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量子激光雷达测距与测速的研究进展

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摘要 激光雷达以其优良的定向性和高分辨率, 成为自动驾驶、测绘和遥感等领域的核心传感器, 但是近年来传统激光雷达也面临探测灵敏度和分辨率限制等诸多挑战. 本文以测距与测速性能为核心, 从经典激光雷达的两类代表——脉冲激光雷达与频率调制连续波激光雷达出发, 分别介绍了量子脉冲激光雷达与量子干涉式激光雷达的研究进展. 通过对目前量子激光雷达研究成果的梳理, 深入了解目前量子激光雷达的研究重点与难点, 为未来量子激光雷达的发展提供帮助.

关键词 量子脉冲激光雷达, 量子干涉式激光雷达, 距离测量, 速度测量, 量子增强

激光雷达有着定向性好、分辨率高、抗干扰能力强等优点，是自动驾驶、测绘、遥感以及航空航天等领域的核心传感器, 在军民领域具有重要应用[1]. 激光雷达的检测机制主要分为非相干检测与相干检测. 非相干检测采用直接检测方法，通过直接测量反射光信号强度的变化实现探测，应用于飞行时间(time of flight, TOF)法的脉冲激光雷达[2]. 相干检测采用外差检测的方法，通过测量回波信号与本振信号的频率或相位差实现探测，应用于频率调制连续波(frequency modulation continuous wave, FMCW)激光雷达与多普勒测速激光雷达[3]. 相干检测方式具有更高的灵敏度，且激光雷达能够以更低的发射功率工作. 然而，由于瑞利衍射极限以及散粒噪声极限的存在，进一步提高传统激光雷达探测灵敏度和分辨率的难度巨大.

随着量子信息技术的发展, 量子传感[4]通过利用量子资源进行调控，有可能实现突破经典极限的物理量(如距离、速度、角速度等)测量. 因此，基于量子传感原理设计的量子激光雷达采用量子光源(如纠缠光源)以及量子探测手段(如单光子探测), 可以突破经典激光雷达探测精度与分辨率极限. 得益于量子增强所带来的探测信噪比提升, 在发送信号功率相同的情况下, 量子激光雷达相比于经典激光雷达有更远的探测距离、更高的探测精度、更优的隐身目标探测能力和更强的抗干扰能力. 目前，与基于飞行时间法的经典脉冲激光雷达对应的量子脉冲激光雷达在国内外已有了比较深入的研究，并且在测距与测速中展现出一定的量子优势. 与经典频率调制连续波激光雷达对应的量子干涉式激光雷达的研究多集中在理论方面，在测速与测距方面还有很大的研究空间.

本文根据经典激光雷达的体制，对现有量子激光雷达工作进行分类与整理，主要包括量子脉冲激光雷达和量子干涉式激光雷达，并对未来的量子激光雷达发展进行了展望.

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1 量子脉冲激光雷达

类比于脉冲激光雷达，量子脉冲激光雷达模型通过发送和探测在时间-频率维度上纠缠多光子态，实现了量子增强的测距与测速.

Giovannetti等人[5]在2001年率先提出一种量子脉冲激光雷达模型. 该模型通过同时发送n光子频率纠缠态脉冲，并在探测端对此n光子进行关联TOF探测，实现了量子增强的测距，如图1所示. 当发送的n光子频率纠缠态脉冲的带宽与经典脉冲激光雷达发送脉冲的带宽一致时，此量子激光雷达测距精度上相比其经典对应有$\sqrt{n}$倍的提升. 近年，Maccone和Ren[6]将图1测距模型推广到目标三维空间坐标的探测.

Lloyd[7]在2008年提出利用纠缠光子对的频率纠缠特性来实现能抵御损耗与背景噪声的目标探测，将其称为量子照明. 量子照明模型[8]如图2所示，其抗噪特性近年来得到了实验的验证[9]. 虽然量子照明是在多年前提出的体系，但只有近年才陆续出现将其与探测脉冲TOF结合起来的测距体系. 近年，Zhuang[10]结合量子照明模型以及距离多段划分模型，构建了纠缠辅助量子测距协议. 在信号光发射后，根据预划分好的距离区间，持续存储不同时刻接收到的回波光. 根据联合探测结果，可以推断出目标在哪个距离区间，达到测距的目的. 此量子测距模型对距离区间的判断正确率相比于其经典对应有6 dB的提升. 之后，Zhuang和Shapiro[11]进一步对基于量子照明的量子脉冲压缩激光雷达测距精度极限进行评估. 如图3所示，得益于量子照明提供的6 dB信噪比提升，量子脉冲压缩激光雷达的测距精度极限相比于其经典对应有数十dB的提升.

