

光学学报

基于磁旋转光谱技术的氧气传感器

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摘要 在全球气候变化导致大气氧气浓度持续下降的背景下,为揭示青藏高原氧含量变化过程,利用氧气的顺磁性和法拉第磁光效应,研制了高精度磁旋转光谱大气氧气传感器。氧气测量选择近红外磁效应较强的 13118.04 cm^{-1} 波数处 $^3\text{P}(1)(J=1)$ 跃迁谱线,结合 Herriott 光学多通池将有效吸收光程提高至 7 m,使用通电螺线管线圈提供 180 Gs ($1\text{ Gs}=10^{-4}\text{ T}$) 直流磁场。基于噪声测量的信噪比分析显示装置中检偏器的最优偏转角为 10° ,此时系统总噪声为 $0.33\text{ }\mu\text{V}/\text{Hz}^{1/2}$ 。最优光谱参数条件下的 Allan 方差评估表明,系统的探测精度为 32×10^{-6} ($1\sigma, 60\text{ s}$)。本装置通过使用稀土永磁体代替通电螺线管线圈,有望进一步提高磁旋转光谱信号强度,提升传感器性能。

关键词 光谱学; 磁旋转光谱技术; 传感器; 氧气

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1 引言

氧气(O_2)是地球大气中最主要的组分之一,约占大气总体积的 21%,对生物的生存和发展有重要作用^[1]。在当前气候变化的影响下,空气中每 100 万个氧分子每年减少大约 19 个,逐渐影响生态环境^[2]。青藏高原是我国最大、世界海拔最高的高原,被称为世界“第三极”,其缺氧条件下敏感和脆弱的生态系统受到氧气浓度总体下降的影响更为显著^[3]。为了能够及时应对并采取有效的防治措施,在青藏高原开展长期的高精度氧气浓度监测来精确描绘大气氧含量的变化过程至关重要。然而,高达 10^{-6} 量级的体积比测量精度及青藏高原极端环境下的长期稳定运行要求对氧气测量技术和仪器提出了挑战。

当前氧气浓度的测量方法主要包括磁动力学方法、化学方法以及光谱学方法。磁动力学方法利用氧气的顺磁特性进行磁动力学检测(如氧气的磁化率平衡检测法),其对氧气具有较高的选择性,不易受抗磁性分子(如 H_2O)的干扰,但对振动非常敏感^[4-5]。化学方法有 Clark 电化学法、化学荧光检测法等,结构相对简单、成本较低,但是其检测过程需要频繁添加反应试剂,难以实现长期无人值守运行^[6-7]。光谱学方法主要包括平衡光检测方法、光声光谱检测方法及磁旋转光

谱检测方法,具有探测灵敏度高、选择性强、非接触测量及无试剂消耗等优势^[8]。平衡光检测方法将参考光和信号光进行差分处理,能够在 300 s 积分时间下实现 65×10^{-6} 的测量精度^[9]。光声光谱检测方法是一种无背景的间接测量方法,利用高灵敏麦克风探测由氧气分子吸收光子转化的内能在释放时产生的声波信号,得到 13×10^{-6} 的测量精度^[10]。

磁旋转光谱技术(FRS)利用顺磁性分子在纵向磁场中的法拉第磁光效应,入射线偏振光的左旋圆偏振(LHCP)和右旋圆偏振(RHCP)分量对分子塞曼子能级 $\Delta m = +1$ 和 $\Delta m = -1$ 跃迁的吸收和色散存在差异,导致通过气体池后的合成线偏振光的偏振面发生旋转,通过解调旋光信号获得分子浓度信息^[11]。相对于传统吸收光谱技术,FRS 只对顺磁性分子响应,能够有效避免其他抗磁性分子的吸收干扰,同时可以有效抑制激光噪声,具有很高的探测灵敏度。目前,国际上开展 FRS 氧气探测研究的团队主要有美国普林斯顿大学的 Wysocki 团队及澳大利亚阿德莱德大学的 English 团队。So 等^[12]使用功放和电阻-电容-电感(RCL)串联回路对磁场进行交流调制,并结合双光路平衡探测,将测量精度提升到 10×10^{-6} 。Brumfield 等^[13]使用稀土永磁体阵列将磁场强度提升到 $(554\pm 64)\text{ Gs}$ ($1\text{ Gs}=10^{-4}\text{ T}$),并结合 45° 平衡探测法,得到

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60 s 积分时间内 1.3×10^{-6} 的探测精度。Zhang 等^[14]将 90° 探测法与 45° 平衡探测法相结合, 利用混合探测方法在 1 s 的积分时间内获得的测量精度为 0.6×10^{-6} 。Westberg 等^[15]将 FRS 与腔衰荡光谱技术结合, 在 100 s 的积分时间内获得 0.16×10^{-6} 的探测精度。以上研究方案虽然具有较高的探测精度, 但是设备复杂性较高, 难以适用于青藏高原的极端条件。

