高效率宽调谐扇形 MgO: PPLN 中红外光参量振荡器

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摘　要：3~5 μm 的中红外激光位于大气窗口，在环境监测、军事、医疗、遥感等诸多领域有着重要的应用。利用纳秒量级的 1 064 nm 调 Q 激光器泵浦扇形掺氧化镁周期极化铌酸锂 (MgO: PPLN)，设计了一种高效率、宽调谐纳秒中红外激光输出光学参量振荡器 (Optical parametric oscillator, OPO)。通过降低泵浦光的重频，有效地减小了 OPO 的振荡阈值，在 10 kHz 的泵浦重频下，OPO 阈值为 0.4 W。在泵浦功率为 4.68 W，晶体极化周期为 30.47 μm 的条件下，获得了 0.833 W 的 3.4 μm 中红外激光输出，对应的光光转换效率为 17.8%。实验研究了不同极化周期下的输出波长，实验结果与理论模拟值较为吻合。通过横向移动 MgO: PPLN 晶体改变其极化周期，在 31.05~28.8 μm 的调节范围内获得了 1 440.7~1607.0 nm 的信号光及 3 171.1~4 088.1 nm 的闲频光输出，其中信号光的脉宽约为 8.1 ns。

关键词：中红外激光；　扇形 MgO: PPLN；　光参量振荡器；　高效率；　宽调谐；　纳秒脉冲

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0　引　言

3~5 μm 的中红外 (Mid-infrared, MIR) 激光位于大气窗口，且其波段内覆盖了许多分子的特征吸收峰，被称为“分子指纹区”，因此其在大气环境监测、军事应用、光电对抗、生物医疗及遥感测量等诸多领域有着重要的应用[1−5]。

基于非线性频率变换的光参量振荡器 (Optical parametric oscillator, OPO) 具有转换效率高、结构紧凑、输出功率高及调谐范围宽等优点，目前已经成为了产生中红外激光的主要技术手段。常用做产生中红外激光的非线性晶体包括砷酸钛氧钾 ($KTiOAsO_4$, KTA)、磷酸钛氧钾 ($KTiOPO_4$, KTP)、磷锗锌 ($ZnGeP_2$, ZGP)、硒镓银 ($AgGaSe_2$)、周期极化铌酸锂 (PPLN) 及周期极化 KTP(PPKTP) 等[6]。

PPLN 具有非线性系数大、透光范围宽等优点，其利用准相位匹配技术，将晶体的二阶非线性极化方向进行周期性反转以补偿相位失配，有效地避免了空间走离效应[7-8]。在 PPLN 晶体中掺入 Mg^{2+} 提高了其光折变损伤的阈值，克服了其无法在常温下实现高功率连续可调谐输出的缺点，因此掺氧化镁周期极化铌酸锂 OPO(MgO: PPLN-OPO) 目前已成为实现宽调谐中红外激光输出的最佳手段。

S. Parsa 等人采用了四腔镜驻波腔结构，获得了重频为 80 MHz 的 2.19~4.02 μm 闲频光输出，并在 3.34 μm 处获得了 1 W 的最大功率输出，对应的光光转换效率为 9.5%[9]; Niu Sujian 等人利用重频为 50 Hz 的纳秒 Nd: YVO_4 激光器泵浦 MgO: PPLN，在 3.4 μm 处获得了最大能量为 2.15 mJ 的中红外激光输出，对应的光光转换效率超过了 10%，调谐范围为 2.2~4.8 μm[10]; 王菲菲等人利用掺 Yb 光纤激光器作为抽运源，结合周期和温度调谐，实现了平均功率大于 1.7 W 的 2.37~4.01 μm 连续调谐中红外激光输出，相应的光光转换效率大于 17.1%[11]; Wang Ke 等人采用内腔式 OPO 结构，同时利用周期和温度调谐，获得了 2.25~4.79 μm 的连续中红外激光输出，在 3.19 μm 处获得最大输出功率为 1.08 W，对应的光光转换效率