量子照明模型在2019年被发展成量子增强噪声雷达[12]. 此雷达模型结构与量子照明类似，但省去了量子存储的过程. 当信号光发射后，本地光直接被探测，并转换成可以复制和存储的经典记录. 同时打开探测器持续接收和探测光信号，并将其转换为经典记录. 最后，利用信号光与本地光的量子关联特性，将接收光与本地光的探测记录进行关联比对，确定信号光子到达时间. 在此模型的基础上，Liu等人[13]提出基于量子增强噪声雷达的量子脉冲激光雷达. 他们实验上验证了此测距模型的性能相比于其经典对应有一定的提升. 如图4所示，增强方案在估计不确定性方面具有高达26.3 dB的性能提升. 他们还通过实验证明了存在强噪声和损耗情况下使用连续波泵浦产生的这些非经典光

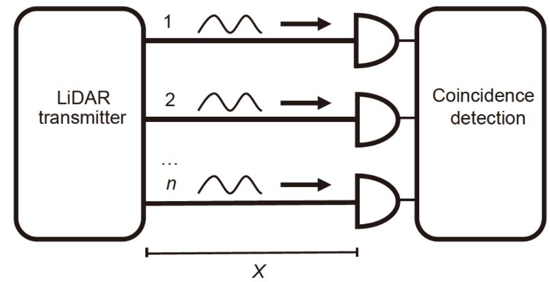

图 1 基于关联TOF探测的量子脉冲激光雷达测距模型[5]
Figure 1 Quantum pulsed LiDAR ranging model based on correlation TOF detection[5]

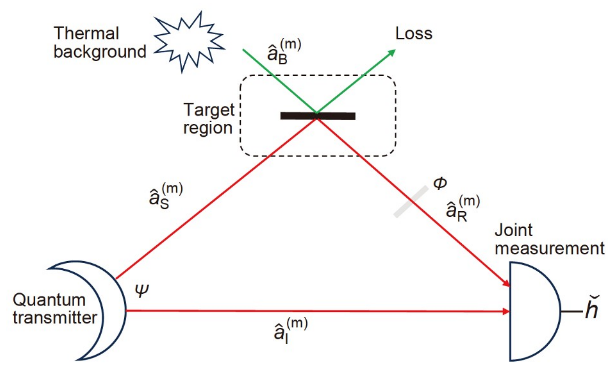

图 2 (网络版彩色)量子照明模型[8]
Figure 2 (Color online) Quantum illumination model[8]

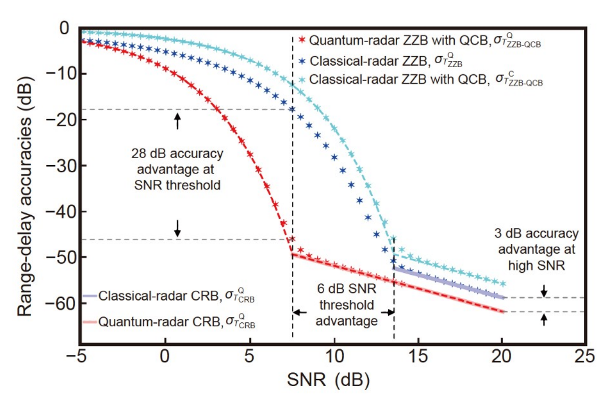

图 3 (网络版彩色)基于量子照明的量子脉冲压缩激光雷达测距精度极限[11]
Figure 3 (Color online) Quantum pulsed compression radar ranging accuracy limit based on quantum illumination[11]

子对的测距，实现了约5 cm的距离分辨率. 近年，Blakey等人[14]研究发现，非局域效应有可能从根本上推动量子增强成像，在实验室环境与实际应用中，都比经典成像更具优势. 他们使用基于时频纠缠的量子增强型激