本文针对青藏高原特殊环境应用需求, 采用 FRS, 结合直流螺线管线圈和 Herriott 光学多通池, 设计了一

套近红外高精度 O_2 传感器, 并对其性能进行了评估。

2 基本原理

2.1 FRS 原理

FRS 原理如图 1 所示, 它由激光器 (laser)、起偏器 (polarizer)、气体吸收池、磁体、检偏器 (analyzer) 及探测器 (detector) 组成。激光器产生的入射光经过起偏器后成为线偏振光并进入气体池内, 带有气体吸收信息的出射光经检偏器后被探测器接收。

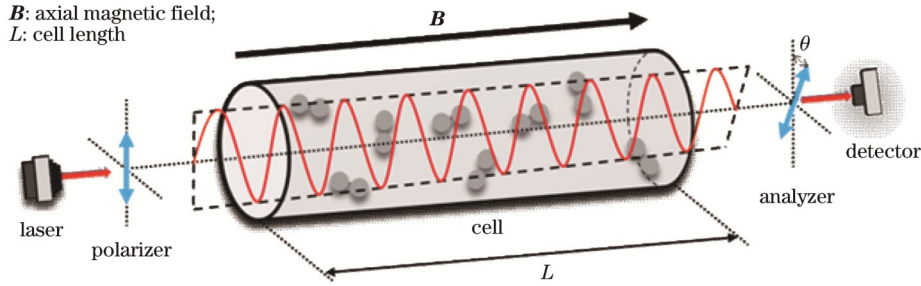


图 1 FRS 原理示意图
Fig. 1 Schematic of FRS

根据 Westberg 等^[16]的理论推导, 磁旋转光谱装置中探测器接收的光强信号可以表示为

$$I = \frac{I_0}{2} \exp(-2\bar{\delta}) \times \left\{ (\alpha^2 + \xi^2 \beta^2) [\cosh(\Delta\delta) - \cos(\Delta\phi + 2\theta)] + 2(\alpha^2 + \beta^2) \xi \sinh(\Delta\delta) + (\xi^2 \alpha^2 + \beta^2) [\cosh(\Delta\delta) + \cos(\Delta\phi + 2\theta)] \right\}, \quad (1)$$

式中: I_0 为入射光强; $\Delta\delta$ 、 $\bar{\delta}$ 及 $\Delta\phi$ 分别为 LHCP 和 RHCP 的衰减差、平均衰减及相位差; α 、 β 分别为沿检偏器主轴方向和垂直于检偏器主轴方向的电场占比; ξ 为起偏器的消光比; θ 为检偏器偏离起偏器正交方向的夹角 (以下简称“偏转角”)。

当气体吸收较弱, 且偏振器件理想消光 ($\alpha = \beta = \epsilon = 0$) 时, 可得到 FRS 透过光强的简化表达式^[17], 即

$$I = \frac{I_0}{2} [1 - \cos(2\theta) + LR_\Delta \sin(2\theta)], \quad (2)$$

式中: L 为气体吸收光程; R_Δ 为包含所有跃迁分量的光谱线型之和^[18]。

$$R_\Delta = \frac{N_c S_0 \sqrt{\ln 2}}{\pi \gamma_D} \sum_{M', M''} (-1)^{M' - M''} \text{Re}[Z(z)], \quad (3)$$

式中: N_c 为分子浓度; S_0 为分子吸收谱线强度; γ_D 为多普勒谱线的半峰全宽; M' 和 M'' 分别为跃迁上下能级的磁量子数; $Z(z)$ 为等离子体色散函数^[19]。

$$\begin{cases} Z(z) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{\exp(-t^2)}{(t-z)} dt \\ z = x + iy \\ x = \sqrt{\ln 2} \left\{ v - \left[v_0 - (g''M'' - g'M') \frac{\mu_B B}{hc} \right] \right\} / \gamma_D \\ y = \sqrt{\ln 2} \gamma_C / \gamma_D \end{cases}, \quad (4)$$

式中: v 为激光频率; v_0 为磁场强度为 0 时吸收线的中心频率; g 为朗德因子; μ_B 为玻尔磁子; B 为磁场强度; h 为普朗克常数; c 为真空中的光速; γ_C 为碰撞展宽。

