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中国激光

基于超稳腔 PDH 稳频的 280 mHz 线宽 DBR 光纤激光器

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摘要 利用超稳腔 PDH(Pound-Drever-Hall)稳频技术，对自研的分布 Bragg 反射(DBR)单纵模光纤激光器稳频，获得亚赫兹线宽超稳激光的稳频结果。通过优化腔结构参数，辅以绝热封装和精密温控等措施，并在腔内设置可快速宽范围调谐激光频率的压电陶瓷(PZT)，研制出了可满足超稳腔 PDH 稳频要求的自由运转 DBR 光纤激光器。基于腔长为 10 cm、精细度为 360000 的超稳光腔频率为参考频率，PDH 稳频后光纤激光器的 1 s 和 100 s 频率不稳定度分别达到了 6×10^{-16} 和 8×10^{-15}，频率噪声降低至 8×10^{-3} $\mathrm{Hz^2/Hz}$@1～10 Hz，激光线宽窄至 280 mHz，由此表明研制的光纤激光器可用于构建亚赫兹线宽超稳激光光源。

关键词 激光器；单纵模；Pound-Drever-Hall 稳频；超稳激光器

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1 引言

频率超稳的低噪声超窄线宽激光在精密测量[1]、光学原子钟[2]、时频传递[3]以及低噪声微波产生[4]等领域具有极其重要的应用，这种超稳激光通常是由自由运转单频激光通过频率锁定来获得。原子分子精细跃迁谱线[5]、光学干涉仪[6]和超稳光学谐振腔的谐振频率[7]均可作为参考频率，通过灵活运用这类参考频率，使其产生出反映激光频率不稳定度的误差信号，并将信号反馈至激光频率调整执行器件，就可锁定激光器的频率。据此，人们已发展出许多不同机制的激光稳频方案[8-12]，其中，基于超稳光学参考腔的 PDH(Pound-Drever-Hall)稳频技术因鉴频灵敏度高等优势而备受人们青睐[13]。利用这种基于超稳腔的 PDH 稳频技术，已成功地将不同类型和波长的单频激光器频率不稳定度降至 10^{-14}@1 s 以下、线宽压窄至亚赫兹水平[14-16]。

因光纤激光器性能优良，人们期望利用光纤激光器获得性能更为优异的超稳激光源。2012 年，德国联邦物理技术研究院(PTB)和美国实验天体物理联合研究所(JILA)合作，采用超低温环境下 21 cm 腔长的单晶硅光腔作为频率参考，演示了对 1.5 μm 波段分布反馈式(DFB)光纤激光器的 PDH 稳频效果，成功地将激光线宽降至 40 mHz、频率不稳定度降至 1×10^{-16}@1 s[17]；至 2017 年，PTB 和 JILA 团队通过降低环境振动等技术噪声对参考腔的影响，进一步将激光频率不稳定度降至 4×10^{-17}@0.8～30 s、线宽大幅降至 8 mHz[18]。同样在 2017 年，中国科学院国家授时中心以 10 cm 腔长的超稳光腔作为频率参考，也成功地通过 PDH 稳频将 1.5 μm 波段 DFB 光纤激光器的线宽压窄至 180 mHz，频率不

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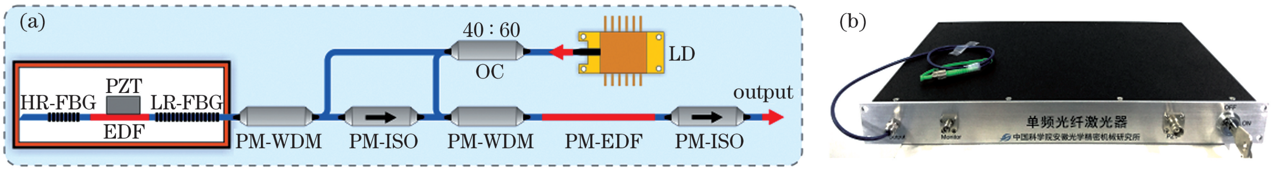
稳定度降至 1×10^{-15}@1～100 s 以下[19]。这些演示实验均表明，运用超稳腔 PDH 稳频技术，可以将光纤激光器线宽稳定到毫赫兹量级；除了超稳腔及伺服系统性能之外，所能获得的超稳光纤激光线宽和频率不稳定度取决于自由运转光纤激光器的线宽、频率漂移与噪声水平以及激光器频率调谐机制等性能的优劣[20]。尽管我国多家科研机构已发展出了具备频率调谐机制的单纵模光纤激光器[21-22]，并采用基于气体分子精细跃迁谱线的饱和吸收稳频方案，已将激光频率长期稳定在百千赫兹以内[23-24]，但是，我国自研的单纵模光纤激光器尚未应用超稳光腔 PDH 稳频技术获得亚赫兹线宽的超稳光纤激光光源。

