

基于MEMS微镜的光谱仪技术

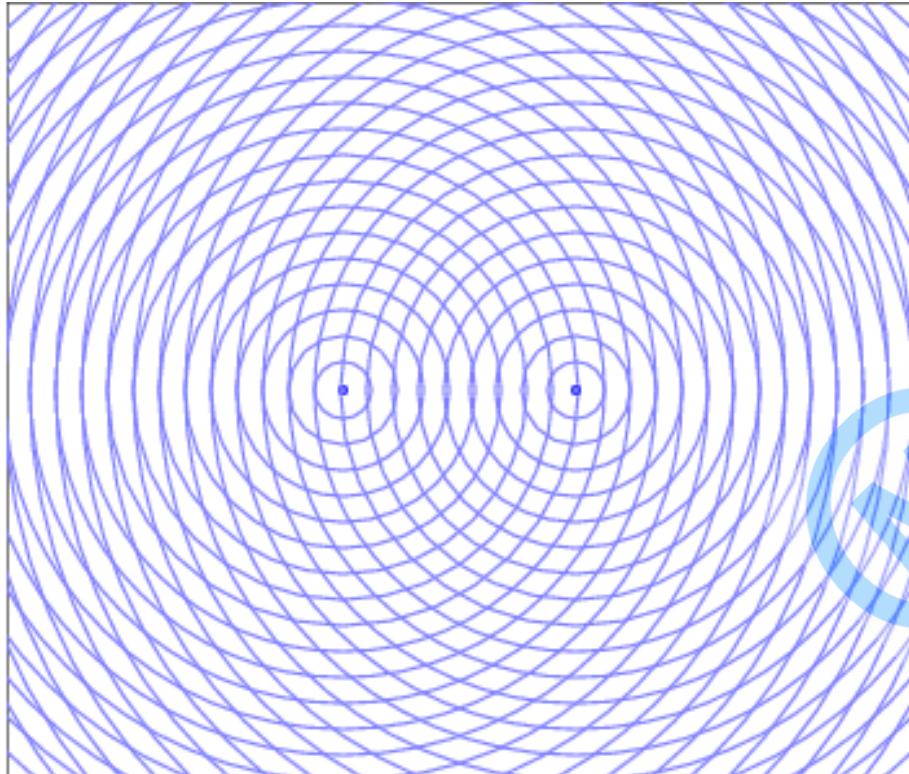


麦姆斯咨询
MEMS Consulting

提纲

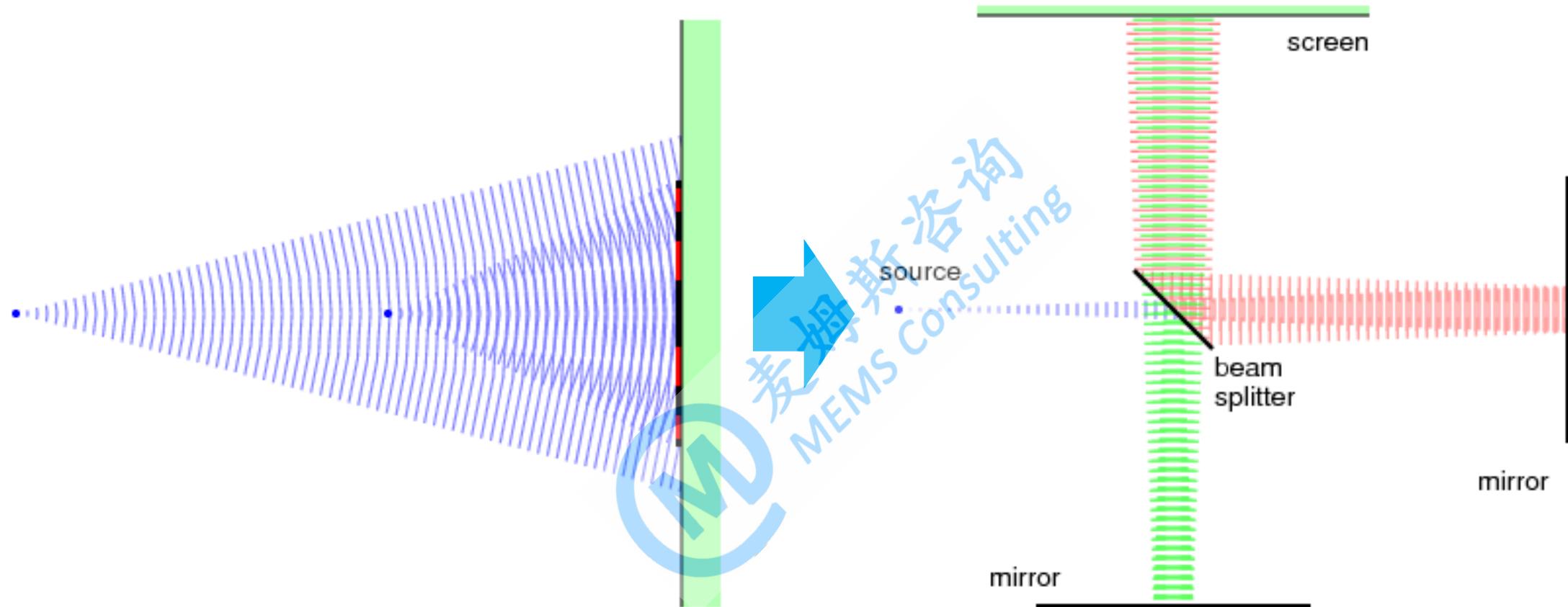
- 1、迈克尔逊干涉仪
- 2、傅里叶变换光谱仪
- 3、为什么MEMS+傅里叶变换光谱仪
- 4、MEMS动镜分类、原理、设计与制造