磁旋转光谱装置的系统噪声 N_{tot} 与检偏器偏转角 θ 有关^[20-21], 可表示为

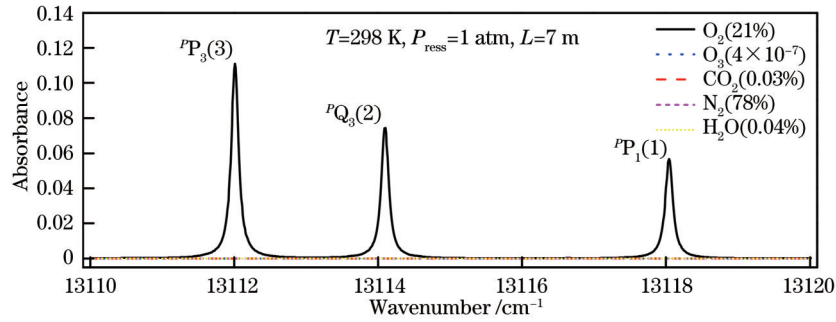
$$N_{\text{tot}}(\theta) = \sqrt{N_0^2 + N_1^2 (\sin^2 \theta + \xi) + N_2^2 (\sin^2 \theta + \xi)^2}, \quad (5)$$

式中: N_0 为探测器噪声; $N_1 \sqrt{\sin^2 \theta + \xi}$ 为散粒噪声; $N_2 (\sin^2 \theta + \xi)$ 为激光噪声。随着检偏器偏转角 θ 增大, 激光噪声将逐渐占据主导地位。磁旋转光谱装置通常有一个最优的检偏器偏转角 θ_{opt} (通常小于 10°), 在此偏转角下可得到最大探测信噪比。

2.2 氧气跃迁线的选择

$$O_2 \text{ 的自旋磁矩和角动量的近似耦合表达式}^{[22-23]} \text{ 为} \\ \frac{g}{g_s} = \frac{J(J+1) + S(S+1) - N(N+1)}{2J(J+1)}, \quad (6)$$

式中: g_s 为电子自旋因子 ($g_s = -2.002$)^[24]; J 为角动量子数; S 为自旋量子数; N 为轨道量子数。朗德因子 g 决定了能级在磁场中分裂的大小, 在低 J 值下能得到更高的 g 因子, 测量时表现出更强的磁旋转光谱信号^[25]。图 2 所示为 O_2 在 762.3 nm 附近的吸收情况, 选择 13118.04 cm^{-1} 波数处的 ${}^3P(1) (J=1)$ 跃迁作为氧气

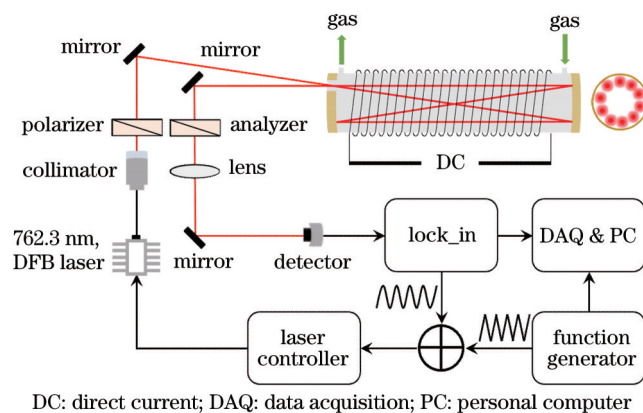
图 2 Spectraplot 数据库 O₂ 吸收仿真结果Fig. 2 Simulation results of Spectraplot database of O₂ absorption

测量谱线,其线强为 3.063×10^{-24} cm/molecule。

3 实验装置

FRS O₂ 传感器的测量实验装置如图 3 所示,探测光源为 762.3 nm 室温工作型分布式反馈激光二极管 (Nanoplus, cw-DFB),激光器的驱动电流和温度使用激光控制器 (Stanford Research Systems, LDC 501) 控制,函数发生器 (Agilent, 33500B) 输出的 50 Hz 锯齿波与锁相放大器 (Stanford Research Systems, SR850) 输出的 33 kHz 正弦波经加法器 (Stanford Research Systems, SR560) 叠加后输入激光控制器,用于波长扫描和调制。激光器出射光经光纤准直器 (Thorlabs, F230APC-780) 准直后由起偏器 (福建福特科光电, Rochon 棱镜, 消光比约为 4×10^{-5}) 建立线偏振态,之后经一块镀银反射镜耦合进入光学多通池。池内多次反射的出射光通过与起偏器型号相同的检偏器后被石英透镜 (焦距 $f=75$ mm) 聚焦于光电探测器 (Thorlabs, PDA10A2) 的光敏面。探测器输出信号用于锁相放大器解调二次谐波 ($2f$) 光谱,锁相放大器的时间常数为 100 μ s。利用采集卡 (NI, USB-6356) 采集锯齿波信号和解调信号,并将这些信号送入上位机进行处理。

