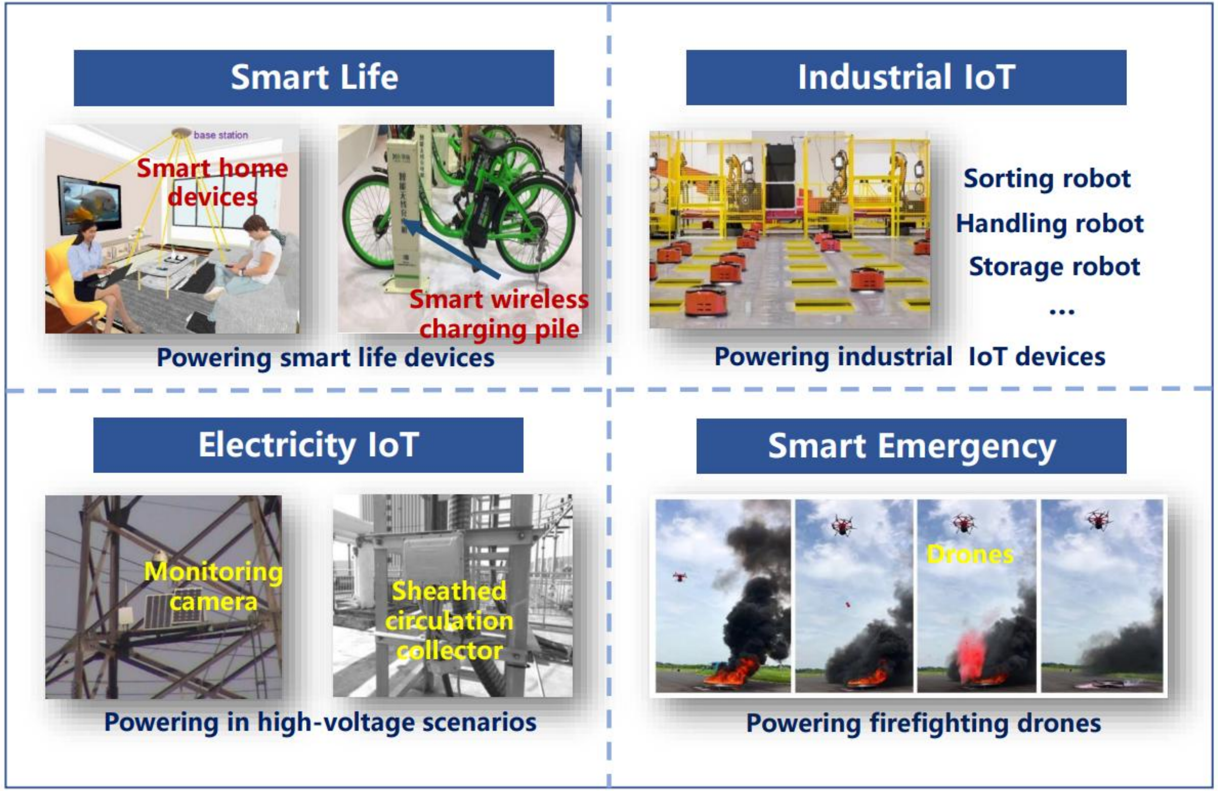
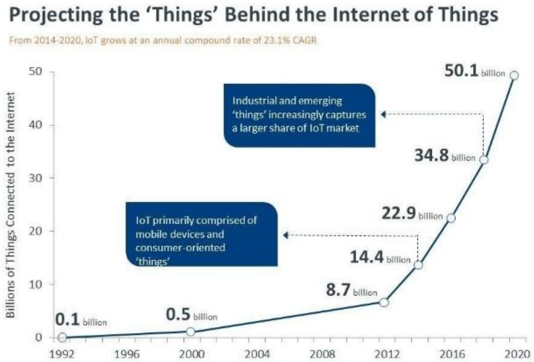
移动自对准腔内激光传能定位一体化系统

