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模式清洁器的噪声转化与输出场噪声分析

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摘　要：根据三镜腔模式清洁器的反射光场及透射光场的传输特性，推导了反射光场和透射光场中振幅和相位两个正交分量的噪声转化函数，理论证明模式清洁器可以实现半导体激光器振幅噪声和相位噪声的相互转化。搭建三镜腔模式清洁器和自平衡零拍探测实验系统，测量了模式清洁器反射光场和透射光场的振幅噪声谱，实验结果与理论结果一致。根据模式清洁器的噪声转化模型，利用实验中模式清洁器共振与非共振锁定情况下测量的反射光振幅噪声谱，计算了半导体激光器的相位噪声。研究结果可为深入理解模式清洁器噪声转化过程提供参考，同时说明利用模式清洁器的噪声转化机制可以实现半导体激光器相位噪声的测量和评估。

关键词：模式清洁器；半导体激光器；噪声转化；振幅噪声；相位噪声
中图分类号：O433.1　　**文献标识码**：A　　**doi**：10.3788/gzxb20225104.0414002

0 引言

外腔半导体激光器是现代物理学实验中广泛应用的光源之一，在量子精密测量中将被测物理量映射到激光的振幅、频率、相位等参数，因此在相敏放大和干涉相位测量[1]应用中，研究半导体激光器的相位、振幅噪声具有重要意义。利用谐振腔构建的激光模式清洁器可以改善激光光束的模式和指向性，提高光束质量[2-4]。近年来，模式清洁器被广泛应用于精密测量[5]、量子通信[6-9]、量子计算[10]、量子密钥分配[11]及引力波探测[12-15]等研究领域。例如激光陀螺仪应用中，利用超稳腔实现了透射光场中频率大于谐振腔线宽的高频噪声良好抑制，可得到超稳窄线宽激光[16-18]。在引力波探测应用中对于谐振腔的反射光场，在自由光谱范围内谐振腔相当于高通滤波器[19-21]，腔线宽以内的低频噪声被抑制。通过操控压缩光噪声的方位角，最终制备了频率依赖的压缩真空态，实现了全频段量子噪声抑制[22-23]。通过高精细度滤波腔可实现相位噪声达到散粒噪声基准的 mW 量级激光输出[24-25]。针对谐振腔的噪声传输特性研究包括：山西大学研究小组[26]根据阻抗匹配因子的取值范围将谐振腔分为过耦合腔、阻抗匹配腔与欠耦合腔三种，理论分析了三种光学谐振腔的功率波动、反射光场的相位与振幅随失谐量的变化关系，最终证实光学谐振腔具有激光强度传输、噪声转化等特性。中国科学院的研究小组[27]测量到无源腔透射光场的振幅噪声在分析频率 2 MHz 附近与散粒噪声极限重合。而反射光场的振幅噪声有一部分来源于输入场相位噪声的转化，间接得到无源腔对钛宝石激光器的相位噪声有抑制效果。

本文根据三镜腔模式清洁器的反射光场及透射光场的传输特性，推导了反射和透射光场中振幅和相位两个正交分量的噪声转化函数，实验上搭建三镜腔模式清洁器和自平衡零拍探测系统，理论与实验研究模式清洁器将 852 nm 半导体激光器相位噪声转换为振幅噪声，利用理论模型和实验结果推算相位噪声，为实际应用提供参考。

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1 理论分析

三镜腔模式清洁器相比于常用的两镜腔等其他形式模式清洁器具有独特优势：1)三镜腔模式清洁器的入射光与反射光空间指向分离[28]；2)三镜腔模式清洁器相比两镜腔具有更好的激光偏振滤波特性[29]。三镜腔模式清洁器可以实现振幅噪声与相位噪声的相互转换。