光学多通池为 Herriott 型,由两块相距 35 cm、直

图 3 FRS O₂ 传感器装置图Fig. 3 Experimental setup for O₂ sensor based on FRS

径均为 4 cm 的凹球面镀金反射镜组成,在其中一块反射镜中心 1.5 cm 距离处开设一个直径为 5 mm 的圆孔,用于激光入射和出射。光束多次反射后在镜片表面形成 10 个反射斑点,总反射次数为 20 次,有效吸收光程达 7 m。多通池腔体为石英玻璃,同轴固定在铝合金管内。石英管外壁和铝合金管内壁形成厚度为 1 cm 的密封夹层,用于水冷。

为磁旋转光谱探测提供直流磁场的螺线管磁体,使用线径为 1 mm 的漆包紫铜线缠绕铝合金管外壁获得。磁体长 30 cm,共绕线 8 层。磁场强度对磁旋转光谱信号有直接影响,在恒定电流的激励下,使用分辨率为 0.1 Gs、精度为读数 $\pm 0.3\%$ 的高斯计 (CH-Hall, Model 1500) 分别在 1 A、2 A、3 A 电流的激励下,沿 Herriott 光学多通池内部中心轴线进行磁场强度测量,结果如图 4 所示。中心磁场强度 (B_c) 与激励电流 (I) 存在线性关系:

$$B_c = -0.01333 + 90.70857I. \quad (7)$$

测量结果表明,每增加 1 A 激励电流,中心磁场强度约增加 90.7 Gs。

磁场强度可能会受到激励电流不稳定的影响而产生波动,为了测量磁场的稳定性,将高斯计的霍尔探头固定在气体池的中心位置,对 2 A 恒定电流激励下的中心磁场强度进行长达 12 h 的持续测量,每 30 min 记录一次数据。测量结果如图 5 所示。可以看到,磁场强度稳定性较好,保持为 181.3 Gs,不会对 O₂ 测量结果产生影响。

4 分析与讨论

4.1 最优偏转角度

磁旋转光谱装置中采用了两块偏振片。在建立光路偏振态并调节光强后,便将起偏器的起偏角度固定;在装置优化过程中转动检偏器,以测量系统的信噪比,确定最优偏转角度。考虑到干涉、光反馈等的影响,偏振片一般不能与光路垂直放置^[26]。如图 6 所示,为评估倾斜放置的偏振片在角度旋转过程中对光路的影响,以 1° 的分辨率测量了检偏器偏转角在 $-16^\circ \sim +16^\circ$ 范围内的光强信号。根据 Malus 定律,利用式 (8) 中的

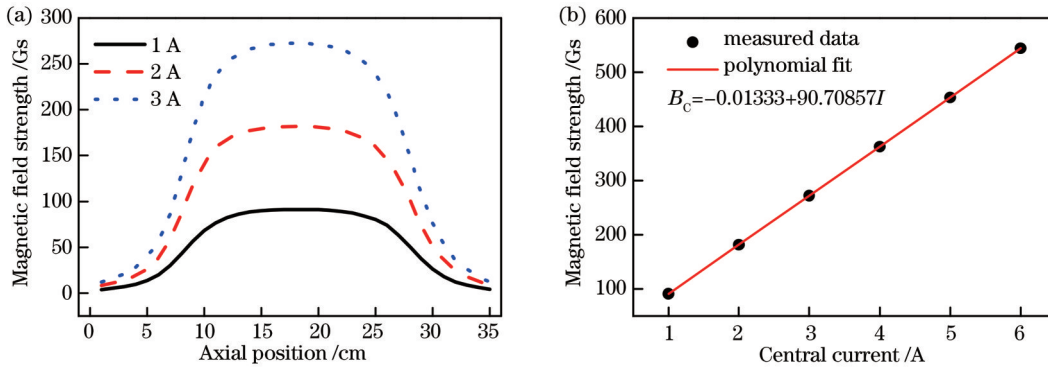


图 4 磁场强度测量结果。(a)Herriott 光学多通池轴向磁场强度分布;(b)Herriott 光学多通池中心磁场强度随激励电流的变化
Fig. 4 Measurement results of magnetic field strength. (a) Distribution of axial magnetic field strength of Herriott multi-cell;
(b) variation of central magnetic field strength of Herriott multi-cell with excitation current

