ECE1461
Advanced Laser Processing

LASER TYPES

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http://photonics.light.utoronto.ca/laserphotonics

Laser Types – I

- For More Depth: *Follow Svelto: Principles of Lasers 4th Ed; Reading sections identified below*
- Also useful: *Hechts' The Laser Guidebook*
- Types of Lasers
  - 9.2 Solid State Lasers: glass, crystal; not Semiconductor
    - 9.2.2.1 Nd:Yag Laser; 9.2.2.2 Nd: Glass
    - 9.2.2.3 YLF, YVO4; 9.2.3 Yb:YAG Laser, 9.2.5 Tm:Ho:YAG, (no class notes)
    - 9.2.6 Fiber Lasers
    - 9.2.8 Titanium Sapphire Laser
  - 10.2 Gas Lasers
    - 10.2.1.1 Copper Vapour
    - 10.2.2 Ar-ion Laser (not HeCd)
    - 10.2.3 Molecular Gas: 10.2.3.1 Co_2 Laser; 10.2.3.4 Excimer Laser
  - 9.4 Semiconductor Diode - overview different geometries; no equations or physics
  - *Curiosity Lasers*: Dye, Chemical, Colour Centre, Free Electron Laser, X-Ray Laser, Gaser (Gamma Ray)

Laser Types – II

- 10s of thousands of different laser transitions have been demonstrated
- Classify by type of lasant (material) and energy pumping method
- Only a handful enjoy wide commercial successful
- **Pumping – 3 Important Types**
  - **Optical Pumping:**
  - **Electrical Discharge, EM Microwave Pumping**
  - **Semiconductor Diodes: e-h injection**
- **Others:** Chemical, Colour Centre, Free Electron Laser, X-Ray Laser, Gaser (Gamma Ray)

Laser Types – III

- **Optical Pumping:** flashlamp, laser, Semiconductor diodes
  - **Solid State:** ion doped optical glass, crystal, ceramic; not Semiconductor
  - Nd:Yag; Nd:Glass; YLF, YVO4; Yb:YAG, Tm:Ho:YAG
  - Rods, disks, optical fiber
  - Titanium Sapphire – short pulse forefront
  - **Liquid**: various dyes in solution…i.e. Jello! *--rare in laser processing*
  - **Gas:** not efficient
- **Electrical Discharge,** EM Microwave Pumping: **Gas lasers**
  - CO_2 gas: longest wavelength – 10 um; lower cost; big and medium
  - Metal Vapours: Copper, gold – now rare in laser processing
  - Ar-ion: becoming displaced by frequency doubled solid state and fiber lasers
  - Excimer Laser: KrF, ArF, other diatomics: high power shortest wavelength
- **Semiconductor Diodes: e-h injection**
  - compact, low cost, long lifetime, popular pump source, multiple VIS, Near IR wavelengths
- **Others:** Chemical, Colour Centre, Free Electron Laser, X-Ray Laser, Gaser (Gamma Ray)

Solid State Lasers

- Nd:Yag as example
- Lamp and diode pumping
- Frequency Conversion (harmonic generation)
- Power scaling (amplifiers)
- Fiber lasers

9.2 Solid State Lasers

(read all except 9.2.1, 9.2.7, 9.2.9)

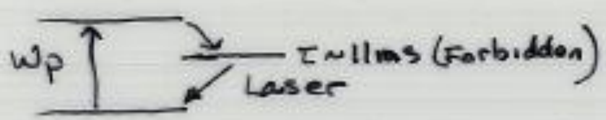
- solid state lasers v. different from semiconductors

– dope transition elements into glass or crystal →
  lasant ions are Cr^{3+}, Nd^{3+}, Er^{3+}, Ho^{3+} etc.

– transition "inner shell electrons" less sensitive to crystal fields
  ⇒ small broadening ($\Delta\nu_0$ small)

– laser transition is <u>not</u> electric-dipole allowed
  ⇒ slow decay rates ~ millsecs → easy pumping conditions
  (normal el-dipole transitions in visible τ_{sp} ~ nsecs)

- Cr^{3+}, Er^{3+} : 3 level lasers with pumping rate requirem'ts



$W_p \simeq \frac{1}{t_{sp}} = 10^{-3}$ Hz per atom

not too extreme to be practical

- Nd^{3+}, Ho^{3+} : 4 level lasers

$\tau_{nr} \gtrsim \tau_{sp}$

$$W_p \propto \frac{1}{\sigma\tau} \simeq \frac{1}{\sigma\tau_{sp}} \propto \Delta\nu_{gain}$$

τ small

low pumping rates required!

Nd:YAG Laser

- also glass or crystal
- rods: 3-6 mm dia
  5-15 cm long
- ceramic - new

~~9.2.2~~ Nd : Lasers "4 Level Lasers" (33)

9.2.2.1

- dope Nd → $Y_2Al_5O_{12}$ (Nd: Yag) YVO_4
  displaces Y^{3+} (1% atomic replacement of Y atoms)
- dope Nd → Phosphate or Silicate Glasses
  (~ 3% Nd_2O_3 per weight in glass)

larger doping quenches fluorescence and/or strains crystal.

Energy Level Diagram

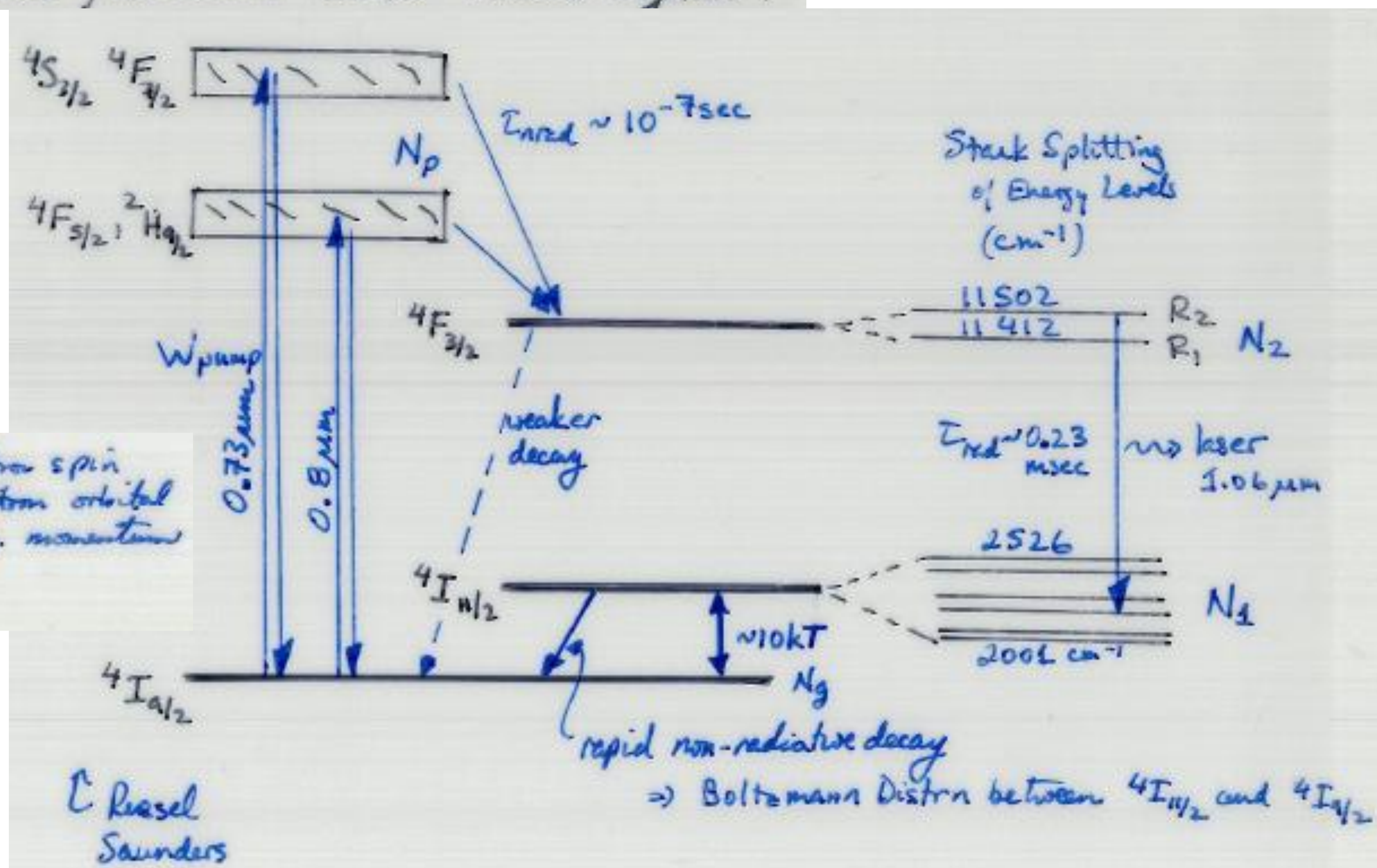
Spectroscopy Russel Saunders Coupling

$^{2S+1}L_J$

$S = \Sigma s_i$ electron spin

$L = \Sigma l_i$ electron orbital ang. momentum

$J = L + S$



$\boxed{\text{Nd: YAG}}$

34

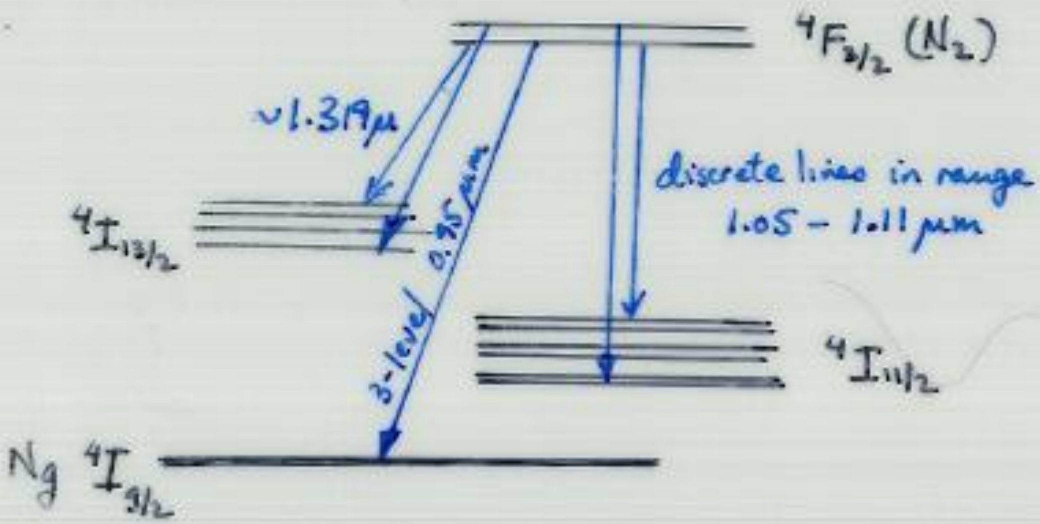
strongest transition: $^4F_{3/2}(R_2) \rightarrow {}^4I_{11/2}$ (3rd lowest level)

$$\sigma = 8.8\times10^{-19}\ \text{cm}^2$$

but treat sub-levels collectively, using partition R_2 level (Boltzmann weighting)

$$\sigma_{eff}(^4F_{3/2}) = 3.5\times10^{-19}\ \text{cm}^2 \text{ in gain calc'ns.}$$

<u>other Nd:Yag laser transitions:</u> (change dielectric mirrors to pre-select desired wavelength)



Nd:YAG laser continued

for $\lambda = 1.06\ \mu m$

lattice phonon collisions

- $\Delta\nu_{Homo} \simeq 6.5\ cm^{-1} = 195$ GHz @ 300K
  ↳ narrow enough for good mode locking
- $\tau_{21} \doteq 0.23$ msec ⇒ good storage reservoir for flash lamp pumping / use Q-switching
- optical pumping configurations + AlGaAs SC LD's
  - all variations are used (helical not popular)
- power available
  $P^{cw\ or\ pulsed} \le$ ~~200 Watts~~ 1-3 kW
  $P^{Q\text{-}switch}_{peak} \doteq 50$ MW

Mode Locking ⇒ 20psec

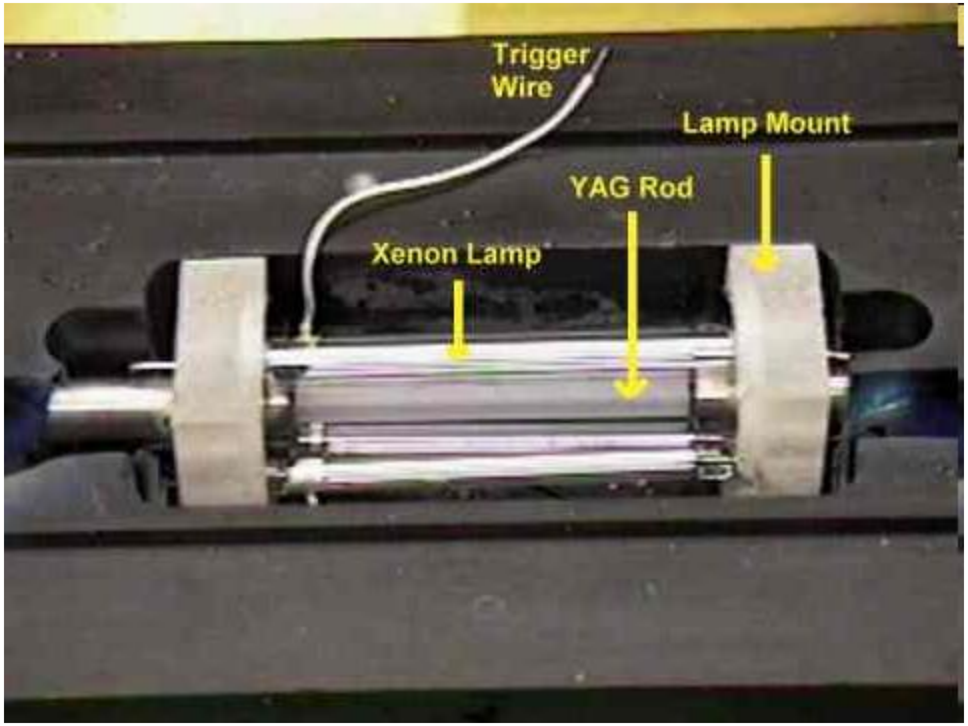
Slope Efficiency ⇒ 1-3%

lamp pumping	1-3kW	cw or pulsed		
SC Diode pumping				
DRILLING	pulsed Q-switch	$>100W_{AVG}$	5-10 J/pulse	1-10ms, 10-100Hz
WELDING	pulsed	$2kW_{AVG}$	fiber delivery (replacing CO_2 lasers)	
MEDICAL	cw	50W	fiber → endoscope → internal (non-invasive surgery) coagulation + tissue ablation	

15W Longitudinal pumping

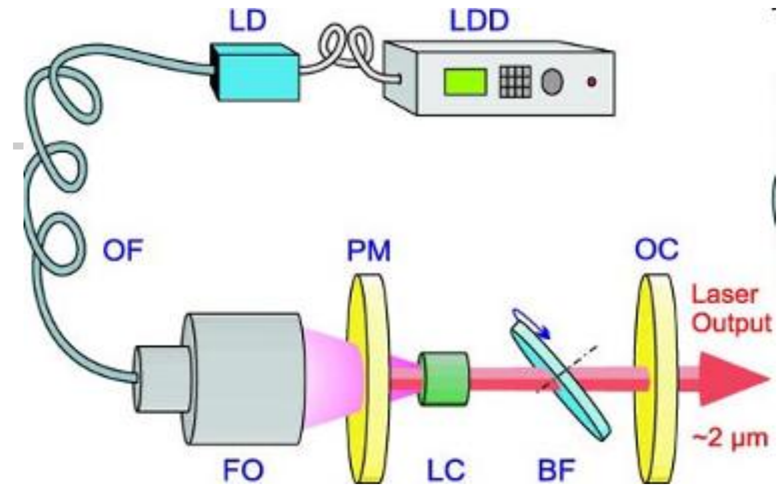
>100W Transverse Pumping

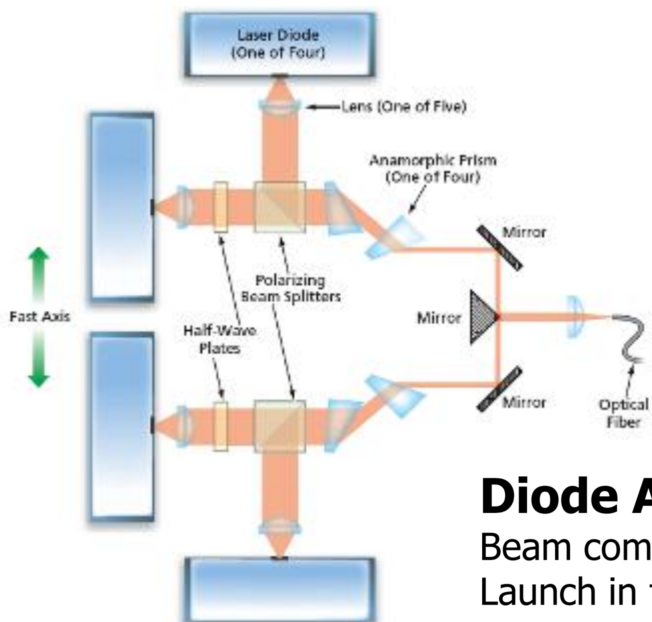
Xenon Lamp Pumped Nd:YAG laser



Diode Pumped Solid State Laser: DPSSL

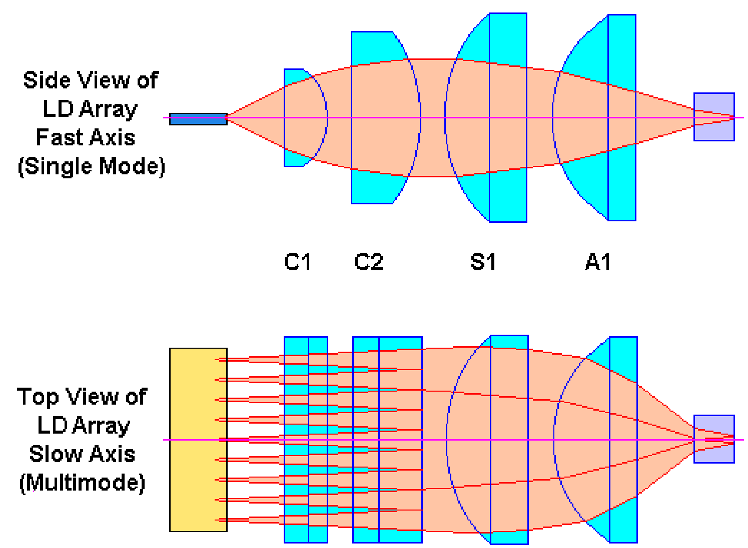
A diode-pumped thulium laser uses a birefringent filter (BF) to provide wavelength tuning. The laser crystal (LC) can be either thulium-doped yttrium aluminum perovskite (Tm:YAP) or thulium-doped gadolinium vanadate (Tm:GdVO4). LDD: Laser-diode driver. LD: Laser diode. OF: Optical fiber. FO: Focusing optics. PM: Flat resonator mirror. OC: Curved output coupler.





Diode Array:

Beam combining optics to Launch in fiber (left) or Direct pump laser rod (right)



Laser Diode Array Beam Shaping Using Optics

Frequency Conversion

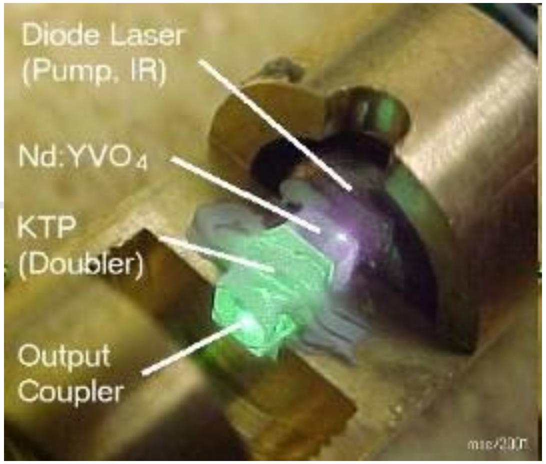
→ shorter wavelengths process more challenging materials
→ cost – lose energy

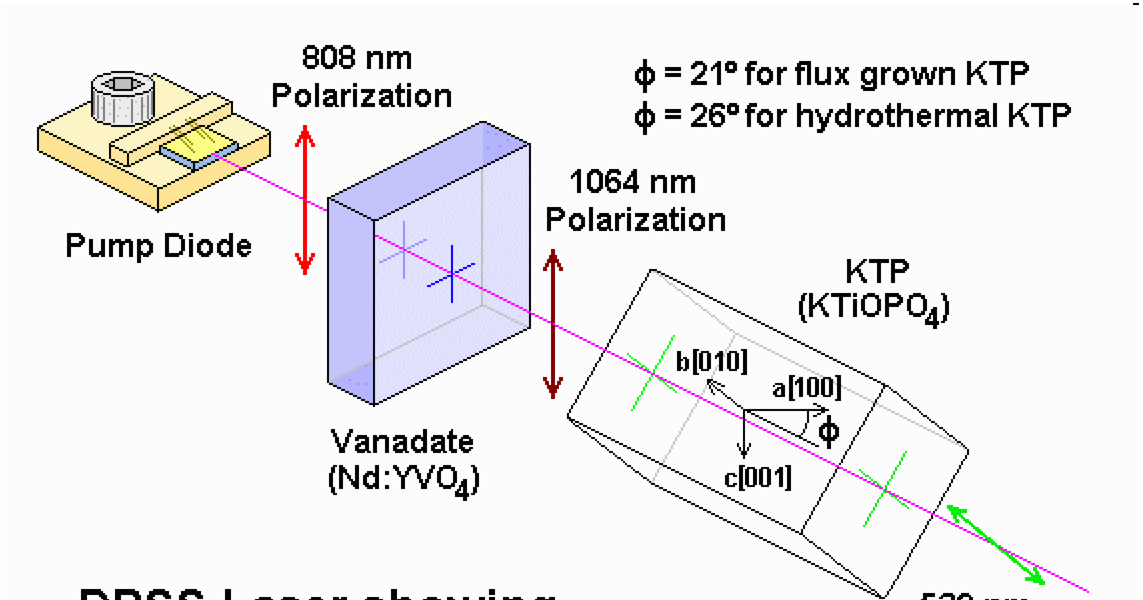
2nd harmonic	(2ω)	532 nm	(50%)	
3rd "	(3ω)	355 nm		→ competes Ar^+ cw
4th "	(4ω)	266 nm	(30%)	→ competes w/excimer

- crystals i.e. KTP, BBO
- periodically poled crystals (new)

- Nonlinear crystals: KDP, BBO, periodically poled Li:Niobate PPLN
- Focus laser (telescope) almost to damage threshold
- Conservation of Energy:
  - Second harmonic Gereration: $h\nu_2 = 2h\nu_1$ $\quad h\nu = hc/\lambda$ = photon energy
  - 3 wave mixing: $h\nu_3 = h\nu_2 + h\nu_1$
    - i.e. Optical Parametric Amplification: $h\nu_3 = h\nu_1 \pm h\nu_2$ generates VIS-IR light
  - 4th harmonic: $h\nu_4 = h\nu_2$ - 2 steps of 2nd harmonic conversion
- 50% efficient each step
- Polarization, phasematching angle (different phase velocities—process reverses to reconvert light to orginal), temperature control, walk-off (2 or 3 wavelengths propagate in different directions)

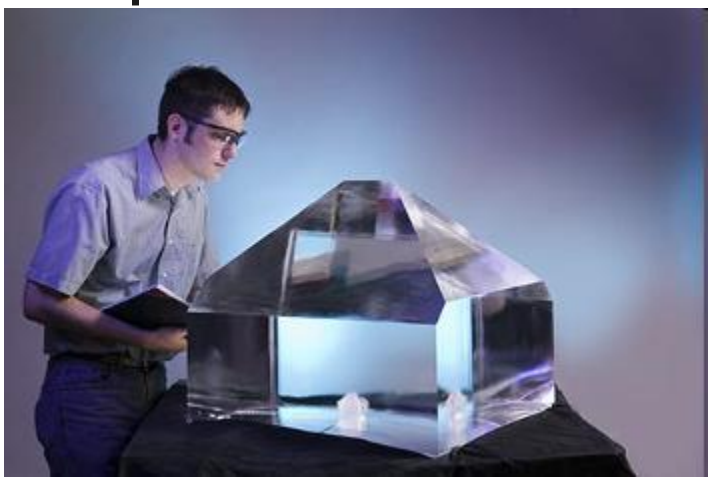
- **Green laser pointer:**
  Diode Laser (IR) pumped Nd:YVO4 (1.04um) focused into KTP doubling crystal → Green light (0.52 um)
- Pulsed power is better…why?





DPSS Laser showing Type-II Phase Matching of KTP

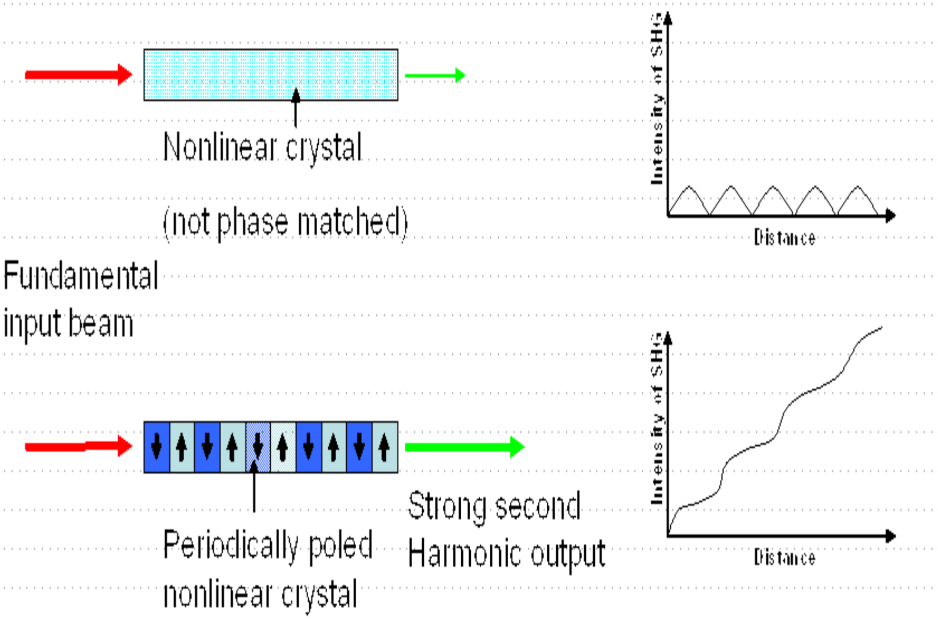
Frequency Conversion



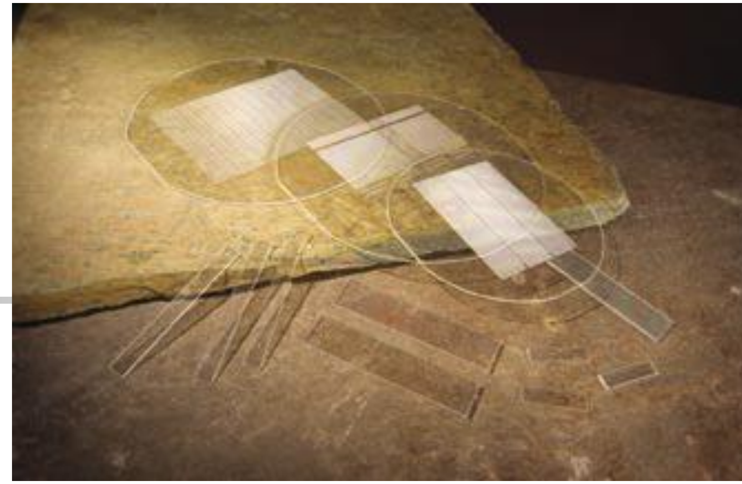
Largest single crystal 2nd harmonic

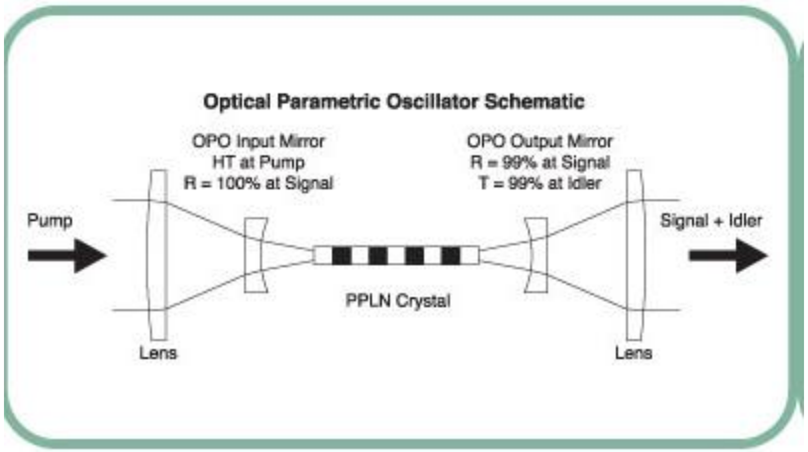
This potassium dihydrogen phosphate (KDP) crystal, weighing almost 800 pounds, was produced through a newly developed rapid-growth process that takes only two months, as opposed to two years using conventional methods. Each crystal is sliced into 40-centimeter-square crystal plates. More than 600 of these plates are needed for National Ignition Facility at LLNL

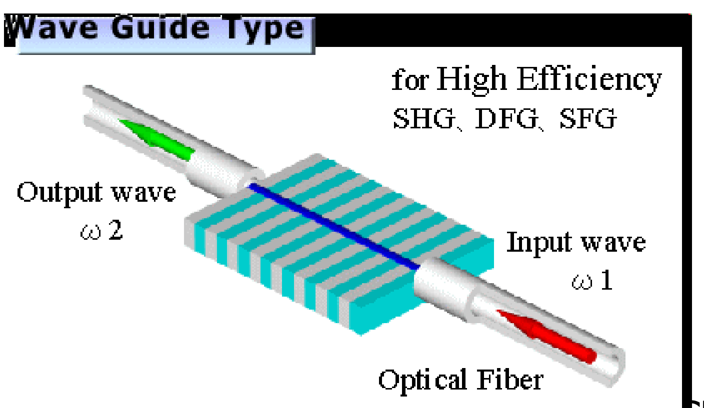
periodically poled Li:niobate: PPLN
- Most efficient; solves phasematching limit

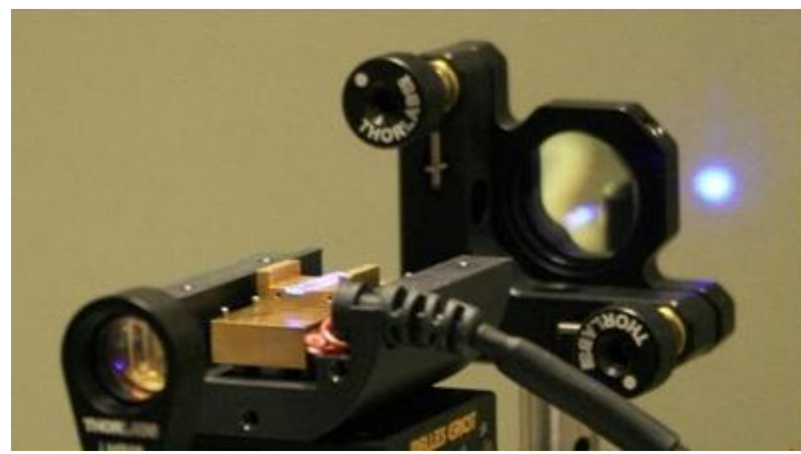


Frequency Conversion
PPLN



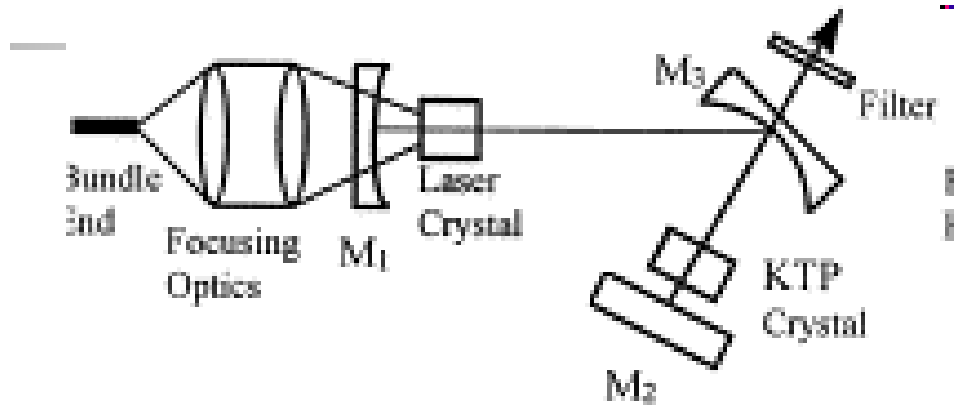


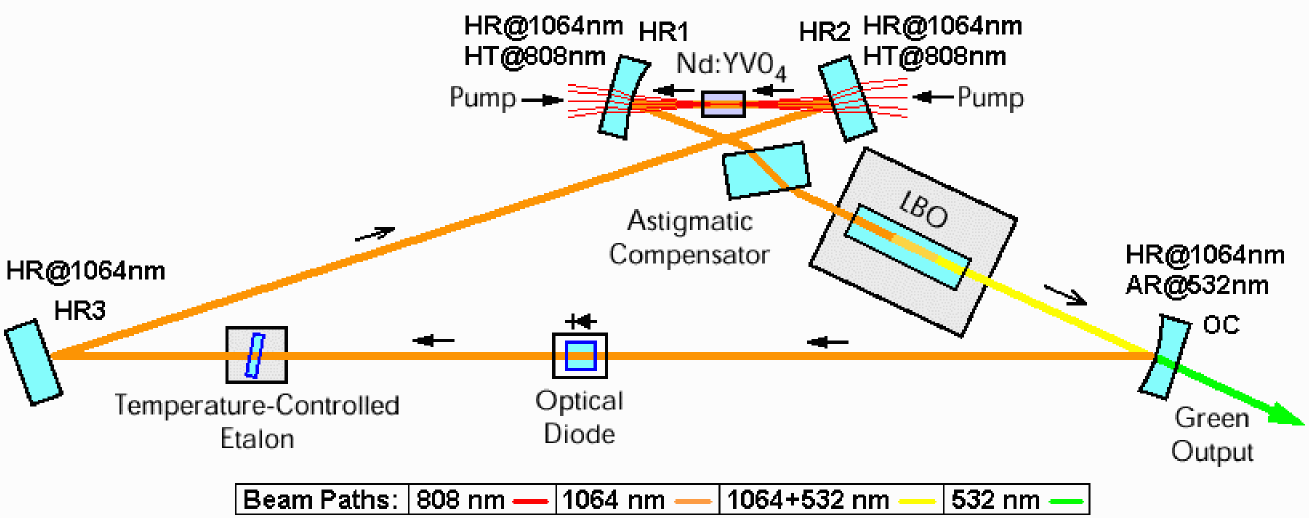




Intracavity Frequency Conversion

- Why put doubling crystal in laser resonator?
- Right: Fiber pumped linear cavity
  - What does the filter do?
  - Why is KTP doubling crystal near flat mirror?
- Below: unidirecitonal laser ring cavity
  - No standing waves; eliminates spatial hole burning to extract more power

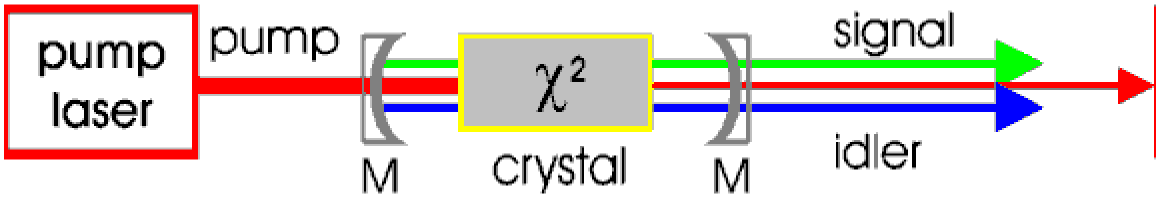




Ring Cavity Resonator of Coherent, Inc. Verdi Green DPSS Laser

Optical Parametric Oscillator (OPO)

- converts laser radiation – the so-called pump wave - efficiently into two coherent light waves with longer wavelengths, called signal and idler wave. The signal and idler wavelengths are tunable and can cover broad wavelength ranges. This wavelength tunability and the high output power make the OPO an ideal light source for many applications: including light detection and ranging (LIDAR), high-resolution spectroscopy, medical research, environmental monitoring, display technology, and precision frequency metrology.
- many different types of OPOs, but all of them have the same general setup shown in Fig. 1. The laser light from a pump source is sent through a special crystal, which is placed in an optical resonator. On traveling through this "optically nonlinear" crystal, a small part of the pump radiation is converted into signal and idler radiation. The generated signal or idler radiation (or both) is fed back by the resonator mirrors to the beginning of the optically nonlinear crystal. Every time the signal (idler) radiation passes through the crystal it is amplified by a certain factor, which depends on the intensity of the pump radiation: The higher the pump intensity the larger the amplification factor. At (and above) the so-called threshold pump intensity, the amplification of the signal (idler) wave compensates the resonator roundtrip losses given by residual mirror transmission, crystal absorption, scattering etc. Only if the OPO is pumped above threshold, a significant amount of pump radiation is converted into signal and idler radiation.
- Rotating the crystal us used to tune the wavelengths – satisfy phase matching and Conservation of energy.
- Also: Optical Parameter Amplifier-OPA pulsed laser applicatior



$$h\nu_3 = h\nu_1 \pm h\nu_2$$

Power Scaling in Solid State Lasers

- Seed / Oscillator provides a high quality optical beam of low power or pulse energy
- Follow with amplifier stages: bigger crystals/gain volume and more aggressive pumping systems to create high power laser systems

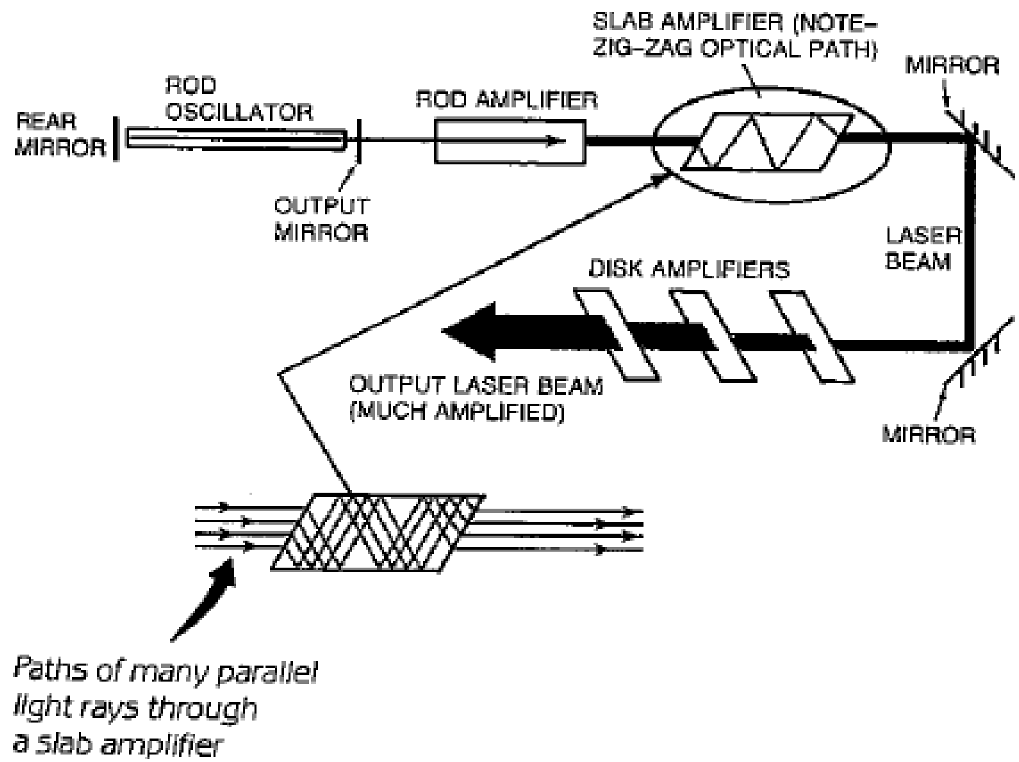
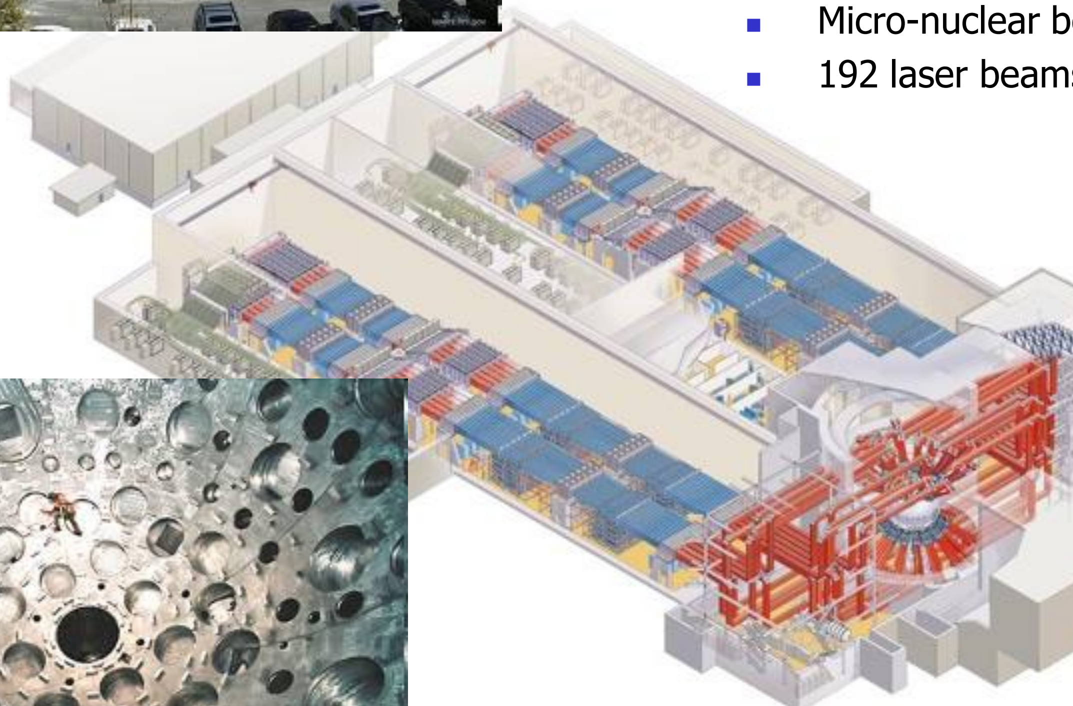


Figure 8-3. Laser oscillator with chain of slab and disk amplifiers.