图1为三镜腔模式清洁器的简化模型。输入场振幅为E_0，反射光场振幅为E_r，透射光场振幅为E_t，三镜腔模式清洁器经过入射镜M_1透射后，在腔内多次循环后振幅为E_1，循环一圈的相位是ϕ，假设入射镜M_1和出射镜M_2的振幅反射率分别为r_1、r_2（M_1、M_2都是平面镜），凹面镜M_3的振幅反射率为r_3（M_3是反射率大于99.99％、曲率半径为1 000 mm的凹面镜，这里不考虑其它影响，看作是全反镜），腔长为L。在稳态条件下，反射光场、透射光场振幅分别表示为

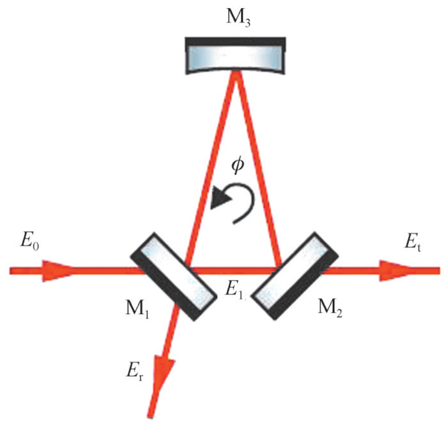


图1 模式清洁器的简化模型图

Fig. 1 Simplified model of mode-cleaner cavity

$$E_r=E_0\left(r_1-\frac{r_2(1-r_1^2)e^{i\phi}}{1-r_1r_2e^{i\phi}}\right) \tag{1}$$

$$E_t=E_0\left(\frac{\sqrt{1-r_1^2}\sqrt{1-r_2^2}}{1-r_1r_2e^{i\phi}}e^{i\frac{\phi}{2}}\right) \tag{2}$$

可得三镜腔模式清洁器的反射率函数及透射率函数分别为

$$r(\phi)=\frac{E_r}{E_0}=r_1-\frac{r_2(1-r_1^2)e^{i\phi}}{1-r_1r_2e^{i\phi}}=\rho(\phi)e^{i\Phi_r} \tag{3}$$

$$t(\phi)=\frac{E_t}{E_0}=\frac{\sqrt{1-r_1^2}\sqrt{1-r_2^2}}{1-r_1r_2e^{i\phi}}e^{i\frac{\phi}{2}}=\tau(\phi)e^{i\Phi_t} \tag{4}$$

透射光场正交振幅分量和正交相位分量[27]可以表示为

$$\hat{Q}_t(\phi)=\hat{a}_t^{\dagger}(\phi)+\hat{a}_t(\phi)=\tau(\phi)\left[\cos\Phi_t\hat{Q}(\phi)-\sin\Phi_t\hat{P}(\phi)\right] \tag{5}$$

$$\hat{P}_t(\phi)=i\left[\hat{a}_t^{\dagger}(\phi)-\hat{a}_t(\phi)\right]=\tau(\phi)\left[\cos\Phi_t\hat{P}(\phi)+\sin\Phi_t\hat{Q}(\phi)\right] \tag{6}$$

透射光场正交分量的噪声起伏为

$$\delta^2_{\hat{Q}_t}(\phi)=\tau^2(\phi)\left[\sin^2\Phi_t\delta^2_{\hat{P}}(\phi)+\cos^2\Phi_t\delta^2_{\hat{Q}}(\phi)\right] \tag{7}$$

$$\delta^2_{\hat{P}_t}(\phi)=\tau^2(\phi)\left[\cos^2\Phi_t\delta^2_{\hat{P}}(\phi)+\sin^2\Phi_t\delta^2_{\hat{Q}}(\phi)\right] \tag{8}$$