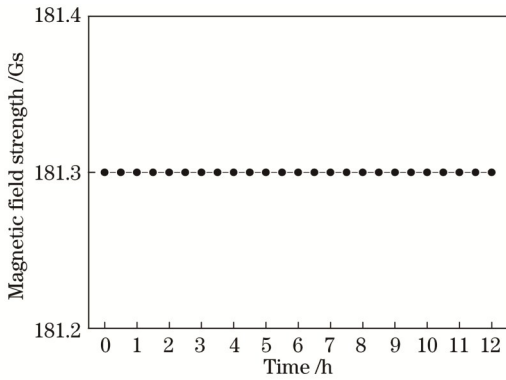


图 5 螺线管磁场强度 12 h 的测量结果

Fig. 5 Measurement results of solenoid magnetic field strength for 12 h

正弦平方函数对测量光强进行拟合。

$$y = y_0 + A \sin^2 \left[\frac{(x - x_0)\pi}{180^\circ} \right], \quad (8)$$

式中: A 表示检偏器偏转角为 90° 时的最大透过光强; x_0 和 y_0 分别为实际消光角度和实际消光角度下探测器信号强度。拟合相关度大于 99.87%, 可认为偏振片倾斜对本实验系统基本无影响。

为确定 FRS 装置中检偏器的最优偏转角 θ_{opt} , 使

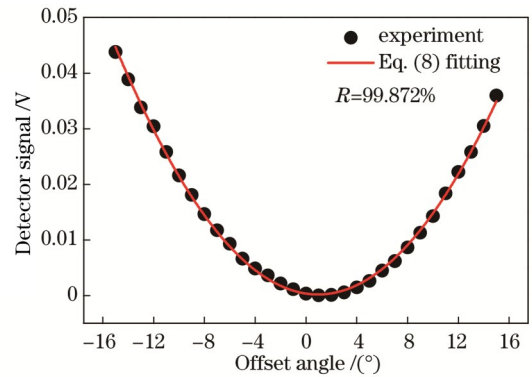


图 6 光强信号与偏转角的关系

Fig. 6 Relation between laser intensity signal and offset angle

用锁相放大器对系统的总噪声 N_{tot} 进行测量, 结果如图 7(a) 所示, 当偏转角大于 12° 时, 总噪声呈显著增加趋势。根据 Kramers-Kronig 关系^[27], 磁旋转光谱信号 S 正比于 $\sin(2\theta)$, 因此系统的信噪比 (SNR) 正比于 $\sin(2\theta)/N_{tot}$ ^[28]。由此得到的 SNR 与 θ 的关系如图 7 (b) 所示, SNR 呈先增大后减小的趋势。系统的总噪声由激光器噪声、散粒噪声和探测器噪声组成^[29]。当探测器噪声占据主导地位时, SNR 会呈现递增的趋势; 随着激光器噪声和散粒噪声逐渐占据主导地位,

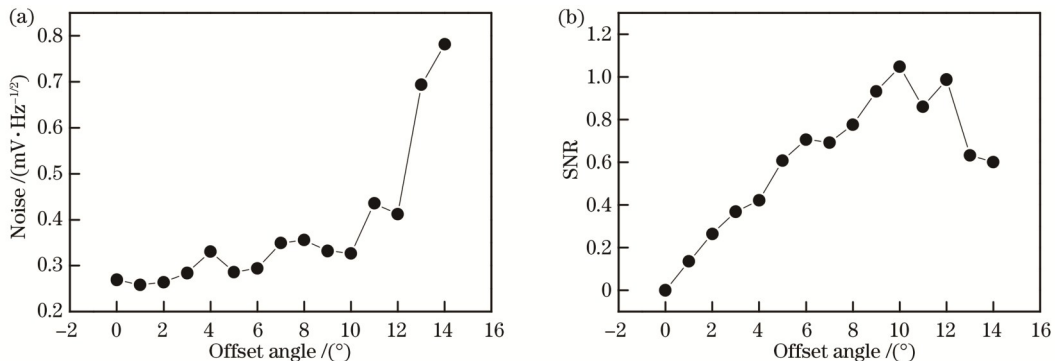


图 7 最优偏转角度测量结果。(a)探测器噪声与偏转角的关系;(b)信噪比与偏转角的关系

Fig. 7 Measurement results of optimal offset angle. (a) Relation between detector noise and offset angle; (b) relation between SNR and offset angle

SNR 会达到峰值,随后下降^[30]。当偏转角为 10° 时, SNR 最大,此时系统的总噪声为 $0.33 \mu\text{V}/\text{Hz}^{1/2}$ 。

4.2 最优调制振幅

在 FRS O_2 传感器中,正弦波作为调制信号,其调制振幅直接影响 FRS 二次谐波信号的强度。为了获得系统的最优调制振幅,以 4 mV 步进测量了从 4 mV 到 30 mV 的磁旋转光谱信号强度,如图 8 所示。结果显示,磁旋转光谱信号随着调制振幅的增大呈现出先增大后减小的趋势,峰值处对应着最优调制振幅 (18 mV)。