How is optical pumping applied in SLAB and DISK amplifiers?

Laser Fusion – *Inertial confinement fusion*

- Lawrence Livermore National Lab
- Lawrence, CA
- National Ignition Facility
- Largest laser in world: Solid State
- Unlimited energy source- when??
- Extreme nonlinear laser optical science
- Physics of stars and nuclear weapons
- Micro-nuclear bomb: 100M ^{o}C x 100B atm pressure
- 192 laser beams: 2 MJ / nsec



NIF uses powerful lasers to heat and compress a small amount of hydrogen fuel to the point where nuclear fusion reactions take place. NIF is the largest and most energetic ICF device built to date, and the first that is expected to reach the long-sought goal of "ignition", in which the fusion reactions become self-sustaining. The construction of the National Ignition Facility was certified complete on March 31, 2009 by the U.S. Dept. of Energy

OR: search Sun to Sun on You TUBE

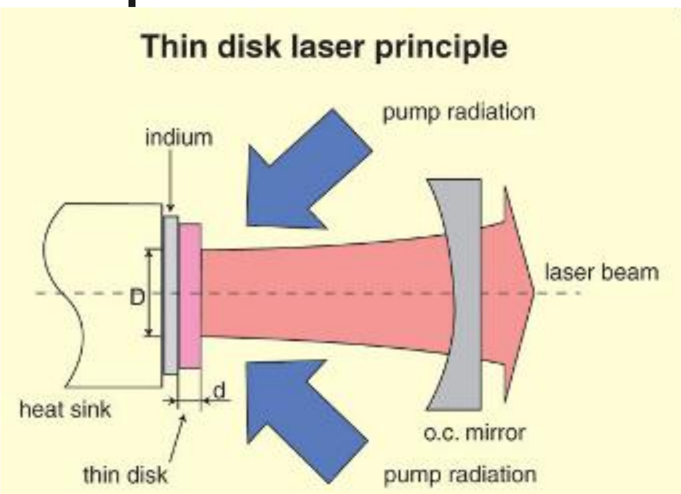
VIDEO link   https://lasers.llnl.gov/education/fusion_fun/science_on_saturday.php

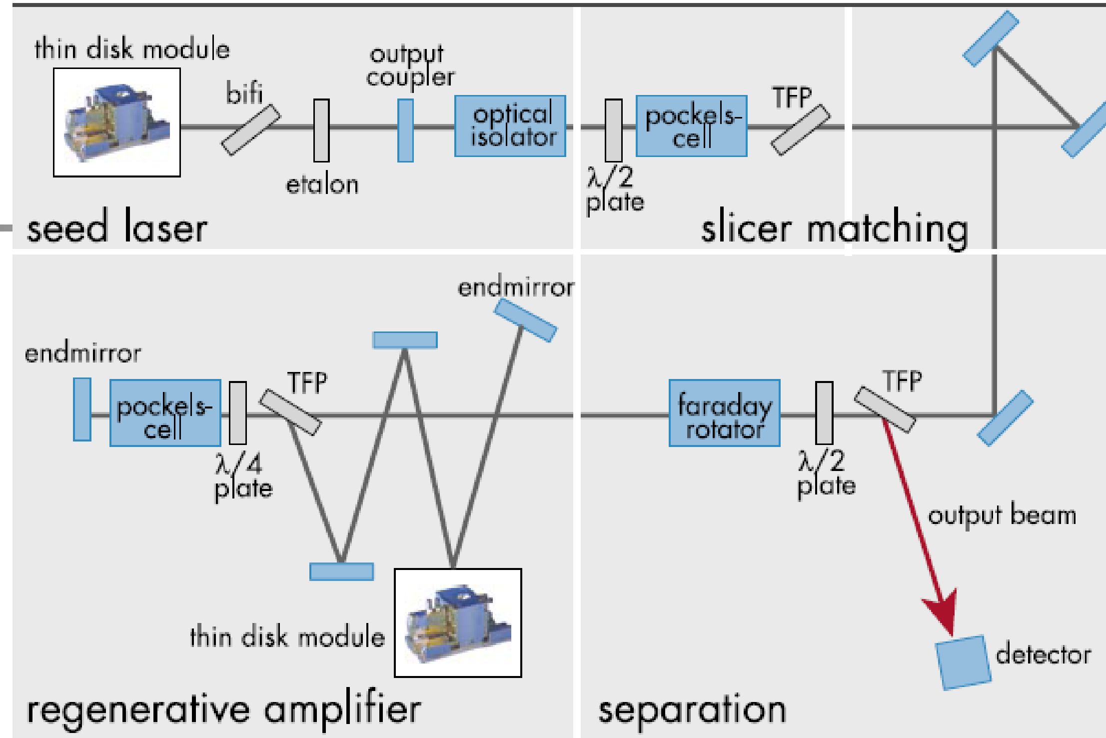
Thin Disk High Power Solid State Laser

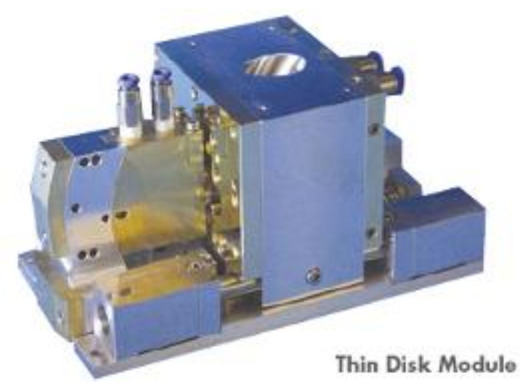
- While most high power solid state lasers have used laser medium in the shape of rods or slabs, a new trend is emerging where a very thin piece of highly doped Nd:YAG or other material is end or side-pumped by one or more laser diodes or laser diode arrays. The typical thickness of the lasing medium is 10 to 500 *microns* (0.01 to 0.5 millimeter). Amazingly, the output power from such a small sliver can be 10s of WATTs, 100s of WATTs, or even potentially much more! What makes this possible and desirable include the following:
- **Excellent heat transfer:** The front and/or back of the disk can be bonded to an excellent heatsink like copper (with a tiny hole in the middle if necessary) or diamond. Due to the thinness of the disk, heat transfer from its interior is very high. THIS BYPASSES THERMAL LENSING PROBLEMS IN RODS-How to get the heat out!
- **Ease of pumping:** The pump spot can be easily tailored to the desired beam shape without worrying too much about divergence since the depth of focus can be very short. The use of the thin disk essentially reduces this from a 3 to a 2 dimensional problem. Pumping can be from the back, or from the front off-axis or via a 45 degree mirror. Multiple pump sources can easily be accommodated.
- **Little to no thermal lensing effects:** The thin disk in contact with a good heatsink reduces the amount of thermal lensing due to heating in the gain medium.
- **Single longitudinal mode operation:** The short length of the gain medium almost assures that only a single longitudinal mode will oscillate if the HR mirror is on the rear face of the disk.
- **Potential for compact construction:** Compared to other geometries, the thin disk is much more easily designed into a small space.

Thin Disk Laser
Seed & Amplifier

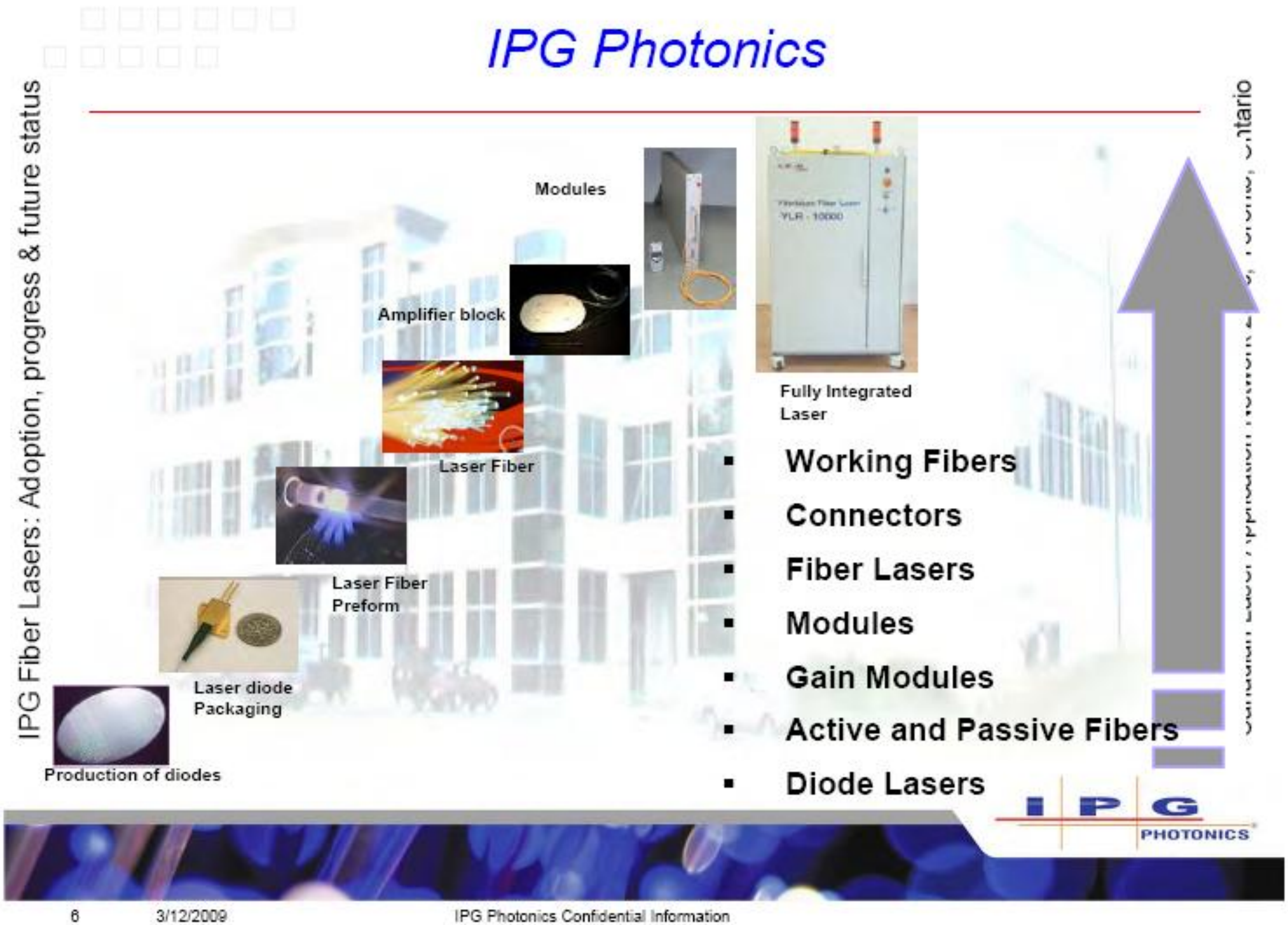
5 kW is common





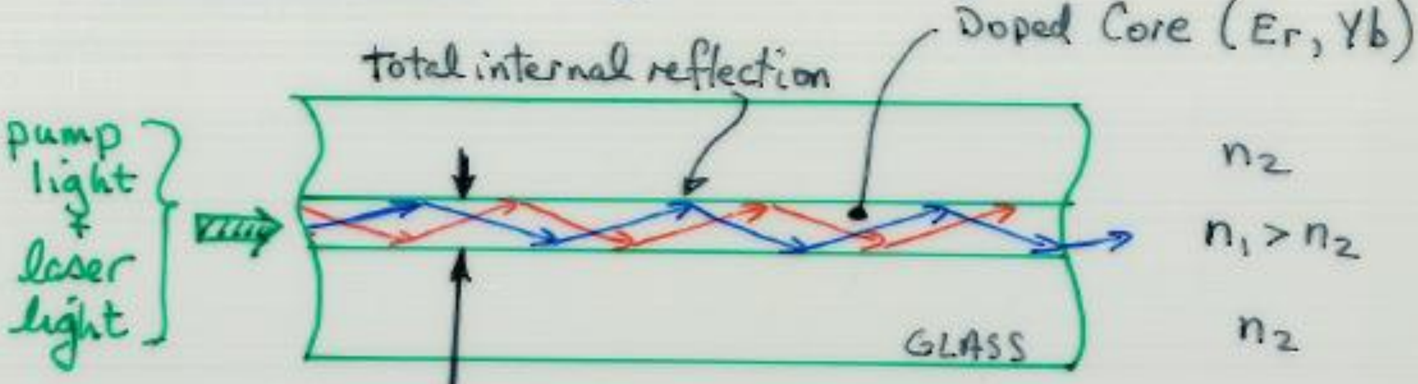


Fiber Lasers: *IPG case study vertically integrated*



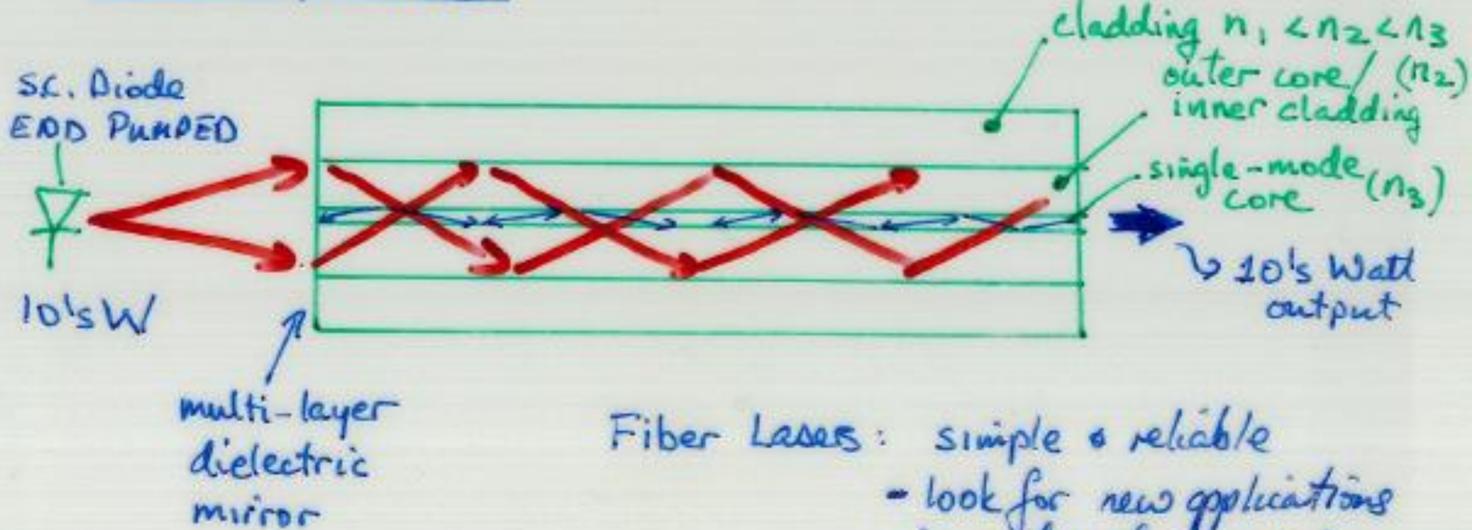
140 (34c)

FIBER LASERS (Svelto 9.2.6)



v. efficient pumping + lasing geometry { DIA ~ 8μm (single mode) / very long }

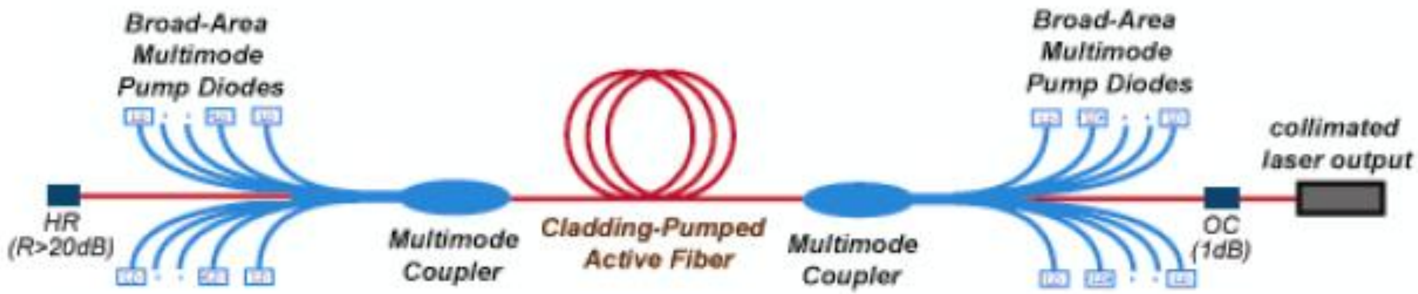
CLADDING PUMPED



Fiber Lasers: simple + reliable
- look for new applications in material processing

IPG Photonics

- IPG's proprietary manufacturing processes enables a robust, solid state, high efficiency, "gapless resonator", fiber laser power source.



Key elements

Active Fiber:

Multi-Clad, Circular Cladding,

Low Diameter, ~2-10m Total Length

High Yb^{3+} Concentration

Pump Diodes:

Multimode, Single emitter

90um stripe

6W to 20W Output Power

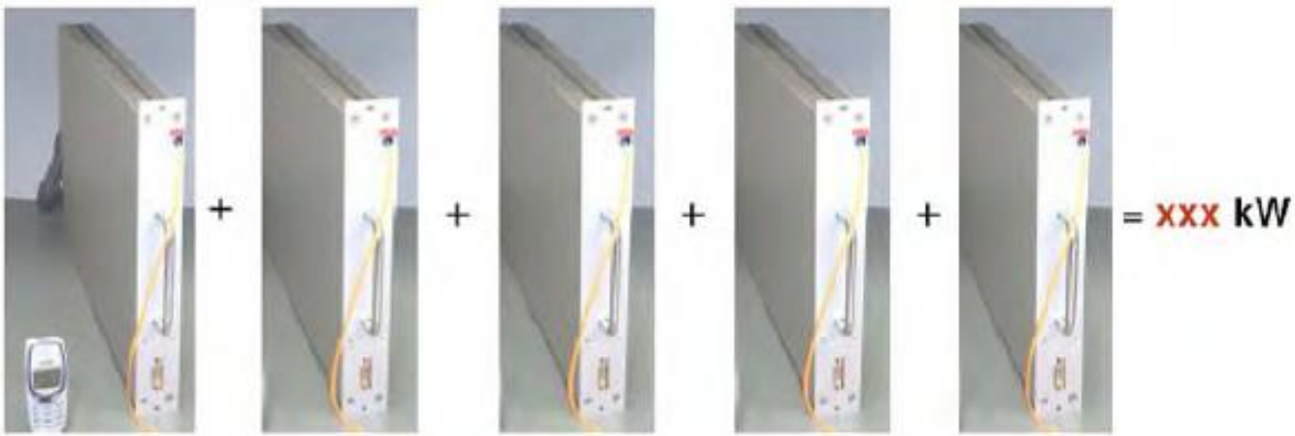
IPG Photonics

A single module can supply:

- 250, 400, 800, 1000+ W of laser power
- Wavelength of 1070nm (NIR)
- One 7 or 15 um fiber core
- 0.34-0.41mm*mrad beam divergence

T x H x D = 60 x 33 x 4.7 cm
Efficiency (DC) > 35%
Building blocks (modules) for HPFLs

High power multi-mode fiber lasers



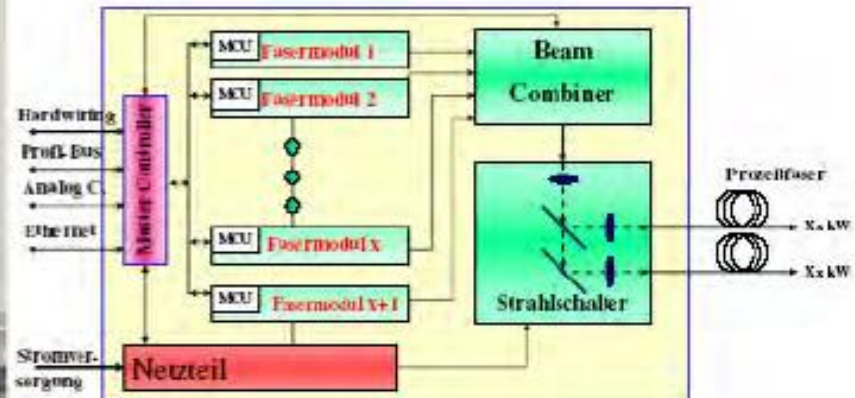
Modular multi-kW fiber laser

High beam quality

IPG Photonics

High Power Fiber Laser

HPFL Layout



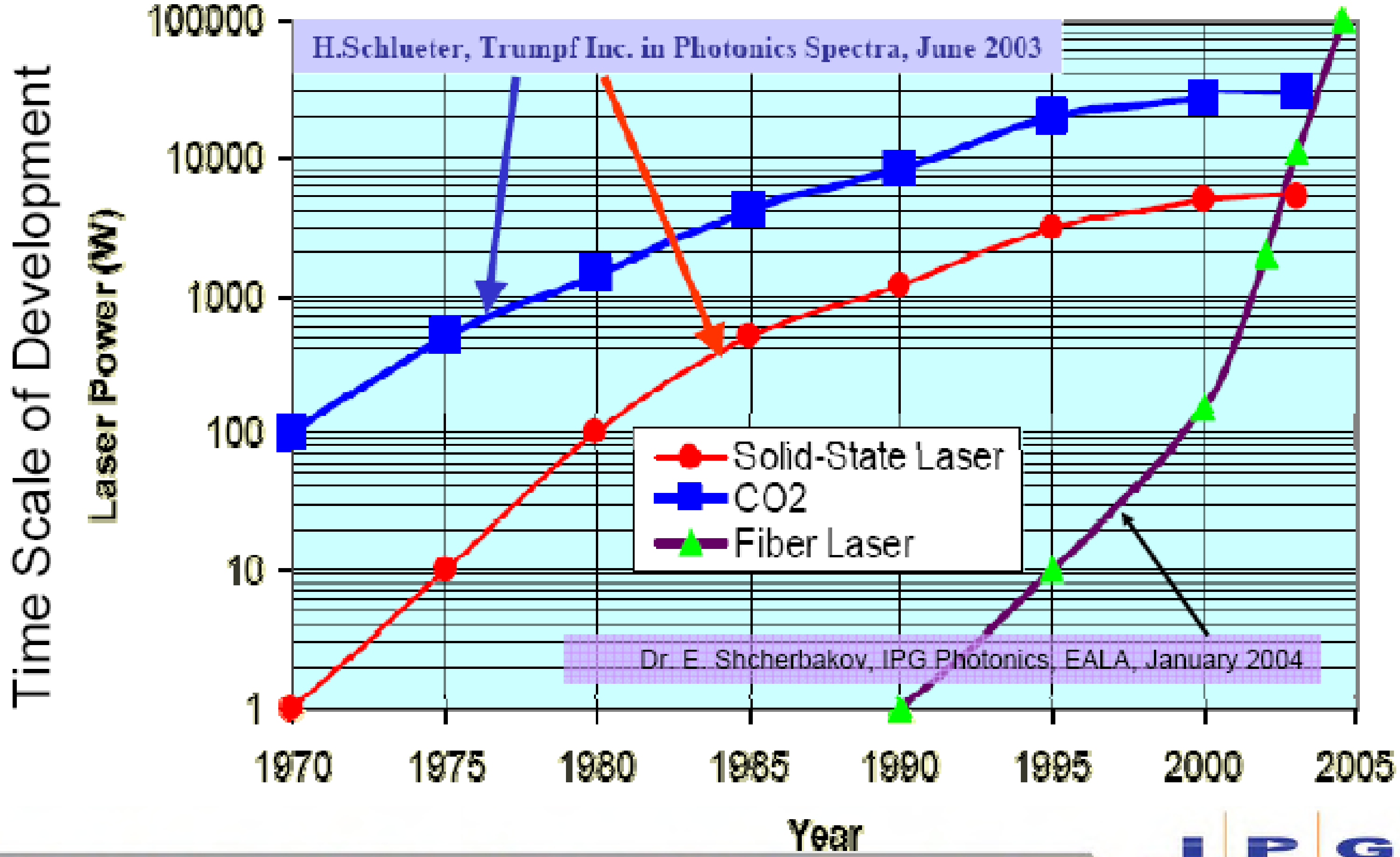
Power 1 – 50 kW

Fiber Laser Adoption and Growth

Fiber Laser History

- 1963: Fiber Laser Invention, E. Snitzer
- 1974: Double Clad (DC) Technology Invented, Maurer
- 1989: First DC fiber laser demonstrated, Polaroid
- 1990: First multi-Watt DC fiber laser, Gaponsev
- 1991: IPG Photonics Incorporated, Gaponsev
- 1993: 5W Nd fiber laser, Polaroid
- 1995: Commercial fiber lasers to market, IPG
- 1999: Multi-kilowatt fiber laser introduced, IPG
- 2002: Kilowatt fiber lasers sold to industry, IPG
- 2007: Deliver 3kW SM fiber laser IPG
- 2007: Deliver 70kW fiber laser IPG
- 2010: Projected 500kW fiber laser IPG

Fiber Laser Adoption and Growth



Fiber Laser Adoption and Growth

IPG Fiber Lasers: Adoption, progress & future status

Brightness = Output power per unit area per unit solid angle.
(Proportional to power divided by square of BPP)

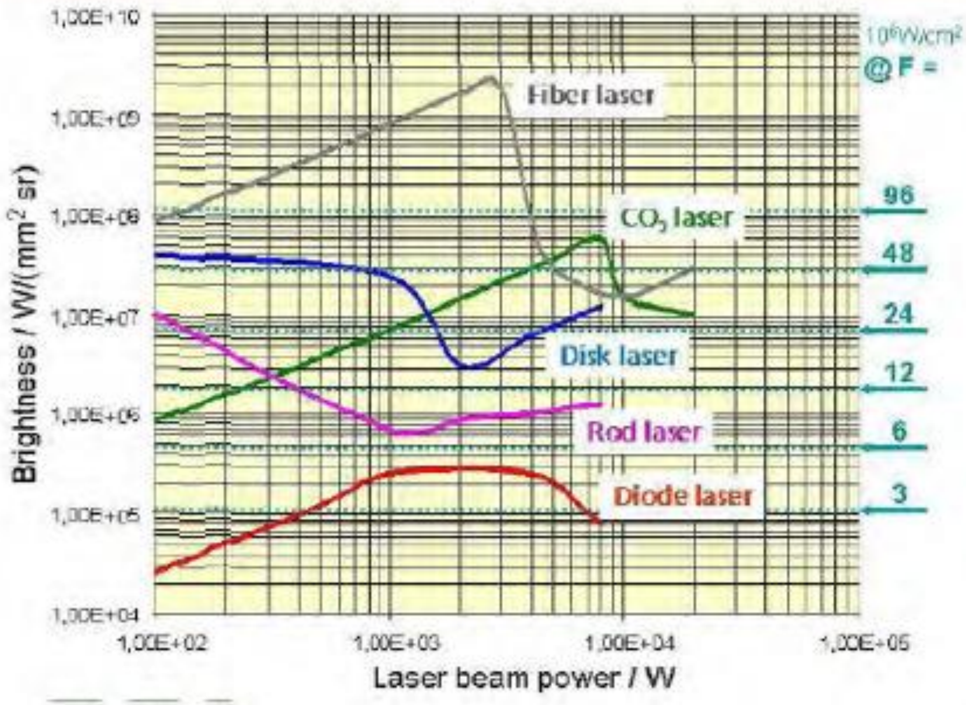


Fig. 1 Brightness map of commercial high-power lasers (end of year 2007), first issue published in 2006 [12].

"The Relevance of Brightness for High Power Laser Cutting and Welding", Paper 206
ICALEO 2008, Dirk Petring, Frank Schneider, Norbert Wolf, Vahid Nazery, Fraunhofer Institute for Laser Technology

Canadian Laser Application Network 2009, Toronto, Ontario

IPG PHOTONICS

Fiber Laser Adoption and Growth

Advantages over previous technologies:

- Long diode life > 100,000 hrs
- High electrical efficiency 30%
- Compact size
- Mobile
- Highest beam quality at all power levels
- Large dynamic power range
- Rapid installation (hours not days)
- No resonator alignment
- Maintenance free
- Single mode - pure Gaussian
- Multi-mode - near top hat
- Consistent spot size over complete dynamic range
- Air cooled to 300 watts
- No warm up, on demand power
- Modules can be added for future power upgrades

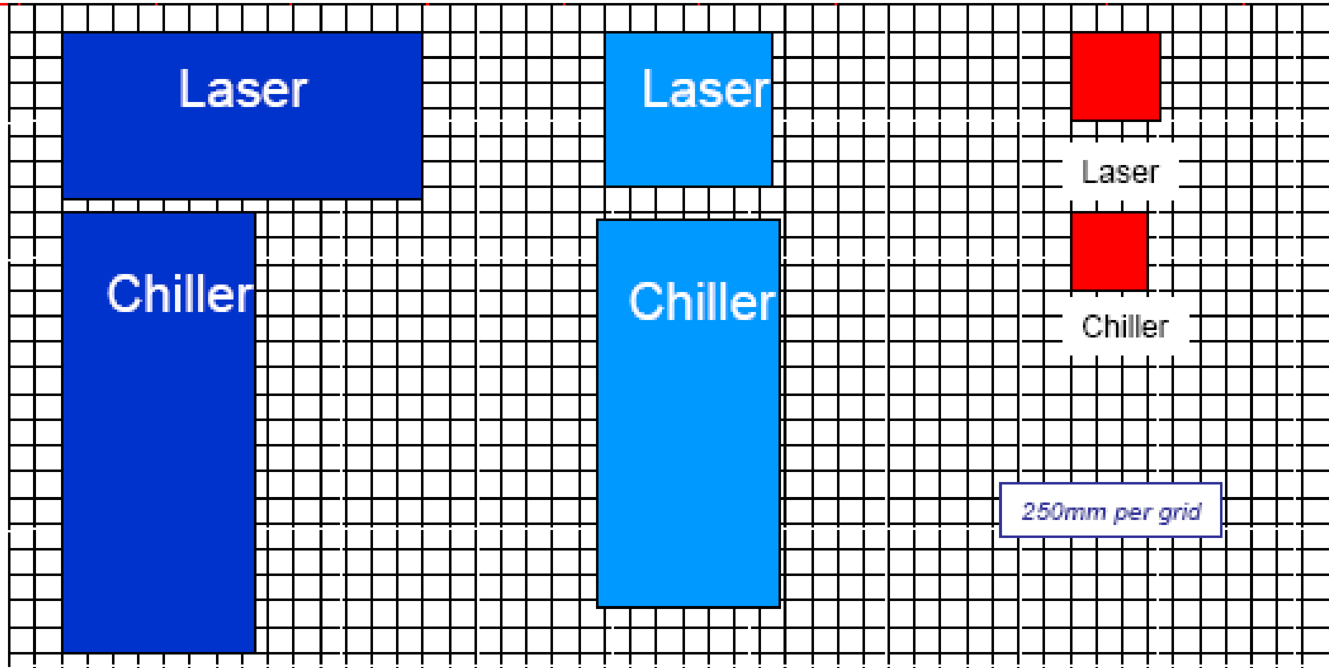
Fiber Laser Adoption and Growth

Fiber laser processing advantages:

- Use of fiber delivery to focus optics
- Use of trans-missive or reflective focus optics
- 2-2.5 faster processing speeds than CO_2 lasers at same power level
- Utilization of long focal length lenses for remote welding and scanner applications
- Multi-use welding, cutting, cladding etc.
- No requirement for Helium cover gas for welding
- Consistent spot size and profile over complete dynamic range
- Same laser can do both micro and macro applications

Fiber Laser Adoption and Growth

Plant floor space is manufacturing real estate: Fiber lasers free up manufacturing capacity.



4KW Nd:YAG	8KW CO2	4KW Fiber Laser
<5% efficient	<8% efficient	~25% efficient
<2000 hrs lamp life	Uses laser & process gas	100,000 hrs diode life
92KW consumption	84KW consumption	16KW consumption
3200 x 1700 x 1250	1665 x 1524 x 1100	860 x 810 x 1500
3000 lbs	3241 lbs	500 lbs
$600-700K USD	$450-500K USD	$350-$450K USD

Fiber Laser Power Sources

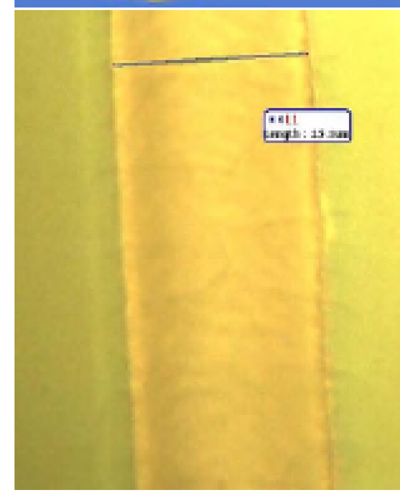
IPG Product Line:

- CW Single Mode fiber lasers from 5 – 5000 watts (10,000 watts under final development)
- Low order mode CW fiber Lasers available from 100 watts to above 50kW
- Pulsed (Q-switched) over 20 models with peak powers to 50 kilowatts and pulse energies to 10-milli-joules

Fiber Laser Applications

Single Mode (SM) fiber laser applications:

- Stent cutting
- Cutting surgical blades
- Cutting solder-masks
- Welding of razor blades
- Silicon cutting (solar panels)
- Adjustment of disc drive flexures (bending)
- Laser engraving (rolls and flat plate)
- Welding of medical devices
- Laser sintering
- Soldering
- Laser marking
- Remote cutting



CdTe Isolation
YLP-RA-1/50/30/30

Fiber Laser Applications

High power, low-mode order fiber laser applications:

- Cutting of hydro-formed automotive frames
- Blank welding for automotive industry
- Titanium welding of aircraft skins and structures
- Laser cladding for Aerospace and Oil industries
- Battery welding for automotive and medical device industry
- Pacemaker welding for medical device industry
- Transmission welding for Automotive Industry
- Sheet metal cutting and welding

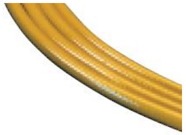
Fiber Laser Competition:

displacing market of CO_2 Lasers and cw Solid State Lasers – 5kW class BELOW

lamp pumped, fiber delivery, cutting

The cw high-power laser
HL 4006 D.

2



Cutting head with capacitive heigh

Fiber Laser Applications

Scannerfree Remote Processing

Working Distances
1000-1500 mm

Scanner Remote Processing

Working Distances
~ 500 mm

Multi-axis robotics: xyz, rotation

Fiber Laser Applications

Robotic Cell Plant 1 BMW Munich

Remote Laser Welding

WELDING is a major application of high power fiber lasers

Fiber Laser Applications

IPG Fiber Lasers: Adoption, progress & future status

Canadian Laser Application Network 2009, Toronto, Ontario

Monfalcone, Italy

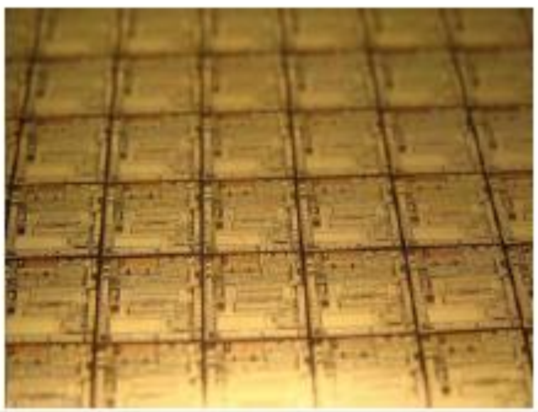
The first outfitting of a welding gantry
with a 10 kW fibre laser source for
hybrid welding in production
at Fincantieri Shipyard
in Monfalcone in 2007

Why pulsed and not cw for these applications?
What dissadvantage does fiber have when pulsed

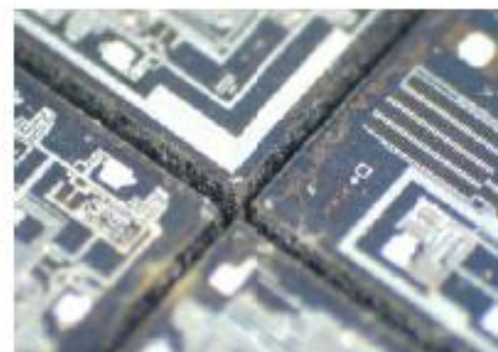
Fiber Laser Applications

Pulsed fiber laser applications:

- Cutting of silicon solar panel substrates
- All types of marking: medical devices, novelty, automotive, aerospace etc. in both plastics and metals
- Scribing thin-film solar panels
- Patterning for the video industry
- High speed drilling and ablation in a variety of materials



Images Courtesy of Laser Photonics
http://www.laserphotonics.com



Gas Lasers for material processing

- Bulky: laser gain from gas is low
- Simpler technology—cheaper; very powerful
- CO_2 – 9 & 10 um wavelength:
- Excimer – UV, incoherent light (no speckle)
  - KrF 0.248 and ArF 0.193 nm
- Others: Argon ion, Copper vapour, N_2
  - decreasing relevance to laser processing today as displaced by solid state and frequency conversion

Gas lasers were predicted to disappear from market; Why are they still very successful in Market?

