Precise and fast measurement of dimensional parameters. Present and future potential of lasers

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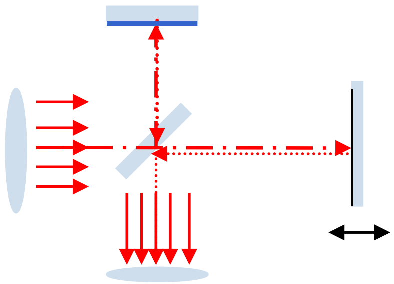

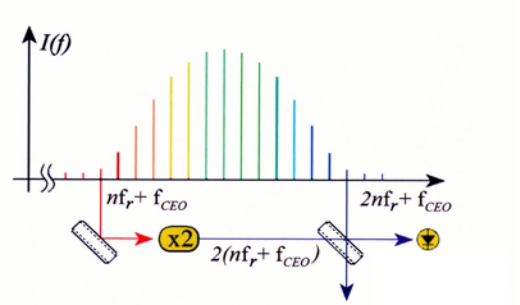

Sensorsysteme, Lichtenwalde 2012

ORGANISATION OF THE TALK

INTRODUCTION

1. OPTICAL APPROACHES. “ANTE (OR WITHOUT) LASER!”

2. WHICH LASER PROPERTIES ARE DECISIVE?

3. ADVANCED SOLUTIONS VERSUS PRESENT & FUTURE DEMANDS

4. SUPER PRECISION. THE FREQUENCY COMB

SUMMARY & OUTLOOK

LIMITS FOR DIMENSIONAL PARAMETERS

FUNDAMENTAL SCIENCE:	
Planck Length	Cosmos
$4x10^{-35}m$	$1x10^{26}m$
APPLIED SCIENCE:	
$\Delta\lambda$	Earth-Moon
$1x10^{-17}m$	$4x10^{8}m$
INDUSTRIAL PROCESSING:	
Δd	**ΔL**
$1x10^{-12}m$ (Urmeter: Δd= $2X10^{-7}m$)	**$10^{5}m$**

WHERE DOES THE FUTURE IMPORTANCE OF PRECISION MEASUREMENTS ORIGINATE FROM?

SCIENCE & WORLD WIDE MEGA TRENDS

fitting micro & macro world | aging, globalisation, resources, environment

↓

NEEDS OF PERSONS, GROUPS, STATES, WORLD

energy food accommodation health mobility IT safety culture leisure

↓

DEMAND FOR PRODUCTS & SERVICES, WITH RELIABLE DIRECT COSTS AND SUBSEQUENT COSTS

↓

THE SENSOR BUSINESS HAS TO FOLLOW THE STRATEGY OF ITS DIRECT CUSTOMERS AND THE FINAL CUSTOMERS!

You have to know the future needs and demands of your customers!

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IDEAL IMAGING, GEOMETRICAL OPTICS. TRIANGULATION. WAWE OPTICS. IDEALS FOR MEASURING

Ideal: Linear and angle-true transformation of the object room into the image room. All lengths can be compared with a unit / etalon.

Optics, optical projection and triangulation: Optics tries to approximate these ideals as close as possible.

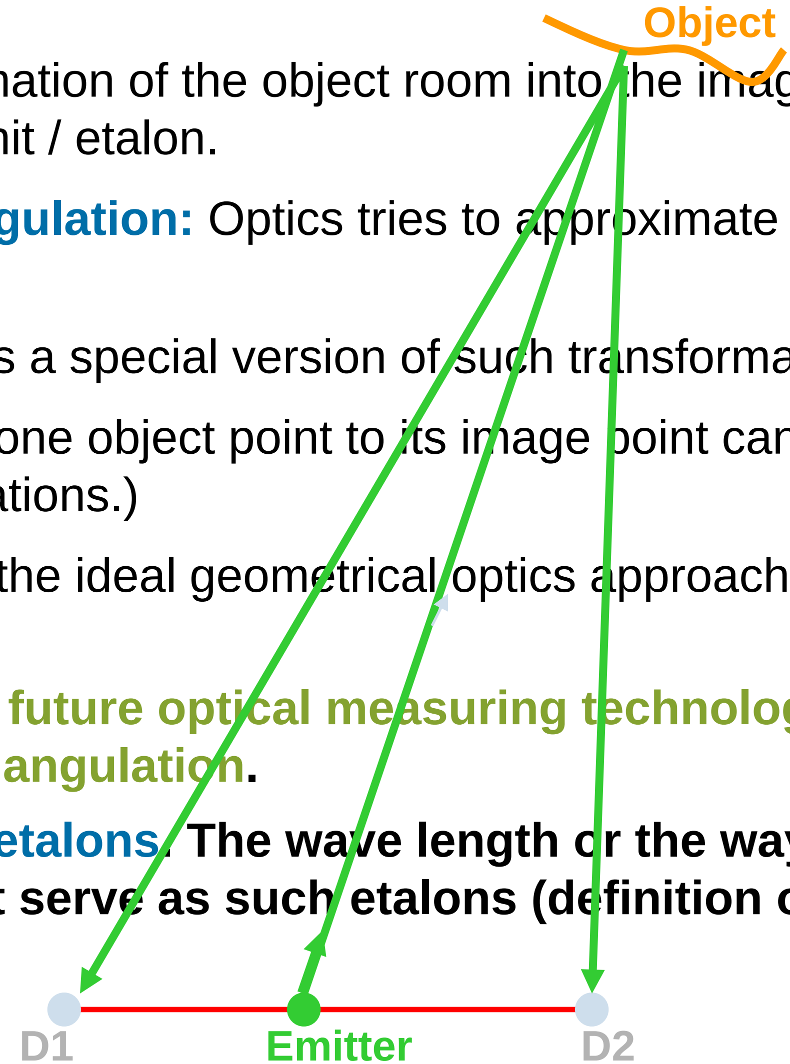
The (ideal & real) geometrical optics is a special version of such transformations.