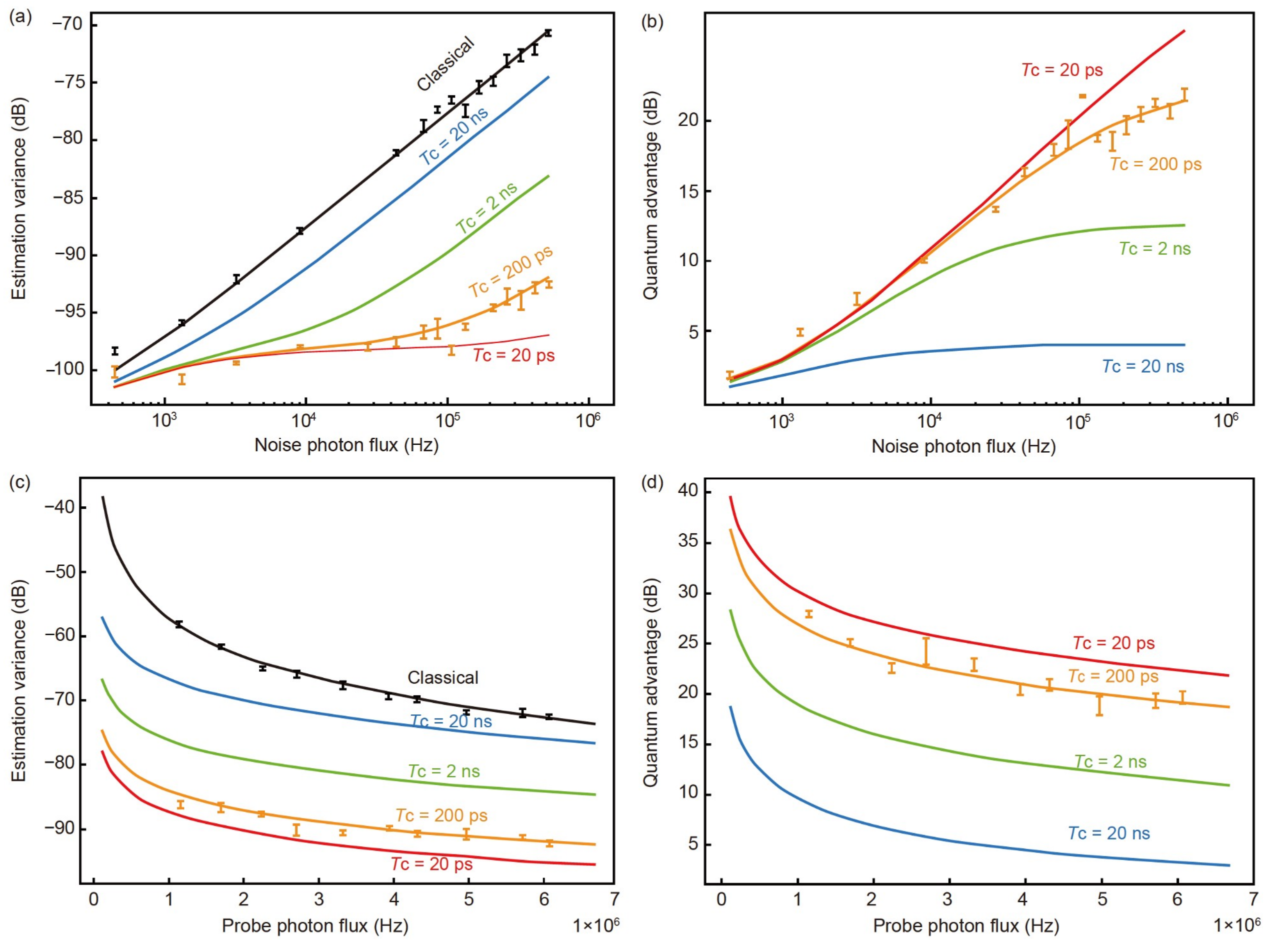

图 4 (网络版彩色)基于量子增强噪声雷达的量子脉冲激光雷达的探测结果(T_C为符合窗口)[13]. (a) 探测误差随噪声光子通量的变化; (b) 量子优势随噪声光子通量的变化; (c) 探测误差随探针光子通量的变化; (d) 量子优势随探针光子通量的变化