本文基于超稳光腔 PDH 稳频技术对我们自研的 1550 nm 分布式 Bragg 反射(DBR)单纵模光纤激光器的稳频结果进行了报道。通过优化 DBR 光纤激光器腔结构参数，并辅以绝热封装和精密温控等措施，再通过在 DBR 腔内设置压电陶瓷(PZT)，设计研制出满足超稳腔 PDH 稳频要求的单纵模 DBR 光纤激光器；进而，采用超稳光腔，实现了该光纤激光器的 PDH 稳频，使得其 1 s 和 100 s 的频率不稳定度分别达 6×10^{-16} 和 8×10^{-15}、线宽窄至 280 mHz，获得的这种超稳光纤激光有望在精密测量等领域发挥重要作用。

2 自由运转单纵模光纤激光器

图 1(a)为我们研制的 1550 nm 波段 DBR 型单纵模光纤激光器的结构示意图，所用增益光纤为一段长度为 8 mm 的单模非保偏掺铒光纤(EDF)，其纤芯直径、数值孔径和吸收系数分别为 3 μm、0.28 和 5 dB/m@975 nm。该 EDF 两端分别熔接两个刻写在匹配光纤上具有不同反射率的光纤光栅(FBG)，构成分布式 Bragg 反射(DBR)谐振腔。其中高反射率 FBG(HR-FBG)的中心波长、反射率和 3-dB 带宽分别为 1550.10 nm、99.94% 和 0.2 nm，低反射率 FBG(LR-FBG)的中心波长、反射率和 3-dB 带宽分别为 1550.09 nm、98% 和 0.08 nm。LR-FBG 的反射率选为较高的 98% 是为了增大 DBR 腔的 *Q* 值，获取自由运转下的窄线宽；由于通过施加应力可使 LR-FBG 形成一定双折射，但该双折射效应较弱，故将其 3-dB 带宽选为较窄的 0.08 nm，以便完全区分这两个正交偏振对应的反射峰，进而便于仅让其中的慢轴反射峰与 HR-FBG 构成谐振腔，获取单偏振的单纵模激光输出。该 DBR 光纤激光器由单模尾纤输出的 975 nm 激光经保偏波分复用耦合器(PM-WDM)提供泵浦，利用高硬度环氧树脂胶将压电陶瓷(PZT)粘接在增益光纤的侧面，通过拉伸调节腔长，实现对激光频率的调谐。该 DBR 光纤激光器先通过物理接触的导热封装固定于黄铜热沉盒中，再由聚四氟乙烯构成的绝热盒对其进行二次封装，并采用半导体制冷器(TEC)对二次封装的绝热盒进行精密温度控制，而 TEC 的制冷面通过导热胶与黄铜热沉热传导。



EDF: erbium doped fiber; HR-FBG: high-reflectivity fiber Bragg grating; LR-FBG: low-reflectivity fiber Bragg grating; PZT: piezoelectric transducer; PM-WDM: polarization-maintaining wavelength division multiplexer; PM-ISO: polarization-maintaining isolator; PM-EDF: polarization-maintaining erbium doped fiber; OC: optical coupler; LD: laser diode

图 1 研制的 DBR 型单纵模光纤激光器。(a) 结构示意图；(b)集成样机照片

Fig. 1 DBR single-longitudinal-mode fiber laser. (a) Schematic diagram; (b) photo of the fiber laser prototype

研制的 DBR 光纤激光器具有稳定的单纵模振荡特性，图 2(a)为利用 F-P 扫描干涉仪[Thorlabs, SA200-12B，自由光谱范围(FSR)为 1.5 GHz]测量得到的结果。通过改变 TEC 控制温度，输出激光的中心频率(波长)无跳模调谐范围大于 150 GHz (～1.2 nm)。当控制温度不变时，输出激光的中心频率漂移量约在±10 MHz 以内。通过改变施加在光纤激光器内置 PZT 上的电压，可以对输出激光进行快速的频率调谐。图 2(b)为对 PZT 施加不同电压下实际测得的输出激光频率改变量随 PZT 电压调制频率的变化关系。可见，由 PZT 调节激光频率的调谐带宽约 8～10 kHz，PZT 与被拉伸光纤之间的机械共振峰约为 33 kHz；在 PZT 调谐带宽内，输出激光频率的 PZT 电压调谐系数约为 266 MHz/V，对于 PZT 允许的最大外加电压为 12 V，激光频率最大调谐量超过 3.2 GHz。由此可见，DBR 光纤激