(The way of “light rays for $\lambda \rightarrow 0$“ from one object point to its image point can be calculated by solving the eikonal equations.)

If the deviations of real systems from the ideal geometrical optics approach zero, only diffraction errors remain.

Measuring technology: **Now and in future optical measuring technology tries to approach ideal projection and triangulation.**

Lengths should be compared with etalons. The wave length or the way, which light travels in a certain time, might serve as such etalons (definition of s & m)



IDEAL SOLUTION? ZERO WAVELENGTH APROXIMATION?

PROBLEM: The interaction between light & matter is rather small for wavelengths below the strong electronic UV bands ($\lambda < 250$nm).

Drawback 1: small reflection at surfaces, “faint pictures“.

Drawback 2: low axial resolution

Drawback 2: optics is more expensive

PARTIAL SOLUTION: Take longer wavelengths, where the influence of diffraction on projection and triangulation results can partially be compensated for by mathematical procedures.

See, e.g.,

N. Erbe, Feingeräte (1972), S. P. Sakhno (1987), Y. V. Chugai (2008)

Other approaches will be discussed in later sections!

EXAMPLE FOR PRECICE AND FAST GEOMETRICAL MEASUREMENT BY USE OF STRUCTURED ILLUMINATION OF OBJECT

Grid projection with adaptable width of “stripes“ (not ante, however without laser!)

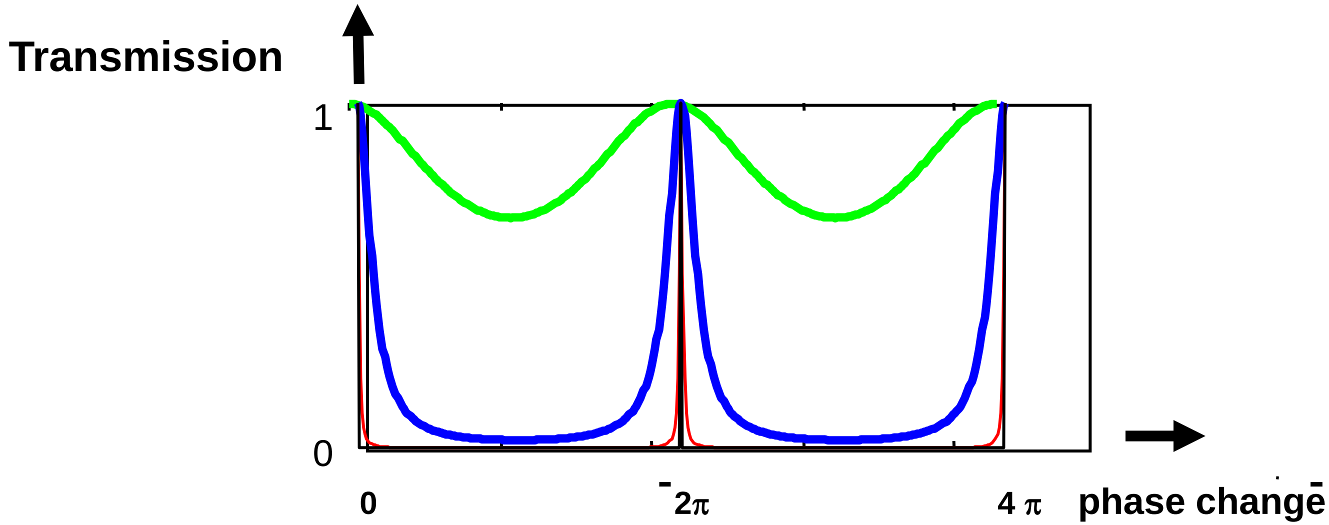
TI Spiegel Array **300.000 object points measured in 40ms: 1.3x10^{-7}s/point**

J. R. Thompson, Laser-Photonik 2008, H. 4, S. 38-41

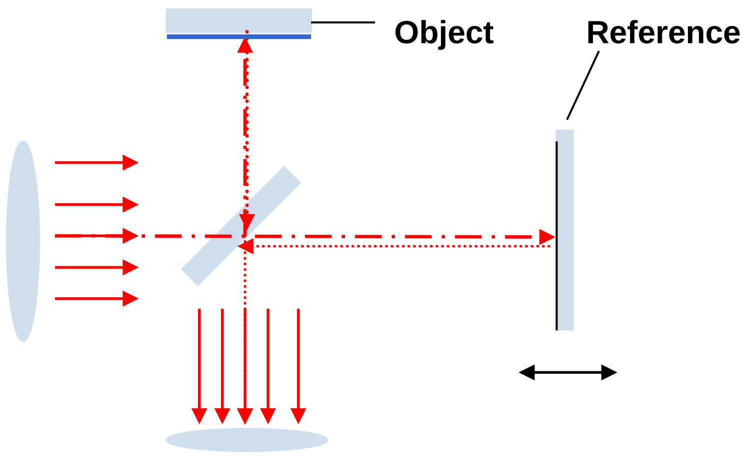
object stripe projection on object cloud of measured points

Simple and fast measuring!

