Interferometers

- Major Applications of Light Interference
- Components of Interferometers
- Components of Laser Interference Systems
- Optical Layout of Interference Length Measuring Machine (ILMM)
- Measures to Increase the Accuracy
- Phase Shifting Technology
- 单频（直流）激光干涉仪
- Heterodyne Type Interferometer

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Major Applications of Light Interference

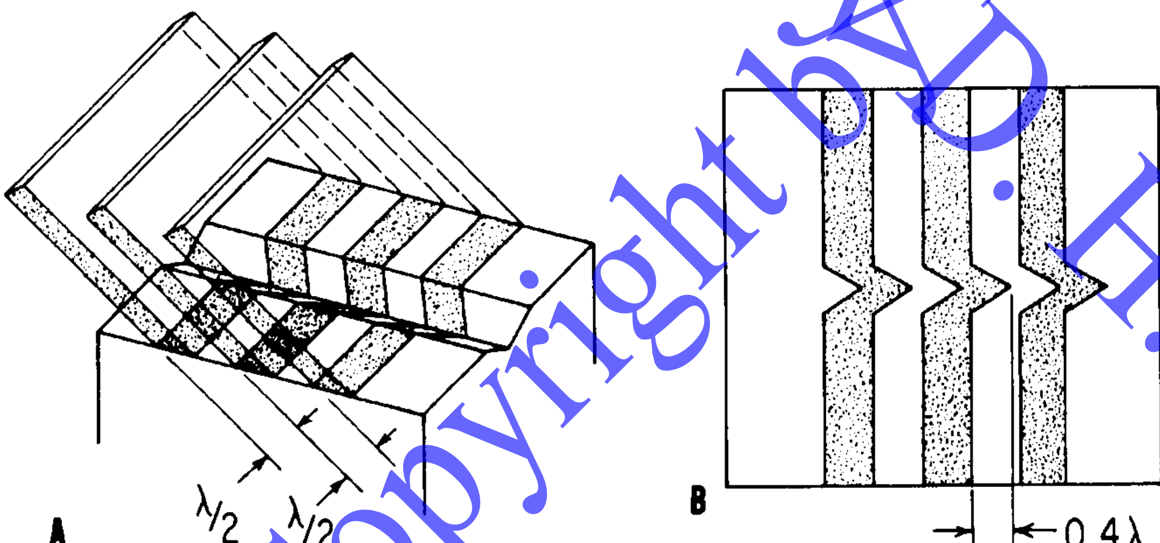
❒ **The physical phenomenon of light interference is utilized in dimensional metrology for different purposes, the major applications being the following**

- **Form Trueness Measurements**
- **Surface Texture Measurement**
- **Length Measurement**
  - ***Distance Measuring Interferometer (DMI)***

Francis T. Farago, *Handbook of Dimensional Measurement*, Industrial Press Inc., 1982

Major Applications of Light Interference

- Diagrams illustrating the principle of surface-texture examination by ***light-interference microscopy***:
  - **(A) A grooved plate intercepted by dark and bright planes, and**
  - **(B) as seen in the microscope**



Francis T. Farago, *Handbook of Dimensional Measurement*, Industrial Press Inc. 1982

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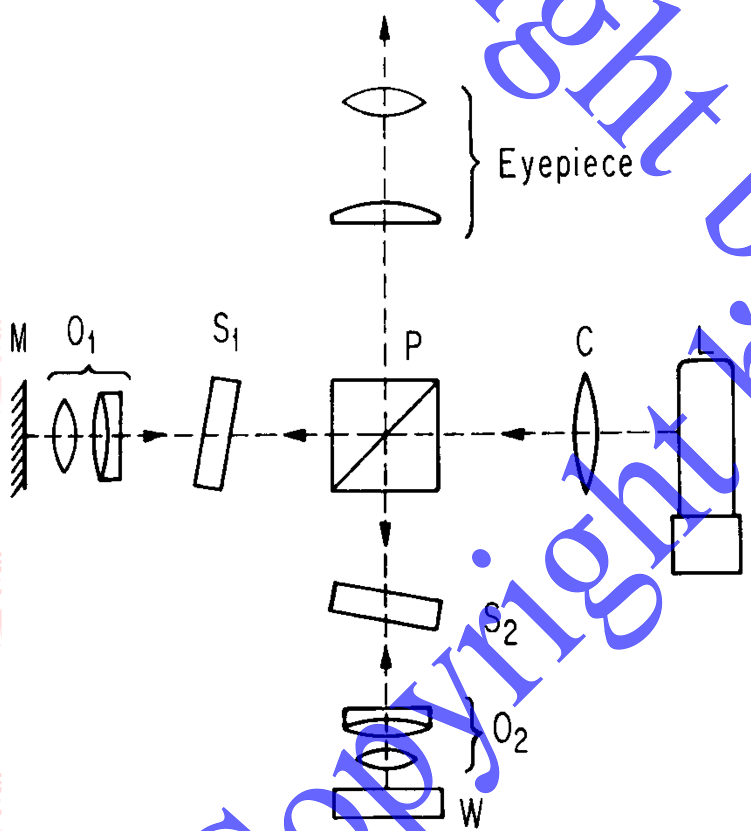
Major Applications of Light Interference

- Diagram of the operating principles of a modified Michelson type, interference microscope



Francis T. Farago, *Handbook of Dimensional Measurement*, Industrial Press Inc., 1982

Laser Interference Length Measuring Machine

The 50 metre interferometer bench at NWML

http://www.npl.co.uk/length/wss/services/ms_interferometers.html

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Application

Precision Displacement Measurement via a Distance Measuring Interferometer (DMI)

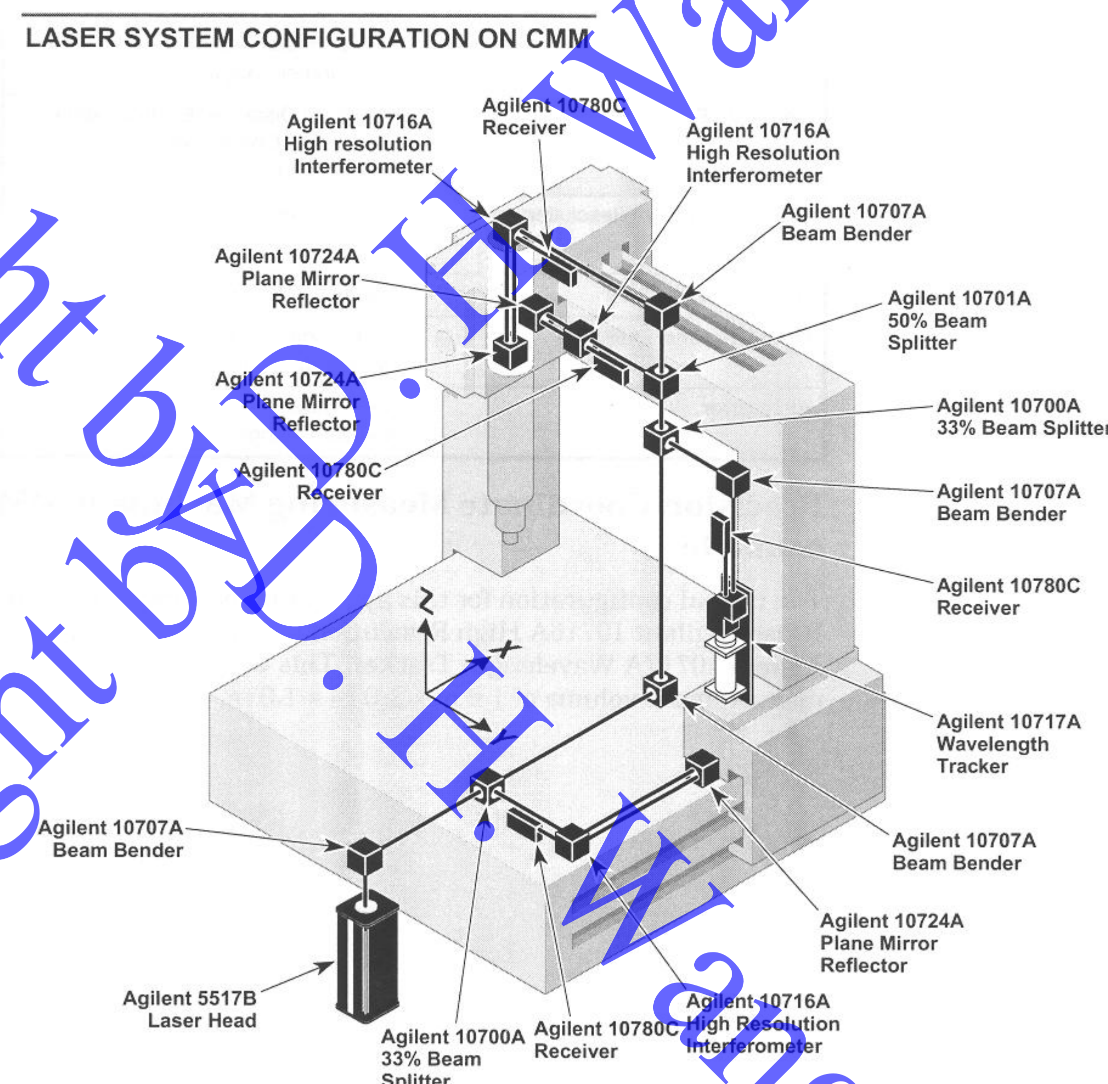
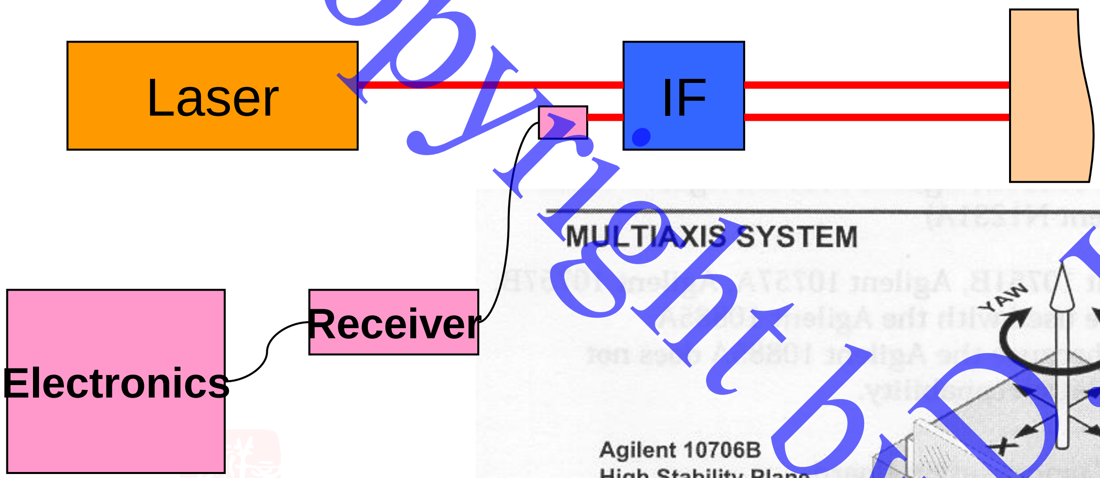


Figure 15-9. Laser system configuration for a precision Coordinate Measuring Machine (CMM)

Application



Precision Displacement Measurement via a Distance Measuring Interferometer

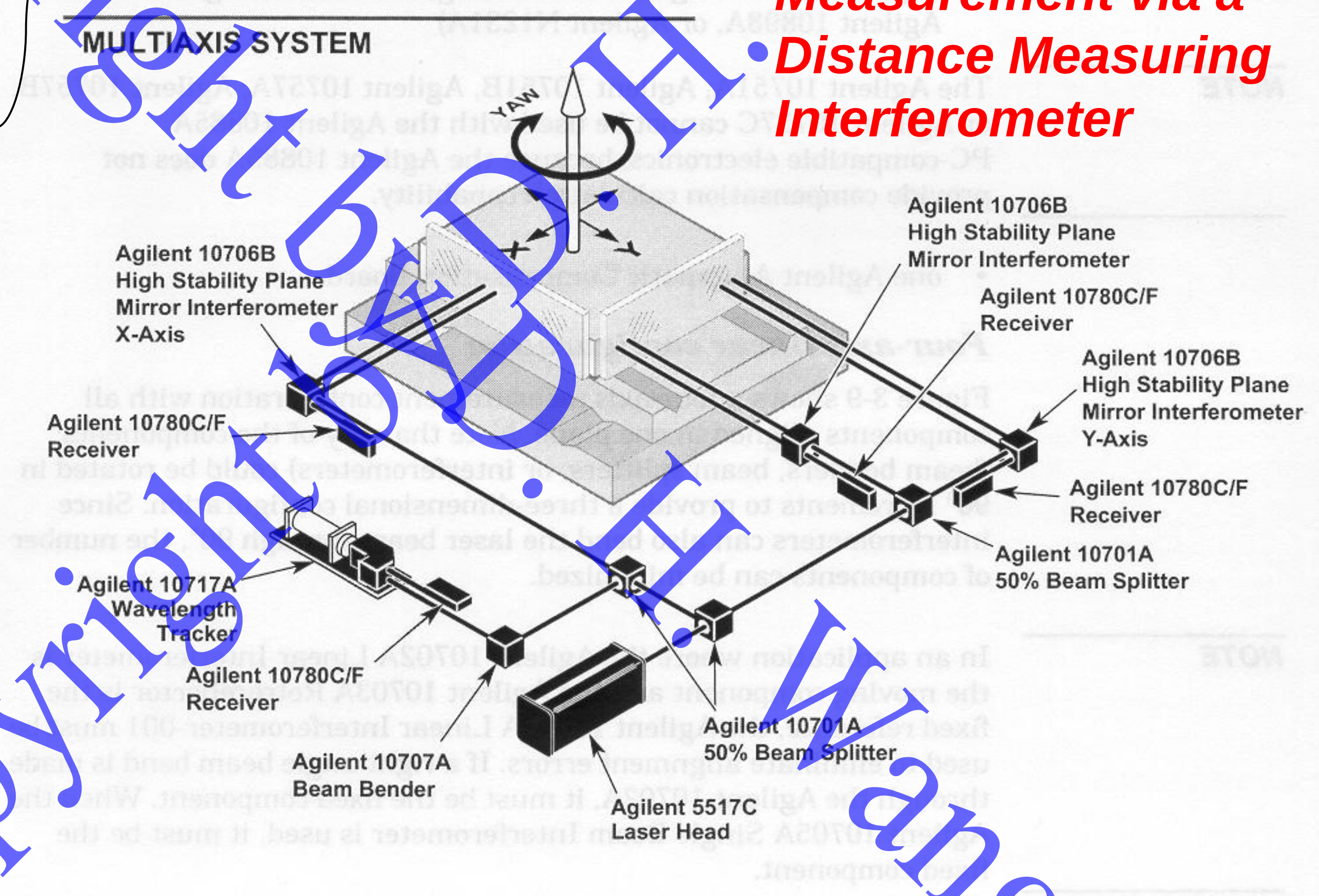


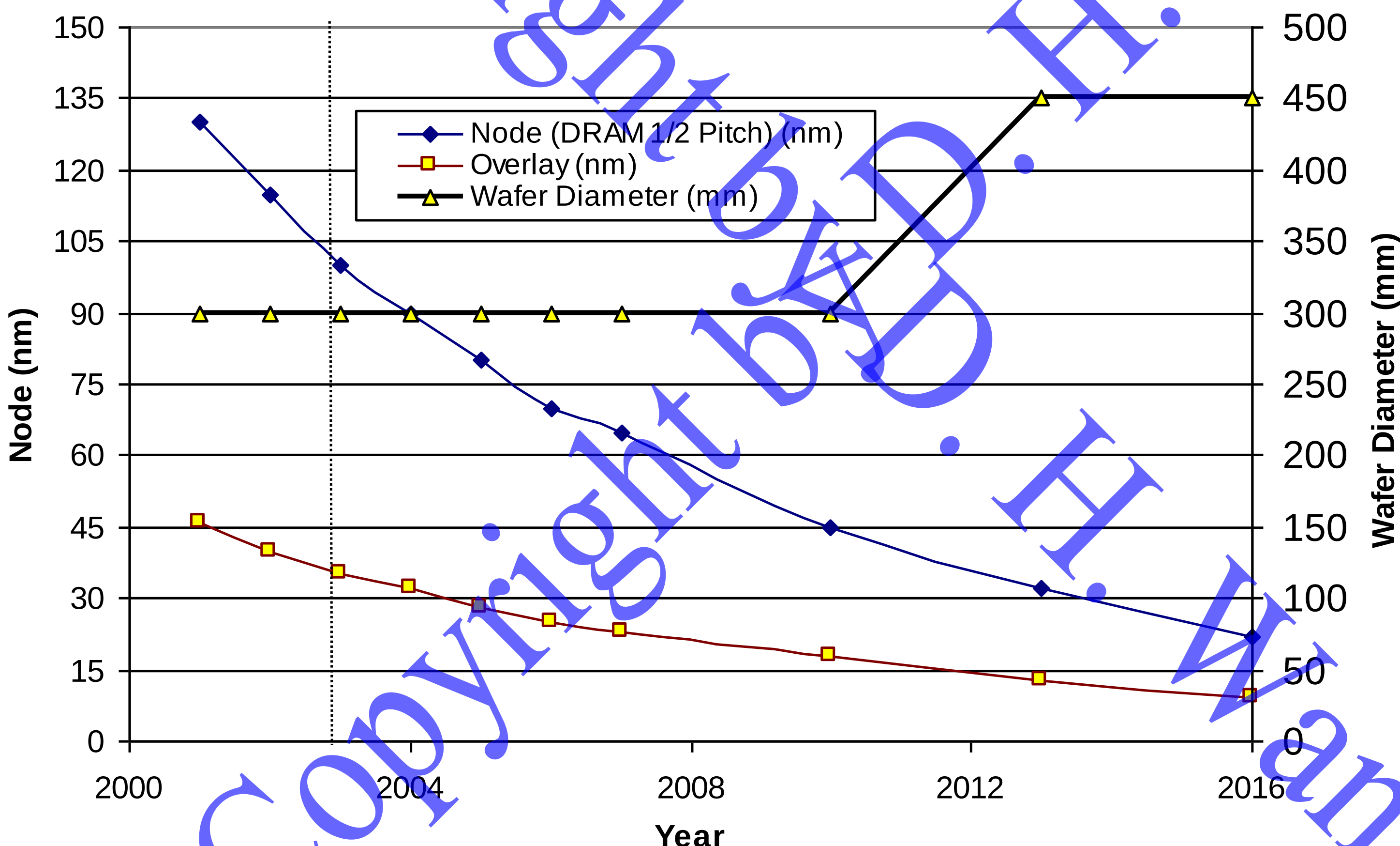
Figure 3-8. Multiaxis system for a precision x-y stage