刘明清 博士
同济大学信息与通信工程系 助理教授

2025年03月26日

1 背景





随时随地，无限服务

智慧生活

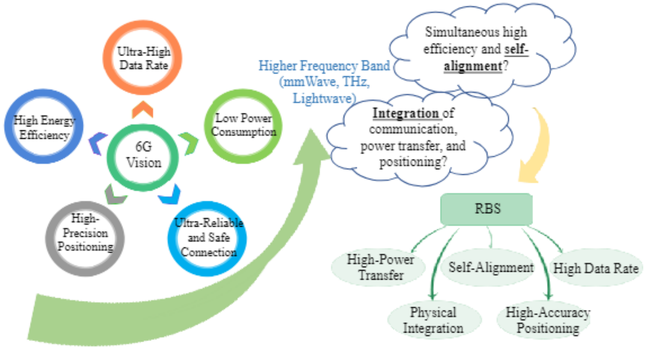
工业物联网

智能电网

应急通信

复杂动态场景下，无人设备的高功率安全自对准传能/通信/感知需求

1 背景



下代网络，万物互联

高速率

大容量

低时延

更高频段利用，实现传能通信感知一体化

高速无线通信

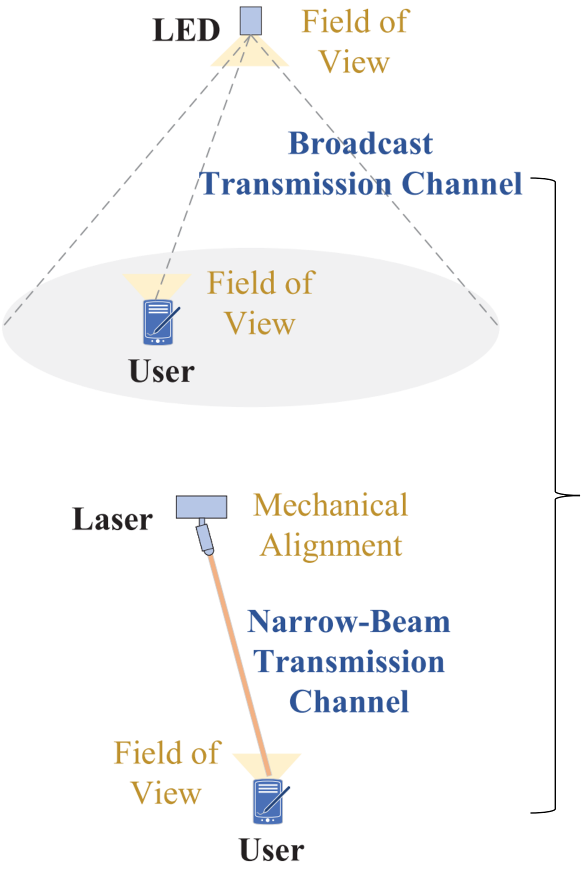
高精度感知

高频电磁波
（毫米波/太赫兹/光频）

挑战：高频电磁波传输

能量聚集 vs. **波束对准**

1 背景



挑战:
高功率能量集中波束传输中的移动接收端追踪/安全

利用 腔内激光 特性
移动自对准 & 本征安全性

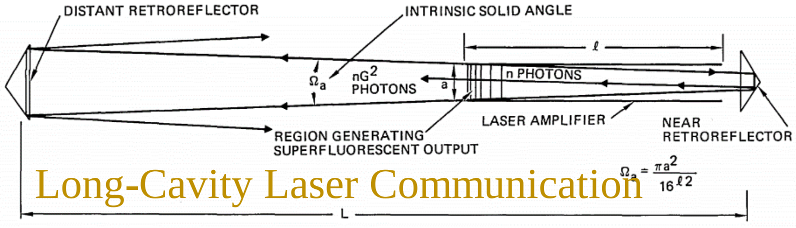
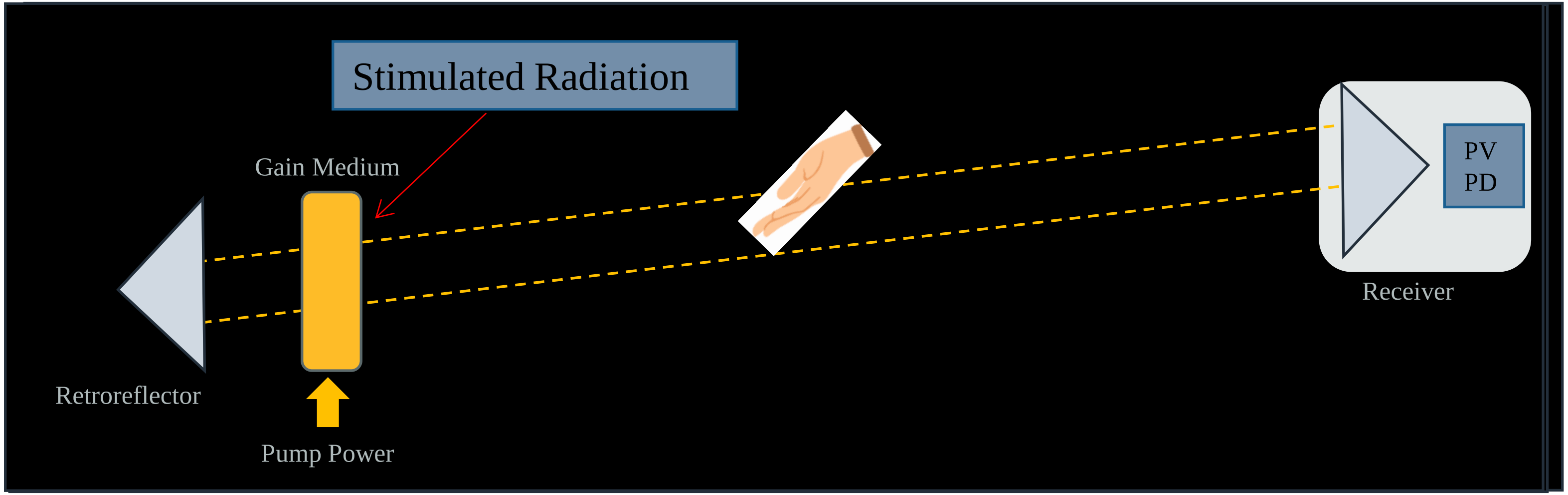


Fig. 1. Geometry of long laser cavity.