迈克尔逊干涉仪



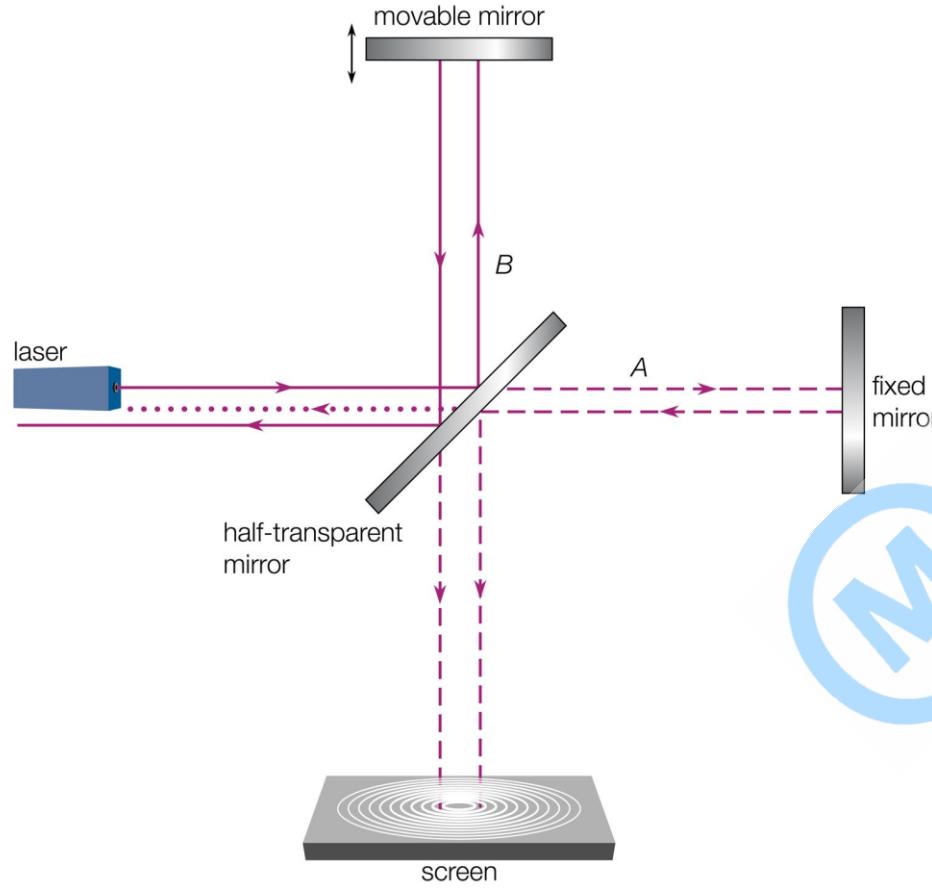
两列相干的波，会因干涉产生相长或者相消

迈克尔逊干涉仪



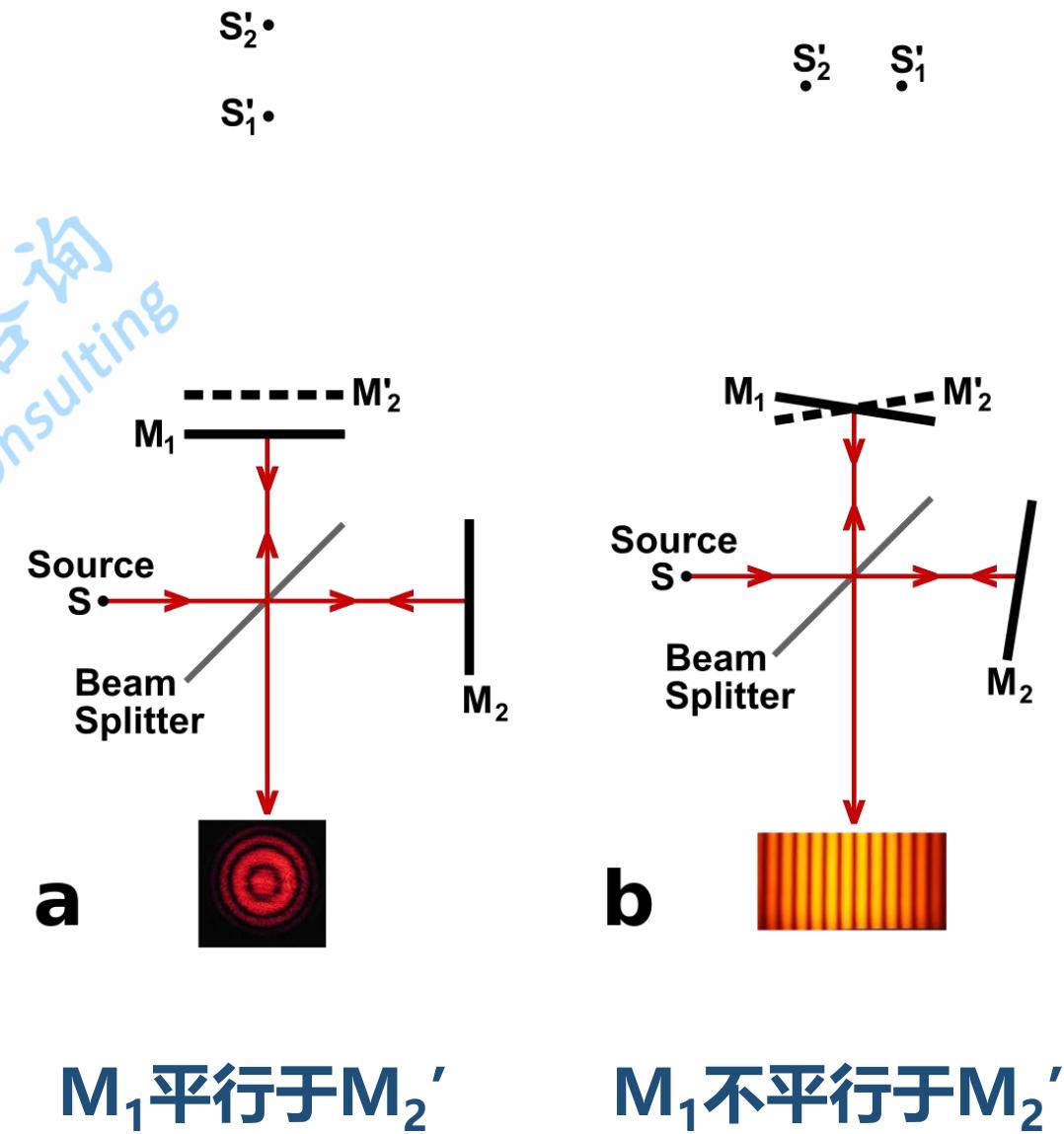
对于光波，我们可以用分光镜将同一光源发出的光分束以产生干涉

迈克尔逊干涉仪

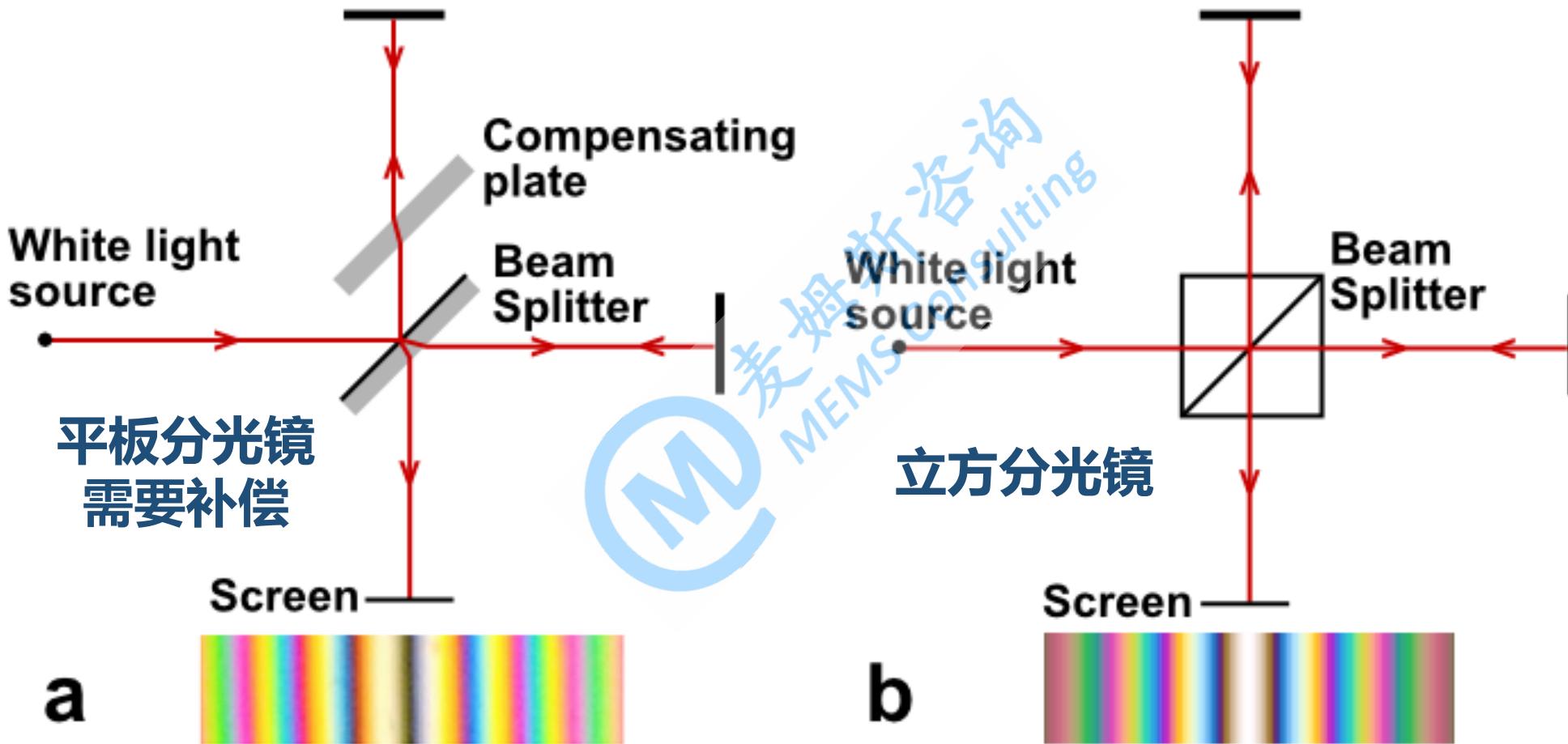


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理想的迈克尔逊干涉仪

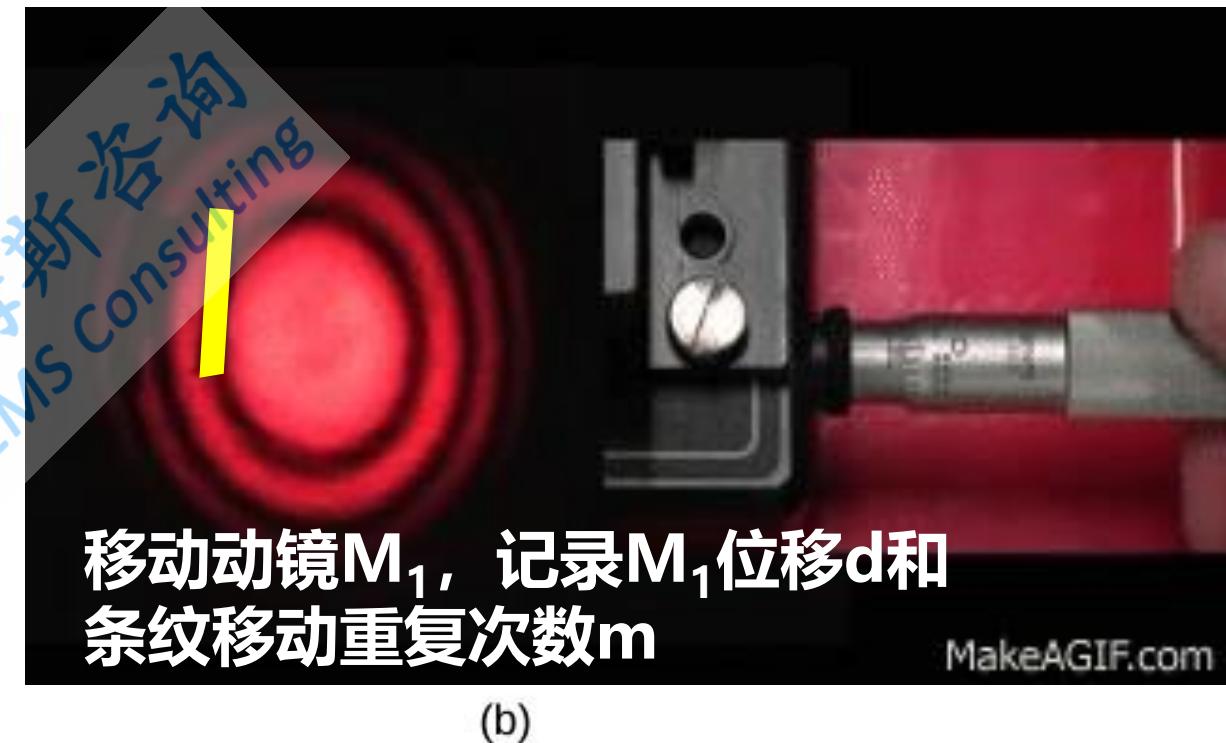
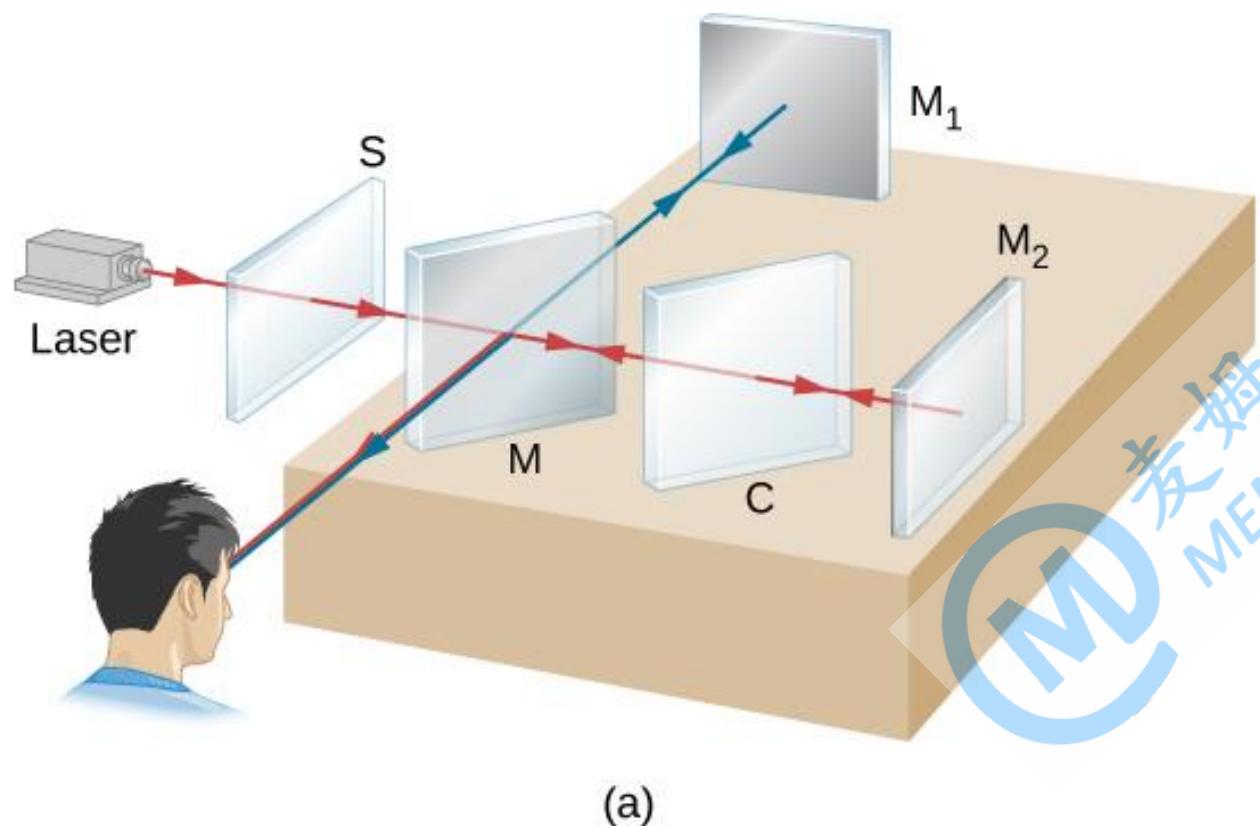