Interferometers: History

Year	Description	DMI Resolution
1887	Michelson-Morley Experiment. *Leads to Michelson interferometer.*	NA
1902	Pieter Zeeman wins Nobel Prize for effects of magnetic fields on atomic spectra. *Leads to Zeeman split laser.*	
1960	Bell Laboratories develop first He-Ne laser	
1964	Airborne Instrument Labs, Division Cutler Hammer, first commercial displacement IF	
1965	Zeeman He-Ne Laser (HP)	
1968	Perkin-Elmer “Lasergage” homodyne IF	
1970	Zeeman laser IF (HP)	$\lambda/16$
1987	20 MHz Heterodyne, with 2-pass (Zygo)	$\lambda/512$
~1996	Current electronics (HP/Zygo).	$\lambda/2048$

Why DMI is Needed

- Important characteristics of “International Technology Roadmap for Semiconductors: 2001” published by SIA



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Components of Interferometers

- Components of Interferometers
  - Light Sources and Lighting System
  - Interference Systems
  - Observing and Detecting System
  - Electronic system for processing data
- Mechanical system

Components of Laser Interference Systems

- Laser tube
- Beam Handling Components
  - Beam splitter
  - Retroreflectors
  - Phase Shifter
  - Beam bender
  - Beam expander
- Observing and Detecting System
- Electronic System for Processing Data

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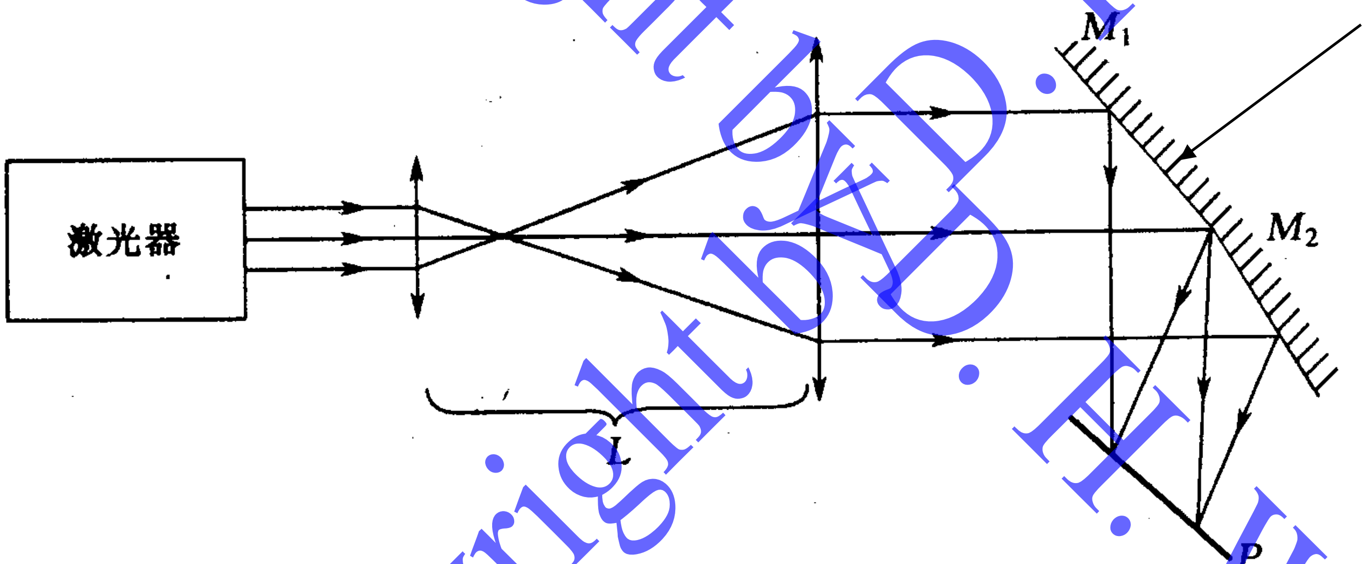
Beam Splitters

- **Functions**
  - **Heart of the interferometer**
  - **Split source beam into reference and measurement legs**

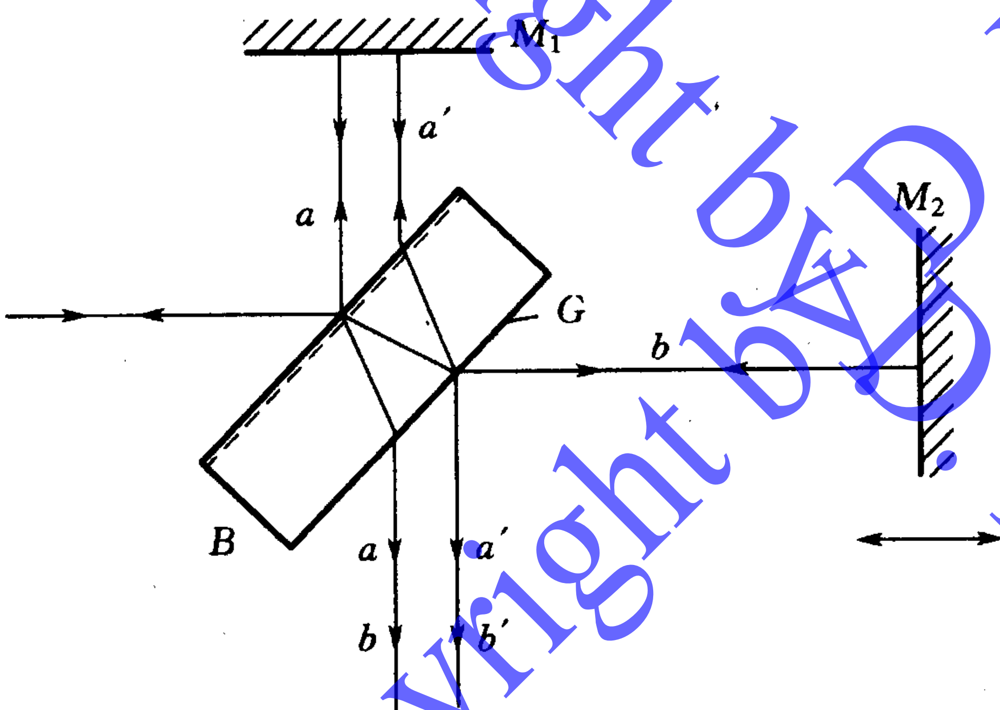
Beam Splitters

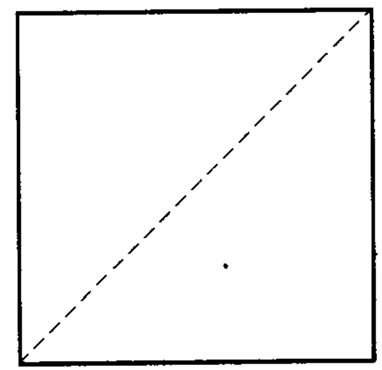
- 分波阵面法



Beam Splitters

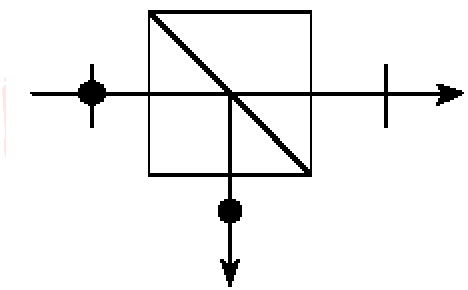
- 分振幅法

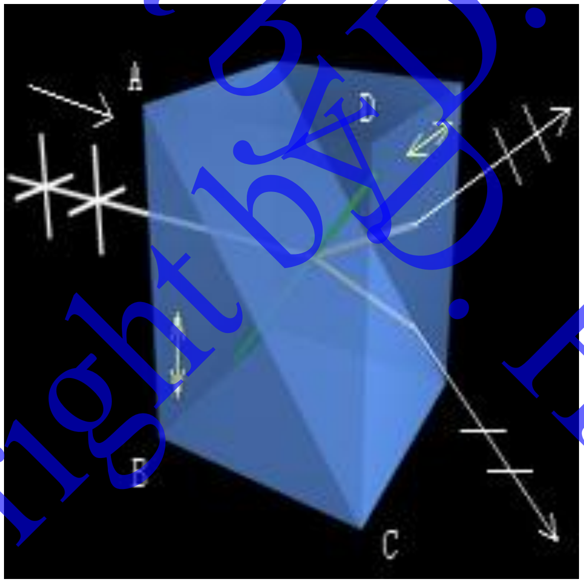


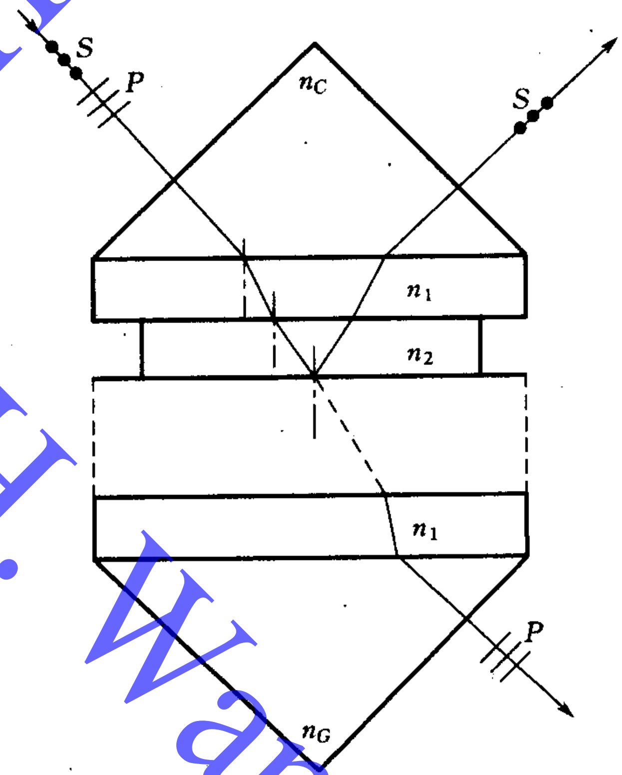


Beam Splitters

- ❒ Polarization sensitive
- ❒ Typically 1/2 or 1 inch cubes



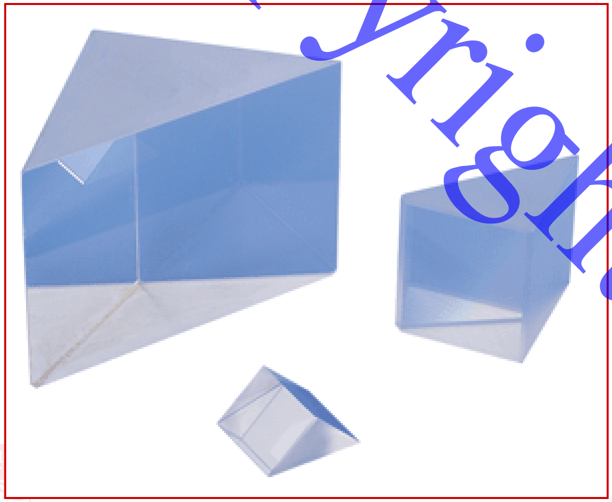


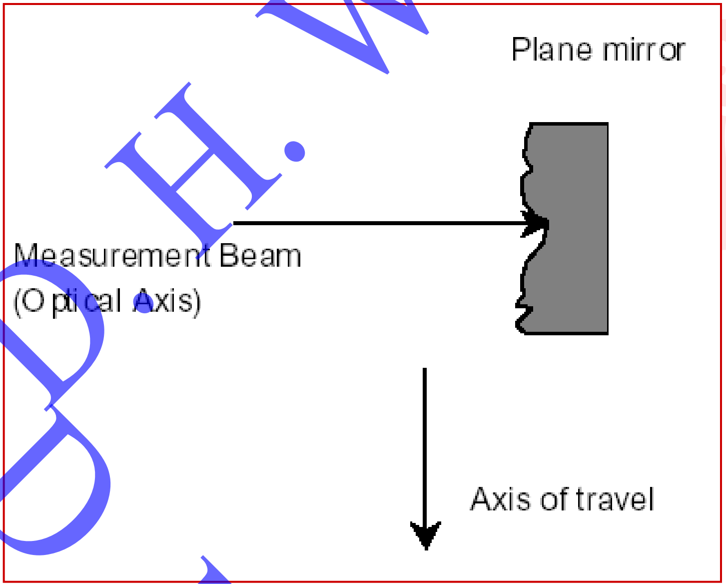


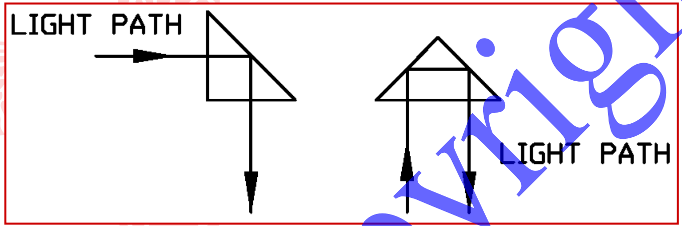
Retroreflectors

- ❒ **Plane mirror**
- ❒ **Right angle prism**
- ❒ **Trihedral prism**

Retroreflectors

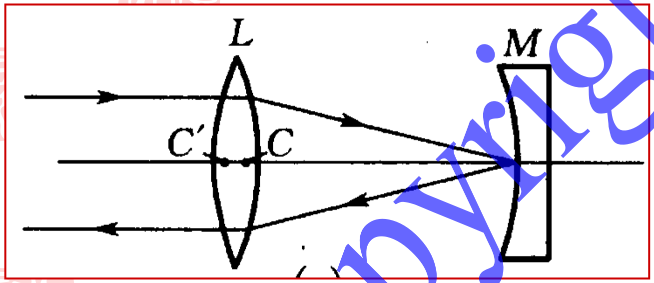




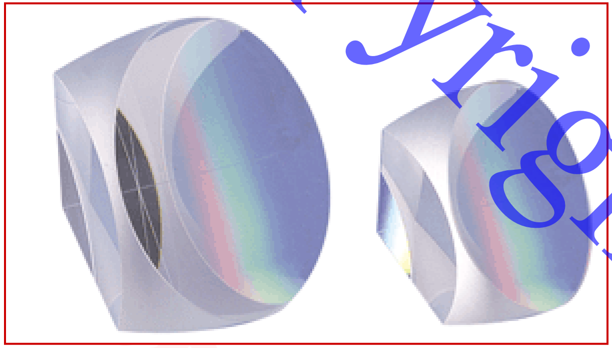


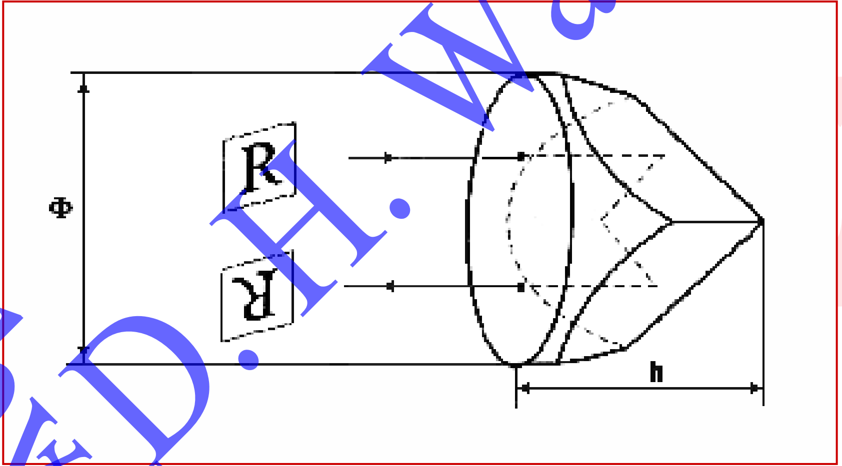
Retroreflectors

- 猫眼反射器
  - 构成
    - 若c’（反射镜的曲率中心）与c（透镜的曲率中心）重合，当透镜与反射镜一起绕c点旋转时，光程保持不变
  - 容易加工
  - <u>不影响偏振光的传输</u>

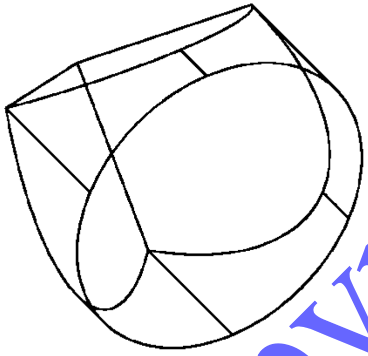


Retroreflectors





Trihedral Prism



Material: BK7

Grade A Fine Anneal

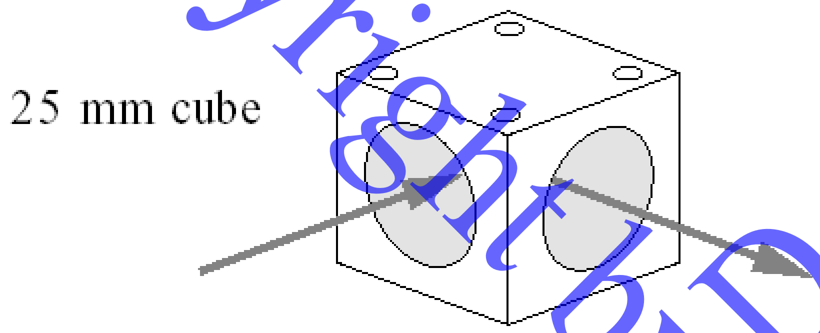
Surface Quality: 40-20

Surface Flatness: l /10 (70% Of Clear Aperture)

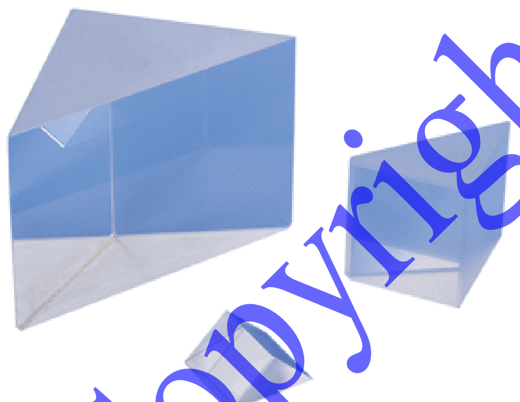
Beam Deviation: 1 Arc Min.