透射光场相对于入射光场的两个正交分量的噪声传递特性传输矩阵形式表示为

$$\begin{bmatrix}\delta^2_{\hat{P}_t}(\phi)\\ \delta^2_{\hat{Q}_t}(\phi)\end{bmatrix}=\tau^2(\phi)\cdot\begin{bmatrix}\cos^2\Phi_t & \sin^2\Phi_t\\ \sin^2\Phi_t & \cos^2\Phi_t\end{bmatrix}\times\begin{bmatrix}\delta^2_{\hat{P}}(\phi)\\ \delta^2_{\hat{Q}}(\phi)\end{bmatrix}=\begin{bmatrix}A & B\\ B & A\end{bmatrix}\times\begin{bmatrix}\delta^2_{\hat{P}}(\phi)\\ \delta^2_{\hat{Q}}(\phi)\end{bmatrix} \tag{9}$$

同理，反射光场相对于入射光场的两个正交分量的噪声传递特性表示为

$$\begin{bmatrix}\delta^2_{\hat{P}_r}(\phi)\\ \delta^2_{\hat{Q}_r}(\phi)\end{bmatrix}=\rho^2(\phi)\cdot\begin{bmatrix}\cos^2\Phi_r & \sin^2\Phi_r\\ \sin^2\Phi_r & \cos^2\Phi_r\end{bmatrix}\times\begin{bmatrix}\delta^2_{\hat{P}}(\phi)\\ \delta^2_{\hat{Q}}(\phi)\end{bmatrix}=\begin{bmatrix}C & D\\ D & C\end{bmatrix}\times\begin{bmatrix}\delta^2_{\hat{P}}(\phi)\\ \delta^2_{\hat{Q}}(\phi)\end{bmatrix} \tag{10}$$

式中，$\phi=\frac{\Omega\times L}{c}$，$\Omega$为探测频率，$c$为光速。

推导得到透射光场和反射光场的振幅和相位两个正交分量噪声起伏传递关系，证明模式清洁器可以实现光场振幅噪声和相位噪声的相互转化。

2　实验装置

模式清洁器传输特性研究实验装置如图2所示，相干光场由外腔半导体激光器（Toptica，BoosTA Pro）产生，其输出中心波长为852.35 nm。为了减小激光随工作时间和温度变化导致的频率漂移，采用饱和吸收光谱技术将半导体激光频率锁定在铯原子D_2线超精细能级$6S_{1/2}(F=4)\rightarrow 6P_{3/2}(F'=5)$的共振跃迁线，锁定后激光线宽约200 kHz。模式清洁器整体为三镜环形腔结构，由航空铝加工制作而成，此结构有效地提高腔体的机械稳定性。三镜腔整体腔长为0.436 m，输入镜M_1和输出镜M_2是反射率均为99%的平面镜，第三面镜M_3是曲率半径为1 000 mm、反射率大于99.99%的凹面镜。M_3安装在压电陶瓷的后端，可采用稳频（Pound-Drever-Hall，PDH）的方式实现模式清洁器腔长的锁定。