Figure 4 (Color online) Measured results of quantum pulsed LiDAR based on quantum-enhanced noise LiDAR (T_C is the coincidence window)[13]. (a) Estimation error as a function of noise photon flux; (b) quantum advantage as a function of noise photon flux; (c) estimation error as a function of probe photon flux; (d) quantum advantage as a function of probe photon flux

光雷达展示了高43 dB的信噪比(signal-to-noise ratio, SNR), 系统可以容忍比经典单光子计数量子成像系统高3个数量级以上的噪声.

基于量子脉冲激光雷达模型[5], 可通过同时发送窄带宽的n光子频率纠缠脉冲, 并在探测端对此n光子进行关联多普勒频移探测实现量子增强的测速, 且测速精度亦能达到海森堡极限[15]. 同年, 与量子照明模型有相似结构的量子增强多普勒激光雷达模型[16]被提出. 此测速激光雷达采用双光束多模压缩真空状态作为发射光源, 信号光被发送到移动目标, 产生反射并且其频率产生多普勒频移. 本地光不与移动目标相互作用并被保留. 反射信号光束和本地光束在接收器处进行独立多普勒频移探测. 在给定激光雷达到目标往返的透射率大于50%的情况下, 具有3 dB信噪比提升的量子增强测速.

上述量子增强脉冲激光雷达测距与测速的精度受时间-能量不确定性原理的影响. 为了解除彼此的制约, Zhuang等人[15]提出将宽带宽的$n/2$光子频率纠缠脉冲和窄带宽的$n/2$光子频率纠缠脉冲利用非线性光学过程进一步纠缠, 从而实现量子脉冲压缩[17]. 图5展示了当$n = 6$时, 此n光子频率纠缠脉冲的制备以及用其实现同时测距与测速的示意图. 此量子脉冲激光雷达模型可在保证测距与测速精度都达到海森堡极限的同时, 解除测距精度与测速精度上的相互制约. 特别地, 当$n = 2$时, 此模型实现了非纠缠光源的纠缠, 虽不提供精度的提升, 但仍可以解除测距精度与测速精度上的相互制

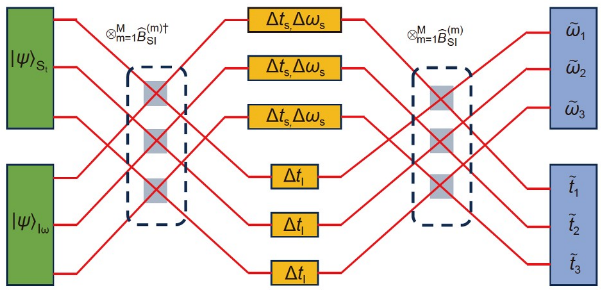

图 5 (网络版彩色)量子增强脉冲激光雷达同时测距与测速示意图[15]

Figure 5 (Color online) Quantum-enhanced pulsed LiDAR for simultaneous ranging and velocity measurement[15]

约. 因此, 该模型需要两种纠缠资源来实现量子增强的同时测距与测速. 最近, Huang等人[18]发现, 特定的频率纠缠双光子脉冲本身就存在量子脉冲压缩, 只需在探测端采用$\hat{B}_{\rm SI}^{(m)}$就能实现同时测距与测速.

上述这些量子脉冲激光雷达主要有以下几个不足之处: 首先, 受探测器的时间与频率分辨率影响, 量子脉冲激光雷达的测距与测速的精度受限; 其次, 为了解除测速与测距精度的相互制约, 需要利用额外的非线性光学过程, 这会降低量子脉冲激光雷达的探测效率; 最后, 由于传播过程中的损耗会极大地降低纠缠光子的纠缠度, 不仅导致量子增强的消失, 而且会削弱速度与距离的同步测量能力, 因此量子脉冲激光雷达对于损耗特别敏感[15,19].