CO_2 LASERS

Svelto 10.2.3.1

- vibrational | stretching bending modes of ground electronic state
- v. powerful 100kW
- η_{SLOPE} = 15 - 25% (best except SD Lasers)
- N_2 + He mixes improve performance
- λ = 9.6μm + 10.6μm
  - dense rotational spectrum [i.e. P(22)]
  - λ-tuning with gratings

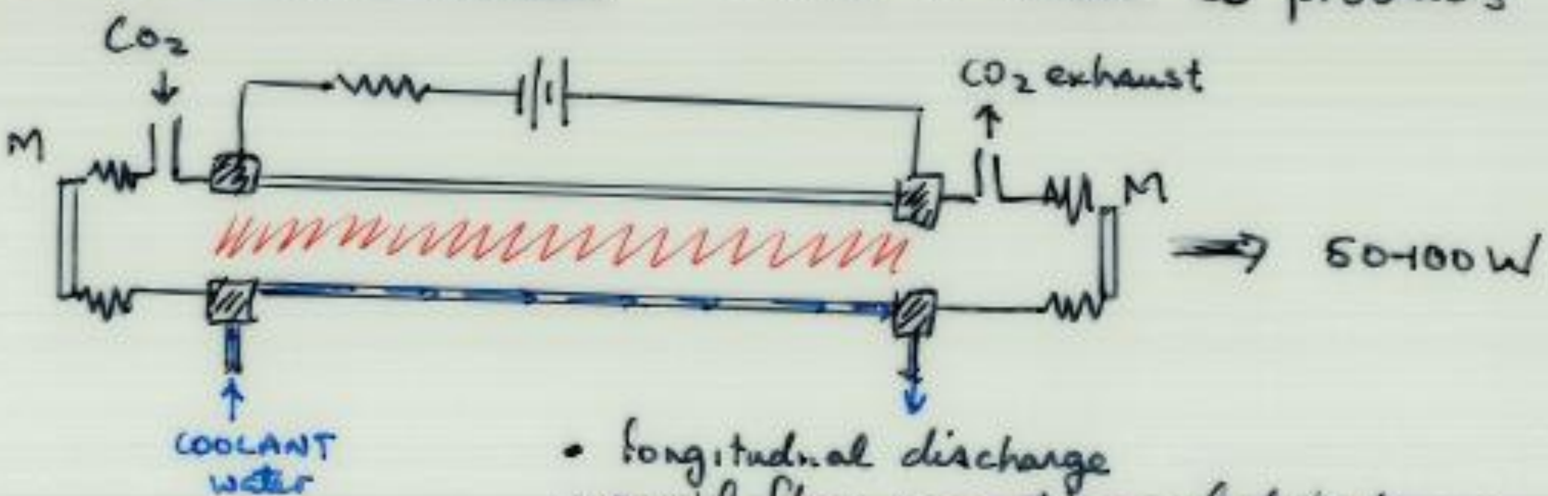
    9.3μm is common for PI etching
- e-discharge excitation

TYPES cw + pulsed

- various bending/vibration modes of CO2 molecule
- study 7 types of excitation: pulsed and cw

CO_2 Laser

1. SLOW AXIAL FLOW – need to remove "CO" products



- longitudinal discharge
- axial flow cannot be scaled to large cross-section for more power

50-60 W / meter

- laser surgery, resister trimming, cutting ceramic plates (electronics), welding thin metal sheets

CO2 Laser

2/ Sealed-Off Lasers

- same configuration as axial flow → sealed tube/NO FLOW
- CO product must be eliminated
  → catalyst converts CO → CO_2

  eg. 1% H_2O or H_2 or Ni cathode

  $CO^* + OH \rightarrow CO_2^* + H$
- Tube Lifetime = 10,000 hours (scheduled maintenance)
- ~ 60 W/meter

TYPICAL SIZES: 1 W Models

10 W Models → laser microsurgery

laser micromachining

CO2 Laser

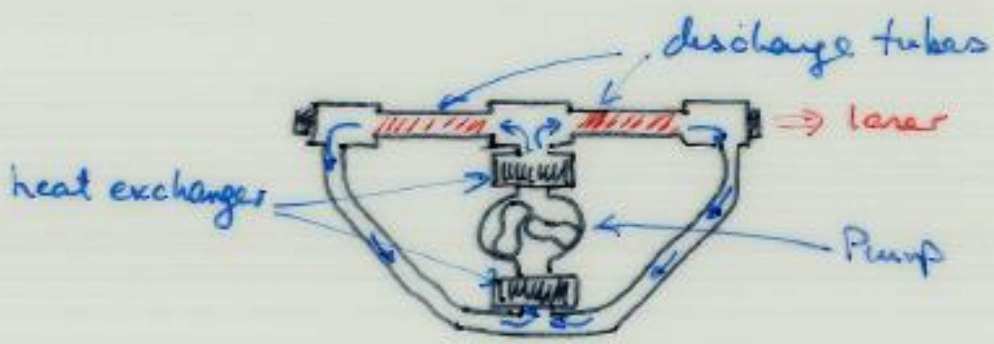
3/ CAPILLARY "WAVEGUIDE" LASERS

- small 2-4 mm dia tubes serve to reflect + guide light
- short + compact
- P < 30W attractive for microsurgery
- usually sealed-off design
  - (i) long axial discharge
  - (ii) transverse RF (30 MHz) excited (see Fig 10.13 Svelto)
- Adv. – AIR COOLED OR NO COOLING

CO_2 Laser

3/ FAST AXIAL FLOW

- over comes power limitation of slow. axial flow etc.
- super sonic gas flow 50 m/s
  - replenishes gas
  - cools by heat removal in gas flow (heat is removed ~~by~~ from gas by heat exchange
- Rf transverse discharge or long axial discharge
- 1 kW/meter P = 1-3 kW cw
- uses catalysts
- Appl'n Material Processing - Cuts many-mm thick metal sheets.



CO2 Laser

4./ DIFFUSION COOLED

d << w

- more power in compact design
- 2.5 kW
- new emerging technology

close electrode spacing provides sufficient heat flow to cool gas at electrodes

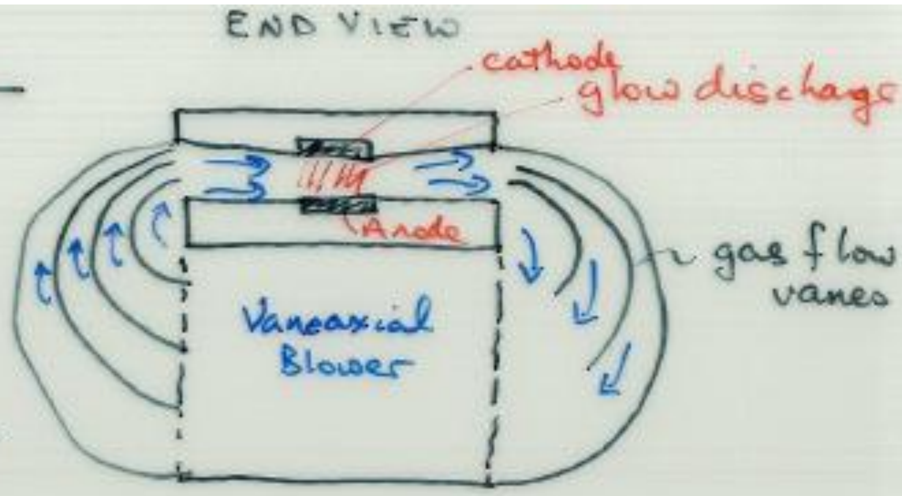
5/ TRANSVERSE FLOW

→ fastest means to replace gas @ discharge

⇒ rapid cooling

⇒ low Pressure 100 Torr

1 → 20 kW



welding, surface hardening, surface metal alloying,

DISADV. poor beam quality

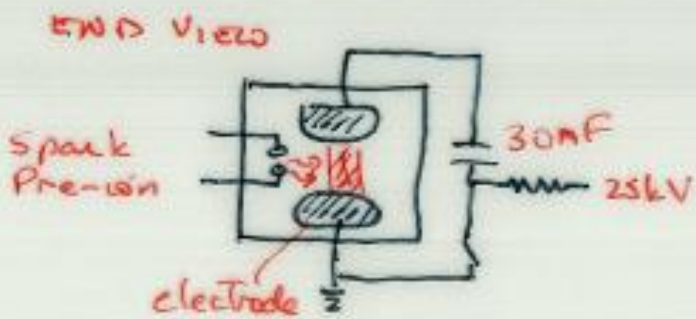
CO_2 Laser

6/ <u>TEA CO_2 laser</u> transverse-excited atmospheric-pressure

- pulsed e-discharge excitation required to break down ~1 atm press. gas ⇒ use "transverse discharge" (like excimer laser)
  ⇒ pre-ionization to aid speed of breakdown ⇒ rapid pumping
- 10 → 50 Joules / litre output (10's cm^3 discharge volume)
- transverse flow for high repetition rate

50 Hz $P_{AVG} \sim 300$ W 10's nsec duration

$P_{Peak} \sim 10^8$ Watts

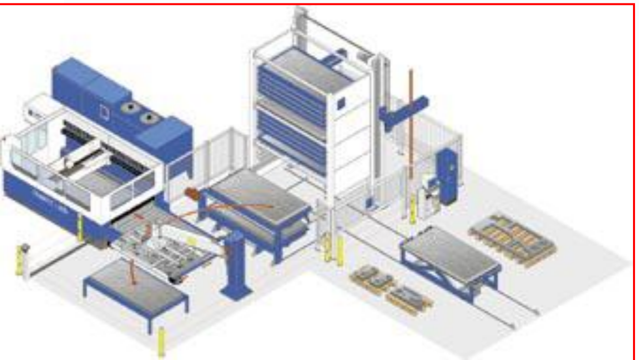


Applns:

- Marking
- Ablation of Polymers

CO_2 Lasers 5+ kW

turbo pump gas

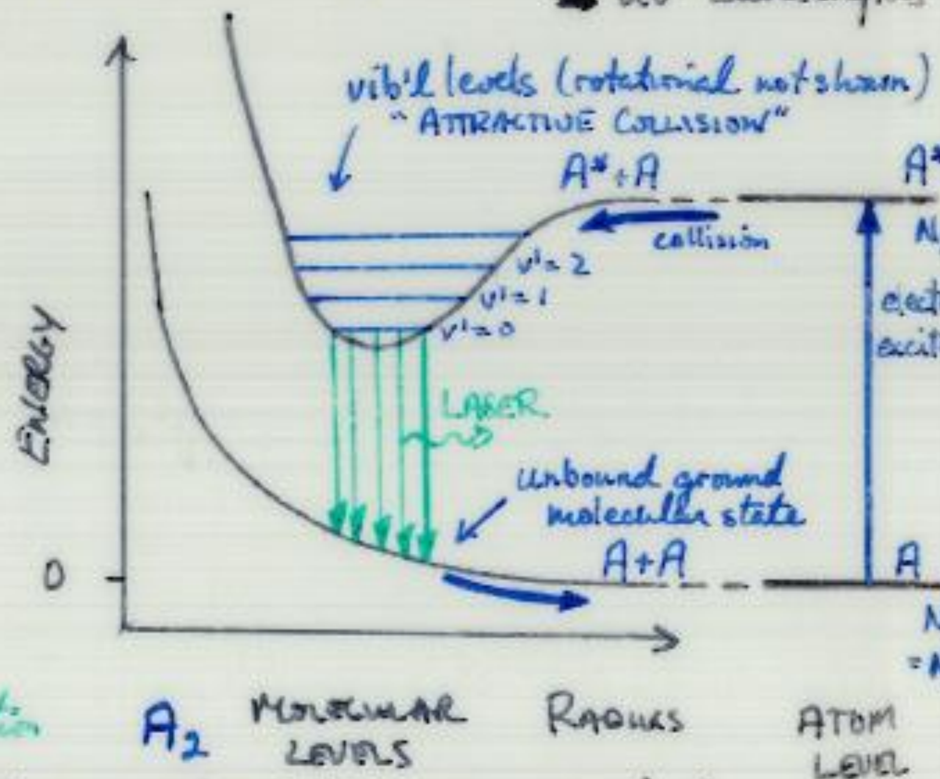


Cutting metals: 1″ SS to 1/2inch Aluminum
With gas assist.

10.2.3.4 Excimer Lasers

between different electronic states
→ uv wavelengths

Typical molecular energy level curves and laser characteristics



Reaction processes:

① $e + A \rightarrow A^* + e$ (e-discharge)

② $A^* + A \rightarrow A_2^*$ { excited dimer (excimer) formation

③ $A_2^*(v' \text{ large}) \rightarrow A_2^*(v' = 0)$ (collisions)

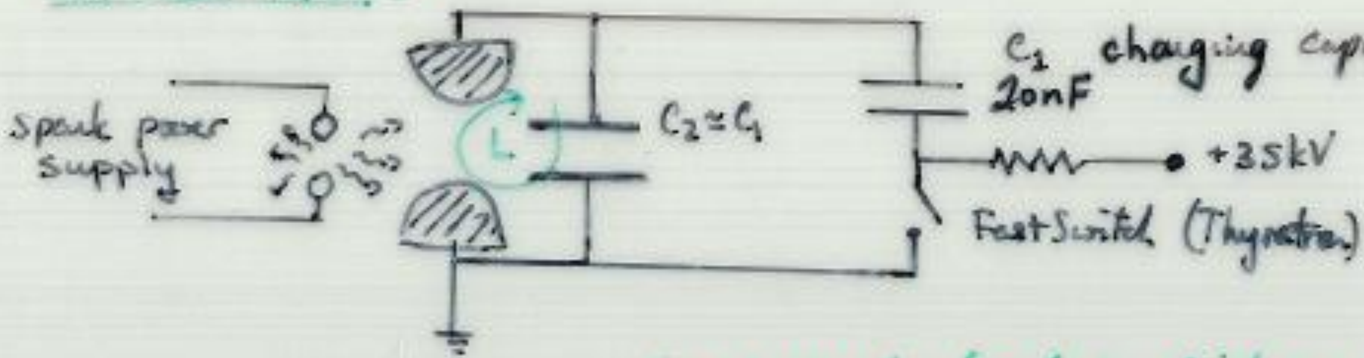
④ $A_2^* \rightarrow A_2 + h\nu \rightarrow A + A$
τ laser τ dissociation

"Repulsive Ground State" ⇒ $N_1 = N_g = 0$ always have pop. inversion!
⇒ larger tuning range (20–100 cm⁻¹)

electric discharge like TEA CO_2 laser
- use preionization uv sparks
- use secondary capacitors close to electrodes to reduce inductance, speed up discharge to overcome spontaneous emission!

Excimer Lasers

EXCIMER LASER: 40



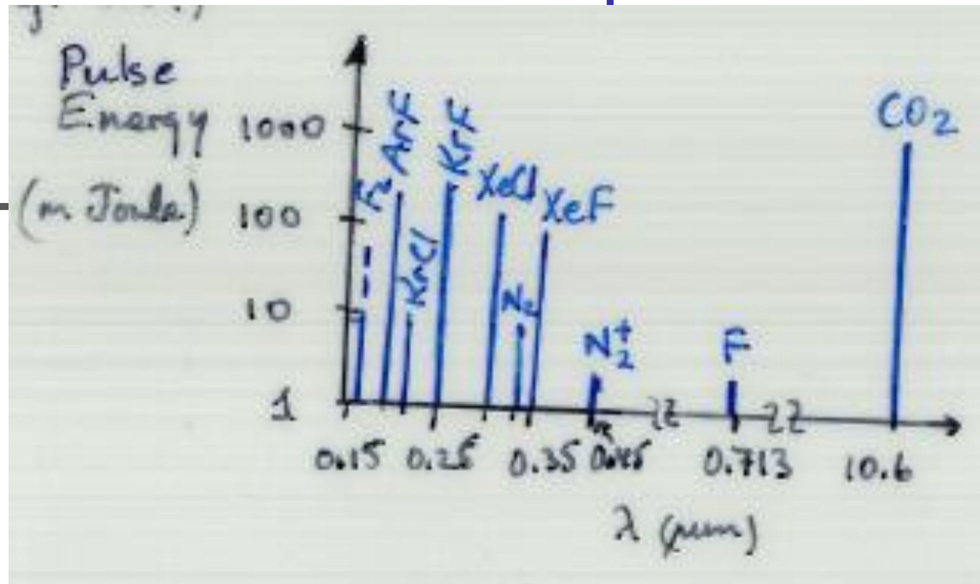
L = 2-10nH for fast discharge of laser exci

- P_{AVG} > 100 W common (→ 1kW ~~research~~ Lithography Appl'ns labs)
- Rate > ~~500 Hz~~ ~2kHz pulsing (no cw operation / discharge unsta
- CHANGE GAS MIX: changes wavelength.
- η_{EFF} ~ 2-4%

Applications
① Photolithography (KrF)
② Photo Ablation (Electronics)
③ Radial Keratomy of Cornea (ArF)

(Fig. 6.27)

Gas Lasers – Pulsed - Comparison



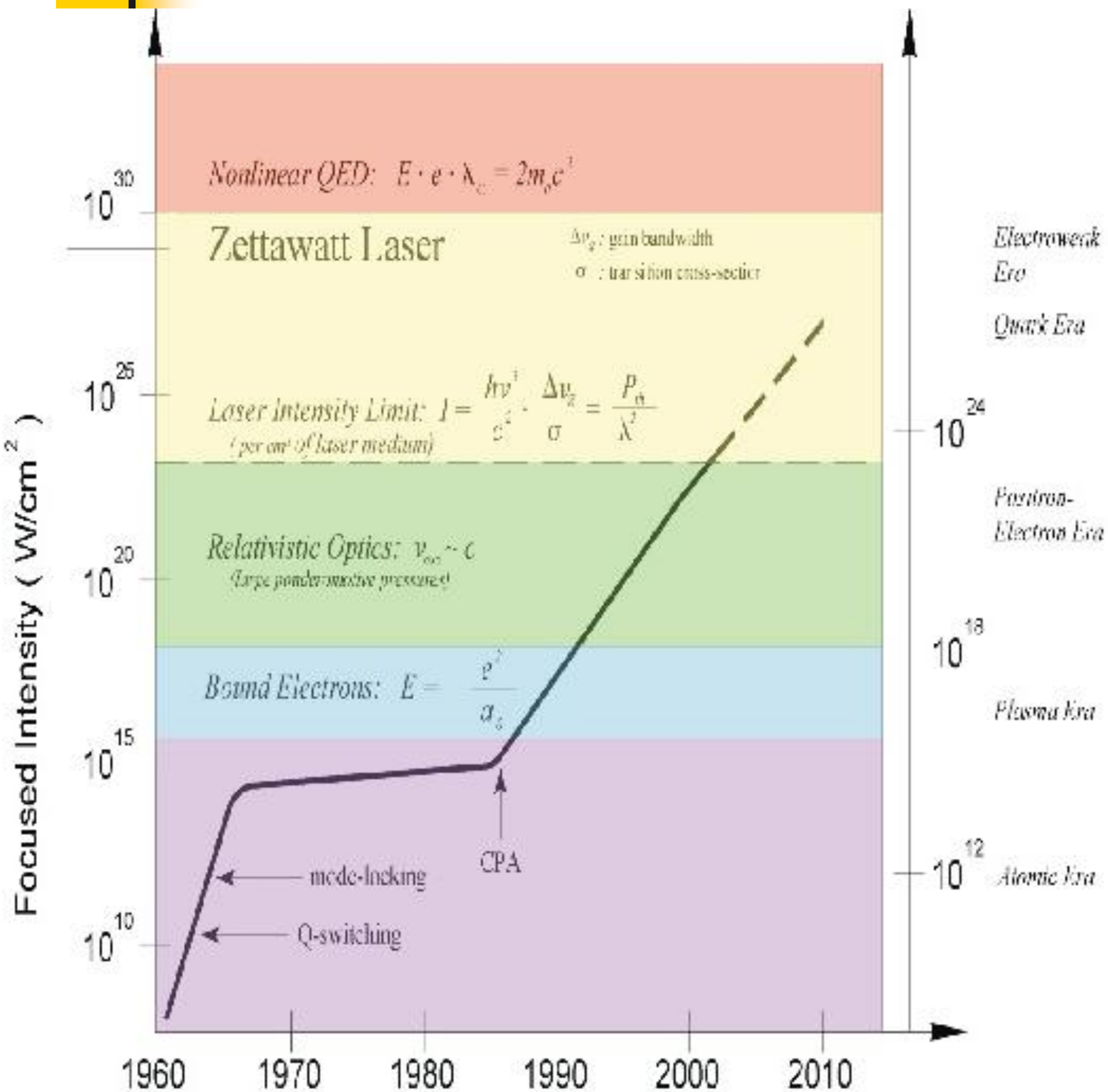
DYE LASERS tunable pulsed/cw lasers from UV - VIS - near IRed.

dy: introduction, energy level, pumping mechanisms, transitions, limitation due to Triplet States,

- pulsed operation : pumping methods; tuning of wavelength.
- cw operation : pumping methods; "jet"
- applications

note shortest duration <u>6 fsec</u> ⇒ "1 optical cycle"

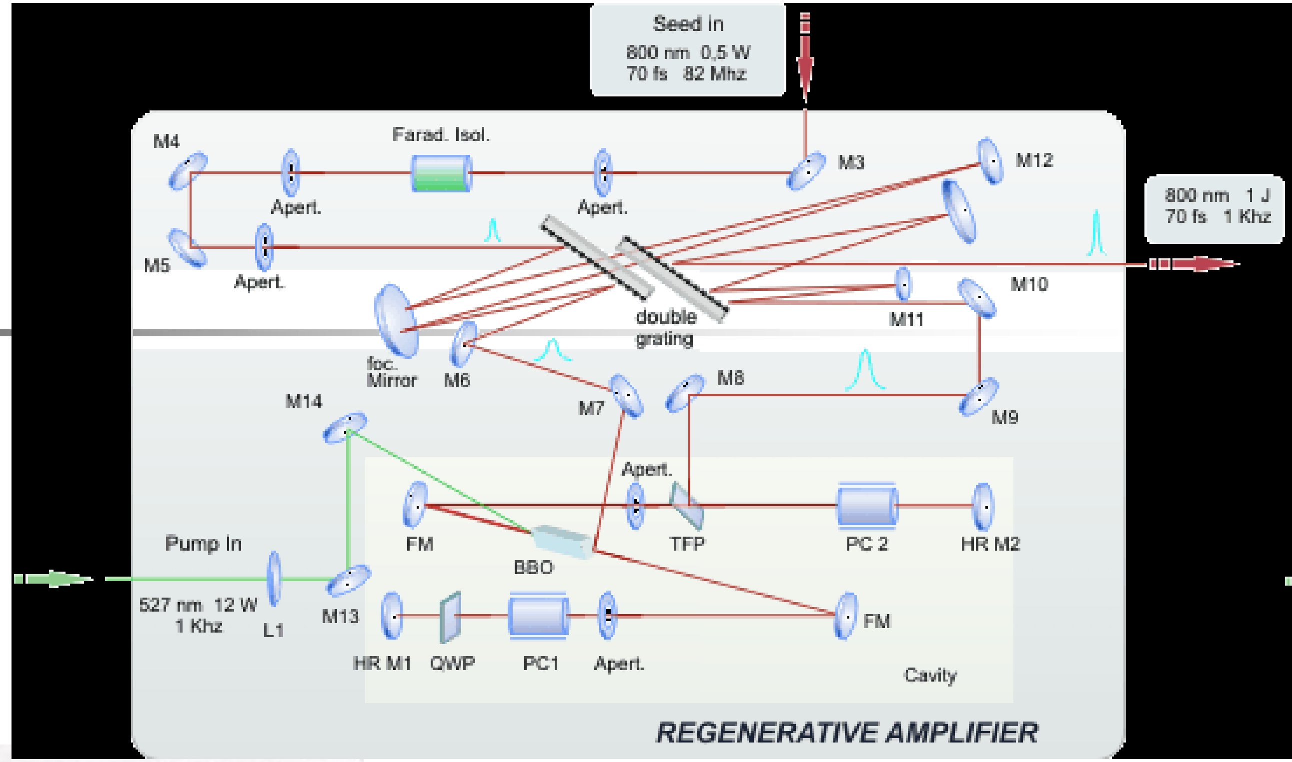
Ultrafast or Ultrashort Lasers

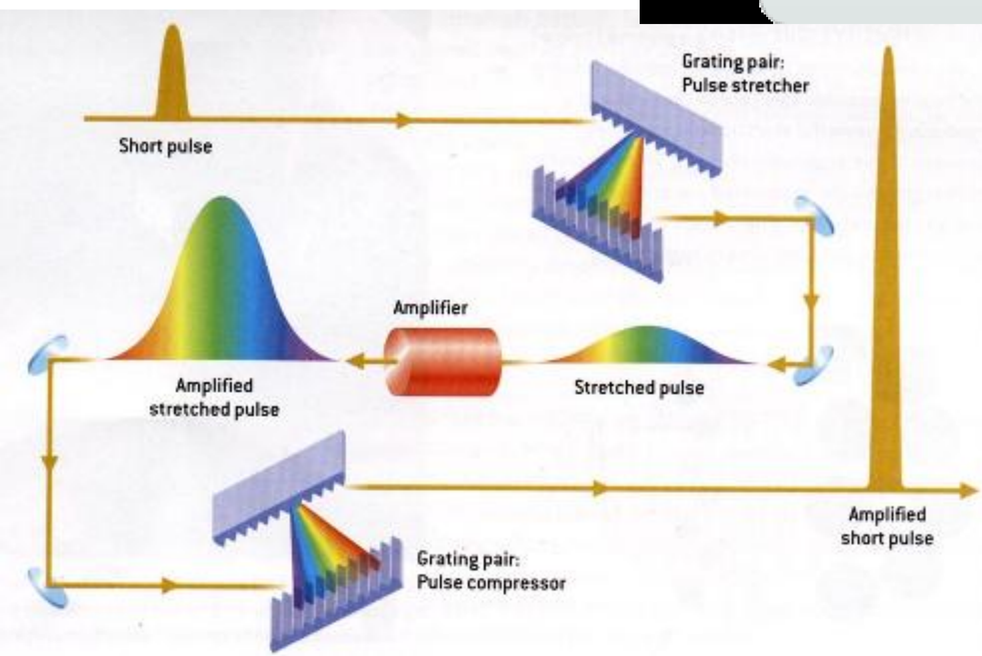


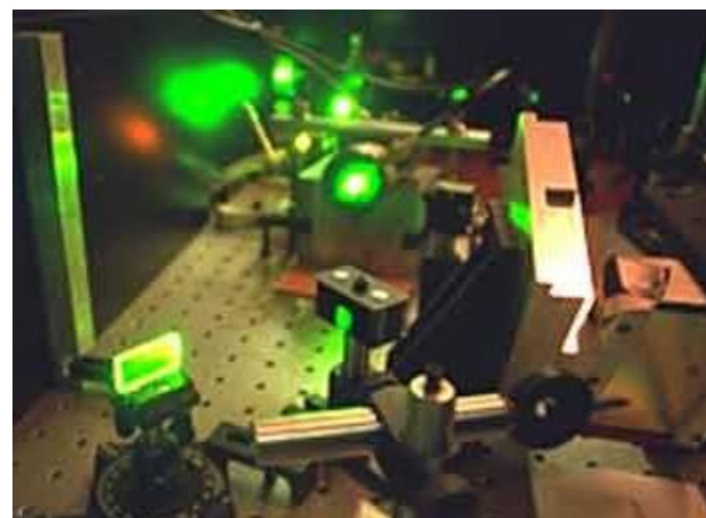
- Development of chirped-pulsed amplification- CPA – led to significant increase in laser intensity, peak power, focusing intensity
- Open new physics and new laser processing appliations as laser technology becomes more reliable and hopefully less expensive
- Originally gas lasers until inventions of Chirped pulse amplification (CPA); today dominated by solid state and fiber lasers

CPA – Ultrafast Laser

5 fs is record
35 fs is scientifically routine
200 fs is reliable (fiber)
5-10 ps domain is developing
Industry appications







PULSED LASER MACHINING: nanosecond vs femtosecond laser pulses

Ultrafast Laser Processing – Handbook by Clark MXR

Videos are downloadable from:

http://www.cmxr.com/Industrial/Handbook/Introduction.htm

Simplified view of physical interactions and applications for ultrafast lasers

Nanosecond Laser Machining; Clark MXR view

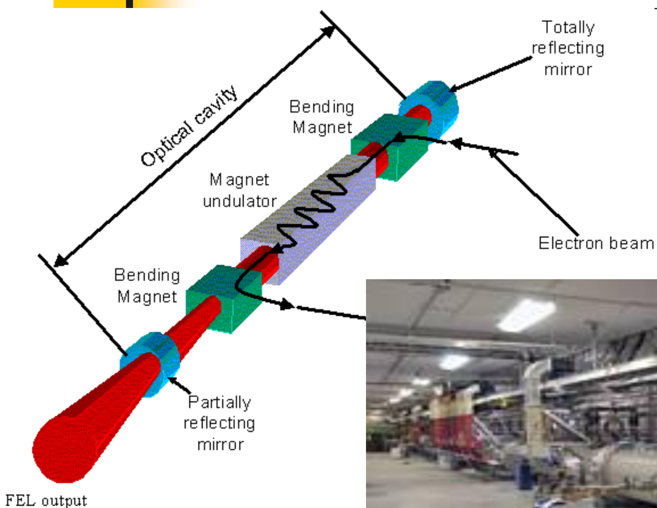
Femtosecond Laser Machining; Clark MXR view

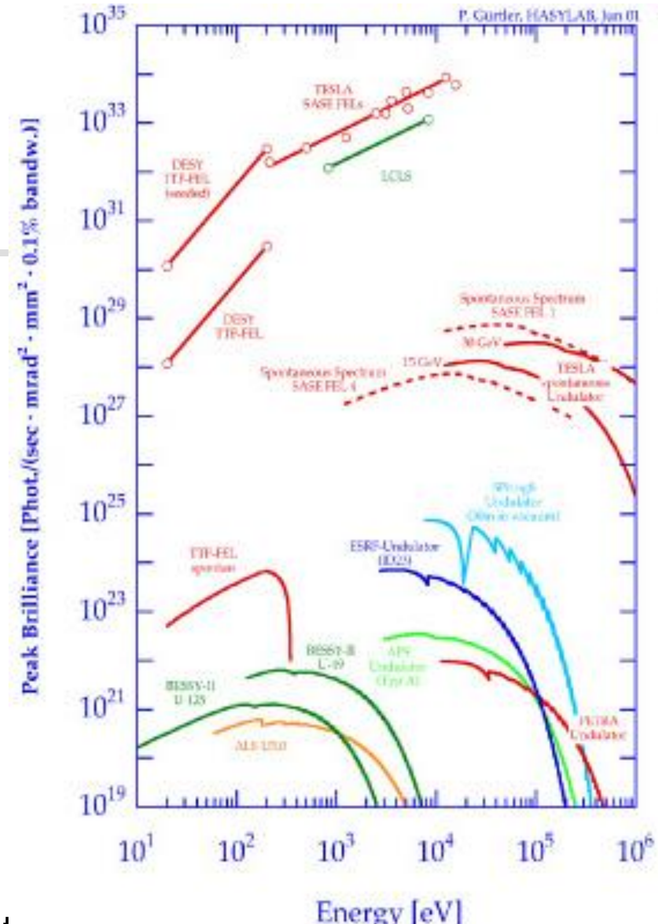
Ultrafast-laser processing Advantages

ULTRAFAST LASERS offer excellent prospects for precise shaping and modification of both transparent and opaque materials

- non-linear absorption mech. in transparent or wide-bandgap materials
- short-pulse provides rapid expansional cooling; minimal collateral damage
- eliminates plume shielding: laser arrives before plasma/plume reflects away light
- small interaction volume ~ 1-μm^3; bulk-internal 3-D writing
- direct-write for flexibility or rapid prototyping
- direct process (not post-processed, etched, etc.)
- deterministic / reproducible etching
- Small heat-affected zone: HAZ
- Vaporization vs. melt ejection: cleaner and less debris

Free Electron Laser



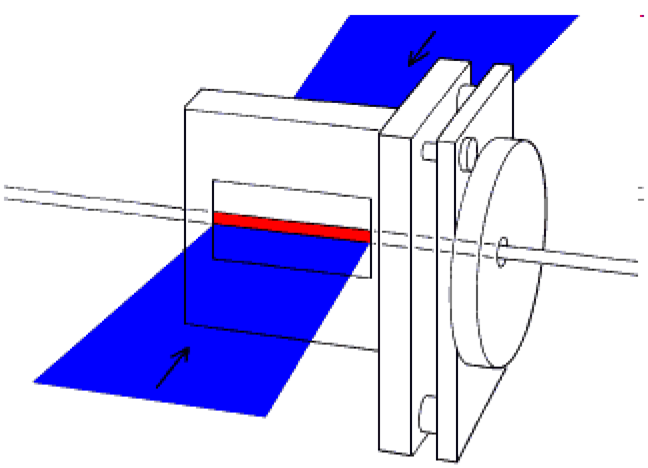


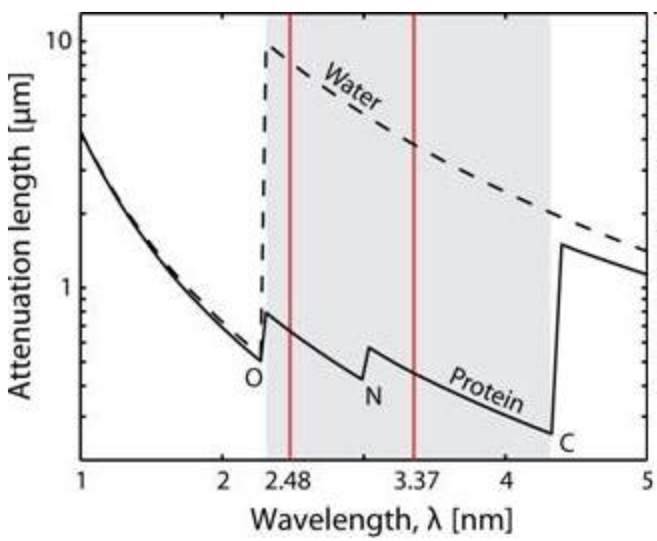
A Free-Electron Laser or FEL uses a beam of relativistic electrons t
intensity electromagnetic radiation, much brighter than that produced by a synchrotron light source. The basic components of a traditional FEL are the magnet undulator, the electron beam (which can be either in a storage ring or from a linear accelerator) and optical mirrors.

- easy wavelength tuning: velocity of beam; frequency conversion in crystals, different undulator period: extreme UV to far infrared tunable laser source
- very expense science machines…100’s meters long linear accelerators or in syncrhrotron rings

(Soft) X-Ray Laser

- Pump threshold for lasing scales as P ~ λ^{-4} to λ^{-6}
- Optically pumped by world's largest lasers; *or a nuclear explosion!*
- Not practical but interesting science
- Exploding foil target—2 line focused laser pump/vaporize foil, rip most or many electrons off of atoms; fast cooling in explosion leads to laser action in 2 to 20 nm region
- Other pumping schemes: laser filament, electric discharge capillary
- Goal: Water Window for biology imaging application





Lasers Sources and Output Characteristics available for Material Processing+

Laser Type	Wavelength	Max. Power (W)	Avg. Pulse Duration*	Repetition Rate (Hz)	Beam Size (mm)	Beam Divergence (mrad)	Notes
CO_2	9 – 11 μm	45,000	40 ns – cw	50-25,000	1 – 200	1 – 10	
Nd:Glass	1.05 μm	500	3 – 30 ns	~3 10	4		Q-switched
Nd:YAG	1.06 μm	2600	10 ns – cw	10-1000	10	2	flashlamp
	1.06 μm	250	10 ns – cw	400-40,000	10	2	diode-pumped
	532 nm	50	10-250 ns	400-40,000	10	1	freq. doubled
	355 nm	10	10-250 ns	400-40,000	10	1	freq. tripled
Laser Diode Array	800, 900 nm	100	10 μs – cw		10 x 0.001	~300	single-array
Laser Diode	800, 900 nm	20	cw		10	~100	fiber delivery
Ar ion	450 – 530 nm	50	cw		2	0.5	
XeCl excimer	308 nm	150	10 – 50 ns	50 – 500	10 x 30	1 x 3	
KrF excimer	248 nm	200	10 – 50 ns	50 – 1000	10 x 30	1 x 3	
ArF excimer	193 nm	150	10 – 50 ns	50 – 500	10 x 30	1 x 3	
F_2	157 nm	20	20 ns	50 – 500	10 x 25	1 x 3	

+ values are representative of many available laser configurations; maximum power will not be available for all combinations.
* cw: continuous wave operation

Review: Types of lasers in Laser Processing

- Different ways of classifying lasers

- by wavelength: CO_2 (10600 nm)
  YAG or Fiber (1319, 1064, 532, 355, 266 nm)
  Ultrafast (1055, 1044 or 800 nm)
  Excimer (157, 193, 248, 308, 351 nm)

- by pulse duration: CO_2 (continuous, milli-seconds, nanosec)
  YAG (milli- to nano-seconds)
  Excimer (nano-seconds)
  Ultrafast (pico- to femto-seconds)

milli = 10^{-3}, micro = 10^{-6}, nano = 10^{-9}, pico = 10^{-12}, femto = 10^{-15}

Suppliers of Laser Processing Systems and Services for Semiconductor Manufacturing (circa 2000; partial list)

Company	Home Location	Telephone	Web Site
AB Lasers, Inc.	MA, USA	978-635-9100	www.ablasers.com
Cambrigde Tech., Inc.	MA, USA	617-441-0600	www.camtech.com
Coherent, Inc.	CA, USA	408-764-4000	www.cohr.com
Continuum, Inc.	CA, USA	800-956-7757	www.ceoi.com
Control Laser, Inc.	FL, USA	407-926-3500	www.controllaser.com
Convergent Energy, Inc.	MA, USA	508-347-2681	www.convergent-energy.com
Cymer, Inc.	CA, USA	619-451-7300	www.cymer.com
Diomed, Ltd.	United Kingdom	44-1223-421799	www.diomed-lasers.com
Electro Scientific Ind., Inc.	OR, USA	800-547-5746	www.esio.com
JMAR Industries, Inc.	CA, USA	619-535-1706	www.jmar.com
JPSA, Inc.	NH, USA	603-595-7048	www.jpsalaser.com
Komatsu, Inc.	Japan	81-3-5711-1911	www.komatsu.com
Lambda Physik, Inc.	Germany	49-(0)551-69380	www.cohr.com
Lasag AG	Switzerland	41-0332224522	www.lasag.com
GSI Group, Inc			
MPB Technologies	Canada	514-694-8751	www.mpb-technologies.ca
New Wave Research, Inc.	CA, USA	408-328-0220	www.new-wave.com
Photomachining, Inc.	NH, USA	603-882-9944	www.photomachining.com
Radiance Services Co., Inc.	MD, USA	301-654-0228	www.RadianceProcess.com
Resonetics Micromachining Tech., Inc.	NH, USA	603-886-6772	www.resonetics.com
Revise, Inc.	MA, USA	617-272-9888	www.revise.com/
Rofin Sinar, Inc.	Germany	49-(0)407-33630	www.rofin-sinar.com
JDS Uniphase (SDL)	CA, USA	408-943-9411	www.jdsu.com
Spectra Physics, Inc.	CA, USA	650-961-2550	www.spectra-physics.com
Sumitomo Heavy Ind., Inc.	Japan	81-3-5488-8000	www.shi.co.jp
Synrad, Inc.	WA, USA	425-349-3500	www.synrad.com

* see also Materials Processingin the Laser Focus World 'Buyers Guide,' Pen Well Publishing, and follow activities of Laser Insitute of Americaa Optical

Others:
Trumpf, Germany
Phillips, Holland
NEC, Japan
Cyber, Japan
Imra America
Exitech, UK
Oxford Lasers, UK
Fraunhofer Insts.

Why lasers for machining?

- Non-contact (no mechanical deformation or tool wear)
- Small diffraction → highly directional beams or optical fiber delivery is efficient energy transport
- Clean (no chemicals, no mess)
- Strong material interactions – focus to high intensity or select laser wavelength for strong absorption
- Can be very fast
- Coherence permits holographic 2D or 3D structuring at resolution < $\lambda/2$
- Short wavelength (excimer UV lasers) provides high resolution → 60 nm in lithography; microprocessing (~1 micron) is standard in industry; CO_2 laser (λ~10 μm) is macroprocessing
- Rapid prototyping (computer design)
- process difficult materials (glass, ceramics…)
- Lend themselves to automation
- Can drill to very shallow angles (<10 degrees)
- Short pulse duration or fast scan → small heat affected zone

Competing technologies

- Mechanical drill bits and saw blades

  good down to 100 μm features on thick materials

- Electric Discharge Machining (EDM)

  slow, not as precise, requires dielectric bath

- Chemical milling

  messy, slow, not suitable for certain materials

- Arc or torch welding less easy to automate

- Water jet wet...