4.3 磁场强度优化

不同激励电流下测量的 O_2 磁旋转光谱信号如图 9 所示,其中 0 A 表示相同装置下的波长调制信号。随着激励电流增加,磁旋转光谱信号的峰峰值增大,且增大效果接近线性。当激励电流达到 6 A 时,磁旋转光谱信号强度依然无明显减弱趋势,说明信号强度还能继续增大,系统未达到最优磁场的拐点。综合考虑螺线管磁体散热能力和安全性,后续探测时将激励电流设置为 2 A ,对应磁场强度约为 180 Gs 。

4.4 磁旋转光谱信号标定

磁旋转光谱信号强度正比于 O_2 体积比,通过对不同体积比下 O_2 的磁旋转光谱信号进行测量,可以得到

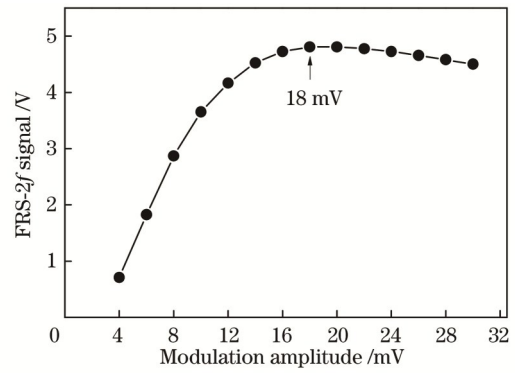


图 8 FRS O_2 传感器的最优调制振幅

Fig. 8 Optimal modulation amplitude of O_2 sensor based on FRS

FRS 系统的信号与 O_2 体积比的标定表达式。向 Herriott 光学多通池内通入高纯度 O_2 ,并用纯 N_2 不断稀释,采集每一次稀释后的直接吸收光谱信号和相应的磁旋转光谱信号,结果如图 10 所示。

在已知测量压力、吸收谱线强度和吸收光程的情况下,多通池 O_2 的实时浓度能利用直接吸收光谱反演得出。磁旋转光谱信号和 O_2 体积比标定结果如图 11 所示,线性拟合相关度为 99.997% ,标定表达式为

$$y = 4.10046 \times 10^{-4} + 0.04642x. \quad (9)$$

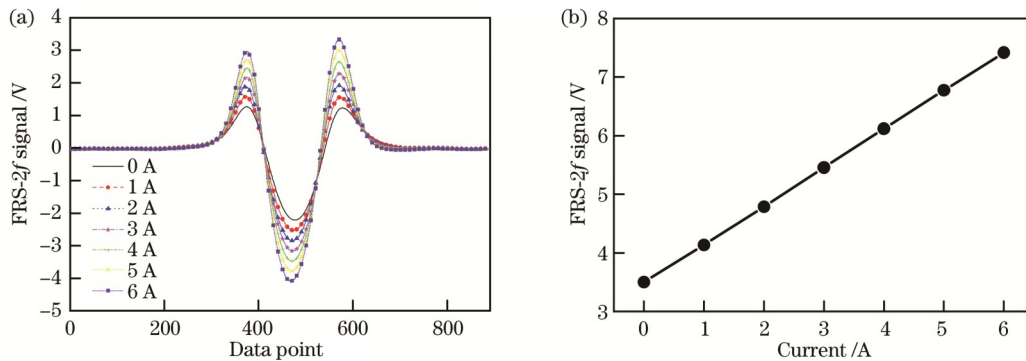


图 9 不同磁场强度下的 FRS- $2f$ 信号。(a) 不同激励电流下的 FRS- $2f$ 信号;(b) FRS- $2f$ 信号峰峰值随激励电流的变化

Fig. 9 FRS- $2f$ signals under different magnetic field strengths. (a) FRS- $2f$ signal at different excitation currents; (b) variation of peak-to-peak value of FRS- $2f$ signal with excitation current

4.5 探测精度评估

为了评估 FRS 系统在最优化条件下对 O_2 的测量性能,对体积比约为 5.36% 的 O_2 进行长达 3600 s 的连续采集,结果如图 12(a) 所示,图中数据点的时间分辨为 1 s 。系统的测量重复性使用直方图统计进行分析,如图 12(b) 所示,对测量的 O_2 体积比频率进行高斯拟合,得到半峰全宽 (FWHM) 为 352×10^{-6} ,利用高斯统计的标准差 (SD) 表征装置的实际测量精度,为 149×10^{-6} 。使用 Allan 方差分析获得系统稳定性和探测精度,如图 12(c) 所示。在 1 s 积分时间内,系统的探测精度为 106×10^{-6} (1σ);系统的最优积分时间为 60 s ,此时探测精度可以提升到 32×10^{-6} (1σ)。上述性能评