2 量子干涉式激光雷达

量子干涉式激光雷达基于干涉测量原理, 通过对2条光路进行干涉探测得到目标信息. 基于经典激光光源, Resch等人[20]在2006年基于马赫-曾德尔干涉仪(Mach-Zehnder interferometer, MZI)采用带有后选择性质的$N00N$态干涉探测, 实现了突破瑞利衍射极限的相位探测分辨率. 但由于对接收信号的后选择, 探测信号的强度降低, 导致探测精度极限差于散粒噪声极限. 此外, Jiang等人[21]结合Gao等人[22]与Plick等人[23]的工作, 提出了采用经典激光光源以及量子平衡零差探测的超分辨率量子干涉式激光雷达, 并证明了该雷达可提供远低于瑞利衍射极限的纵向和角度超分辨率, 且相位灵敏度可达到散粒噪声极限.

Pezzé和Smerzi[24]在2008年基于MZI提出相干态和压缩真空态输入的方案. 该研究发现相干态端和压缩真空态端的平均光子数相等时, 采用光强探测手段可使得系统相位灵敏度接近海森堡极限. Zhang等人[25]对此物理模型进一步研究并提出基于压缩真空态注入的相位超灵敏度干涉型量子激光雷达方案. 该方案对比了Z探测法、强度差探测法和奇偶探测法. 他们发现, 若采用奇偶探测法, 该系统不仅可以通过增大压缩真空态的压缩系数提高相位测量的灵敏度, 而且还能在有较大损耗的实际情况下保持超灵敏度. 近年, 高丽等人[26]搭建出基于外差干涉的量子增强多普勒激光雷达. 他们利用光学参量放大器对激光干涉雷达的本振光进行驱动, 形成具有压缩光特性的本振光, 并将其与存在多普勒频移的信号光进行外差干涉后, 采用自零拍探测形成拍频信号. 压缩光抑制了拍频信号中的散粒噪声, 从而提高了测速精度. 如图6所示, 量子增强多普勒激光雷达的探测灵敏度有3 dB的提高.

在量子干涉式激光雷达中, Dowling课题组[27,28]基于采用$N00N$态的超分辨率量子光刻[29]将n光子$N00N$态的应用拓展到MZI以及传感器中, 之后进一步应用到干涉式量子成像[29,30]. 在这些量子相位估计体系中, 相位探测精度极限相比于经典对应会有$\sqrt{n}$倍的提升, 同时相位分辨率提升n倍. 然而, 这种$N00N$态的性质在大气传输过程中并不能很好地保持. 通过费希尔信息的计算, Lee等人[31]发现在大损耗下$N00N$态所测得的相位精度弱于经典激光. 为了解决此问题, Dorner等人[32]提出用$N00N$态的推广态作为相位估计的光源, 可在一定损耗下保证相位估计精度的量子增强. 随后, Kacprowicz等人[33]实验验证了双光子$N00N$态的推广态的相位

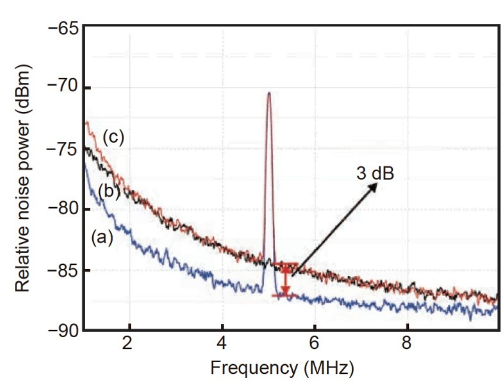

图 6 (网络版彩色)量子增强多普勒激光雷达的探测结果[26]. (a) 压缩光注入的回波信号噪声谱; (b) 散粒噪声基准噪声谱; (c) 相干光注入的回波信号噪声谱

Figure 6 (Color online) Measured results of quantum-enhanced Doppler LiDAR[26]. (a) Noise spectrum of the squeezed light injection echo signal; (b) noise spectrum of the shot noise datum; (c) noise spectrum of the coherent light injection echo signal

估计. 此外, Larson和Saleh[34]通过在双光子MZI中引入额外的可调控的偏振自由度, 增强双光子纠缠态进行相位估计时对于退相干噪声的鲁棒性.

