信号光单谐振 OPO 产生的中红外闲频光的光束质量较差，因此，多位研究者提出利用闲频光单谐振 OPO 来提高中红外激光的光束质量[15]。2018 年，He Yang 团队采用全光纤激光器泵浦基于闲频光单谐振 MgO:PPLN-OPO，获得了在 3.67 μm 处最大功率为 5.84 W 的中红外激光输出，得到两个正交方向的光束质量因子分别为$M_x^2\approx1.57$和$M_y^2\approx1.49$[16]。2019 年，西班牙的 Parsa S 团队提出采用波长为 1.064 μm 的皮秒光纤激光器泵浦基于 MgO:PPLN 闲频光谐振 OPO，实现了中红外闲频光在 2.198~4.028 μm 范围内的可调谐激光输出，并且测量得到两个正交方向的光束质量因子分别为$M_x^2\approx1.5$和$M_y^2\approx1.8$[17]。

文中采用 1.064 μm 纳秒脉冲 Nd:YAG 激光器泵浦基于 MgO:PPLN-OPO，在中红外波段实现了高光束质量、波长可调谐的激光输出。通过在 25~200 ℃ 范围内改变 MgO:PPLN 晶体温度，获得了近红外信号光在 1.505~1.566 μm 和中红外闲频光在 3.318~3.628 μm 范围内的连续可调谐激光输出。在最大泵浦能量为 21 mJ 时，输出信号光和闲频光的最大能量分别为 3.2 mJ 和 1.12 mJ，对应的斜效率分别为 24% 和 9%。通过刀口法测量得到两个正交方向的光束质量因子分别为$M_x^2\approx1.2$和$M_y^2\approx1.2$。

1 实验装置

基于闲频光单谐振的高光束质量、波长连续可调谐 MgO:PPLN-OPO 的实验装置如图 1 所示。采用波长为 1.064 μm 的传统纳秒调 Q Nd:YAG 固体激光器 (Lotis LS-2136, pulse duration: 25 ns; Pulse Repetition Frequency (PRF): 50 Hz; wavelength: 1.064 μm) 为泵浦源，其输出光束具有高斯空间分布。通过半波片 (λ/2) 来调整泵浦光的偏振方向，使其满足 MgO:PPLN 的 0 型 (e→e+e) 准相位匹配。利用焦距为 750 mm 的聚焦透镜 (Lens) 将泵浦光聚焦为 1 mm 光斑入射到 OPO 谐振腔中。非线性增益介质采用尺寸为 40 mm×4 mm×2 mm 的 MgO:PPLN 晶体，其晶体的两端面均镀有对泵浦光 (1.064 μm)、信号光 (1.4~1.6 μm) 和闲频光 (3~5 μm) 的增透膜，MgO 掺杂浓度为 5 mol%，极化周期为单周期 30 μm。利用温控炉在 25~200 ℃ 范围内控制 MgO:PPLN 晶体温度，温控精度为±0.1 ℃。

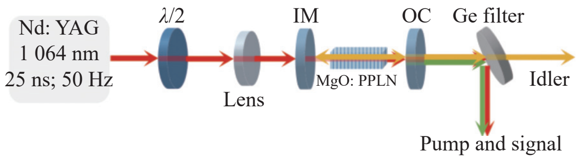

图 1 基于闲频光谐振高光束质量 MgO:PPLN-OPO 的实验装置

Fig.1 Experimental setup for the high beam quality idler resonant MgO:PPLN-OPO

基于闲频光单谐振高光束质量 MgO:PPLN-OPO 的谐振腔由曲率半径为 R=200 mm 的凹面输入镜 (IM) 和平面输出耦合镜 (OC) 组成，平凹腔的设计保证了参量光之间最大的非线性增益和最高的转换效率。输入镜 IM(R=200 mm) 对 1.064 μm 泵浦光高透射，对 1.4~1.6 μm 信号光和 3~5 μm 闲频光高反射；输出耦合镜 OC 对泵浦光和信号光高透射，对闲频光具有约 80% 反射率的介质膜，谐振腔总腔长固定为 80 mm。Ge 滤光片对 1.505~1.566 μm 的近红外信号光高反射，对 3.318~3.628 μm 的中红外闲频光透射率为 93% 以上。在实验中，通过使用两片 Ge 滤光片来有效分离了闲频光与信号光和泵浦光。测量信号光时，采用对 1 μm 全反射的滤光片来反射泵浦光，使信号光透射到照相机和功率计观察空间强度分布和输出能量。