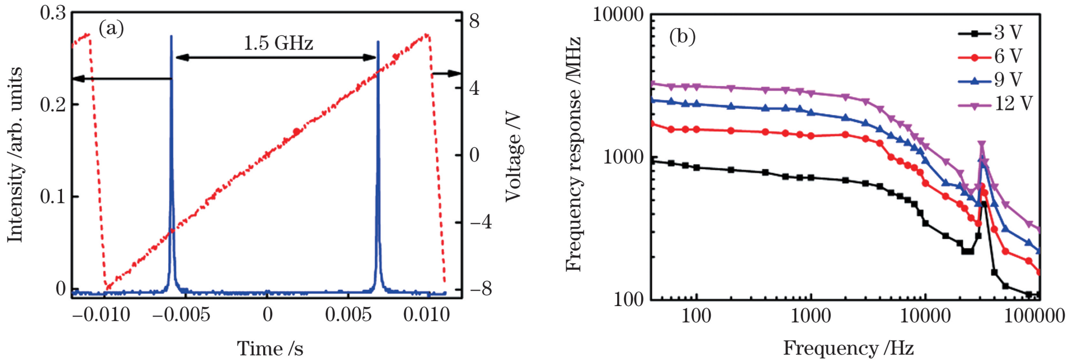


图 2 DBR 光纤激光器纵模与频率调谐特性。(a) 利用 F-P 扫描干涉仪测得的激光器单纵模振荡特性;(b) 对 PZT 施加不同电压值时实测的输出激光频率改变量随施加在 PZT 上电压的调制频率的变化关系

Fig. 2 Characteristics of longitudinal mode and frequency tuning of DBR fiber lasers. (a) Single-longitudinal-mode oscillation characteristics of the laser measured by F-P scanning interferometer; (b) measured the relationship between the amount of change in output laser frequency and the modulation frequency of the tuning voltage when the PZT is applied at different voltage values

光器中内置 PZT 的调谐带宽和对激光频率的调谐范围都能达到超稳腔 PDH 稳频的要求[20]。

为避免自脉冲效应[25],研制的 DBR 光纤激光器中所用的增益光纤为掺杂浓度适中的普通商售掺铒石英玻璃光纤,故激光器在 300 mW 泵浦功率(约 6 倍阈值)下,输出功率仅为 0.8 mW。考虑到目前单模尾纤输出的 975 nm 的激光输出功率普遍可达 700~800 mW,而若将单纵模光纤激光器后接掺铒光纤放大器(EDFA),只要 EDFA 具有低噪声性能,则这种主振荡功率放大(MOPA)激光源就可以保持种子源激光器的优良特性,因此,本研究将 DBR 单纵模光纤激光器输出激光经保偏隔离器(PM-ISO)后,耦合至保偏单模 EDFA 中进行功率提升,而该 EDFA 则与 DBR 光纤激光器共享同一个泵浦激光器,由光纤耦合器(OC)分配泵浦激光总功率 750 mW 的 60%后,再经保偏 WDM(PM-WDM)为 EDFA 提供泵浦。EDFA 所用掺铒光纤的纤芯直径、数值孔径和吸收系数分别为 4 μm、0.2 和 45 dB/m@975 nm,优化后的长度选为 70 cm,经 EDFA 放大后的激光再经保偏光隔离器(PM-ISO)输出,最大输出功率约 45 mW。值得指出的是,EDFA 也封装于包含 DBR 光纤激光器的同一绝热盒中,所有驱动与温控电子线路均集成在 1U 标准机箱内,集成样机外形如图 1(b)所示。

图 3(a)为采用光谱分析仪(Yokogawa,AQ6370D)测得的激光器集成样机的输出激光光谱,输出的 1.55 μm 激光信噪比约 60 dB。图 3(b)为采用 50 km 单模光纤延迟线的标准自外差方法对激光器集成样机输出激光拍频谱的测量结果。经对实测数据的洛伦兹拟合表明,样机自由运转下的