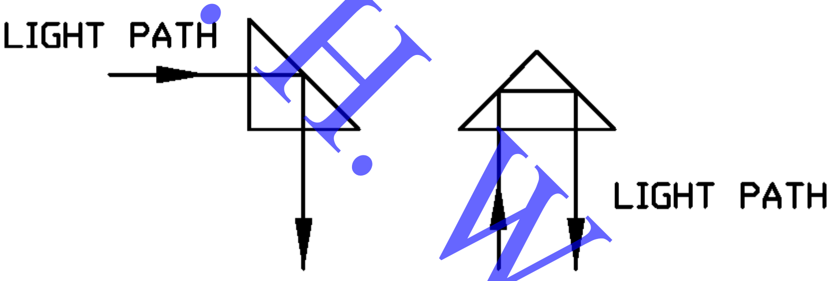
Beambenders

❒ Cube type beambender (fold mirror)



❒ Right angle prism





Optical Layout of ILMM

- ❐ 整体式布局
- ❐ 光学倍程式
- ❐ 最短程差式
- ❐ 齐端式(零光程差的结构布局)
- ❐ 误差自动补偿式

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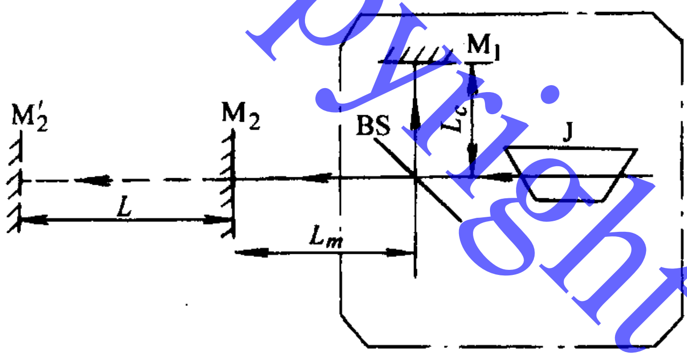
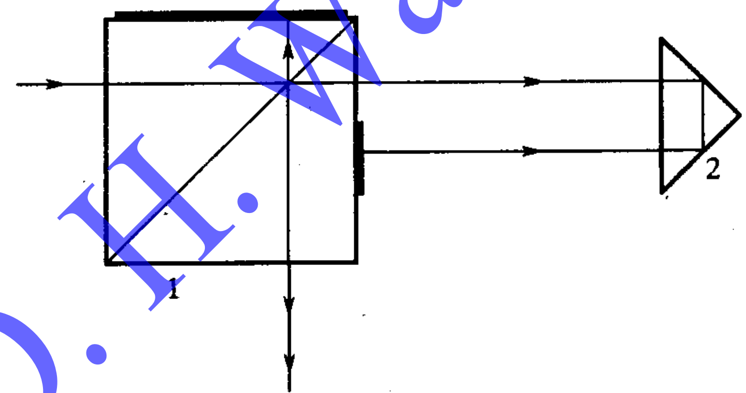
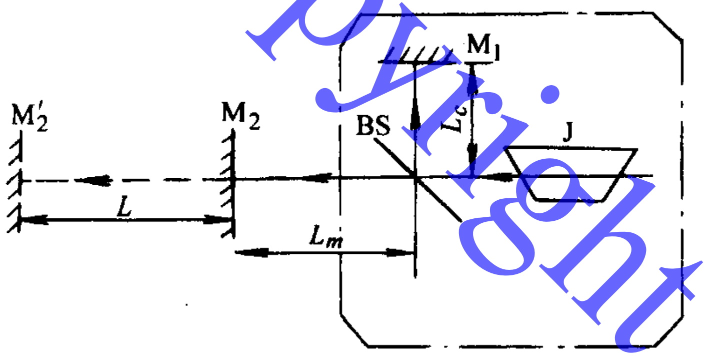
整体式布局 (1/2)

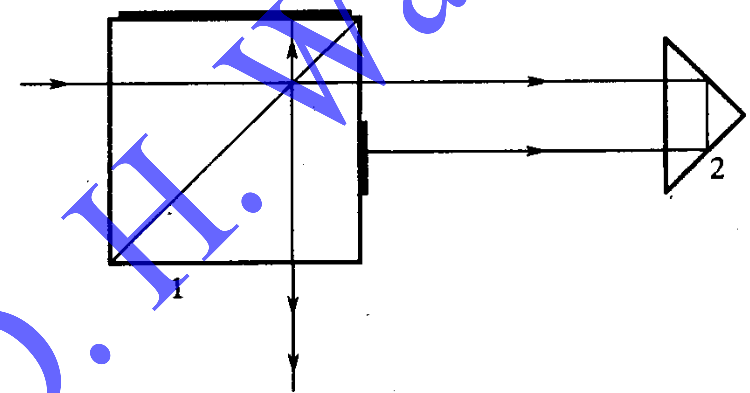




- 整体式布局
  - 把参考反射镜M1、分光镜BS、激光器J均密封于一体内，而测量反射镜M2与被测物体相连结，测量时置于外界条件下
- 优点/缺点
  - 。。。

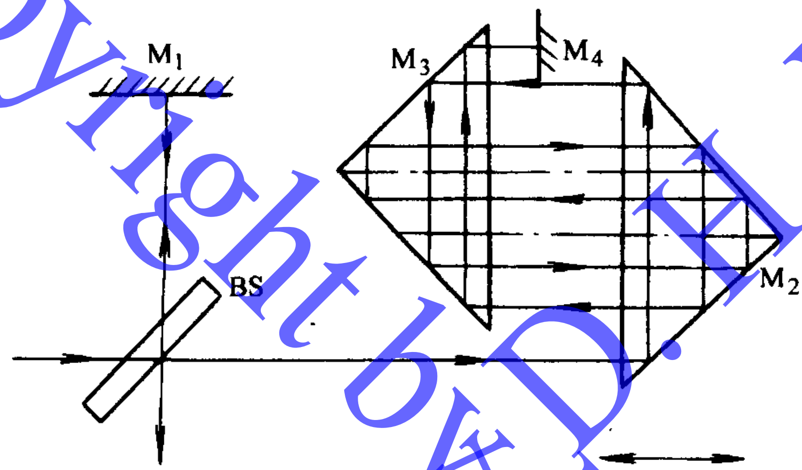
整体式布局 (2/2)





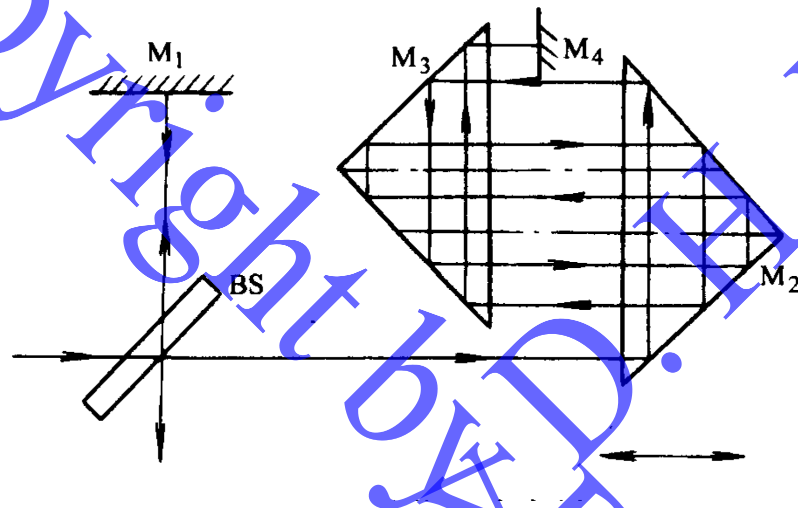
- **优点/缺点**
  - 这种布局整体性好，系统对外界的抗干扰性好，抗动镜多余自由度能力强，测量灵敏度提高一倍
  - 干涉仪的参考臂区域与测量臂区域处于不同的环境条件下，因此计算“零点漂移误差”时，应考虑测量过程中空气折射率和被测长度对起始状态变动量的影响
  - 调整不方便，对光的吸收严重

光学倍程式 (1/2)



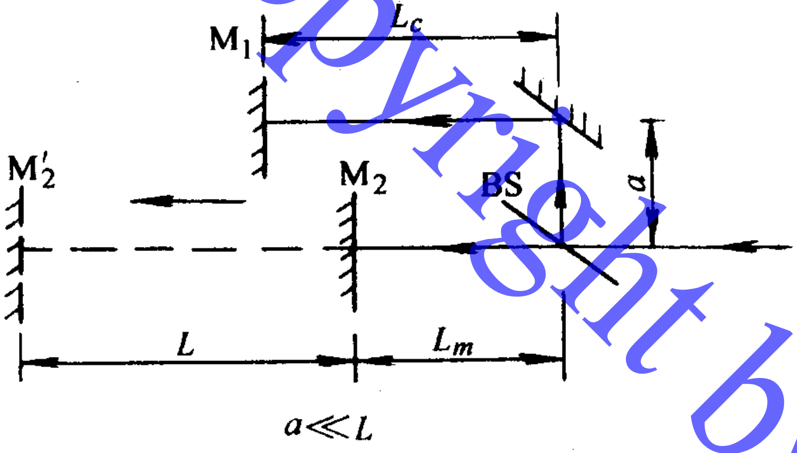
- 特点
  - 使测量光束在测量镜内多次往返

光学倍程式 (2/2)



- 优点
  - 实现对位移灵敏度的提高，使之产生光学多倍程的效果（光学倍程法）
- 缺点
  - 初始程差不为零，零点漂移误差较大

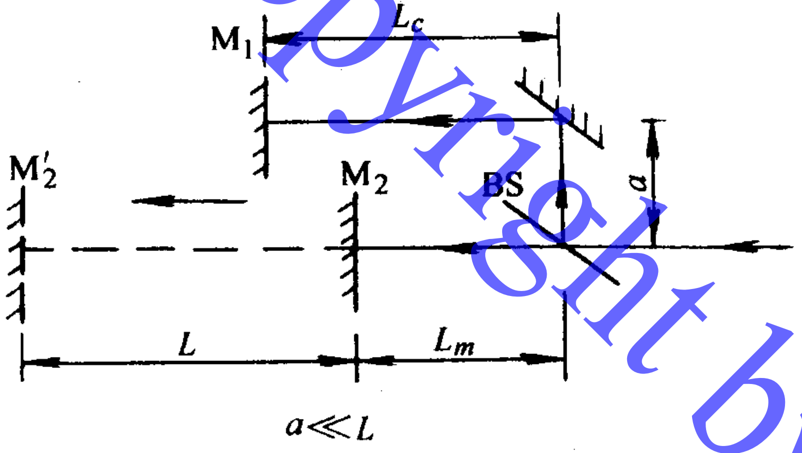
最短程差式 (1/2)



$a << L \quad |L_m - L_c| = \frac{L}{2}$

- **特点**
  - 所谓最短程差式布局，其目的是在最大测量行程时，使两相干光束具有最短的相干长度
- **优点**
  - 由于参考反射镜**M1**和测量反射镜**M2**布置在同一侧，可认为干涉仪的两臂经受相同的环境因素，因此零漂移误差较小

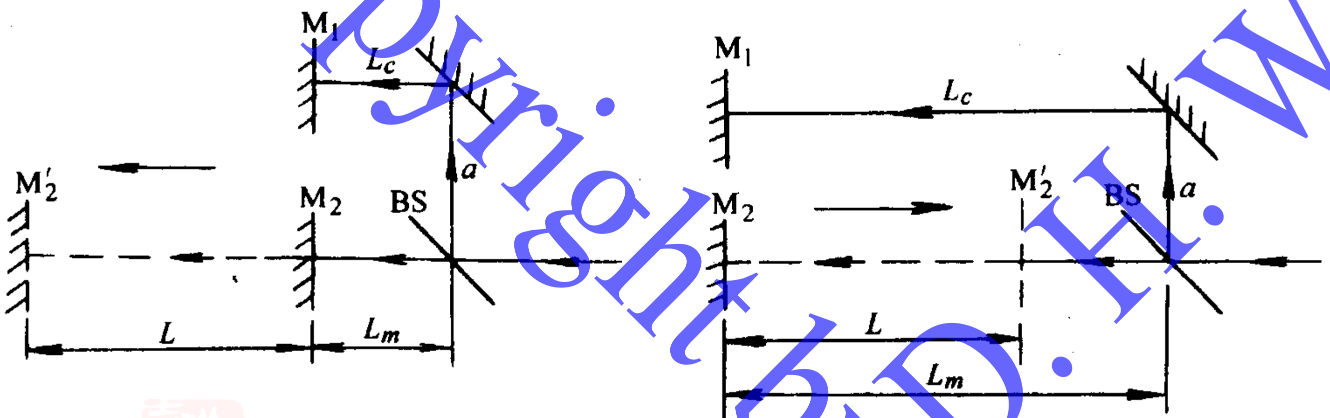
最短程差式 (2/2)



$$a \ll L \qquad |L_m - L_c| = \frac{L}{2}$$

- 缺点
  - 零点漂移误差不为零

齐端式 (1/2)



$a << L$

$L_m - L_c = 0$

$\Delta(L_m - L_c) = 0$

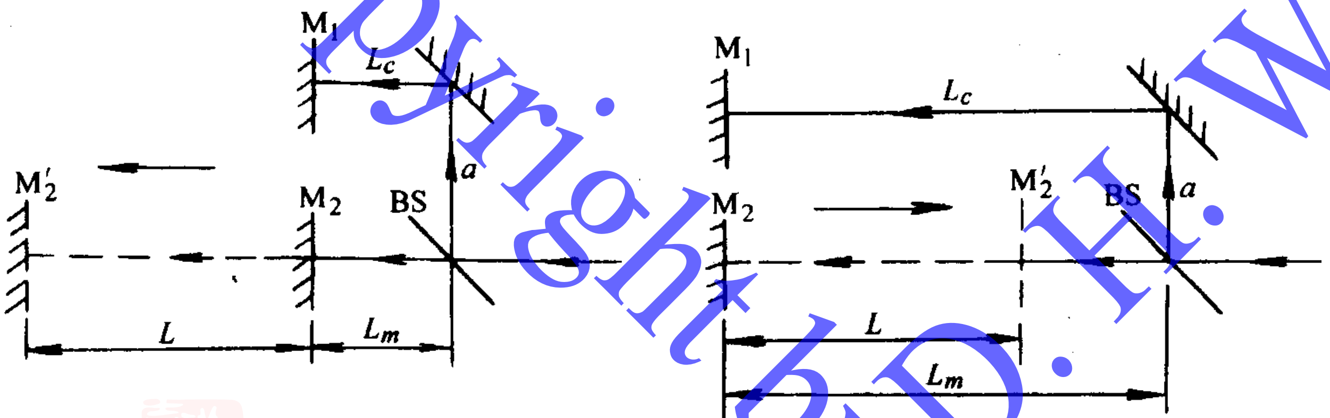
❐ 特点

- 干涉仪的参考反射镜和测量反射镜在开始测量时"齐端"
- 干涉系统两臂布置在同一侧
- 在这种布局情况下，**Lm - Lc＝0**

❐ 优点

- 齐端式是使零点漂移误差为零的布局：**Δ(Lm - Lc)＝0**

齐端式 (2/2)



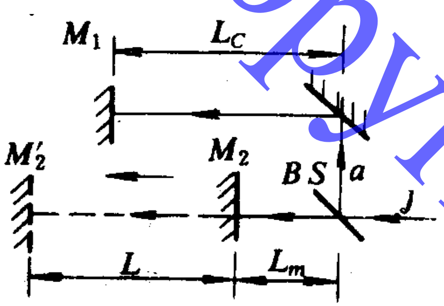
$a << L$

$L_m - L_c = 0$

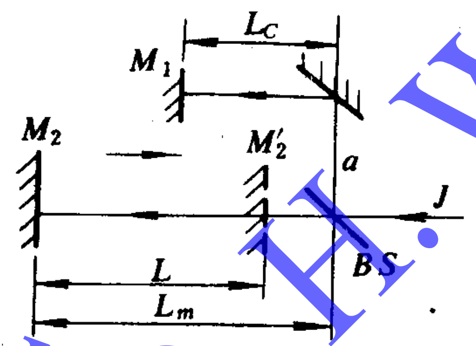
$\Delta(L_m - L_c) = 0$

- 缺点
  - 干涉仪的参考臂区域与测量臂区域处于不同的环境条件下

误差自动补偿式



$L_m < L_c$



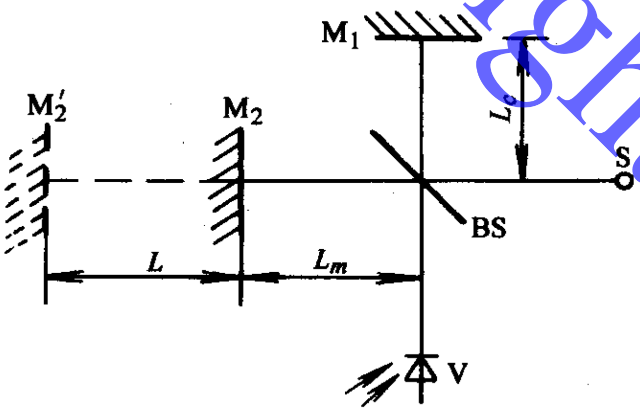
$L_m > L_c$

- 特点
  - 当Lm<Lc时测量镜向左移动
  - 当Lm>Lc时测量镜向右移动
- 优点
  - 误差能相互补偿，对提高仪器精度有利
- 缺点：增加系统复杂程度

Measures to Increase the Accuracy

- 迈克尔逊激光干涉系统的误差分析
- **Measures to Increase the Accuracy**
  - 遵守“共路”原则
  - 光波长的稳定和修正
  - 空气折射率修正
  - 非期望光线的抑制和消除
  - 正确选择光电器件
  - 等光强原则
  - 光学退耦