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为 11.88%[12]。

由于多周期 MgO: PPLN 的极化周期呈阶跃式分布，必须结合温度调谐才能实现连续调谐输出，这大大增加了系统的复杂性。而扇形 MgO: PPLN(Fan-out MgO: PPLN) 具有极化周期连续变化的特点，仅通过平移晶体位置便能实现输出光的连续调谐，此方法在需要快速实现调谐激光输出时尤为重要。B. Xiong 等利用调 Q Nd: YVO_4 激光器作为泵浦源，结合扇形 MgO: PPLN 实现了 0.36 W 的 4.58 μm 中红外激光输出，光光转换效率为 2.67%，调谐范围为 3.78~4.62 μm[13]; D.B. Kolker 等利用调 Q Nd: YVO_4 激光器泵浦扇形 MgO: PPLN，获得了 2.6~4.2 μm 的调谐激光输出，在 3 μm 处获得了 0.206 W 的最高功率输出，对应的光光转换效率为 12.3%[14]; In-Ho Bae 等基于扇形 MgO: PPLN 实现了 2.5~3.6 μm 的连续波中红外激光输出，在 1.1 W 的泵浦条件下，在 3.5 μm 处获得了最高功率为 64 mW 的输出，光光转化效率为 5.8%[15]; E Erushin 等将扇形 MgO: PPLN-OPO 与可调谐连续波注入种子相结合，实现了 3.1~3.4 μm 的调谐激光输出，最大的光光转换效率为 6.15%[16]。

文中采用 1064 nm 高重频纳秒调 Q 激光器作为泵浦源，扇形 MgO: PPLN 作为非线性晶体。为了提高转换效率，采用简单紧凑的双通单谐振直腔结构，通过调节晶体周期实现了 3.17~4.09 μm 的中红外高效率宽调谐激光输出。当泵浦功率为 4.68 W 时，3.4 μm 的闲频光输出功率可达 0.833 W，对应的光光转换效率为 17.8%。文中所设计的架构为制造小型化高功率、高效率、宽调谐中红外激光器提供了可行的技术方案。

1 实验装置

实验装置如图 1 所示。采用高重复频率 Canlas 调 Q 激光器 (中心波长 1064 nm、脉宽 10 ns、重频可调) 作为 OPO 的泵浦源。反射镜 M1 和 M2 呈 45°角放置，用于将泵浦光准直后入射至 OPO。准直泵浦光经半波片 1(HWP-1) 和偏振分束器 (PBS) 后通过隔离器 (ISO)。隔离器能有效防止泵浦光反射回激光器，避免激光器的损坏。HWP-1 和 PBS 构成光功率控制器，可以控制注入谐振腔的泵浦功率大小。泵浦光经过半波片 2(HWP-2) 后，偏振方向变为竖直方向，以满足 MgO: PPLN 的 0 型 (e-ee) 准相位匹配，提高非线性转换效率。焦距为 200 mm 的聚焦透镜 (*L*) 将泵浦光聚焦后入射到 OPO 谐振腔中，束腰位于 MgO: PPLN 晶体的中心。