估结果说明,该 FRS 装置可以实现 O_2 体积比的高精度探测。

5 结 论

研制了基于 FRS 的 O_2 测量传感器,分析并选择了 13118.04 cm^{-1} 处 $^1\text{P}(1)$ ($J=1$) 吸收线为探测谱线,使用 Herriott 光学多通池将有效吸收光程增加到 7 m ,噪声测量分析结果表明,该装置中检偏器的最优偏转角 θ_{opt} 为 10° ,该条件下装置的探测精度可达到 32×10^{-6} ($1\sigma, 60 \text{ s}$),能够用于大气 O_2 的高精度测量。下一步将使用钕铁硼稀土永磁体代替通电螺线管线圈,提供更高强度的稳恒磁场,寻求降低系统功耗和复杂性的同

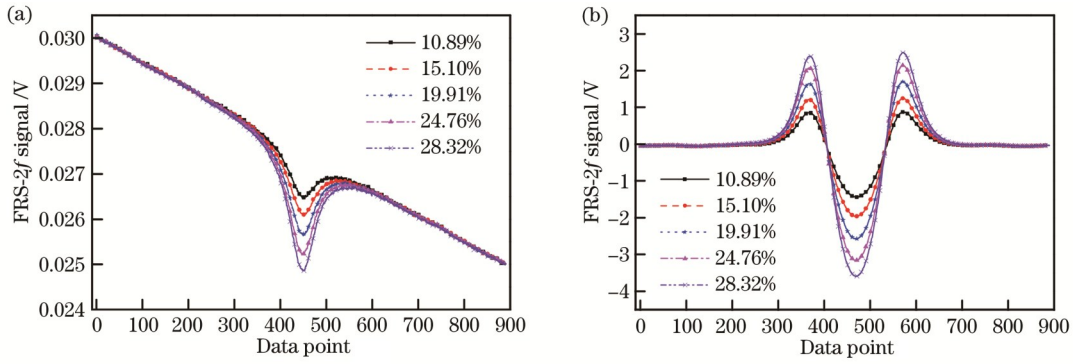


图 10 不同体积比下 O₂ 的谱线。(a)直接吸收谱线;(b)FRS-2f谱线

Fig. 10 Spectra of O₂ at different volume ratios. (a) Direct absorption spectra; (b) FRS-2f spectra

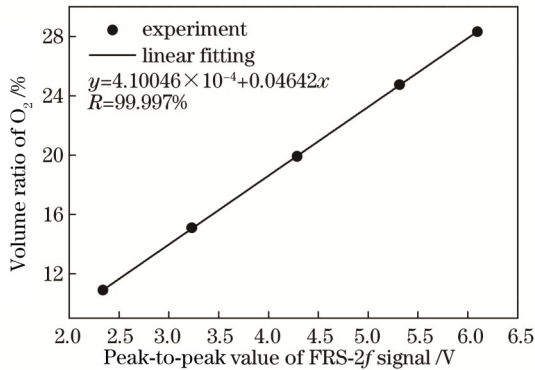


图 11 磁旋转光谱信号和 O₂ 体积比标定

Fig. 11 Calibration of O₂ volume ratio and Faraday rotation spectrum signal

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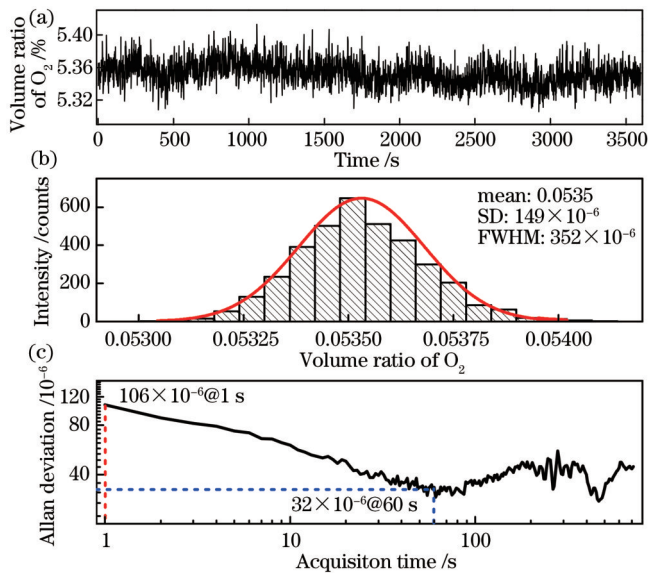


图 12 FRS O₂ 测量装置性能评估。(a)1 h 连续测量;(b)直方图高斯统计分析;(c)Allan 方差

Fig. 12 Performance evaluation of O₂ sensor based on FRS. (a) Time series of O₂ for 1 h; (b) histogram plot of Gaussian statistics; (c) Allan deviation

时,进一步增大磁旋转光谱信号强度,尝试继续提升传感器的性能,以便将来能够在青藏高原组网中应用。

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Oxygen Sensor Based on Faraday Rotation Spectroscopy