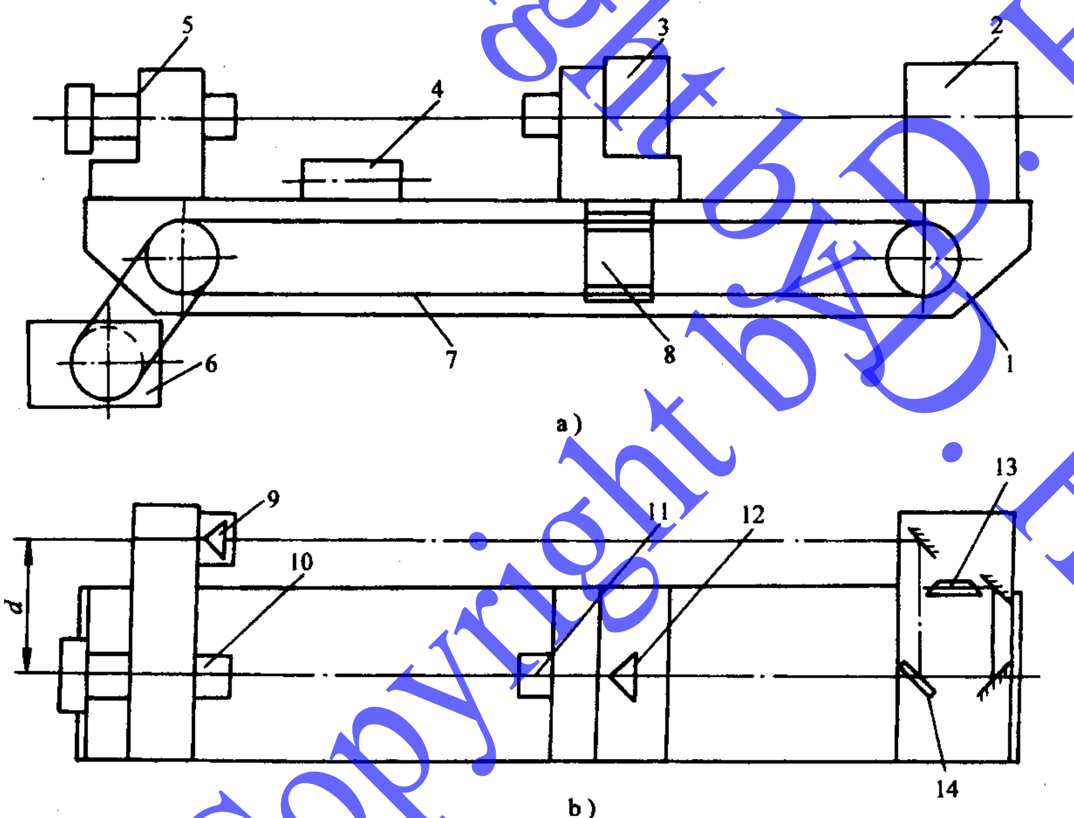
❐ **Error analysis of a laser interferometer**



$$\Delta L \approx L\left(\frac{\Delta K}{K}+\frac{\Delta\lambda_0}{\lambda}-\frac{\Delta n}{n}\right)-\Delta(L_m-L_c)$$

“共路”原则

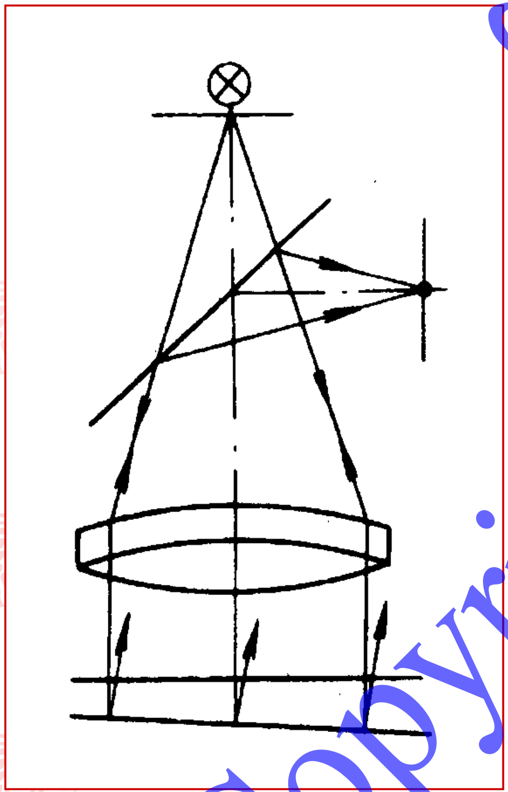
- ❐ “共路”原则：测量光束与参考光束尽量接近同一路径
  - 1 m Laser Interference Length Measuring Machine



遵守“共路”原则

❒ 遵守“共路”原则：测量光束与参考光束尽量接近同一路径

- 菲索式干涉仪原理



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URL: http://www.pilab.coe.cqu.edu.cn/

❐ 光波长的稳定和修正

$$\Delta L \approx L\left(\frac{\Delta K}{K}+\frac{\Delta\lambda_0}{\lambda}-\frac{\Delta n}{n}\right)-\Delta(L_m-L_c) \Rightarrow \frac{\Delta L}{L}=\frac{\Delta\lambda}{\lambda}$$

If $\frac{\Delta L}{L}<\frac{1\mu m}{1m}$, then $\left|\frac{\Delta\lambda}{\lambda}\right|=\frac{0.1\times10^{-6}}{1}=1\times10^{-7}$ $\left|\frac{\Delta\nu}{\nu}\right|\leqslant10^{-7}$

$$\nu=\frac{c}{2nL_s}k \qquad \frac{\Delta\nu}{\nu}=-\left(\frac{\Delta L_s}{L_s}+\frac{\Delta n}{n}\right)$$

腔长变化

介质折射率变化

光波长的稳定和修正

❒ 稳频方法

- 兰姆凹陷法
- 饱和吸收法
- 塞曼效应法
- 干涉腔法

空气折射率修正

❐ 空气折射率修正

$$\Delta L \approx L\left(\frac{\Delta K}{K} + \frac{\Delta\lambda_0}{\lambda} - \frac{\Delta n}{n}\right) - \Delta(L_m - L_c)$$

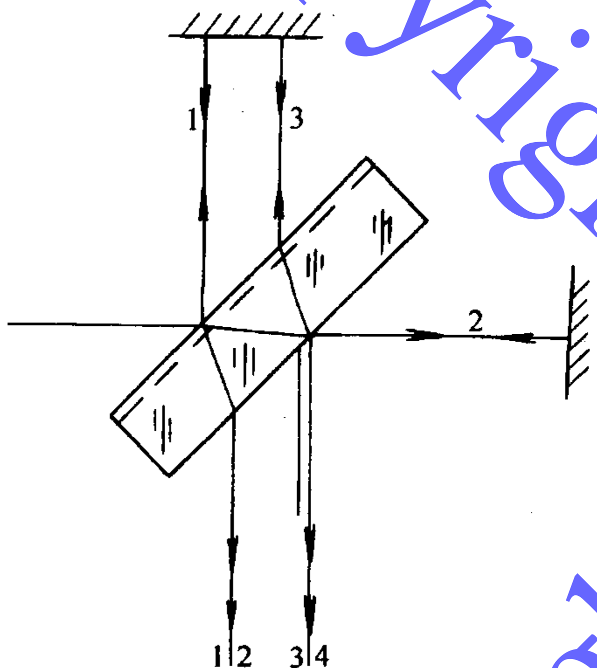
$$\frac{\Delta L}{L} = -\frac{\Delta n}{n}$$

$$\lambda = \frac{\lambda_0}{n}$$

❐ 空气折射率修正方法

- 利用折射率干涉仪直接测量空气折射率
- Ex: *Optoelectronic Measuring Machine for Line Scales*

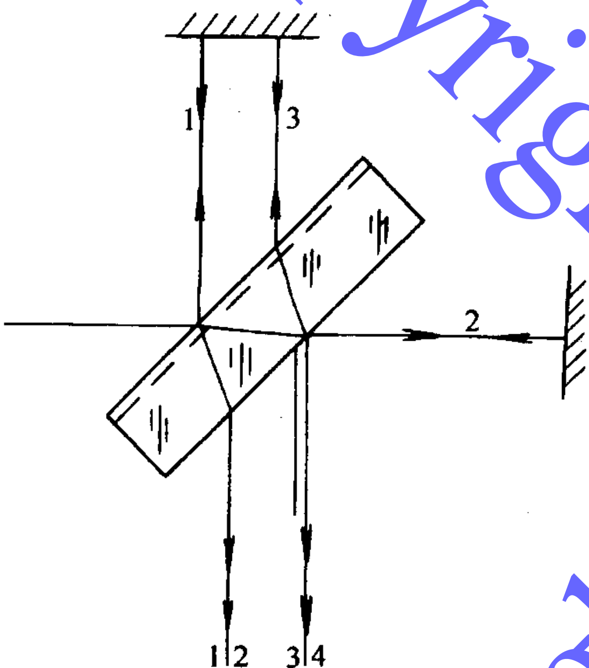
非期望光线的抑制和消除（1/3）



1，2—期望光线
3，4—非期望光线

- 非期望光线的抑制和消除
  - 设计时尽可能减少干涉系统中光学零件的数量，以减少产生非期望光线的机会
  - 采用平行平板作为分光器时常常产生非期望光线（左图）
  - 在光路中适当地方放置一个针孔光阑，针孔光阑一般设置在透镜的焦点或高斯光束的束腰位置上
  - **Next Slide…**

非期望光线的抑制和消除（2/3）

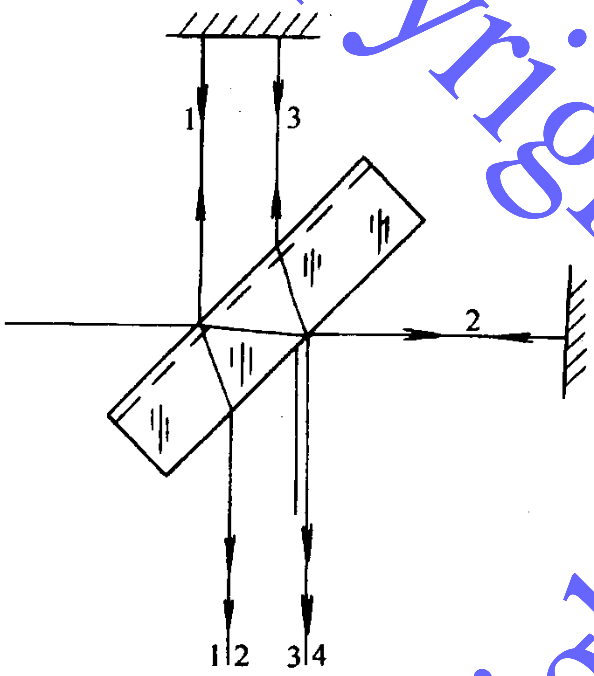


1，2—期望光线
3，4—非期望光线

❒ 非期望光线的抑制和消除

- 光学零件表面的尘埃会产生衍射花样，这种现象在激光束很细的地方尤为严重，必须做好光学元件的清洁工作
- 严格控制光学材料的气泡、麻点等质量指标
- 用偏振干涉方法来消除非期望光线是一种有效的方法

非期望光线的抑制和消除（3/3）



1，2—期望光线
3，4—非期望光线

- 采用平行平板作为分光器时常常产生非期望光线
  - 实际设计平行平板分光器时常常设计成具有很小楔角的光楔，如果适当增加厚度及楔角，并在出瞳处加一光阑，可以抑制非期望光线
  - 在光束口径较小的场合选用立方体棱镜形式的分光器可以消除非期望光线

正确选择光电器件（1/2）

- 正确选择光电器件
  - 选择光电器件时应考虑它的响应度，要注意尽量工作在光电器件的光电特性线性区，减小非线性误差
  - 还应考虑光电元件的光谱特性与光源的光谱匹配，即应有最大的光谱响应度
  - 在探测动态光信号时应注意光电元件的频响特性，要满足动态光信号的动态特性要求等

正确选择光电器件（2/2）

❒ 激光干涉系统中常用的光电元件

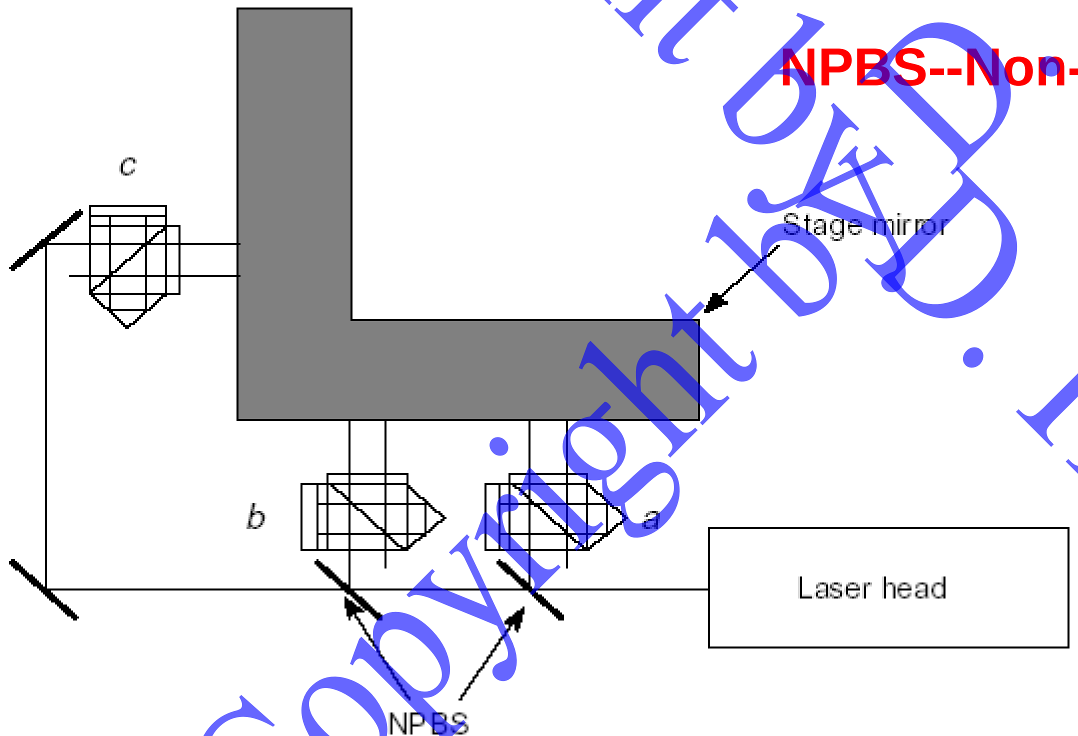
- **PIN管**
- 光电二极管
- 光电池
- 光电倍增管

等光强原则 (1/2)

❐ 等光强原则

- 在相干点的光强等，获得对比度好、清晰的干涉条纹
- 照度合适，使光电接收器工作在线性工作区

NPBS--Non-polarizing beamsplitters

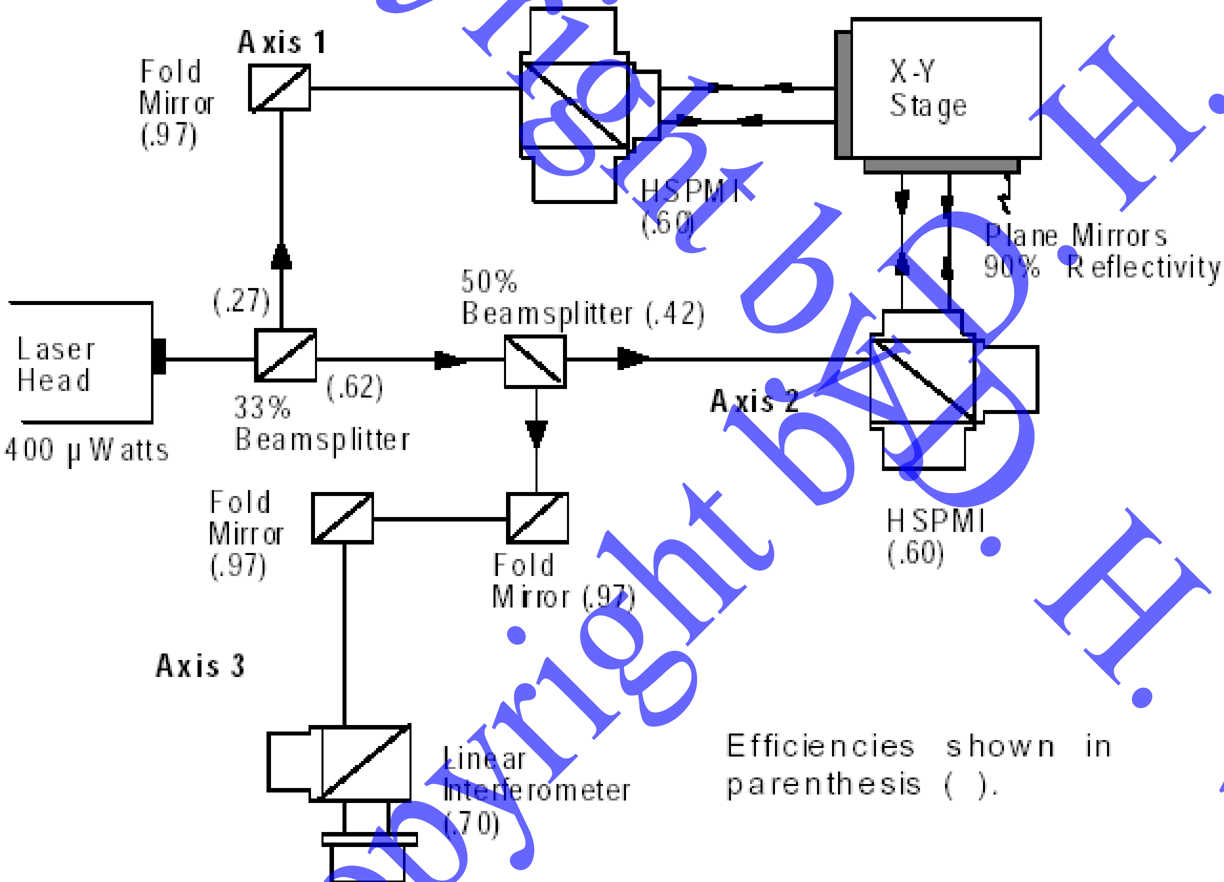


a--33%/67%

b--50%/50%

等光强原则 (2/2)