1. G. J. Linford and L. W. Hill, "Nd:YAG Long Lasers," Appl. Opt., vol. 13, no.6, pp.1387-1394, June 1974.

2. Wi-Charge: https://www.wi-charge.com/

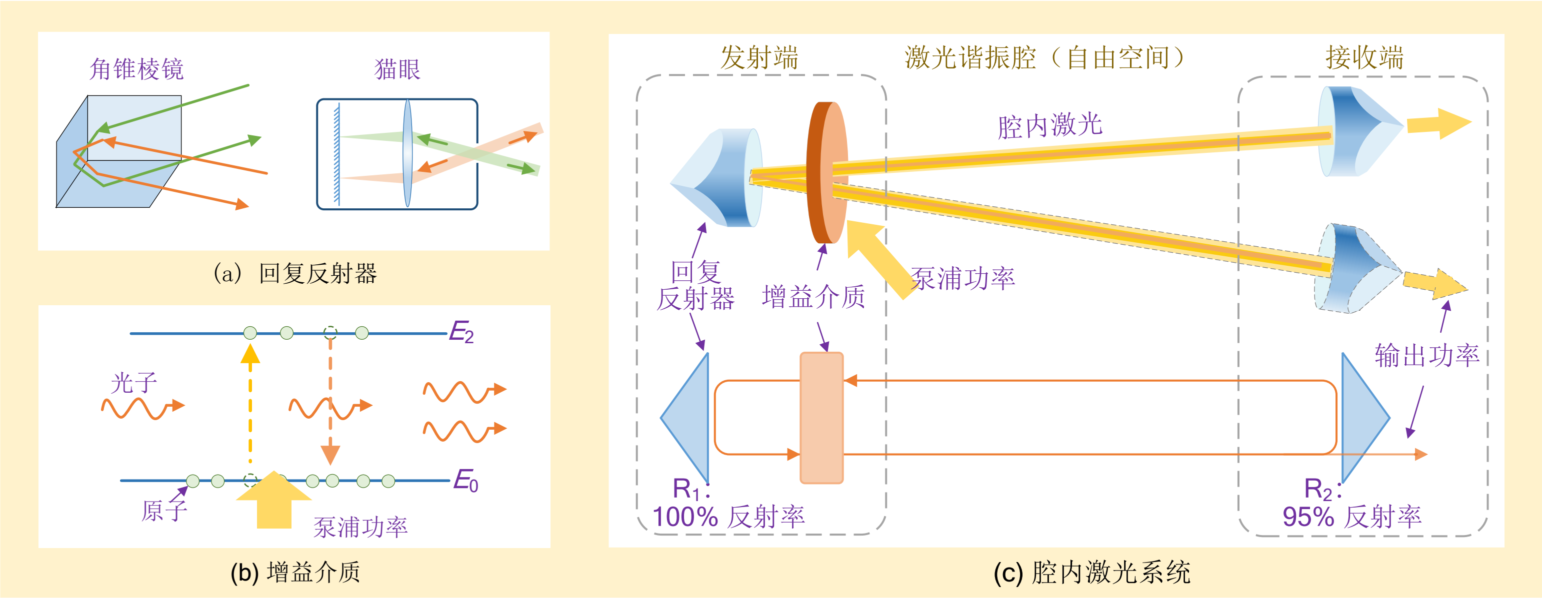
2 腔内激光原理及关键特性



增益介质 泵浦源 光学谐振腔	激光生成	接收端为合作目标 回复反射器	传输通道自动建立 异物侵入自动中断	移动自对准 本征安全

Q. Liu, J. Wu, P. Xia, S. Zhao, W. Chen, Y. Yang, and L. Hanzo, "Charging unplugged: Will distributed laser charging for mobile wireless power transfer work?", IEEE Vehicular Technology Magazine, vol. 11, pp. 36–45, Dec. 2016.

2 移动自对准特性

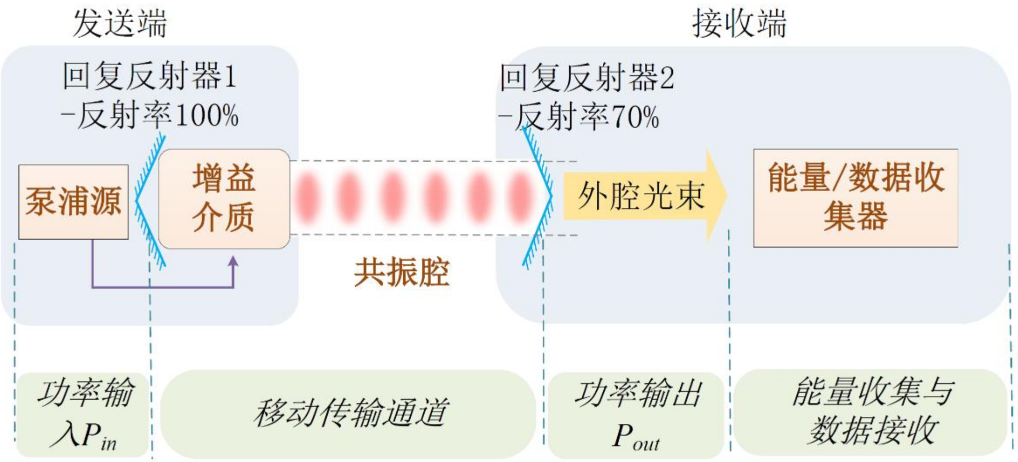


关键部件：

- 回复反射器：保证在大范围内从不同角度入射的光束都可原路返回（角锥棱镜、猫眼回复反射器）
- 双回复反射谐振腔：两端腔镜之间存在角度，仍然支持光束在腔内往返传输而不溢出谐振腔
- 增益与损耗交互：腔内激光的增益放大与损耗之间动态交互，当增益≥损耗，稳定激光链路形成

3 研究一：移动自对准机理

1）腔内激光移动传输通道模型-移动状态下功率输入vs.输出关系？

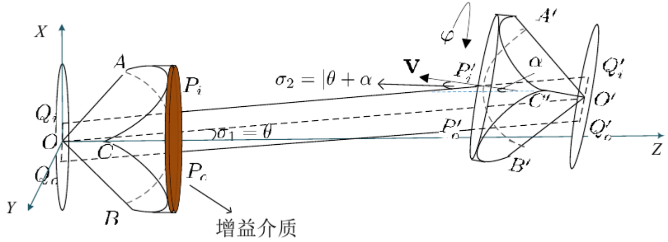


传输损耗制约可移动角度/距离

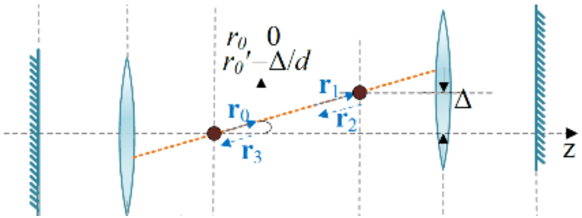
建立移动传输通道模型求解
自由空间传输损耗

循环功率模型描述增益损耗关系

分析：移动状态的光场|损耗|功率



双角锥棱镜谐振腔



双猫眼谐振腔

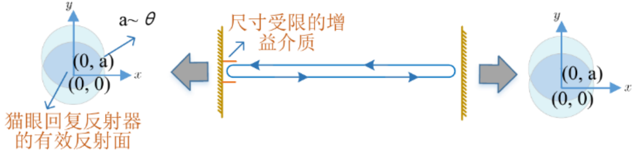
如何描述腔内激光在**腔镜不完全对准**的谐振腔内传输过程？

3 研究一：移动自对准机理

1）腔内激光移动传输通道模型-移动状态下传输损耗求解？

等效谐振腔分析方法

几何证明等效



角度vs等效反射面尺寸

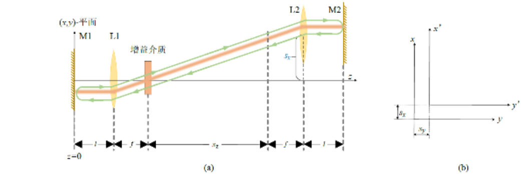
$$\mathbf{T}_{\mathrm{cube}}(x,y)=\begin{cases}1, & \frac{(x+D\cos\theta/2)^2}{A}+\frac{y^2}{B}\le 1 \quad \text{and} \quad \frac{(x-D\cos\theta/2)^2}{A}+\frac{y^2}{B}\le 1\\ 0, & \frac{(x+D\cos\theta/2)^2}{A}+\frac{y^2}{B}\ge 1 \quad \text{or} \quad \frac{(x-D\cos\theta/2)^2}{A}+\frac{y^2}{B}\ge 1\\ 0, & \frac{(x+D\cos\theta/2)^2}{A}+\frac{y^2}{B}\ge 1 \quad \text{or} \quad \frac{(x-D\cos\theta/2)^2}{A}+\frac{y^2}{B}\ge 1\\ 0, & -\frac{w}{2\cos(30^\circ+\varphi)}<y_1-\tan(30^\circ+\varphi)x_1<\frac{w}{2\cos(30^\circ+\varphi)}\\ 0, & \frac{w}{2\cos(150^\circ+\varphi)}<y-\tan(150^\circ+\varphi)x<-\frac{w}{2\cos(150^\circ+\varphi)}\\ 0, & \frac{w}{2\cos(90^\circ+\varphi)}<y-\tan(90^\circ+\varphi)x<-\frac{w}{2\cos(90^\circ+\varphi)}\end{cases}$$