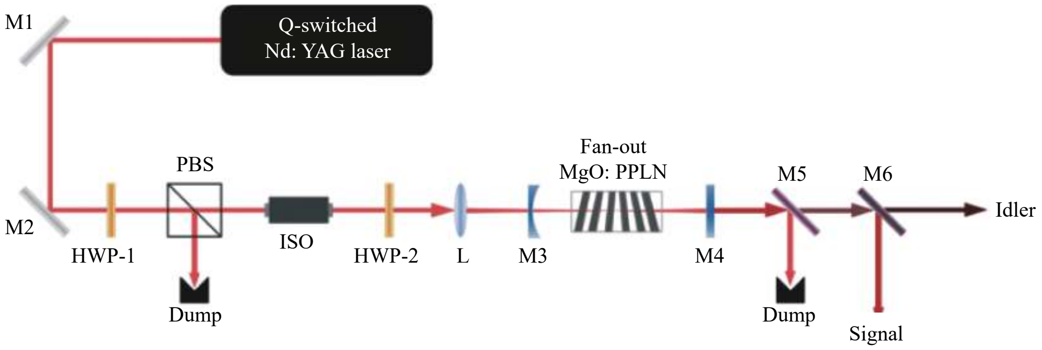


图 1 实验装置示意图

Fig.1 Schematic diagram of experimental setup

扇形结构的 MgO: PPLN 晶体 (CTL Photonics) 尺寸为 40 mm×10 mm×1 mm (长×宽×高)，MgO 掺杂浓度为 5 mol%，极化周期为 27.7~32.4 μm。晶体两端面均镀有基频光、信号光及闲频光的增透膜 (*R*≤2%@1020~1080 nm & 1200~1900 nm, *R*≤5%@2500~5000 nm)。晶体放置在温控炉中，工作温度设定在室温 (25 ℃)，温控精度为± 0.1 ℃。

OPO 谐振腔由平凹镜 M3 和平面镜 M4 构成。M3 的曲率半径为 100 mm，表面镀有 1064 nm 基频光高透、1200~1900 nm 信号光和 2500~5000 nm 闲频光高反的介质膜。M4 镀有 1064 nm 基频光高反、1200~1900 nm 信号光部分透过 (*T*=2%) 和 2500~5000 nm

闲频光高透的介质膜。

M5 为长通滤波片，截止波长为 1200 nm，用于将基频光与信号光和闲频光分离。信号光和闲频光通过锗窗口片 M6 进行分束。

2　实验结果与分析

当入射泵浦光平均功率达到 4.7 W 时，在实验过程中观察到晶体产生了极强的绿色荧光及少数亮斑，笔者认为这是由于 MgO: PPLN 晶体内部随机分布的缺陷或杂质造成的。因此，为了避免损坏晶体，实验中保持最高泵浦功率在 4.7 W 以下。在泵浦光重复频率分别为 10 kHz、20 kHz 及 30 kHz 的情况下，对信号光及闲频光的功率输出特性进行了研究，实验结果如图 2 所示。实验结果表明，随着泵浦光重频的增加，OPO 的振荡阈值不断提高，3 个重频对应的阈值分别为 0.4 W、1 W 及 1.6 W。这是由于在较低的重频下，泵浦光的单脉冲能量更高，腔内的增益更强从而降低了振荡阈值。在泵浦光功率为 4.68 W，重频为 10 kHz 的条件下，得到了最大平均功率为 0.833 W 的 3.4 μm 中红外激光输出，对应的最大光光转换效率为 17.8%。

通过横向移动晶体可以改变晶体的极化周期，以实现调谐输出。在最佳的泵浦条件下，对信号光及闲频光的调谐范围进行了研究。图 3 给出了输出光的调谐范围，利用红外光谱仪 (Thorlabs OSA-205C) 对输出波长进行了测试，并对实验数据进行了归一化处理。实验结果表明，在晶体极化周期为 31.05~28.8 μm