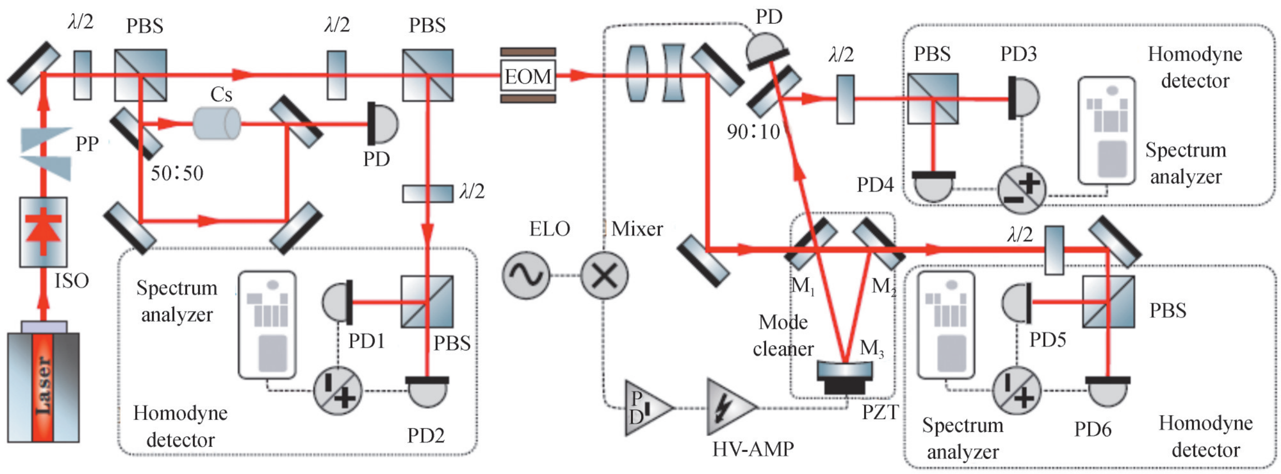


图2　实验装置

Fig. 2　Experimental scheme

实验中，通过偏振分束器反射的光进入自平衡零拍探测系统，光被50∶50的分束器分成相等的两部分，分束器的每个输出端分别被送入经过校准的两个光电探测器，产生的光电流被放大并经过混频器产生和电流$i+$和差电流$i-$，频谱分析仪接收这些电流信号并记录噪声功率$V_{\rm det}(i+)$、$V_{\rm det}(i-)$。$V_{\rm det}(i-)$测量散粒噪声水平；$V_{\rm det}(i+)$与光束的振幅噪声成正比。通过偏振分束器透射的光，经过电光调制器调制产生一个33.88 MHz的边带信号，通过匹配透镜将光束匹配到模式清洁器中，模式清洁器反射的光通过分束镜一部分到达光电探测器，探测器的直流信号用来监视模式清洁器的反射峰，交流信号与本地振荡信号调制解调得到误差信号，负反馈系统经过高压放大器放大后反馈至压电陶瓷，实现模式清洁器腔长的锁定，当腔被锁定时，在30 mW的入射功率下，实验上测量到了23.4 mW的透射光功率，相当于78%的传输效率。通过模式清洁器另一部分反射和透射的光都再分别经过自平衡零拍探测系统，测量透射光场和反射光场的振幅噪声。

3　实验结果与分析

3.1　模式清洁器透射光场和反射光场的振幅噪声

用饱和吸收光谱将半导体激光器激光频率锁定后，输出的激光进入模式清洁器，由于腔共振频率与腔长是线性关系，通过调节高压控制模式清洁器腔镜的压电陶瓷进而改变腔长，在示波器上可以得到腔透射信号，如图3(a)所示。从图中可以看到，模式清洁器自由光谱区的扫描时间为6 499 μs，透射峰半高全宽的扫描时间为24.5 μs，根据腔长计算得到的模式清洁器自由光谱区（Free Spectral Region，FSR）为652 MHz，按照时间到频率的等比例换算关系可得腔模线宽为

$$\frac{\rm FSR}{\Delta\nu}=\frac{6499\mu{\rm s}}{24.5\mu{\rm s}}=\frac{652{\rm MHz}}{\Delta\nu}$$