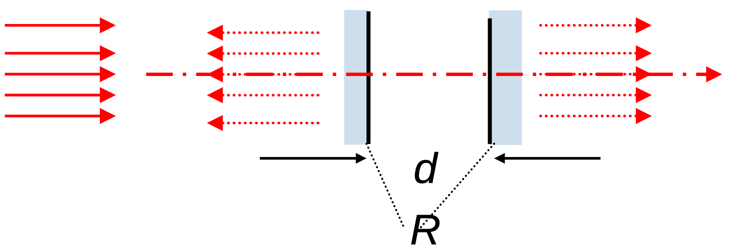
OPTICAL INTERFEROMETRY. Highest precision in length and wavelength measurement for more then 100 years



Michelson Interferometer (2 beams)



Fabry-Perot Interferometer (many beams)



Transmission: $T = I_t/I_0 = 1/[1+F\sin^2(\delta/2)]$,

Phase change $\delta = (4\pi n(d/\lambda_0)\cos\Theta$, $(n=1,\ \Theta=0)$

Finesse: $F = [2R^{1/2}/(1-R)]^2$

ORGANISATION OF THE TALK

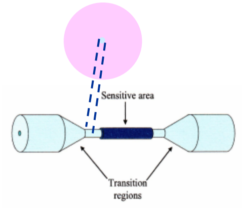
COMPARISON: LASER AGAINST OTHER SOURCES

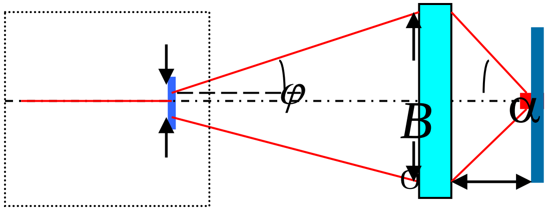
In which properties does laser light differ from light emitted by "classical" (e.g., "thermal") light sources?

Answer: There exist 2 groups of differences?

1. First group: The laser light differs **qualitatively** from "classical" light. From the scientific viewpoint these differences are of fundamental importance. However, in "real life" applications these differences play only a minor part at present and probably also in the next few decades.

2. Second group: The laser light differs **only quantitatively** from "classical" light. **But**, the most important present applications benefit from these differences (and will do so in near future).



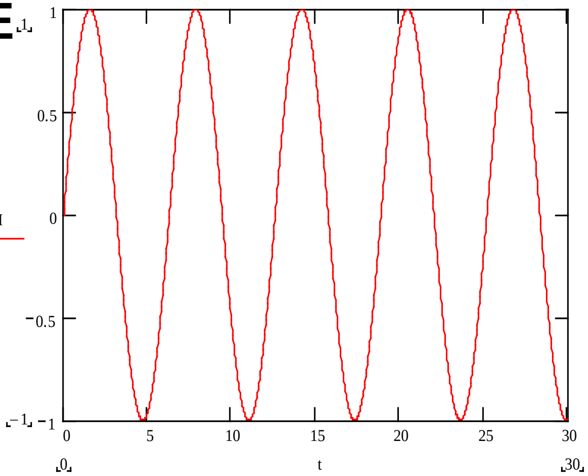


COMPARISON. LASER AGAINST OTHER SOURCES. FIRST GROUP

Fieldstrength E = **A** ·sin(**(**ωt**+φ)**

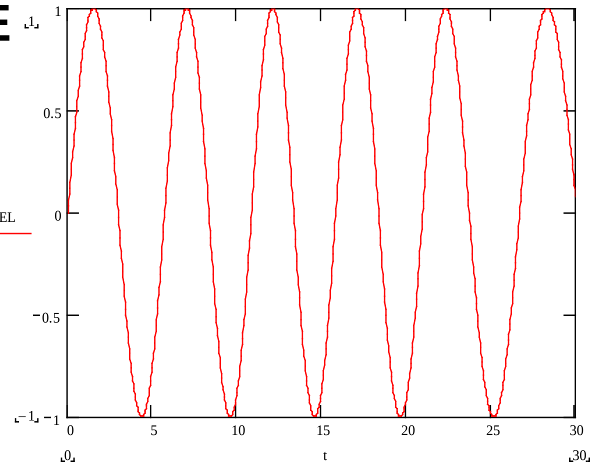
IDEAL EMITTER	**IDEAL LASER**	SONNE/LAMPE

E



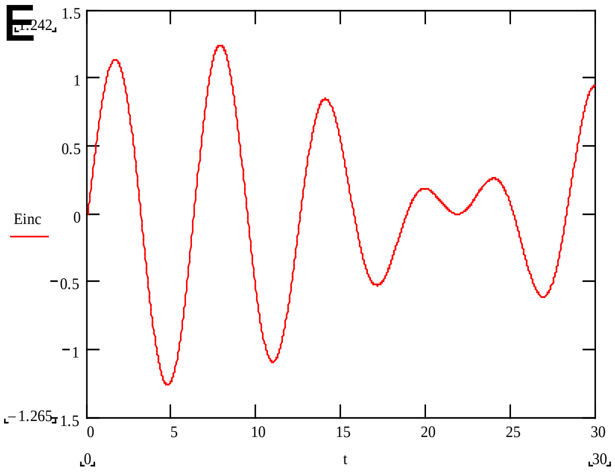
TIME

E



TIME

E



TIME

A & φ STABLE	**φ FLUCTUATES**	**A & φ FLUCTUATE**

ALL 3 LIGHT WAVES CAN BE DESCRIBED CLASSICALLY! RARELY QUANTUM EFFECTS!

COMPARISON. LASER AGAINST OTHER SOURCES. FIRST GROUP.