- Wet Lithography

- Stamping / molding: expensive development cost

ECE1461
Advanced Laser Processing

Optical Delivery Systems

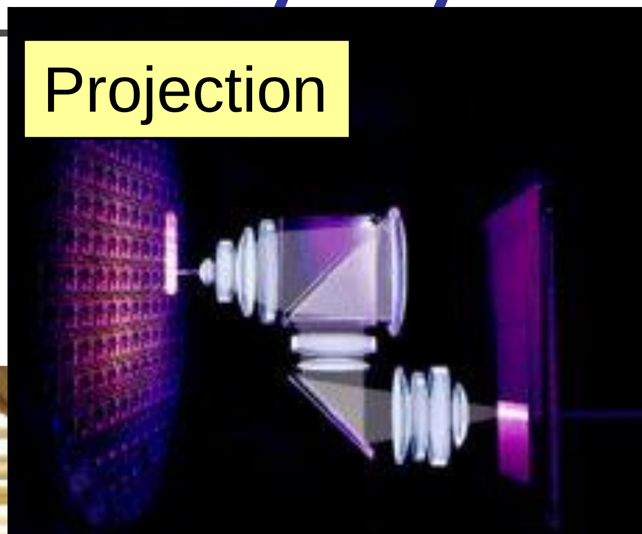
Peter R. Herman

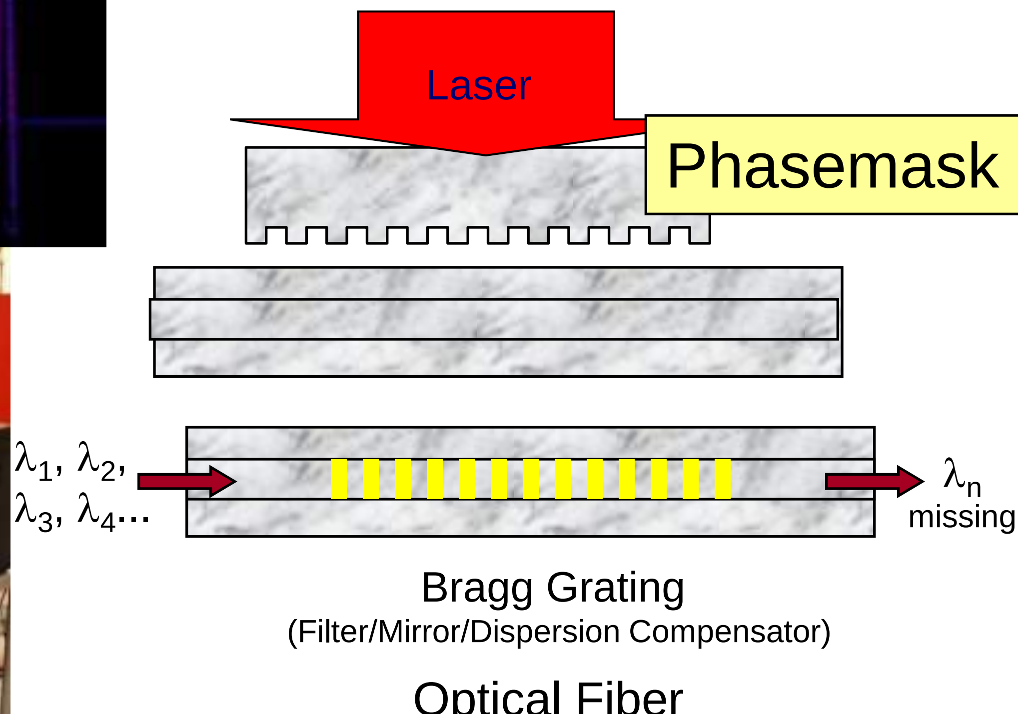
Purpose – *to deliver an arbitrary shaped beam of a specific pattern onto the sample at the appropriate fluence or intensity and time duration*

Optical Delivery Systems

- Optical Systems
  - very simple (direct beam with no lens) to very complex optical systems costing millions of dollars! Often includes sample handling, alignment, robotics, vision systems, metrology, feedback diagnostics…
- Four Basic Delivery Modes
  - Direct Write (i.e. laser scanning a tight focus)
  - Mask Projection
    - replicate a magnified or demagnified pattern of mask
    - phasemask projection (new)
  - Uniform Flooding (complex or simple)
  - Fiber Delivery (direct write or mask or uniform)

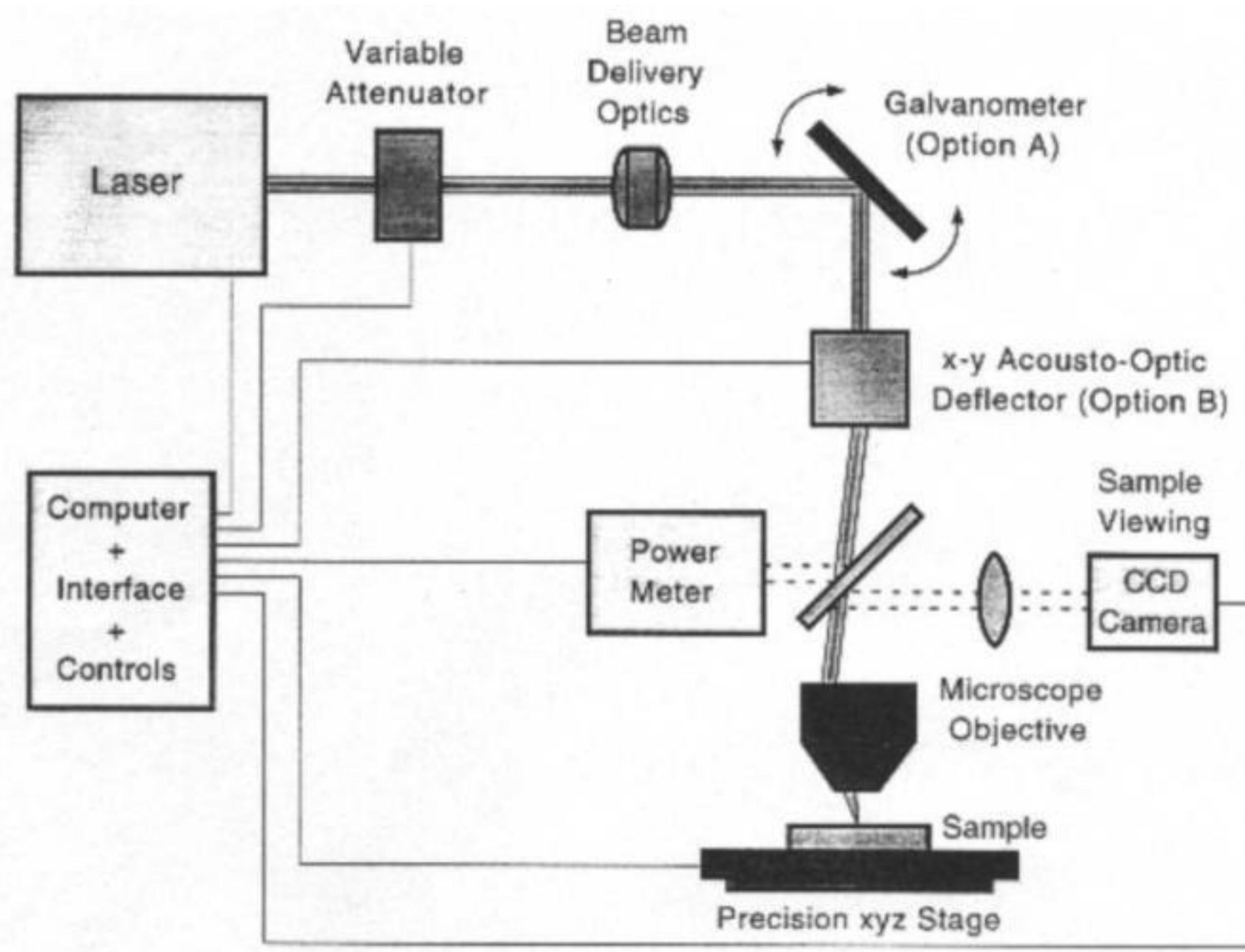
Delivery Systems - Examples





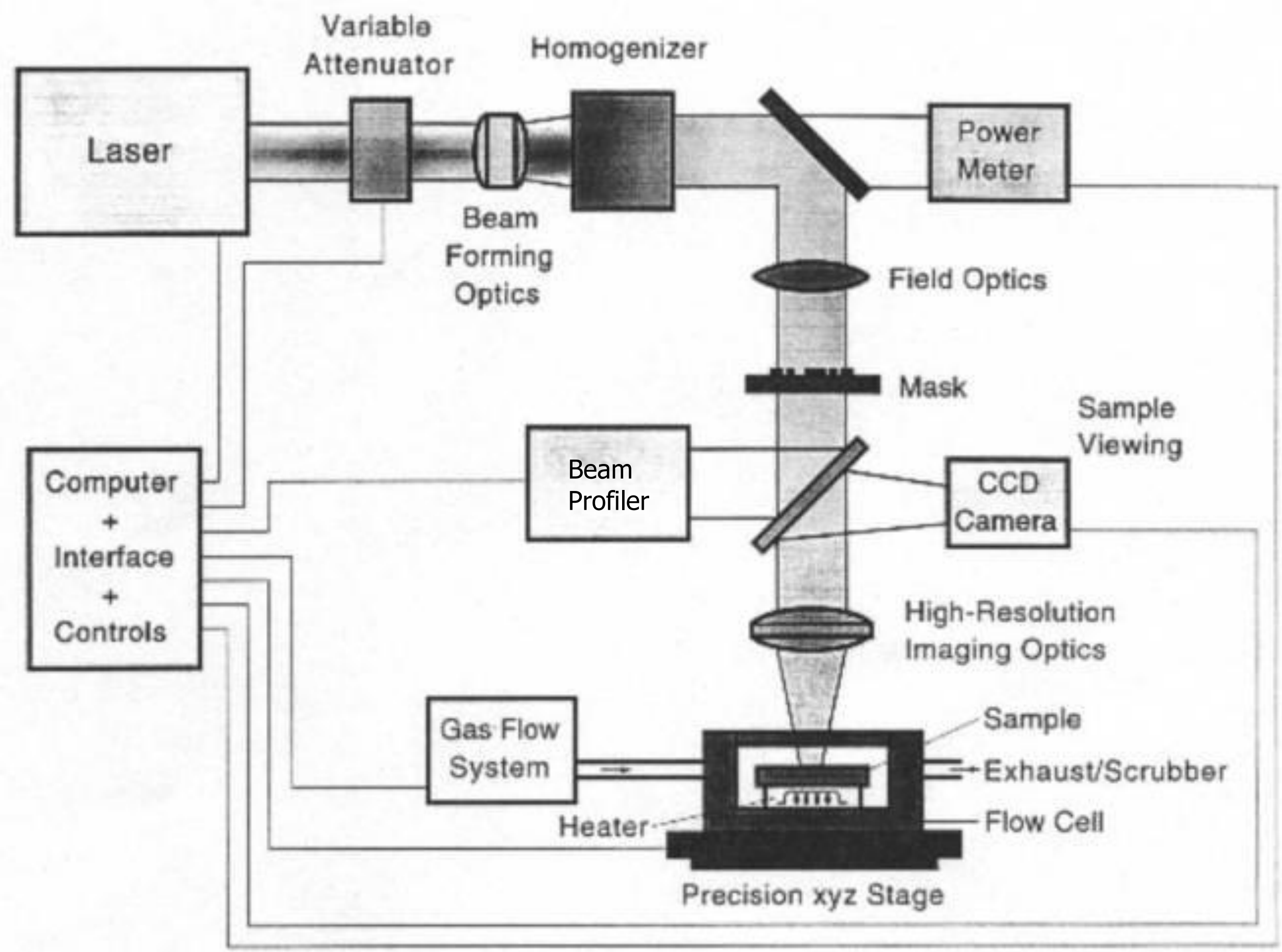
Direct Write Optical Delivery
Generic System Components

A processing system for laser direct writing. A microscope objective focuses the beam tightly onto the sample surface Beam steering is provided eithe by deflection from a mirror galvanometer (option A) or fro an acousto-optic deflector. Thi motion can be computer synchronized with a precision x y-z positioner to laser-write tw dimensional patterns or three-dimensional structures on the sample surface. A sample flow cell identical to the one shown in next Figure can also be employed. Beam diagnostics, machine vision, and computer interfaces are common elemen to commercial laser-writing systems.



Projection Mask Optical Delivery
Generic System Components

A beam-delivery arrangement based on large-area mask projection. The assembly consists of beam shaping optics, a mask and lens projection system, an optional sample-flow cell for regulating etching or deposition, and various diagnostics and computer interfaces for monitoring and controlling alignment and exposure.

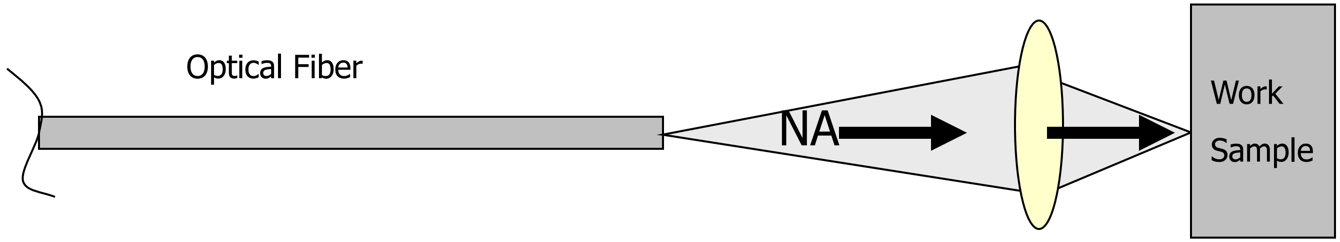


Beam Delivery
Uniform Flooding

- Step or scan a very uniform (homogenized) beam across a sample surface to achieve a physio-chemical change
- Applications:
  - Surface annealing (rapid temp. cycle in thin surface layer)
  - Re-crystallization
    - Annealing Silicon Thin-film-transistor TFT active-matrix LCD displays
      - increase Si crystal size for good electronic properties
      - Download and Read:
        - http://www.lambdaphysik.com/pdf/pdf_178.pdf
  - Surface treatment
    - Hardening of engine cylinder walls for high wear resistance

Beam Delivery:
Fiber Delivery

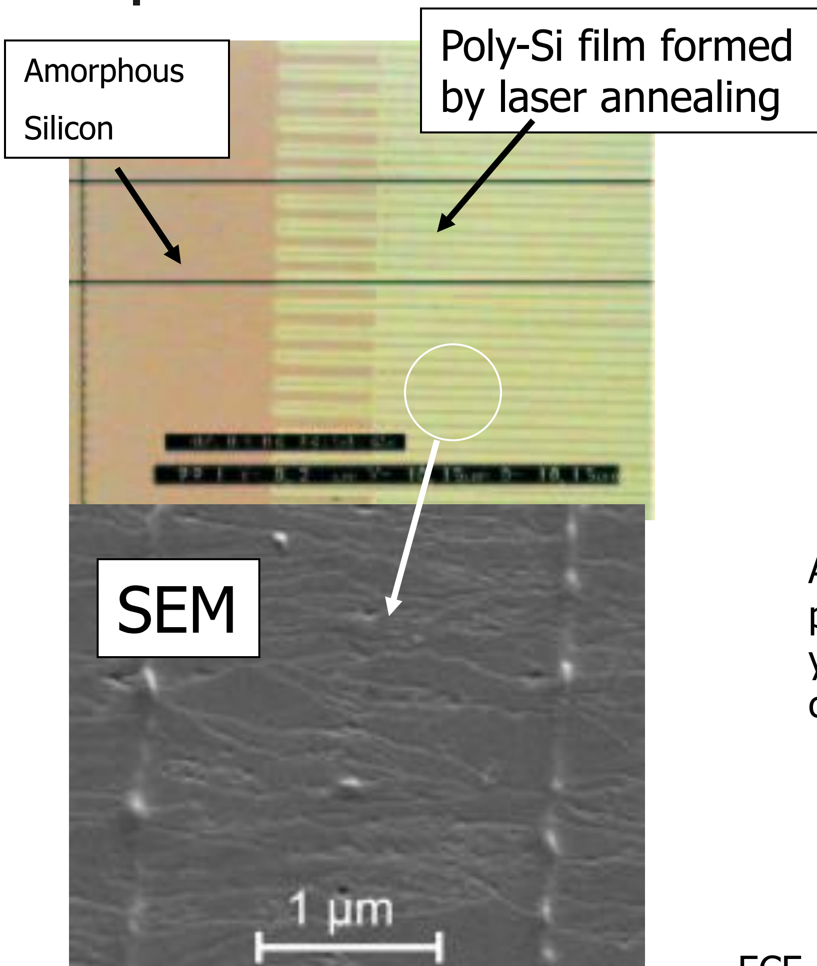
- Light guiding fibers can be routed like wires
- Nd:Yag → fiber is very transparent at ~1um wavelength
  - Multi-mode (large diameter: tens of um) → multi-kW delivery
  - Single-mode (~9um dia core and 125um dia glass + buffer): power limited
  - can maintain good beam quality
  - couples efficiently to multi-mode fiber
- Multi-launch systems → support numerous processing stations
- Fibers: simple to construct/layout unlike rigid beam tubes
  - eye safety friendly
- Output -> requires large NA lens to capture multi-mode beam
- Fiber→Lens focusing assembly integrated to laser direct write system



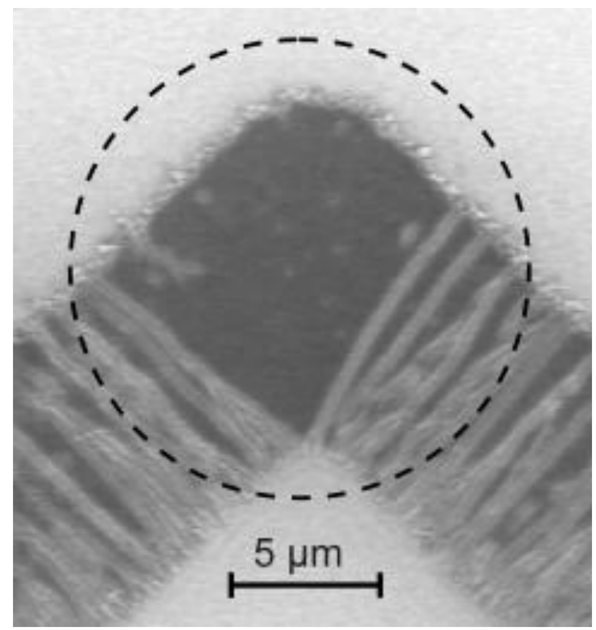
Beam Delivery - Uniform Flooding – MicroLas Si TFT Annealing (case study)

Print reference below and study laser Annealing and optical deliver system

http://www.lambdaphysik.com/pdf/pdf_178.pdf

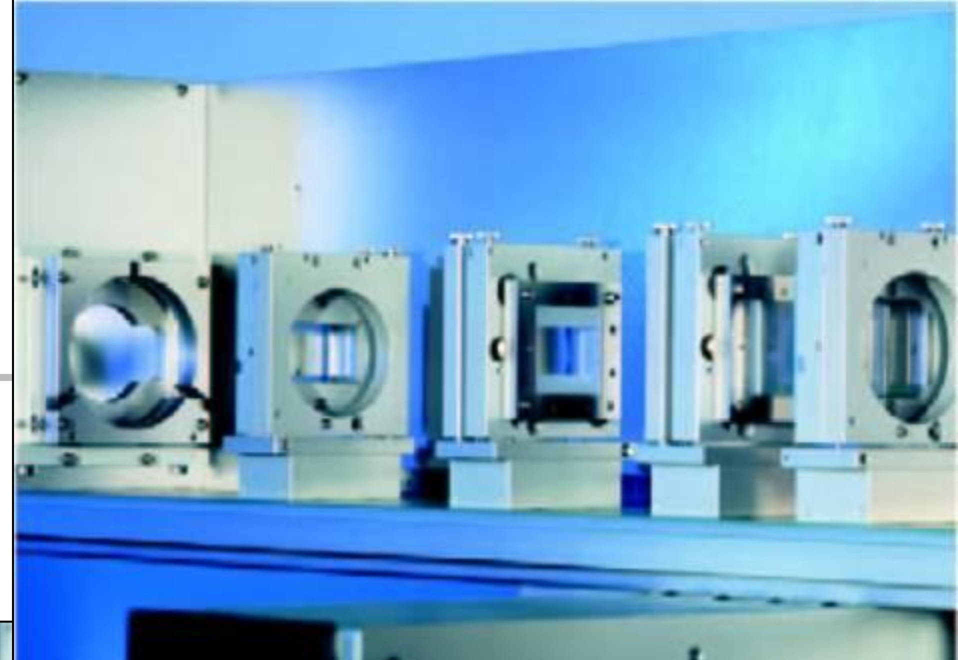


A scanned chevron pattern exposure yields a single crystal like region



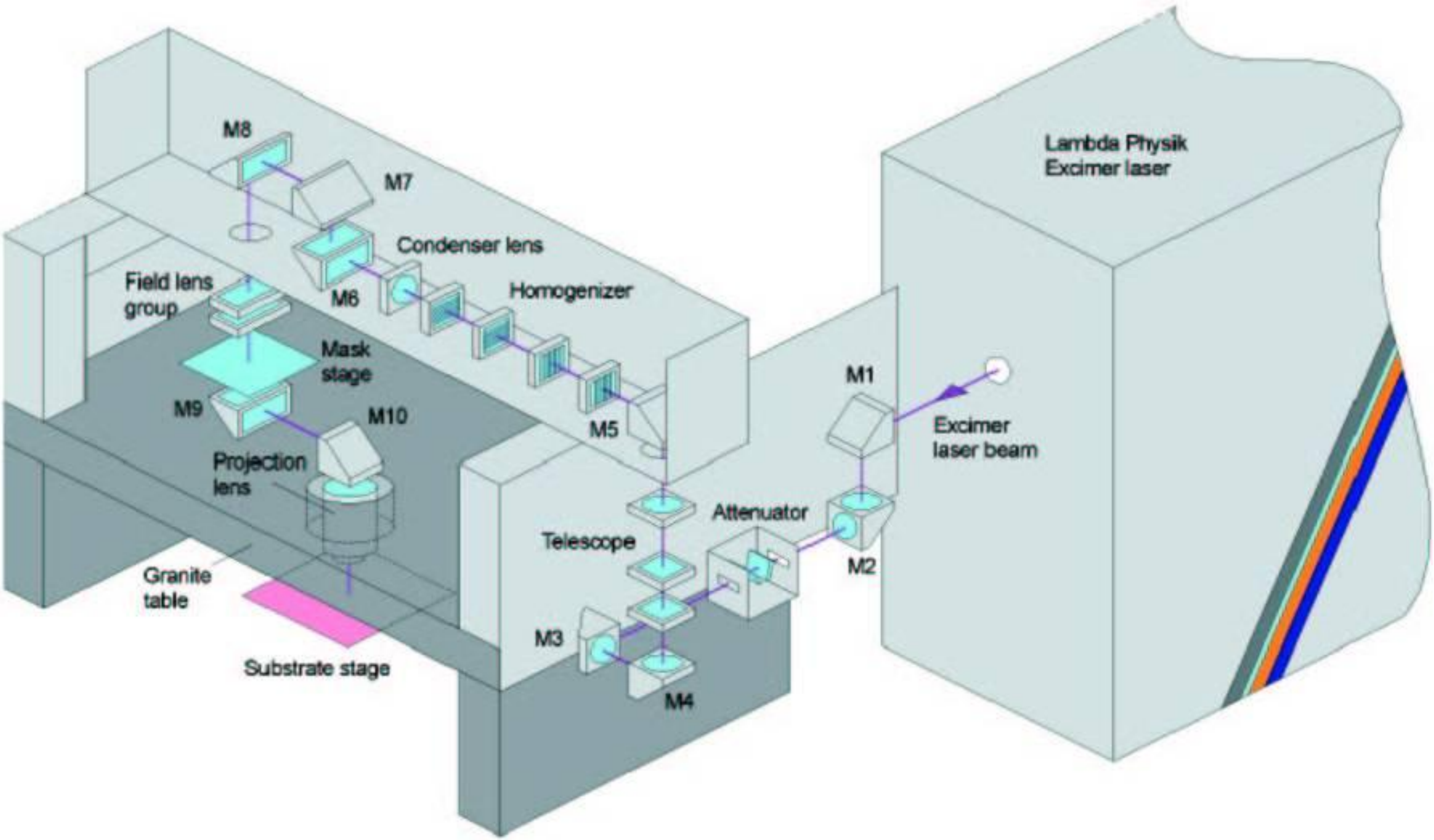
Optical Delivery
– uniform flooding with direct write capability

Homogenizer:
Cylindrical Lens Array



Beam Delivery

Uniform Flooding – MicroLas Si TFT Annealing



System Components

The schematic drawing of the CRYSTALAS optical system shows the optical beam path and all optical components necessary to perform high precision laser annealing. The entire optical set-up is mounted on a granite table that ensures the required mechanical stability. The length of the granite table can be varied to meet customer requirements.

System Beam Entrance

The way the laser beam enters the optical system can be individually adapted to any beam height and beam orientation of Lambda Physik excimer lasers.

Attenuator

A variable attenuator with a dynamic range of 10 to 1 can adjust the energy density on the substrate. In case a pulse duration extender is employed, the attenuator also controls the amount of energy in the extender.

Telescope

An anamorphic telescope configuration efficiently adapts the beam profile to the aperture of the homogenizer. Anamorphic: MAG_x not equal MAG_y

Beam Delivery

Uniform Flooding – MicroLas Si TFT Annealing

Homogenizer

The homogenizer consists of two pairs of lens arrays – two for each beam axis. The condenser lens generates the uniform illumination field on the mask. By exchanging the homogenizer elements, different field sizes on the mask can be adjusted.

Field Lens Group

The field lenses are used to project the light into the entrance aperture of the projection lens.

Mask Stage

The high precision 6“ x 6“ mask stage allows accurate positioning of the mask to the uniform beam profile. Different travel ranges and mask sizes are possible.

Projection Lens

The diffraction limited projection lens allows annealing processes to be performed with a resolution of 2 µm. Projection lenses with a field of view (FOV) of 18 mm or 30 mm are available.

Beam Delivery

Uniform Flooding – MicroLas Si TFT Annealing

CRYSTALAS System Specifications

Three system Versions:

- System wavelength: Excimer XeCl: 308 nm
- Optical system efficiency up to 40 %
- Projection lens 5x- Demagnification
- NA 0.13 diffraction limited: Resolution 2.0 µm 2.0 µm 2.5 µm
- Field of view (FOV) 10 mm, 18 mm, 30 mm
- Depth of focus (DOF) ±15 µm, ±15 µm, ±25 µm
- Minimum uniform beam profile width on mask 5 mm x 5 mm
- Homogeneity of beam profile at mask $\delta \pm 2.5\%$
- Substrate beam profile for full FOV in one axis:

  10 mm x 1 mm OR 16 mm x 1 mm OR 30 mm x 1mm
- Energy density at 1100, 1300, or 1300 mJ/cm^2

Beam Delivery
Mask Projection - I

- Image and demagnify a patterned mask or phasemask onto a surface with a lens system

$$1/s + 1/s' = 1/f \qquad \text{DeMag} = -s'/s$$

- Replicate complex mask features in high volumes
- require large area and uniform laser beams (not Gaussian beams)
  - CO_2 and excimer laser
- High-volume production of identical patterns
  - Photolithography of microelectronic Si chips:
    - 45 nm features x several cm^2 area chip on 30-cm wafer, >1 wafer per minute (30nm in Development)
    - Lasers: \$0.5M Optical System: \$10M
  - Multi hole arrays in ink-jet nozzles
  - Packaging: Surface Relief Structures, microlens assemblies
  - Medical: Corneal Shaping of Eye

Beam Delivery
Mask Projection - II

Components:

eg. *Similar with many features of the MicroLas CrystaLas Uniform Flooding system*

- Power meter for exposure control and feedback
- Beam forming optics
- Homogenizer (multireflection mirrors, prisms, lenses, lens assemblies, cullus tube)
- Field optics (match NA of incoming beam to input NA of imaging lens)
- Require uniform backlighting of transmission mask, with NA matched to NA of projection lens
- Masks: Cr on fused silica is very common, patterned dielectric mirrors, phasemask
- Beamsplitter and CCD Cameras:
  - Profile of beam, homogenous, pointing direction, monitor damage to optics
  - fiducials for target alignment
- Imaging: Mask to Lens to Target Sample: $1/s + 1/s' = 1/f$ DeMag = $-s'/s$
- XYZ precision mounting stages to place sample

Beam Delivery
Mask Projection - III

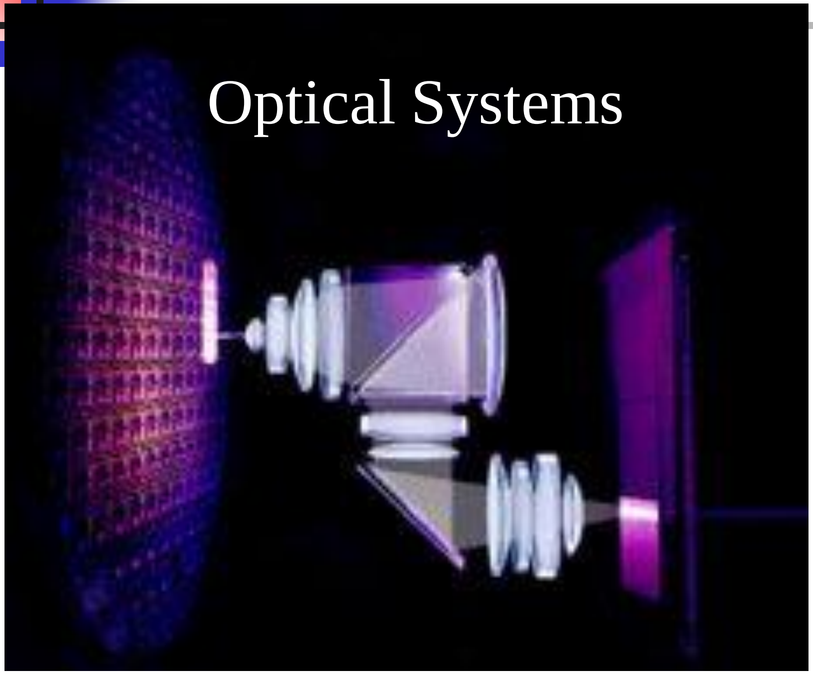
- System Control
  - Computer systems integrate and run all systems
  - Vision systems for target alignment and motion; autofocus
  - AutoCAD driven functions

- Ambient Controls:
  - Temperature, vibration, humidity controls - +/- 0.5 ^{o}C for 1 micron precision
  - Lens-Nozzles: project gas towards sample
    - to protect lens from debris, aid ejection of molten material in some processes
    - chemical assist to laser process (oxygen to exothermically aid laser cutting of metals; prevent oxidation such as aluminum welding)
    - Transparency optical path when ambient air absorbs (157nm F2 lasers)

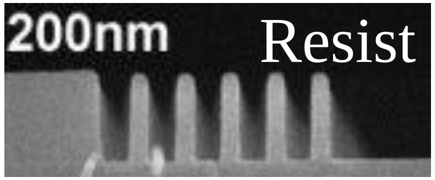
Beam Delivery
Mask Projection - IV

- Projection Masks typically used with large area laser beams (not Gaussian beams)
  - CO_2 and excimer laser
- Disadvantages:
  - Not flexible—only replicates the mask feature
  - Very inefficient---only transmit open areas of Mask

Excimer Laser Lithography:
Semiconductor Electronic Chips



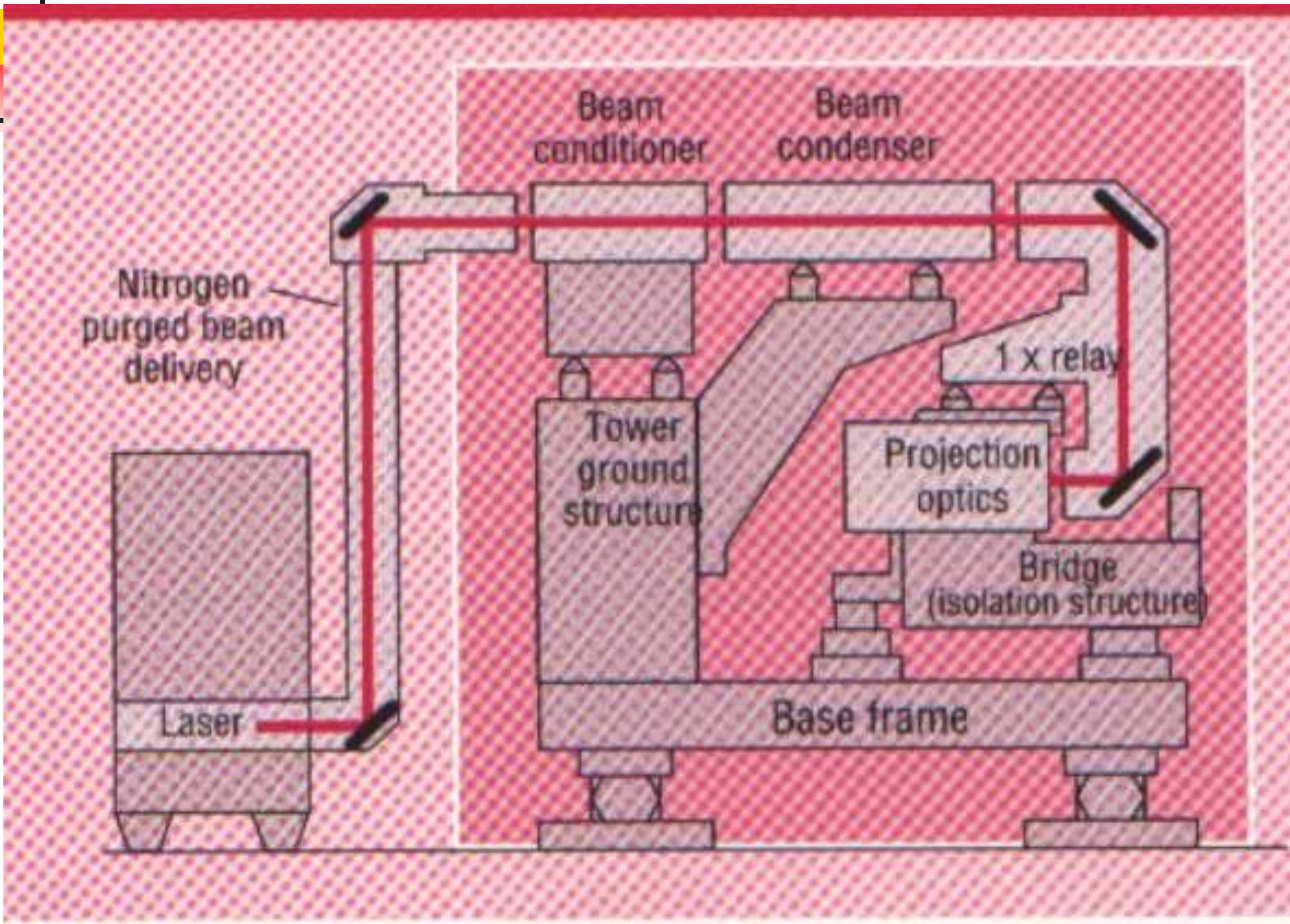
ASM Lithography (SVG)



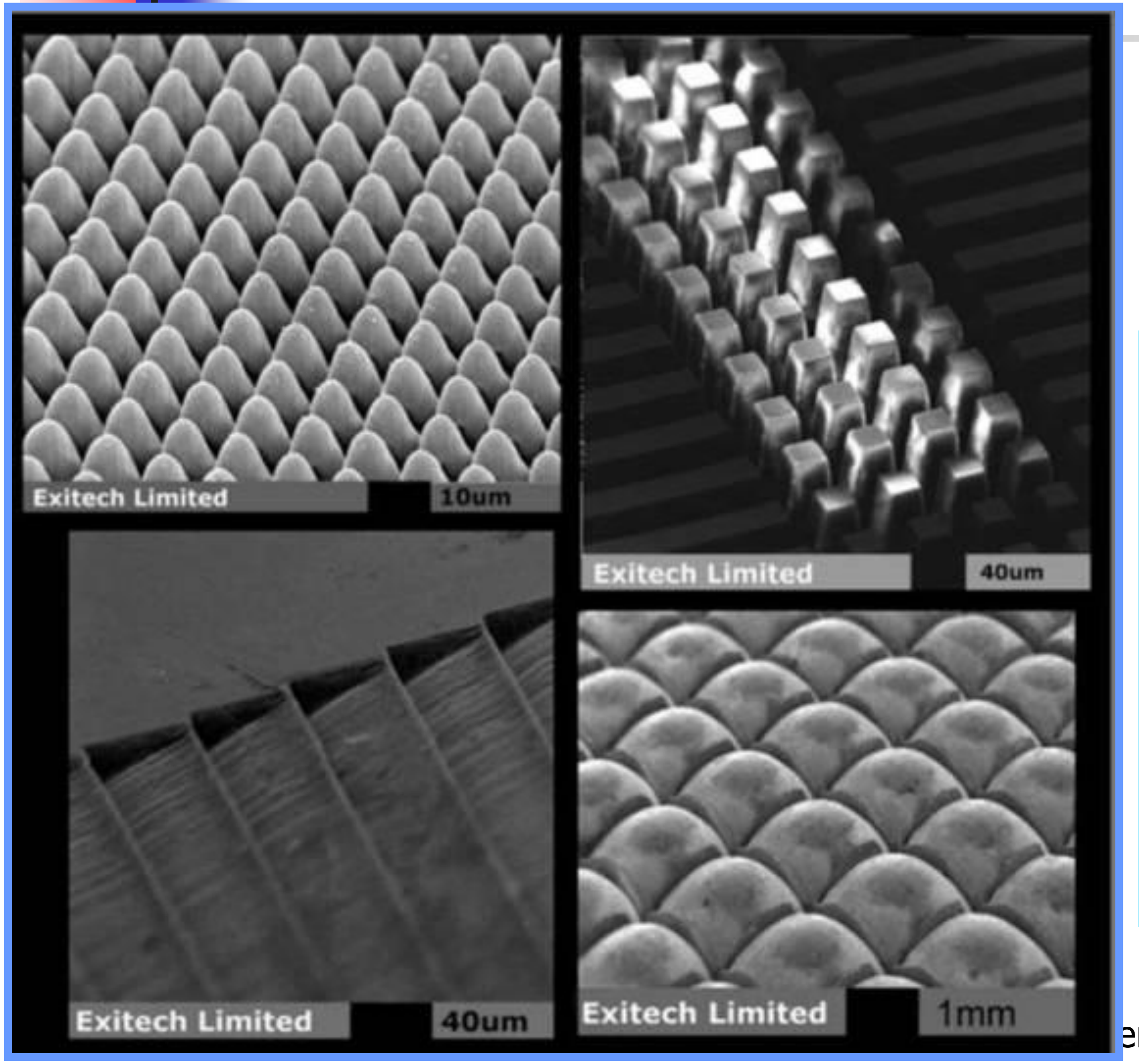
Pushing Conventional Optical Limits

- ~60-nm in production
- <45-nm in Research
- Less than One-Half of Wavelength

Schematic layout of excimer laser, optical delivery, projection optics and wafer handling equipment.



Excimer Laser Micromachining: Micro-Optics Manufacturing



Exitech

www.Exitech.co.uk

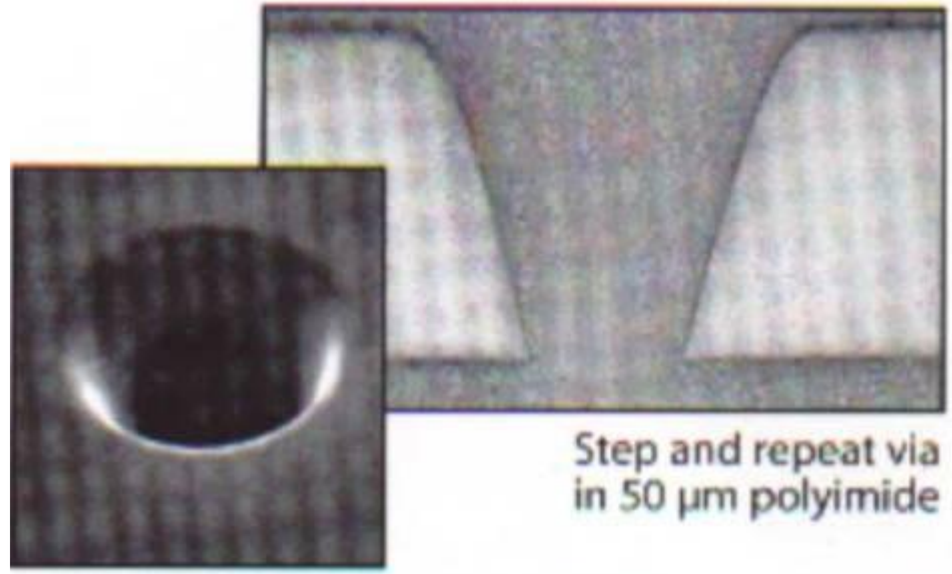
Ultraviolet excimer lasers provide strong interactions in transparent glasses:

- Microlens Arrays for fiber couplers
- Blazed Gratings
- Several micron features

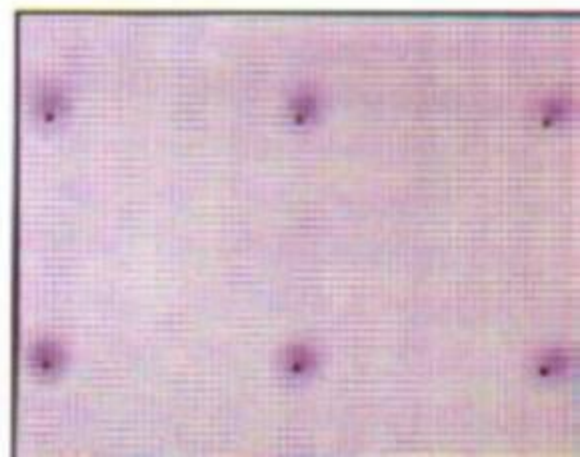
Tamarack Excimer Laser Ablation Systems:
example of high-end mask-projection micromachining

Precision step and repeat system with automated mask and substrate handling. The optics and sample manipulation robotics can cost 2 to 3 times the cost of the laser.