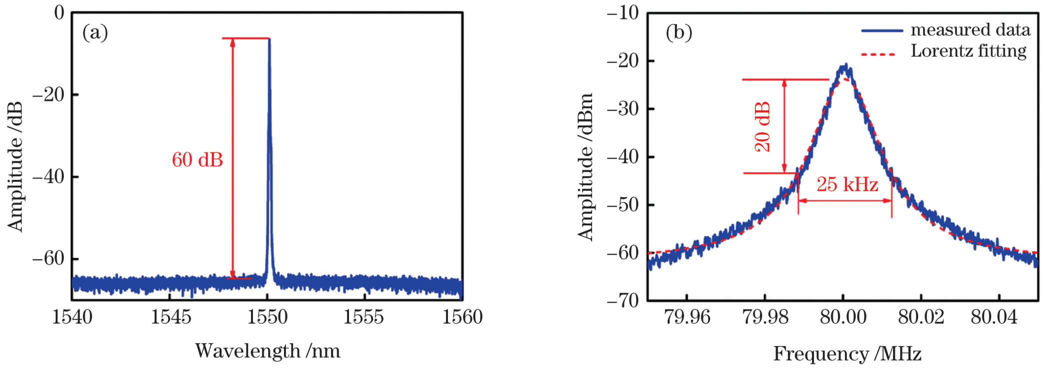


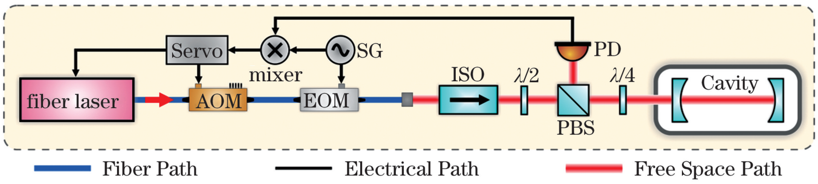
图 3 DBR 光纤激光器光谱与线宽特性。(a)利用光谱分析仪测得的激光器集成样机的输出光谱;(b)采用 50 km 单模光纤延迟线标准自外差方法测得的激光器集成样机输出激光拍频谱

Fig. 3 Characteristics of optical spectrum and linewidth of DBR fiber lasers. (a) Output optical spectrum of the laser prototype measured by an optical spectrum analyser; (b) measured results of beat frequency spectrum of the laser using a self-heterodyne system with a 50 km single mode fiber delay line

输出激光的拍频谱的 20 dB 谱宽为 25 kHz，对应的 3 dB 谱宽约 2.5 kHz，由此可得激光的 3 dB 线宽约为 1.25 kHz[26]，这十分有利于基于超稳腔的 PDH 稳频技术来获取超窄线宽的激光。

3　超稳腔 PDH 稳频

图 4 为采用超稳光腔 PDH 稳频技术对研制的光纤激光器集成样机进行稳频的实验装置。所用光学超稳腔由超低膨胀系数（ULE）的玻璃构成，腔长为 10 cm，对应的 FSR 为 1.5 GHz，精细度达 360000。该光腔安装在真空密闭隔震室中，并配有主动精密温度控制来减小环境温度扰动的影响，安装光腔的真空密闭隔震室放置在隔震光学平台上。待稳光纤激光器输出激光经声光调制器（AOM）产生 80 MHz 的频移（+1 级衍射光）后，由电光调制器（EOM）产生调制边带，再经准直以及偏振调节[半波片（$\lambda/2$）、偏振分束器（PBS）和四分之一波片（$\lambda/4$）]后，耦合进入参考光腔，进入光腔的激光功率可通过偏振调节进行控制。光腔反回的带有调制边带的激光经 PBS 分离后，由光电探测器（PD）探测，再与 EOM 驱动信号经混频器（Mixer）混频，获取激光稳频所需的误差信号。误差信号由伺服控制系统（Servo）处理后，低频成分反馈控制激光器内置 PZT 的电压，实现对激光频率低频段波动的补偿；高频成分则反馈至 AOM 驱动控制器，实现对激光频率高频段（PZT 调谐带宽以上）波动的补偿。AOM 驱动控制器由压控振荡器（VCO）后接射频功率放大器构成，VCO 可将反馈电压转换成频率信号，实现对 AOM 频移光的频率补偿。



AOM: acousto-optic modulator; EOM: electro-optic modulator; SG: signal generator; Servo: servo control system;
ISO: spatial isolator; PBS: polarization beam splitter; PD: photodetector; $\lambda/2$: half-wave plate; $\lambda/4$: quarter-wave plate;
Cavity: ultrastable optical cavity

图 4　采用超稳光腔 PDH 稳频技术对光纤激光器进行稳频的实验装置示意图

Fig. 4　Schematic diagram of the experimental setup of fiber laser frequency stabilization using PDH technology based on ultrastable optical cavity