2 分析与讨论

实验中采用电耦合照相机 (CCD) 记录了 1.064 μm 泵浦光的空间分布图，如图 2(a) 所示，其空间分布为高斯分布。使用热释电相机 (Spiricon Pyrocam III, Spatial Resolution: 75 μm) 分别记录了在 1.522 μm 和 3.534 μm 处信号光和闲频光的空间分布图，如图 2(b)、(c) 所示。由图所示，在整个波长调谐范围内，输出信号光和闲频光空间强度分布与泵浦光相同，均为近高斯空间分布，且其强度分布非常均匀。

图 3 所示为 1.522 μm 信号光和 3.534 μm 闲频光的输出能量与泵浦光能量之间的函数关系。晶体温

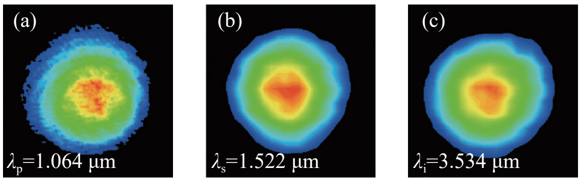

图 2 空间分布。(a) 1.064 μm 泵浦光; (b) 1.522 μm 信号光; (c) 3.534 μm 闲频光

Fig.2 Spatial distribution. (a) 1.064 μm pump beams; (b) 1.522 μm signal beams; (c) 3.534 μm idler beams

度固定在 110 ℃、泵浦光最大能量为 21 mJ 时，输出信号光和闲频光的最大能量分别为 3.2 mJ 和 1.12 mJ，对应的斜效率分别为 24% 和 9%。实验数据表明，OPO 输出的信号光和闲频光能量与泵浦光能量呈线性增大。在谐振腔的设计中选择高精度镀膜参数的腔镜、缩短腔长来减少谐振光的损耗，并选取合适曲率半径的腔镜来优化泵浦光与谐振闲频光在晶体内的模式耦合，可以进一步提高输出激光的能量和转换效率。

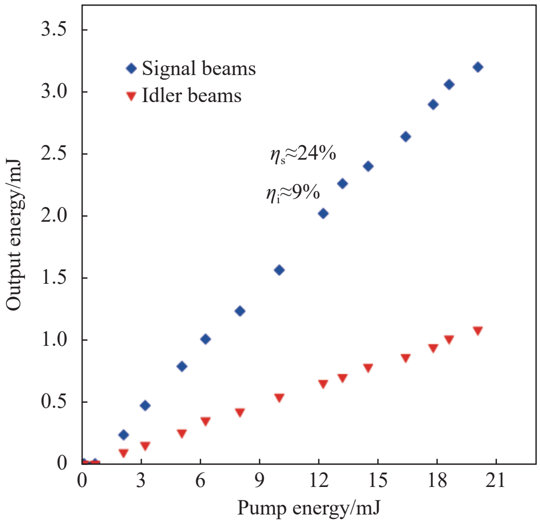

图 3 晶体温度在 110 ℃ 时，近红外 1.522 μm 信号光和中红外 3.534 μm 闲频光输出能量与泵浦光能量之间的函数关系

Fig.3 Near-infrared (1.522 μm) signal beams and mid-infrared (3.534 μm) idler beams energies as a function of the pump beams energy at crystal temperature of 110 ℃

通过改变 MgO:PPLN 晶体工作温度来实现信号光和闲频光的波长调谐输出 (如图 4 所示)。使用高性能光谱仪 (SpectraPro HRS-500, 300 line/mm, 孔径尺寸: 50 μm, 光谱仪的分辨率在 0.1~0.2 nm 之间) 测量了 OPO 输出的信号光和闲频光的激光光谱，蓝色和绿色的离散点分别表示信号光和闲频光的实验数据，红色实线为根据 Sellmeier 色散方程[18]计算出的 MgO:PPLN 晶体温度调谐的理论曲线。通过在 25~200 ℃ 范围内改变 MgO:PPLN 晶体温度，获得了近红外信号光波长为 1.505~1.566 μm 和中红外闲频光波长为 3.318~3.628 μm 的连续可调谐激光输出，实验结果与理论模拟良好吻合。