迈克尔逊干涉仪



白光光源的迈克尔逊干涉仪

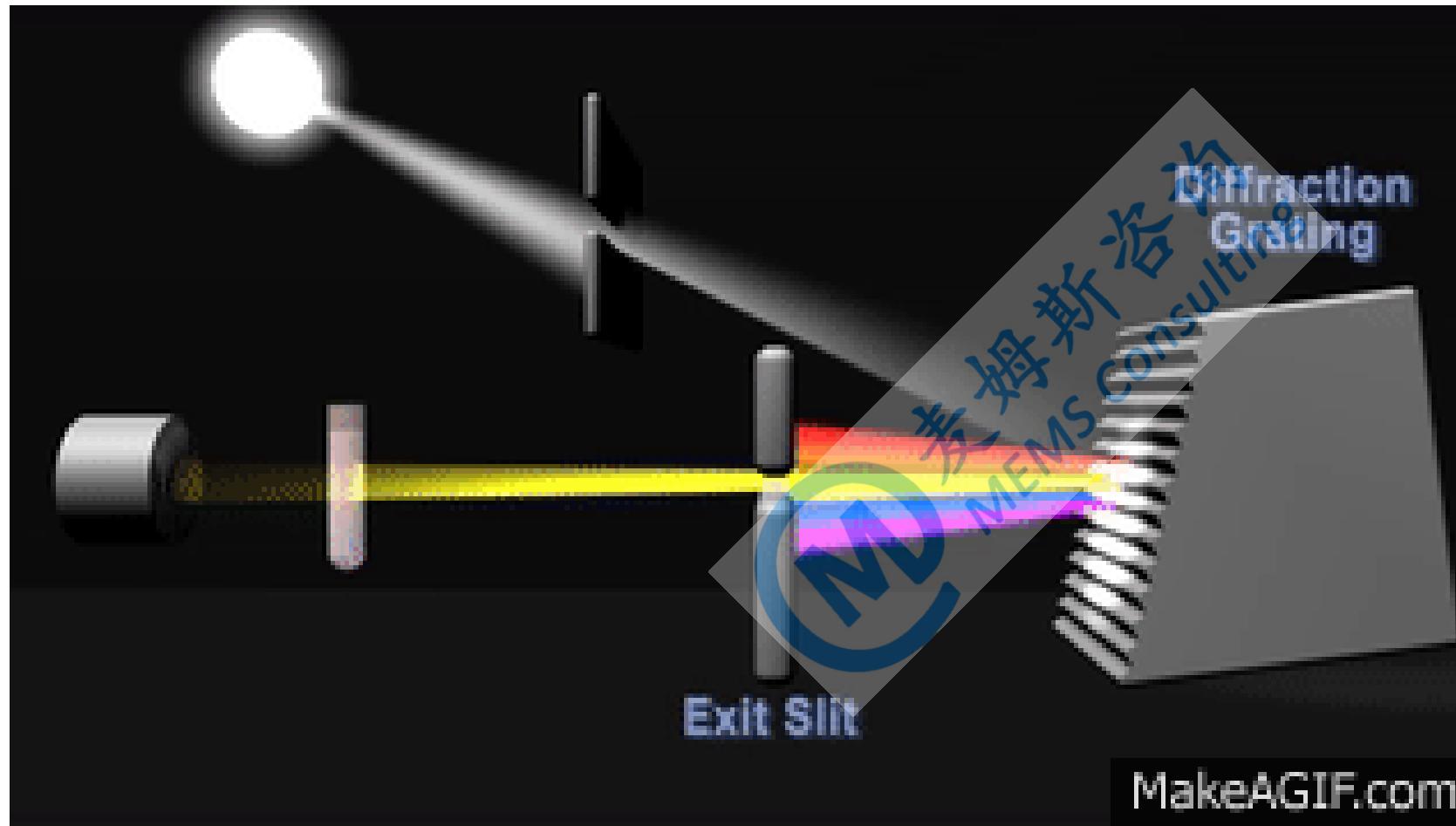
迈克尔逊干涉仪



$$\lambda = 2d/m$$

波长已知算距离，距离已知算波长

傅里叶变换光谱仪

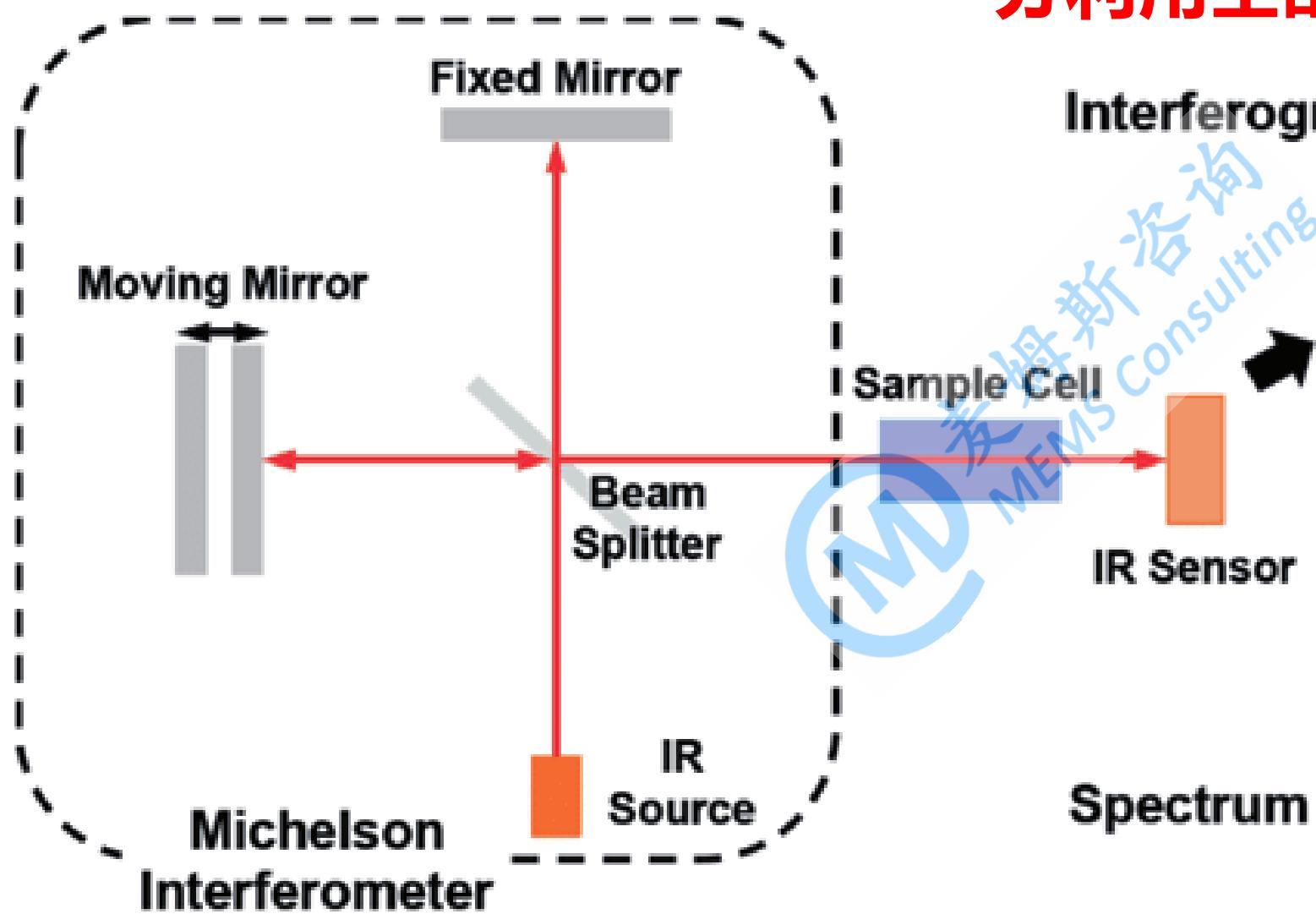


色散型光谱
仪光能量输出小、光谱
范围窄、测量时间长

色散型光谱仪原理

傅里叶变换光谱仪

傅里叶变换光谱仪不需要分光，充分利用户部波长的全部光强信息



Interferogram



干涉图

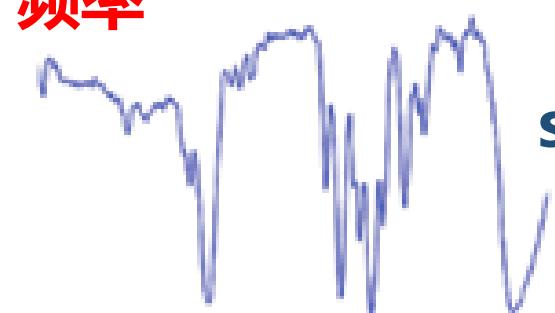
interferogram

时域

Fourier

Transformation

频率

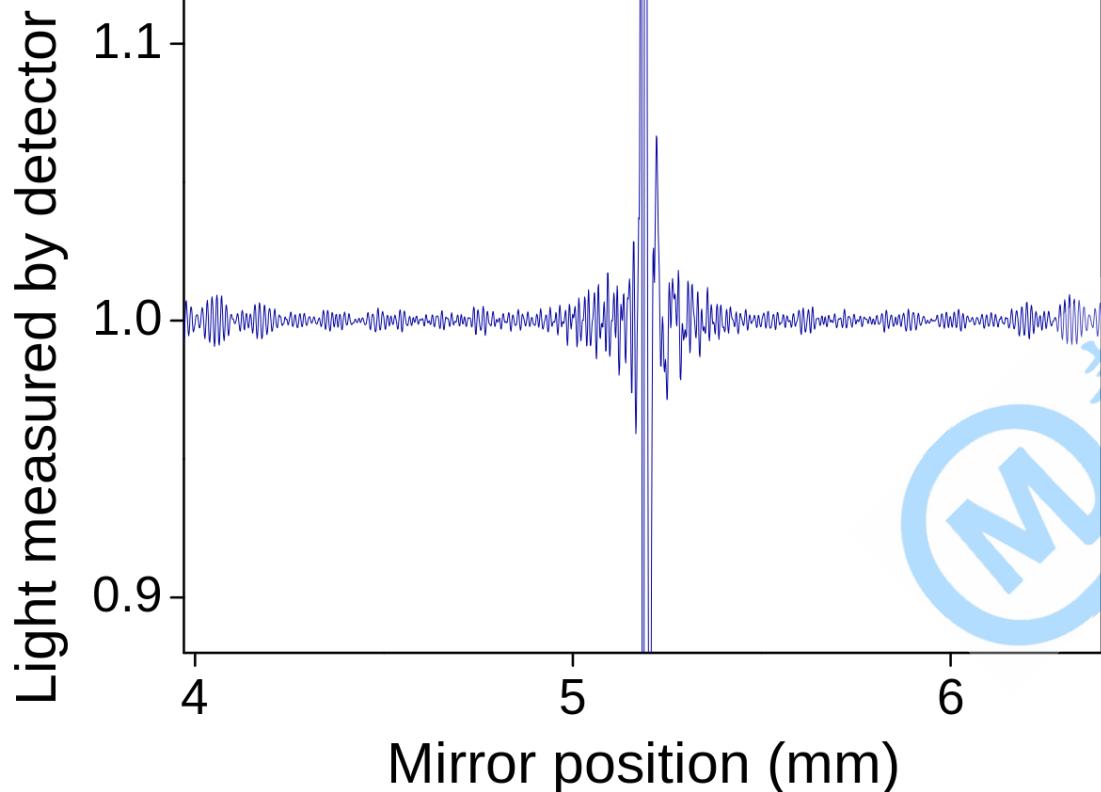


Spectrum

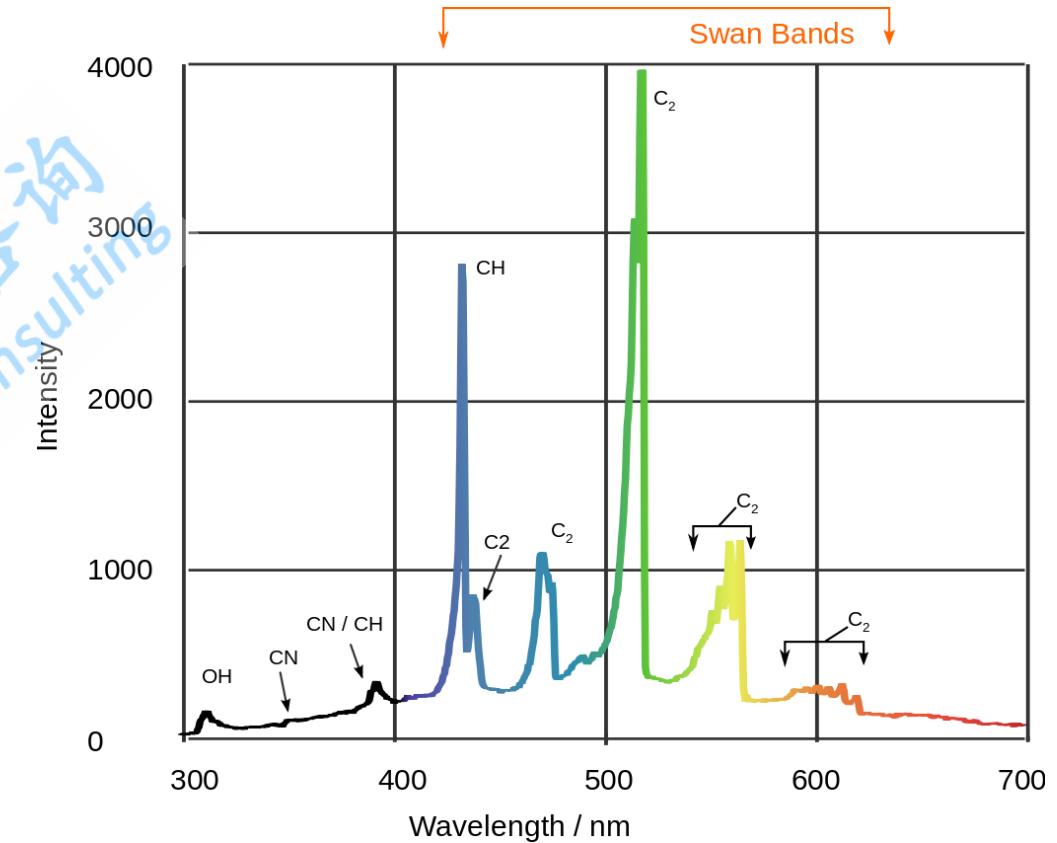
光谱图

spectrum

傅里叶变换光谱仪

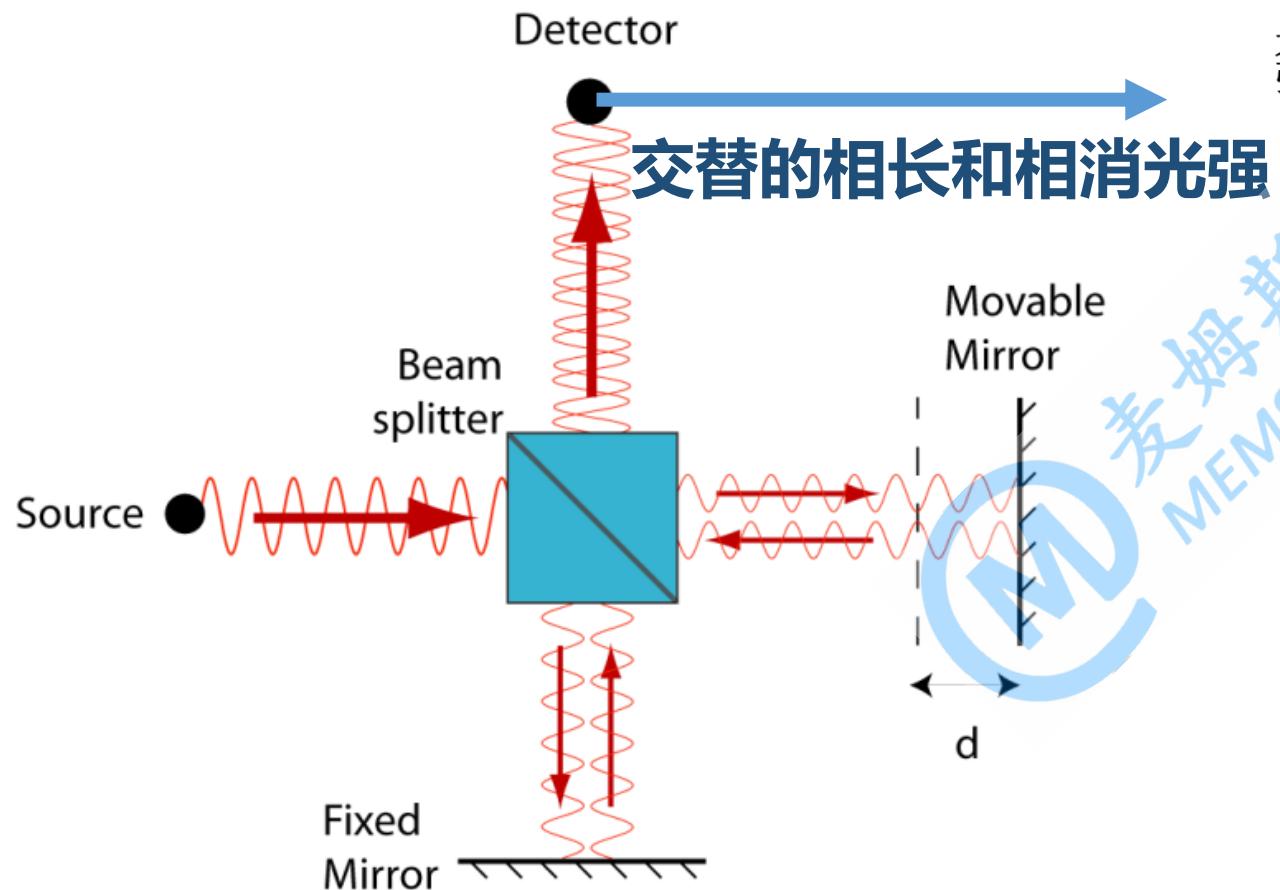


干涉图
interferogram



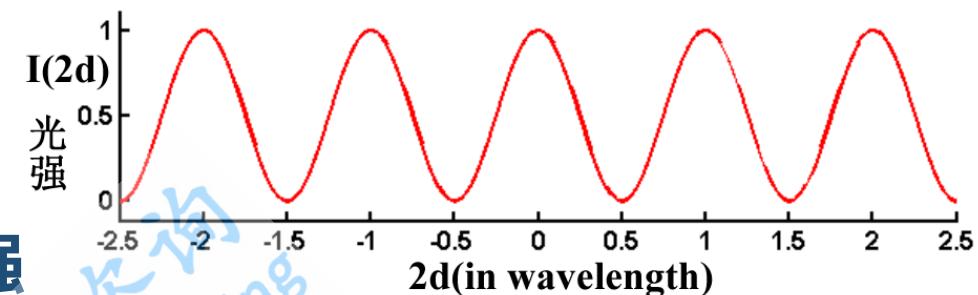
光谱图
spectrum

傅里叶变换光谱仪

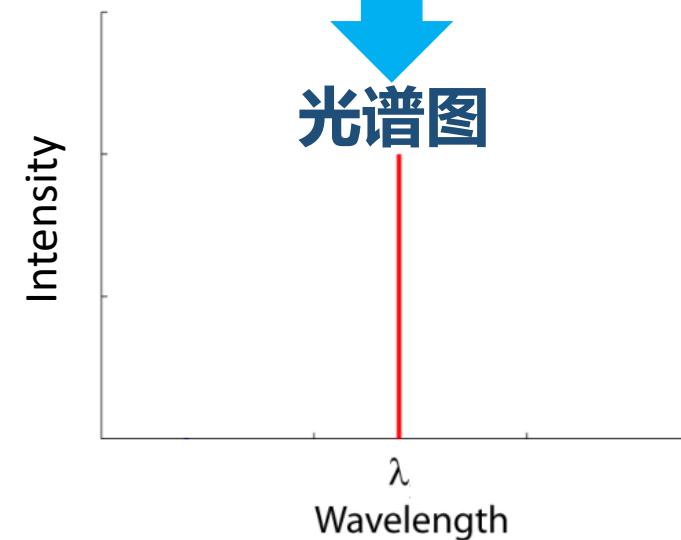
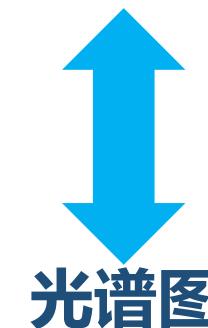


单波长迈克尔逊干涉仪

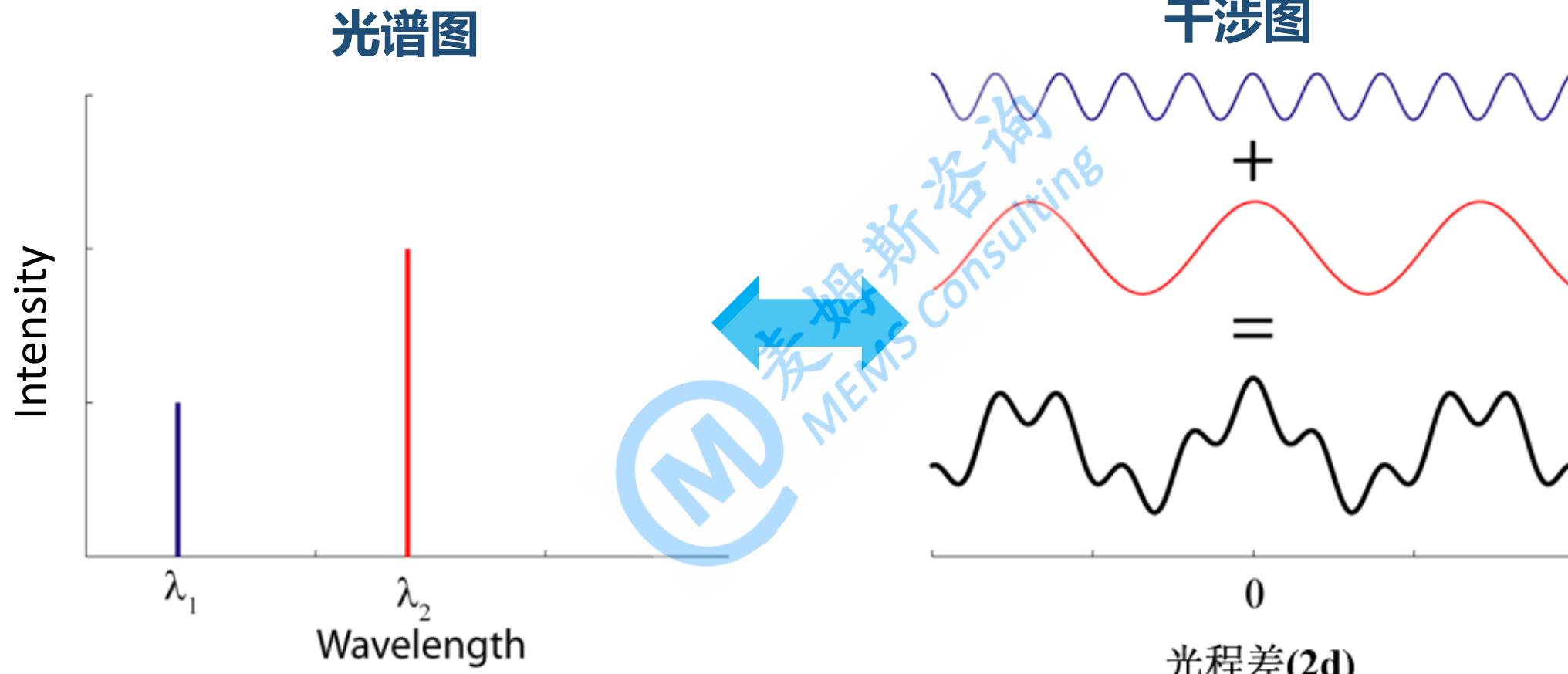
干涉图



$$I(2d) = \frac{I_0}{2} \left[1 + \cos\left(\frac{2\pi}{\lambda} 2d\right) \right]$$