式中，$\Delta\nu$为透射峰的半高全宽，$\Delta\nu\approx 2.5$ MHz。

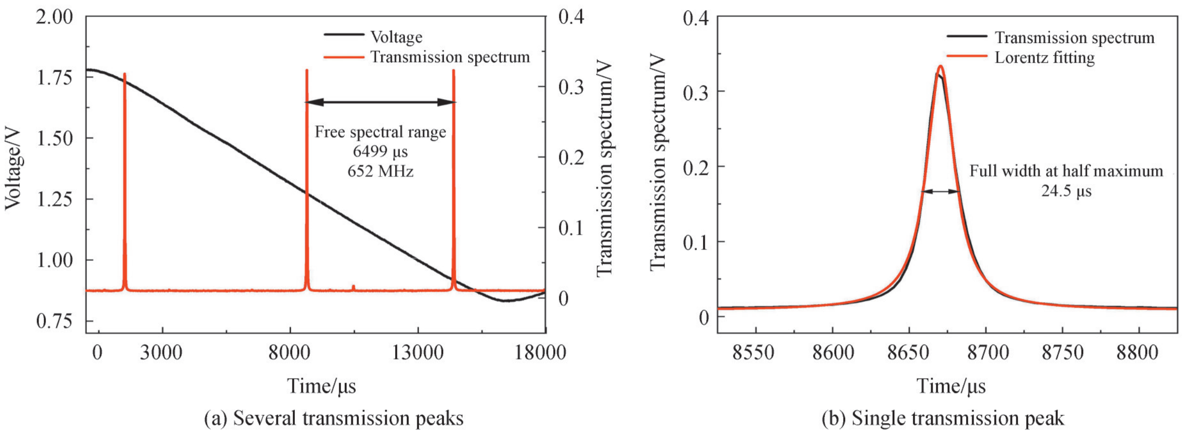


图3　模式清洁器的透射信号

Fig. 3　Transmission signal of mode-cleaner cavity

实验中利用自平衡零拍探测器测量了透射、反射的振幅噪声，如图4(a)所示。可以看到，透射光场的振幅噪声随探测频率逐渐降低，在探测频率为15 MHz时，透射光场的振幅噪声达到散粒噪声极限。而反射光场的振幅噪声远高于透射光场的振幅噪声，整体上振幅噪声也随着随探测频率逐渐降低。由透射光谱计算得到模式清洁器线宽为2.5 MHz，在满足谐振条件下，对于透射光场，模式清洁器可以看作是低通滤波器，频率小于腔线宽的低频噪声通过模式清洁器，频率大于腔线宽的高频噪声直接被反射，图中可以清楚地看到，探测频率在0～2.5 MHz范围内，透射光场的振幅噪声远高于散粒噪声，探测频率在2.5～20 MHz范围内，随着分析频率的增加，透射光场的振幅噪声逐渐降低，当探测频率为15 MHz时，透射光场的振幅噪声达到散粒噪声极限。而反射光场，分析频率在0～20 MHz，其振幅噪声都远高于散粒噪声，一部分原因是对于反射光场，模式清洁器可以看作是高通滤波器，频率大于腔线宽的高频噪声都到反射光场，还有一部分原因是，根据噪声转化函数可知，腔入射时的相位噪声一部分会转化成振幅噪声[30]。根据理论推导的模式清洁器噪声转化理论模型，可以理论上得到透射光场和反射光场的振幅噪声，如图4(b)所示。

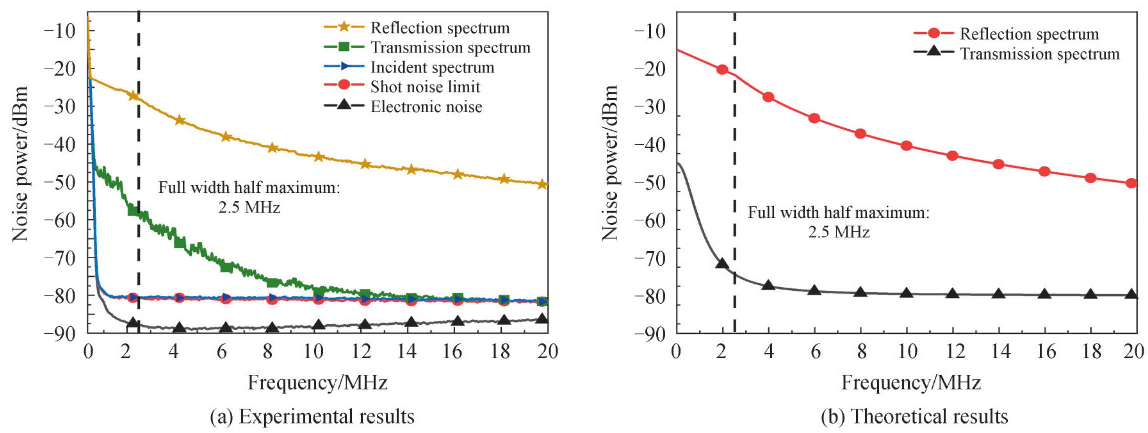


图4　模式清洁器的透射、反射振幅噪声

Fig. 4　Amplitude noise of the reflection field and transmission field under the mode-cleaner cavity