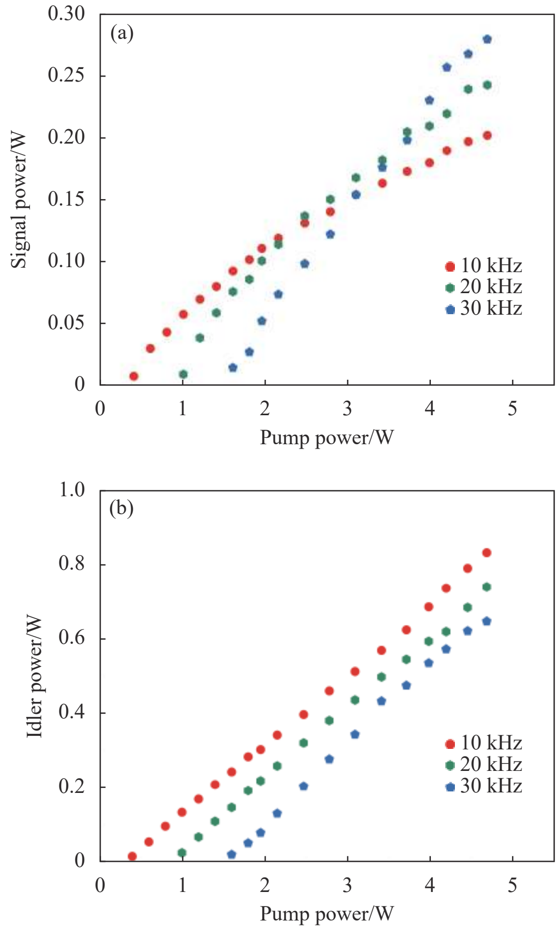


图 2 不同重复频率下 (a) 信号光和 (b) 闲频光输出功率随泵浦功率的变化关系 (MgO: PPLN: 30.47 μm)

Fig.2 (a) Signal and (b) idler output power as a function of pump power for different repetition frequencies (MgO: PPLN: 30.47 μm)

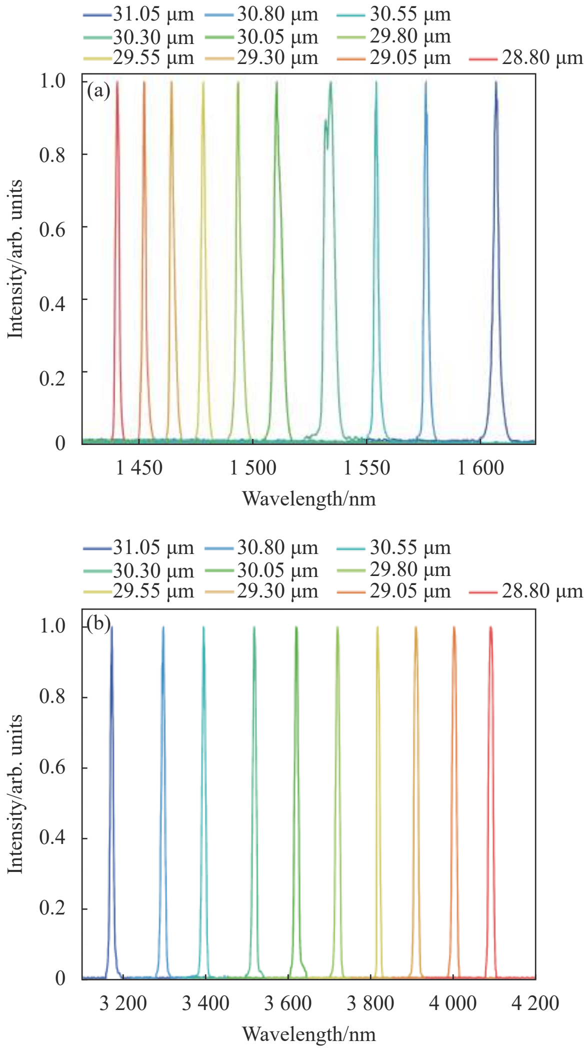


图 3 输出波长调谐范围。(a) 信号光; (b) 闲频光

Fig.3 Tuning range of output wavelength. (a) Signal; (b) Idler

的调节范围内，获得了信号光波长为 1440.7~1607.0 nm 和闲频光波长为 3171.1~4088.1 nm 的调谐激光输出。

根据 Dieter H. Jundt 提供的 Sellmeier 方程[17]，对周期调谐情况下的理论波长进行了计算。图 4 所示为晶体固定在室温 (25 ℃) 的情况下，所得理论输出波长调谐曲线与实际测量所得波长数据。实验结果表明，实验中所测数据与理论结果较为吻合。