1.) Spontaneous emission, which acts as noise in the laser as a nonlinear noise generator with feedback, is a quantum effect. **But it is very small in the high output of "good" lasers!**

2.) Higher order (>2) fieldstrength correlations,

e.g. $\langle E_1E_2E_3E_4 \rangle$, intensity correlations, anti-bunching of light, squeezed states

Appl.: increase of SNR: **(Time until economic success world wide)** **T_{ESWW} ~10 years**

3) Entanglement (Verschränkung) of photons

+ Measurement of one of two entangled photons delivers complete information on the second one. **Appl.: security in communication** **T_{ESWW} ~10-15 years**
+ Measurement of both photons increases signal noise ratio.

  Appl.: spectroscopy, diagnostics in health care **T_{ESWW} ~10-15 years**
+ Allows to "play" around with Heisenberg's uncertainty relation.

  "weak L. A. Rozema et al. Sept. 2012, " (non-demolition) measurements

  Appl.: high resolution & accuracy (detection of grav. waves) **T_{ESWW} ~25 years?**
+ Quantum computation: **breaking long codes** **T_{ESWW} ~30 years**

Present state: great science & great fun, small money!

COMPARISON. LASER AGAINST OTHER SOURCES. SECOND GROUP

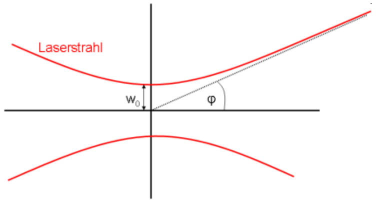
Bandwidth, divergence, spatial coherence, width at focus

Thesis 1: Any value of named parameters attained by use of existing lasers can principally be achieved by passive filtering light from thermal light sources.

Thesis 2: **But:** In reality, the loss by spatial & spectral filtering of light from thermal sources is prohibitively large in many, many applications! Costs! Environment!

Conclusion: Lasers are the cheaper and smaller sources in many applications!

Example: efficiency of high power LD[1] : > 85%

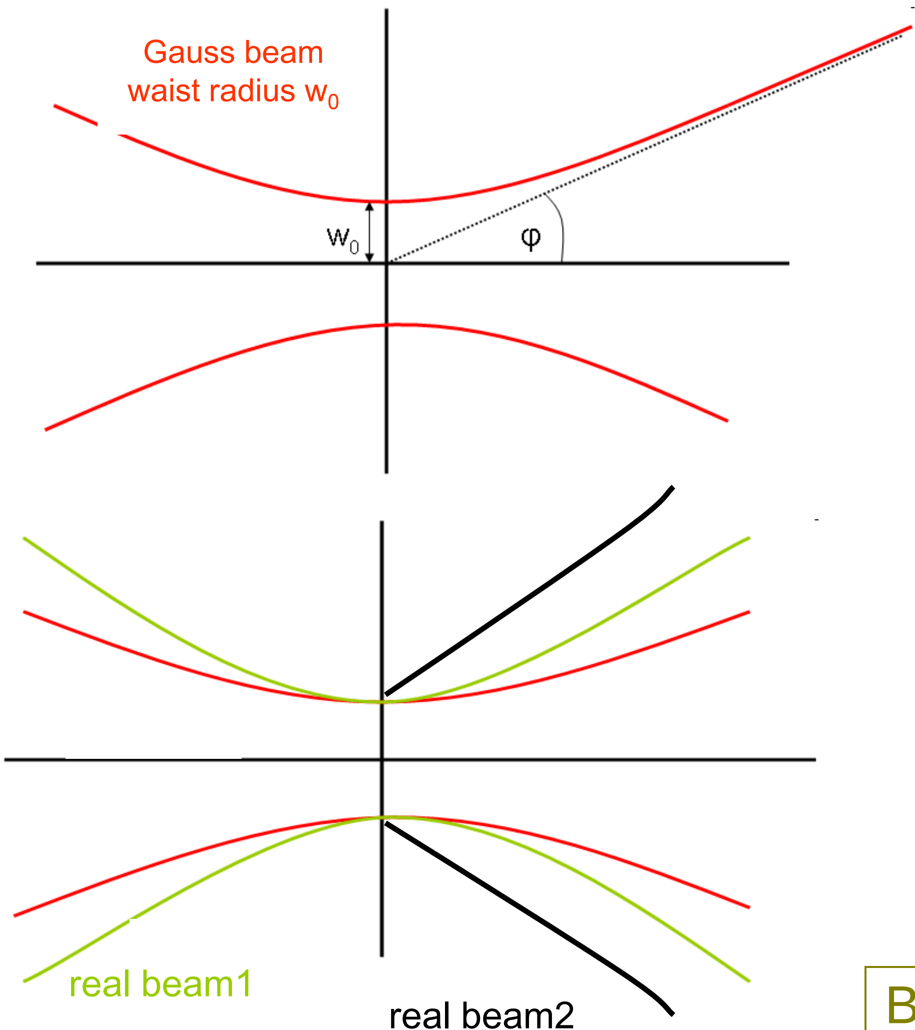


Small lasers instead of huge power plants!

Small science, but great application & money!