对比图4(a)和(b)可以发现，透射场的振幅噪声实验与理论结果整体趋势基本一致。需要注意的是，透射光场的振幅噪声在分析频率为15 MHz时才达到散粒噪声极限，相对于理论计算结果7.5 MHz达到的散粒噪声相差较大。导致噪声较大的原因是半导体激光器相位噪声较大，PDH锁定腔模可以看作是相敏解调过程，导致锁定环路振幅噪声大，因此与理论值有一定的偏差。

3.2　半导体激光器的相位噪声测量

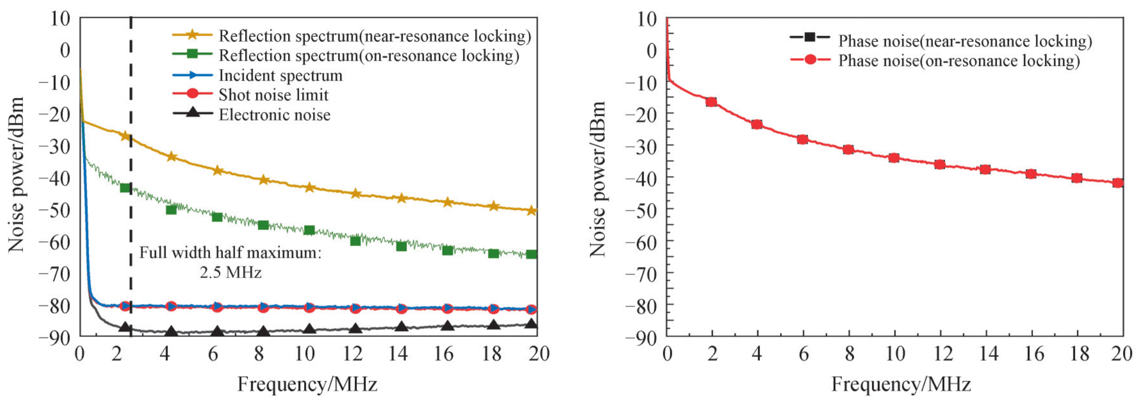
利用推导的噪声转化理论模型，可以得到半导体激光器共振状态和近共振状态的相位噪声分别为

$$\delta_{\hat{p}_1}^2(\phi)=\frac{1}{\rho^2(\phi)\sin^2\Phi_r}\delta_{\hat{Q}_{r1}}^2(\phi)-\frac{1}{\tan^2\Phi_r}\delta_{\hat{Q}_1}^2(\phi) \tag{11}$$

$$\delta_{\hat{p}_2}^2(\phi)=\frac{1}{\rho^2(\phi)\sin^2\Phi_r}\delta_{\hat{Q}_{r2}}^2(\phi)-\frac{1}{\tan^2\Phi_r}\delta_{\hat{Q}_2}^2(\phi) \tag{12}$$

式中,$\delta_{\hat{Q}_{r1}}^2(\phi)$、$\delta_{\hat{Q}_{r2}}^2(\phi)$是腔共振状态和近共振状态的反射振幅噪声,$\delta_{\hat{Q}_1}^2(\phi)$、$\delta_{\hat{Q}_2}^2(\phi)$是腔的初始振幅噪声。

实验上分别测量了腔共振状态和近共振状态的反射振幅噪声谱和初始振幅噪声谱,如图5(a)所示,利用式(11)、(12)可以计算得到半导体激光器的相位噪声。从图5(b)可以看到,通过模式清洁器锁定在共振和近共振两种情况下,计算得到的半导体激光器的相位噪声基本重合,证明通过模式清洁器的噪声转化机制可以实现对半导体激光器的相位噪声的测量和评估。