依据参考光腔精细度，将信号发生器（SG）提供的 EOM 微波调制信号频率设定为 18 MHz。通过 Servo 内置电压模块对激光器内置 PZT 施加低频三角波扫描电压信号，利用 PD 探测光腔返回的带有调制边带的激光，就可获取激光稳频所需的误差信号。图 5(a)中曲线为在当 PZT 施加 7 V、20 Hz 三角波扫描电压时由示波器记录下的误差信号。可见，当激光载波及其调制边带与参考腔谐振峰重合时，均会产生误差信号，但载波与参考腔谐振峰重合时所产生的误差信号幅度最大，如图 5(a)插图所给出的局部放大图所示。根据该插图，误差信号幅度峰-峰值约为 67 mV，对应的频率失谐量为 90 kHz，故鉴频系数约为 1.3 kHz/mV。将 PZT 电压设置为插图中 O 点所对应的值，开启 Servo 反馈回路并优化参数，则可锁定激光频率。当激光频率锁定到参考光腔后，由示波器抓拍到的误差信号如图 5(b)所示，且在持续锁定的 8 h 内，该误差信号均与图 5(b)的曲线相似，不再出现任何图 5(a)所示曲线中的尖峰，因此，激光频率已锁定到光腔谐振频率。

为评估光腔 PDH 稳频技术对光纤激光器频率锁定的效果，将两台自由运转下性能相同的光纤激光器样机同时锁定到该参考光腔的两个相邻谐振腔模上，再通过对这两台稳频后的激光器拍频，测量获得稳频光纤激光器的性能参数。在锁定第二台激光器时，其 EOM 微波调制信号频率改为 24 MHz，以避免在提取两台激光器稳频误差信号时的相互干扰。锁定后的两台激光器输出激光经 OC 合束后，由 PD 探测拍频信号，再与锁定到氢钟（稳定度优于 2E-13）的射频信号发生器（keysight N5171B EXG）经混频器混频处理后将其频率降至测量仪器带宽以内，由频率计数器（Agilent 53220A）、快速傅里叶频谱分析仪（Stanford research systems SR785）和相位噪声测试仪（Microsemi3120A）等仪器记录测量。

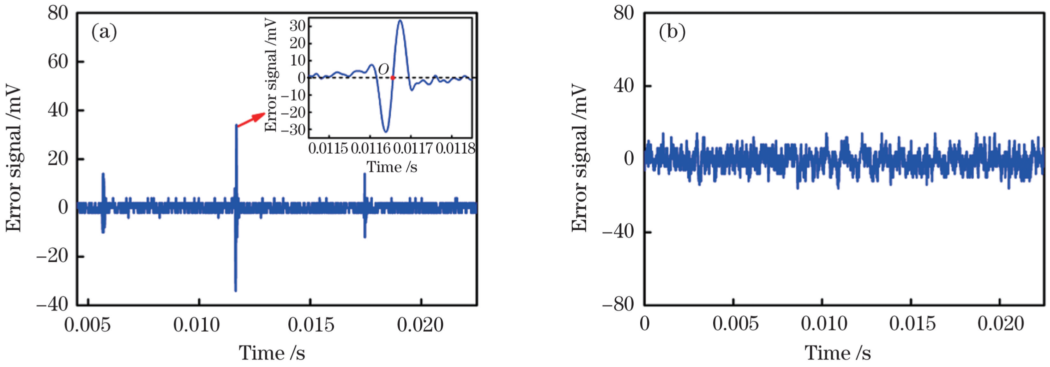


图 5 激光稳频前后误差信号。(a)当对 PZT 施加 7 V、20 Hz 的三角波扫描电压时,由示波器记录的误差信号,插图为激光载波处的误差信号的局部放大图;(b)当激光频率锁定到参考光腔后由示波器抓拍到的误差信号

Fig. 5 Error signal before and after laser frequency stabilization. (a) Error signal recorded by the oscilloscope when a triangular-wave sweep voltage of 7 V, 20 Hz is applied to PZT, in which the inset is a partial enlarged view of the error signal at the laser carrier; (b) error signal after the laser frequency is locked to the reference cavity

图 6(a)为由采样率设置为 100 Hz 的频率计数器测得的拍频信号随时间的变化关系,拍频信号已混频至零频附近。由该图可见,拍频信号频率存在漂移,1 h 内的漂移量小于±20 Hz。这种漂移可能源于实验室开关式空调造成的环境温度周期性波动[见图 6(a)中插图]。系统位置处的环境温度随时间呈周期性变化,影响了包括超稳光腔在内的稳频激光系统的稳定性,从而造成了拍频信号的漂移。由于两台光纤激光器在自由运转下性能相近,且采用相同的伺服系统锁定于同一光腔的相邻谐振模,因此,稳频后每台激光器的频率漂移小于±10 Hz,这比自由运转状态下的频率漂移量低了 6 个量级。图 6(b)为利用图 6(a)中测得的拍频信号数据,计算得到的单台光纤激光器频率不稳定度的修正艾伦方差[27]。可见,对应于 1 s 和 100 s 的稳频光纤激光器频率不稳定度分别达 6×10^{-16} 和 8×10^{-15}。下一步,将进一步降低环境温度波动对超稳光腔稳定性的影响,以提升对光纤激光器稳频的长期稳定性。