[1] **(laser power) / (electric power at electric wall socked)**

SUPERIOR QUALITY OF LASER BEAMS IN PROPAGATION



Comparison of real laser with ideal TEM_{00} Gauss beam

beam-parameter-product:

$BPP = w_0 \bullet \varphi = M^2 \bullet (\lambda/\pi)$

diffraction measure: M^2,

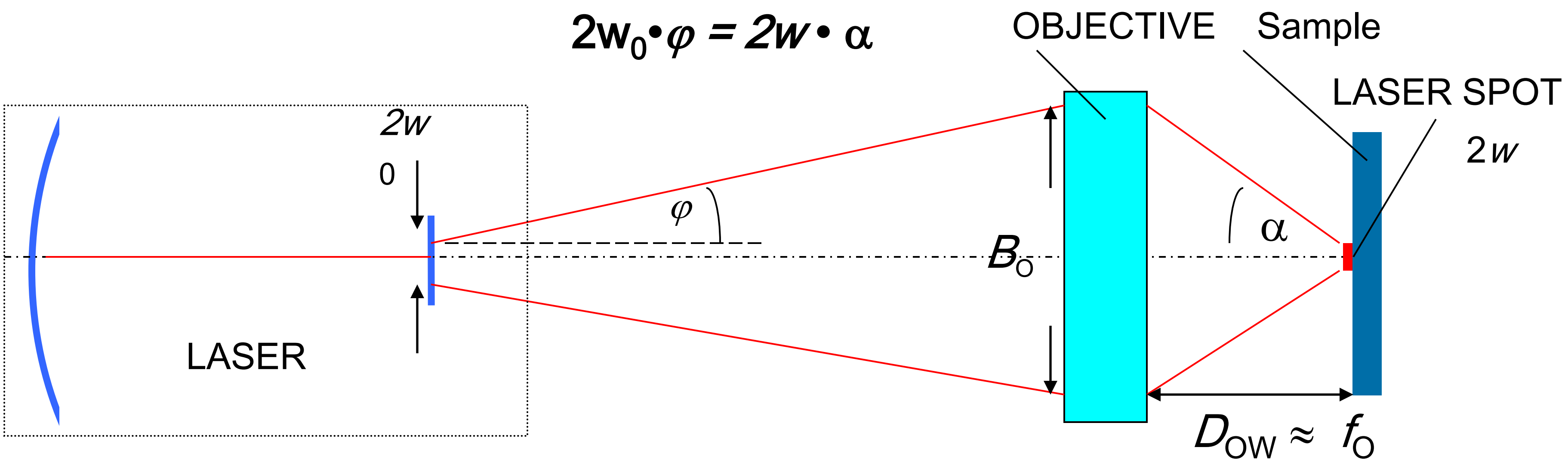
Gauss: $M^2 = 1$, real sources : $M^2 > 1$

“good“ lasers: $M^2 < 1{,}1 - 2$

Excellent lasers: (e.g., kW fiber laser $M^2 = 1{,}05$)

BPP is invariant in beam propagation through passive optical systems!

IMPORTANCE OF BEAM PARAMETER. QUALITY VERSUS COSTS!



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SUMMARY & OULOOK

PRESENT TOP DEMAND: MICRO/NANO LITHOGRAPHY

Lithography Systems –

(High precision - large extension!)

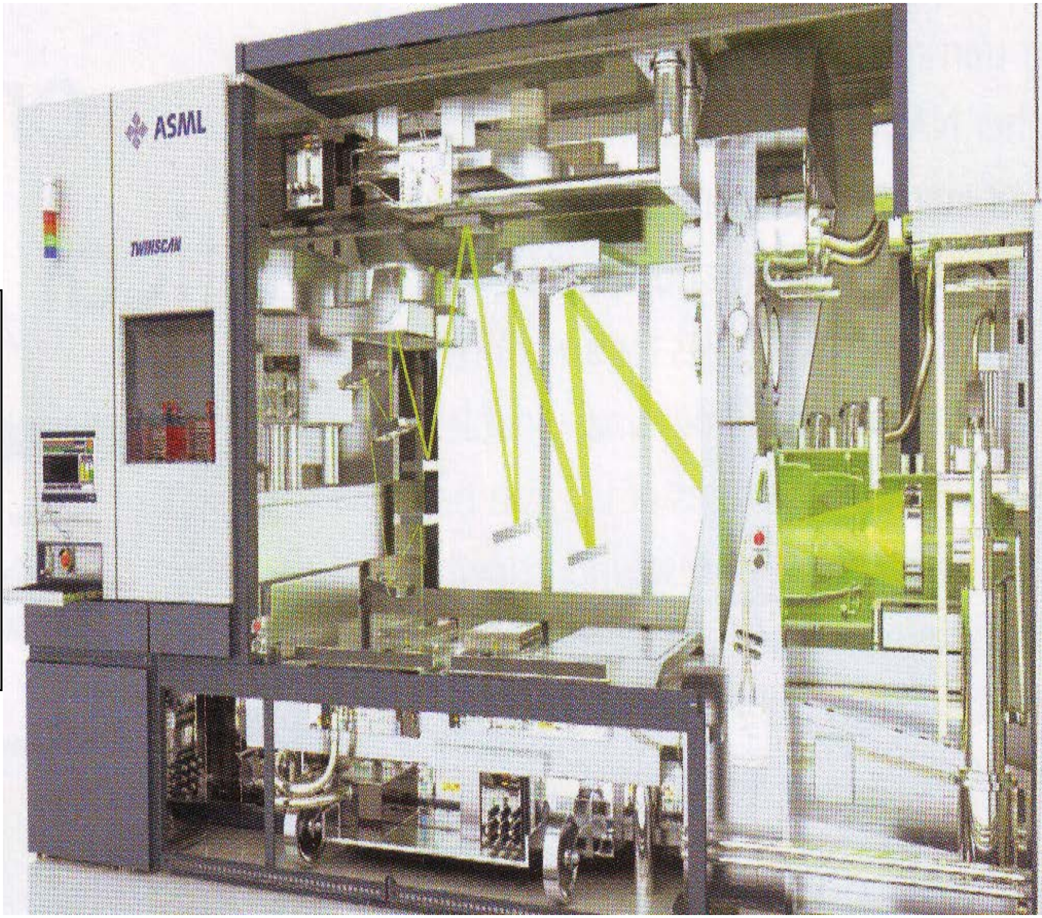
(ASML; CANON; NIKON):