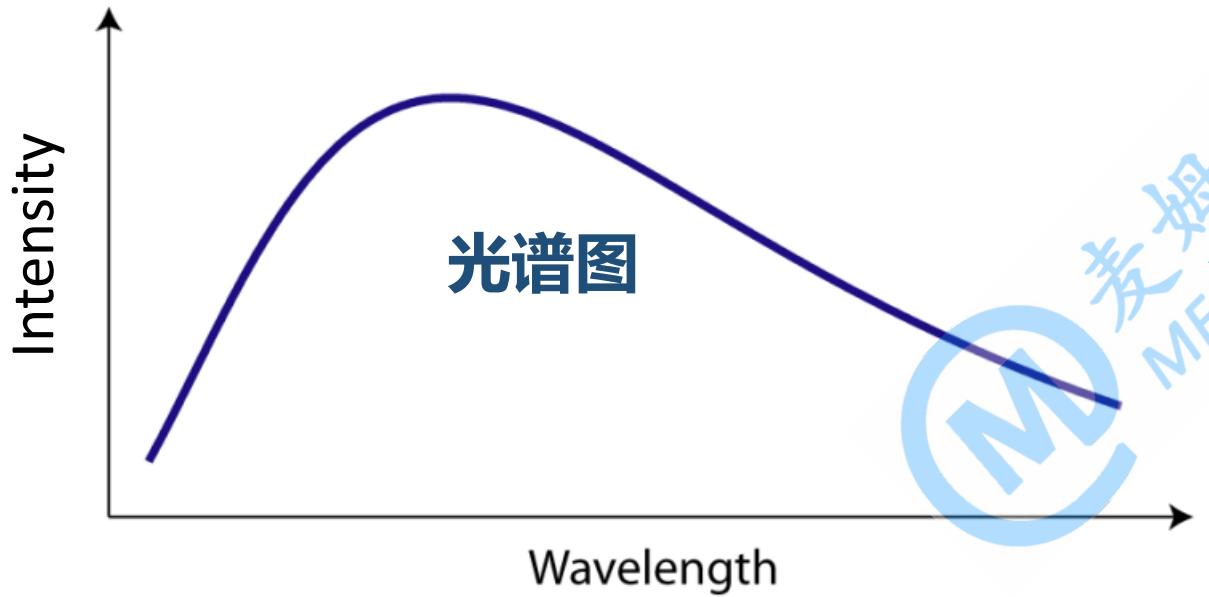


傅里叶变换光谱仪



双波长迈克尔逊干涉仪

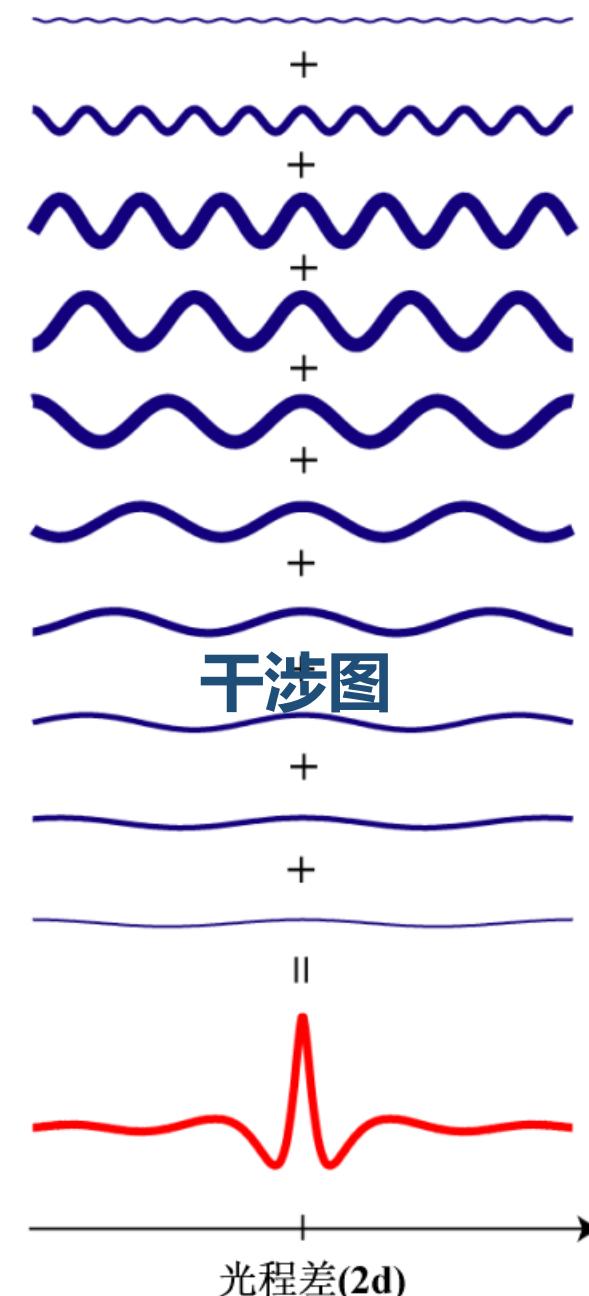
傅里叶变换光谱仪



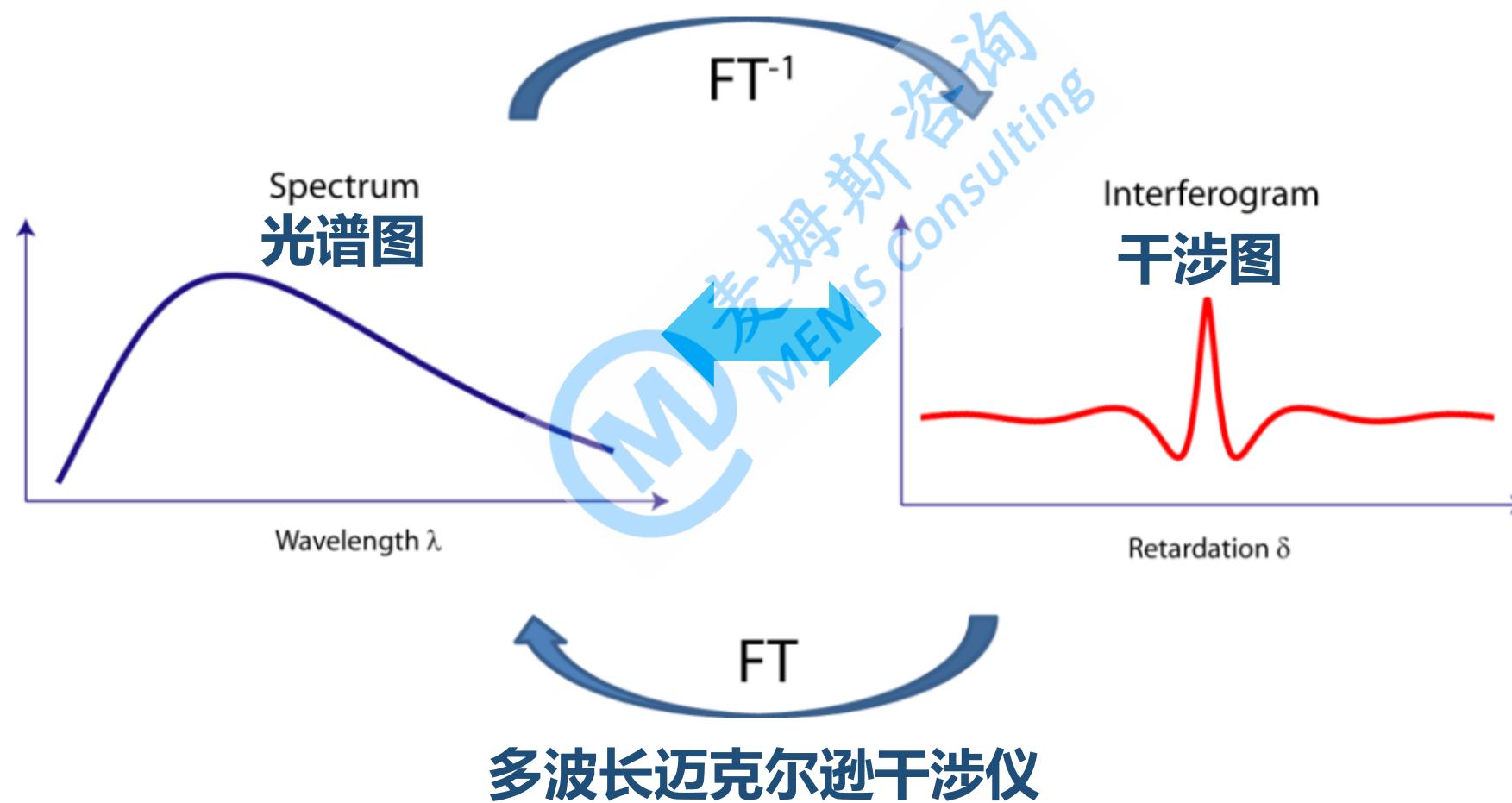
多波长迈克尔逊干涉仪

参考文献: DOES, HOW. "BASICS: FOURIER TRANSFORM SPECTROMETRY."

麦姆斯咨询
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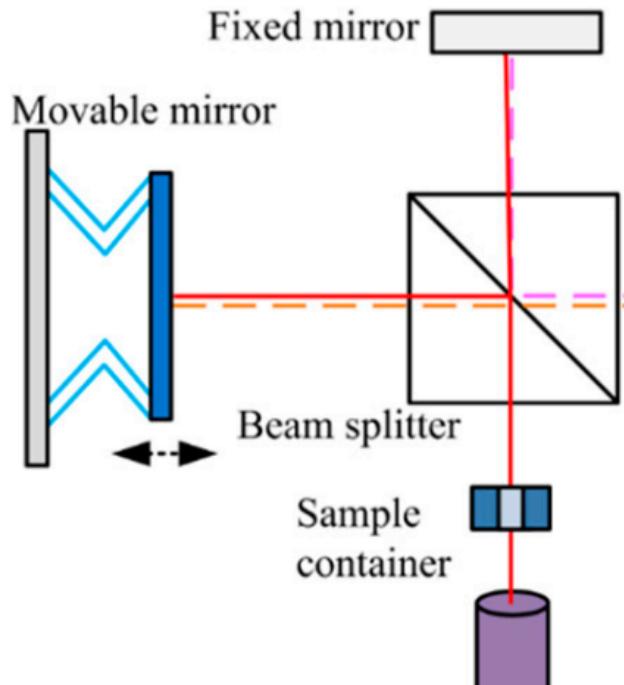


傅里叶变换光谱仪



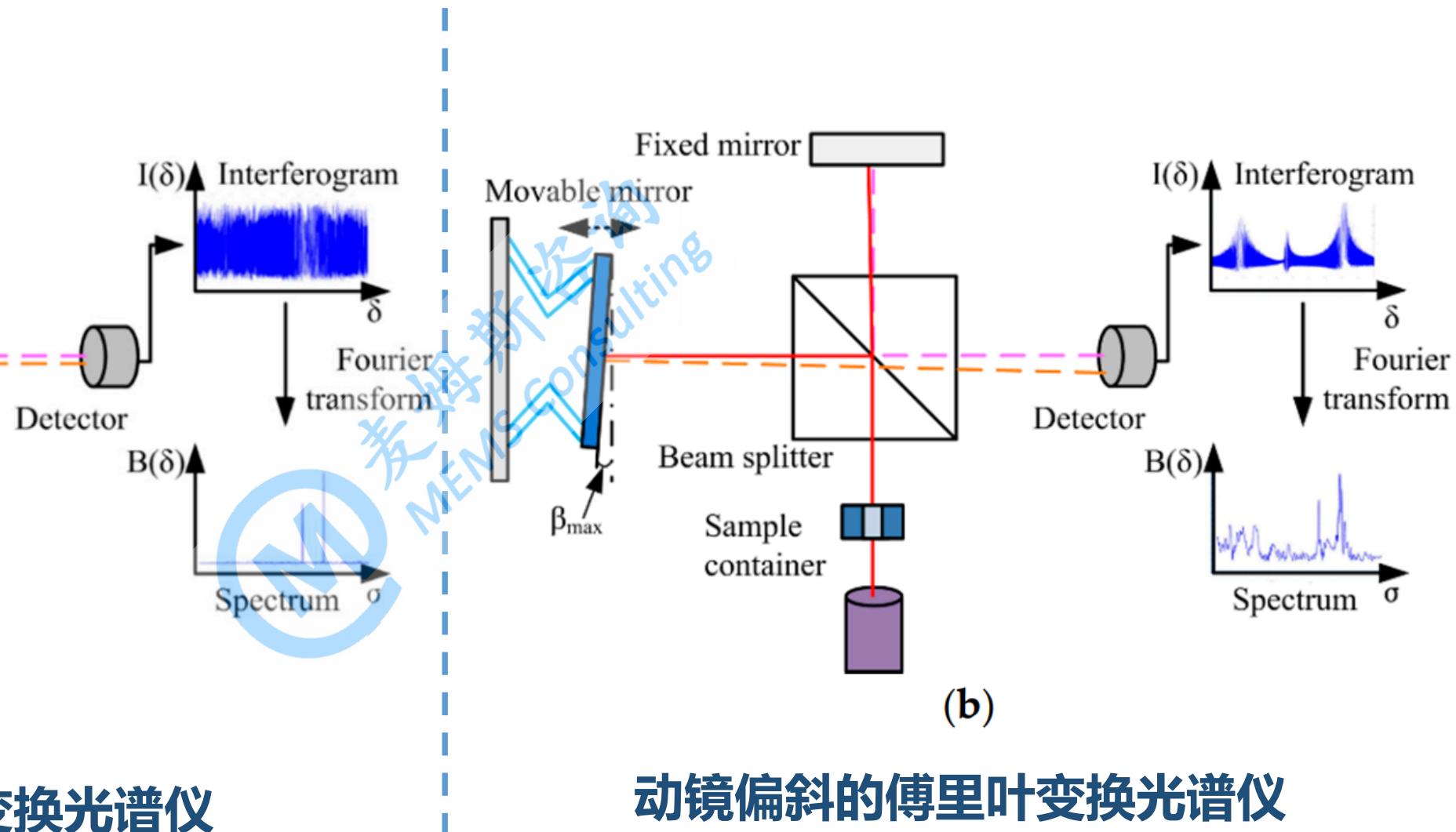
参考文献: DOES, HOW. "BASICS: FOURIER TRANSFORM SPECTROMETRY."

为什么MEMS + 傅里叶变换光谱仪?



(a)

理想的傅里叶变换光谱仪



(b)

动镜偏斜的傅里叶变换光谱仪

为什么MEMS + 傅里叶变换光谱仪?

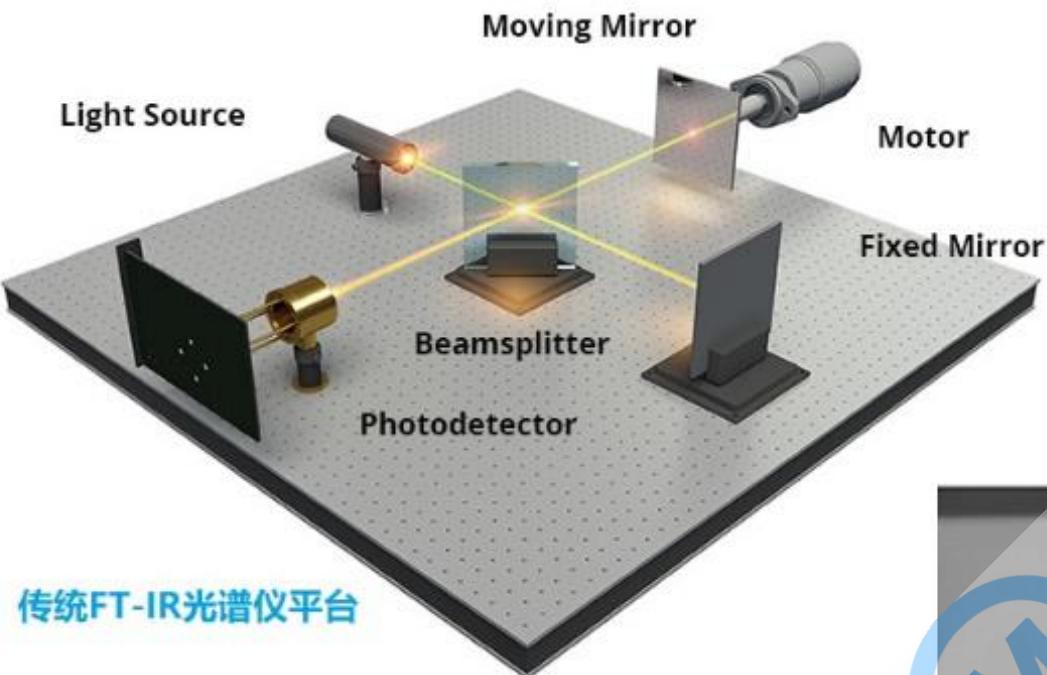
动镜的倾斜，减少了动镜的有效行程，也影响了光谱测量准确性

$$\beta_{max} < \frac{1}{20 \cdot D \cdot v_{max}}$$

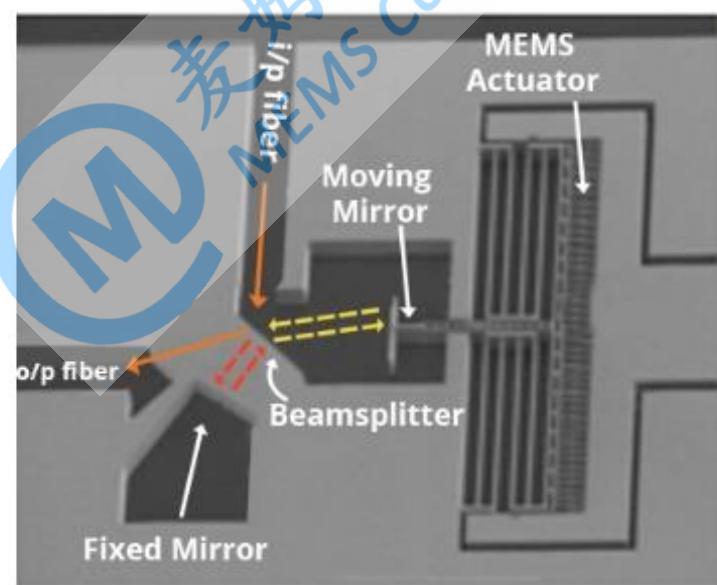
β_{max} : 最大倾斜角度
 D : 光束直径
 v_{max} : 光源最短波长的波数

例如 $D=0.1\text{cm}$, $v_{max}=15800\text{cm}^{-1}(\approx 633\text{nm})$, 那么最大允许的 β 是 0.002°

为什么MEMS + 傅里叶变换光谱仪？

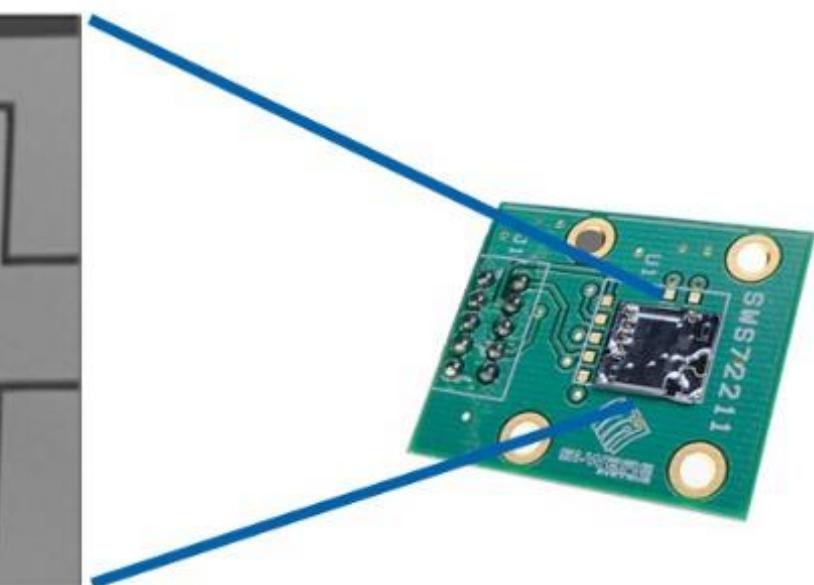


传统FT-IR光谱仪平台

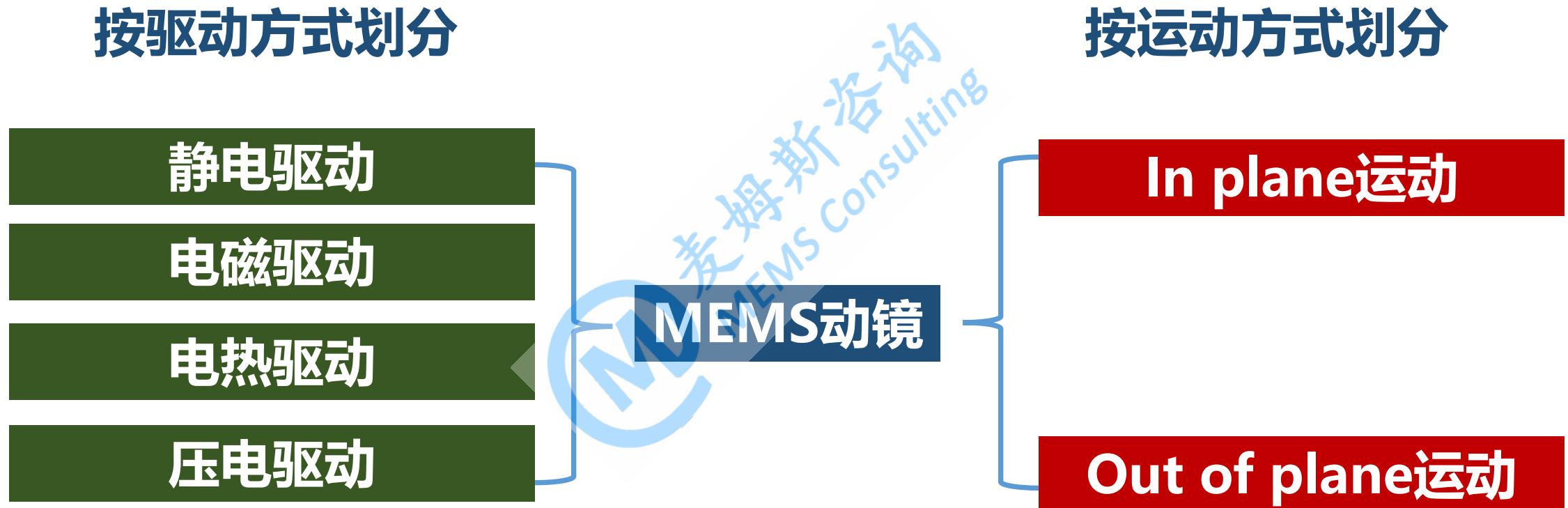


基于SiMOST的单片FT-IR光谱仪

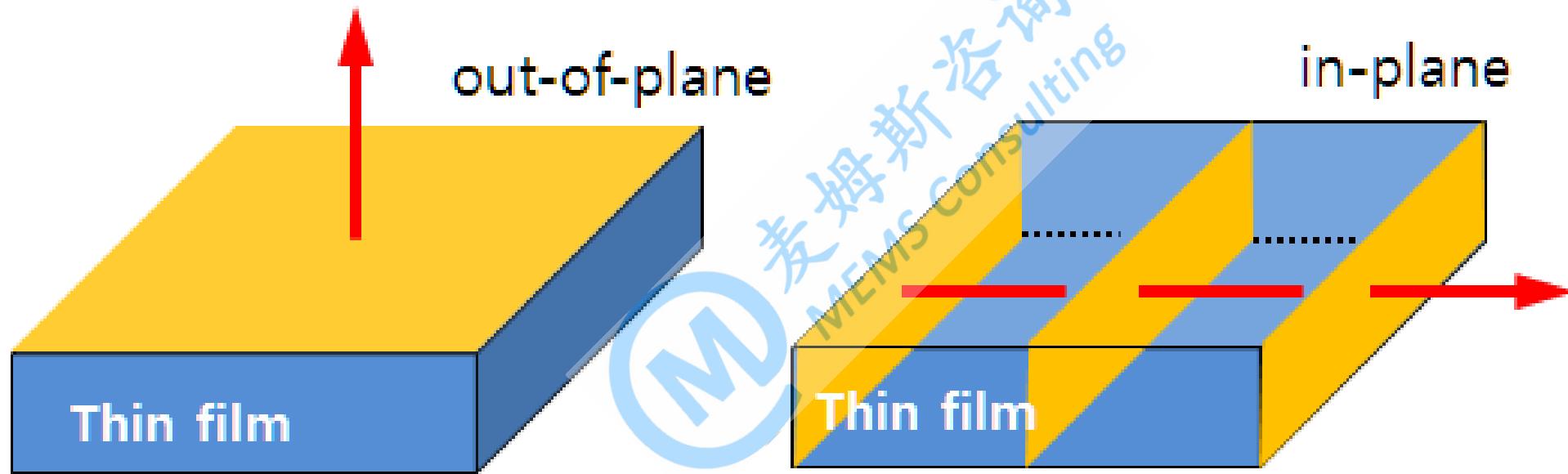
引入MEMS技术，不仅仅解决了傅里叶变换光谱仪微型化的问题，同时通过**制造精度取代装配精度**来保证动镜的倾斜角度，降低光谱仪的装调成本