- 等光强原则



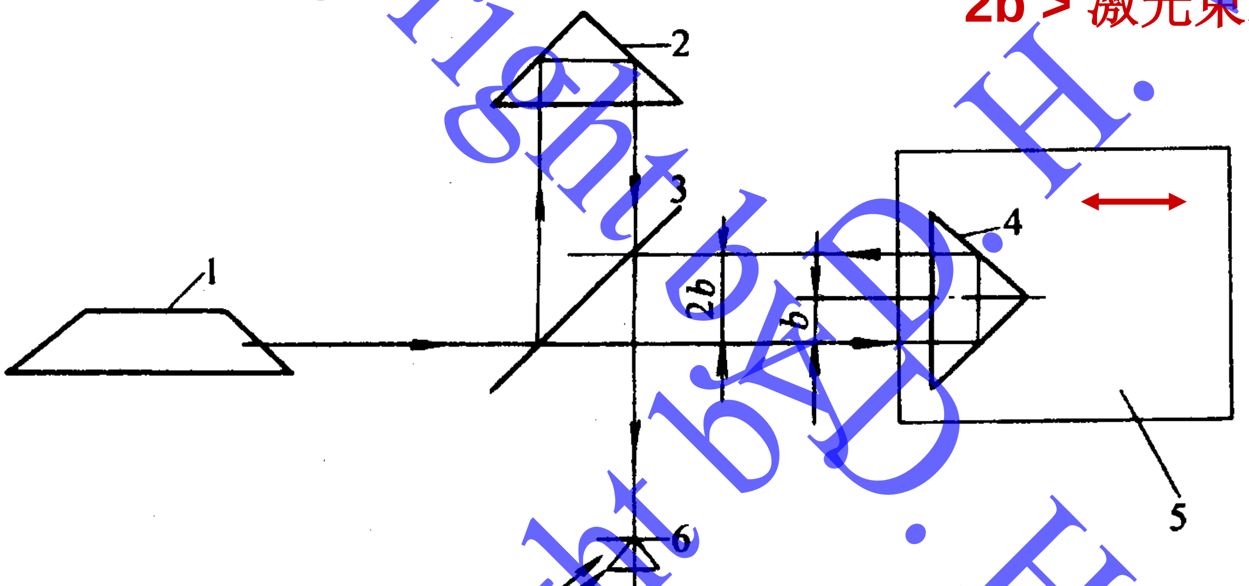
光学退耦

- 回綬
  - 当激光器发出的光束在空间传播一定路程后，有部分光束又重新返回到激光器谐振腔中的现象
  - “回綬”会破坏激光器的工作稳定性，使输出光强发生变化，并使激光输出频率不稳定
- 光学退耦
  - 为了消除回绶，使激光器工作稳定，就要防止光束返回激光器，此过程一般称为“光学退耦”
  - 方法
    - **Beam Splitting Method**
    - 半口径法
    - **Polarizing Method**

光学退耦方法

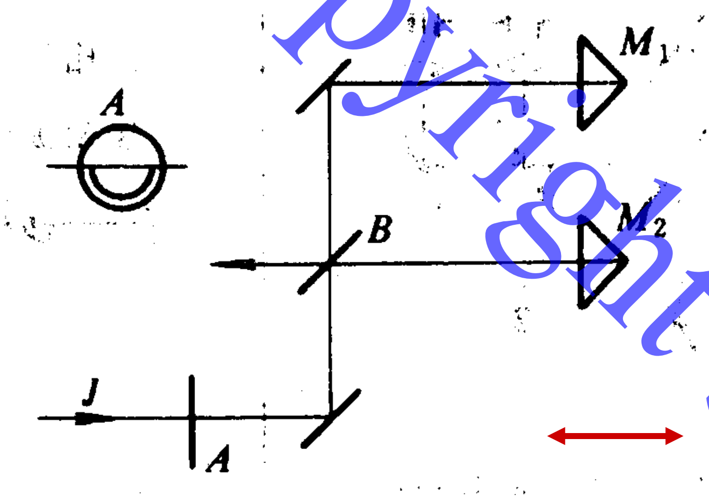
❒ **Beam Splitting Method**

2b > 激光束通光光阑口径



1 – Laser tuber
2, 4 – Corner Cuber prism or Right angle prism
3 – Beam splitter; 5 – Carriage; 6 – Detector

光学退耦方法



J – Laser beam

B – Beam splitter

M1, M2 – Coner cuber prism

- 半口径法
  - 光路上设置半圆孔光阑A，使准直使用的反射光被挡住，光束不会返回到激光器
- 方法简单，但损失了一半光能
- 应用实例：GGB型光电光波比长仪

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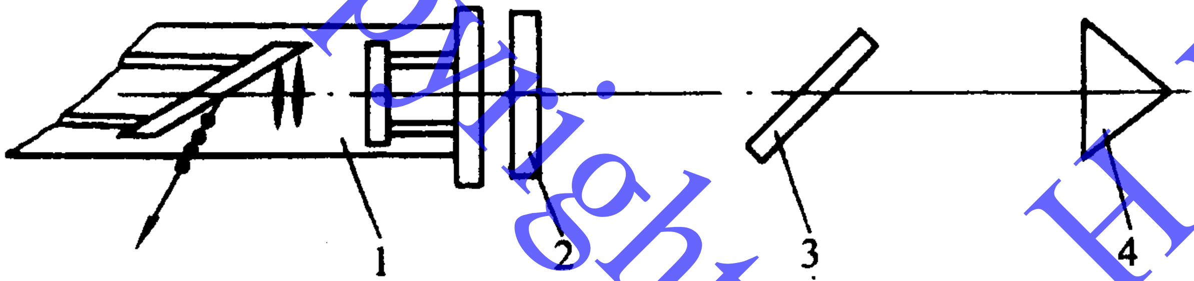
光学退耦方法



1 – Laser tube

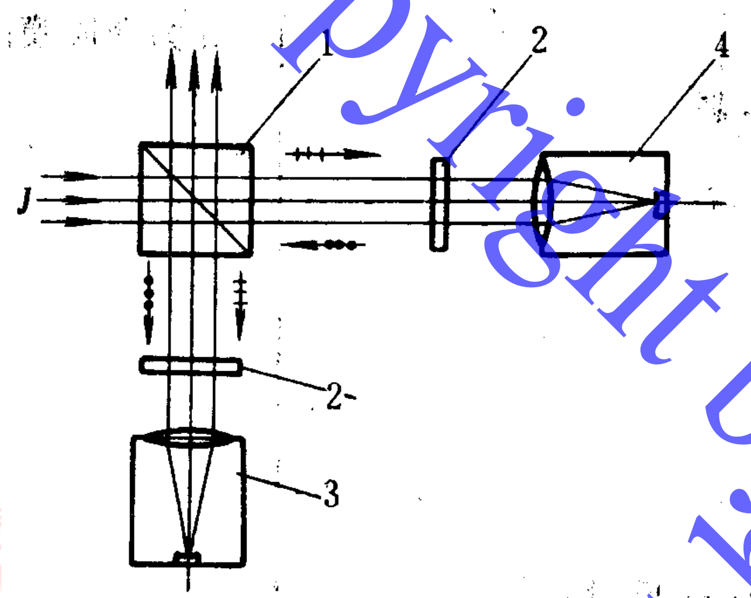
2 – Quarter waveplate

3 – Beam splitter

4 – Retroreflector

- **Polarizing Method:** 应用 ¼ 波片
  - 激光器（1）发出平行于屏幕的线偏振光
  - 如在激光器出口处放一块λ/4波片（2），则经过该波片后，线偏振光变为椭圆偏振光
  - 经过分光器（3）、反射器（4）返回的光束，重新通过λ/4波片，又变成线偏振光，不过其偏振方向较原来的转过90°，即变成垂直于屏幕的线偏振光，它被激光器的布儒斯特窗口反射，不能进入激光器谐振腔

光学退耦方法



1 – Polarization Beamsplitter

2 – Quarter waveplate

3, 4 – Retroreflector

J – Laser beam

❒ **Polarizing Method:** 应用偏振分光器

- 应用偏振分光器（**1**）及**λ/4**波片（**2**），使反射相干光不能再通过偏振分光器的分光面

Phase Shifting Technology

- ❒ 作用
- ❒ 方法

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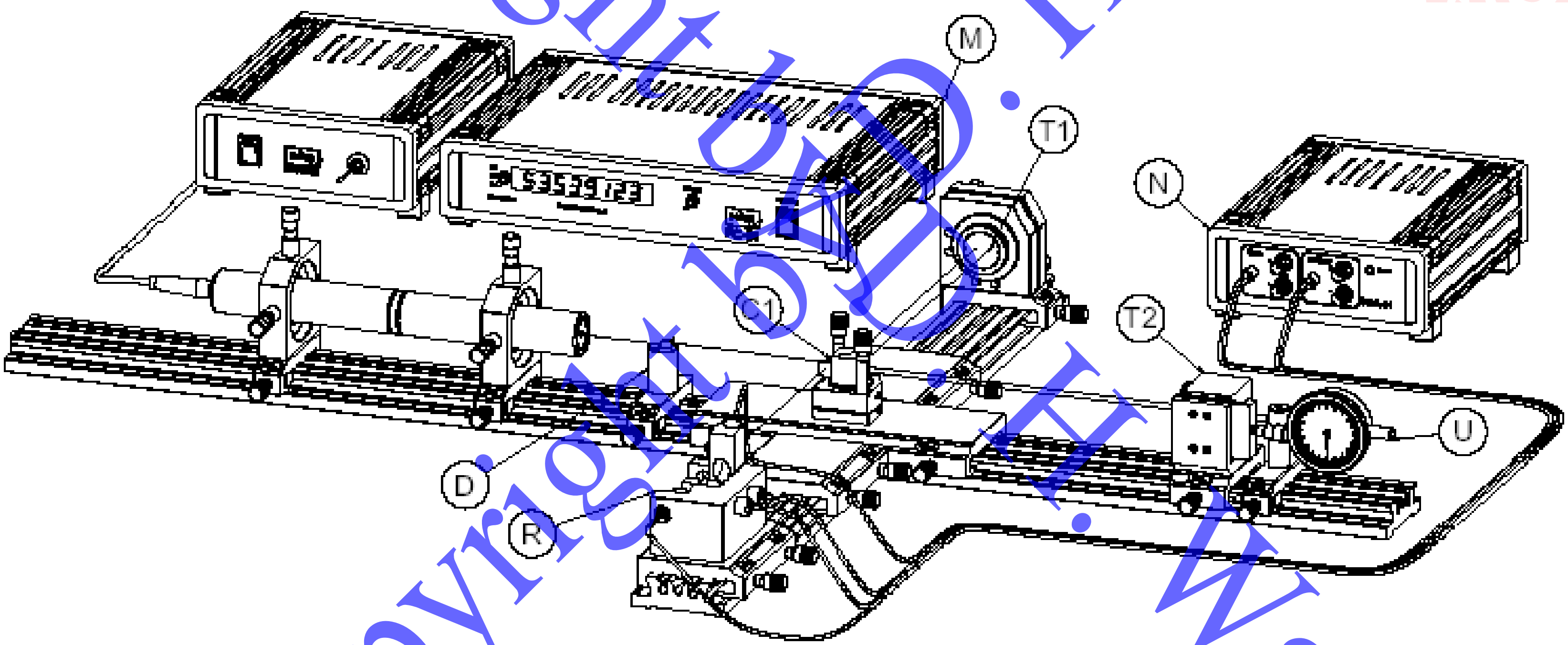
- **Objective**

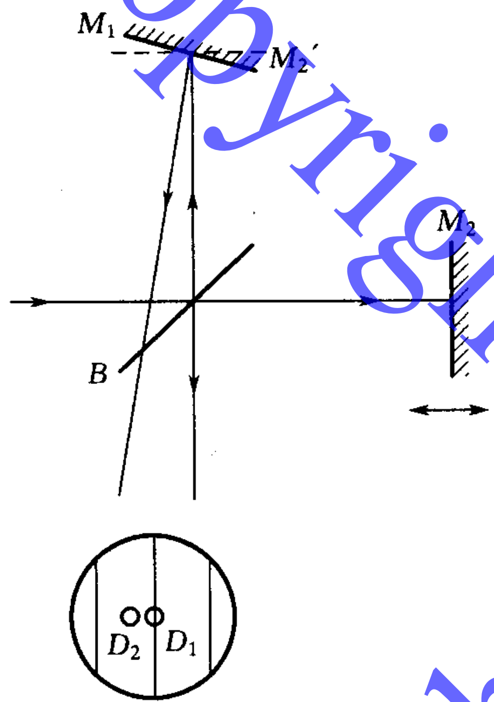
Set-up of technical Laser Interferometer showing the additional modules

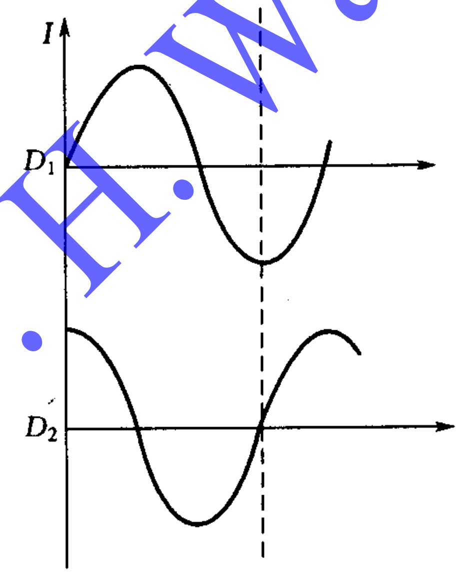


Phase Shifting Technology

- **Methods**
  - **Mechanical Method**
  - **Phase Shifting Plates**
  - **金属膜移相**
  - **Polarizing**

Phase Shifting Technology--Mechanical method

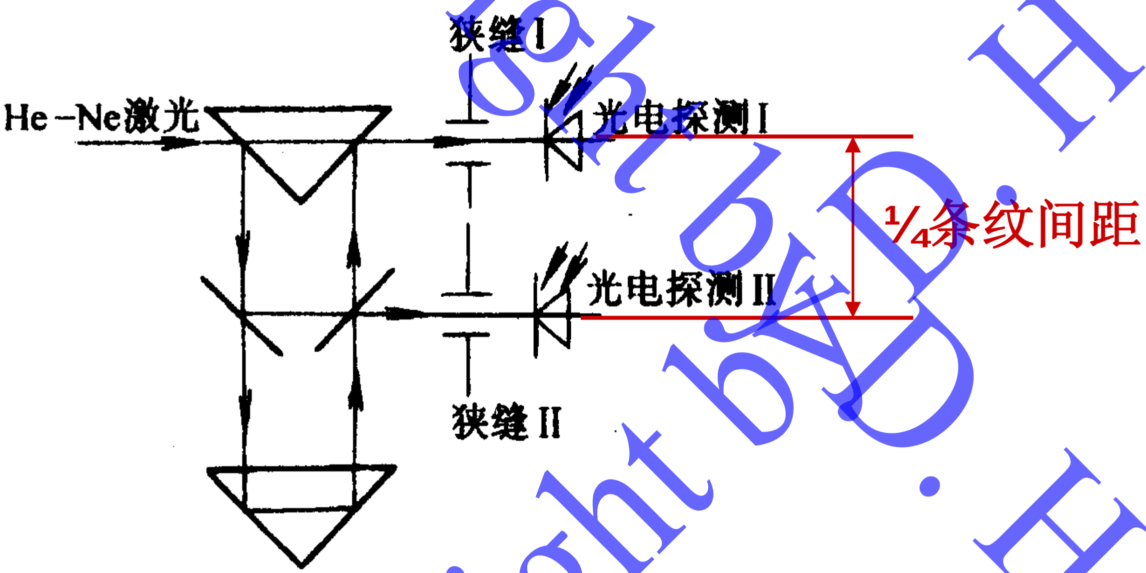




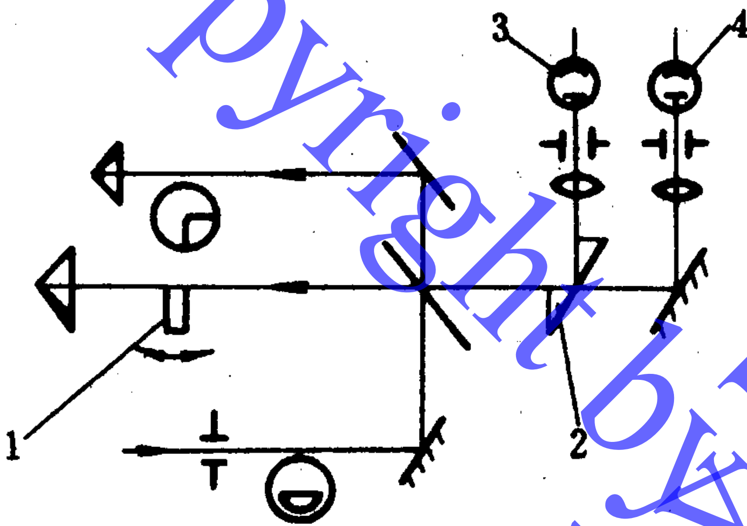
- 将干涉参考臂的M1倾斜一定角度，再在干涉场放置**D1, D2**，使**D1, D2**的间距为条纹间距的**1/4**