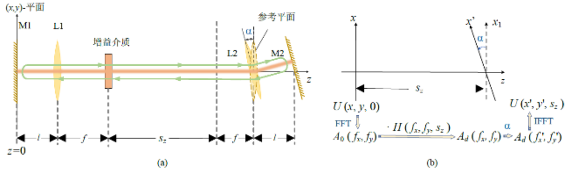
惠更斯-菲涅尔衍射本征方程

$$\gamma U(x,y,L)=\mathcal{F}^{-1}\{\mathcal{F}\{\mathcal{F}^{-1}\{\mathcal{F}\{U(x,y,L)\cdot T_2(x,y)\}\cdot \mathcal{F}\{h(x,y)\}\}\cdot T_1(x_1,y_1)\}\cdot \mathcal{F}\{h(x,y)\}\}\cdot T_2(x,y)$$

全衍射理论分析方法

倾斜/离轴平面衍射传输





任意平面间传输过程建模

$$\mathcal{A}[U(x,y)]=U(x,y)\cdot\begin{cases}1, x^2+y^2\le r_c^2\\ 0, \text{else}\end{cases}$$

$$\mathcal{B}[U(x,y)]=U(x,y)\cdot\begin{cases}1, x^2+y^2\le r_g^2\\ 0, \text{else}\end{cases}$$

$$C[U(x,y)]=U(x,y)\cdot\begin{cases}e^{\frac{-i\pi(x^2+y^2)}{\lambda f}}, x^2+y^2\le r_c^2\\ 0 \quad , \text{else}\end{cases}$$

$$\mathcal{D}[U(x,y)]=\mathcal{F}^{-1}\{\mathcal{F}\{U(x,y)\}\cdot H(f_x,f_y,l)\}$$

$$\mathcal{E}[U(x,y)]=\mathcal{F}^{-1}\{\mathcal{F}\{U(x,y)\}\cdot H(f_x,f_y,f)\}$$

全衍射理论本征方程

$$U(x,y,0)=\mathcal{T}^{-1}\mathcal{P}_t^{-1}\mathcal{R}\mathcal{P}_t\mathcal{T}[U(x,y,0)]$$