MEMS动镜的分类、原理、设计与制造



MEMS动镜的分类、原理、设计与制造



MEMS动镜的分类、原理、设计与制造

光谱分辨率 $\Delta\sigma$

$$\Delta\sigma = \frac{1}{2 \times \Delta Z_{max}} = \frac{1}{\delta_{max}}$$

$\Delta\sigma$: 光谱分辨率(cm^{-1})

ΔZ_{max} : 动镜最大位移

δ_{max} : 最大光程差(OPD)

100 cm^{-1} 的光谱分辨率→100
微米的动镜位移



动镜/静镜面积(光斑直径)

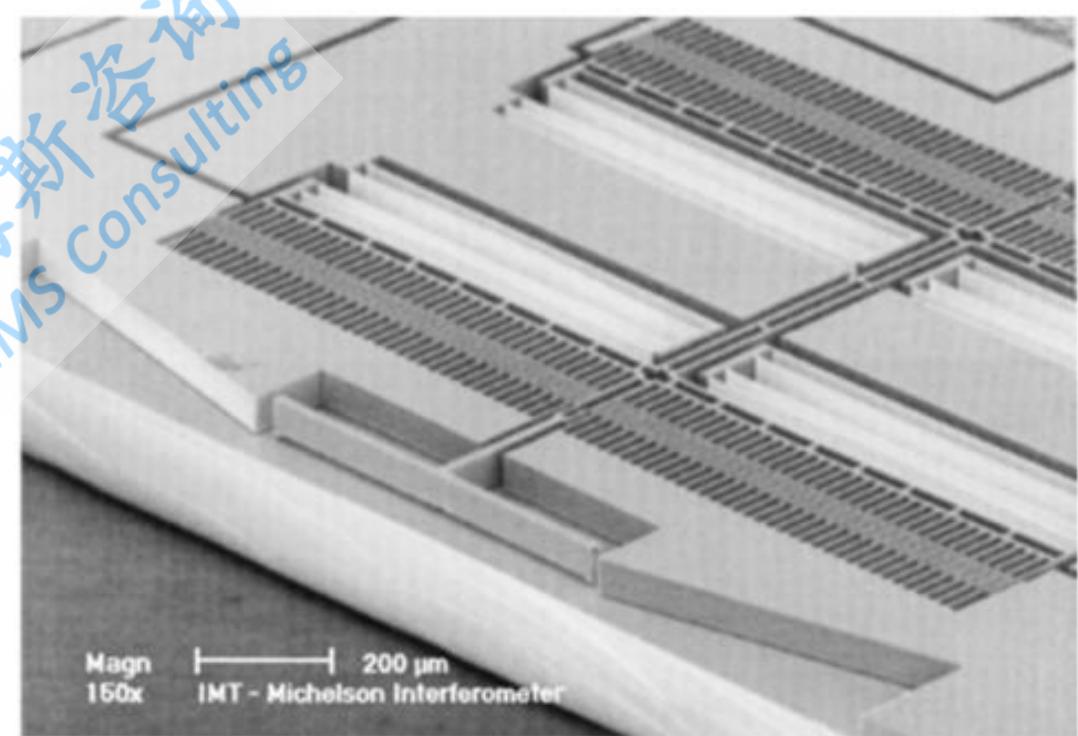
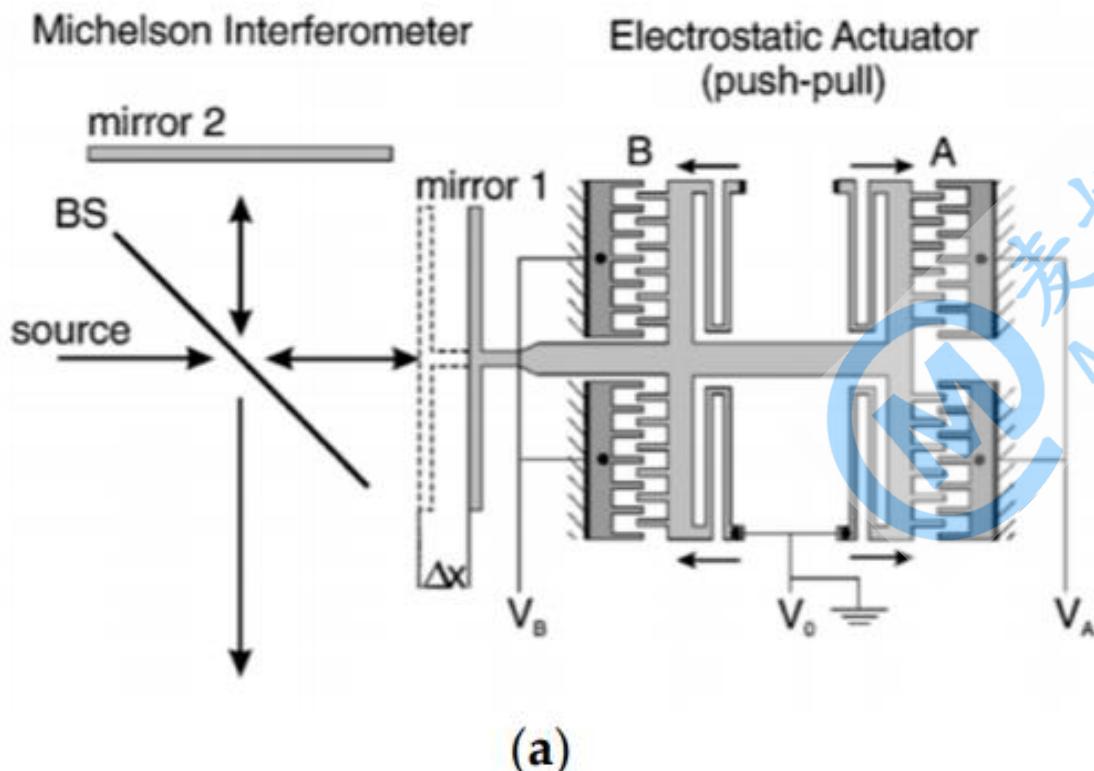
光学表面质量

3个对比MEMS动镜优劣的指标

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例

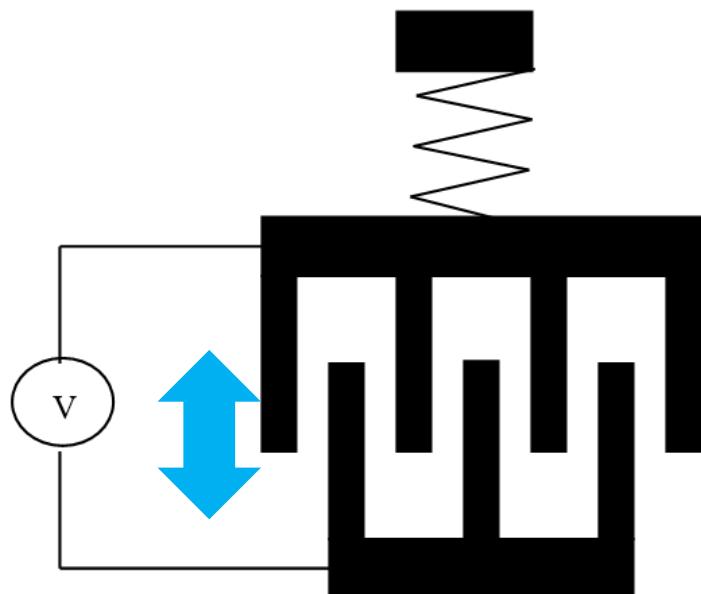
WHY静电梳齿驱动?



(b)

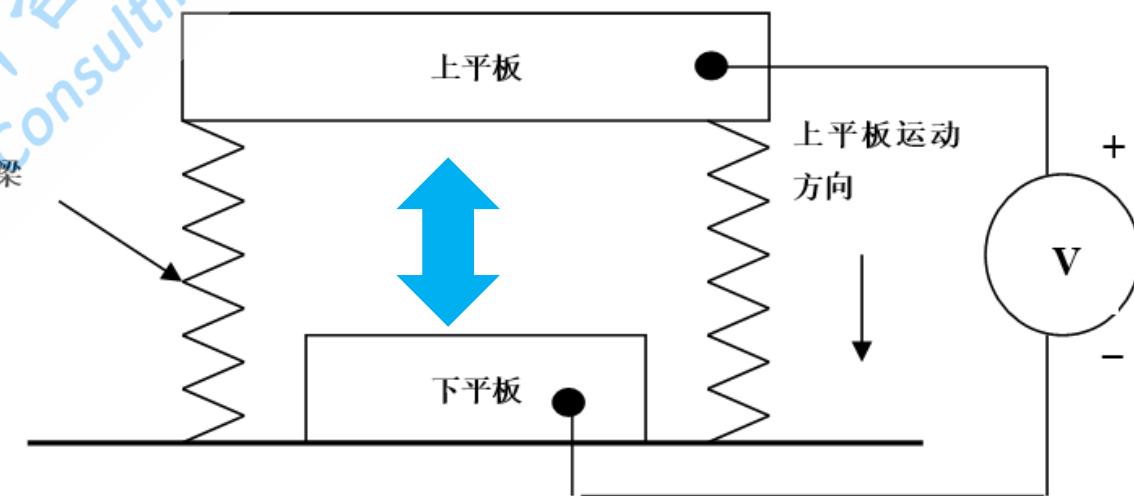
MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例



静电梳齿驱动器

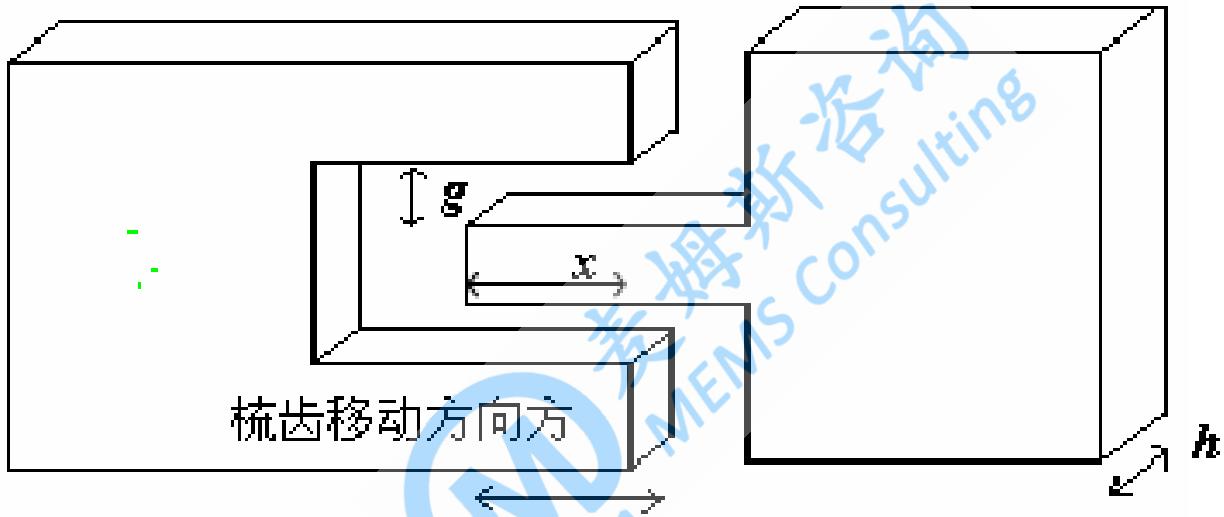
活动电极
固定电极



静电平板电容驱动器

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例

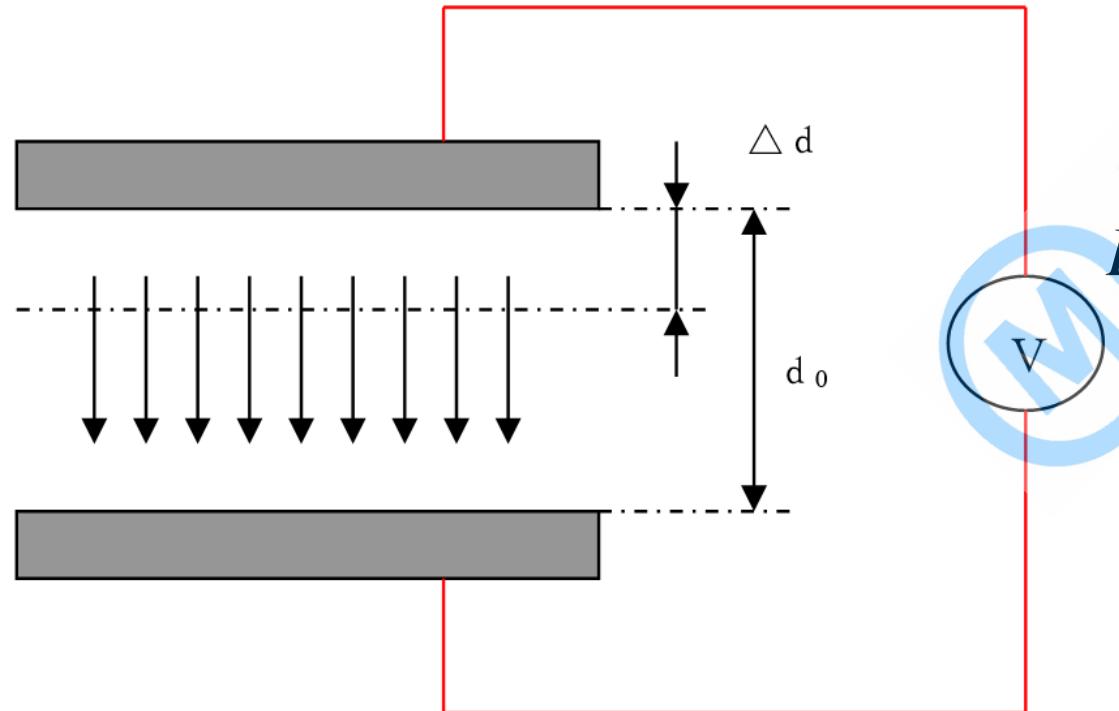


$$F = \frac{\partial W}{\partial x} = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{1}{2} \frac{\partial}{\partial x} \left(\frac{\epsilon_r \epsilon_0 x h}{g} \right) V^2 = \frac{1}{2} \frac{\epsilon_r \epsilon_0 h}{g} V^2$$

在驱动电压确定的情况下，静电梳齿驱动器的静电力F与驱动位移x无关

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例



平板电容静电驱动器的静电力
 F_{pp} 随驱动位移 δd 非线性增加

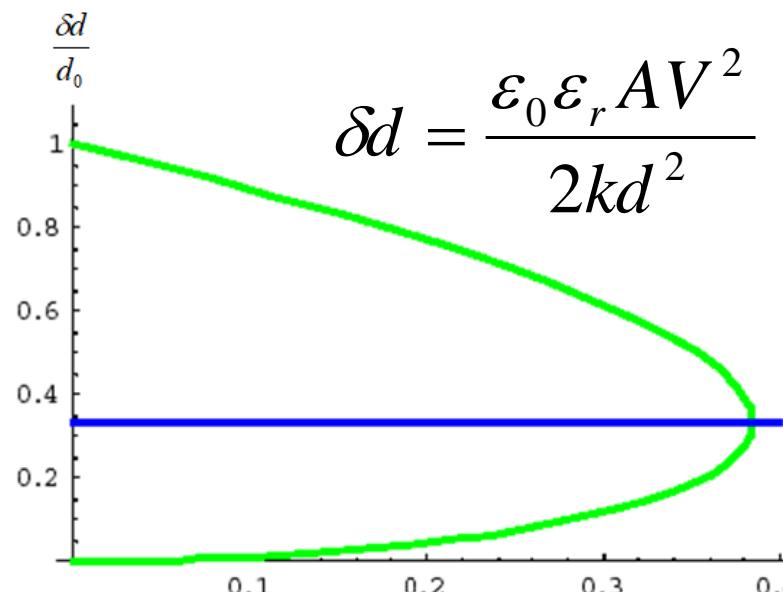
$$F_{pp} = \frac{\partial W}{\partial d} = \frac{\partial CV^2}{2\partial d} = -\frac{\varepsilon_0 \varepsilon_r A V^2}{2d^2} = -\frac{\varepsilon_0 \varepsilon_r A V^2}{2(d_0 - \delta d)^2}$$