Phase Shifting Technology--Mechanical method

❒ 狭缝移像法



Phase Shifting Technology--移相板



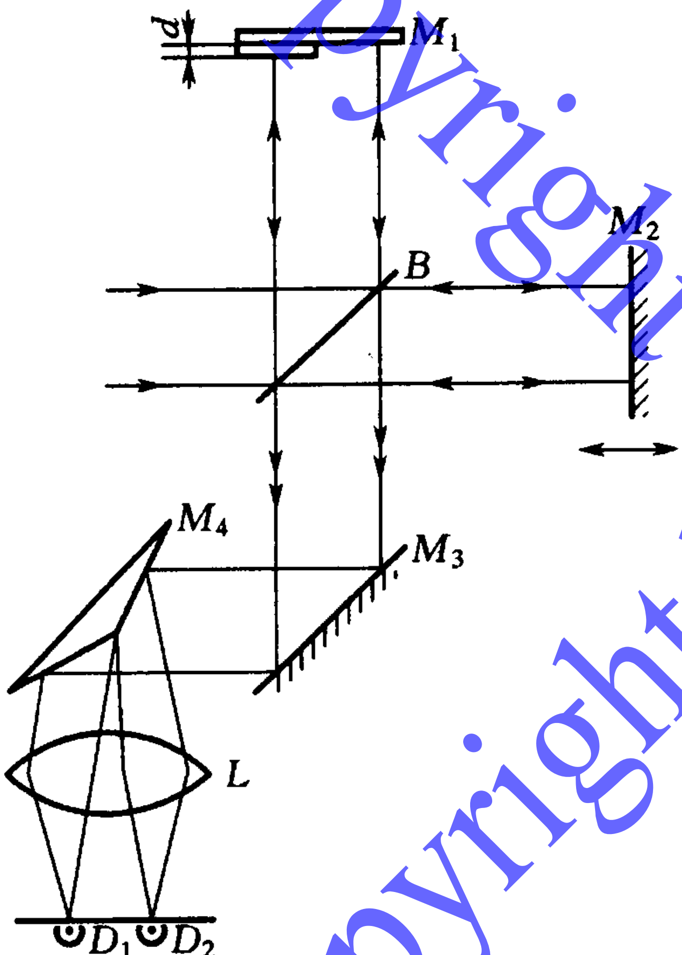
$$d = \frac{\left(k + \frac{1}{4}\right)\lambda}{n}$$

n--移相板折射率

k--正整数

- 在测量或参考光路中第四象限插入一块移相板，使**1**，**3**与**2**，**4**象限的干涉光相位差π/2

Phase Shifting Technology--阶梯板

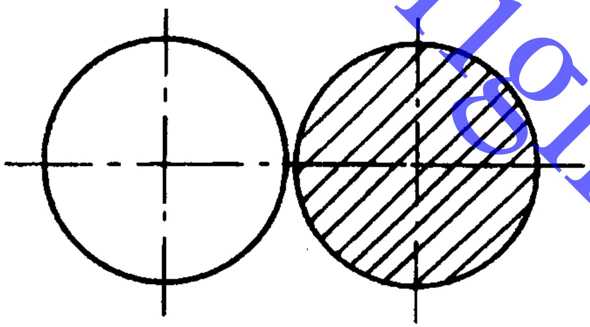


- 在反射器M1的一半蒸镀一层厚度为 *d* 的透明介质，使入射光一半获得λ /4的光程差

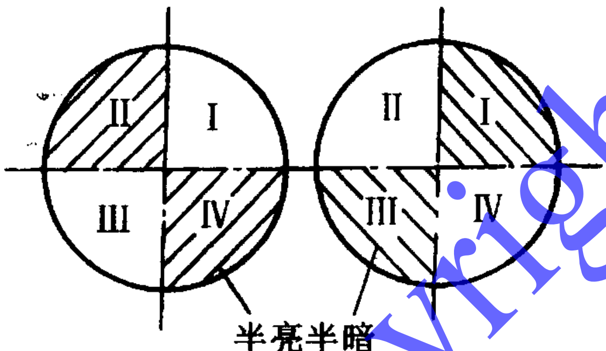
$$d=\frac{\lambda}{8(n-1)}$$

Phase Shifting Technology--翼形板

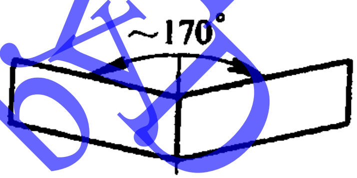
❒ 翼形板：由两块厚度相同、材料相同的玻璃平板胶合而成

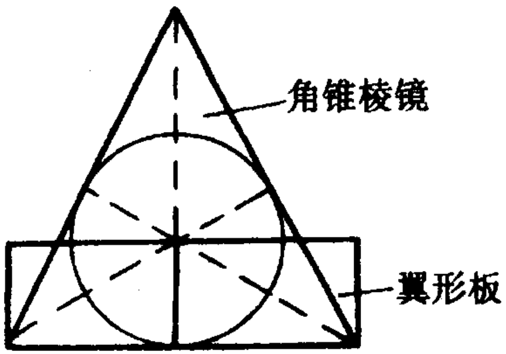


无翼形板时的干涉场

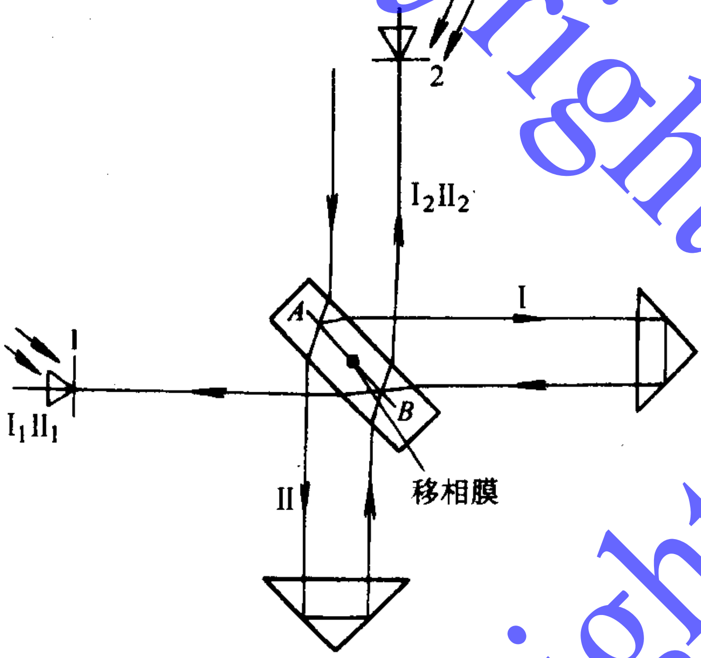


有翼形板时的干涉场





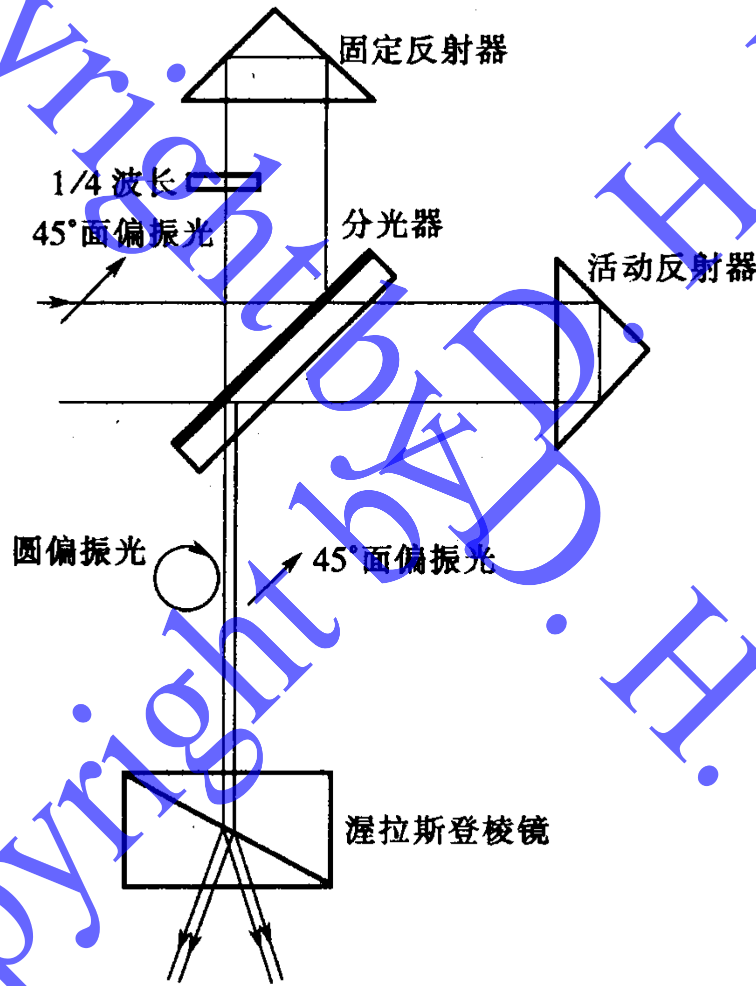
Phase Shifting Technology--移相膜法



- 在干涉仪的分光镜上镀以分光移相膜，该移相分光膜不仅使入射光线分为两束，而且能使光线在该膜层上每反射一次就产生π／4的相位跳变
  - 到达光电探测器1的两相干光束在A、B处各反射一次，两者没有相对附加的相位移动
  - 到达光电探测器2的两相干光束I2反射两次，II2透射两次，相位跳变π／2

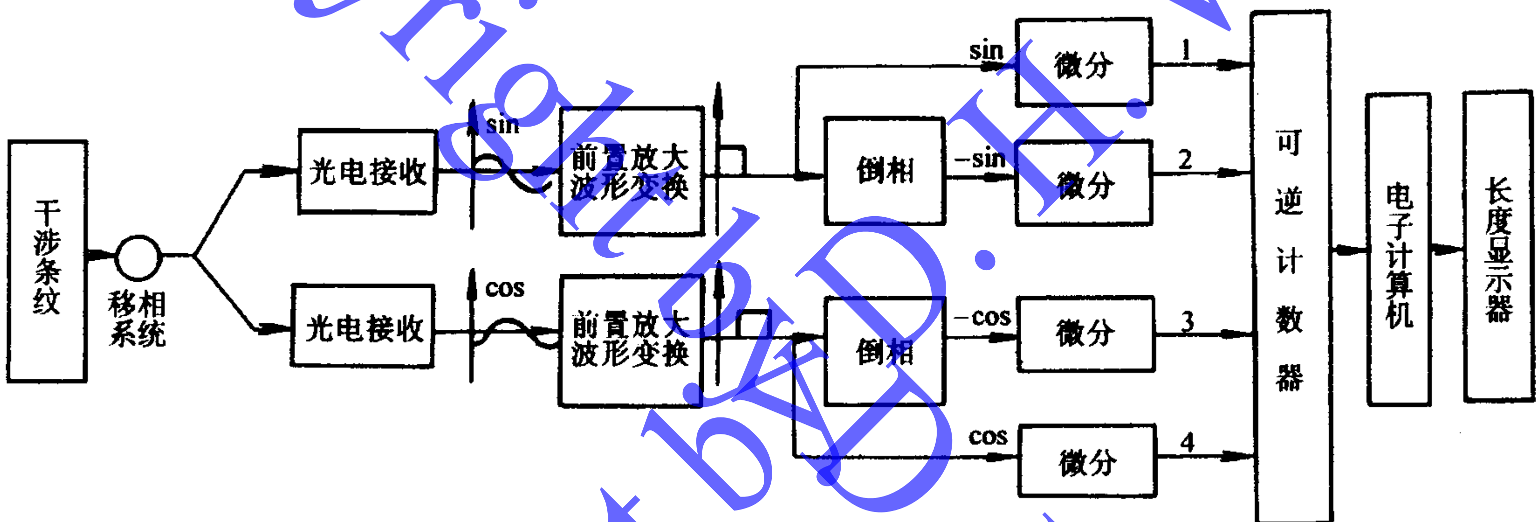
Phase Shifting Technology--偏振移相法

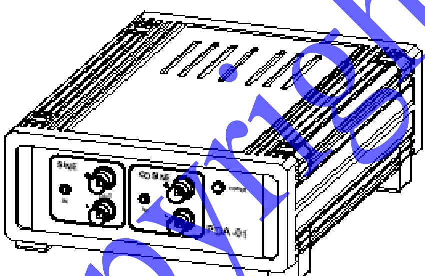
❒ 原理

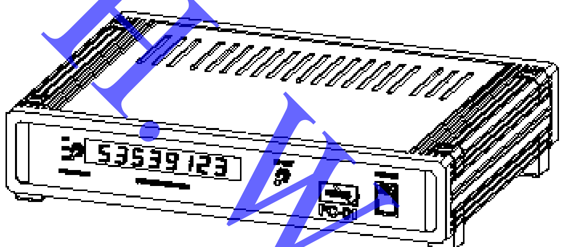


Electronic Equivalent of the Fringe Counting

❒ 原理



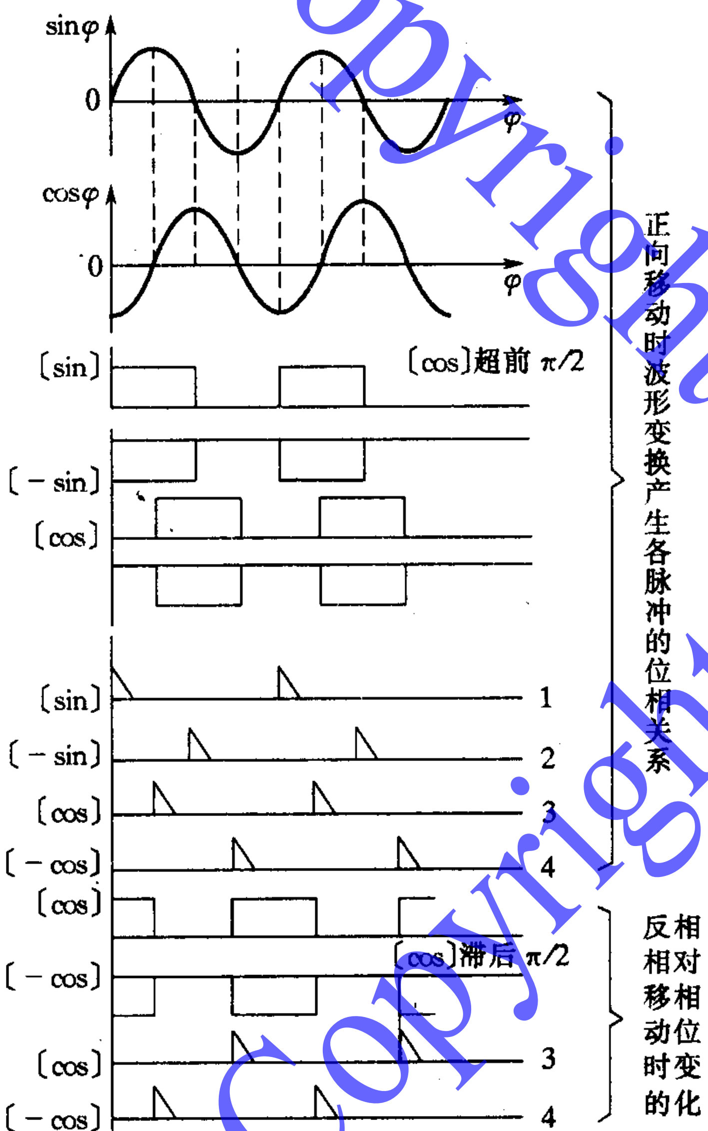




Preamplifier

Up and down counter

Electronic Equivalent of the Fringe Counting

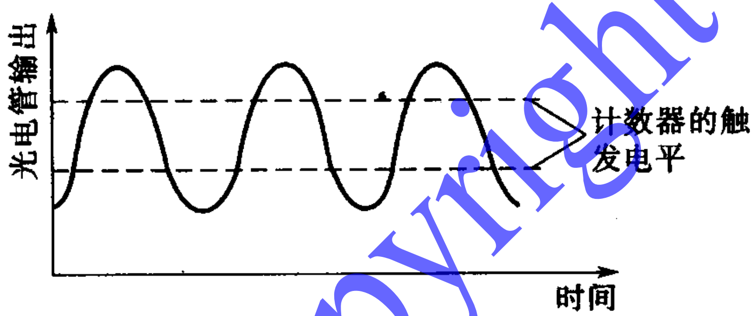


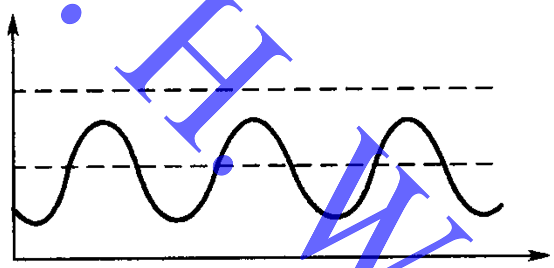
正向 1, 2, 3, 4

反向 1, 4, 3, 2

单频（直流）激光干涉仪: 特点

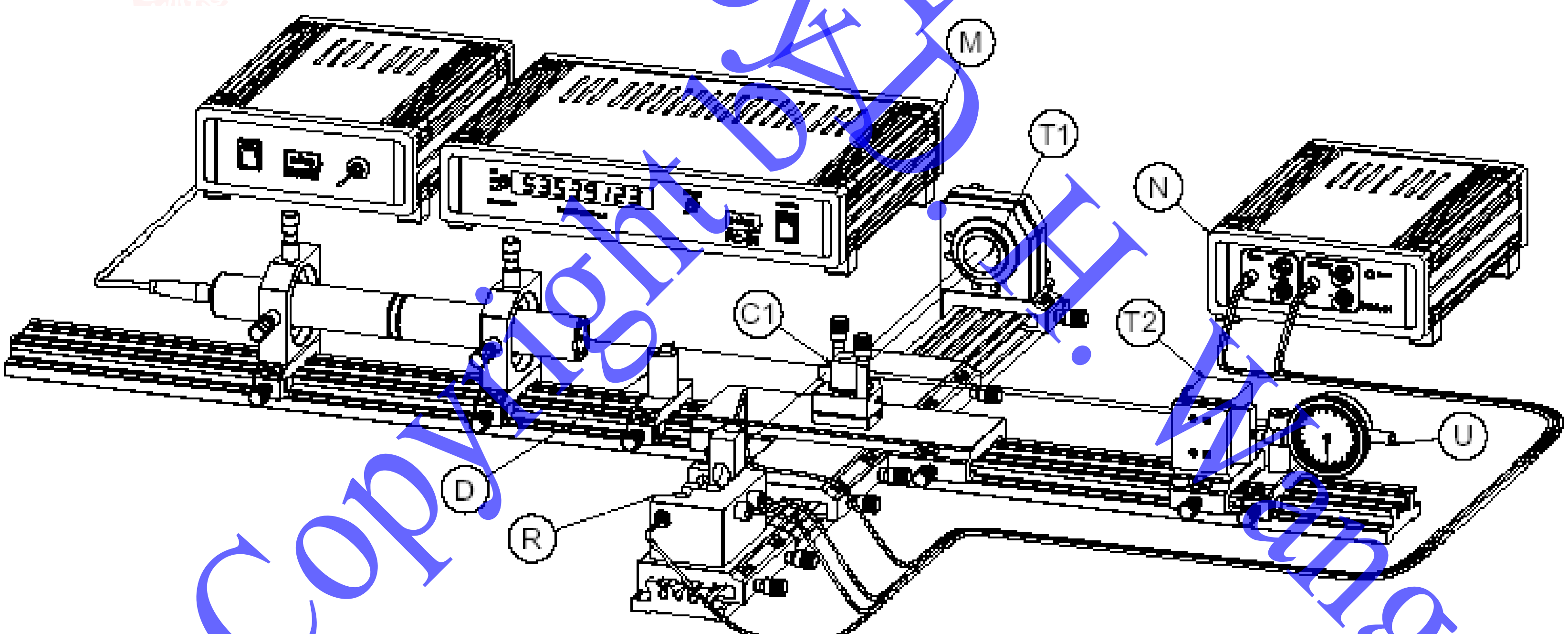
- 前置放大器只能用直流放大器
- 对测量环境要求较高—恒温、防振
  - 干涉条纹光强的变化要以计数器平均触发电平为中心对等分布
  - 如果光强变化引起干涉信号强度落于触发电平之下，必须重新调整触发电平





Question?