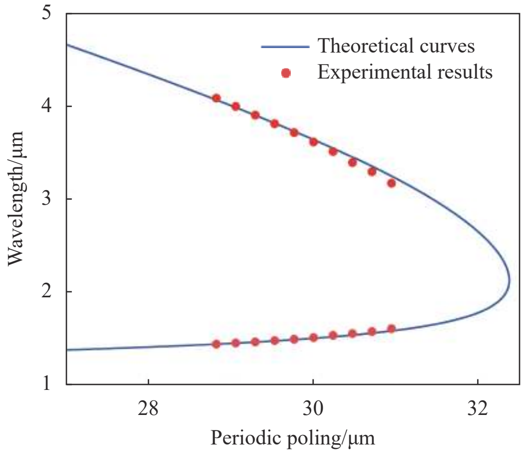
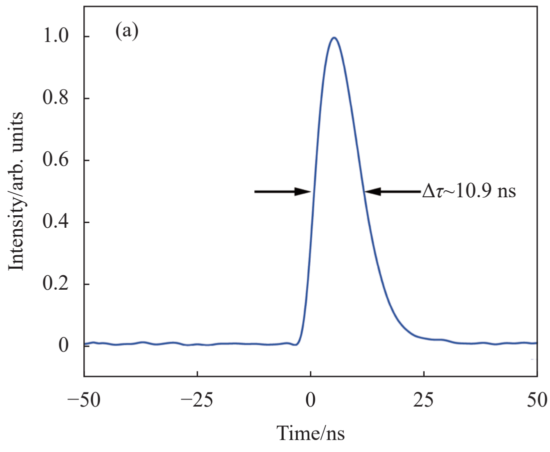


图 4 输出波长调谐曲线 (T=25 ℃)

Fig.4 Output wavelength tuning curve(T=25 ℃)

由于受到探测器响应范围的限制，实验中仅对泵浦光及信号光的时域特性进行了测试，实验结果如图 5 所示。实验结果表明，泵浦光的脉宽约为 10.9 ns，信号光的脉宽约为 8.1 ns，可以看出信号光的脉宽比泵浦光的脉宽略窄，这是由于泵浦光的振荡阈值作用导致的。



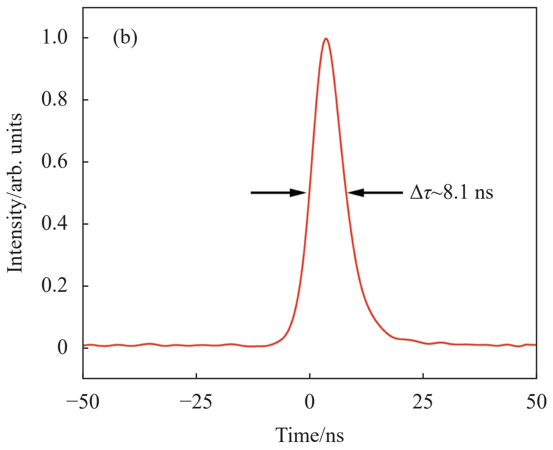


图 5 (a) 泵浦光和 (b) 信号光的脉冲波形图 (MgO: PPLN: 30.47 μm)

Fig.5 Pulse profile of (a) pump and (b) signal (MgO: PPLN: 30.47 μm)

3 结 论

文中利用纳秒量级、重复频率可调的 1064 nm 调 Q 激光器作为泵浦源，极化周期为 27.7~32.4 μm 的扇形 MgO: PPLN 作为非线性晶体，设计了一种高功率、高效率、宽调谐、窄脉宽单谐振光学参量振荡器。在泵浦激光重频分别为 10、20、30 kHz 时，测得 OPO 振荡阈值分别为 0.4 W、1 W 及 1.6 W。当泵浦功率为 4.68 W，重频为 10 kHz 时，获得了最大输出功率为 0.833 W 的 3.4 μm 中红外激光输出，对应的最大光光转换效率为 17.8%。通过改变 MgO: PPLN 晶体的极化周期，实现了信号光波长为 1440.7~1607.0 nm 和闲频光波长为 3171.1~4088.1 nm 的调谐激光输出，实验所测波长调谐数据与理论值吻合较好。在泵浦光脉宽约为 10.9 ns 的情况下，得到的信号光脉宽约为 8.1 ns。在文中的工作基础上，利用尺寸更大、光学质量更好的扇形 MgO: PPLN 晶体，有望实现超过瓦量级的宽调谐中红外激光输出，为实现紧凑型高功率、高效率、宽调谐中红外激光器光源提供了一种可行方案。