Step and Repeat System



Step and repeat via in 50 µm polyimide

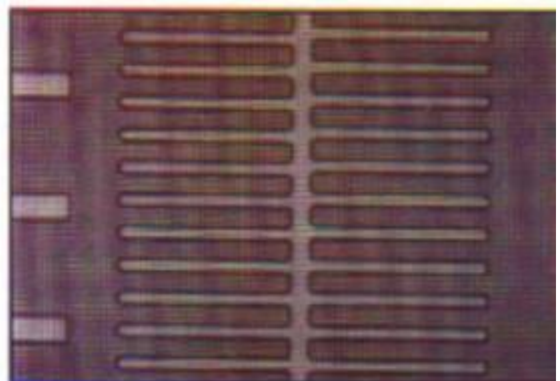


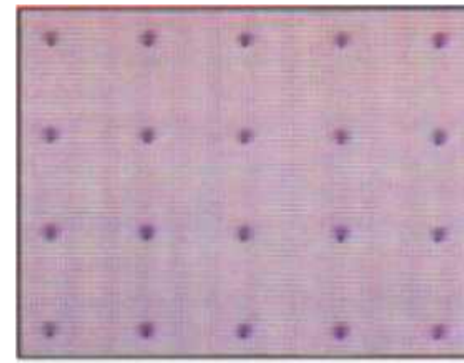
1 µm holes in reel-to-reel 25 µm polymer film

Tamarack Excimer Laser Ablation Systems:

example of high-end mask-projection micromachining

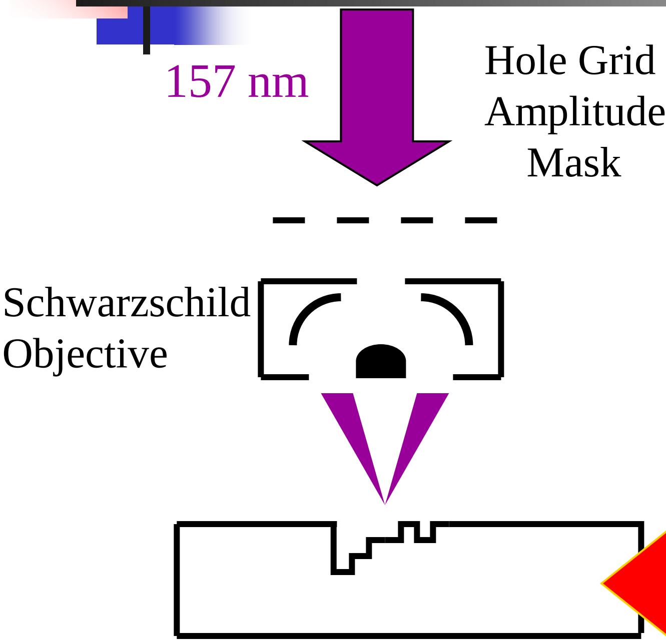
Automated reel-to-reel system for tape samples. On right are 8-μm features in 5 μm thick polyimide produced by scanning laser ablation.





Series	300	400	500
Configuration:	Scanning	Step and Repeat	Reel to Reel
Work Area:	200 x 200 mm - 400 x 500 mm	150 x 150 mm- 600 x 600 mm	width: 35 mm - 70+ mm
Optical Resolution better than:	4 μm	5 μm	10 μm
Alignment Accuracy:	±2 μm	±1 μm	±3 μm

F_2-Laser Micromachining in Glass: *4-Level* Diffractive Optical Element (DOE)



Glass Sample
(Corning 2947)

Far-Field Pattern

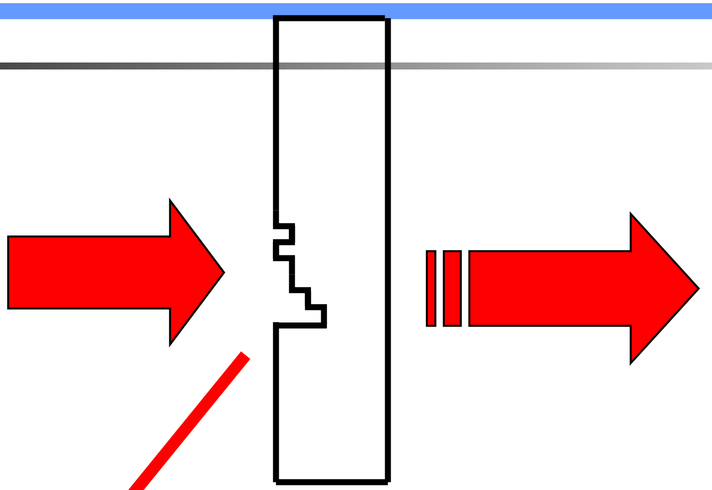
DOE Computer Design

Step-and-Expose Target Motion
Stage Control – 1 hr @ 100 Hz

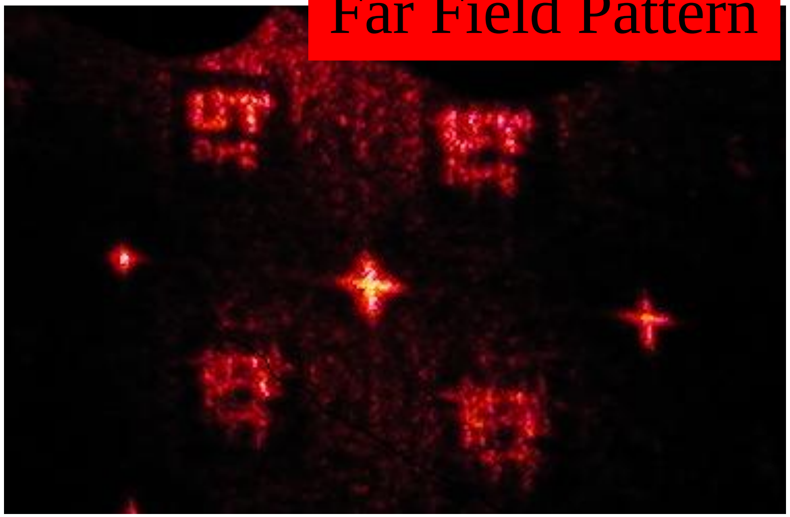
(Newport TSPI with 200nm precision)

F_2-Laser Micromachining in Glass: *4-Level* Diffractive Optical Element

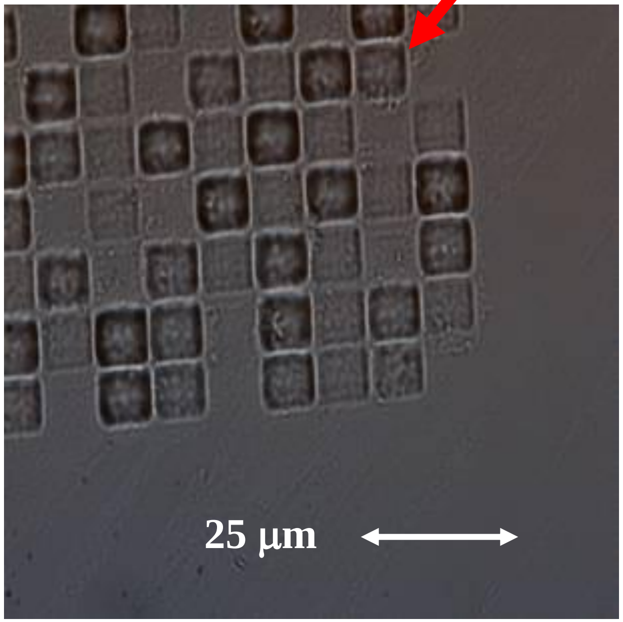
633 nm
Spatially
Filtered



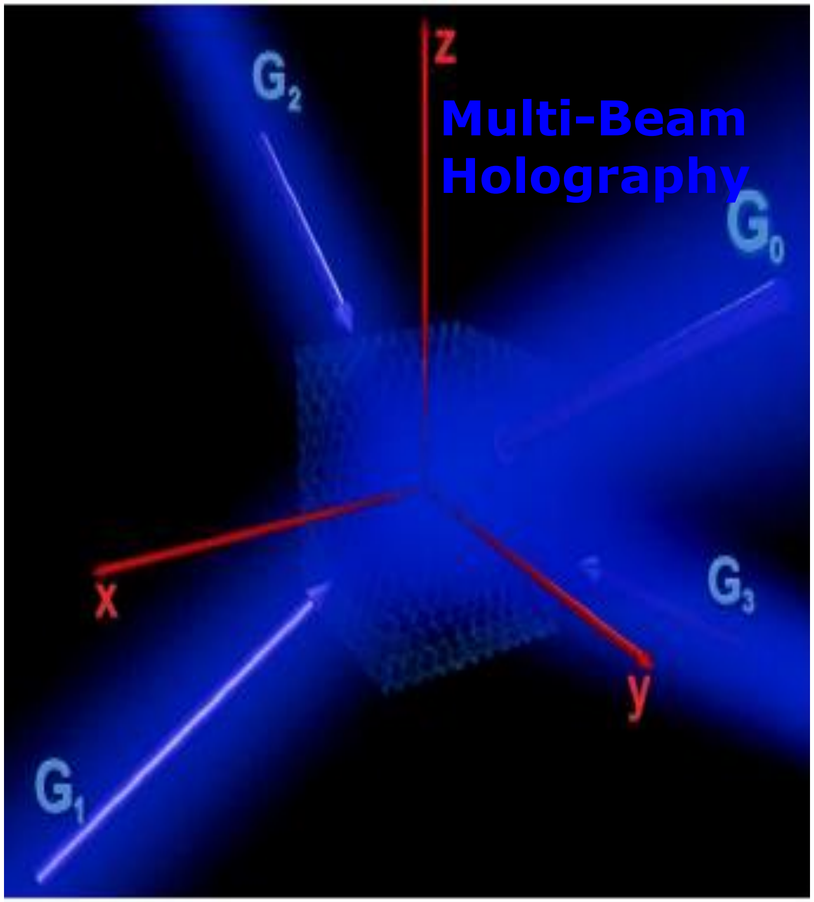
Far Field Pattern



Improve depth control, ablation debris, edge resolution



3D Holographic Lithography



Interference of Light:

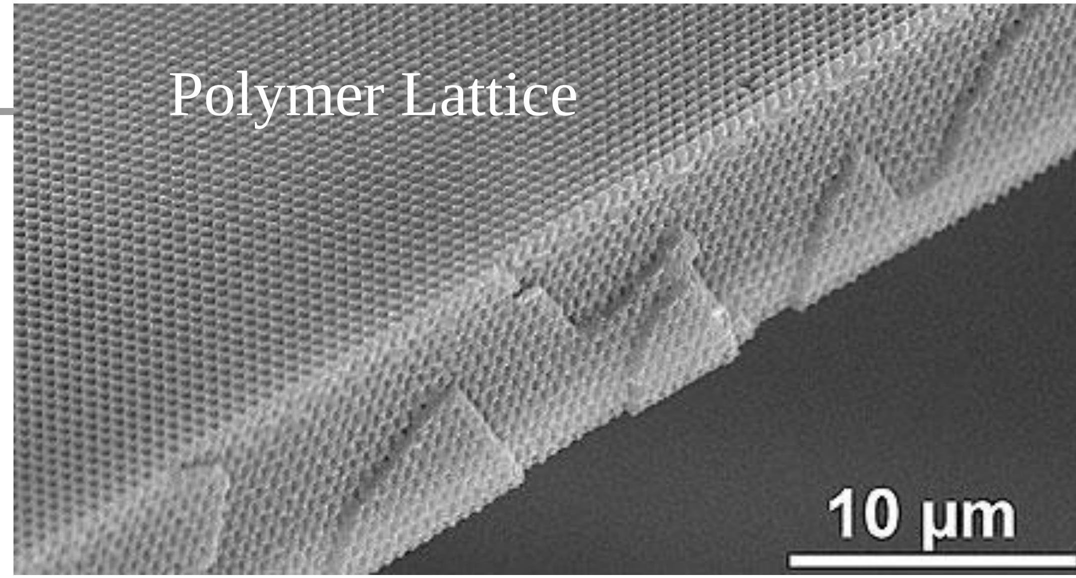
-Period is half wavelength

-Feature size is $\lambda/4$

-Sub wavelength Manufacturing

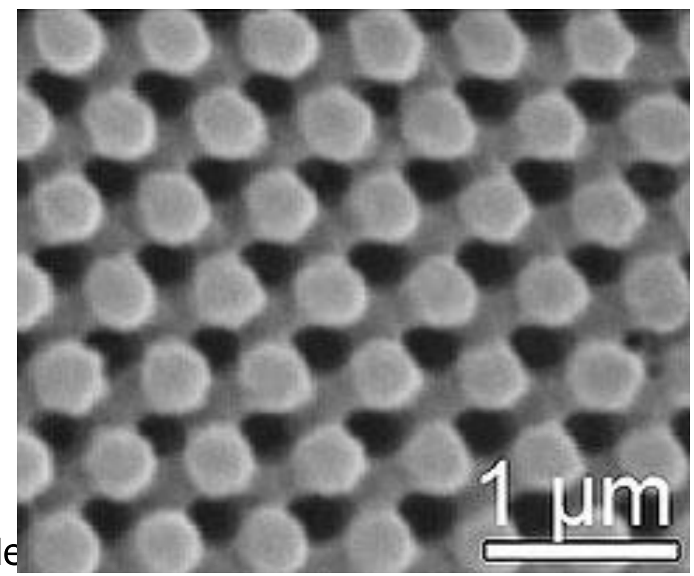
3D Holography: Photonic Crystals

3-D Photonic Crystals



Four Laser Beam Interference:
6-ns laser pulse
thick resist
Invert resist
→Photonic Bandgap

Inverted Titania photonic crystal



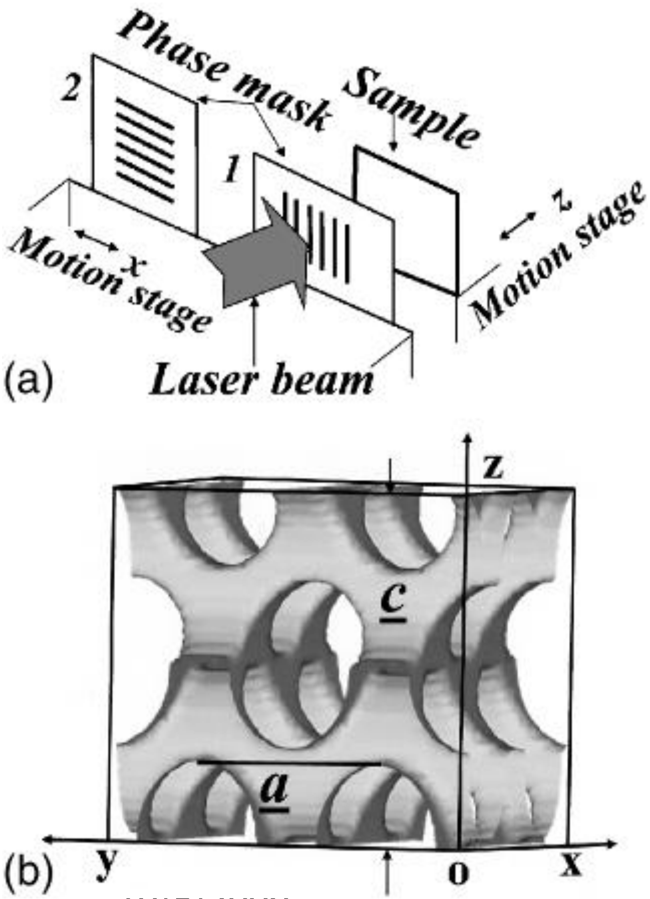
Andrew Turberfield, Bob Denning
Oxford University
www.eetimes.com/story/OEG20000925S0061

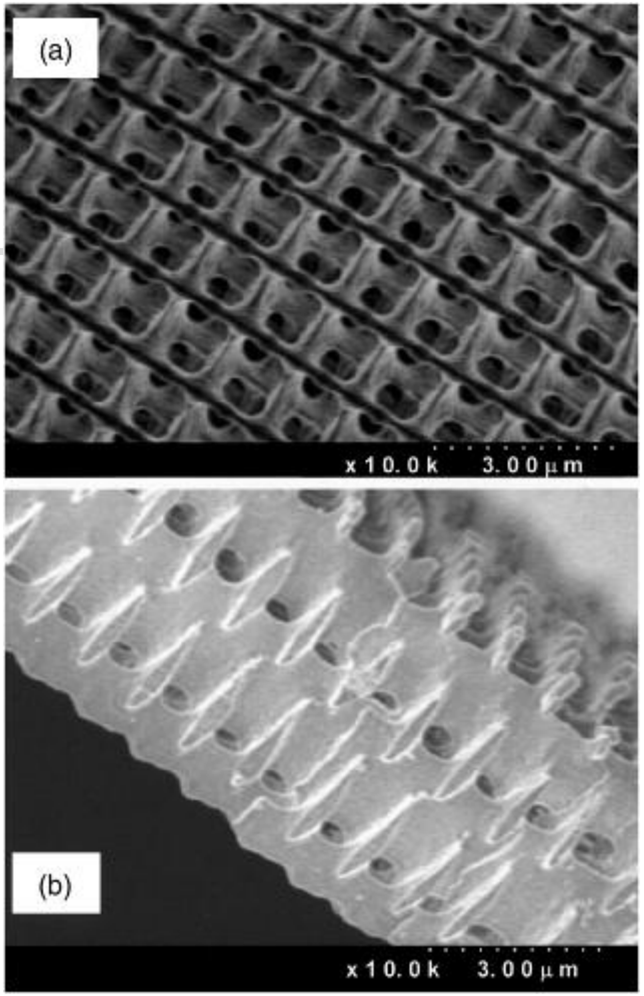
- PRHe

3D Laser Processing:

Phase-Mask Writing of Photonic Band Structure

- more stable than multi-beam splitters due to locked phases!

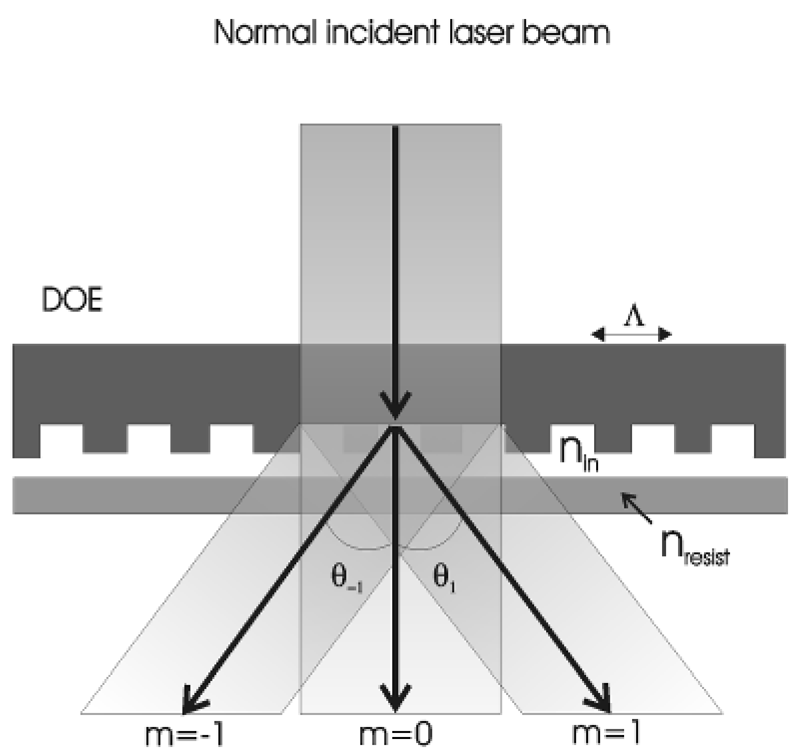




SEM of woodpile-type photonic crystal recorded in the modified SU-8 photoresist: a top view of the photonic structure in 001 plane; b cleaved cross-section view of the photonic structure. The elliptical rods of second neighbor are clearly seen to be shifted by half lattice constant in the direction perpendicular to the rod axes.

Phase Mask Based 3-D Holographic Lithography

Herman Group:
DOE based HL



New Method of writing 3D photonic Bandgap Devices

Phasemask/DOE is more efficient that amplitude grating mask

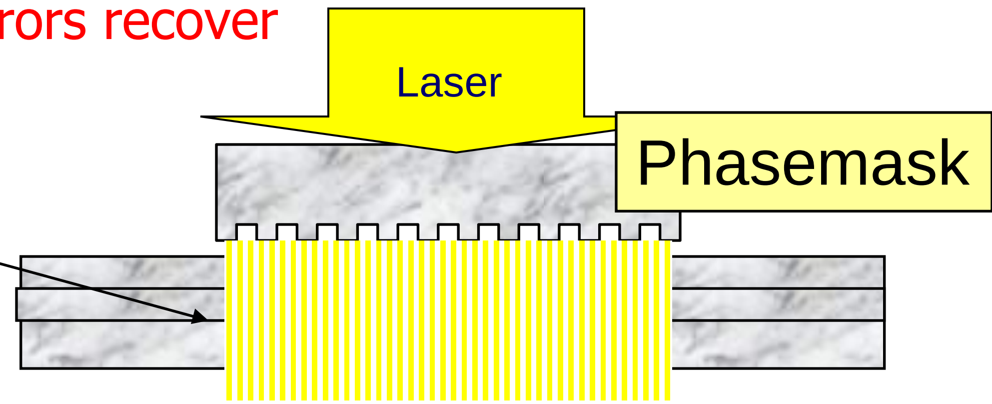
Y. Lin, PR Herman, K. Darmawikarta,
Appl Phys. Lett. **86**, xx, 2005

Beam Delivery
Mask Projection – How to Improve Efficiency?

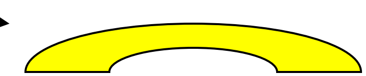
- Phasemask or Diffractive Optic: Near-Field and Projection Diffractive Elements pattern light by structuring phase delays of the phase front of the light
- Multi-mirrors or Dielectric Mirrors recover reflected light

Interference patterns in near field—Cosine Grating

All LIGHT is used in pattern



OR…In Far Field: Diffractive Beam shaping by Fourier Transform; resolution enhancement when combined with amplitude masking …Holography



Beam Delivery
Mask Projection – Fiber Bragg Gratings

- Linear Phasemask : Near-Field
- 1st and -1st order only interfere to create planes of light behind phasemask

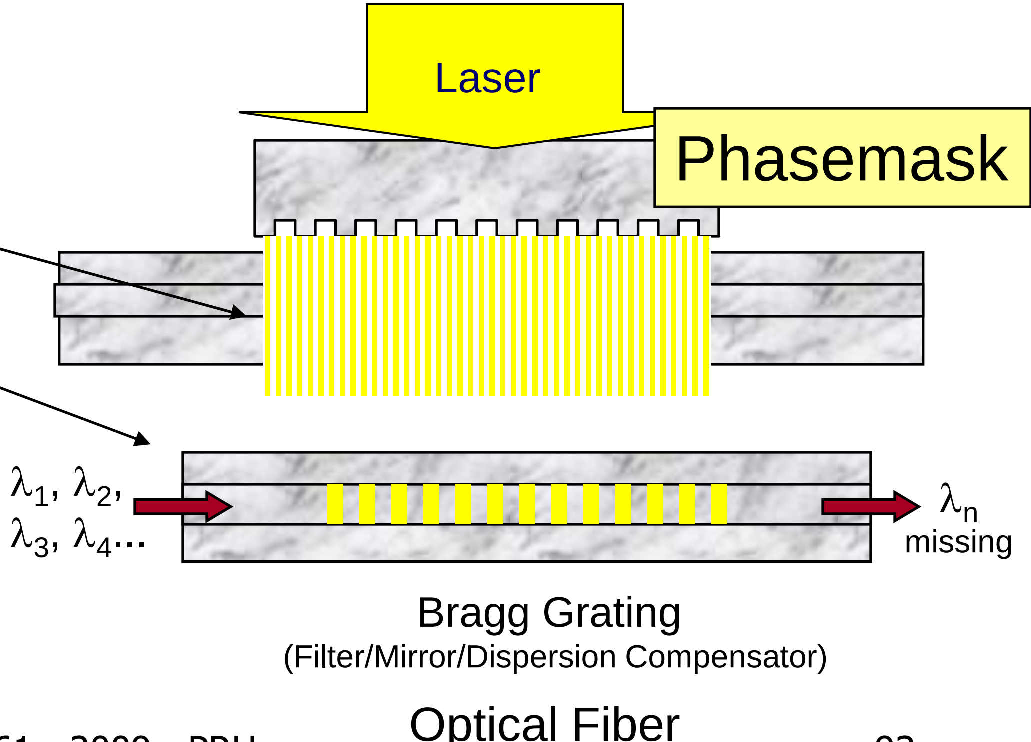
Interference patterns in near field—Cosine Grating

All LIGHT is used in pattern

FIBER BRAGG GRATING

High intensity regions burn in a refractive index modulation along fiber core

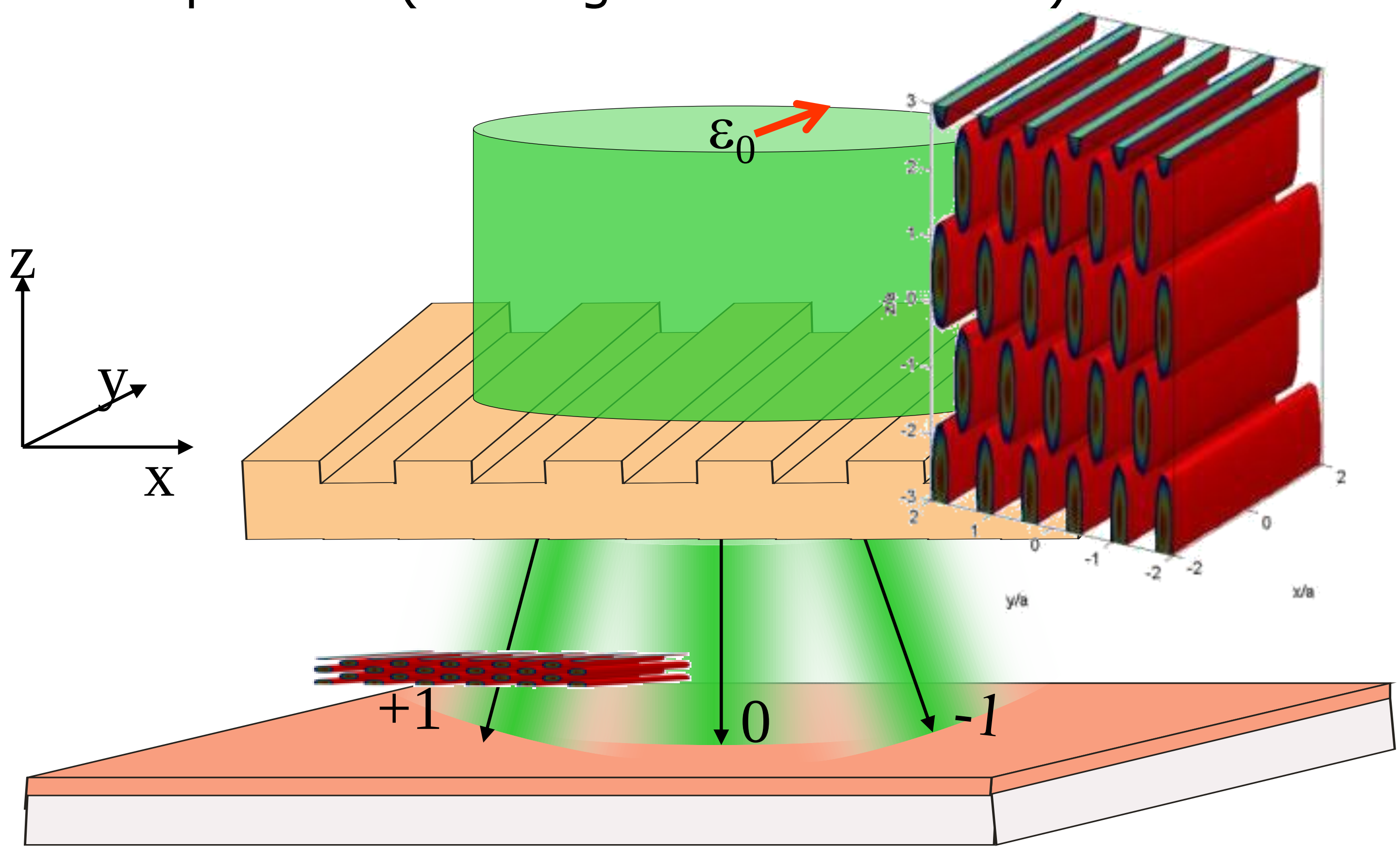
- Notch filter for sensing and telecommunications



1D-Diffractive Optical Element: Holographic Lithography

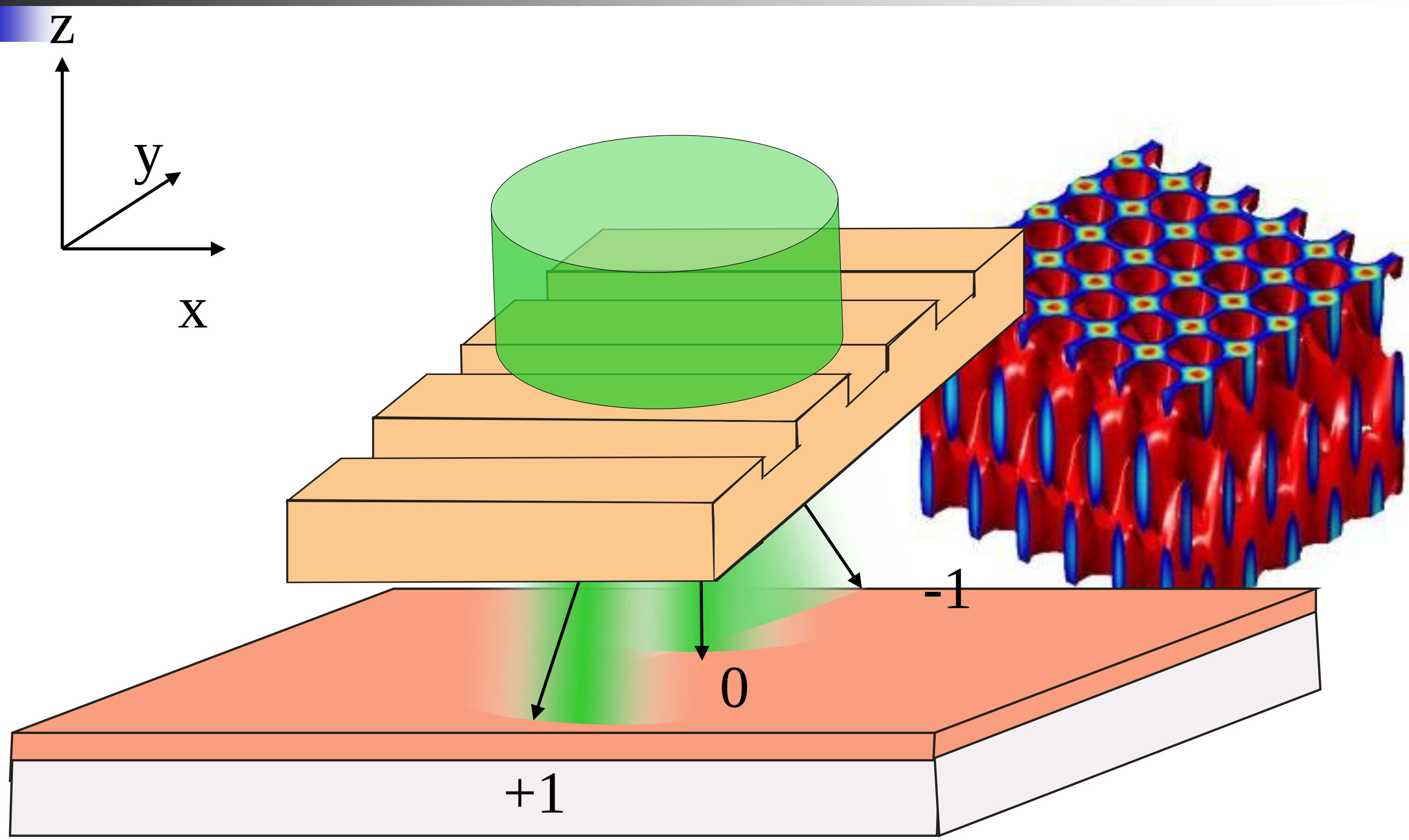
Formation of Woodpile Type Structures with TTR/FCT Symmetry

- First Exposure (Grating is in x direction)



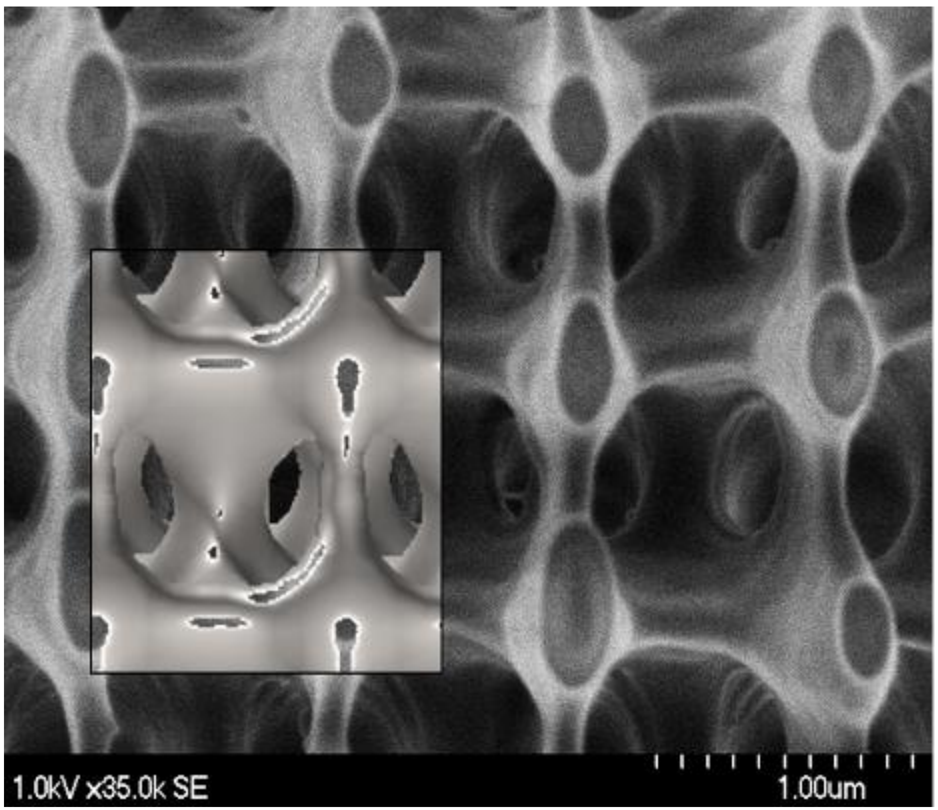
1D-DOE based Holographic Lithography

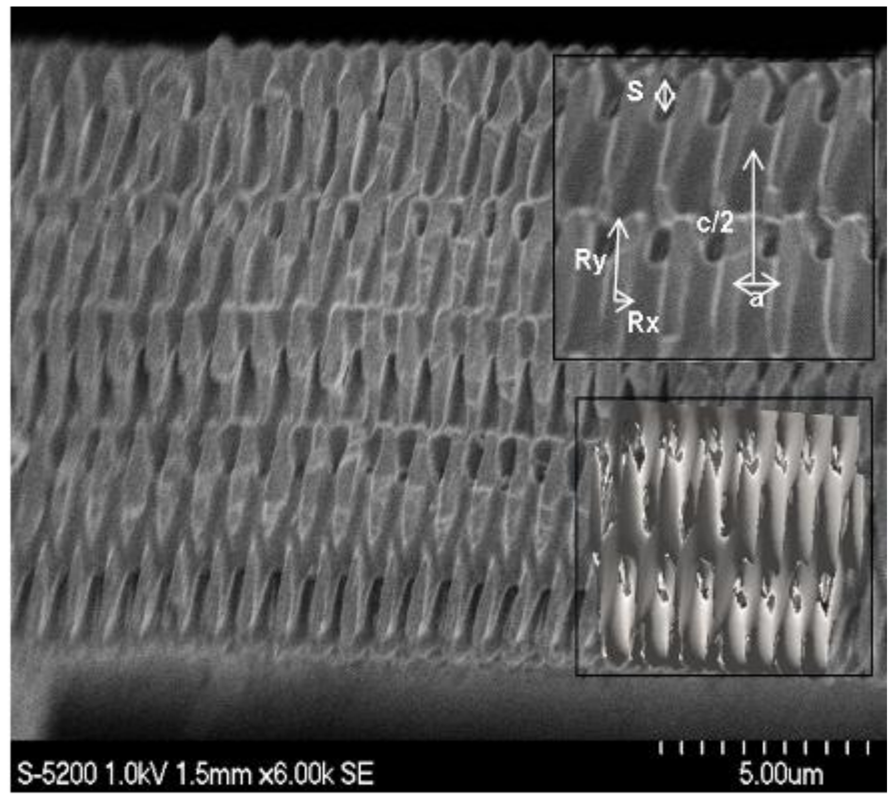
- Second Exposure (Grating is in y direction)



Fabricated 3D Photonic Crystal Templates
- possible with single-exposure 2D Diffractive Optic

SEM of woodpile-type photonic crystal recorded in the modified SU-8 photoresist: a top view of the photonic structure in 001 plane; b cleaved cross-section view of the photonic structure. The elliptical rods of second neighbor are clearly seen to be shifted by half lattice constant in the direction perpendicular to the rod axes.