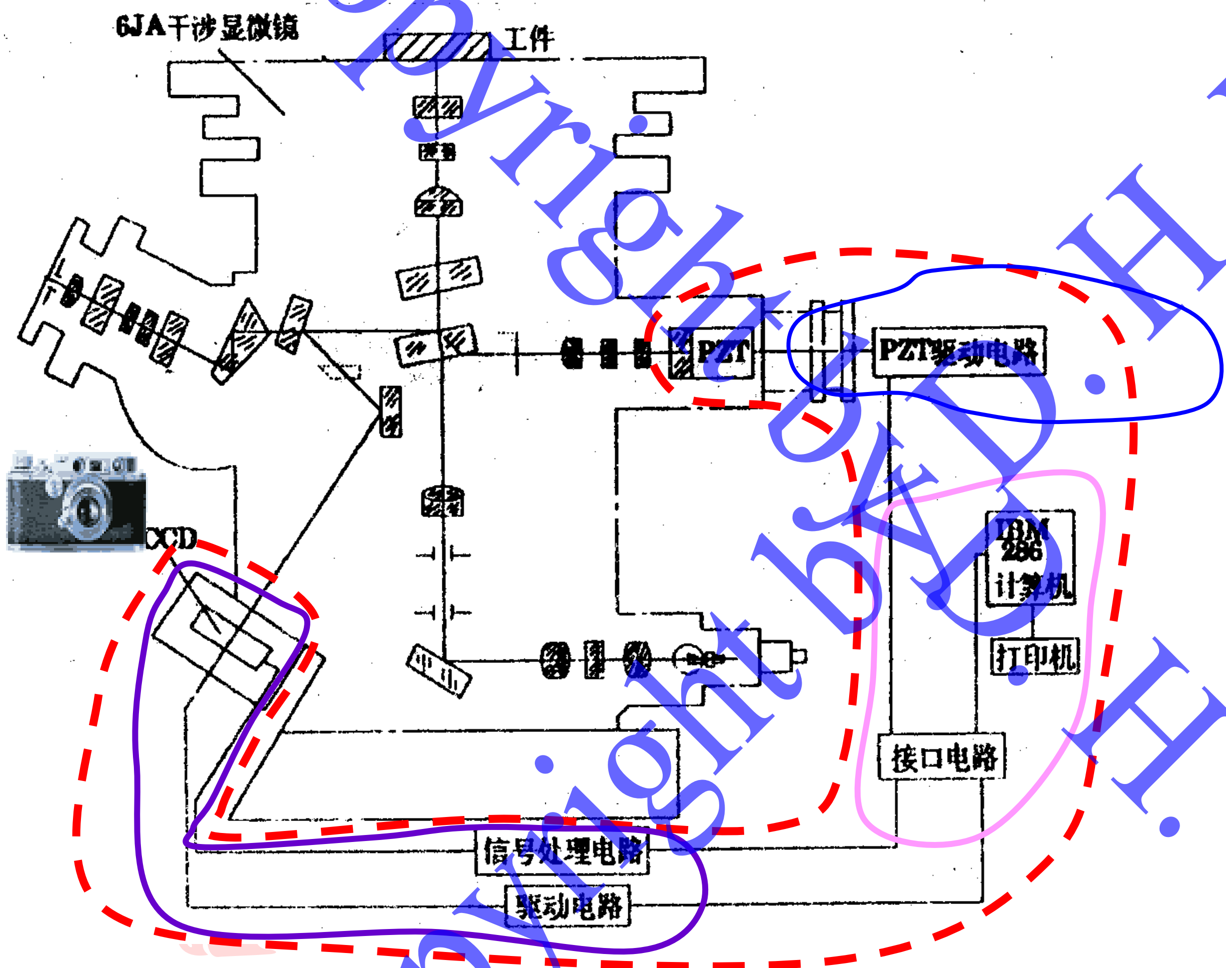
- ❒ 前置放大器能否用交流放大器?
  - 调频型交流（AC）干涉仪（双频激光干涉仪、外差干涉仪）
  - 调相型交流干涉仪（位相扫描干涉仪）



交流激光干涉仪--类型

- 调频型交流（AC）干涉仪（双频激光干涉仪、外差干涉仪）
  - 载波由双频器件产生，如双频激光器、声光调制器、电光调制器
- 调相型交流干涉仪（位相扫描干涉仪）
  - 在干涉仪参考光路的参考镜上引入一定频率的附加振动（附加的位相变化），以调制测量光束的位相

Trends--Update (2/2) 调相型交流干涉仪



自动扫描读数外差干涉显微镜

6JA干涉显微镜

参考相位调制系统

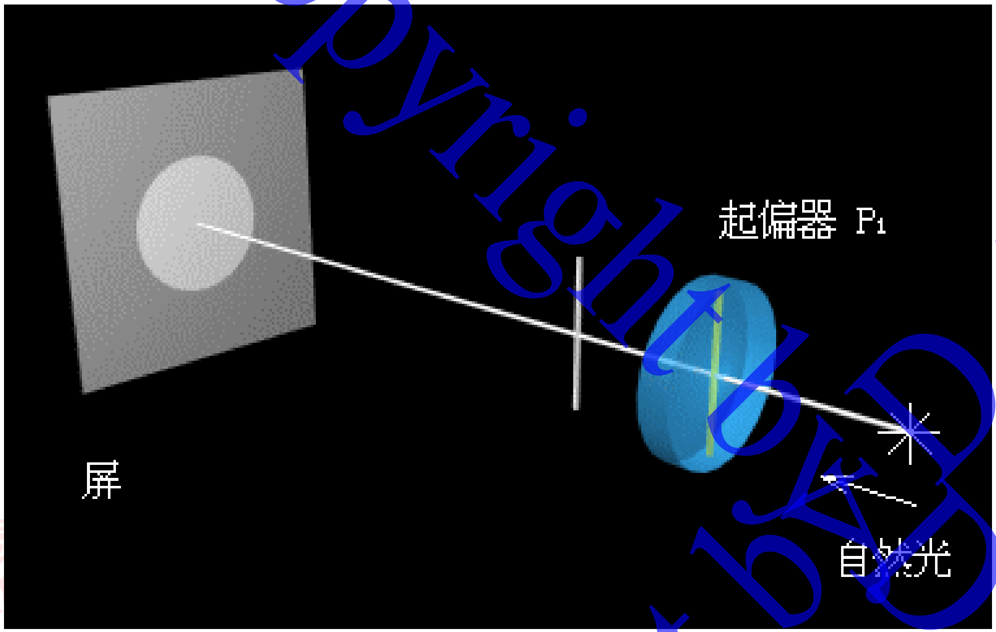
CCD扫描采样系统

计算机处理及控制系统

双频激光干涉仪: 预备知识

- ❒ 马吕斯定律
- ❒ 双频激光器
- ❒ 多普勒（Doppler）效应

马吕斯定律

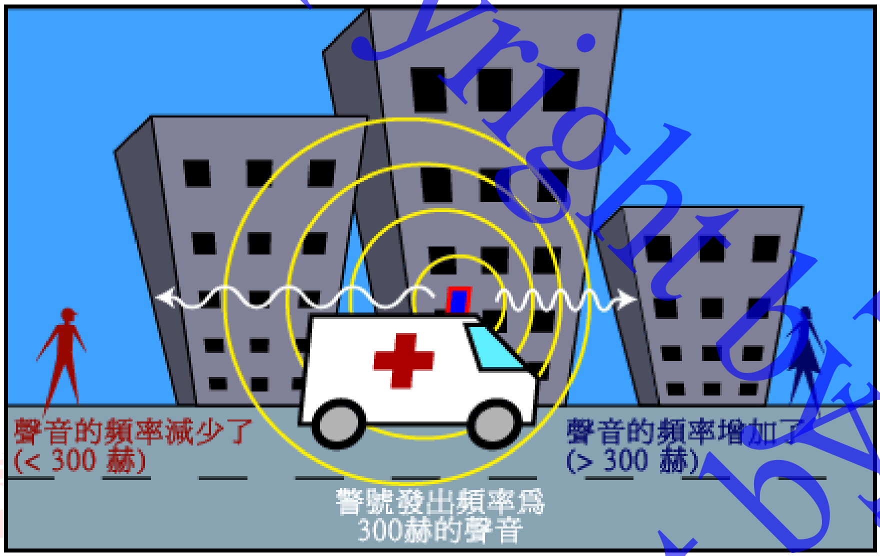


- 一束光强为 I_0 的线偏振光，透过检偏器以后，透射光的光强为

$$I = I_0 \cos^2 \alpha$$

式中 α 是线偏振光的光振动方向与检偏器透振方向间的夹角

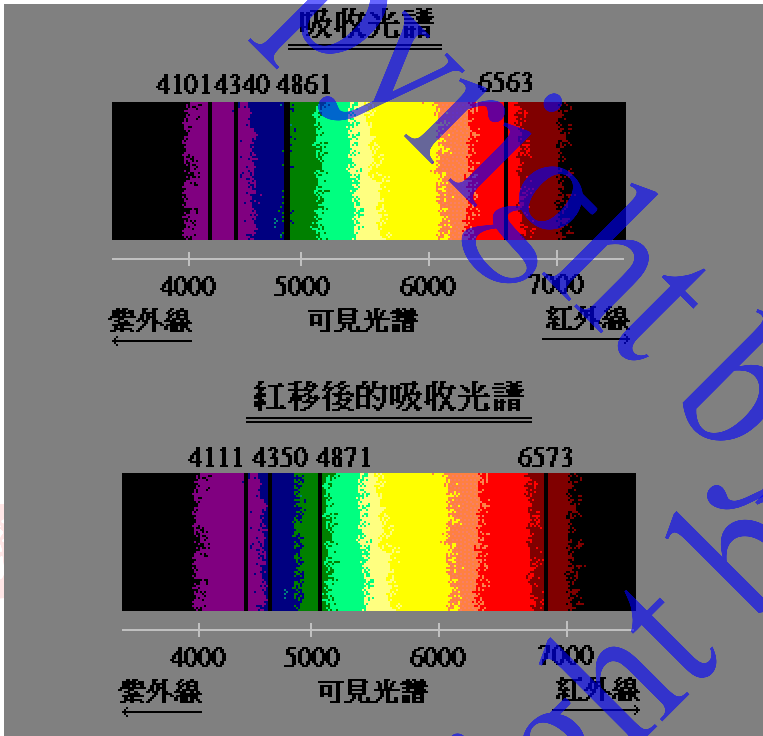
多普勒效应 （Doppler Shift, Doppler-Fizeau Shift）



http://hometown.aol.com/lklstars2/4c.htm

- 當一架消防車迎面而來時,它的嗚嗚聲會因多谱勒效應,波長縮短而變成高音(不是大聲!大細聲和波長沒有關係!!!只和振幅有關係!)
- 而當它飛馳而去時，它的嗚嗚聲會因多普勒效應,波長增長而變成低音

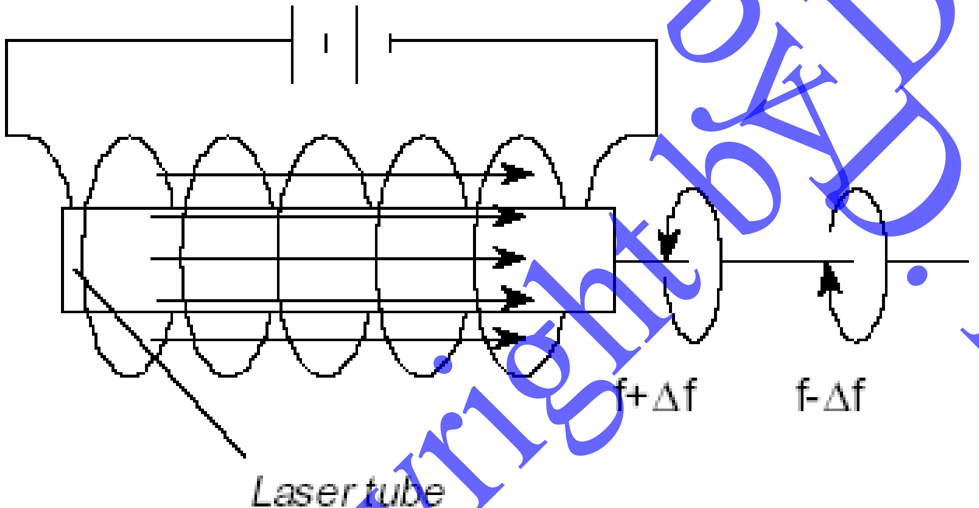
多普勒效应 (Doppler Shift, Doppler-Fizeau Shift)



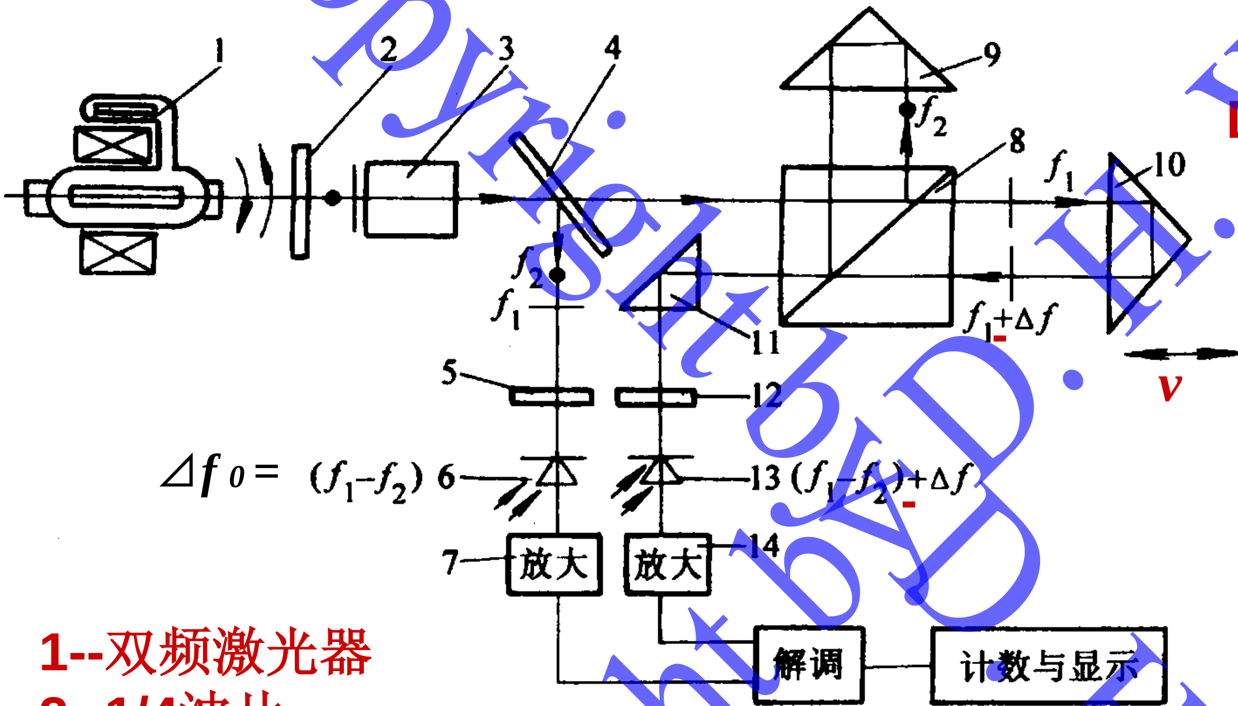
- 當一個發光的物體靠近我們時,它的波長會縮短,可見光譜上所有的吸收線會移向藍端，此現象叫藍移 **(Blue Shift)**
- 當一個發光的物體遠離我們時，它的波長會增長，可見光譜上所有的吸收線會移向紅端，此現象叫紅移**(Red Shift).**

双频激光器

- 在小功率全内腔单频He-Ne 激光器上加约0.03 T的轴向磁场，由于塞曼效应和频率牵引效应，激光器发出一束有两个不同频率的右旋和左旋圆偏振光，频率差Δf约为1.5 MHz



Heterodyne Type Interferometer



Doppler Shift $\Delta f = \dfrac{2v}{\lambda}$

- 测量镜静止，$v=0$，干涉场条纹变化频率由Δf_0决定；
- 测量镜移动，干涉场条纹变化频率由 $\Delta f_0+\Delta f$ 决定。

1--双频激光器
2--1/4波片
3--扩束器
4--分光镜
5, 12--透光轴与纸面成45° 的检偏器
6, 13--光电接收器
8--偏振分光棱镜

$$N = \int_0^t \Delta f dt = \int_0^t \frac{2v}{\lambda} dt = \frac{2}{\lambda}\int_0^t v dt$$

$$L = N\frac{\lambda}{2}$$

Heterodyne Type Interferometer--基本要求

- 对于塞曼双频激光干涉仪，激光器双频频差为$f1$-$f2$=1.5 MHz，为使Δf不失真，一般应保证$f1 - f2 \geq 3\Delta f$
- 允许测量速度约为150 mm/s，对应的Doppler频移Δf为±0.5 MHz，处理电路的工作频率可以设定在1.0~2.0 MHz之间，可以滤掉小于1.0 MHz的全部噪声

Heterodyne Type Interferometer--基本特点

- ❐ 双频激光干涉仪中双频起调频作用，被测信号 Δf 被载波频率 $f1-f2=\Delta f\ 0$ 所调制
- ❐ 被测对象对于干涉仪静止时，仍然保留一个 $\Delta f0$ =1.5 MHz的交流信号
- ❐ 前置放大器可以使用交流放大器
- ❐ 单频激光干涉仪光强变化50%就不能继续工作，双频激光干涉仪光强损失达95%时，仍能继续工作

德国Polytec公司的激光多普勒测振仪

Homodyne v.s. Heterodyne

- Homodyne v.s. Heterodyne
- Homodyne (Single frequency or DC)
  - Intensity detection
- Heterodyne (Two frequency or AC)
  - Phase detection
- Detection bandwidth
- Error detection schemes