在有损耗的情况下, Joo等人[35]理论研究对比了纠缠相干态与$N00N$态的相位估计性能并发现纠缠相干态优于$N00N$态. 基于他们的工作, Wang等人[36]在2016年研究了采用纠缠相干态的超分辨量子激光雷达在存在损耗和相位扩散情况下的性能. 理论模拟结果表明, 在无损和无噪声情况下, 他们的奇偶探测方案的分辨率相对于采用奇偶探测和强度探测的相干态方案分别有$\sqrt{n}$与n倍的提高(n为输入态的平均光子数). 在有相位扩散情况下, 纠缠相干态比$N00N$方案具有更好的分辨率和灵敏度. 在有损耗的情况下, 他们方案的相位灵敏度可以超越散粒噪声极限, 分辨率远远优于瑞利衍射极限.

近年来, 还有很多使用不同非经典光源以及非经典探测构造的量子相位估计体系[37~44]. 如Sahota和James[37]在MZI中对单光子$N00N$态的两个路径分别进行单模压缩, 制备出路径纠缠的压缩态并使用奇偶探测, 其模拟结果表现出超越散粒噪声与超分辨率的优势; Yu等人[40]从理论与实验出发, 详细分析了单模压缩态的纯度和压缩水平对量子相位估计精度的影响, 发现超出散粒噪声极限的相位估计区间的宽度与压缩状态的纯度相关; Zhang等人[41]研究了非高斯操作后的双模压缩真空态在MZI中使用奇偶探测进行相位估计的方案, 其结果表明, 相位精度在有光子损失的情况下可超越散粒噪声极限.

上述量子干涉式激光雷达受到调制维度的限制, 对探测目标获取信息能力有限. 针对这一不足, 深圳大学微系统与半导体技术实验室[45]将纠缠光源的调制扩展到时间-频率维度, 提出量子FMCW干涉式激光雷达系统. 该系统如图7所示, 调制后的纠缠光束经过分束系统之后, 分为参考光与信号光. 信号光发射到速度为v、距离为d的目标上, 之后回波信号光与参考光在合束系统进行外差干涉, 信号探测与处理系统将干涉光解调得到速度与距离信息. 此系统不仅可以实现测量精度以及分辨率的量子增强, 而且能够同时实现距离和速度的优化测量. 若采用线性频率调制的n光子$N00N$态作为系统的发送态, 对于距离和速度的测量, 此系统将提供n倍分辨率以及$\sqrt{n}$倍精度极限的量子增强. 此量子增强源自频率调制前纠缠n光子在时间-频率维度上的量子纠缠, 这将导致在频率调制后纠缠n光子的等效调制带宽为实际调制带宽的n倍. 在系统实现方面, 与量子脉冲压缩方案相比, 其无需额外非线性过程, 将光频降低到微波频段进行精确电子测量, 并非常适合片上集成和小型化.

3 总结与展望

对目标信息获取的需求促使着激光雷达技术的不断发展, 从TOF激光雷达到FMCW激光雷达, 再到现在的量子激光雷达, 不仅使其性能逼近甚至突破标准量子极限, 而且在特定情况下对比经典激光雷达表现出高信噪比优势, 在测速与测距方面都展现了一定优势. 本文从经典TOF激光雷达与经典FMCW激光雷达出发, 介绍了量子脉冲激光雷达与量子干涉式激光雷达, 并介绍了本课题组的研究进展.

量子激光雷达作为新兴的激光雷达体制还处于探索阶段, 目前还有很多问题有待解决, 包括高效制备量子光源的手段不足、量子态对环境敏感易退化、调制量子光源的维度较低、探测器灵敏度有待提升等. 因此, 未来量子激光雷达的研究将以高效的量子光源、高维调制手段以及高灵敏度的探测器为重点, 以提升