(a) Amplitude noise in the different locking conditions　　(b) Phase noise of laser

图5　腔在不同锁定状态的振幅噪声和激光器的相位噪声

Fig. 5　Amplitude noise in the different locking conditions and phase noise of laser

4　结论

本文理论与实验研究了模式清洁器反射光谱和透射光谱的噪声转化机制,实验结果表明,透射光场的振幅噪声在探测频率为15 MHz时达到散粒噪声极限,而反射光场的振幅噪声远高于透射光场的振幅噪声,实验结果与理论结果一致。同时通过测量模式清洁器反射光共振状态和近共振状态的强度噪声,计算得到半导体激光器在探测频率为0~20 MHz时的相位噪声。研究结果可为深入理解模式清洁器噪声转化过程提供参考。

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Noise Conversion of a Mode-cleaner Cavity and Noise Analysis of Output Fields

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Abstract: Semiconductor laser is one of the very important sources in a variety of modern physics experiments, the measured quantities in quantum precision measurement will be demonstrated to the laser parameters such as amplitude, frequency, and phase, so researching semiconductor laser's phase noise and amplitude noise is significant in the domain of phase-sensitive amplification and interferometric phase measurement. As an optical cavity to improve beam quality and beam mode, mode-cleaner cavity has important applications in quantum precision measurement, quantum communication, quantum computing, quantum key distribution and gravitational wave detection. The noise conversion functions of phase and amplitude fluctuation of a light beam can be deduced, according to the properties of reflection field and transmission field for the mode-cleaner cavity. The mode-cleaner cavity and the balanced homodyne detection are constructed after locking the laser's frequency. The balanced homodyne detection measures amplitude noise of reflection field and transmission field, the experimental results show that the amplitude noise of transmission field decreases gradually with the detection frequency, and the noise at the frequency far larger than the linewidth reaches the shot noise limit. Nevertheless, the amplitude noise of the reflection field is far larger than that of the transmission field. As a whole, the amplitude noise also decreases gradually with the detection frequency. Linewidth of mode-cleaner cavity is calculated as 2.5 MHz by transmission spectrum, mode cleaner can be regarded as a low-pass filter under the condition of meeting the resonance in the transmission field, the high-frequency noise is greatly suppressed. In this case, when the detection frequencies range from 0 to 2.5 MHz, the amplitude noise of the transmission field is far larger than the shot noise limit. In the range of detection frequencies from 2.5~20 MHz, the amplitude noise decreases gradually with the increase of the analysis frequency in the transmission field. When the detection frequency is 15 MHz, the amplitude noise of the transmission field reaches the shot noise limit. However, when the detection frequencies range from 0 to 20 MHz, the amplitude noise of the reflection field is far larger than the shot noise limit. On the one hand, the mode-cleaner cavity can be regarded as a high-pass filter in the reflection field, which makes a significant contribution to the results. On the other hand, mode-cleaner cavity can interconvert the phase noise and amplitude noise after reflection or transmission. The amplitude noise of transmission field and reflection field can be calculated theoretically based on the noise conversion functions. By comparing the theoretical results with experimental results, the experimental results are consistent with the theoretical results. The phase noise of semiconductor laser is analyzed by measuring the amplitude noise of the reflection field with on-resonance locking and near-resonance locking. The results indicate that the experimental results are consistent with the theoretical results under the condition of on-resonance locking and near-resonance locking. Thus the research demonstrates that phase noise of semiconductor laser can be measured and evaluated by the noise conversion function. Moreover, this study provides a theoretical basis and provides an important complement for the noise conversion of mode-cleaner cavity. The mode-cleaner cavity is studied from the point of noise conversion in this paper, and the research demonstrates that the experimental results are consistent with the theoretical results in the transmission and reflection field. At the same time, the phase noise of semiconductor laser is measured and evaluated, which promotes the development of quantum precision measurement.

Key words: Mode-cleaner cavity; Semiconductor laser; Conversion of noise; Amplitude noise; Phase noise

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