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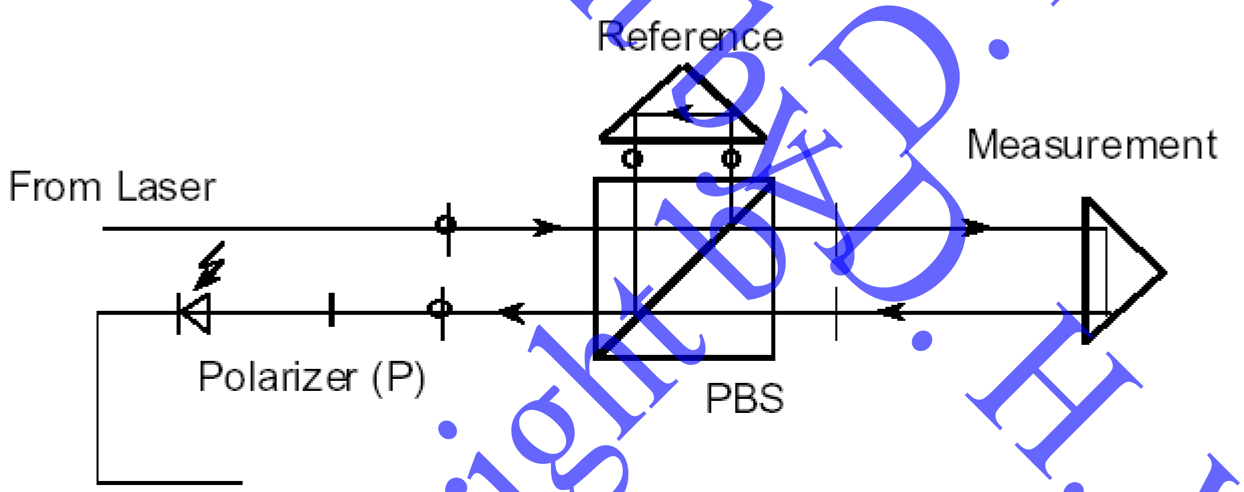
URL: http://www.pilab.coe.cqu.edu.cn/

Homodyne--Intensity Detection

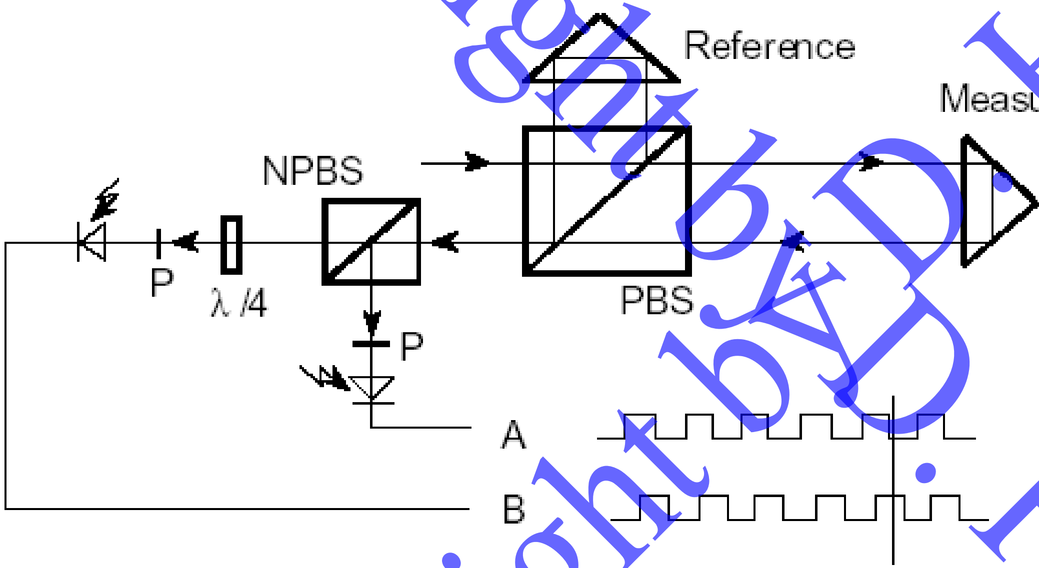
- Single detector
- Count the light blinks (fringes)
- Fringes move only when OPD changes



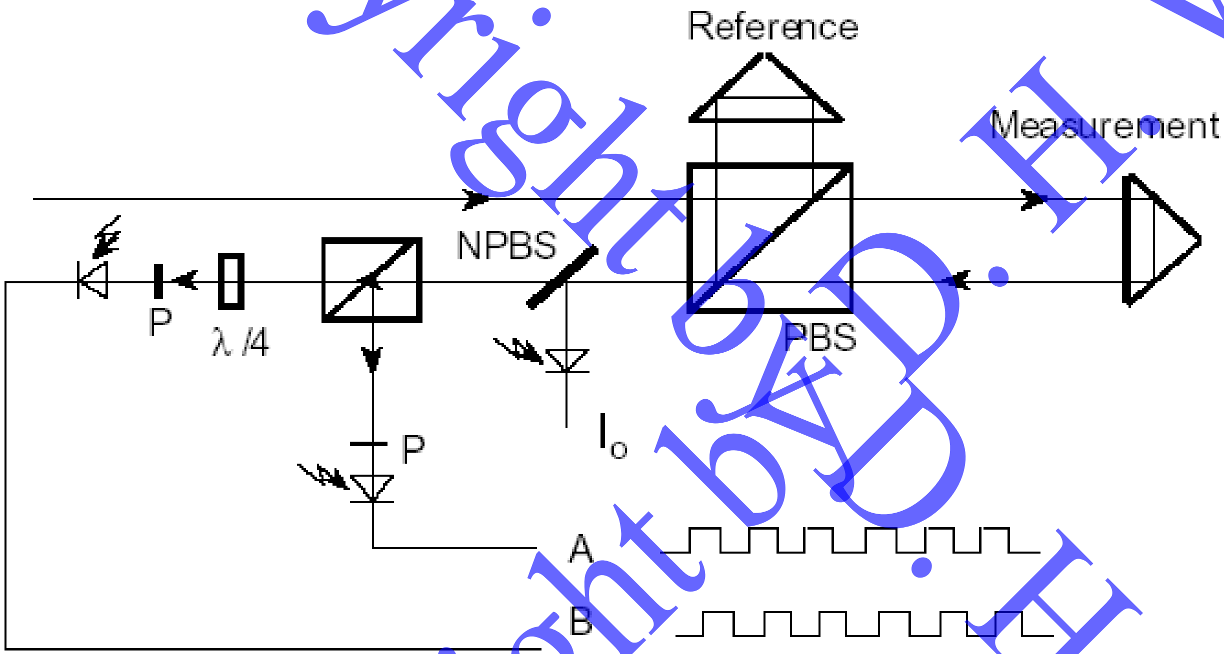
Homodyne = single frequency = DC

Homodyne--Quadrature Detection

❒ **Relationship of A & B edges yields direction sense**

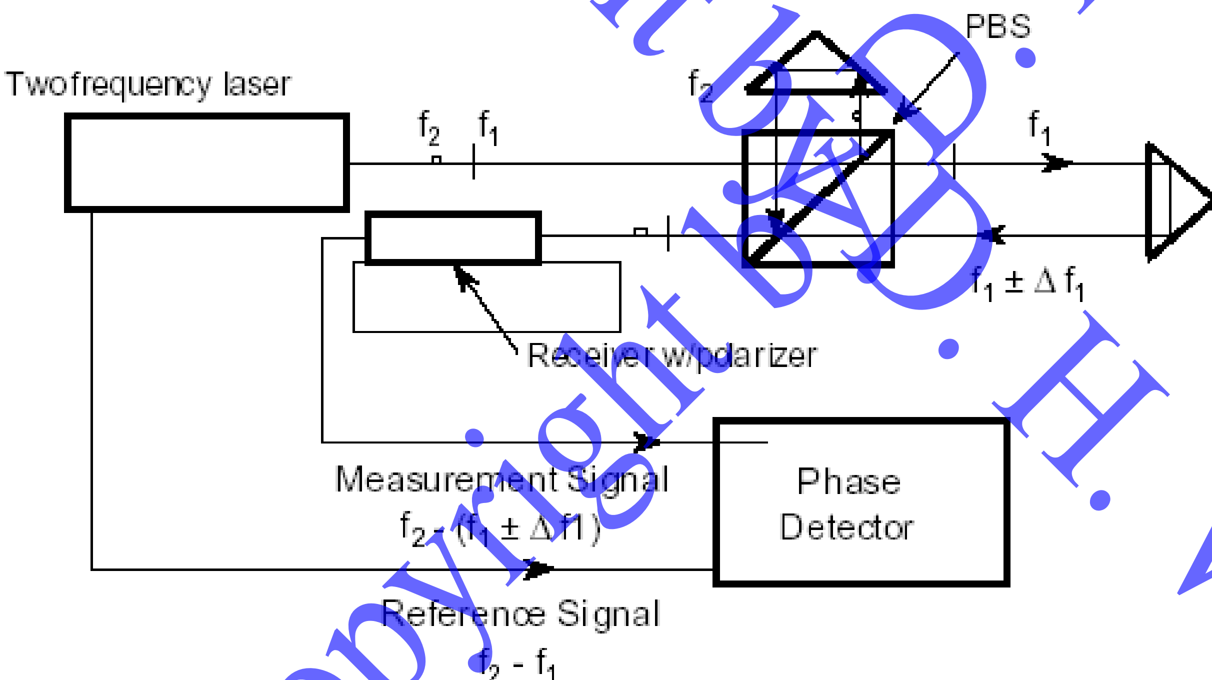


Homodyne--Power Normalization



Heterodyne--Phase Detection

- High signal to noise ratio
- Direction sensing
- Measures phase not intensity

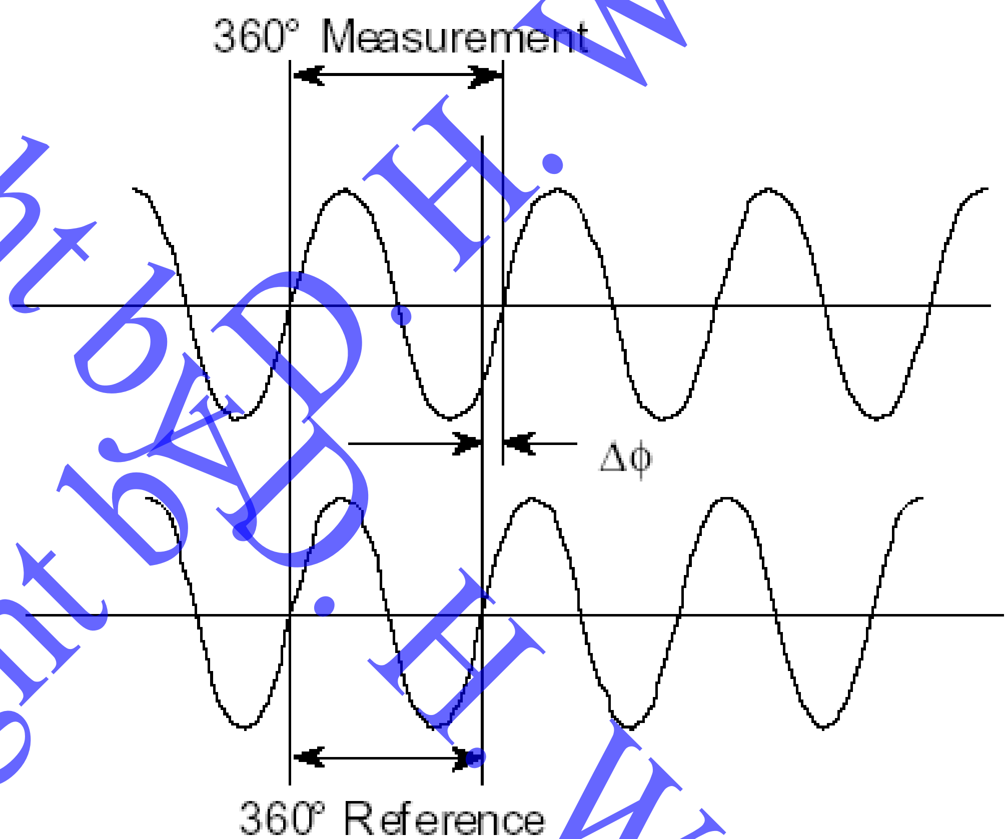


Heterodyne = two frequency = AC

Heterodyne--Phase Detection

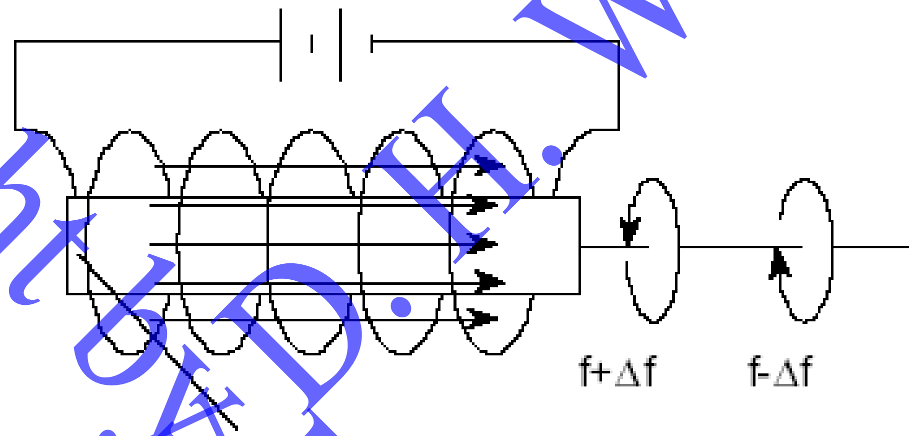
Measurement
(Doppler shifted)

Reference
(fixed split frequency)

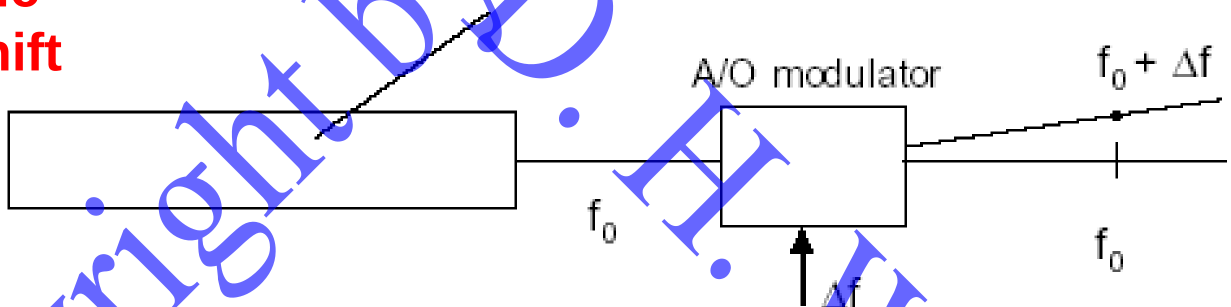


Heterodyne--Two Frequency Laser

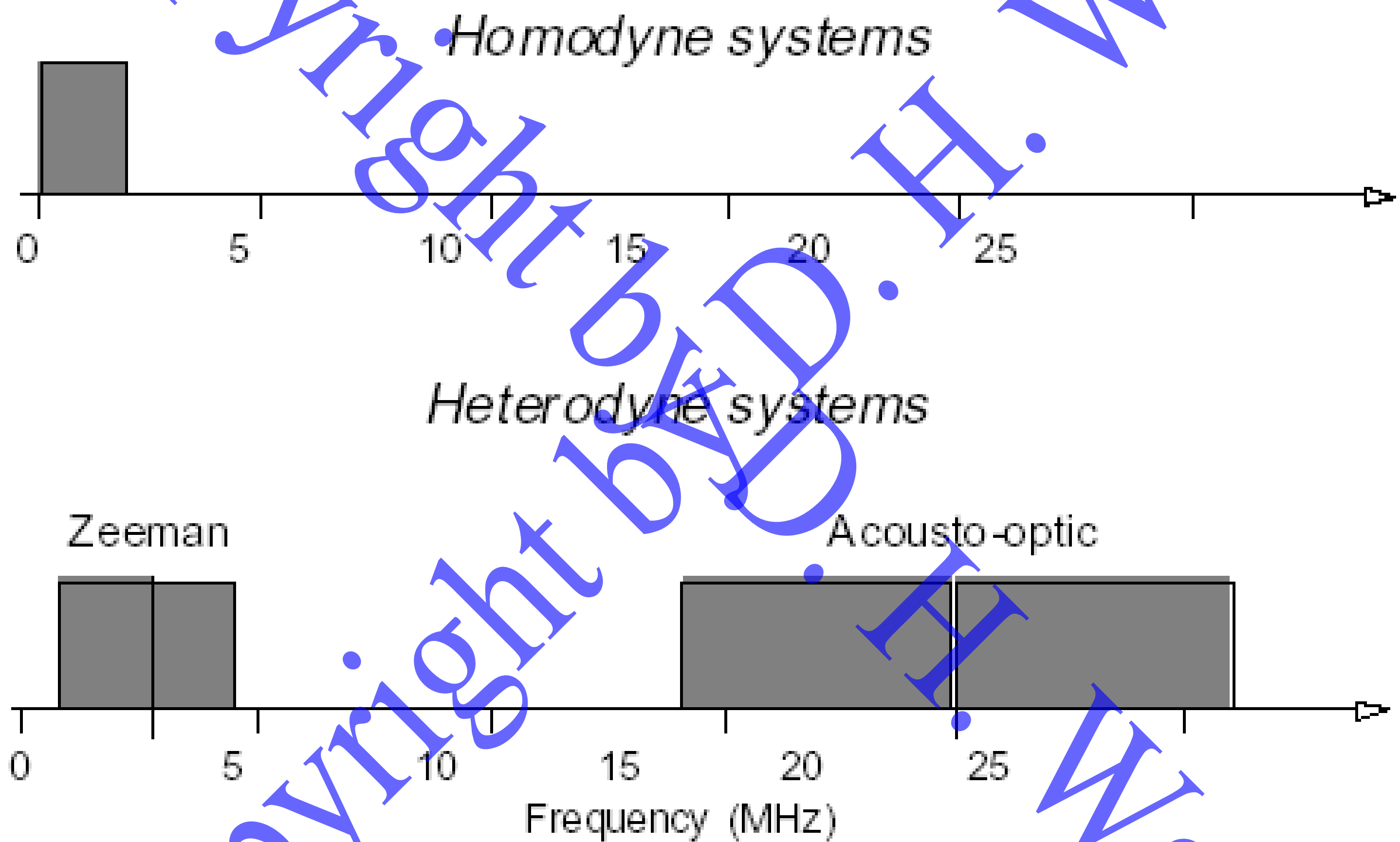
Zeeman split laser



Acousto-optic frequency shift



Homodyne v.s. Heterodyne--Detection Bandwidth



Homodyne v.s. Heterodyne

	Homodyne	Heterodyne
Always measuring	no	yes
Direction sensing	quadrature	always
Quadrature output	available	available
Error detection	ambiguous	unambiguous
Intensity sensitivity	yes	no
Sensitive to ambient light	yes	no
Bandwidth of electronics	$0 - 2v/\lambda$	$f_1-f_2 \pm 2v/\lambda$
SNR at detector	6-12+ bits	2-3 bits
Multi-axis	limited	yes
Complexity of Receiver(s)	complex	simple
Easy to Align	no	yes

The End

Thank you very much for your attention!

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