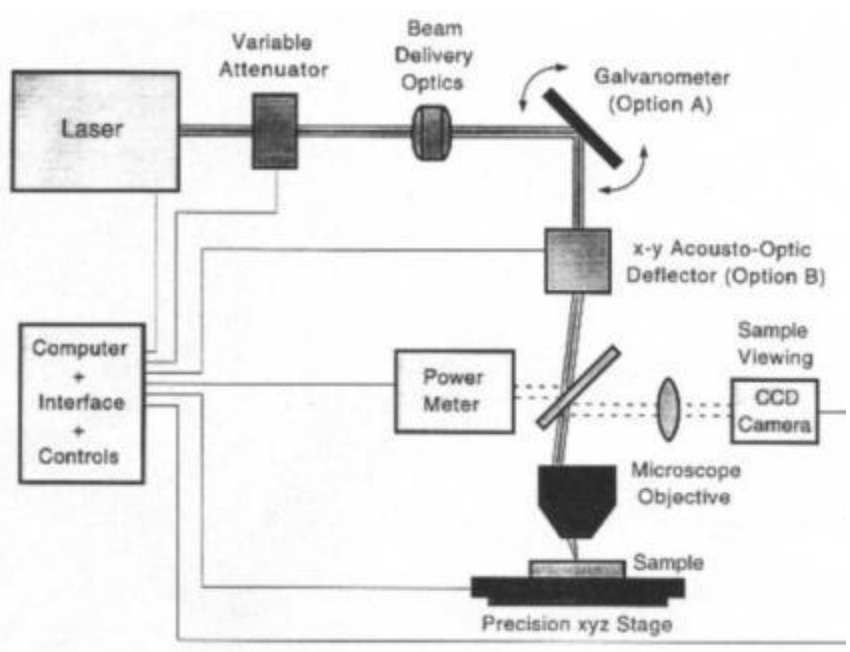




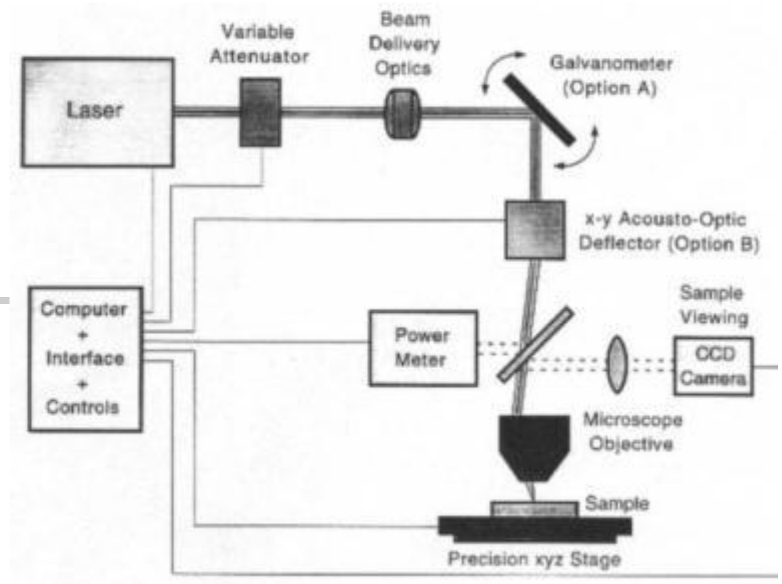
- SEM of fabricated structure

Beam Delivery: Direct Write - I

- Flexible, rapid pattern changes, excellent for prototyping or custom fabrication
- Fast random access
- CAD interpreter programs and computers drive laser shutters, positioning stages, laser power, beam deflectors, focusing optics and often use feedback diagnostics to control laser-interaction processes
- cw or pulsed lasers with Gaussian Beam
- precision micro- and nano-fabrication with modest power lasers
- Macroprocessing: cutting / welding / marking
- Micro- and nano-fabrication: microelectronics, solar cells, marking
- Slow compared to mask projection
- efficient in use of laser energy better than mask projection when only a small portion of the surface is to be processed

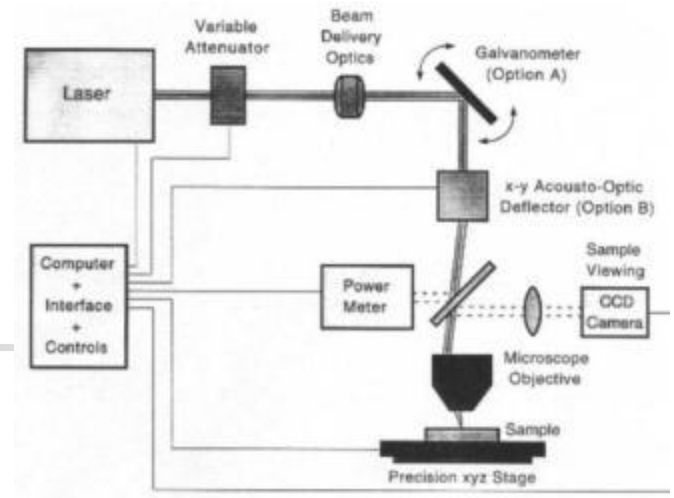


Beam Delivery: Direct Write - II



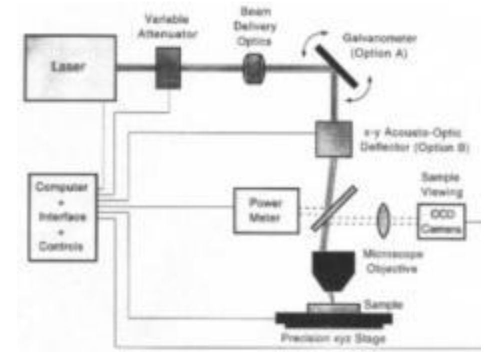
- Diffraction-limited focus with microscope objectives or GRIN lens
  - 1-um features now common in industry; forefront in research is ~100nm
- High Power: large focused beams typically much larger than diffraction limits to reduce alignment precision for processing large objects.
- Focus entire beam
  - Move sample by xyz computer-controlled stages
  - Steer beam with galvanometer mirrors
  - Combination is common

Beam Delivery: Direct Write - III



- Fast writing speed depends on:
  - power of laser
  - beam deflector (fast) vs. xyz stages (slow)
  - heat transport in sample
  - Physio-chemical processes
  - Required resolution
  - Random access is slower than continuous scanning
  - Direct write is slow compared to parallel processing of projection method and well suited to batch processing; but direct write is more efficient in use of energy and excellent when only a small portion of the surface is to be processed
- xyz motion stages for sample positioning
  - can offer 20 nm resolution over 10 cm travel, and with poor resolution, meters of travel
  - xyz stages can only move so fast with acceleration; Beam deflection is much faster

Beam Delivery: Direct Write - IV



- Beam Deflection - Galvanometer or Acousto-optic deflector
  - Fastest access across a potentially large field-of-view(w/ large field lens) of sample surface
  - Resolution = total scan angle / Diffraction-Aberration angle i.e q_{scan} D/l
  - High Resolution: 10,000 spots/scan in reconnaissance graphics (polygon and holographic)
  - Med. Resolution: 2,000 to 10,000 spots/scan in Business graphics
  - Low-Resolution: < 2000 spots/scan Bar code and video scan
- **Beam Deflection: Mirror Galvanometers**
  - Low inertia mirrors rapidly tilted with electric drives: 1-3 kHz and 99% reflection
- **Beam Deflection: Acousto-optic deflector**
  - Only 60% diffraction efficiency
  - Excellent for random access as required in mask repair and circuit board interconnect processing

Beam Delivery: Direct Write

Galvanometer Scanners

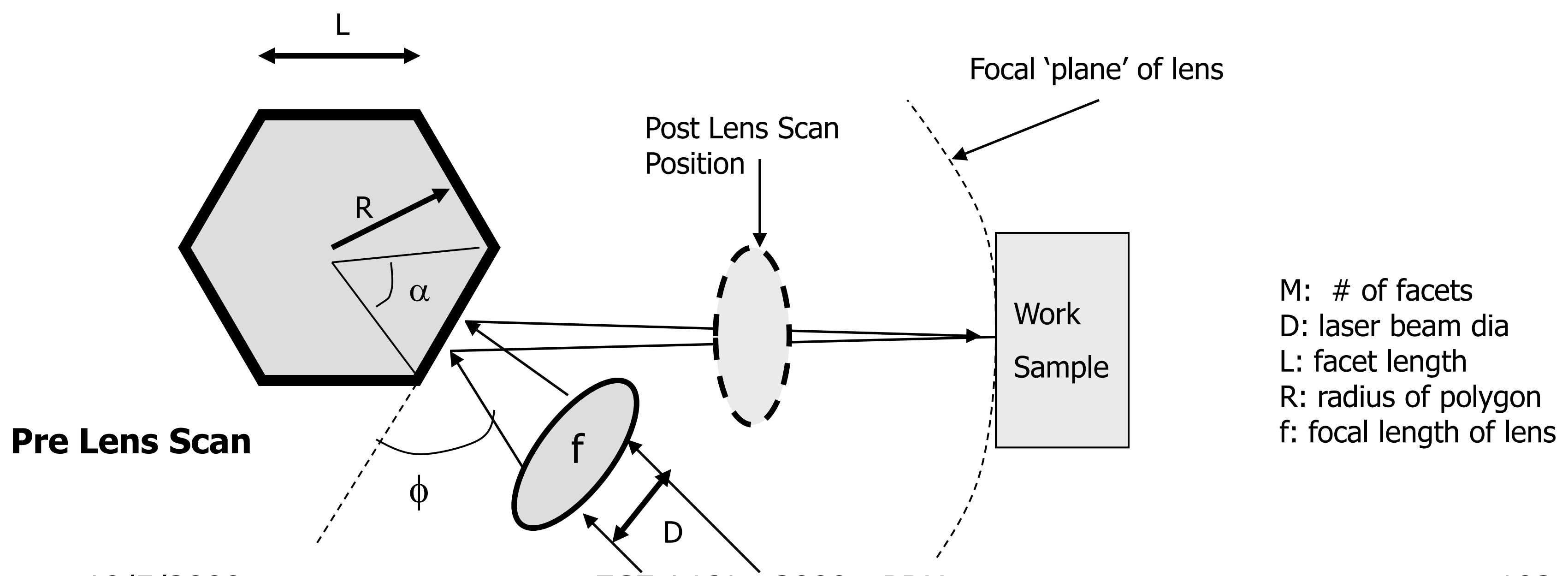
- Applications: laser acoustic microscopes, color separators, facsimile transmitters/receivers, bar-code readers, optical disk readers, laser pattern generator
- >1000s of spots / scan
- Work near mechanical resonance frequency of ν_R = 1-3kHz scan rates for fastest speed and largest area coverage
- Broadband Mode: $\nu < \nu_R$ which uses sinusoidal or saw tooth patterns for sample coverage; good for rapid random access
- Pointing Angle precision: 50 urad (wobble) and 10 urad (repeatability) for modest systems; higher resolution is available (GSI Lumonics is one state of the art supplier)
- Example: 4000 x 4000 points @ 25 um spot size x 142 mm diag. Field;

  Random Access or Raster Scan

Beam Delivery: Direct Write

Polygon Scanner

- High speed, wide scan angle and high resolution
- Unidirectional, fixed rotation speed $d\alpha/dt$, Mechanical stability for high mass
- Duty cycle: 1 facet = (L-2D)/L due to corners
- Example: large polygon: M ~ 60; D ~ 7cm dia; 30 to 20,000 Hz rotation
  Resolution: 20,000 spots / scan line



Polygon Scanner

similar methods used in laser processing system fast scanning & large ar coverage

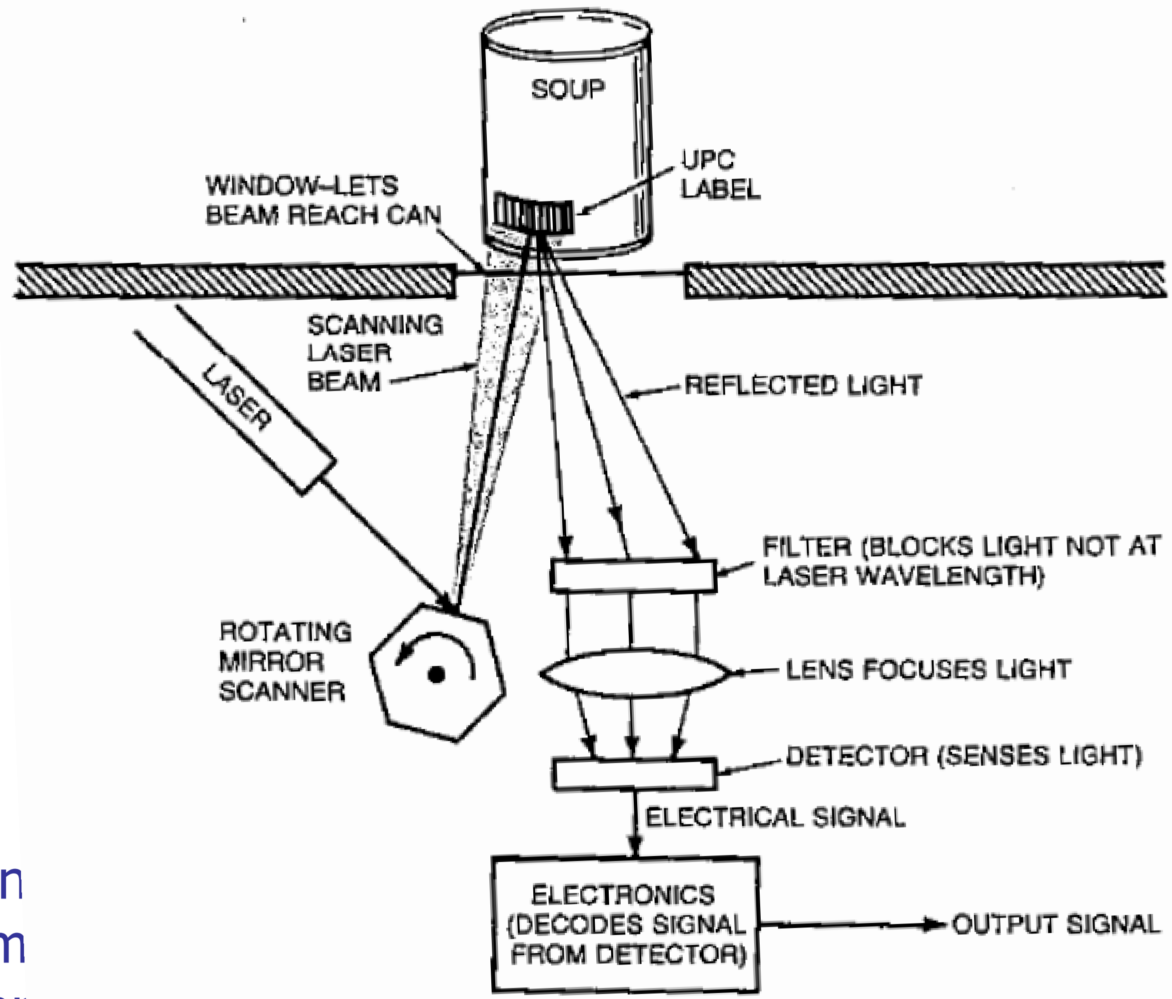
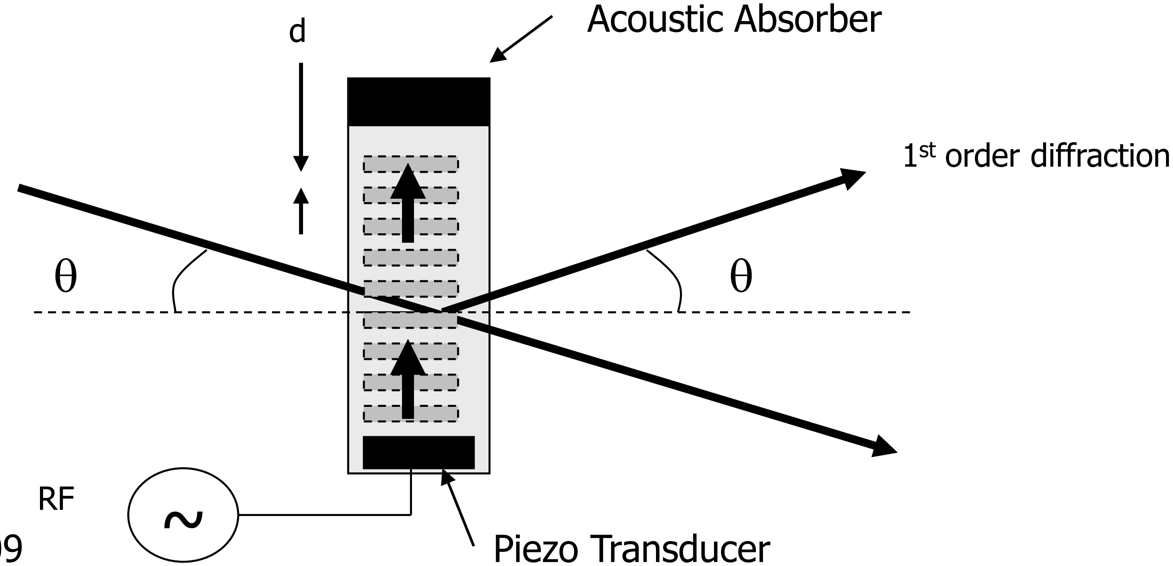


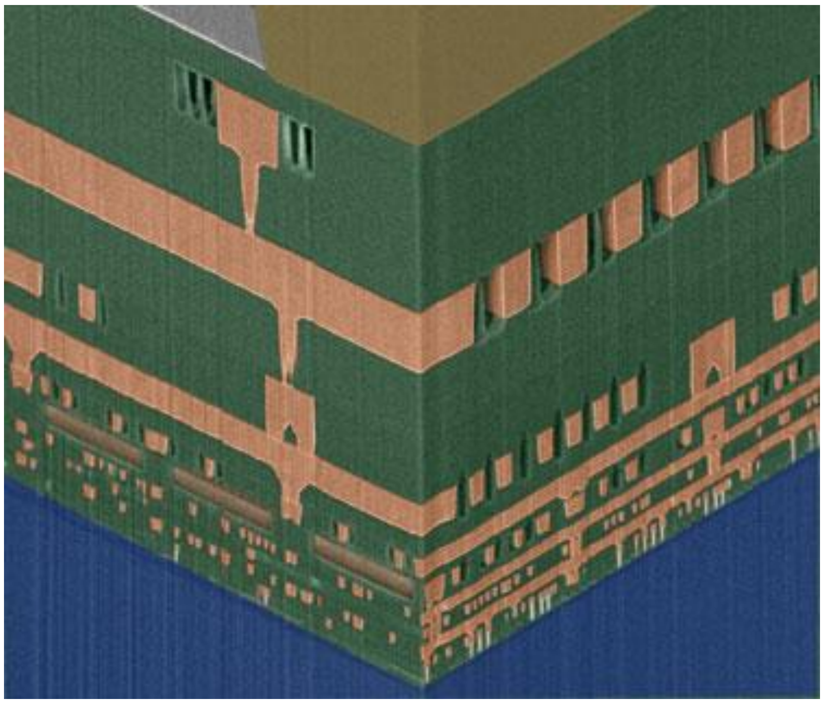
Figure 11-1. A laser bar-code reader.

Beam Delivery: Direct Write

- **Acoustic-Optic Scanner**
- IC processing of interconnects, mask repair, laser microscope
- Small scan field, high scan rate, random access
- Acoustic Grating launch with piezodrive: $m\lambda = 2\,d \sin\theta$; d: rf controlled sound wave
- $\lambda \sim$ 1mm → $\theta \sim 1$ mrad deflection; $\eta \sim$ 50 to 60 % 1st order diffraction efficiency
- Drive: V(t) → sweep, scan, or random
- Resolution: depends on freq. Bandwidth & transit time of acoustic wave across laser beam width D; resolution trades against freq. response (scan speed/random access time)



Interconnect Challenge in Microelectronics



- How do you interconnect multi-Giga transistors without cross-talk/shorts?
- 10 km of wiring in 10 or more wiring levels in today's microelectronic chip
- Why are finer 'wires' used at the bottom layer near the transistor
- Laser-Lithography (with plasma etching) used for high density interconnects
- Laser-direct write via-drilling may be used for vertical interconnects
- Why are 'vacuum' holes used beside the wires (only higher layers)?
- Vacuum → low κ value → low C → faster speed

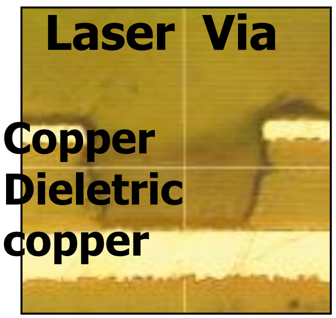
When to trade projection for direct write in this application?

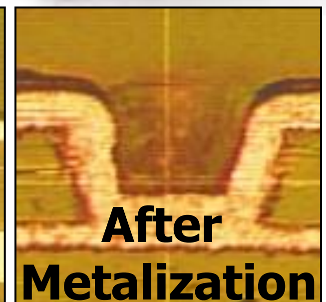
IBM - http://www.spectrum.ieee.org/jan08/5811/1

Beam Delivery: Direct Write

GSI Lumonics
PCB Micro-Via Drilling

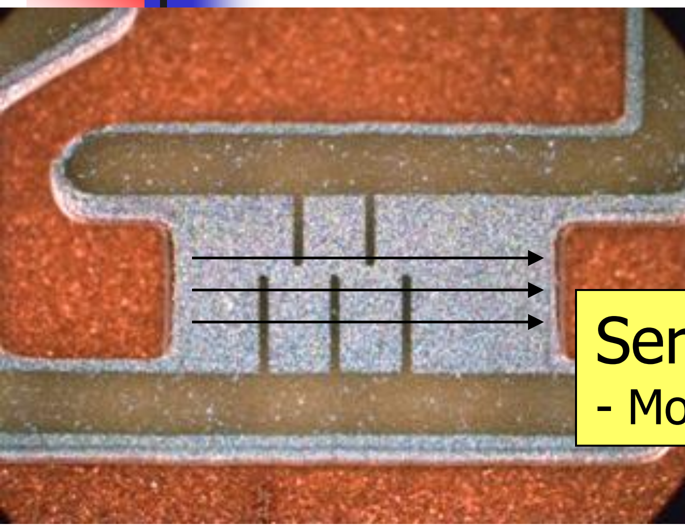
Micro vias can be created in HDI-PCBs (**High Density Interconnect - Printed Circuit Boards**) using two lasers to drill through both the copper and the dielectric layers of the PCB in two steps. With this technique, a high-power UV laser first ablates through the upper copper layer; then, a CO_2 laser is used for drilling the dielectrics. This dual-laser setup combines the ablation speed of CO_2 on dielectric materials with the ability of UV to drill copper. It boosts panel throughput by exploiting the advantages of both lasers and circumventing their limitations. Moreover, the dual-laser technique, like other laser processes, requires only a single panel run to complete all steps of micro via formation.





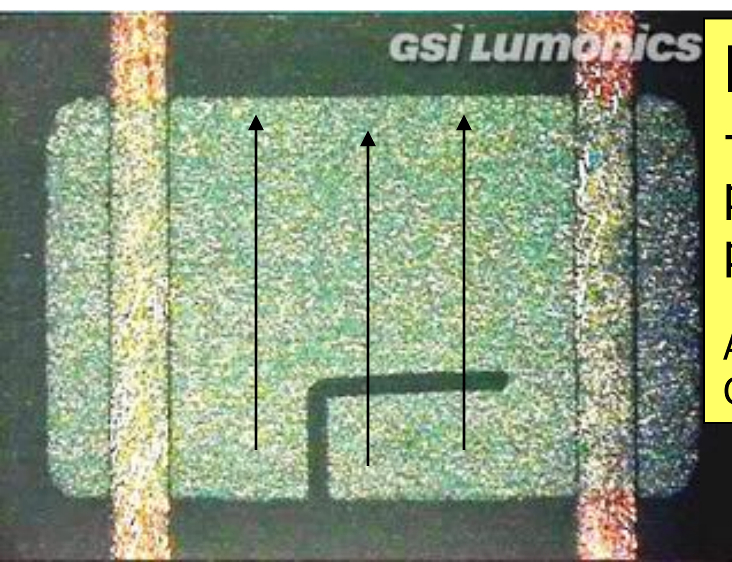
Dual λ with Multi-layer copper drilling

Beam Delivery: Direct Write
GSI Lumonics Resistor Trimming



Serpentine Cut
- More control

- 1-micron lines is state of the art while 10's of microns is common practice
- various lasers (IR → UV w, 2w, 3w solid state lasers) to address challenging materials like thin-film glass and ceramics without damaging substrate material



L-Cut
-Faster, 2nd cut provides precision

Arrows show Current direction

- Capacitor trimming also growing in importance
- LASER SCRIBING—dicing silicon wavers and glass flat panel displays
- Download and Read Article on resistor trimming from ESI: http://??? I will Send by Email

Beam Delivery: Direct Write

ESI Videos (no longer available from ESI)

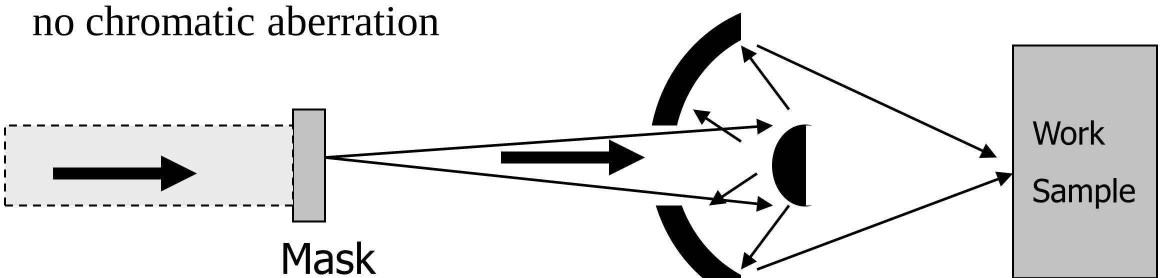
- ESI Laser trimming AWG
- ESI beam shaping
- ESI 9820 Laser Memory

Beam Delivery: Lenses

Both Imaging or Focusing Lens

- Melles Griot catalogue/web has good practical application notes for none expert
- Doublet Lens: combine two lens with different refractive index and pos/neg focus for aberration control
- Anti-reflection (AR) coatings ($\lambda/4$) improve efficiency and safety (multi-reflections)

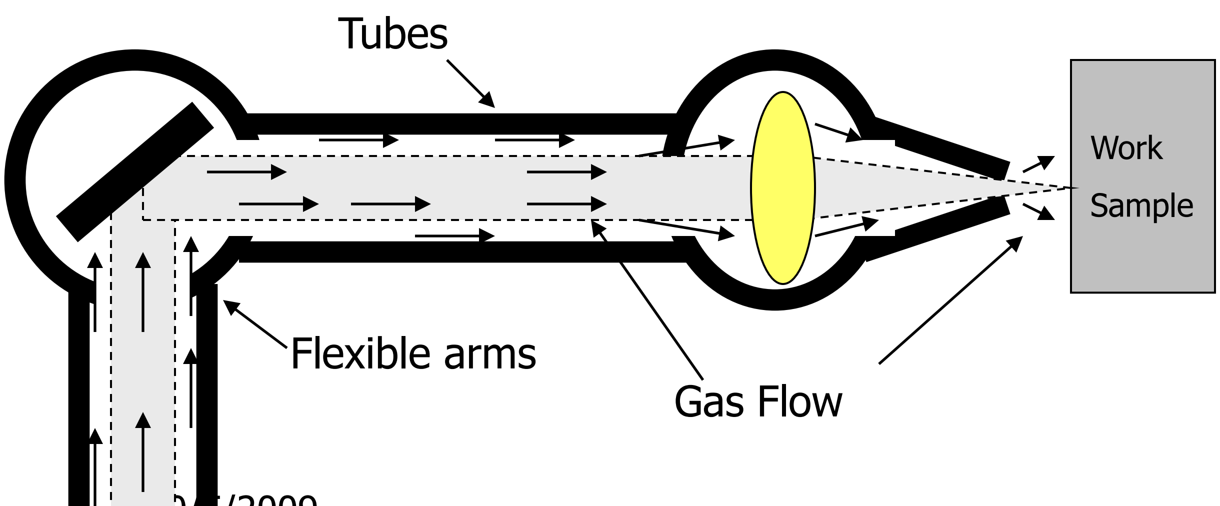
  4% loss per surface for air:glass interface ($n_{glass} = 1.5$)
- Microscope objective: multi-lens with AR coating for spherical, chromatic, etc aberration
- Aspherical Shape (diamond milling rather than polishing) now common to counter spherical aberration; mold injection plastic is low cost but not high damage resistant
- GRIN: gradient-index lens: dope centre with high index material compared with edge of lens; control of radial doping profile overcomes spherical aberration
- Reflective optics: <u>Schwarzschild lens</u>: exact cancellation of 3rd order spherical aberration and no chromatic aberration



<u>Schwarzschild:</u>
Two spherical
mirror reflectors

Beam Delivery: Nozzles, Beam Tubes, and Gas Flow

- Eye and other hazard Safety, dust/dirt protection of optics, gas conduit
- Gas: reactive oxygen speeds metal cutting
- Gas: inert argon prevents oxidation for aluminum welding
- Gas: transparent gas: ArF 193nm laser sensitive to moisture and hydrocarbons in air; F_2 157nm laser absorbed by oxygen (use N_2 gas)
- Gas Flow: push away debris from laser interaction volume; clean out holes, prevent ablation products from coating focusing lens



Case Study:
F_2-lasers: High-Resolution Optical Processing System
for Shaping Photonic Components

in Laser Applications in Micorelectronic and Optoelectronic Manufacturing, SPIE Proc. ***4274****, 2001Full paper PDF file at* http://photonics.light.utoronto.ca/laserphotonics/publications/F2MicroLas_SPIE01.pdf

ABSTRACT

A high-resolution 157-nm optical system has been developed for the first time to microprocess optical materials with record short-wavelength F_2-laser radiation. The F_2-laser photons drive strong material interactions in silica glasses for microsculpting surfaces and for imprinting internal refractive index structures. The high-resolution optics delivers a homogenized beam of high on-target fluence (~2.5 J/cm^2) for ablation of fused silica and other wide bandgap optical materials. The system resolution is approaching 1-micron lateral and <100-nm depth – sub-wavelength features appropriate for defining optical communication components at 1.55-µm wavelength. This paper describes this novel processing system and offers prospects for F_2-laser microfabrication and trimming of photonic components in the telecommunication and general optics manufacturing fields.

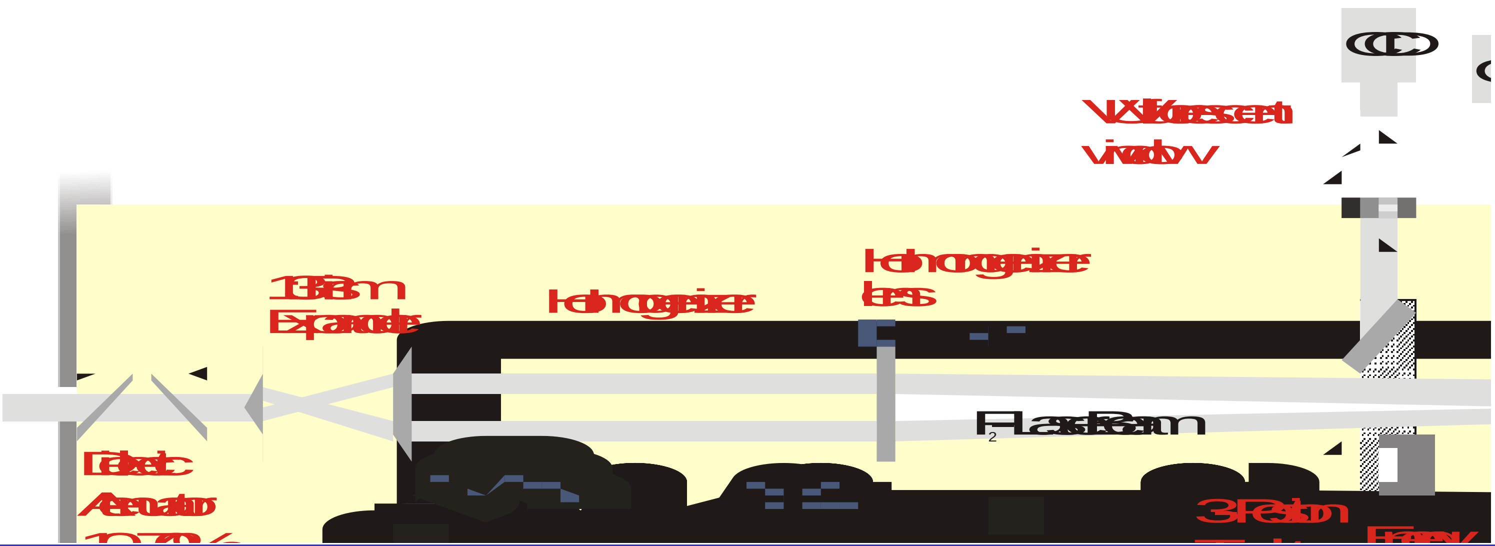
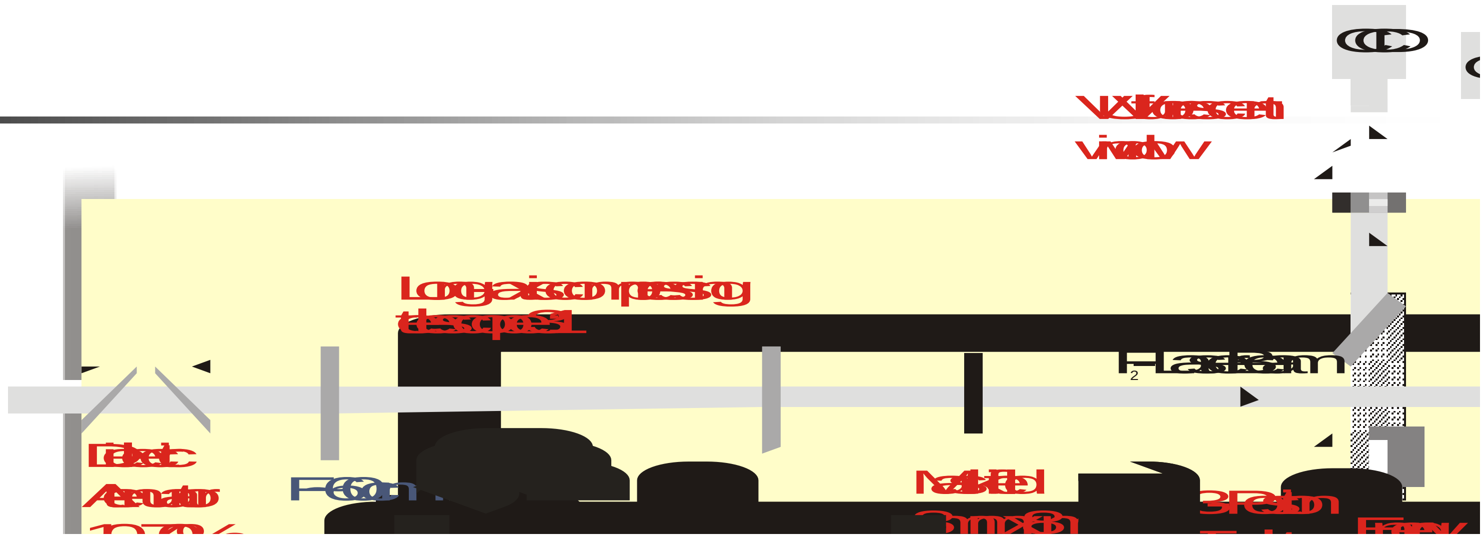


Fig. 2 High-resolution Schwarzschild configuration of the F_2-laser optical processing system.

F_2-lasers: High-Resolution Optical Processing System for Shaping Photonic Components

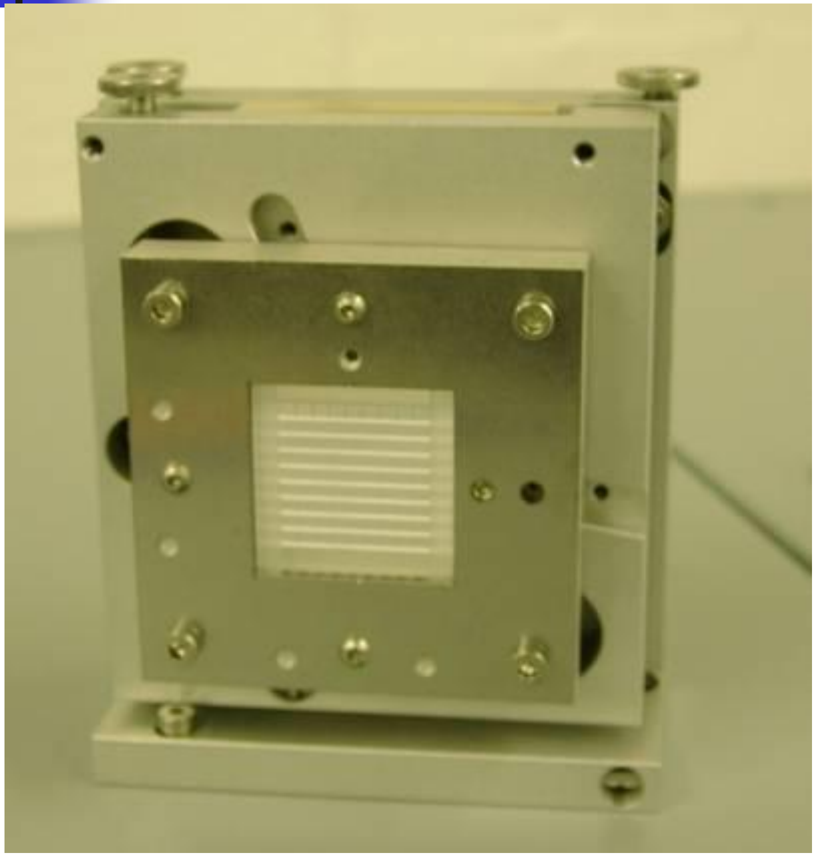


	High-Resolution Schwarzschilds Optics	Medium-Resolution CaF_2 Doublet Optics
Mask Field Size	6 mm x 6 mm	8 mm x 8 mm
Uniformity	Homogenized ± 5%	Non-uniform raw laser beam
Demagnification	25X	10X
NA	0.4	~0.1
Target Field Size	0.24 mm x 0.24 mm	0.8 mm x 0.8 mm
Resolution	~1 μm full field (0.25 μm theoretical)	~5 μm full field
On-Target Fluence	~2.5 J/cm^2	~1 J/cm^2

Fig. 3 Medium-resolution CaF_2-doublet configuration of the F_2-laser optical processing system.

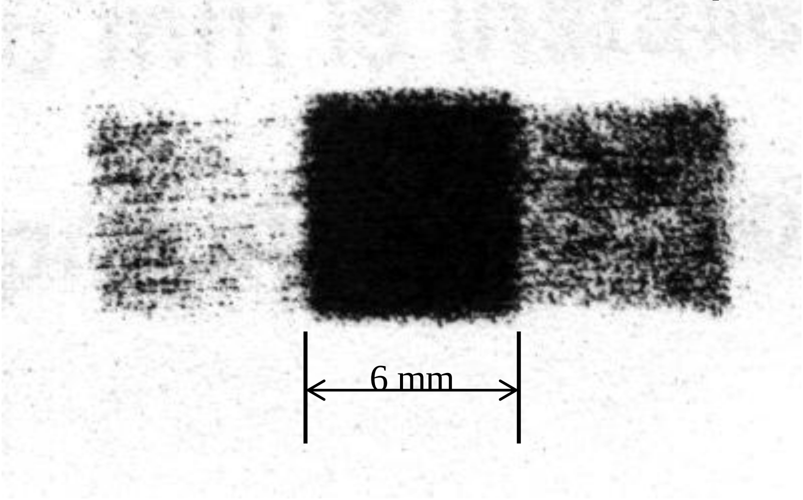
Table 1: Comparison of high and medium resolution configurations of the 157-nm optical system

Homogenizer: 157-nm Beam Profile

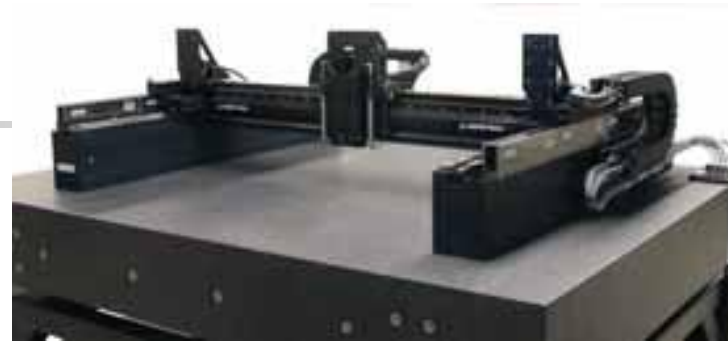


9 x 9 cylindrical lens arrays

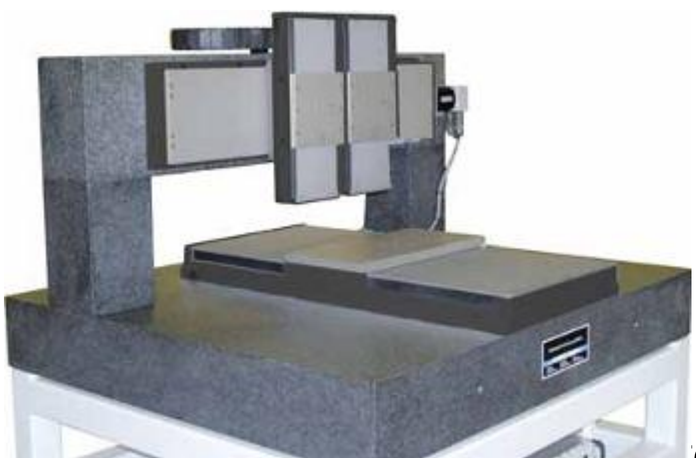
- Mask Plane
  - ~ 6 mm x 6 mm
  - ~ 10 mJ/cm^2
  - +/- 5% uniformity

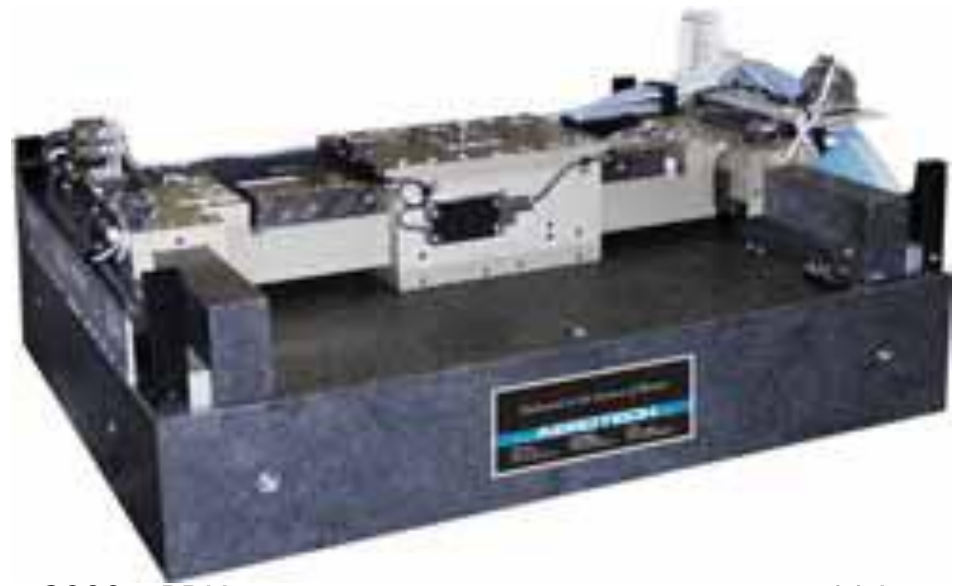


Target Positioning (static beam)



- High precision → high cost
- Laser Lithography:
  - synchronous scanning mask and wafer
  - 32 nm /4 -> 8nm precise stages
- Why granite bases?
- Why air-floating table?