图 5 所示为中红外闲频光输出能量与波长的关

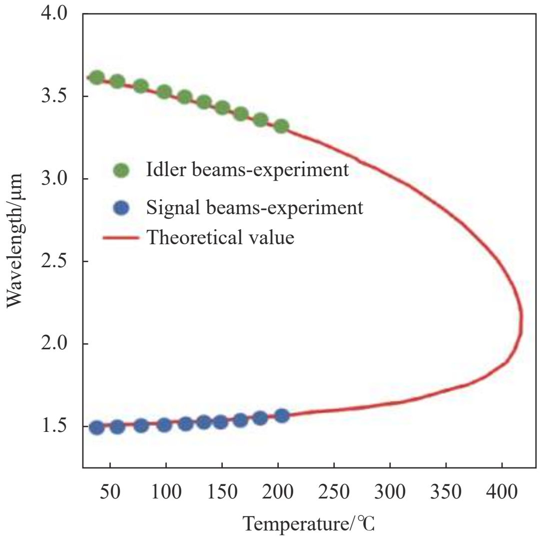

图 4 基于 MgO:PPLN 晶体 OPO 输出波长随温度的调谐曲线

Fig.4 Wavelength tuning curves of the OPO outputs versus the temperature of the MgO:PPLN crystal

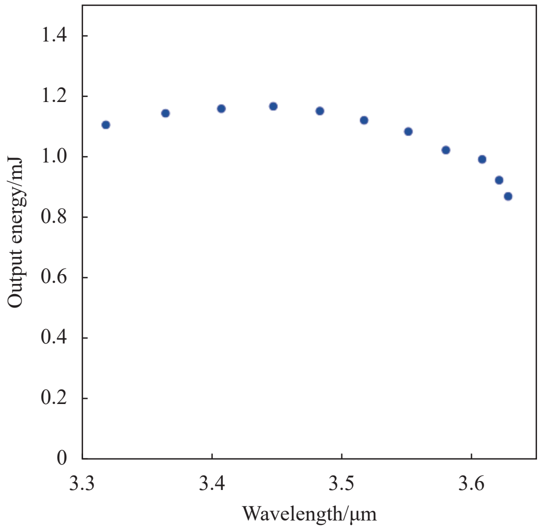

图 5 泵浦能量为 21 mJ 时，中红外闲频光输出能量与波长之间的关系

Fig.5 Mid-infrared idler beams output energy of the wavelength tuning at a pump energy of 21 mJ

系。随着波长的增大，输出能量持续减小，这是由于在波长大于 3.5 μm 时，MgO:PPLN 晶体的吸收增加，导致中红外激光输出能量下滑、转换效率降低。另外，泵浦光与闲频光之间较大的波长差也是导致转换效率低的原因。同时测量了 OPO 输出能量的稳定性，在 10 h 内的能量稳定性均小于 1% rms。

如图 6 所示，利用刀口法测得输出中红外闲频光在两个正交方向上的光束质量因子分别为$M_x^2\approx 1.2$和$M_y^2\approx 1.2$。嵌入图表示在 f=150 mm 聚焦透镜焦点附近处的闲频光空间强度分布。

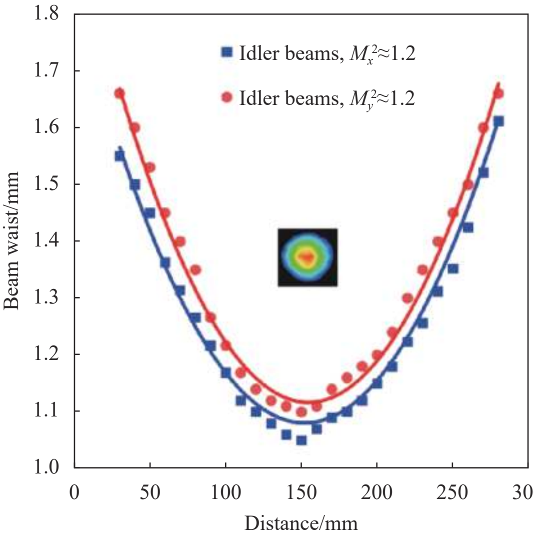

图 6 中红外 3.534 μm 闲频光光束质量测试

Fig.6 Beam quality measurement of the mid-infrared idler beams at 3.534 μm

基于闲频光单谐振的 OPO 具有较大的衍射损耗和光束发散角，可利用菲涅耳数分析闲频光单谐振 OPO 对输出光束质量的优势[19]，即表达式为：

$$N_F=\frac{a^2}{\lambda L} \tag{1}$$

式中：N_F 为菲涅耳数；a 为光束半径；λ 为波长；L 为谐振腔有效长度。在闲频光谐振 OPO 中，闲频光具有较小的菲涅耳数并且谐振光束在腔内多次振荡，可以有效抑制高阶模的产生从而可提高输出中红外闲频光的光束质量[20]。