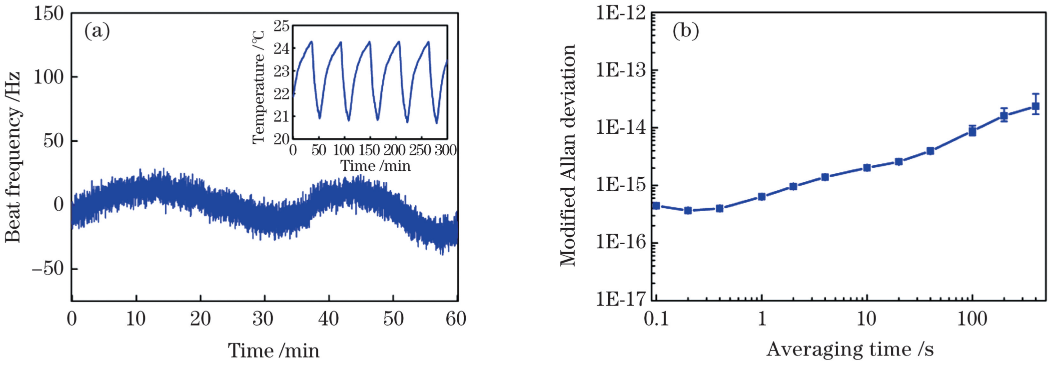


图 6 稳频激光拍频信号漂移与频率不稳定度。(a)利用频率计数器测得的拍频信号随时间的变化关系,插图为稳频系统位置处的环境温度随时间的变化关系;(b)利用(a)图中的拍频信号数据计算得到的单台光纤激光器频率不稳定度的修正艾伦方差

Fig. 6 Beat frequency signal drift and frequency instability of frequency-stabilized lasers. (a) Relationship of the beat frequency signal with time measured by the frequency counter, in which the inset is the change of the ambient temperature over time at the location of the frequency stabilization system; (b) modified Allan deviation of the frequency instability of each fiber laser calculated using the data of beat frequency signal in the Fig. 6 (a)

图 7(a)为测量得到的稳频光纤激光器频率噪声功率谱,1 mHz~0.5 Hz 频段的频率噪声是通过对频率计数器测得的拍频信号经快速傅里叶变换(FFT)计算获得,而 0.5 Hz~100 kHz 频段的频率噪声则是由相位噪声测试仪直接测量获得。由于频率计数器已锁定到氢钟,而相位噪声测试仪的本底噪声优于−170 dBc/Hz,即所用两种测量仪器均具有极高的精度,因此利用它们所得的测量结果具有良好的一致性,在 0.5 Hz 频率处能自然衔接。为便于比较,图中也给出了光纤激光器在自由运转下的

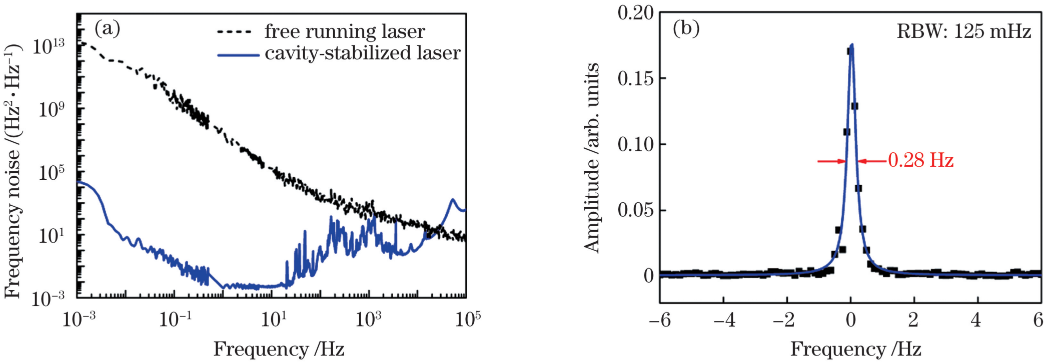


图 7 稳频激光的频率噪声和线宽。(a)实测的稳频光纤激光器在 1 mHz～100 kHz 频段内的频率噪声功率谱，自由运转光纤激光器的频率噪声功率谱也示于图中；(b)利用傅里叶变换(FFT)频谱分析仪测得的稳频激光的拍频线宽