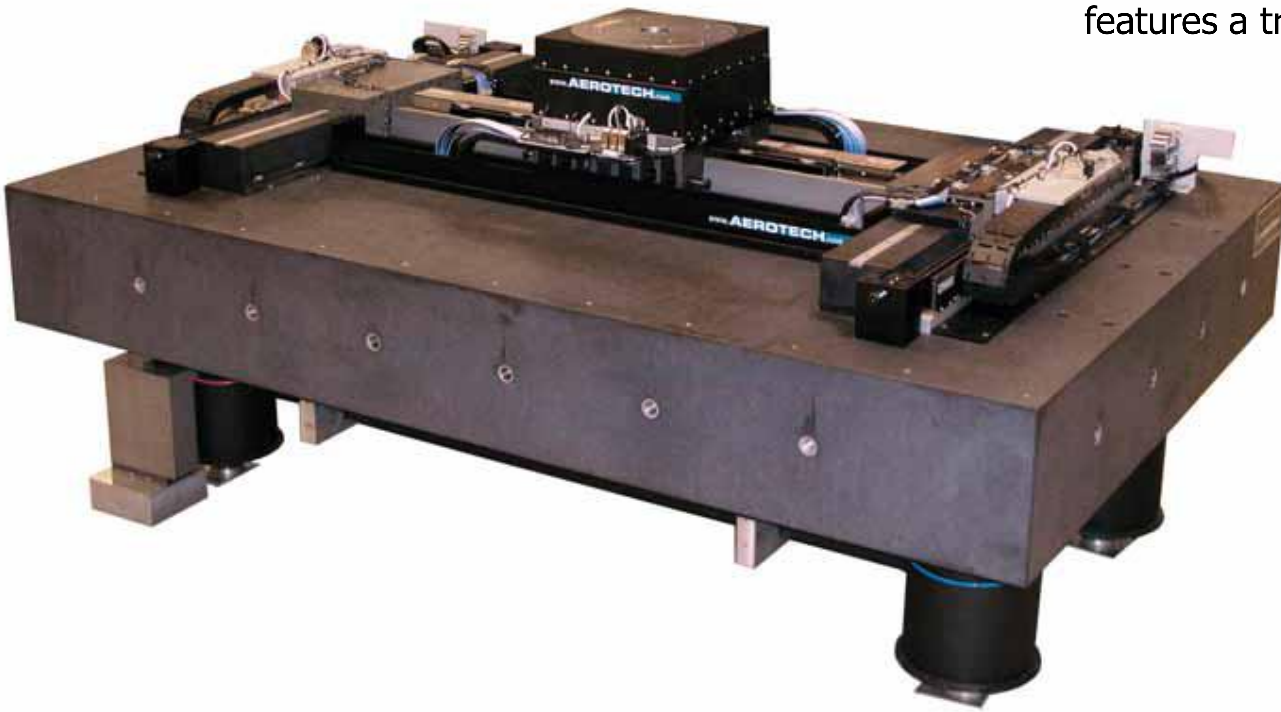




Flat Panel Display

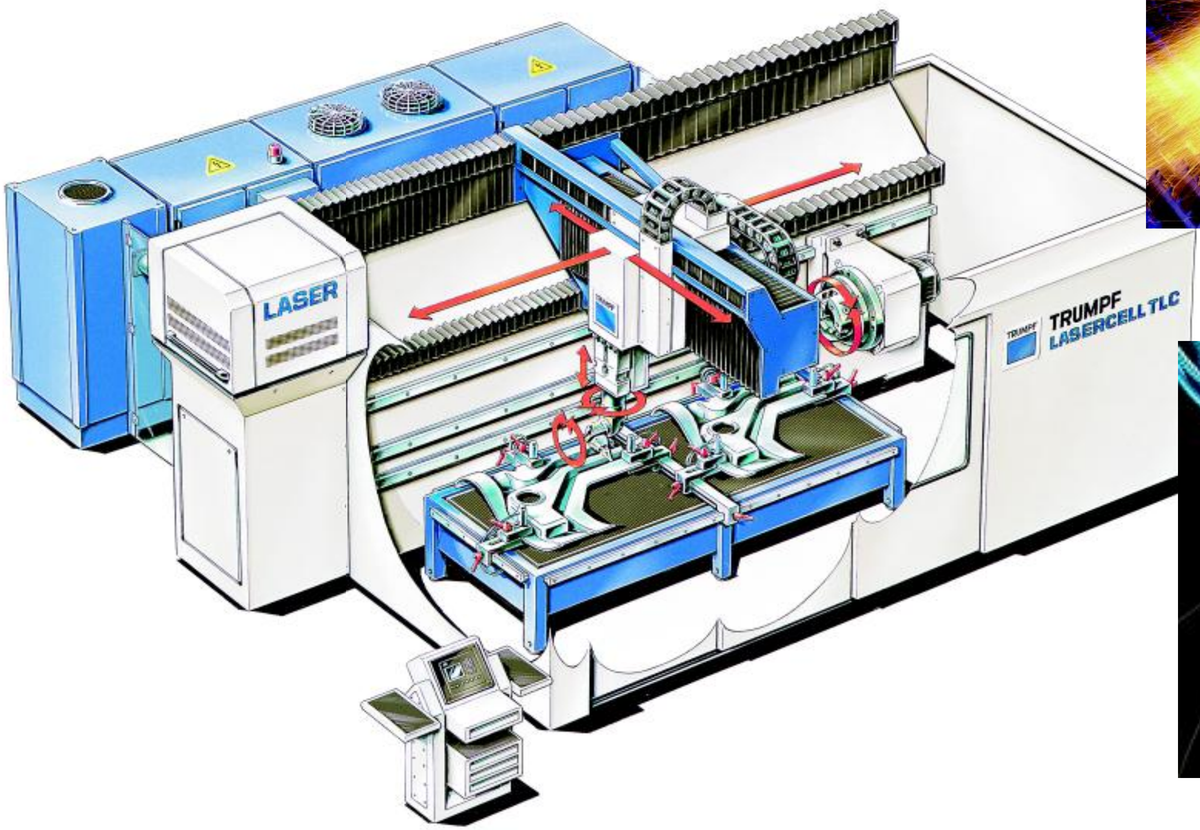
What laser applications are required in FPD manufacturing?

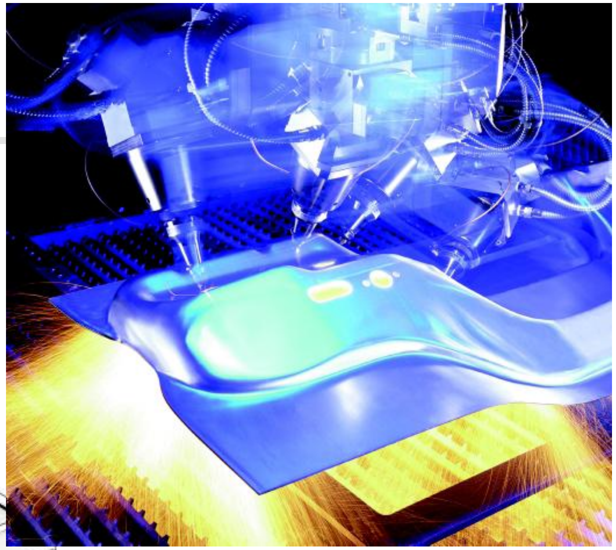
This gantry-style FPD inspection station features a travel of 1800 x 800 x 200 mm.

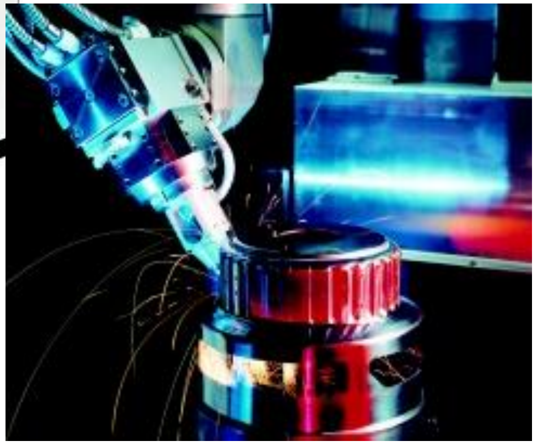


Multi-axis (5) Beam Delivery

- Laser cutting
- Warp-free welding
- Partial hardening







Optical Resolution

- How to make things small

Laser Microfabrication Overview

- Making Things Small
  - Lasers- shorter wavelength; shorter pulse duration
  - Optical Systems and Limits
    - Conventional limits
    - Pushing new frontiers

- Examples in Laser MicroFabrication – *Nanotechnology*
  - Industry Short Wavelength: Laser Lithography
  - Industry Near Field: Chrome Mask Repair
  - 3-D Resin Structuring: the *Bull*
  - Biology: chromosome dissection by ultrafast nonlinear
  - Interferometry (Presented above): $\lambda/3$ features
    - 1-D Interferometry: Fiber Bragg Gratings & Photochemistry
    - 3-D Interferometry: 3-D Holographic Photonic Crystals

Lasers for Nanofabrication

- Highly directional form of energy – *in many shapes!*
- Drive strong interactions with materials
  - Photon energy $E = h\nu$
  - High intensity non-linear interactions
  - Near-threshold delicate interactions
- High Resolution
  - Focusable to sub-wavelength dimensions into *nanometer domain*
- Nanostructuring: *ablation, photochemistry, forming, microwelding, annealing, 3-D structuring, etc.*

Optical Resolution

Ehrlich and Tsao, Laser Microfabrication, Ch. 1, YS Liu ISBN 0-12-233-430-2

Optical resolution is one component that defines the feature size available

Feature size is a CONVOLUTION OF;

- Optical resolution of lens system
- Heat transport on surface (sometimes gas phase physics is significant)
- Precision of alignment stages, mechanical and thermal stability
- Gas-phase diffusion for laser-assisted chemical processes
- Enhancement by nonlinear absorption mechanisms or threshold fluence process (ie ultrafast)
- 'gain' by interactions that sharpen features (resist lithography, or ultrafast interactions)

OPTICAL RESOLUTION:

- wavelength, beam size at lens, lens aberration, source bandwidth (spectral aberration), beam quality (spatial coherence)

LENS:

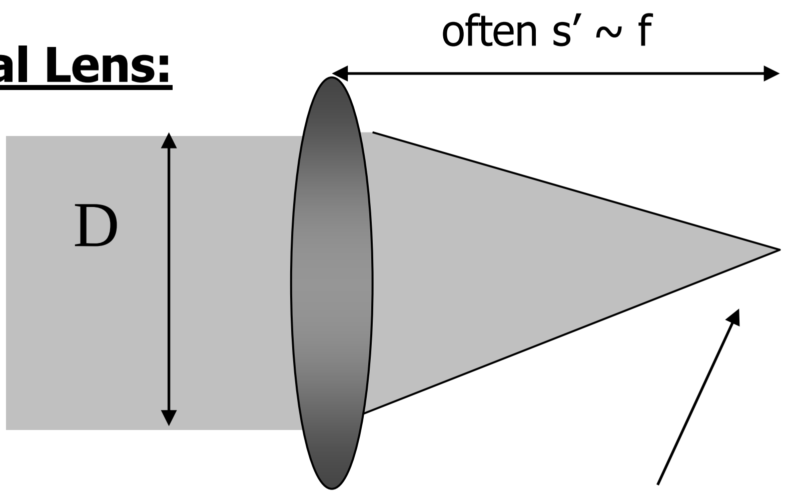
- aberration notes by Melles Griot offers very simple guidance; ray tracing codes are required
- Diffraction is ultimate barrier
- Tricks to *beat* diffraction: near field, nonlinear interactions, gain in resist, phase-shift masks

Lasers: Resolution Limits

- Conventional Limits
  - Optical Diffraction (short λ, large NA optics)
  - Lens Aberration (multi-lens to overcome)
  - Thermal Transport in Material (short duration pulses for high-heating gradients)
- Beating Conventional Limits
  - Chemical amplifiers (resists)
  - Non-linear optical interactions (ultrafast lasers)
  - Phase-shift masks and interferometry
  - Near-Field Optics: Proximity Masks

Diffraction Limits (Coherent Beams):

a) Uniform Illumination of Spherical Lens:



- diameter of uniform plane wave: D
- focal length f
- Airy Disk from scalar diffraction theory
- focal spot intensity radius

  from (peak to first zero) **$s' \times \phi_{diff}$**

  $\boldsymbol{\phi_{diff} = 1.22\ \lambda/D}$

  $NA = 1/(2f_{\#}) = D/(2f) = n \sin\theta$

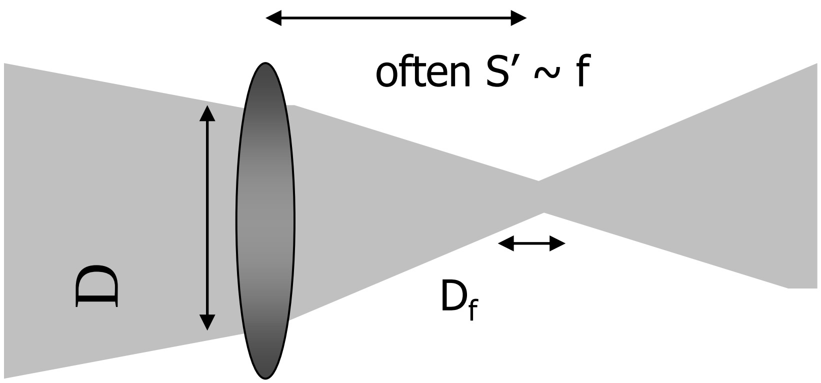
- Tighter focal spot size: large D; small wavelength; small focal length (or image distance); Large NA; larger refractive index n (immersion)
- aberration limits NA to values less than 1.0 except in v. expensive lenses

Diffraction Limits (Coherent Beams):

b) Gaussian Beam (TEM_{00}) through spherical Lens: (Direct Write)

- from ABCD treated of complex radius of curvature, we already discovered that spot size (1/e radius of E-field) is:

  $$\mathbf{w_f = 2f\lambda/D = 2\lambda f_{\#} = \lambda/NA}$$



- values are similar to uniform case

- Good NA ~ 1 suggests a best focus of ~2 λ (E field) or λ (intensity)

  Compare with good Lithography imaging: define λ/3 features when using phase-shift masks to sharpen features, immersion, and large NA ~1.25

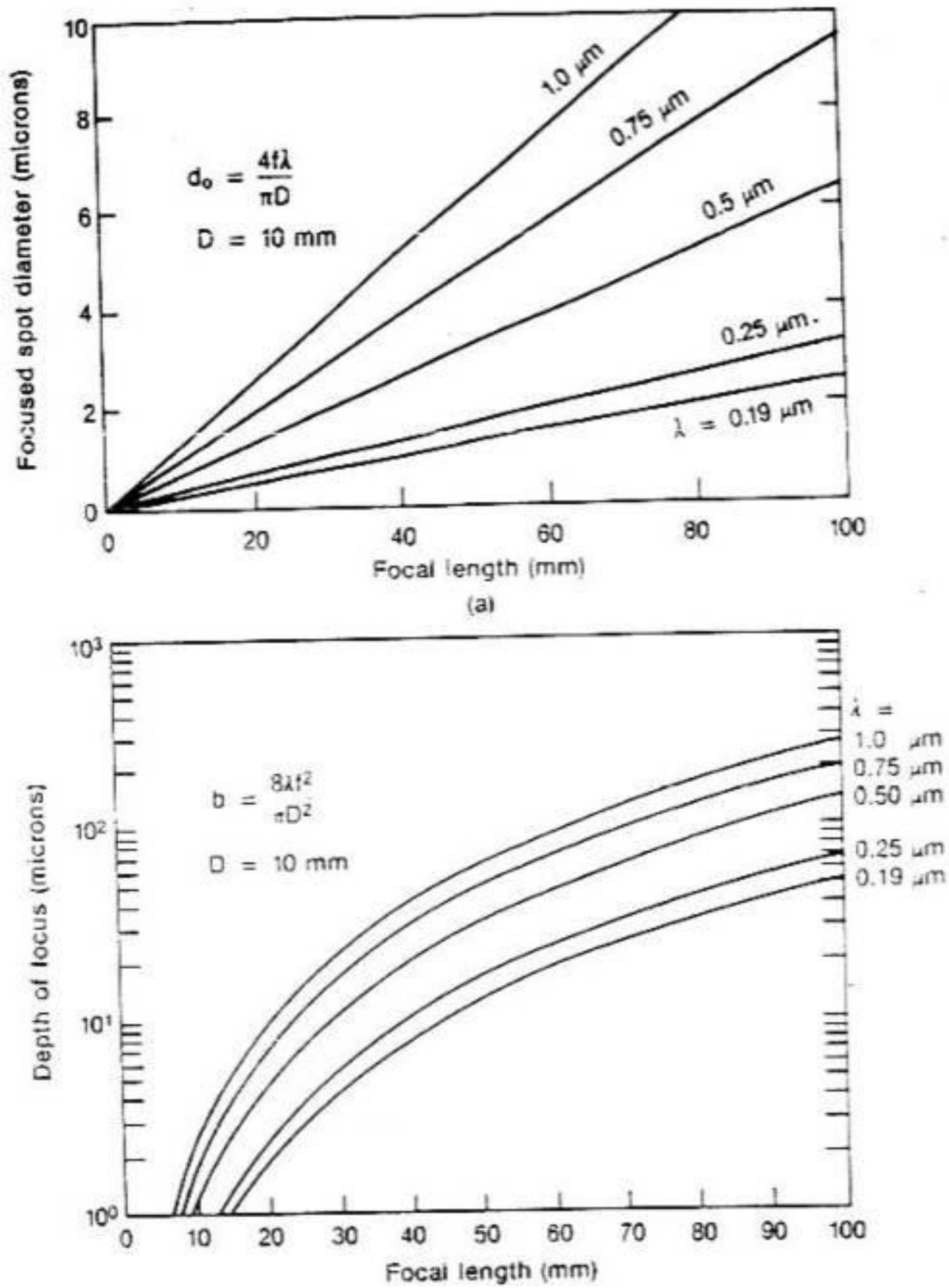
- Depth of Focus: (Rayleigh range) $D_f = 2\pi f^2\lambda/D^2 = 2\pi\, f_{\#}^{\,2}\lambda = \pi\lambda/(2\ NA^2)$

Diffraction Limits (Coherent Beams):

Precision Alignment
Machine vision, drive stages, registration of laser beam and optics with sample:

D_f defines z-axis resolution and blur;
w_f defines x-y axis resolution:

Trades against
small spot size with more costly alignment tools



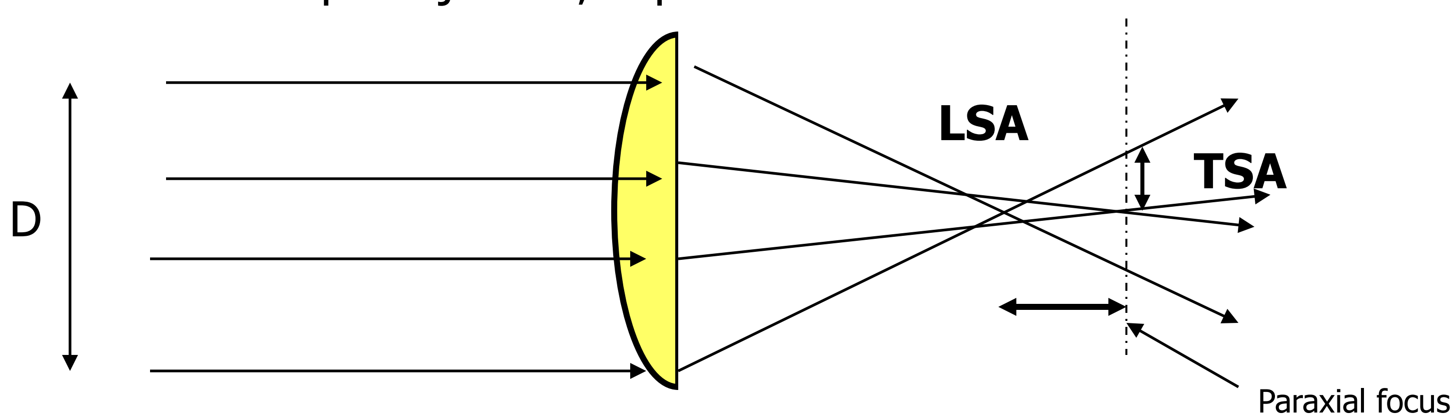
Lens Aberration

- Spherical aberration (one of many distortions of ray optics)
- LSA: longitudinal spherical aberration
- TSA: transverse spherical aberration:

Often: s′ = f

$$TSA \sim 0.067\ f/\ f_{\#}^{3}\ ;\ f_{\#} = s'/D = 1/2\ NA$$

- Assume: monochromatic, plano convex, 3^{rd} order spherical abberation
- Melles Griot Reference
- Options to overcome aberation: Lens doublet, Grin (graded-index) Lens, muli-lens as in microscope objective, aspherical lens



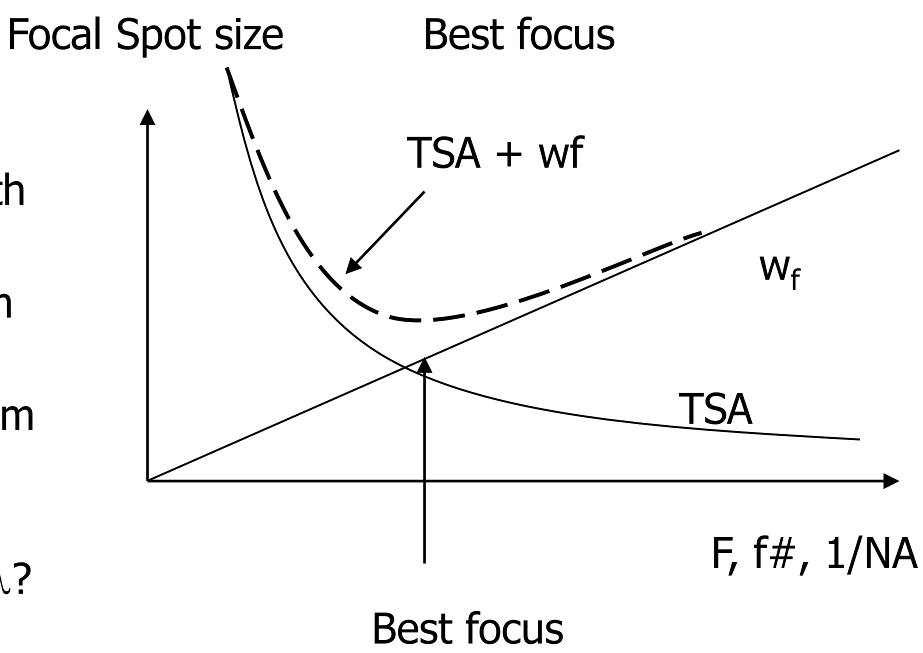
Spherical Aberration (TSA) vs. Diffraction

- Gaussian Beam on right graph

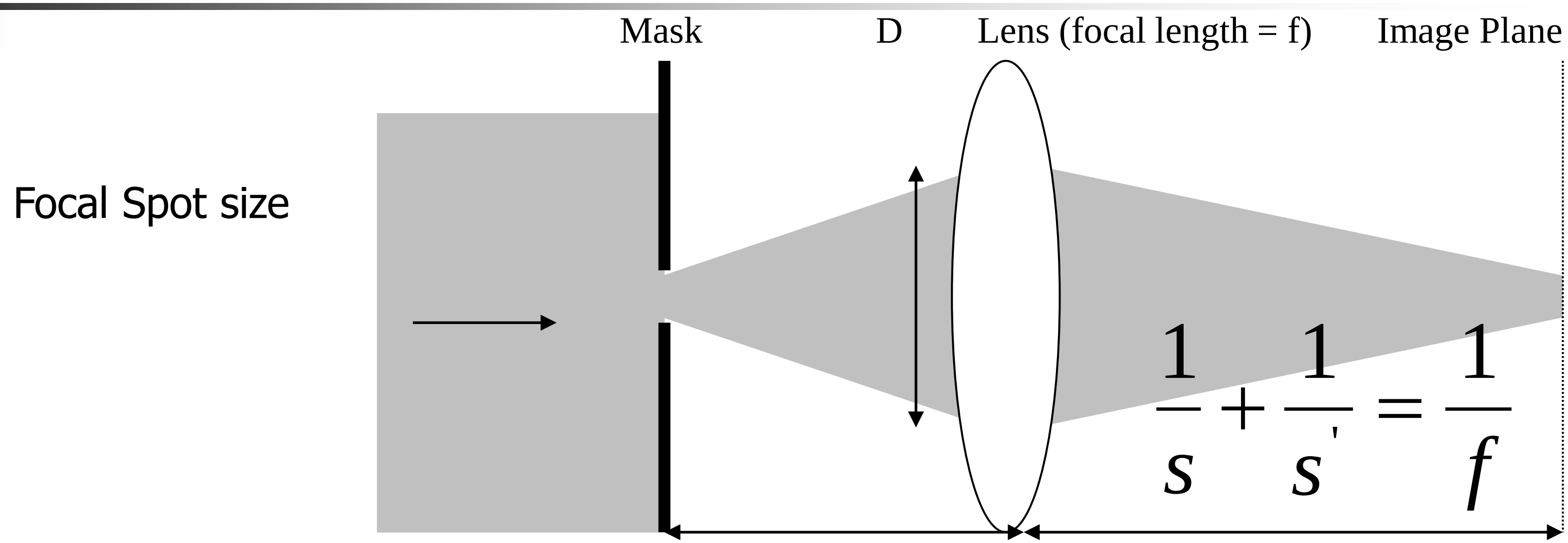
- For non-Gaussian, expect large spot sizes
- For poor spatial coherence: replace D with transverse spatial coherence
- i.e. exicimer lasers: D ~1cm l_{tr} ~ 100 um

values yield: $w_f \sim 100\ \mu$m in best focus compared with ~ 1μm for a Gaussian beam

If we cannot focus Excimer beam tightly with a single lens, then why can a mask projection lens system define features ~ λ? i.e. ~200nm? Are we breaking a fundamental optical principle?



Mask-Projection Resolution
tight focusing with incoherent light



$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f}$$

- A large beam is cut into a small size at the Mask plane; this small beam diffracts to a larger size, D, at the lens. The smaller the slit the more perfectly and coherently are the superimposed wavefronts at the lens. Diffraction limit of for lens focusing is then defined by the diffracted beam size: D.
- Note that D will increase as the mask feature size decreases; wavelength increases; or mask-lens distance, s, increases!

Excimer Laser Lithography: Semiconductor Electronic Chips

poor spatial coherence light

Two most fundamental characteristics of any imaging system:

Resolution → $R = \dfrac{k_1 \lambda}{NA}$

Depth of Focus → $DOF = \dfrac{k_2 \lambda}{(NA)^2}$

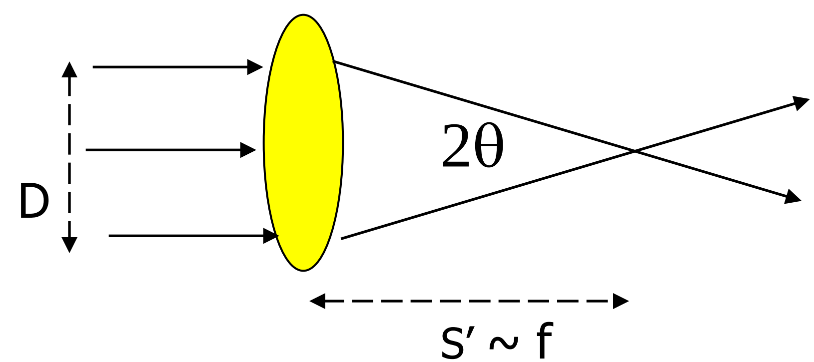
- NA – numerical aperture: NA = n sin θ ~ D/2s' (Intensity)
  - k_1 and k_2 – empirically constants
    - chemical amplifiers in resist
    - phase-shift masks
    - optical aberrations
    - source coherence

•DOF is similar to confocal beam parameter

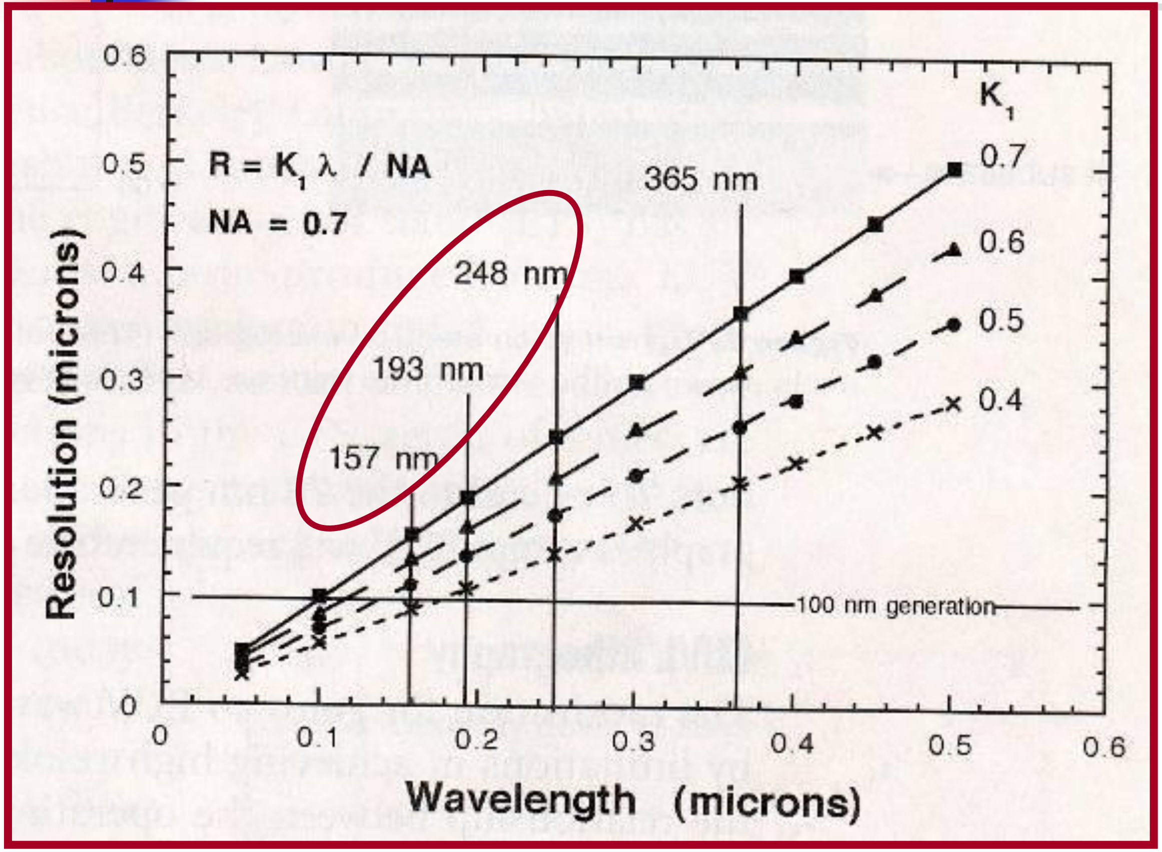
•for a good lens: $DOF = \dfrac{0.61\lambda}{NA^2}$ $\quad d_{feature} = \dfrac{0.61\lambda}{NA}$

• note similarity to Gaussian beam case!

•Mask projection looks better.



Excimer Laser Lithography:
conventional optical limits



$$R = \frac{k_1 \lambda}{NA}$$

$$DOF = \frac{k_2 \lambda}{(NA)^2}$$

Wavelength Scaling

to smaller features

International Roadmap for Semiconductors

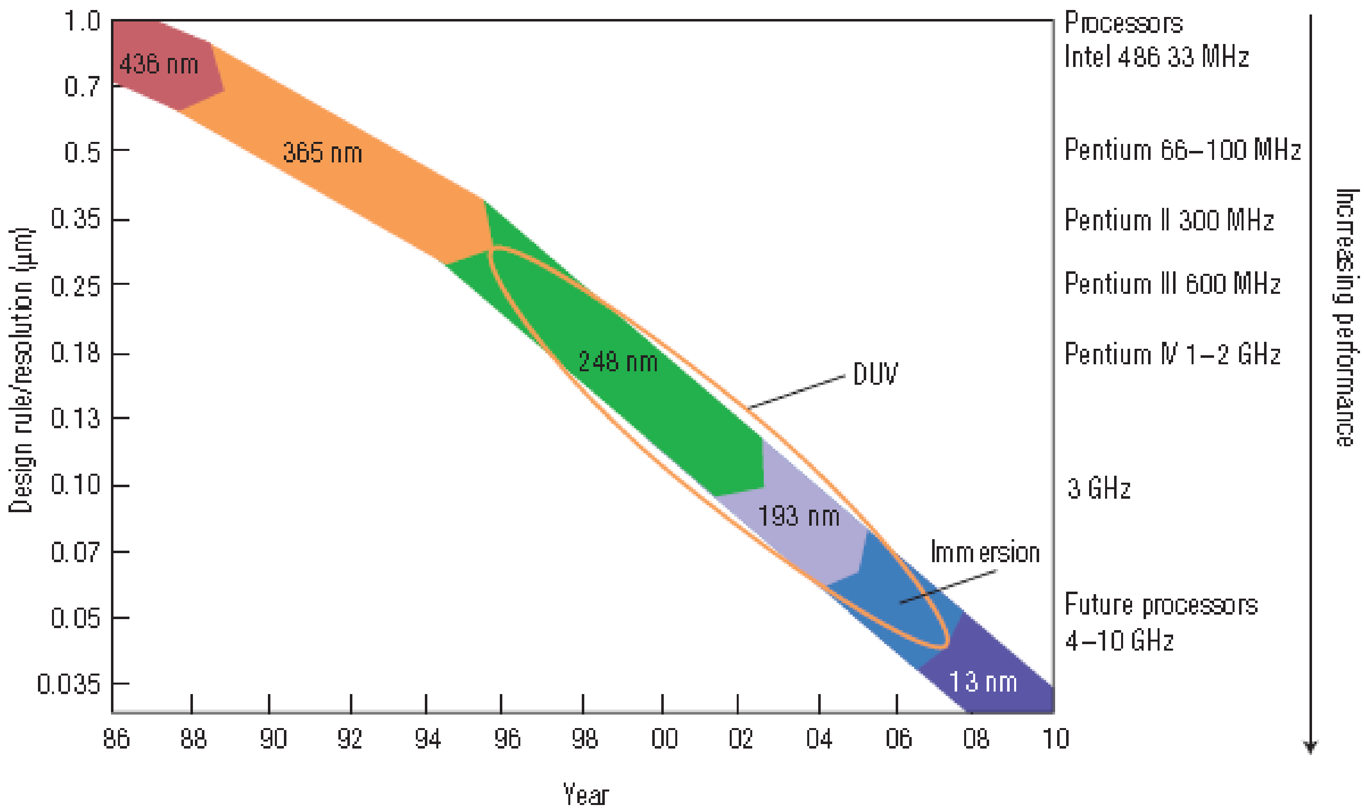


Figure 1 Increasing the resolution of photolithography. Data courtesy of Zeiss.

Current: 193nm excimer laser & Immersion

Next Generation:

Extreme UV—when?