而平衡静电力的弹性梁回复力
 F_r 随驱动位移 δd 线性增加

$$F_r = k\delta d$$

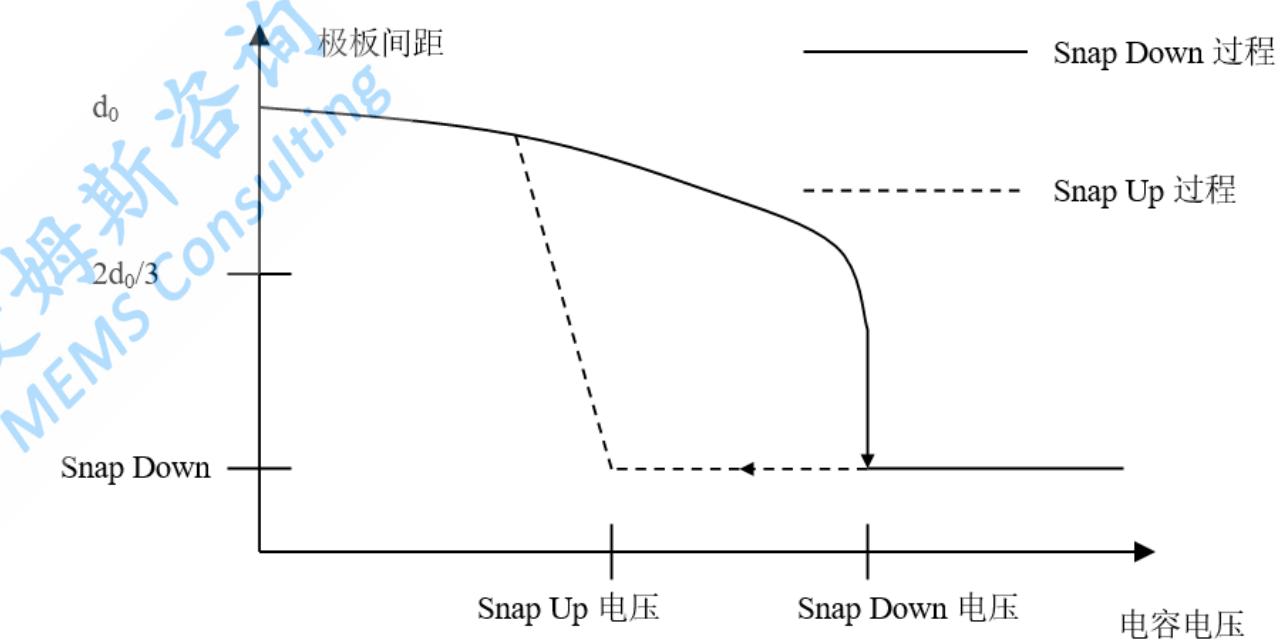
MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例



$$V \frac{1}{d_0} \sqrt{\frac{A \epsilon_r \epsilon_0}{2 k d_0}}$$

位移-电压关系曲线



Snap down(Pull-in)吸合问题

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例

那么采用静电梳齿驱动而不是静电平板电容驱动的原因是什么?

$$F = \frac{\partial W}{\partial x} = \frac{1}{2} \frac{\partial C}{\partial x} V^2 = \frac{1}{2} \frac{\partial}{\partial x} \left(\frac{\epsilon_r \epsilon_0 x h}{g} \right) V^2 = \frac{1}{2} \frac{\epsilon_r \epsilon_0 h}{g} V^2$$

准静态驱动下、静电力几乎不受温度的影响，驱动精度高，甚至可以完全开环控制

光谱分辨率

$$\Delta\sigma = \frac{1}{2 \times \Delta Z_{max}} = \frac{1}{\delta_{max}}$$

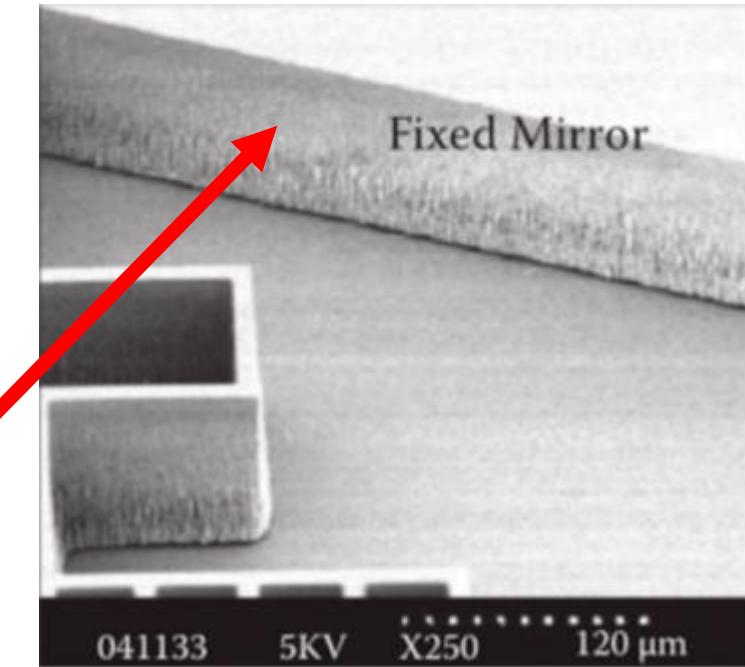
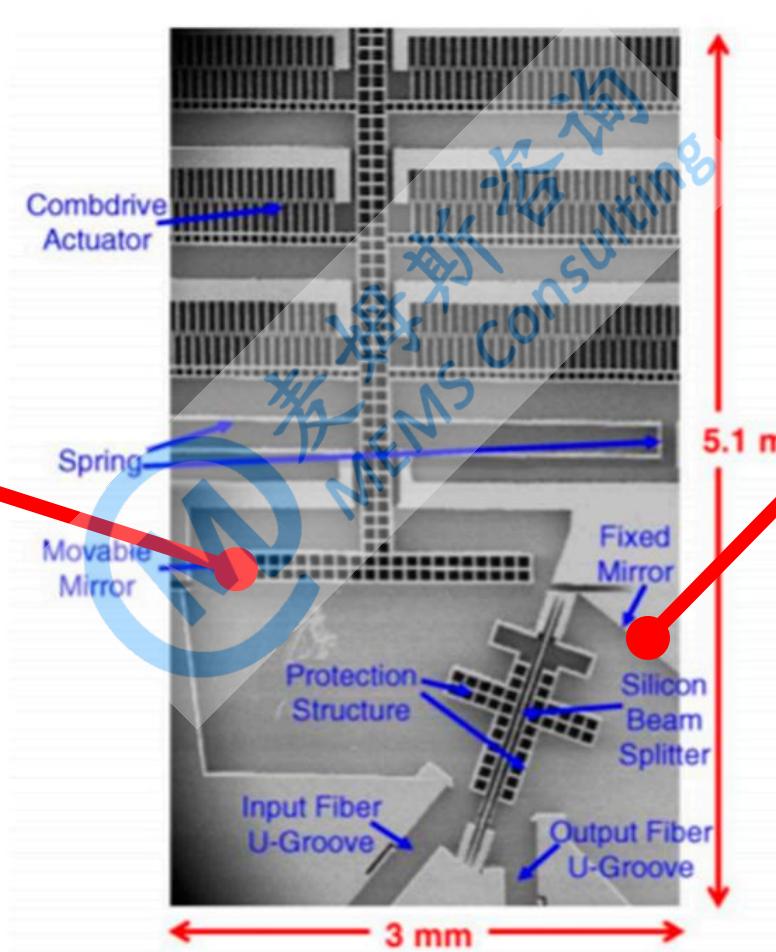
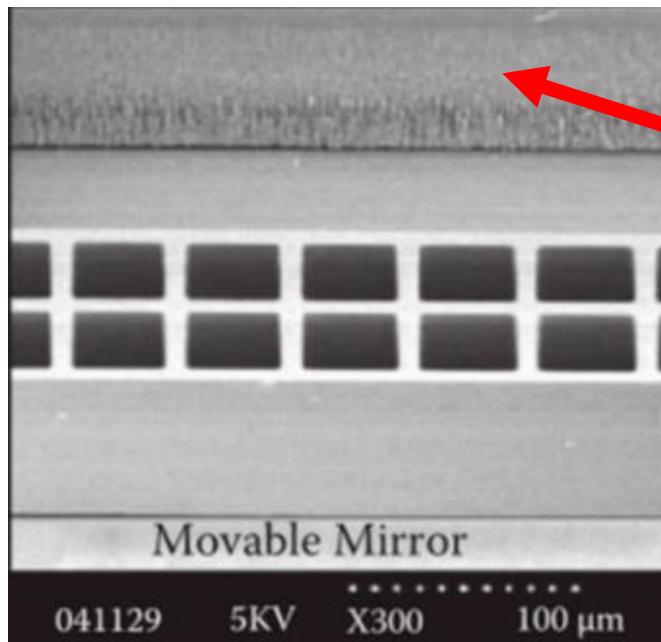
$\Delta\sigma$: 光谱分辨率(cm^{-1})
 ΔZ_{max} : 动镜最大位移
 δ_{max} : 最大光程差(OPD)

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例

静镜表面质量

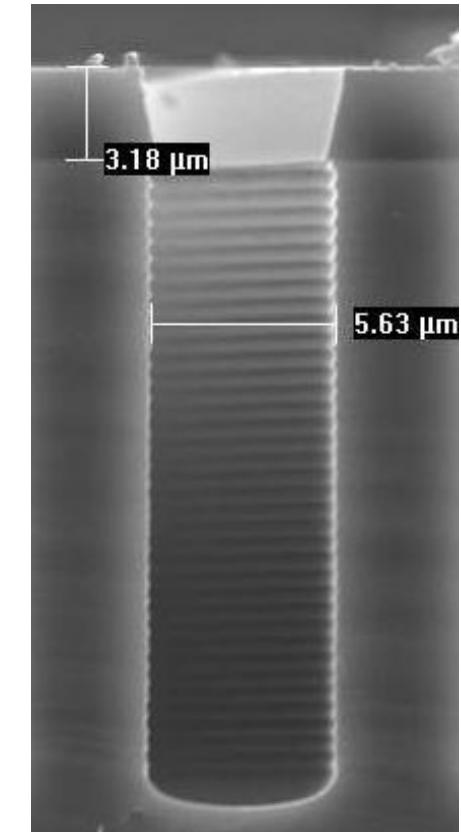
动镜表面质量



MEMS动镜的分类、原理、设计与制造

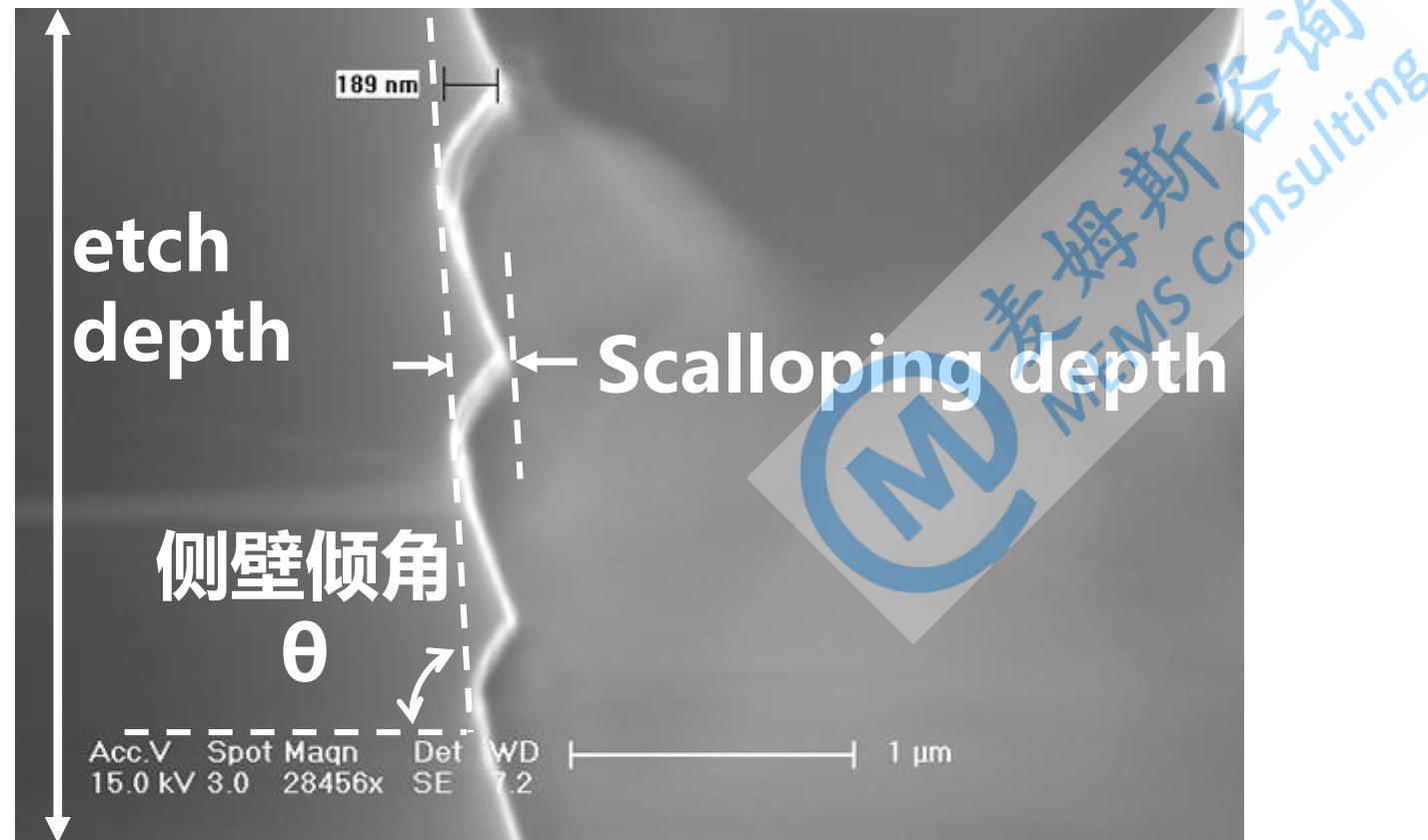
1) 静电驱动的In plane案例

DRIE采用刻蚀和钝化交替的Bosch工艺，侧壁形成特有的扇贝纹(scalloping)，严重影响光学质量



MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例



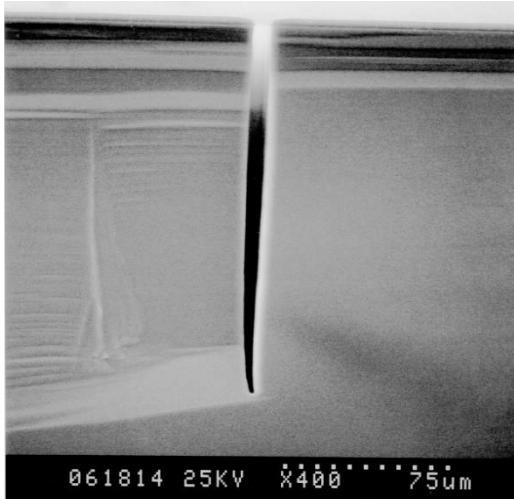
Etch Depth
决定了光斑直径
(300μm)

Scalloping depth
影响光学损耗
(60nm)

侧壁倾斜角
影响光路对准
($90^\circ \pm 0.1^\circ$)

MEMS动镜的分类、原理、设计与制造

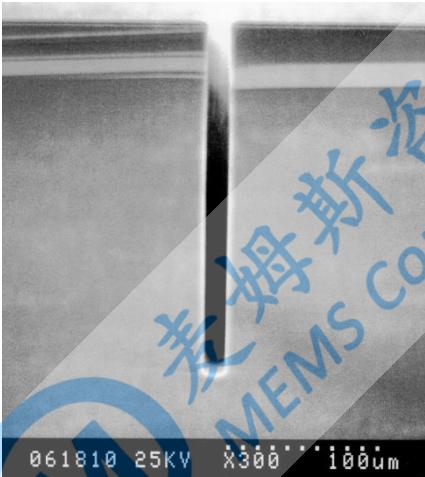
1) 静电驱动的In plane案例



Positive

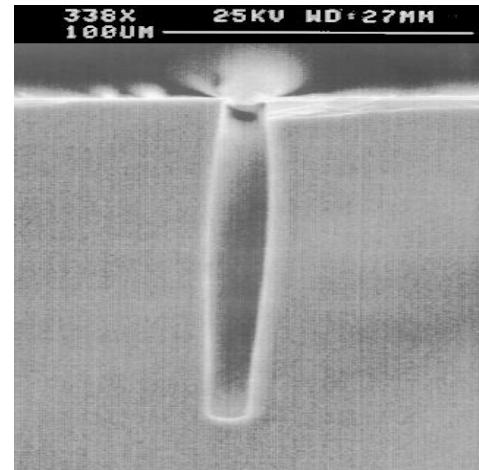
To optimise:

- Increase etch platen power
- Reduce pressure



**Perfect
Side Wall**

优化侧壁陡
直度



Bowing

To optimize:

- Reduce etch platen power
- Reduce pressure

MEMS动镜的分类、原理、设计与制造

1) 静电驱动的In plane案例

A=刻蚀时间

B=钝化时间

R=A/B

保持R不变

等比例减小A和B

可以减小scalloping



刻蚀完成后通过多次
侧壁氧化+HF腐蚀抛
光，可以减小
scalloping

优化scalloping

MEMS动镜的分类、原理、设计与制造

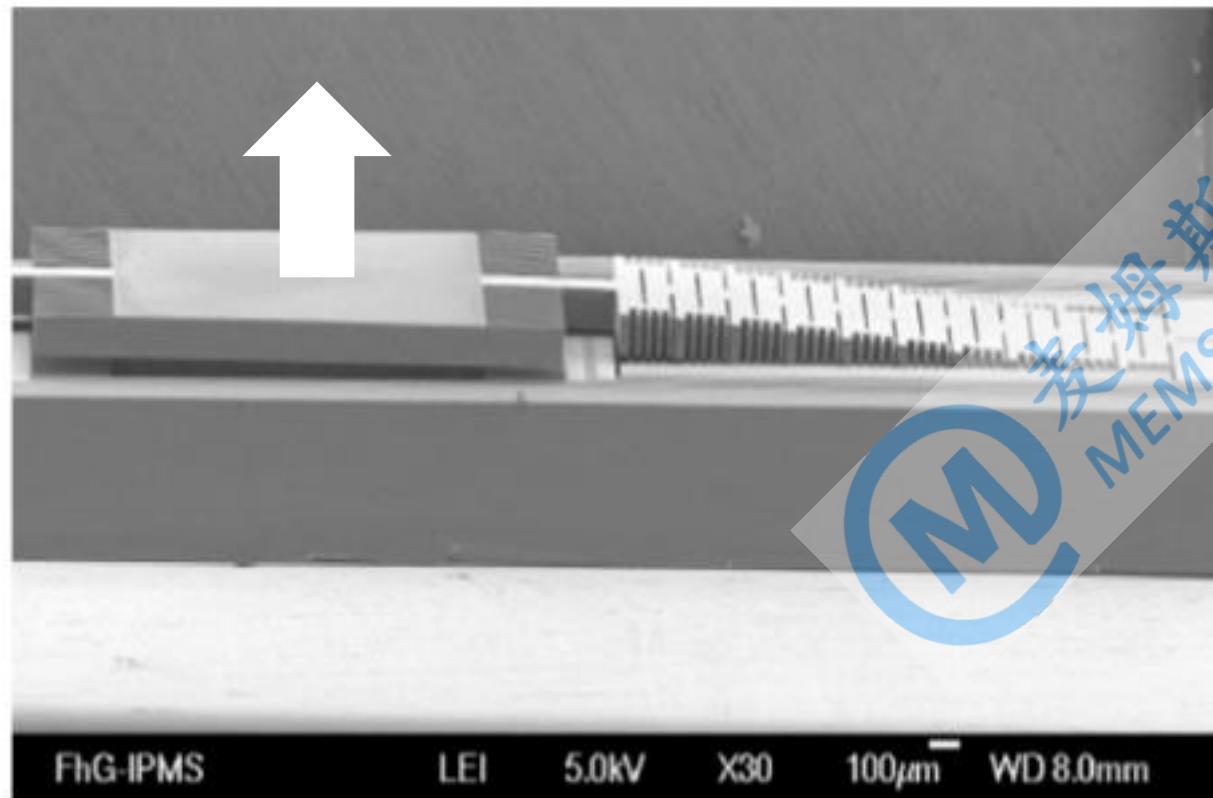
1) 静电驱动的In plane案例

Authors	Institution	Actuation Type	Core of FTS	Displacement	Work Condition	Device Size
Manzardo et al.	UniNE	In-plane	MI	77 μm	10 V-amplitude	MEMS chip: $5 \times 4 \text{ mm}^2$ (Mirror: $75 \times 500 \mu\text{m}^2$)
Manzardo et al.	UniNE	In-plane	LGI	145 μm	65 V	MEMS chip: $5 \times 5 \text{ mm}^2$
Merenda et al.	ARCoptix and EPFL	In-plane	LGI	>500 μm	-	Entire FTS: $10 \times 15 \times 7 \text{ cm}^3$
Yu et al	SNU, Stanford, and SNL	In-plane	MI	25 μm	150 V @ 5 Hz	Entire FTS: $4 \times 8 \times 0.6 \text{ mm}^3$
Khalil et al.	ASU and SWS	In-plane	MI	48 μm	@ resonance	-
Khalil et al.	ASU and SWS	In-plane	MZI	62.5 μm	70 V @ resonance	Entire FTS: $1 \times 2 \text{ mm}^2$
Mortada et al.	SWS, EP, and ASU	In-plane	MI	62.5 μm or 200 μm	-	-
Eltagoury et al.	ASU and SWS	In-plane	FPI	-	-	-

驱动方式普遍是静电梳齿驱动，动镜/静镜厚度受限于DRIE刻蚀深度，普遍小于1mm，采用准静态驱动最大位移普遍为100微米左右，但是准静态驱动不受温漂影响，可以开环控制

MEMS动镜的分类、原理、设计与制造

2) 静电驱动的Out of plane案例



优点

1、动镜尺寸不受限于DRIE刻蚀深度
($1.5 \text{ mm} \times 1.1 \text{ mm}$)

2、光学表面质量可以通过CMP保证，不受刻蚀影响

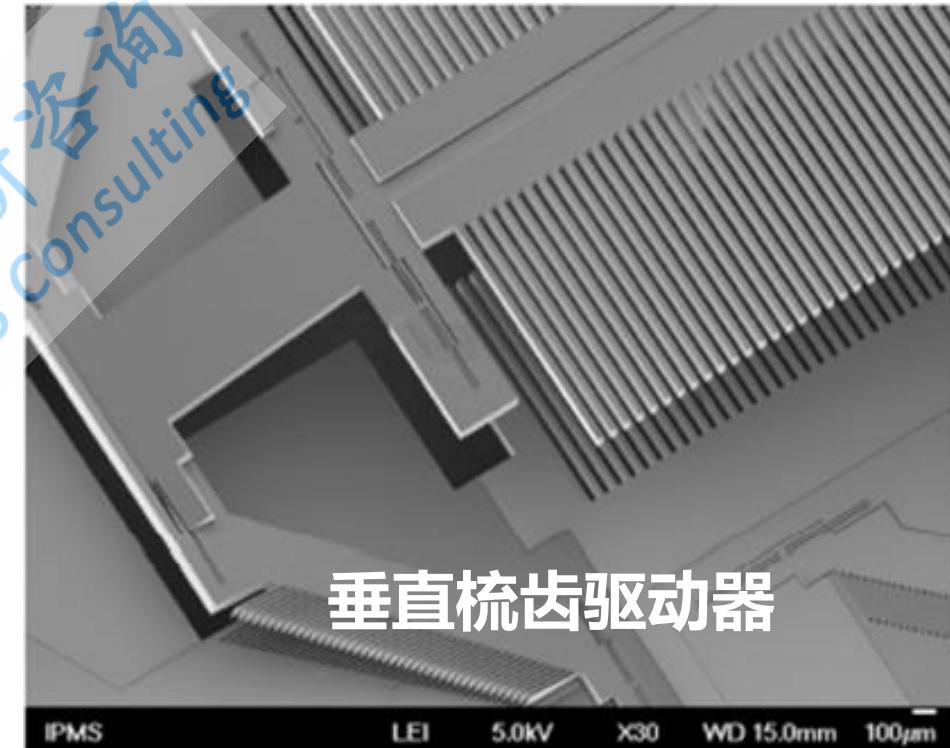
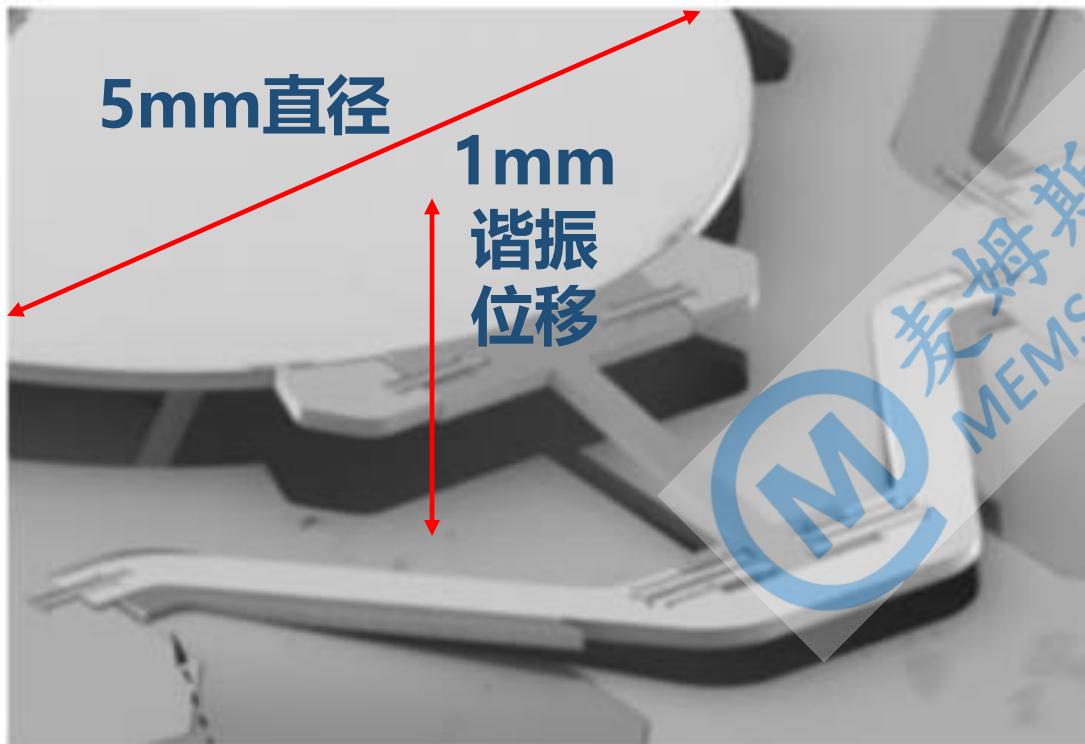
缺点

1、out of plane变形不容易做大，通常需要在真空中封装下谐振来放大位移
(200微米@40V/5kHz谐振、100Pa真空)

2、动镜和静镜不方面集成在同一芯片上，需要通过装配精度保证光路对准精度

MEMS动镜的分类、原理、设计与制造

2) 静电驱动的Out of plane案例



参考文献: Translatory MOEMS actuator and system integration for miniaturized Fourier transform spectrometers. J. Micro/Nanolithogr. MEMS, MOEMS 2014

MEMS动镜的分类、原理、设计与制造

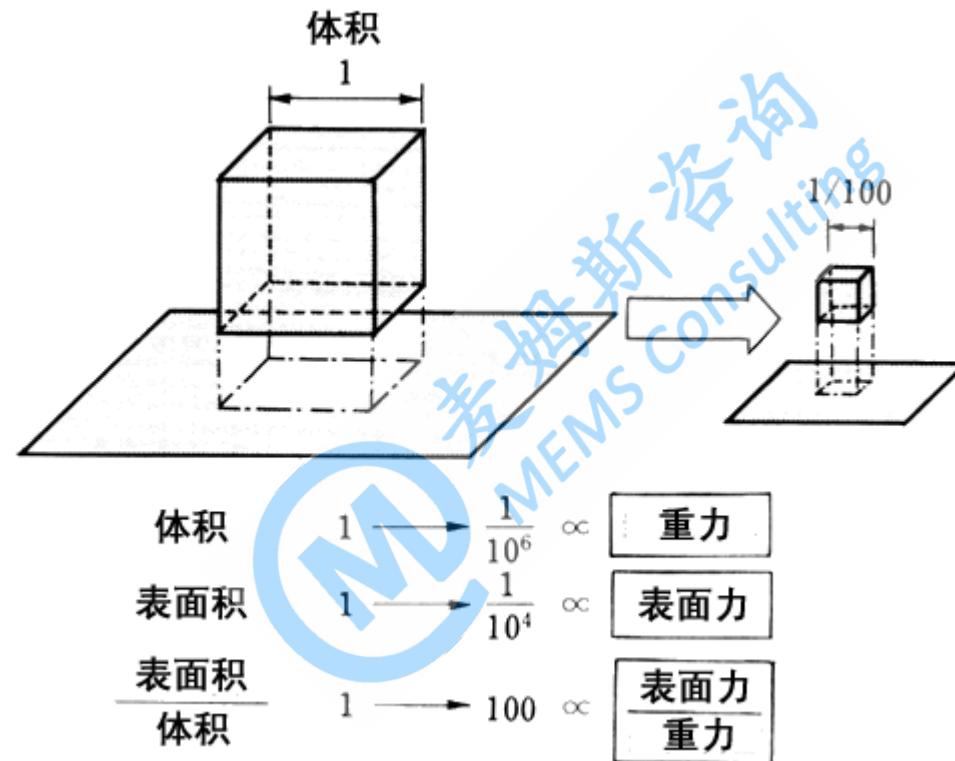
2) 静电驱动的Out of plane案例

Authors	Institution	Actuation Type	Core of FTS	Displacement	Work Condition	Device Size
Sandner et al.	IPMS	Out-of-plane	-	200 μm	40 V @ 100 Pa vacuum, 5 kHz	MEMS chip: $1.8 \times 9 \text{ mm}^2$ (Mirror: $1.5 \times 1.1 \text{ mm}^2$)
Sandner et al.	IPMS	Out-of-plane	-	500 μm	500 Hz	Aperture: 3 mm in diameter
Sandner et al.	IPMS	Out-of-plane	-	1.2 mm	50 V @ 30 Pa vacuum, 500 Hz	Aperture: 5 mm in diameter
Ataman et al.	KU and IPMS	Out-of-plane	LGI	106 μm	28 V @ resonance	Aperture: $3 \times 3 \text{ mm}^2$
Seren et al.	KU and IPMS	Out-of-plane	LGI	355 μm	76 V @ 971 Hz	Aperture: $10 \times 10 \text{ mm}^2$