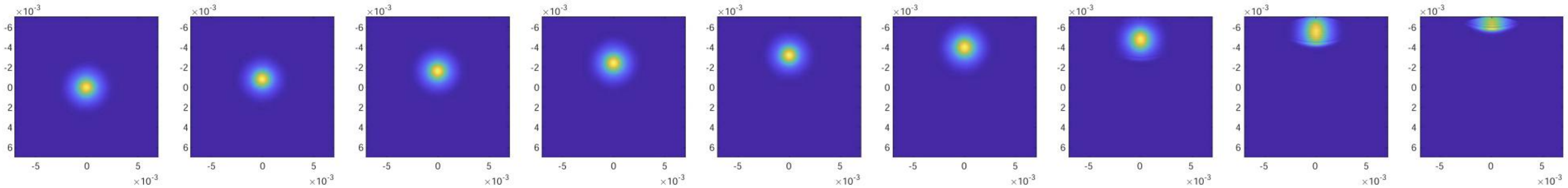
FoxLi迭代方法求解

U(x, y, z)：腔内激光稳定振幅分布

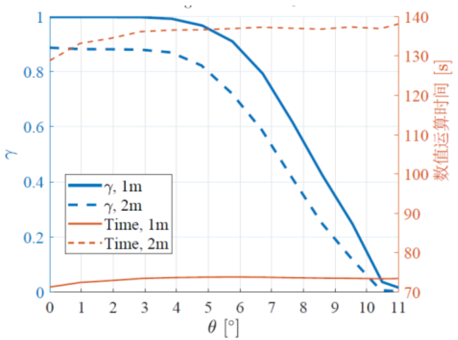
γ: 腔内激光一个往返传输的传输系数，即传输效率

研究一：移动自对准机理

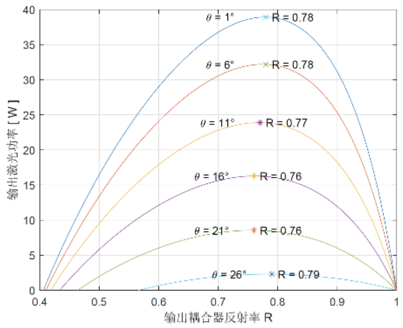
1）腔内激光移动传输通道模型-移动状态下结果分析



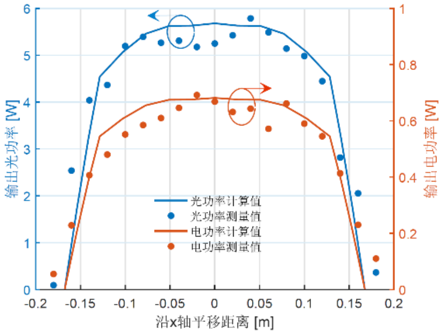
(a) 随收发端角度变化的腔内激光光场分布



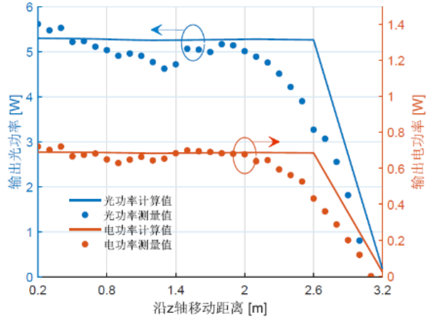
(b) 角度vs.传输效率



(c) 输出耦合率vs.输出功率



(d) 横向移动实验理论对比

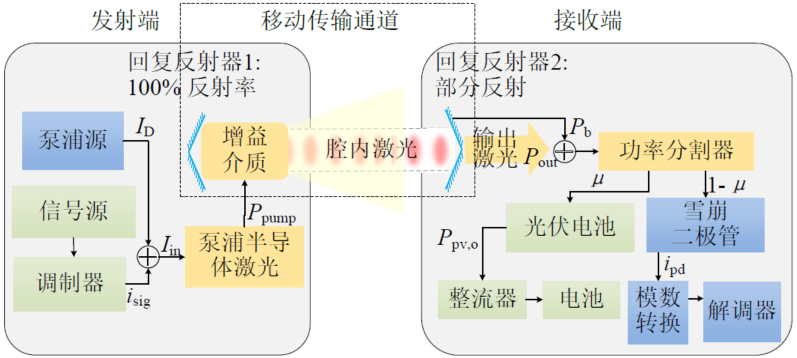


(e) 纵向移动实验理论对比

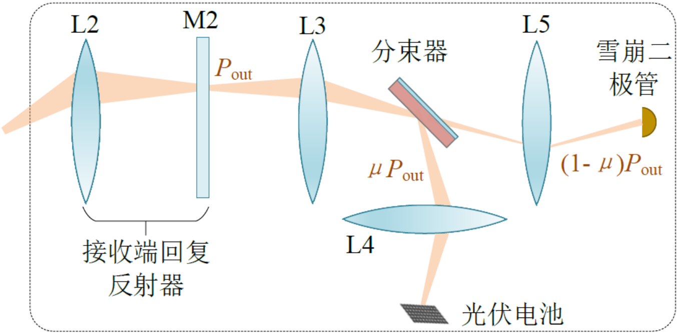
M. Liu, H. Deng, Q. Liu, et al, “Simultaneous Mobile Information and Power Transfer by Resonant Beam,” ***IEEE Transactions on Signal Processing***, vol. 69, pp. 2766-2778, May 2021.
M. Liu, Q. Jiang, Q. Liu, et al, "Simultaneous Localization and Power Transfer via Resonant Beam," ***IEEE Internet of Things J.***, vol. 10, no. 2, pp. 1414-1425, Jan. 2023.

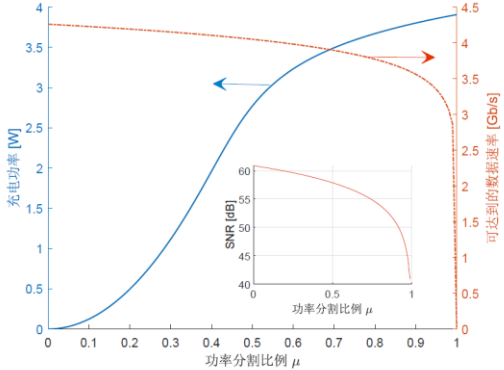
3 研究一：移动自对准机理

2）传能通信一体化方法设计及性能分析

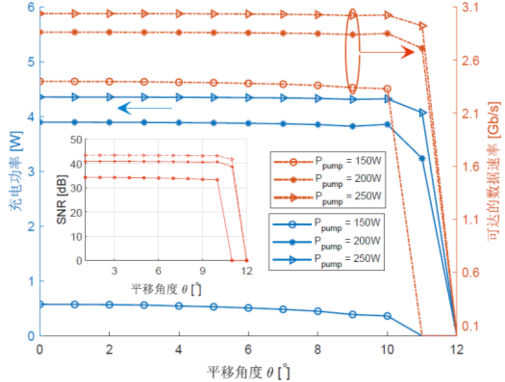


能量分割方案





(a) 传能通信性能权衡



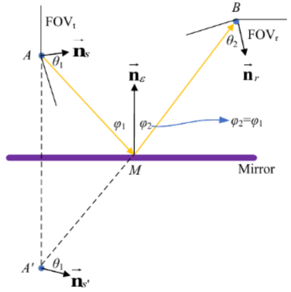
(b) 20° 视场角
4W充电功率
2.6Gbps速率

M. Liu, et al, “Mobility-Enhanced Simultaneous Lightwave Information and Power Transfer,” ***IEEE Trans. Wireless Commun***., vol. 20, no. 10, pp. 6927-6939, Oct. 2021.

3 研究一：移动自对准机理

3）腔内激光非视距传输系统模型与分析方法

基于几何光学的NLoS传输链路等效



反射镜辅助NLoS链路限制条件：

$$0 < \cot\left(-\vec{n}_s \cdot \mathrm{unit}(\mathbf{AM})\right) < \mathrm{FOV}_t$$

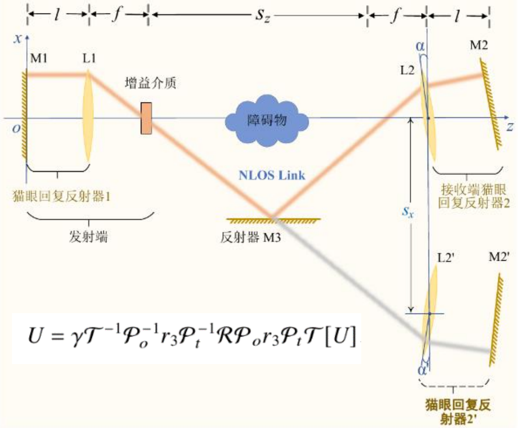
$$0 < \cot\left(-\vec{n}_r \cdot \mathrm{unit}(\mathbf{AM})\right) < \mathrm{FOV}_r$$

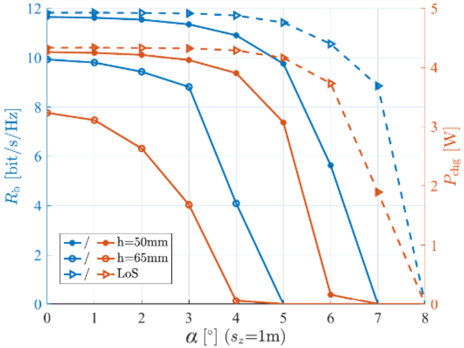
$$\mathbf{MB} = \mathbf{AM} - 2(\vec{n}_\epsilon \cdot \mathbf{AM}) \cdot \mathbf{AM}$$

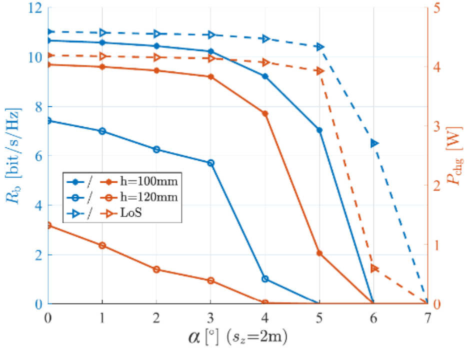
光程等效性：

$$|\mathbf{AM}| + |\mathbf{BM}| = |\mathbf{A'M}| + |\mathbf{BM}| = |\mathbf{A'M}|$$