10^{13} Pixel/Image

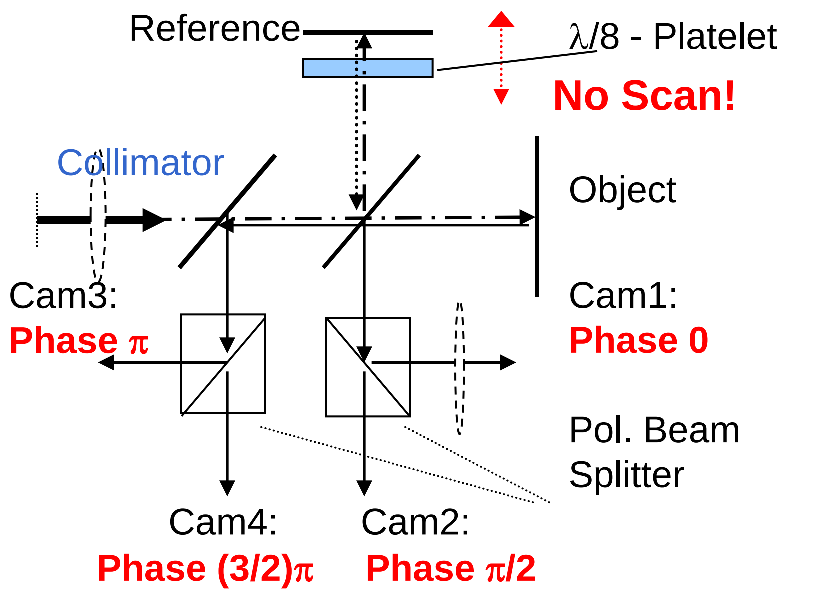
Resolution ≈ 10nm, precision ~ 0.1nm

Quality of optical surfaces:

- shape < 0.05 nm
- layer thickness < 0.05 nm
- roughness: < 0.2 nm

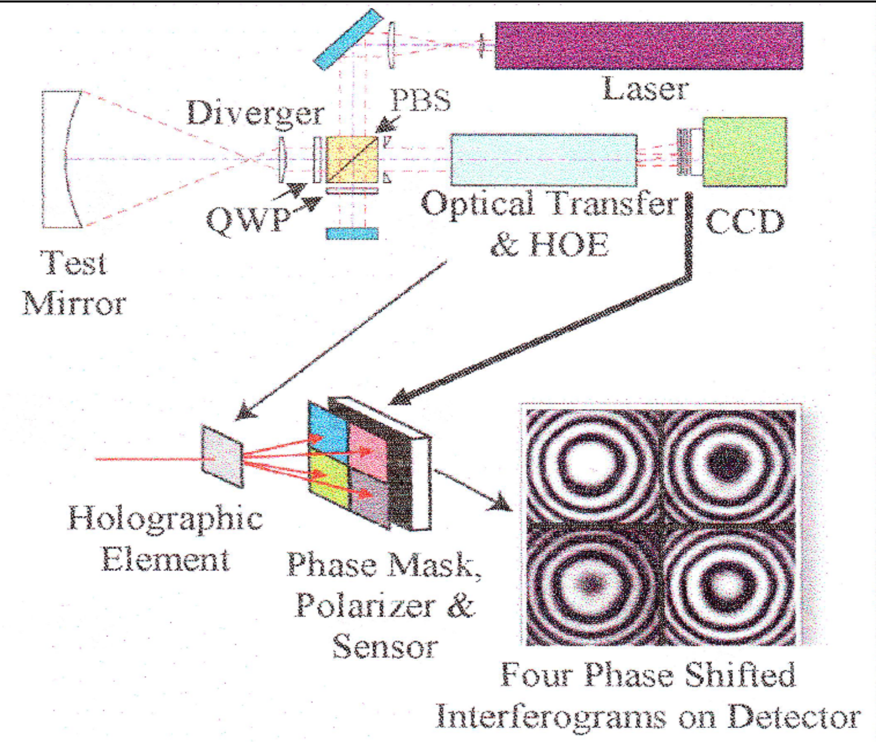


PRECISION WITH LARGE OBJECTS? DYNAMIC LASER INTERFEROMETERS!



N. Brock et al., www.optics.arizona.edu, 2005

C. Holton, Laser Focus World , Feb. 2008



- Object extension and distance to camera up to 10m, also out of lab and clean room!
- No movable parts, simultaneous comparison with several references!
- Almost no influence of vibrations and atmospheric changes (averaging in picture, sequence!),

Large high precision parts (errors < 1nm)!

ONLY LARGE SENSORS, e.g., INTERFEROMETERS? SOLUTION: INTEGRATED OPTICS OR FIBER TECHNOLOGY

State of the art:

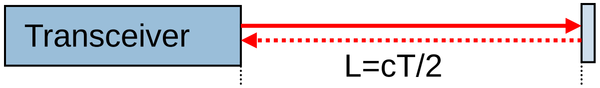
THORLABS, 2012

Fiber Sensors

Bragg Gratings

Fabry-Perot I.