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Highly efficient, widely tunable fan-out MgO: PPLN mid-infrared optical parametric oscillator

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Abstract:

Objective The mid-infrared (MIR) laser of 3-5 μm has low propagation loss in the atmosphere, which is located in the atmospheric transparency window, and contains many absorption spectral lines of molecules and atoms. It is also known as the "molecular fingerprint region". Therefore, mid-infrared laser in this wavelength range have important applications in many fields such as environmental monitoring, military, medical, and remote sensing. Currently, the main methods for generating MIR laser output include fiber lasers, quantum cascade lasers, transition metal ion-doped solid-state lasers, and optical parametric oscillator (OPO) based on nonlinear frequency conversion technology. Among them, OPO has many advantages such as compact structure, flexible tuning methods, and high output efficiency, which has become an important means for generating mid-infrared lasers. A nanosecond mid-infrared fan-out MgO-doped periodically poled lithium niobate (MgO: PPLN) OPO is studied with wide tunning range and high conversion efficiency. It is pumped by a 1 064 nm Q-switched laser.

Methods The entire system consisted of a pump source, mirrors, half-wave plate (HWP), polarizing beam splitter (PBS), optical isolator (ISO), lens, OPO resonant cavity, nonlinear crystal, and filters (Fig.1). The power and polarization of the pump were adjusted by the HWP and PBS. An optical isolator was used to prevent the reflection of pump wave back into the laser source to avoid damaging the source. The pump wave was then focused by the lens into the center of the MgO: PPLN crystal. Under high-power pumping conditions, the parametric light oscillated inside the cavity, and the output light was separated by a long-pass filter (LPF) with cut-off wavelength of 1 100 nm and a germanium (Ge) window.

Results and Discussions By reducing the repetition rate of the pump, the oscillation threshold of the OPO was effectively reduced. At the repetition rates of 10 kHz, 20 kHz, and 30 kHz of the pumping laser, the OPO oscillation thresholds were measured to be 0.4 W, 1 W, and 1.6 W, respectively. When the pumping power was 4.68 W and the poling period of MgO: PPLN was 30.47 μm, a maximum MIR laser output power of 0.833 W at 3.4 μm was obtained, corresponding to an optical-to-optical conversion efficiency of 17.8% (Fig.2). The poling periods of MgO: PPLN can be changed by shifting the crystal from 31.05 to 28.8 μm. This corresponds to the generation of a signal wave from 1 440.7 to 1 670.0 nm and an idler wave from 3 171.1 to 4 088.1 nm (Fig.3), respectively. The experimental results were in good agreement with the theoretical simulation values (Fig.4). Using a photodetector and an oscilloscope, the pulse widths of the pump and signal waves were measured to be 10.9 ns and 8.1 ns, respectively (Fig.5).

Conclusions A mid-infrared optical parametric oscillator based on a fan-out MgO: PPLN crystal was designed, which features a wide tuning range, high output efficiency, and narrow pulse width. At a pumping frequency of 10 kHz, the maximum output power of 3.4 μm mid-infrared laser was 0.833 W, with a pumping power of 4.68 W, and the corresponding optical-to-optical conversion efficiency was 17.8%. The output wavelengths at the different poling periods of MgO: PPLN were measured, which were well-matched with the theoretical values. By means of period tuning, signal light with wavelengths of 1 440.7-1 607.0 nm and idler light with wavelengths of 3 171.1-4 088.1 nm were obtained. And the FWHM pulse width of the signal light was ~8.1 ns. This experiment provides a feasible solution for developing compact, high-power, wide-tuning nanosecond mid-infrared laser sources.

Key words: mid-infrared laser; fan-out MgO: PPLN; OPO; high conversion efficiency; wide tunning; nanosecond pulse

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