3 结 论

实验中利用波长为 1.064 μm 的调 Q 纳秒脉冲激光器作为泵浦源，设计了基于 MgO:PPLN 闲频光单谐振可调谐、高光束质量、高稳定性的近红外和中红外 OPO。在最大泵浦能量为 21 mJ 时，输出信号光 (1.522 μm) 最大能量为 3.2 mJ、闲频光 (3.534 μm) 最大能量为 1.12 mJ，信号光和闲频光对应的斜效率分别为 24% 和 9%。采用刀口法测量得到中红外闲频光在两个正交方向的光束质量因子分别为$M_x^2\approx 1.2$和$M_y^2\approx 1.2$。在 25~200 ℃ 范围内改变 MgO:PPLN 晶体温度，实现了近红外信号光在 1.505~1.566 μm 范围内连续可调谐，中红外闲频光在 3.318~3.628 μm 范围内可进行 310 nm 连续可调谐激光输出。为了进一步提高中红外激光在实际中的应用，可以选择多周期或扇形 MgO:PPLN 晶体，优化腔型设计，更进一步扩展近-中红外激光波长调谐范围，提高输出能量和转换效率。

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High-beam-quality idler-resonant mid-infrared optical parametric oscillator based on MgO:PPLN

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Abstract:

Objective Widely tunable, high-energy, stable, compact, high-beam-quality, mid-infrared 3-5 μm light sources based on optical parametric oscillator (OPO) and optical parametric amplifier (OPA) systems, known as the fingerprint region, are of considerable importance in applications including remote sensing, atmospheric monitoring, spectroscopy analysis, and photoelectric detection surveys. In particular, it is desirable to utilize high-energy, mid-infrared light sources with large wavelength tunability for highly sensitive and selective photoacoustic trace-gas sensing, in which most molecules have strong vibrational transitions. At present, the technologies available that can achieve the desired laser output in the widely tunable and highly-energized mid-infrared region of 3-5 μm are primarily quantum and inter band cascade lasers (QCLs) and OPOs. Although OPO technology has been around for a long time, it is still an excellent light source choice for the widely tunable mid-infrared region. It provides selectivity owing to its large wavelength tunability, high energy, increased beam quality, and compact, cost-effective devices for the generation of mid-infrared light in the 2-5 μm spectral range.

Methods Experimental setup for the high beam quality, idler-resonant MgO: PPLN-OPO is shown (Fig.1). A solid-state Nd:YAG laser (pulse duration: 25 ns, wavelength: 1.064 μm, PRF: 50 Hz, maximum pulse energy: 21 mJ, spatial form: Gaussian profile) was used as the pump source of the OPO. The pump beam was observed by a conventional CCD camera. The spatial forms of the signal and idler outputs were measured by using a Spiricon pyroelectric camera III (Fig.2). The energy scaling of the compact idler-resonant OPO has been investigated with the increasing pump energy (Fig.3). Spectral properties of a compact idler-resonant OPO have been measured by spectrometer (SpectraPro HRS-500, 300 line/mm) (Fig.4). Idler output energies as a function of the idler wavelength at a pump energy of 21 mJ was shown (Fig.5). To validate the high beam quality idler output, the beam quality factor (M^2) of the mid-infrared idler output was measured by means of the knife-edge method (Fig.6).

Results and Discussions The maximum signal and idler output energies of 3.2 mJ and 1.12 mJ were obtained at a pump energy of 21 mJ, corresponding to the slope efficiency of 24% and 9%, respectively (Fig.3). The wavelengths of the signal and idler outputs were tuned in the ranges of 1.505-1.566 μm and 3.318-3.628 μm by changing the MgO: PPLN crystal temperature in the range of 25-200 ℃ (Fig.4), and the beam quality factor of the mid-infrared idler output was measured by means of the knife-edge method, resulting beam quality factors were estimated as 1.2 and 1.2 along the horizontal and vertical directions, respectively (Fig.6).

Conclusions We have successfully demonstrated the high-beam-quality, idler-resonant tunable optical parametric oscillator based on single-grating MgO: PPLN crystal. A maximum idler output energy of 1.12 mJ and signal output energy of 3.2 mJ was achieved at a pump energy of 21 mJ, and the beam quality factors of 1.2 and 1.2 in the two orthogonal directions, respectively. The wavelengths of the signal beams and idler beams outputs were tuned in the ranges of 1.505-1.566 μm and 3.318-3.628 μm by changing the MgO: PPLN crystal temperature in the range of 25-200 ℃. In the future work, by using a PPLN crystal with multiple gratings, a broader range of wavelength tuning is expected.

Key words: nonlinear optics; high beam quality; optical parametric oscillator; mid-infrared laser

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