基于全衍射理论的本征方程构建





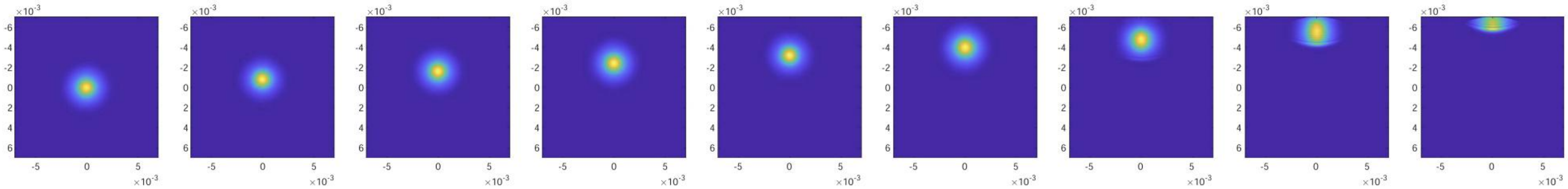


非视距传输下可以允许接收端±4°的倾斜角

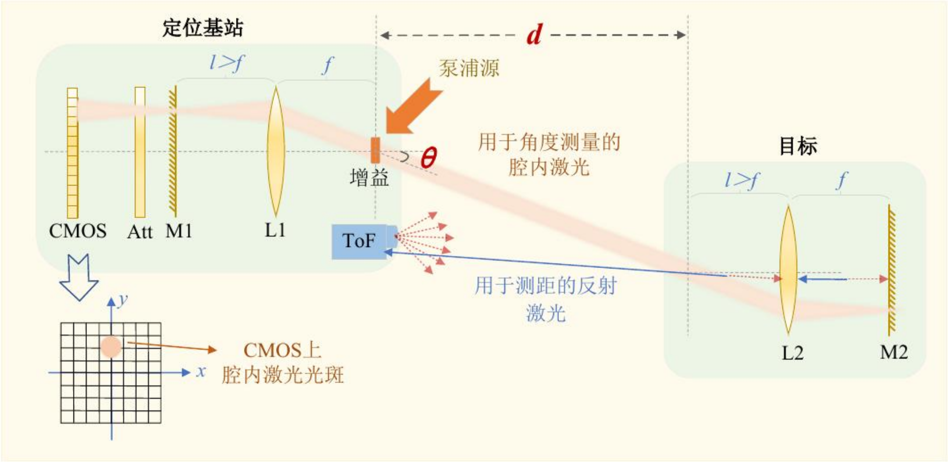
M. Liu, S. Xia, M. Xiong, M. Xu, Q. Liu and H. Deng, “NLOS Transmission Analysis for Mobile SLIPT Using Resonant Beam”, ***IEEE Transactions on Wireless Communications***, vol. 23, no. 1, pp. 334-346, Jan. 2024.