Fig. 7 Frequency noise and linewidth of frequency stabilized laser. (a) Measured frequency noise power spectrum of the frequency-stabilized fiber laser in the range of 1 mHz～100 kHz, and the frequency noise power spectrum of the free-running fiber laser shown in the figure; (b) beat frequency linewidth of frequency-stabilized laser measured by FFT spectrum analyzer

频率噪声功率谱[28]。相比于自由运转状态，稳频激光器低频段频率噪声得到了明显改善，在 1 mHz～10 Hz 频段内，频率噪声降低了 8 个量级以上，特别是在 1～10 Hz 频段，频率噪声降低到了约 8×10^{-3} $\mathrm{Hz}^2/\mathrm{Hz}$；但在 1 mHz 附近，因环境温度波动对光腔的长期稳定性有影响，对频率噪声的抑制不如 1～10 Hz 频段[29]；在 20 Hz～30 kHz 频段，可能存在环境振动的影响，稳频激光的频率噪声谱中出现了杂乱尖峰；而在高于 30 kHz 频段，受反馈回路带宽(实测约 30 kHz)的限制，稳频激光的频率噪声反而逐渐高于自由运转下的噪声。尽管如此，利用我们研制的光纤激光器，经超稳腔 PDH 稳频后，在 1 mHz～10 Hz 波段内的频率噪声指标依然接近或达到了引力波探测对激光光源的要求[29]。

图 7(b)为由快速傅里叶频谱分析仪测得的稳频激光的拍频线宽，这里的拍频信号已混频至 50 Hz 附近。在 125 mHz 分辨带宽(RBW)和 8 s 扫描时间下，利用测得的拍频数据，经洛伦兹拟合后的激光线宽为 280 mHz，这表明：基于自研的单纵模 DBR 光纤激光器，利用超稳腔 PDH 稳频，可以获得频率高度稳定的百毫赫兹超窄线宽激光输出。并且，利用上述 DBR 光纤激光器的腔结构与输出功率等参数，估算的 Schawlown-Townes 线宽极限[30]约为 60 mHz，因此，若能进一步提升超稳光腔稳定性，相信稳频 DBR 光纤激光器的线宽有望进一步压窄。

4 结 论

基于自研的 1550 nm 单纵模 DBR 光纤激光器演示了超稳光腔 PDH 的稳频结果。通过优化单纵模 DBR 光纤激光器的腔结构参数，并辅以绝热封装和精密温控等措施，可以确保其在自由运转下的窄线宽和低噪声特性；通过在 DBR 腔内设置 PZT，实现了对激光频率的快速和宽范围调谐，故运用超稳光腔 PDH 稳频技术可实现该激光器的超稳激光输出。采用腔长 10 cm、精细度 360000 的超稳光腔，PDH 稳频后的光纤激光器频率漂移小于±10 Hz，1 s 和 100 s 的频率不稳定度分别达 6×10^{-16} 和 8×10^{-15}，频率噪声降低至 8×10^{-3} $\mathrm{Hz}^2/\mathrm{Hz}$@1～10 Hz，激光线宽窄至 280 mHz，这表明其主要指标已能用于构建亚赫兹线宽超稳激光光源，应用于引力波探测、精密测量和时频传递等领域。

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280 mHz Linewidth DBR Fiber Laser Based on PDH Frequency Stabilization with Ultrastable Cavity

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Abstract

Objective Ultrastable low-noise ultranarrow linewidth laser light source has a wide range of applications in precision measurement, optical atomic clock, time-frequency transmission, and low-noise microwave generation. Ultrastable cavity Pound-Drever-Hall(PDH) frequency stabilization technology is one of the most important solutions for obtaining such ultrastable lasers. Based on this, the linewidth of the distributed feedback(DFB) single-frequency fiber laser has reached the order of millihertz. In addition to the performances of the ultrastable cavity and servo system, the available linewidth and frequency instability of the ultrastable fiber laser depend on the performances of the linewidth, frequency drift and noise level of the free-running fiber laser, and the laser frequency-tuning mechanism. Although many research institutions in China have developed single-longitudinal-mode fiber lasers with frequency-tuning mechanisms and the laser frequency has been stabilized within a hundred kilohertz for a long time by the saturated-absorption frequency stabilization technology based on fine transition spectral lines of gas molecules, home-made single-frequency fiber laser has not been applied to ultrastable cavity PDH frequency stabilization technology to obtain subhertz-linewidth ultrastable fiber laser source. Therefore, it is very necessary to investigate the PDH frequency stabilization with such home-made single-frequency fiber lasers.