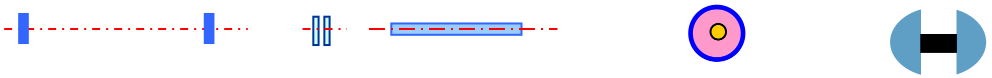
Laser Radar Sensors



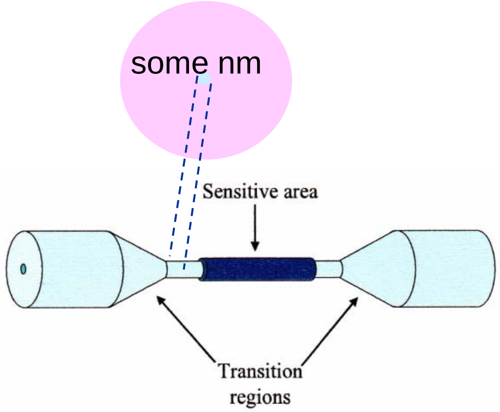
Reflector

L: Present Limits: 10^{-6}m – 10^{11}m

R&D, Future:



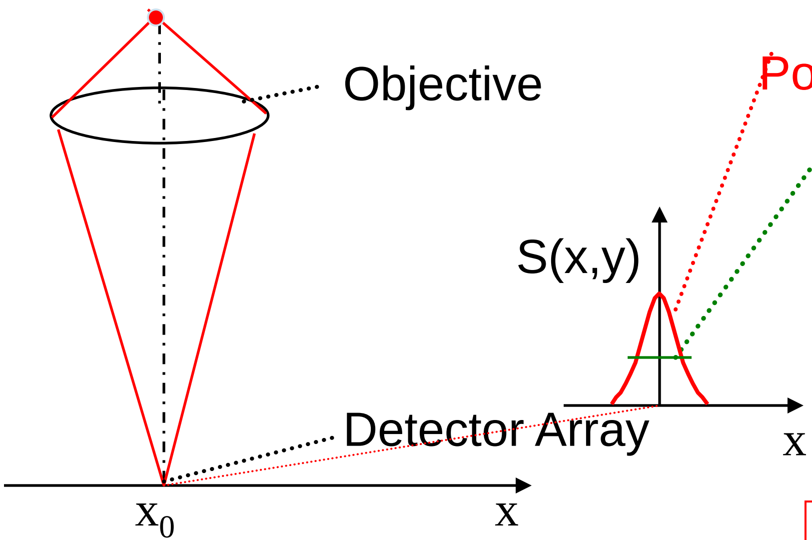
Mie L.	FP L.	Nano Fiber L.	SP L.	LC Res.
λ/5	λ/2	100nm	50nm	λ/10



PRECISION OF POSITION

Basic radiation proce

The position of small objects (or “sharp“ edges or spots at large objects) can be measured by optical means where the error can decreased to values orders of magnitude below the far field resolution λ/2.



$$\Delta x_0 = \frac{1}{\sqrt{2\pi \ln 2}} \frac{\delta}{\sqrt{n_{total}}} \approx 0.3 \frac{\lambda}{\sqrt{n_{total}}}$$

position error = wavelength/ √(number of photons)

B. Wilhelmi 2003

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SUMMARY & OULOOK

THE PROBLEM:

Time, frequency and length have been the most precisely measured physical parameters already for about 100 years, where optics played an important part.

However, increases in accuracy were achieved by strongly rising expenses:

The problem for realisation of the second, meter and all derived quantities consisted in the difficulty to couple the frequency of optical radiation phase-sensitively to the radiation of radio waves, this means over 9 orders of magnitude (large clean rooms with various high precision lasers, magnetrons, klystrons and fast counters):

$$f_{VIS} \rightarrow m \bullet f_{NIR} \rightarrow n \bullet f_{MIR} \rightarrow p \bullet f_{FIR} \rightarrow q \bullet f_{MW} \rightarrow r \bullet f_{HF}$$ (*m, n, p, q, r* whole numbers)

About one decade ago Th. Hänsch et al. introduced the so called frequency comb, which works as a substitute for the complete chain:

$$f_{VIS} \rightarrow r \bullet f_{HF}$$

The frequency of a VIS or NIR laser is coupled in one step to an electronic HF oscillator! **From large hall to table top!**

Far higher precision at far smaller costs! Rare example in science!

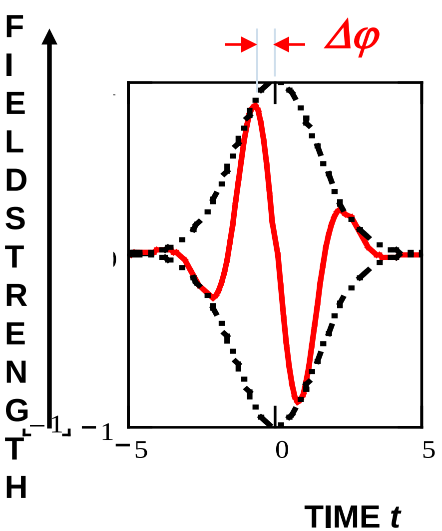
FREQENCY COMB: MEASUREMENT & CONTROL OF shift δ

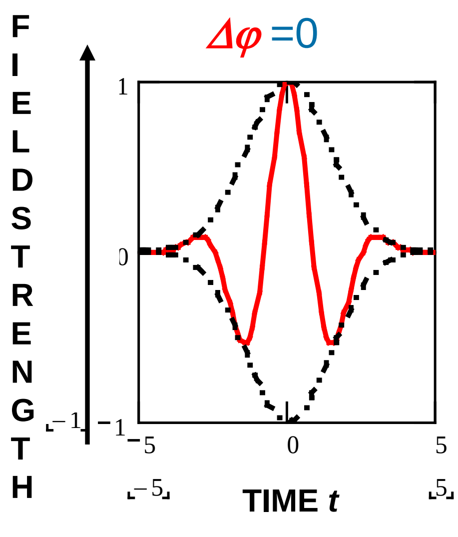
Chance for measurement :

Control of shift $\Delta\varphi$ between pulse maximum and nearest maximum of carrier wave!