4 研究二：高精度定位

1）米级距离毫米级精度的腔内激光单目定位技术



发射端光斑偏移与收发端之间角度——对应关系



角度估计

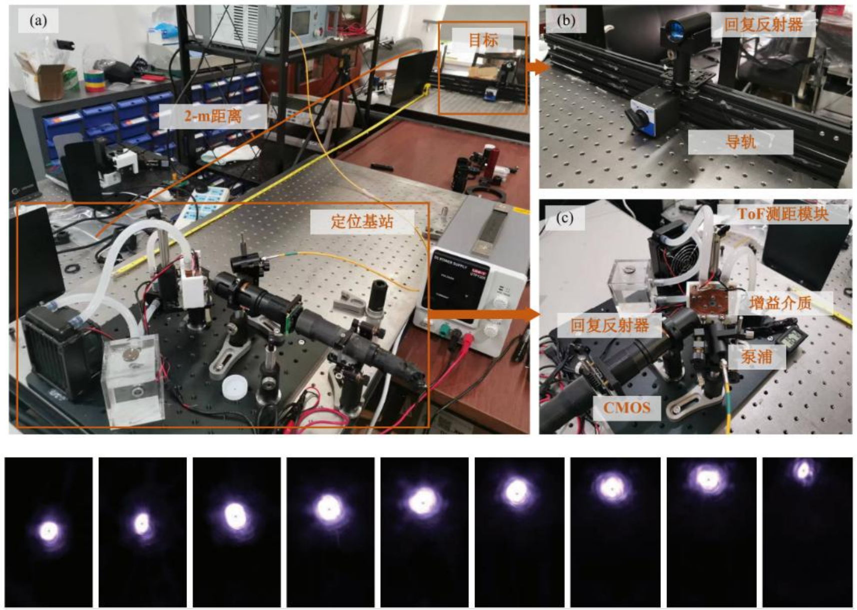
集成激光测距模块

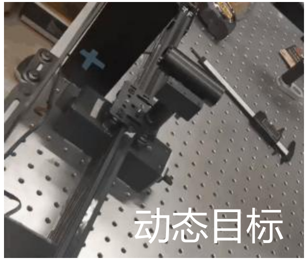
三维坐标估计

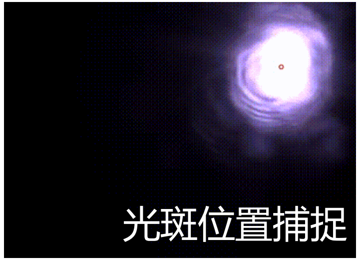
目标无需主动发射信号

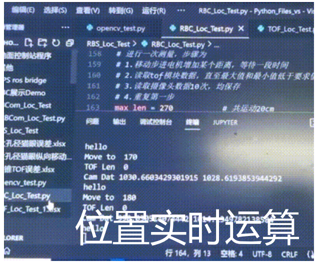
4 研究二：高精度定位

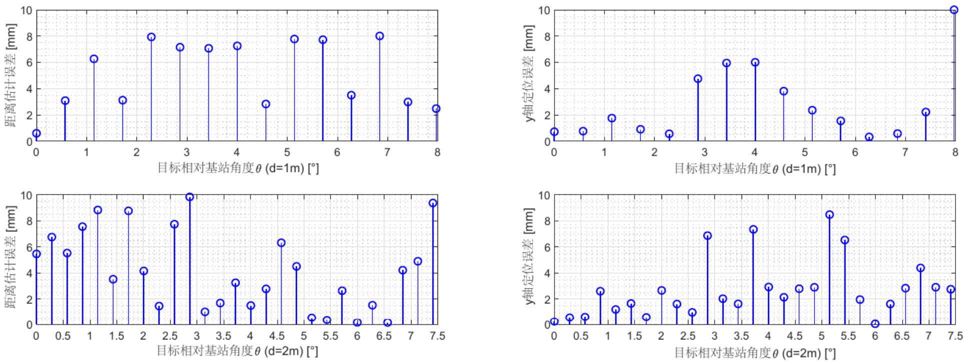
1）米级距离毫米级精度的腔内激光单目定位技术











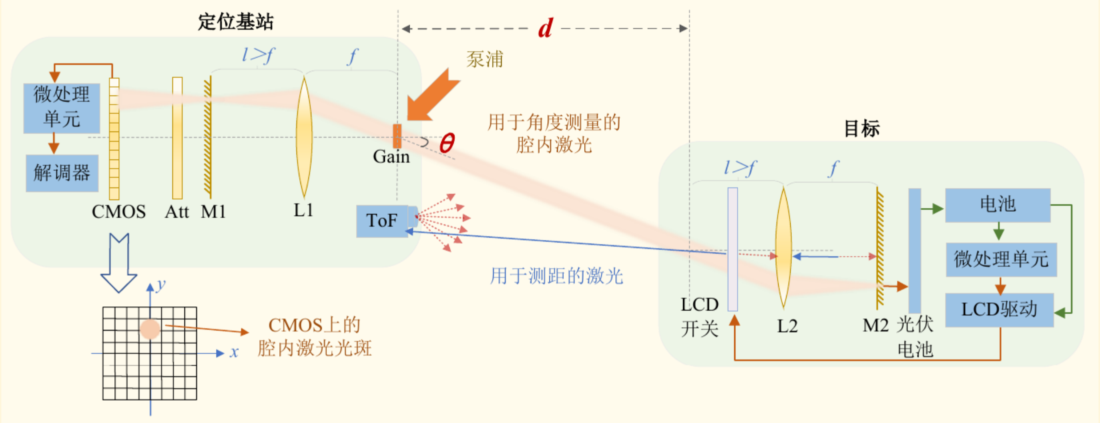
原型搭建-CMOS处光斑捕捉

2m距离、16° 视场角内三维空间定位精度<1cm

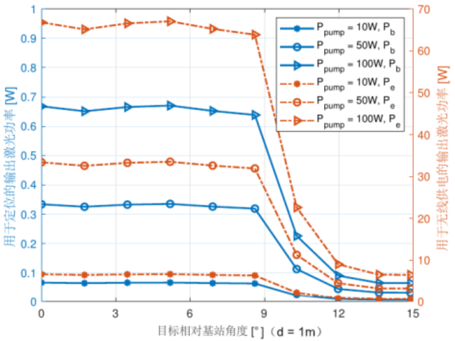
M. Liu#, Q. Jiang#, M. Xu, and Q. Liu, “Passive Location Estimation via Resonant Beam”, ***IEEE Transactions on Vehicular Technology***, vol. 72, no. 10, pp. 13055-13066, Oct. 2023.