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Abstract

Objective Oxygen (O₂) is one of the most important components in the atmosphere and plays a key role in the survival of all living organisms on Earth. However, the atmospheric O₂ concentration is decreasing due to the rapid expansion of human activities. The Tibet Plateau, known as the third pole, is a plateau with the highest altitude in the world. For a long time, as the O₂ content of the local atmosphere is lower than that of other regions, the ecosystem is extremely fragile and sensitive. Long-term quantitative monitoring of atmospheric O₂ concentration is crucial to understand the evolution pattern of decreasing O₂ and its effects on the ecosystem of the Tibet Plateau. However, it requires a very challenging detection precision of 10⁻⁶ level. Various O₂ measurement methods have been proposed. The commonly employed electrochemical techniques and magnetic dynamics methods are compact and easily commercial available but suffer from long-term stability and vibration. In contrast, laser absorption spectroscopic techniques based on the Beer-Lambert law can provide high reliability, completely non-contact measurement, and long-term performance. In particular, Faraday rotation spectroscopy further offers high selectivity for paramagnetic molecules and is a powerful tool for O₂ measurement with high

precision. Our paper develops a simply easy-to-deploy and maintenance-free O₂ sensor based on FRS and provides a feasible sensor scheme for O₂ detection in Tibetan Plateau.

Methods A 762.3 nm continuous wave distributed-feedback laser working at room temperature is employed as the probe laser. The laser current and temperature are controlled by a commercial laser controller. O₂ measurement selects the ^PP(1) ($J=1$) line with a strong near-infrared magnetic effect and a strength of 3.063×10^{-24} cm/molecule at 13118.04 cm^{-1} . The static magnetic field is generated by a solenoid coil under constant current excitation. A Herriott optical multi-pass cell with two 8 cm diameter spherical mirrors separated at 35 cm is adopted to provide an effective absorption path length of 7 m. The cell is made of aluminum alloy which is oxidized and blackened to reduce stray light. A polarizer is utilized before the laser beam incidence in the cell to clean the polarization state, and a second polarizer, placed after the light beam exits the cell, acts as a polarization analyzer. Various parameters of the sensor are optimized to ensure that the sensor operates in optimal conditions, including magnetic field strength, offset angle, and modulation amplitude. Finally, the performance of the sensor performance is assessed by continuous O₂ measurement with a fixed concentration. The system stability and detection precision are analyzed by Allan deviation and a histogram of frequency counts.

Results and Discussions The parameters of the sensor are optimized. The noise measurement shows that the optimal offset angle is 10° and the corresponding total noise of the system is $0.33 \mu\text{V}/\text{Hz}^{1/2}$ (Fig. 7). The optimal modulation amplitude for O₂ detection at atmospheric pressure is 18 mV (Fig. 8). We find that the measured Faraday rotation spectral signals are proportional to magnetic field strength in the range of 0 to 540 Gs (Fig. 9). The 180 Gs field strength is chosen due to the safety and heat. The stability of the magnetic field strength is tested continuously for 12 hours by a Gaussmeter with a resolution of 0.1 Gs and an accuracy of $\pm 0.3\%$ of the reading (Fig. 5). The results indicate high stability. System calibration is performed with a strong linear relationship between Faraday rotation spectral signals and O₂ concentrations. A fixed volume ratio of about 5.36% is continuously measured for 3600 s and the time resolution is 1 s (Fig. 12). A Gaussian profile is fitted to the frequency distribution histogram. The standard deviation value which corresponds to the actual instrument precision is 149×10^{-6} . Allan deviation evaluation demonstrates that the optimal average integration time of the system is 60 s, at which the detection precision can be improved to 32×10^{-6} .

Conclusions A high-precision atmospheric O₂ sensor based on Faraday rotation spectroscopy is developed. The measurement selects the ^PP(1)($J=1$) line with a strong near-infrared magnetic effect at 13118.04 cm^{-1} . A Herriott optical multi-pass cell with coils wounded is designed specifically for Faraday rotation spectroscopy to offer an absorption path length of 7 m and a magnetic field strength of 180 Gs, which effectively enhances the detection signal and improves the system performance. The operating parameters of the sensor system are optimized, and the performance is evaluated. As a result, a detection precision of 32×10^{-6} with the acquisition time of 60 s is achieved, thereby confirming the precision and reliability of the sensor, and providing a feasible scheme for long-term O₂ detection in Tibet Plateau. In future work, we will develop permanent rare-earth magnets instead of solenoid coils, try to provide higher-strength constant magnetic fields, and pursue lower power consumption and higher performance. We hope that our future research can achieve the networking O₂ measurement in the Tibet Plateau.

Key words spectroscopy; Faraday rotation spectroscopy; sensor; oxygen