Methods By optimizing the structure parameters of the laser cavity, adopting adiabatic packaging and precision temperature control, and integrating the piezoelectric transducer (PZT) in the cavity that can quickly and widely tune the laser frequency, a free-running DBR fiber laser that can be used to obtain an ultrastable laser via ultrastable-optical-cavity PDH frequency stabilization was developed. The laser power was boosted by a low-noise single-mode polarization-maintaining fiber amplifier. The ultrastable optical cavity used for frequency stabilization was made of ultralow expansion (ULE) glass with a cavity length of 10 cm. The corresponding free spectral range(FSR) was 1.5 GHz and the fineness was 360000. The fiber laser was modulated by an electro-optical modulator (EOM) and then coupled into the optical cavity. The laser with modulated sidebands reflected by the optical cavity was detected with a photodetector and then mixed with the drive signal of the EOM through a mixer to obtain the error signal for laser frequency stabilization. The error signal was processed by the servo system, and the low-frequency component was fed back to control the voltage of the PZT to compensate the low-frequency fluctuations of the laser frequency. The high-frequency component was fed back to the acousto-optic modulator (AOM) drive controller to achieve the high-frequency fluctuation compensation of the laser frequency. To evaluate the effect of PDH frequency stabilization of our fiber laser, two DBR fiber lasers were stabilized to the two adjacent cavity modes of the optical cavity at the same time. The performance parameters of the frequency stabilization fiber laser were then measured by the beat frequency of the two frequency-stabilized lasers.

Results and Discussions The developed DBR fiber laser exhibits stable single-longitudinal-mode oscillation characteristics [Fig. 2(a)]. The relationship between the amount of change in the output laser frequency and the modulation frequency of the tuning voltage when the PZT is applied with different voltage values is given [Fig. 2(b)]. The tuning bandwidth of the laser frequency adjusted by PZT is about 8–10 kHz and the maximum tuning range exceeds 3.2 GHz. The signal-to-noise ratio of the output laser is about 60 dB [Fig. 3(a)] and the 3-dB linewidth of the laser is about 1.25 kHz [Fig. 3(b)]. The error signal is recorded by the oscilloscope when a triangular-wave sweep voltage of 7 V at 20 Hz is applied to PZT [Fig. 5(a)]. The error signal then changes to a straight line after the laser frequency is locked to the reference cavity [Fig. 5(b)]. There is a drift in the frequency of the beat frequency signal. The range of drift within 1 h is less than ±20 Hz [Fig. 6(a)] and the frequency drift of each laser after frequency stabilization is less than ±10 Hz. The frequency instability of the frequency-stabilized fiber laser corresponding to 1 s and 100 s is 6×10^{-16} and 8×10^{-15}, respectively [Fig. 6(b)]. Fig. 7(a) displays the measured frequency noise power spectrum of the frequency-stabilized fiber laser in the range of 1 mHz–100 kHz. The frequency noise is reduced by more than eight orders in the range of 1 mHz–10 Hz. The frequency noise is reduced to about 8×10^{-3} $\mathrm{Hz}^2/\mathrm{Hz}$ especially from 1 to 10 Hz. Using the measured beat frequency data, the laser linewidth after Lorentz fitting is 280 mHz [Fig. 7(b)].

Conclusions We have demonstrated the results of ultrastable cavity PDH frequency stabilization based on a home-made single-frequency DBR fiber laser at 1550 nm. By optimizing the structure parameters of the laser cavity, adopting adiabatic packaging and precision temperature control, and integrating the PZT in the cavity that can quickly and widely tune the laser frequency, a free-running DBR fiber laser that can be used to obtain an ultrastable laser via ultrastable-optical-cavity PDH frequency stabilization is developed. Using an ultrastable optical cavity with a length of 10 cm and a fineness of 360000, the frequency drift of the fiber laser after PDH frequency stabilization is less than ±10 Hz and the frequency instability at 1 s and 100 s is 6×10^{-16} and 8×10^{-15}, respectively. The frequency noise is reduced to 8×10^{-3} $\mathrm{Hz}^2/\mathrm{Hz}$ at 1–10 Hz and the linewidth is narrowed down to 280 mHz. It is shown that the main performances of our lasers can be used to construct subhertz-linewidth ultrastable laser light sources, which can be used in fields such as gravitational wave detection, precision measurement, and time-frequency transmission.

Key words lasers; single longitudinal mode; Pound-Drever-Hall frequency stabilization; ultrastable lasers

OCIS codes 140.3510; 140.3570; 140.3425