Advantage: drawbacks (or limitations) of interferometers at large distances on the one hand side and laser radar at small distances on the other hand can be overcome.

Laser radar and interferometer in one device: one measurement!
Interferometric accuracy up to very large lengths!





Interferometric laser radar:
Wilhelmi, Metr. Abh. 8, 47-63, 1988, rapid absolute, not only slow incremental position measurement!
Unsolved Problem: No control of distance between maxima of pulse envelope and carrier.

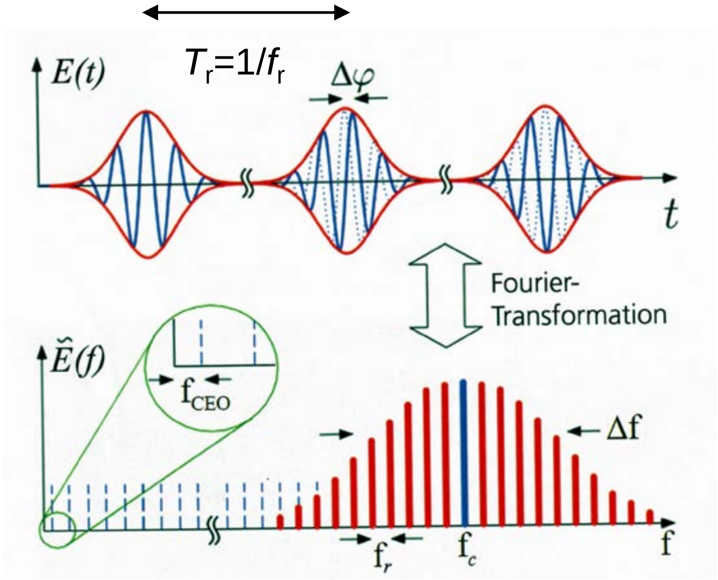
Solution:

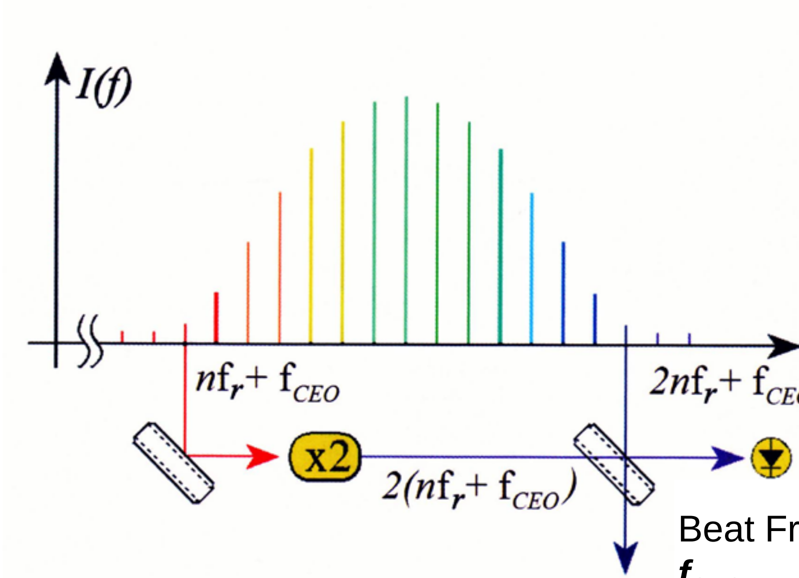
T. Hänsch et al. 2000

Mini Devices:

C. Wang et al. 2011
C. Philips et al. 2011

FREQENCY COMB: MEASUREMENT & CONTROL OF TIME SHIFT $\Delta\varphi$ & CARRIER-ENVELOPE OFFSET FREQUENCY f_{CEO}





carrier-envelope-offset frequency (CEO) f_{CEO}= beat frequency=$2(nf_r + f_{CEO}) - (2nf_r + f_{CEO})$

Conclusion: All frequencies of the "comb" which extends over more than 1 octave can be composed of of f_{CEO} and multiples of f_r where both can be precisely controlled by standard counting methods.

2005 Nobel Prize (Hänsch), 2011 completely integrated mini device (D, CH, F, US), 2012 relative frequency error of some 10^{-17}, commercial devices (by Menlo, Coherent, IMRA) since 2005.

Great future, in science (metrology & spectroscopy) **& economy!**

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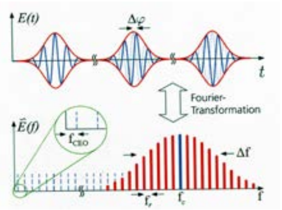
Summary:

SINCE THE ADVENT OF LASERS OPTICAL SENSORICS HAS BECOME VERY IMPORTANT FOR MANY REASONS:



+ accuracy, gauging & calibration,

+ resolution, reproducibility,

+ integrability and miniaturisation (micro & nano),

+ low energy consumption.

Outlook:

Feeling strong difficulties and even danger in the main crowd, a well known racing driver claimed:

“In front is plenty of free space! One should make use it!”

Later on he had to realize huge obstacles within this simple recipe!

Fortunately, the difficult future tasks in the complex branch of laser sensorics allow other approaches:

WE CAN AND SHOULD COOPERATE WITH MANY OTHERS, AMONG THEM OUR COMPETITORS!

THANKS FOR YOUR ATTENTION!

I HOPE FOR MANY REMARKS AND SUGESTIONS, today or later!