普遍是垂直梳齿驱动，动镜/静镜厚度不受DRIE刻蚀深度限制，普遍大于1mm，准静态驱动位移太小，只能谐振驱动，谐振振幅比较容易受到温漂影响，必须闭环控制

MEMS动镜的分类、原理、设计与制造

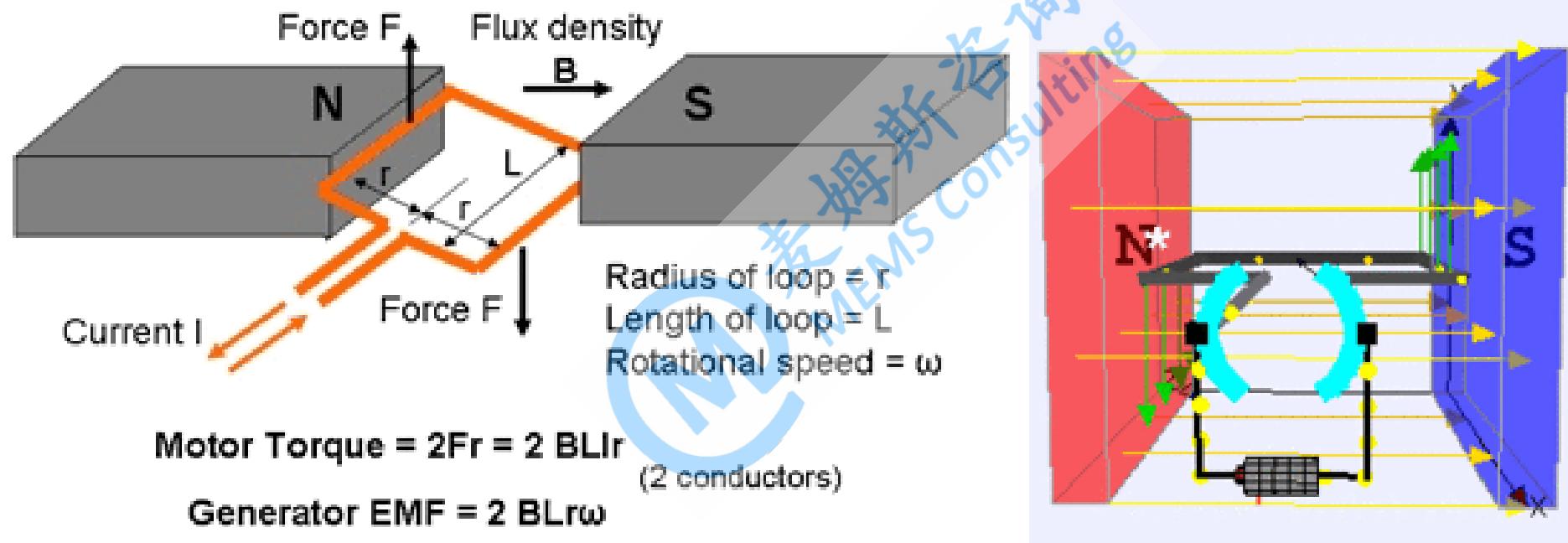
3) 电磁驱动的in plane & out of plane案例



由于尺度效应，微观尺度下，和表面积相关的力(如静电力)相对增大，和体积相关的力(如电磁力)相对减小。但是，在亚毫米尺度，电磁力还是比静电力更大

MEMS动镜的分类、原理、设计与制造

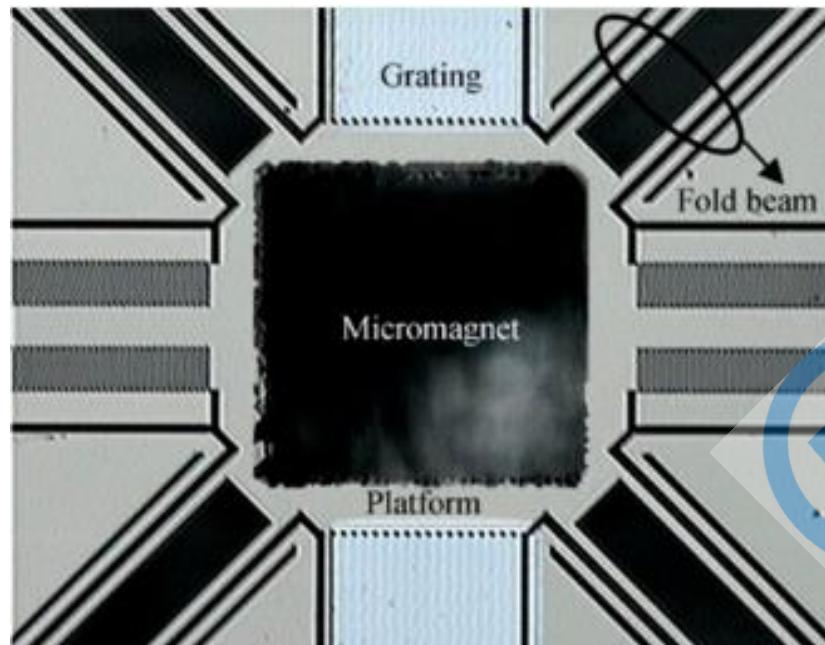
3) 电磁驱动的in plane & out of plane案例



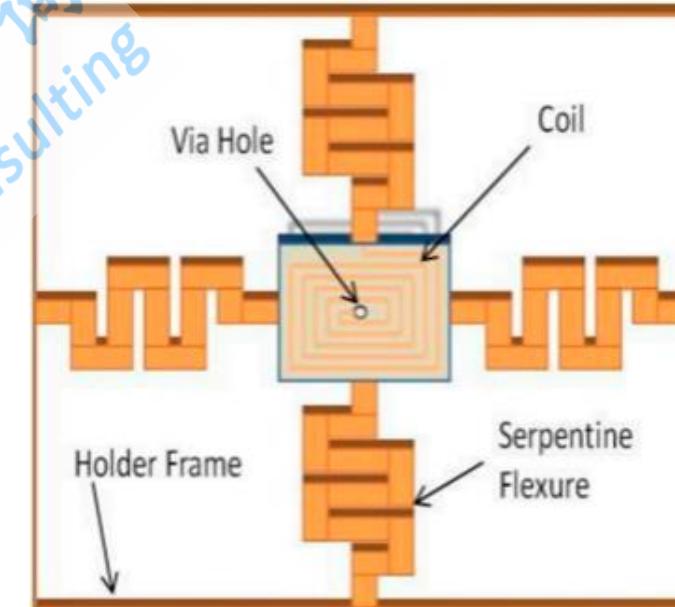
产生电磁力（洛伦兹力），需要磁场和通电线圈，磁场和通电线圈的布置方式决定了是out of plane还是in plane运动方式

MEMS动镜的分类、原理、设计与制造

3) 电磁驱动的in plane & out of plane案例



磁铁在镜面上^[1]



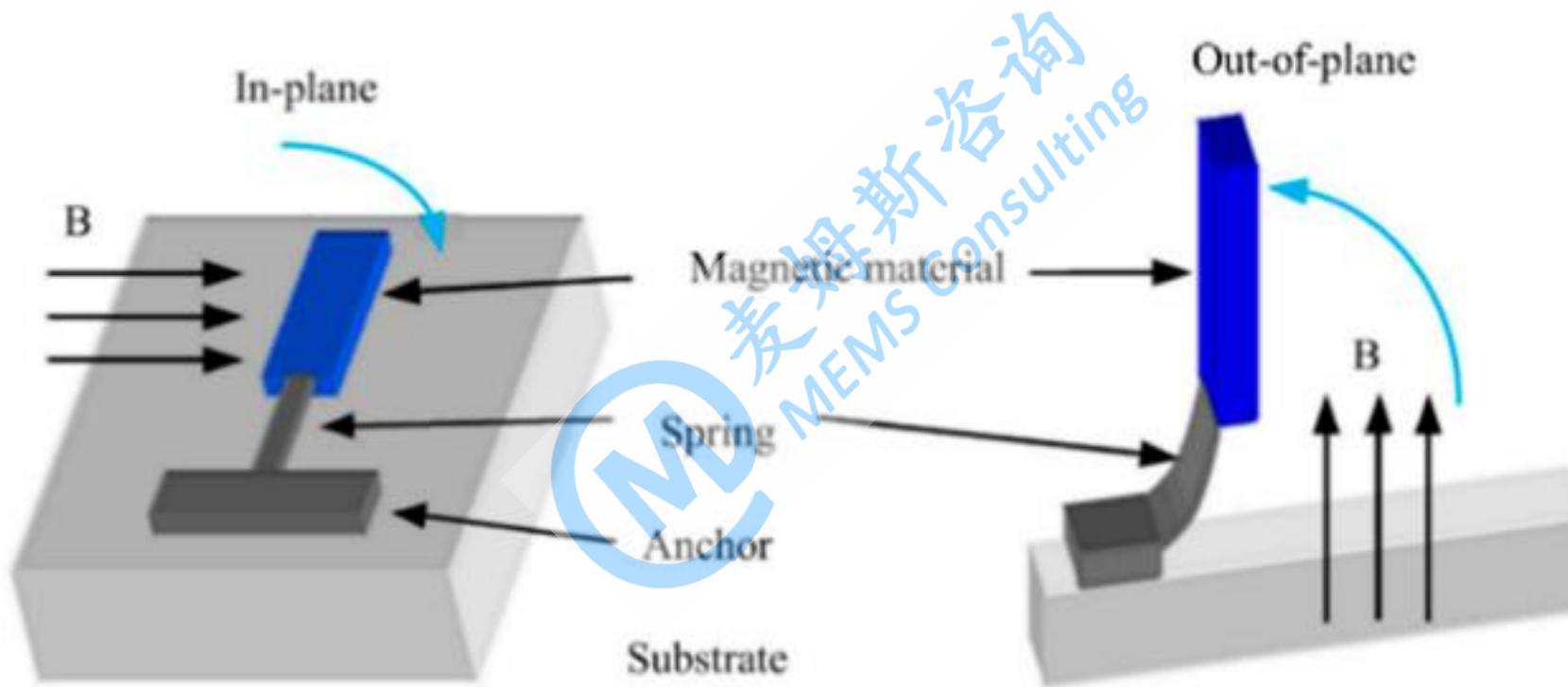
线圈在镜面上^[2]

参考文献:

- [1] An electromagnetically driven Lamellar grating based Fourier transform microspectrometer. J. Micromech. Microeng. 2008
- [2] FR4 Electromagnetic Scanner Based Fourier Transform Spectrometer. In Proceedings of the Volume 2: 31st Computers and Information in Engineering Conference, Parts A and B; ASME International: New York, NY, USA, 2011

MEMS动镜的分类、原理、设计与制造

3) 电磁驱动的in plane & out of plane案例



改变磁路布置，可以在in plane和out of plane之间变换

MEMS动镜的分类、原理、设计与制造

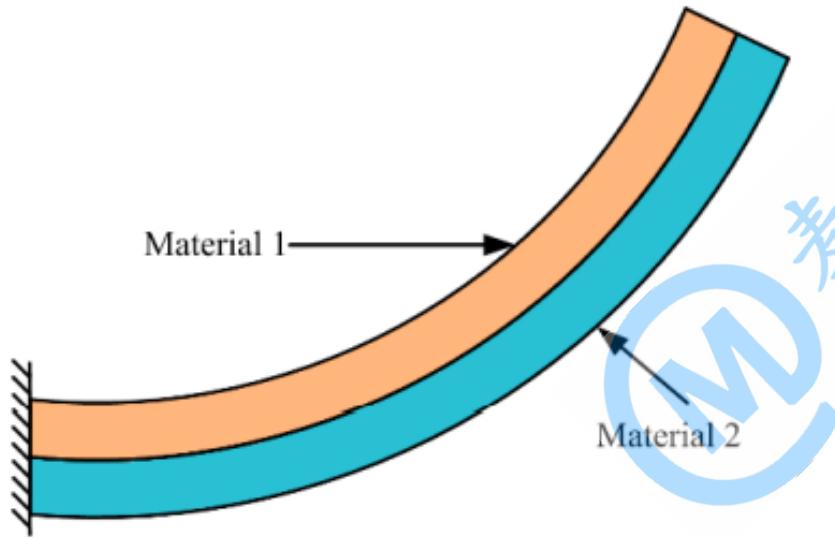
3) 电磁驱动的in plane & out of plane案例

Authors	Institution	Actuation Type	Core of FTS	Displacement	Work Condition	Device Size
Wallrabe et al.	Uni Freiburg and FK	Lorentz-type	MI	110 μm	12 mW	Entire FTS: 11.5 \times 9.4 mm^2
Yu et al.	NUS and DSI	Lorentz-type	LGI	125 μm	129 mA-amplitude	-
Baran et al.	KU	Lorentz-type	MI	325.6 μm	120 mVpp @ 149 Hz	MEMS chip: 7 \times 8 cm^2 (Mirror: 1 \times 1 cm^2)
Xue et al.	RU	Magnetic pole-type	-	123 μm	400 mA.	Mirror: 2 \times 2 mm^2
Xue et al.	RU	Magnetic pole-type	-	144 μm	140 mA	Mirror: 2 \times 2 mm^2

电磁驱动，力量大，位移大。但是磁路的存在，增大了体积，降低了集成度，同时磁路的装配引入了对准误差

MEMS动镜的分类、原理、设计与制造

4) 热驱动的in plane & out of plane案例



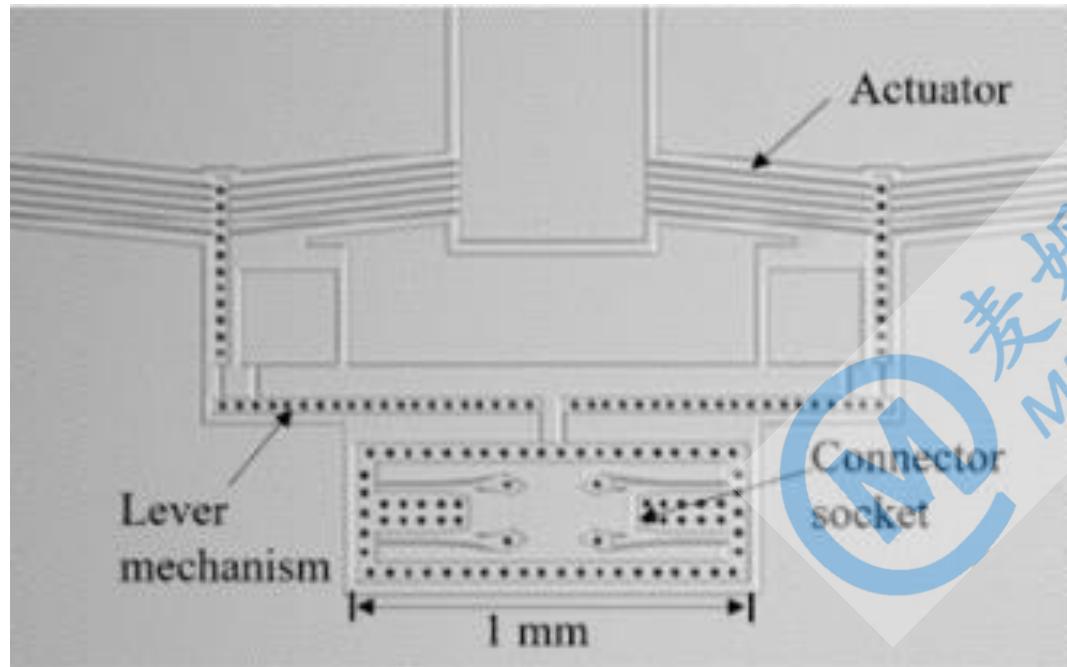
不同材料组成的热驱动器



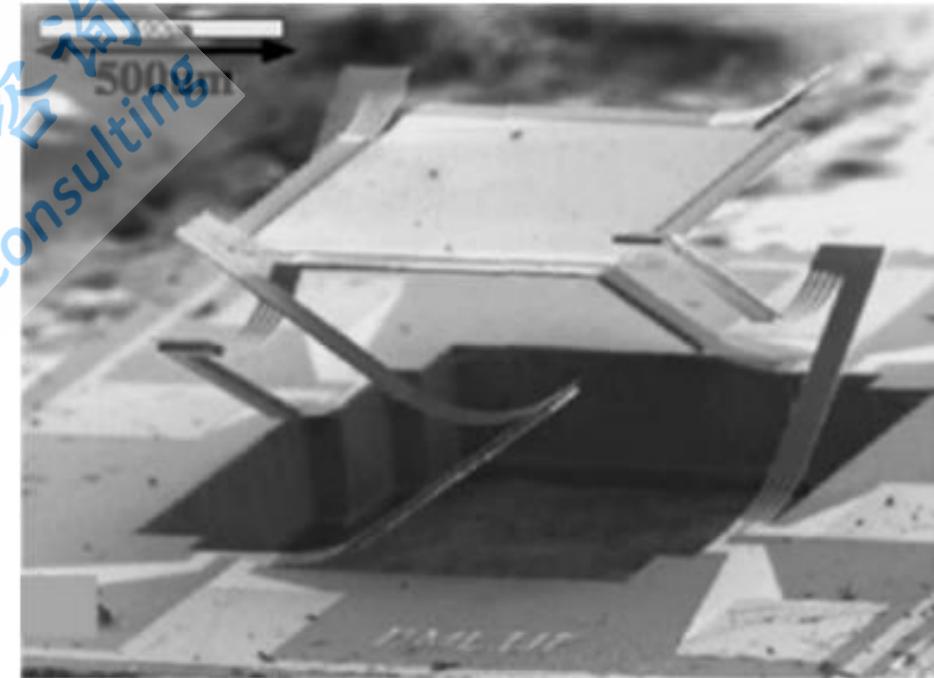
相同材料组成的热驱动器

MEMS动镜的分类、原理、设计与制造

4) 热驱动的in plane & out of plane案例



In plane运动的热驱动器^[1]



Out of plane运动的热驱动器^[2]

参考文献:

[1] Assembled Fourier transform micro-spectrometer. Proc. SPIE, 2006

[2] A large vertical displacement electrothermal bimorph microactuator with very small lateral shift. Sensors Actuators A Phys. 2008

MEMS动镜的分类、原理、设计与制造

4) 热驱动的in plane & out of plane案例

Authors	Institution	Actuation Type	Core of FTS	Displacement	Work Condition	Device Size
Sin et al.	UTA	In-plane	MI	30 μm	22 V	Entire FTS: $10 \times 10 \text{ mm}^2$ (Mirror: $0.5 \times 0.45 \text{ mm}^2$)
Das et al.	UTA	In-plane	MI	45 μm	45 V	Entire FTS: $10 \times 10 \text{ mm}^2$ (Mirror: $1 \times 0.8 \text{ mm}^2$)
Reyes et al.	BML	In-plane	MI	600 nm	-	-
Wu et al.	UF	Out-of-plane	-	620 μm	5.3 V.	-
Wu et al.	UF	Out-of-plane	MI	131 μm and 308 μm	-	Entire FTS: $12 \times 5 \times 5 \text{ cm}^3$
Wang et al.	SJTU and UF	Out-of-plane	MI	550 μm	7 V DC	MEMS chip: $4.3 \times 3.1 \text{ mm}^2$ (Mirror: $1.1 \times 1.1 \text{ mm}^2$)
Samuelson et al.	UF	Out-of-plane	-	90 μm	1.2 V DC	MEMS chip: $1.9 \times 1.9 \text{ mm}^2$ (Mirror Aperture: 1mm)
Chai et al.	USST, WiO Tech, and UF	Out-of-plane	MI	200 μm	5 Vpp @ 5 Hz	MEMS chip: $3.65 \times 11.4 \text{ mm}^2$ (Mirror: $1.4 \times 1.2 \text{ mm}^2$)

热驱动，力量大，位移大（比电磁驱动和静电驱动都大）。但是因为加热和散热的延时，热驱动的响应速度慢，容易受到环境温度的影响

MEMS动镜的分类、原理、设计与制造

不同驱动方式MEMS动镜的综合比较

Various Actuators	Advantages	Disadvantages
Electrostatic actuators	Fast response	Vacuum package and resonance operation
	Low power consumption	Limited displacement Pull-in behavior
Electromagnetic actuators	Moderately large displacement	External magnetic field needed Large size
Electrothermal actuators	Large displacement Moderately fast response	Large power consumption Sensitivity to environmental temperature changes

总结

- 1、In plane运动的MEMS动镜更好的把整个迈克尔逊干涉仪一次性制备到单芯片上，减少装配引起的光路偏差；
- 2、静电梳齿驱动的MEMS动镜能易于准静态控制，受温度影响小，不需要外加任何驱动辅助元件，基本上是全硅工艺，工艺集成度高，和半导体工艺兼容性好

感谢大家
的聆听