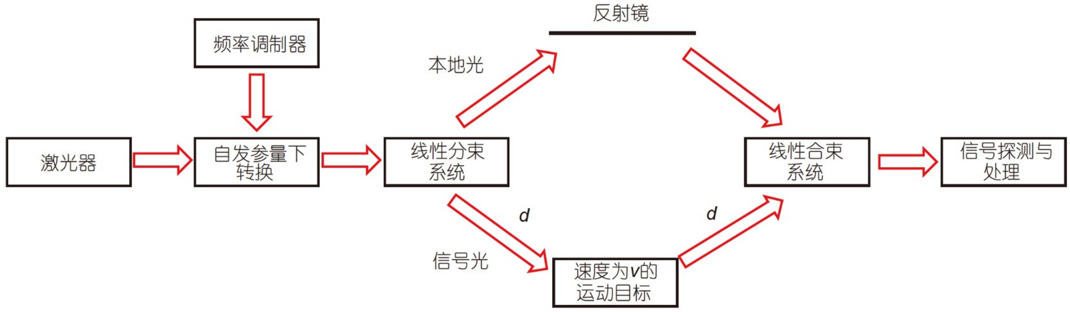

图 7 (网络版彩色)量子FMCW干涉式激光雷达模型[45]
Figure 7 (Color online) Quantum FMCW interferometric LiDAR model[45]

系统的稳定性以及小型化为方向，实现更高性能的目标探测. 此外，目前量子激光雷达仍旧着重于成像与测距方面，对于同时实现测速与测距的研究相对较少，需要广大科研工作者不断研究探索.

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Summary for “量子激光雷达测距与测速的研究进展”

Research progress of quantum LiDAR with ranging and velocity measurement

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Light Detection and Ranging (LiDAR) has emerged as a pivotal sensor across diverse domains such as autonomous driving, mapping, and remote sensing, owing to its exceptional orientation capabilities and high resolution. The detection mechanism of LiDAR is fundamentally categorized into non-coherent detection and coherent detection. Non-coherent detection employs the direct detection method, which involves measuring changes in the intensity of the reflected light signal to achieve detection. Pulse LiDAR, which determines the target range through pulsed time-of-flight measurements, falls within this classification. On the other hand, coherent detection employs heterodyne detection techniques and achieves detection by measuring the frequency or phase difference between the echo signal and the local oscillator signal. This approach is utilized in frequency modulation continuous wave (FMCW) LiDAR and Doppler speed LiDAR. LiDAR systems employing coherent detection methods can attain heightened sensitivity while operating at lower transmission power levels. However, due to the limitations posed by quantum noise, conventional LiDAR systems have encountered challenges in terms of detection sensitivity and resolution, prompting the need for advancement.

In recent times, spurred by the emergence of quantum metrology, a quantum version of LiDAR has been conceptualized, promising superior precision and resolution. Leveraging the enhanced signal-to-noise ratio made possible by quantum advancements, quantum LiDAR demonstrates the potential to extend detection ranges, elevate detection accuracy, bolster anti-jamming capabilities, and enhance anti-stealth performance beyond that of classical LiDAR, all while operating at equivalent transmission signal power levels. As an emerging technology, quantum LiDAR is currently in its exploratory phase, and several challenges must be confronted prior to its practical implementation. These challenges encompass a restricted array of methods for the effective generation of quantum light sources, the vulnerability of quantum states to environmental factors, resulting in their deterioration, the constrained techniques for modulating quantum light sources, and the critical necessity to augment detector sensitivity. Furthermore, present quantum LiDAR efforts primarily concentrate on imaging and ranging capabilities, with limited research dedicated to simultaneous velocity measurement and ranging. Hence, forthcoming investigations into quantum LiDAR will center around optimizing quantum light source efficiency, exploring high-dimensional modulation techniques, and advancing high-sensitivity detectors. These efforts aim to enhance system stability and enable miniaturization, ultimately leading to superior target detection performance.

This review centers on the evaluation of ranging and velocity measurement performance within quantum LiDAR systems. Following a concise introduction to two renowned categories of classical LiDAR—namely, pulse LiDAR and FMCW LiDAR, the paper delves into the progress made in quantum pulsed LiDAR and quantum interferometric LiDAR. In particular, this review highlights the advancements in quantum FMCW LiDAR, a system proposed for achieving simultaneous range and velocity measurements with quantum enhancement. By conducting a thorough assessment of the current accomplishments in quantum LiDAR research, the study seeks to attain a more profound comprehension of prevailing research focal points and obstacles, thus offering invaluable insights to steer its prospective advancement.

quantum pulsed LiDAR, quantum interferometric LiDAR, ranging, velocity measurement, quantum enhancement

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