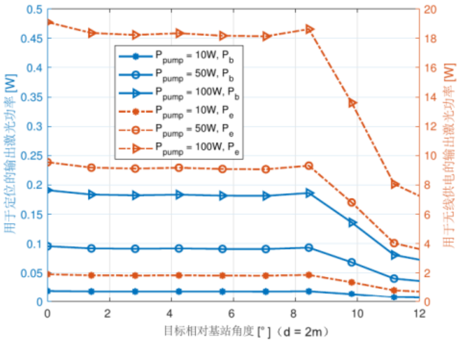
4 研究二：高精度定位

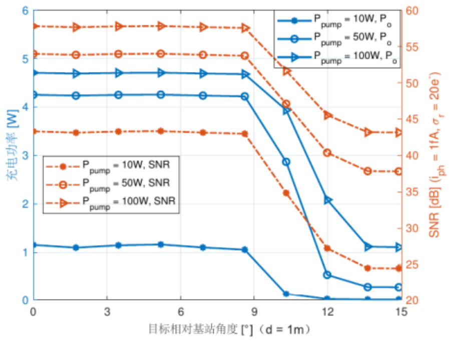
2）定位传能与定位通信一体化方案

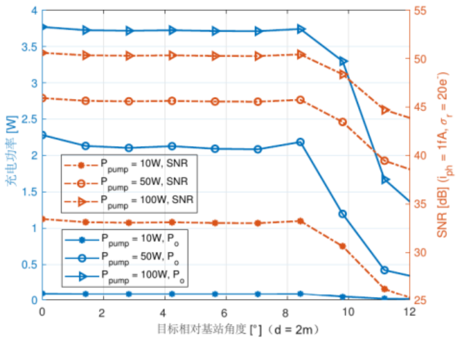


2m距离、16°视场角
三维空间定位精度<1cm
W级充电功率



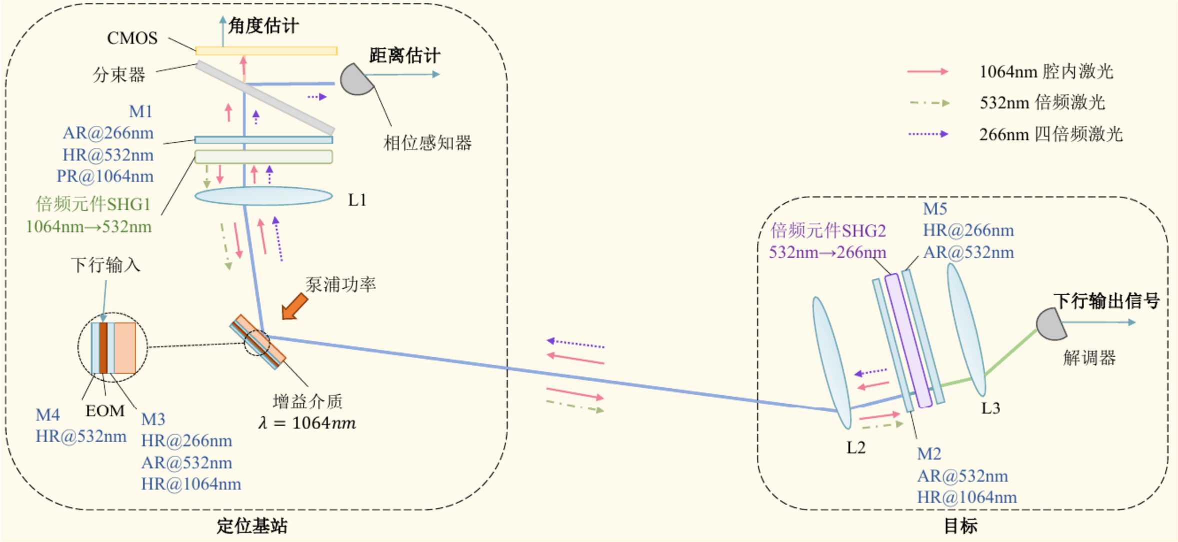


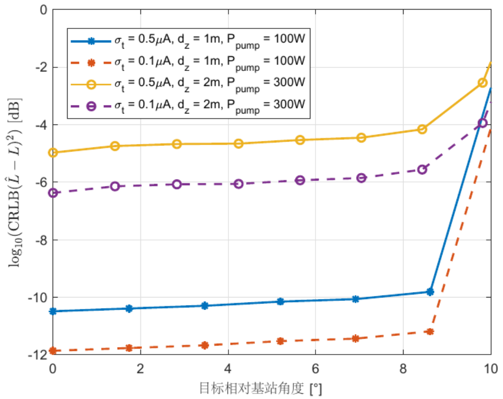


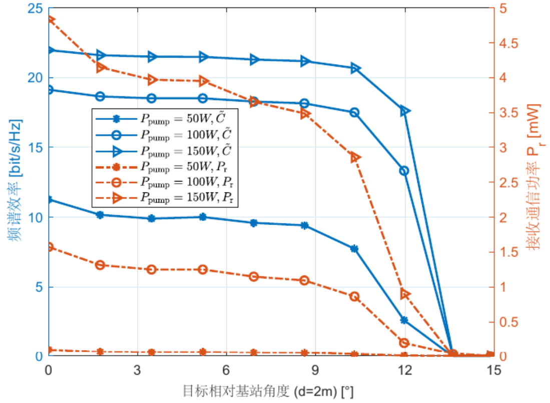


M. Liu, Q. Jiang, Q. Liu, M. Xu, M. Xiong and W. Fang, "Simultaneous Localization and Power Transfer via Resonant Beam," ***IEEE Internet of Things J.***, vol. 10, no. 2, pp. 1414-1425, Jan. 2023.

2）定位传能与定位通信一体化方案





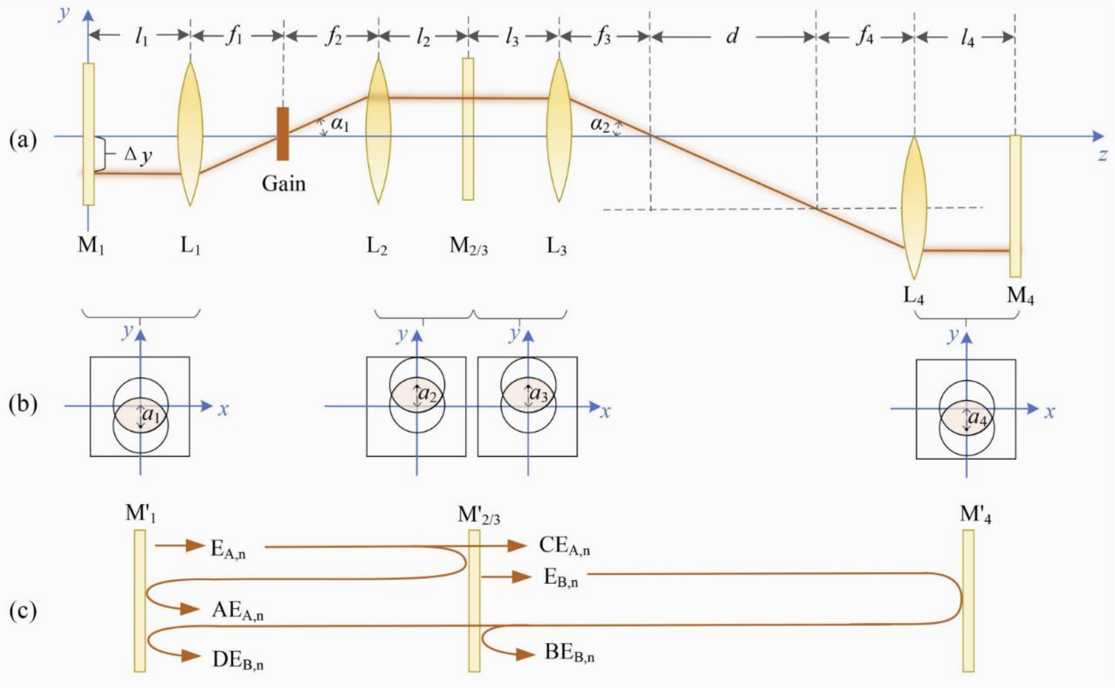


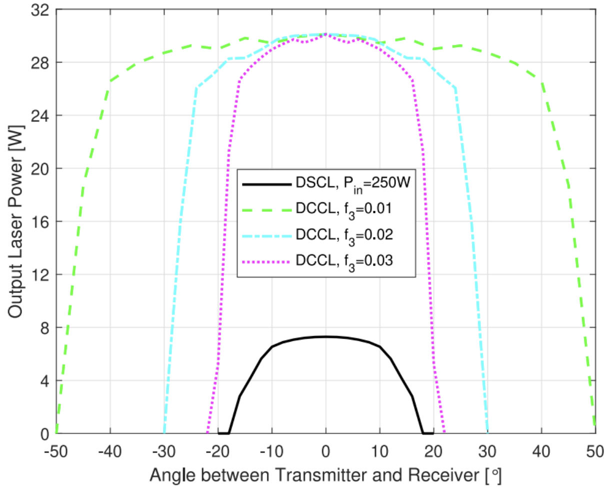
2m距离、16°视场角，三维空间定位精度<1cm，10bps/Hz频谱效率

M. Liu, S. Xia, M. Xiong, M. Xu, W. Fang, and Q. Liu, “Integrated communication and positioning with resonant beam”, *IEEE Transactions on Wireless Communications*, vol. 21, no. 11, pp. 9186-9199, Nov. 2022

5 研究三：耦合腔安全性移动性提升

1）安全性移动性提升的耦合腔腔内激光分析模型





移动视场角从单腔±10°
提升至±40°

H. Deng, S. Zhao*, M. Liu*, Q Liu, "Joint Sensing and Power Transfer via Distributed Coupled-Cavity Lasers," ***IEEE Internet of Things Journal***, vol. 11, no. 01, pp. 1122-1135.

同济 TONGJI UNIVERSITY

敬请各位指导！