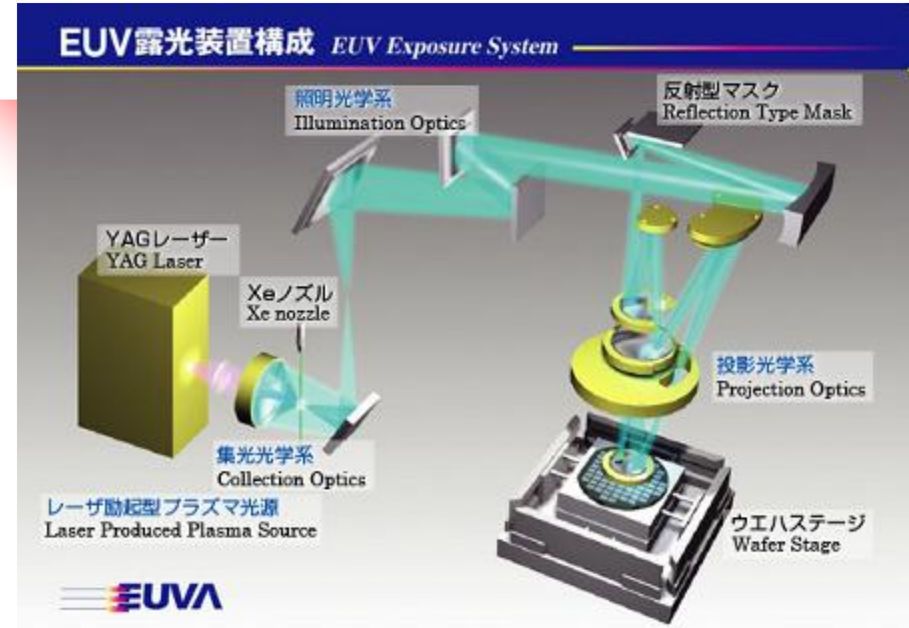
Nature Photonics, 629, Nov. 2007

Deep UV Lithography – 2007

Carl Zeiss Starlith 1900

- >1 meter height
- Immersion (water) NA =1.35
- κ1 is empirical, depending on illumination and detection techniques used, stability and transfer function of the optical system. Physical limit of 0.25 is reached when two diffraction orders, the minimum number to generate an image, are present at opposing edges of the pupil. Current volume-production processes of the critical layers of an IC reach down to κ1 = 0.28
- Double Patterning: flash memory patterns with 32-nm half-pitch have successfully been printed with an NA = 1.2 lens, corresponding to a process with κ1 = 0.19.
- At diffraction limit: 36.5 nm half pitch

EUV – Lithography *10-15 nm extreme ultraviolet*

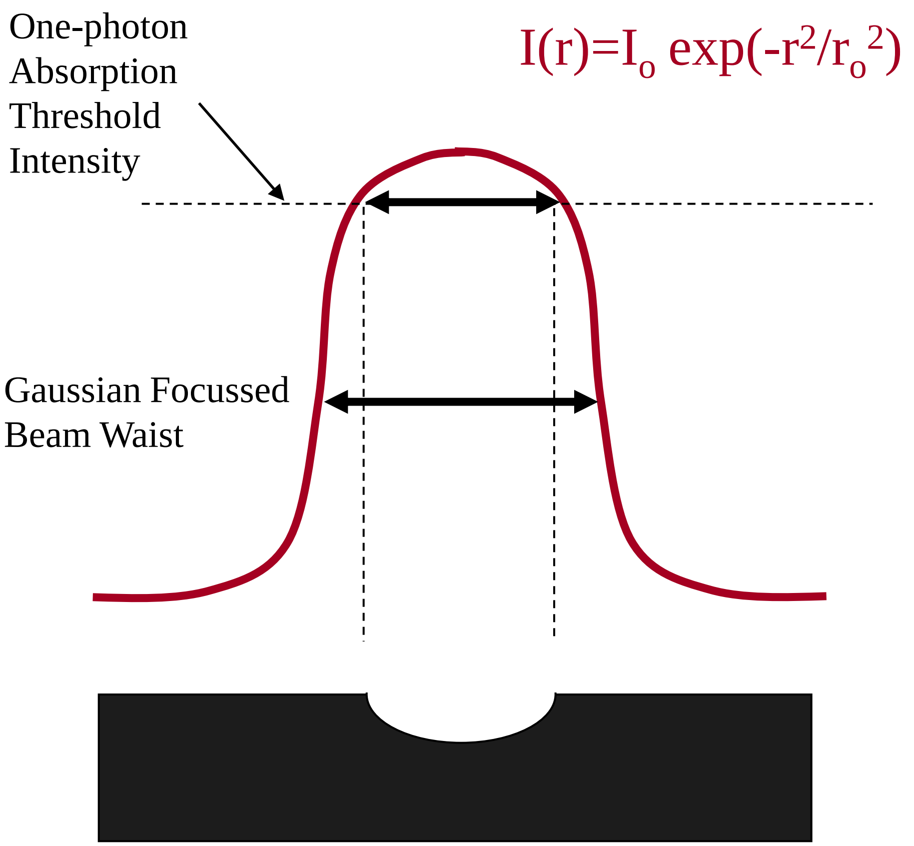


- Laser produced plasma emits EUV light
- Cluster/droplets from jet in vacuum synchronized with laser pulse
- Air absorbs EUV- Vacuum Required
- Only reflective optics
- Low efficiency, not a laser
- Discharge also studied but low power scaling
- Q: can semiconductor industry afford development cost when production plants will exceed $5B
- ArF imersion lithography will be stuck close to 32nm node diffraction limit; but double exposure is being considered seriously
- What advantages does 12nm light have over current ArF 193nm light?
  - Lateral Resolution: less demanding optics for aberration control
  - Depth of focus more forgiving on alignment

Beating Conventional Optics: Ultrafast Laser Nonlinear Absorption

Short-pulses – 5-100's femtoseconds – yield high intensities

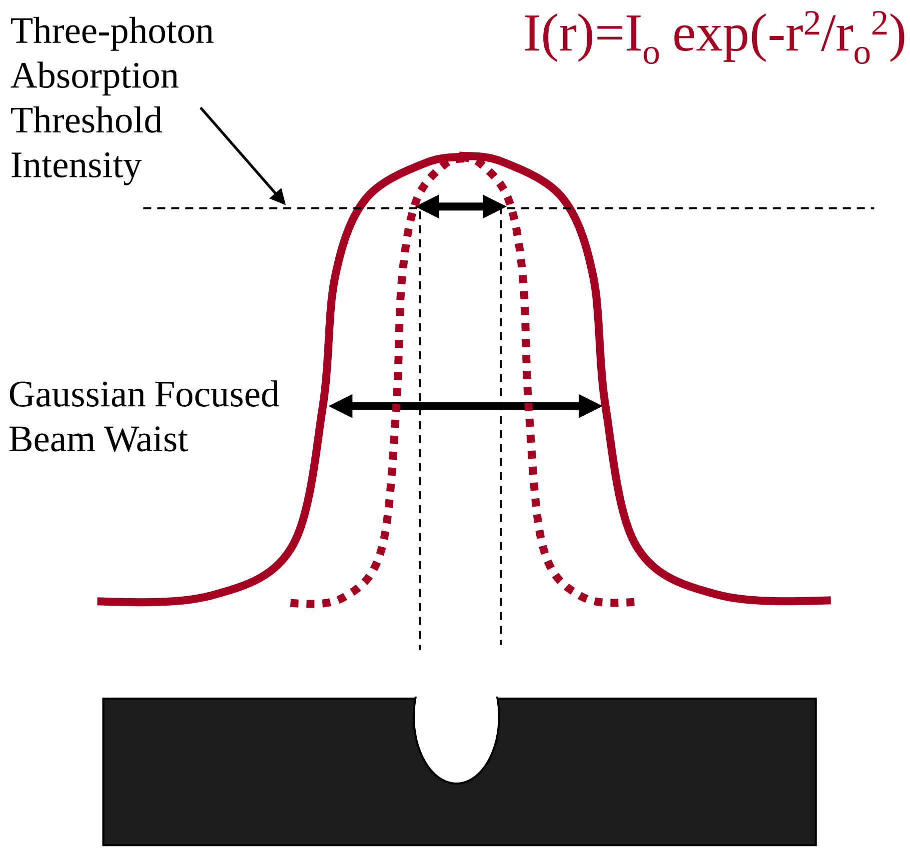
- Nonlinear absorption mechanisms in transparent or wide-bandgap materials
- Short pulse minimizes collateral damage: scale length ~ $(Dt)^{0.5}$
- Short pulse eliminates plasma/plume shielding
- Small interaction volumes in tight focusing
- Deterministic / reproducible etching



Beating Conventional Optics: Ultrafast Laser Nonlinear Absorption

n-Photon Absorption

Absorption Profile at Sample Surface:
Absorption Coef: $\alpha \sim I(r)^{n-1}$
Absorbed Energy: $\sim \alpha I \sim I(r)^n$



Nonlinear Absorption:
Penetration in transparent material

Heat dissipation is proportional to the Intensity gradient: $\frac{dI}{dz} = -\alpha I - \beta I^2$

2nd order: 2 photon absorption

Integration yields:

$$I(z) = \frac{I_o}{(1+\frac{\beta I_o}{\alpha})e^{\alpha z} - \frac{\beta I_o}{\alpha}} \xrightarrow{\alpha=0} \frac{I_o}{1+\beta I_o z}$$

Simple linear fall of by 2-photon absorption
- ignores beam diameter changes with focussing
- other nonlinear effects cause filaments and plasma defocussing
- 50% penetration depth is $1/\alpha_{eff} = 1/\beta I_o$
- higher intensity gets concentrated closer to surfac
- I(x,y,z): ultrafast interactions offers higher resolution than with linear absorption since absorption falls off with intensity laterally across the surface

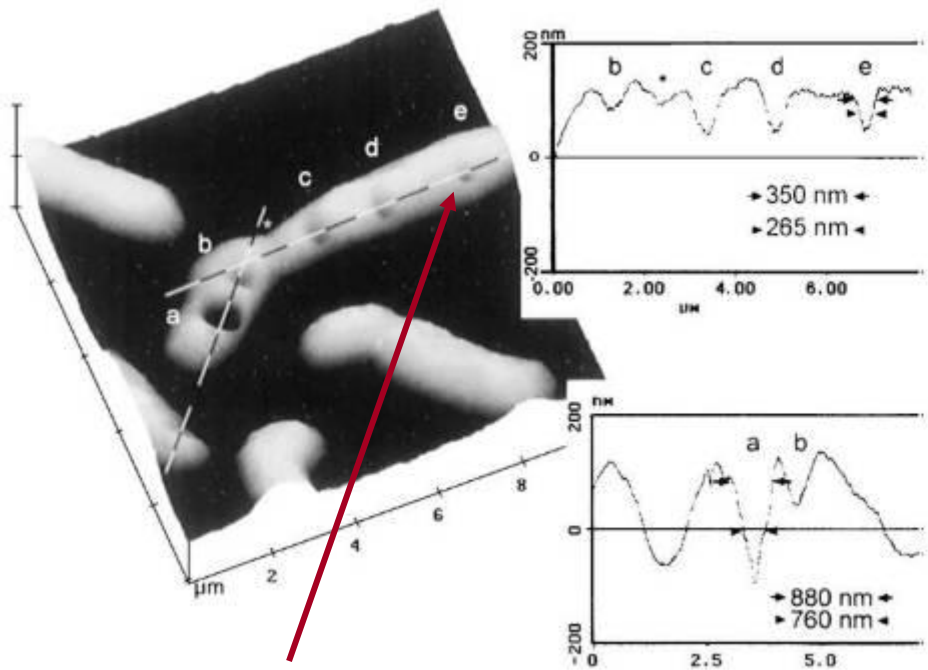
Nanodissection of Human Chromosomes Ultrafast Laser Nonlinear Absorption

Konig et al., Optics Letters **26**, 819, 2001

Ultrafast Laser:
80 MHz, 800 nm,
170 fs

Focusing:
100x 1.3 NA
Objective

N-Photon
Absorption



Holes: 265nm dia.
~ 2x smaller than
diffraction limit

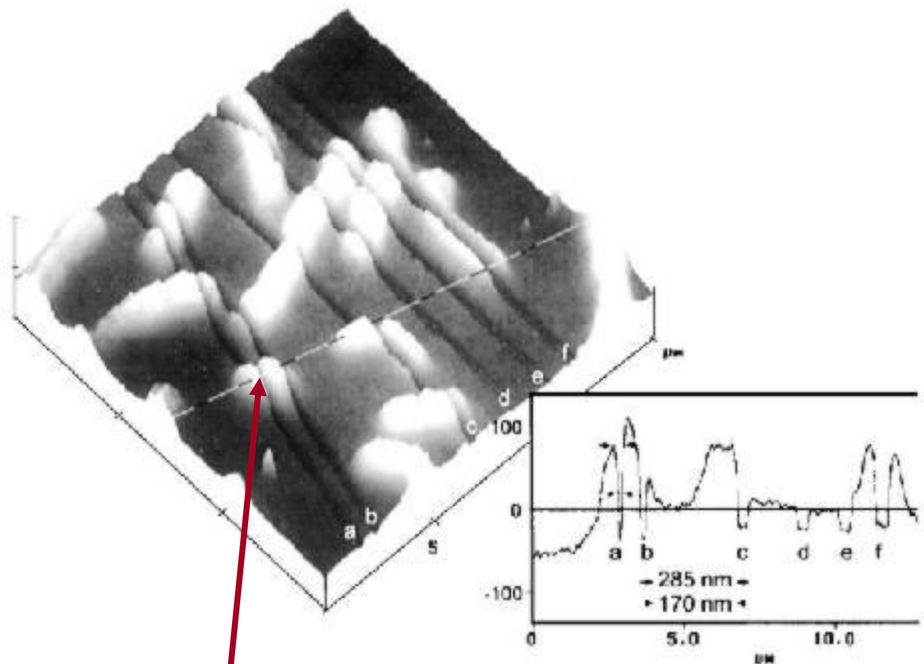
Nanodissection of Human Chromosomes Ultrafast Laser Nonlinear Absorption

Ultrafast Laser:
80 MHz, 800 nm,
170 fs

Focusing:
100x 1.3 NA
Objective

N-Photon
Absorption

Konig et al., Optics Letters **26**, 819, 2001



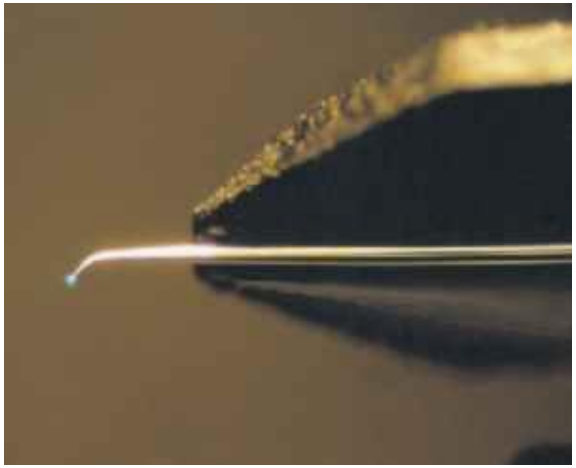
Dissection of Human Chromosome:
~170 nm wide cut
~ 3x smaller than diffraction limit

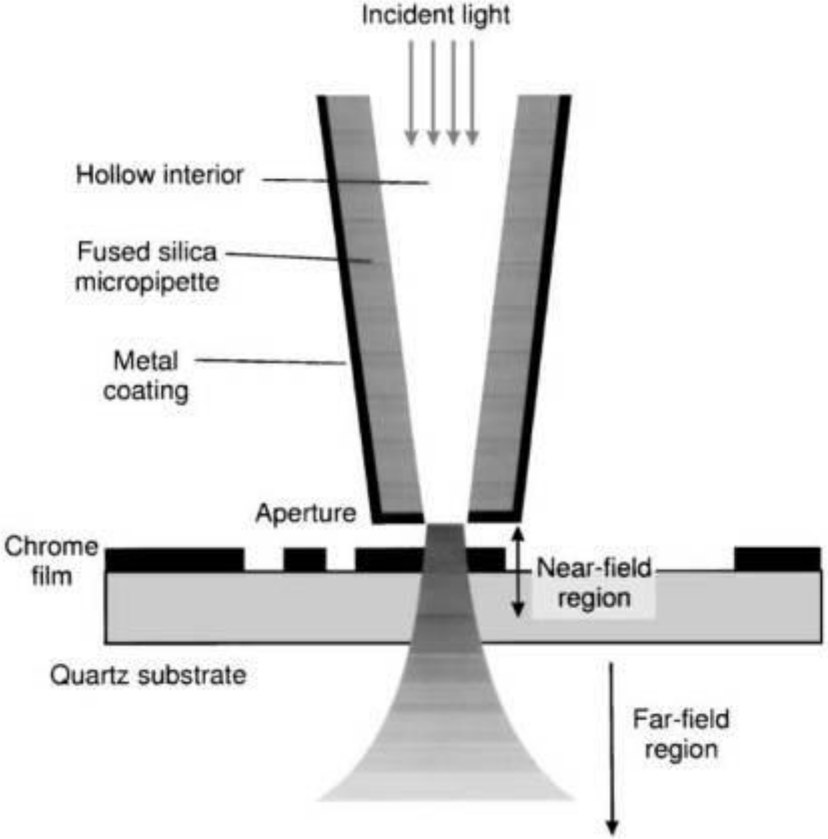
Beating Conventional Optics:
Near-Field Proximity Masks – Tapered Fibers

Ultrafast Laser:
1 kHz, 780 nm, 100 fs

Focusing: SNOW or NSOM
200-nm sub-diffraction grooves

Nolte et al., Optics Letters **24**, 914, 1999



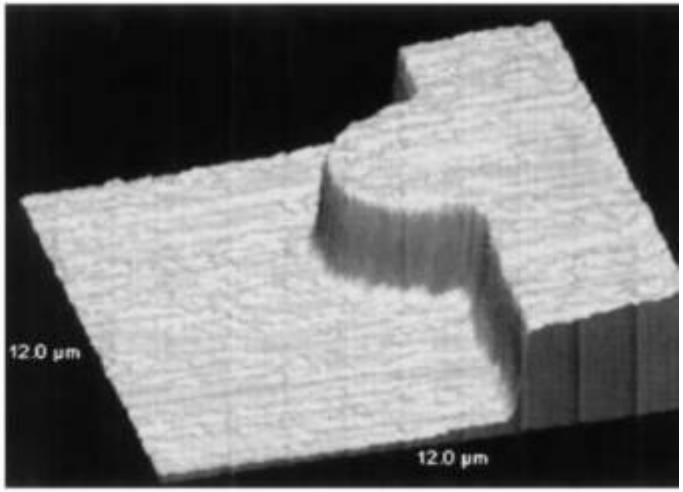


Beating Conventional Optics:
Near-Field Proximity Masks – Tapered Fibers

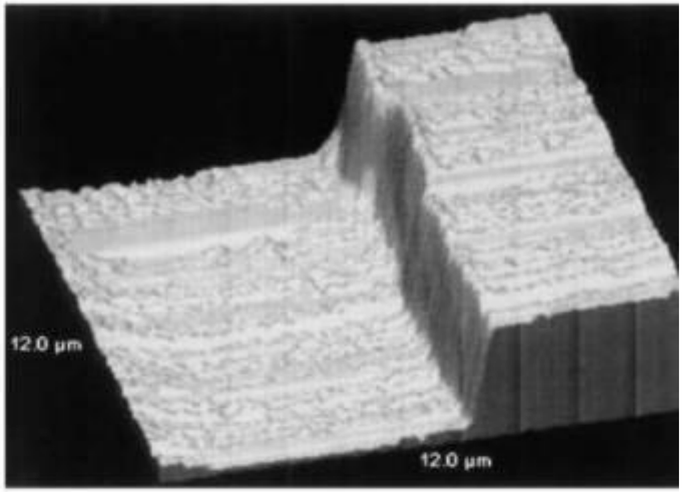
Ultrafast Laser:
1 kHz, 780 nm, 100 fs

Focusing: SNOW or NSOM
180-nm sub-diffraction grooves

Mask Repair



(a)

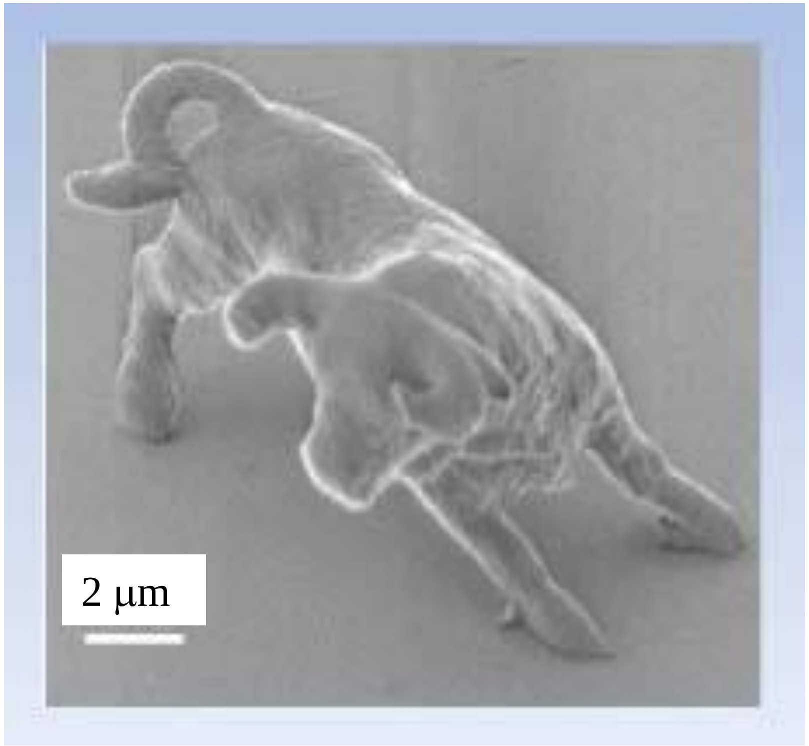


(b)

Nolte et al., Optics Letters **24**, 914, 1999

Laser's Make it Small

World's smallest Bull - ~10 µm – Prof. Kawata, HanDia



- 2-photon photopolymerization
- two IR laser beams
- IR-transparent urethane acrylate monomers, oligomers, photoinitiator
- 120 nm sub-diffraction spatial resolution

S. Kawata et al., Nature **412**, 697 (2001)

Gain in Resolution: Photochemistry / Photoresist

Chemical Reaction Process – Arrhenius driven, i.e. use laser to heat sample

Reaction Rate scales as

$$\boxed{e^{-E_a/kT} \qquad \gamma^* = \frac{\ln(10) E_a T}{k(T+T_s)^2}}$$

E_a *activation energy*

T_s *substrate*

T *local temperature rise*

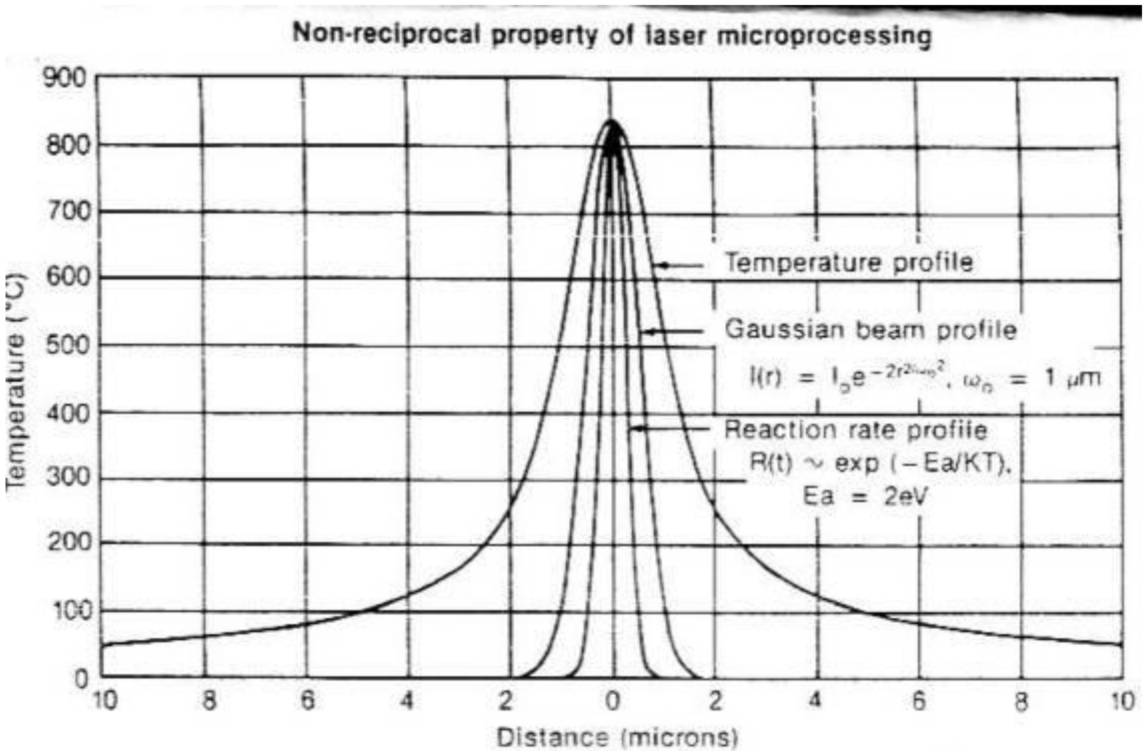
Expect γ^* ~ 10 to 20 range

For Arrenhius processes: $$\boxed{\frac{L_0}{2w_f} = \frac{1}{\left[2\log(e)\gamma^*\right]^{1/2}} = \frac{1.07}{\sqrt{\gamma^*}}}$$

then, γ^* = 20 yields L_o = 25% of $2w_f$

Photoresist: Chemical amplification and sharp activation threshold reduces modification region in 30 to 60% of laser spot size

Exceeding Diffraction Limits Arrenhius Reaction Process



A Gaussian Ar-ion laser beam with 1/e E-field spot size of 1 um heats a surface to create a broader temperature profile due to thermal transport (1-D) in the medium. Because a thermally-driven chemical process is driven, the exponential nature of the Arrhenius reaction with 2-eV activation energy dramatically narrows the width of the process below the beam waist in a direction transverse to the scanning laser direction.

Laser Matter Interactions

- ***Laser Source***
- ***Optical Delivery***
- Material Properties
- Interaction Physics / Chemistry
  - Absorption
  - Heat Transport
  - Melting & Vaporization Phases
  - Shock Waves and Plume Formation

Complex interactions must be tuned to optimize laser process

  - Speed thruput
  - Sharpen resolution
  - Lower cost
  - Reliable or wide processing windows
  - Reduce material damage, debris, dross

Laser Matter Interactions

- Light interactions by material type
  - Metals
    - interaction with conduction electrons; relaxation heats lattice
    - Losses due to reflective surfaces
    - Thermal transport reduces resolution
  - Semiconductors
    - Transparent/opaque below/above bandgap
  - Insulators
    - Infrared - thermal lattice heating supports only pyrolysis
    - Visible - transparency and nonlinear interactions or some forms of electronic excitation
    - UV - electronic excitations -> photochemical decomposition or lattice heating by e-relaxation

When the laser hits

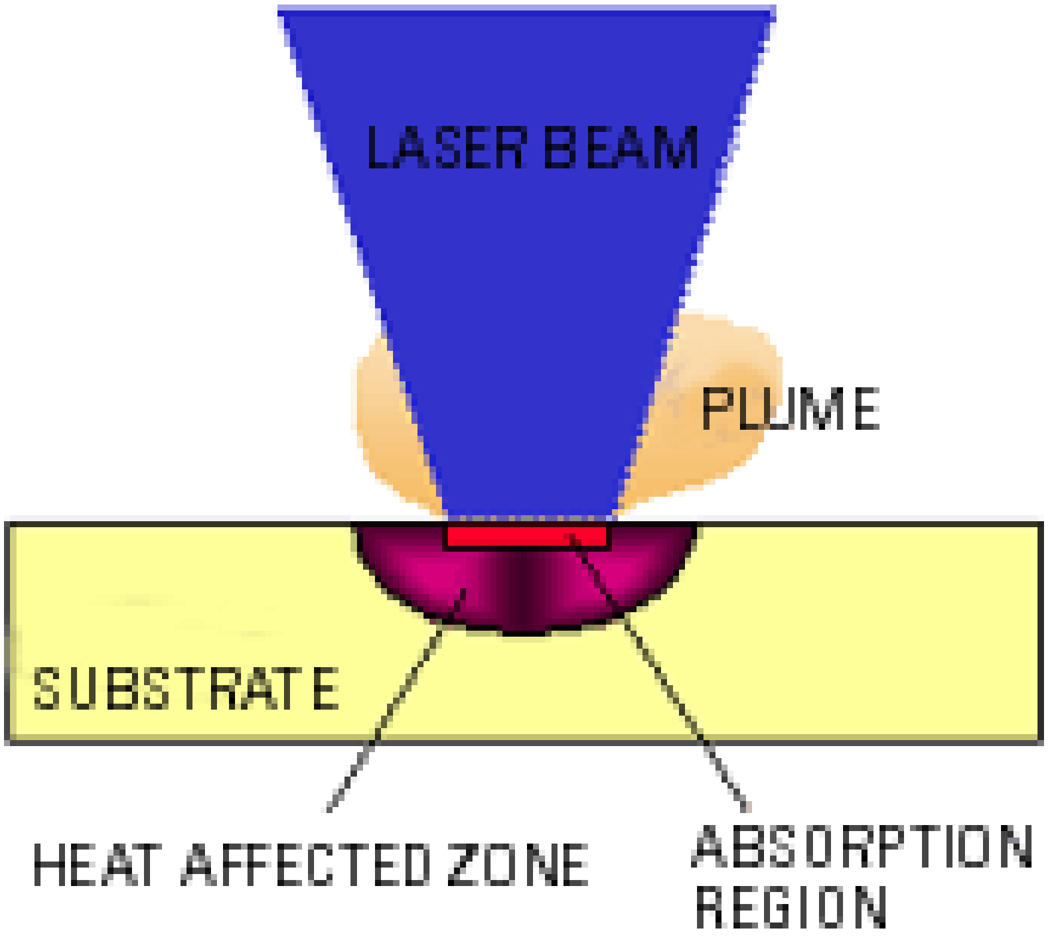
- Solid → heat-treating, hardening, photochemistry

Liquid → cladding, welding, consolidation, texturing, marking

Gas → marking, drilling, cutting

Plasma → marking, drilling, cutting

High-intensity interaction



Coupling the energy

For an efficient and clean interaction, we need the sample to absorb just the amount of laser energy needed.

- Absorption curve of sample

  - ceramics: far infrared (CO_2)
  - metals: near infrared and visible (YAG)
  - plastics, glass: ultraviolet (excimer, YAG)

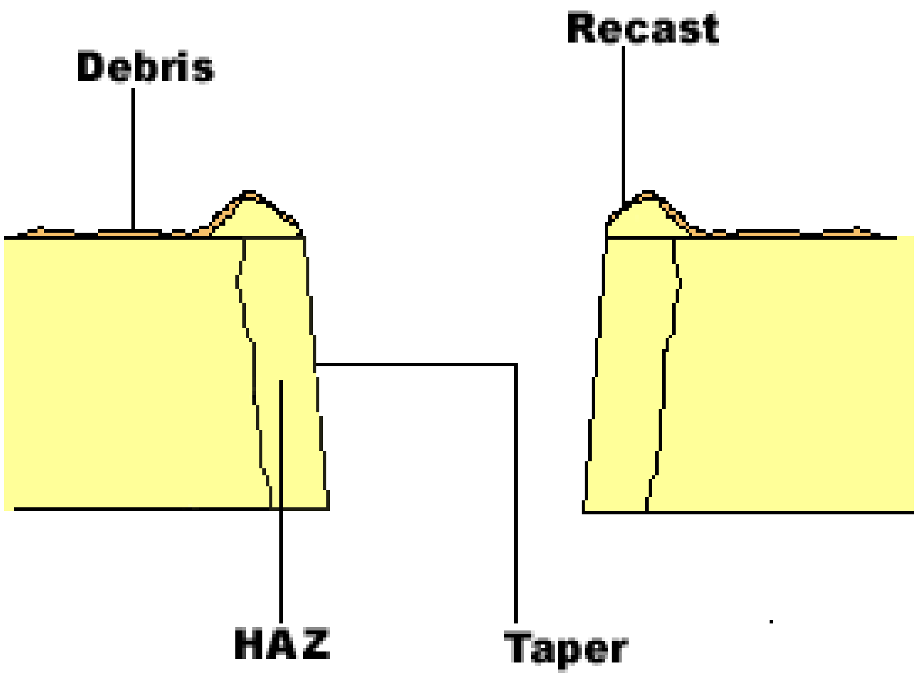
- Pulse duration/plasma shielding

  - heat-treatment: continuous
  - welding, cladding: long pulses
  - marking, drilling, cutting: short pulses

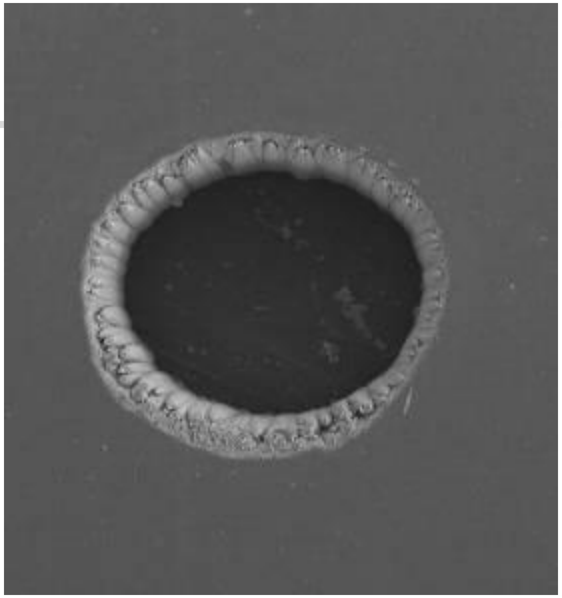
Laser machining processes

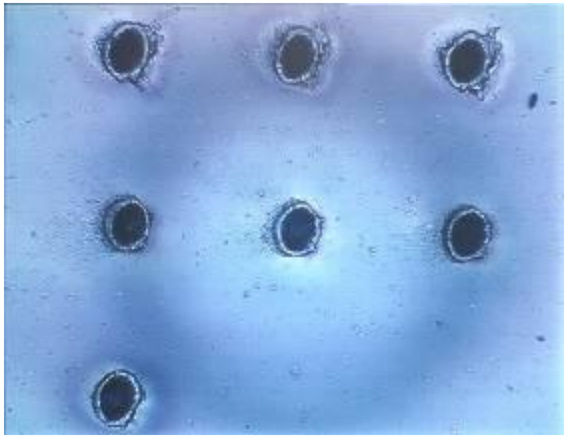
Solid phase	- Heat treating (annealing) - Hardening
Liquid phase	- Cladding - Hardfacing - Laser consolidation - Welding
Gas/plasma phases	- Marking (engraving) - Scribing - Drilling - Cutting - Trimming
Diagnostics	- Measurements → feedback/control

Aftermath...



Cross-section of a laser-drilled hole showing secondary effects





Laser Matter Interactions

Light interactions: consider both Reflection and Absorption

REFLECTION

$$R = \frac{(N-1)(N-1)^*}{(N+1)(N+1)^*} = \frac{(n-1)^2 + K^2}{(n+1)^2 + K^2} \qquad \alpha = \frac{4\pi K}{\lambda}$$

- Calculate from Fresnel equations (Maxwell's boundary equations)
- Expect n (refractive index) and K (extinction coef) to be tabulated for numerous materials as a function of wavelength; complex index: $N = n + iK$
- reduce R to maximize power coupling into material
- R is temperature dependent (i.e. increases in Si due to e-h pair generation)
- R changes dramatically with *state:* solid / melt / vapour / plasma
- Material segregation will change R (example: GaAs will form metallic Ga islands as volatile As leaves surface during laser treatment)
- Wavelength dependent
- Surface quality dependent; rough or dirty surface absorb more than smooth ones
- Smearing dirt / roughening glass is sometimes useful to increase absorption

Laser Matter Interactions

- Light interactions: consider both Reflection and Absorption

ABSORPTION - α

$$I(z,t) = I_0(t)\,(1-R)\;\; e^{-\alpha z}$$

or replace intensity with Fluence (J / cm^2)

$$F(z) = \int I(z,t)dt \quad \rightarrow \quad F(z) = F_0(1-R)\;\; e^{-\alpha z}$$

- Absorption, α, will change with wavelength; surface morphology; temperature; state of matter (solid; liquid; vapour); intensity; transient absorption species; plasma or plume; accumulated damage (incubation)
- Effective Absorption, α_{eff}, is often used to account for changes in the bulk material, small-signal absorption, α, during laser interactions.

Absorption

(Hecht – Understanding Lasers)

Table 12-1. Surface absorption (percent) at important laser wavelengths

	Laser and wavelength			
Material	Argon-ion, doubled Nd or Yb (near 500 nm)	Ruby (694 nm)	Nd or Yb (1064 nm)	CO_2 (10.6 μm)
Aluminum	9%	11%	8%	1.9%
Copper	56%	17%	10%	1.5%
Human skin (dark)	88%	65%	60%	95%
Human skin (light)	57%	35%	50%	95%
Iron	68%	64%	~35%	3.5%
Nickel	40%	32%	26%	3%
Seawater	low	low	low	90%
Titanium	48%	45%	42%	8%
White paint	30%	20%	10%	90%

Laser Matter Interactions

Two broad means of coupling energy into solids:

- IR – infrared: phonon or thermal interaction (i.e. CO_2 laser at 10 μm)
- UV – electronic or photochemical decomposition; bond breaking (i.e. ultraviolet excimer lasers)

Metals and Semiconductors (if $h\nu > E_{gap}$)

- Semiconductors behave like metals when photon energy $h\nu > E_{gap}$

  → generates e-h carriers
- In metals, electron density can be high and light interacts most strongly with free electrons to be absorbed and reflected; same in semiconductors with $h\nu > E_{gap}$
- hot electrons bump into ions/holes/lattice atoms/defects to heat the lattice (phonons) in picosecond time scales
- Absorption in very thin layers because of high electron density
- heated electrons (holes) efficiently carry heat thru solid by thermal diffusion
- if enough fluence, melt and then vaporization

Laser Matter Interactions

Polymers and Insulators

- no free electrons; light interacts with bonds

  IR – vibration / shaking; UV - photochemical bond breaking
- thermal transport is not efficient as in metals/good conductors;
- optical penetration often controls laser heating zone:
- example: for polymers

  $\alpha \sim 10^5\ cm^{-1}$ ~ 100 nm penetration in UV

  $\alpha \sim 0\text{-}10\ cm^{-1}$ >1 mm penetration in IR
- Wavelength dependence of absorption coefficient defines the strength of interaction, penetration depth, etc., which ultimately defines the processing precision, quality, and damage

Laser Matter Interactions Wavelength Selection - UV is Best!

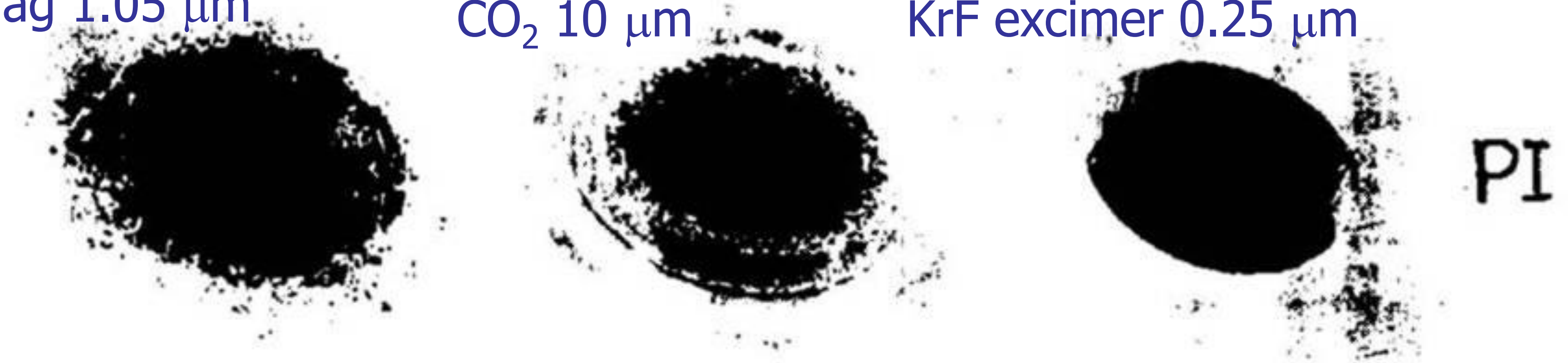
GSI Lumonics by Terry McKee et al.

- Polyimide (PI) is a popular insulator for the electronics industry
- defines optical resolution, choice of optical materials, precision of interaction, and often sets the complexity of the optical delivery system

SEM photographs show the effect of laser wavelength in etching vias in 75-μm thick polyimide by pulsed-laser ablation.

- The 300-μm diameter holes were formed by a 1.06-μm wavelength Nd:YAG laser (left), a ~10-μm wavelength CO_2 laser (middle), and a 248-nm KrF excimer laser (right). The ultraviolet source offered the highest precision with minimal heat-affected zone due to strong absorption, photochemical decomposition and generation of volatile ablation products. Optical absorption is very weak at longer wavelengths leading to heat flow and pyrolytic decomposition.

Nd:Yag 1.05 μm | CO_2 10 μm | KrF excimer 0.25 μm



Wavelength Selection – IR is best? -revisited by GSI Lumonics

While IBM developed excimer laser systems for PI etching on PCB in 1980s, Lumonics studied the threshold fluence at various vibrational-rotational wavelengths of the CO_2 laser and discovered a strong absorption feature at a slightly weaker laser wavelength in the 9R branch.

The threshold fluence correlates with the transmission absorption spectrum (solid line; inversely proportional to *ln* of absorption coefficient) below supporting the notion that αF_t remains constant for a given material. Lumonics pioneered CO_2 laser processing in etching vias for printed circuit board applications by tuning the CO_2 laser wavelength with a grating to the strong PI absorption feature in the 9R branch. CO_2 laser processing is much cheaper than excimer or solid state laser processing.

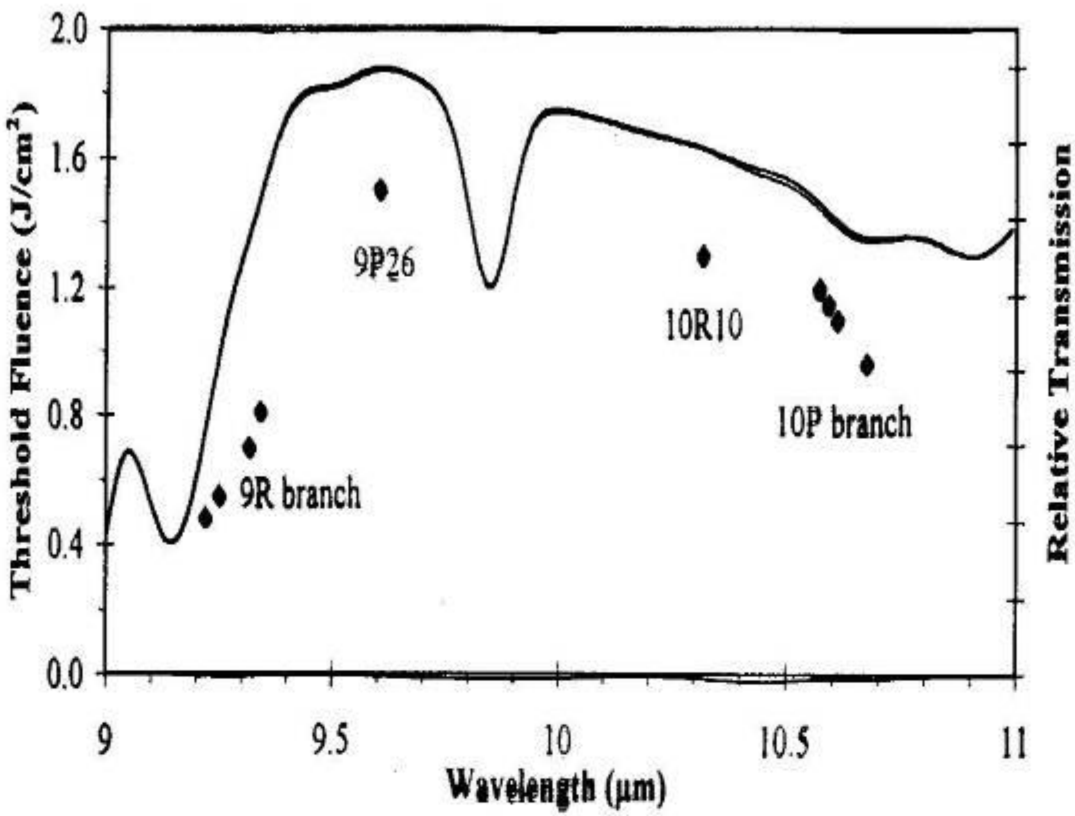


Figure shows wavelength dependence of ablation threshold fluence, F_t (diamonds), for polyimide (PI) obtained with a tunable CO_2 laser.

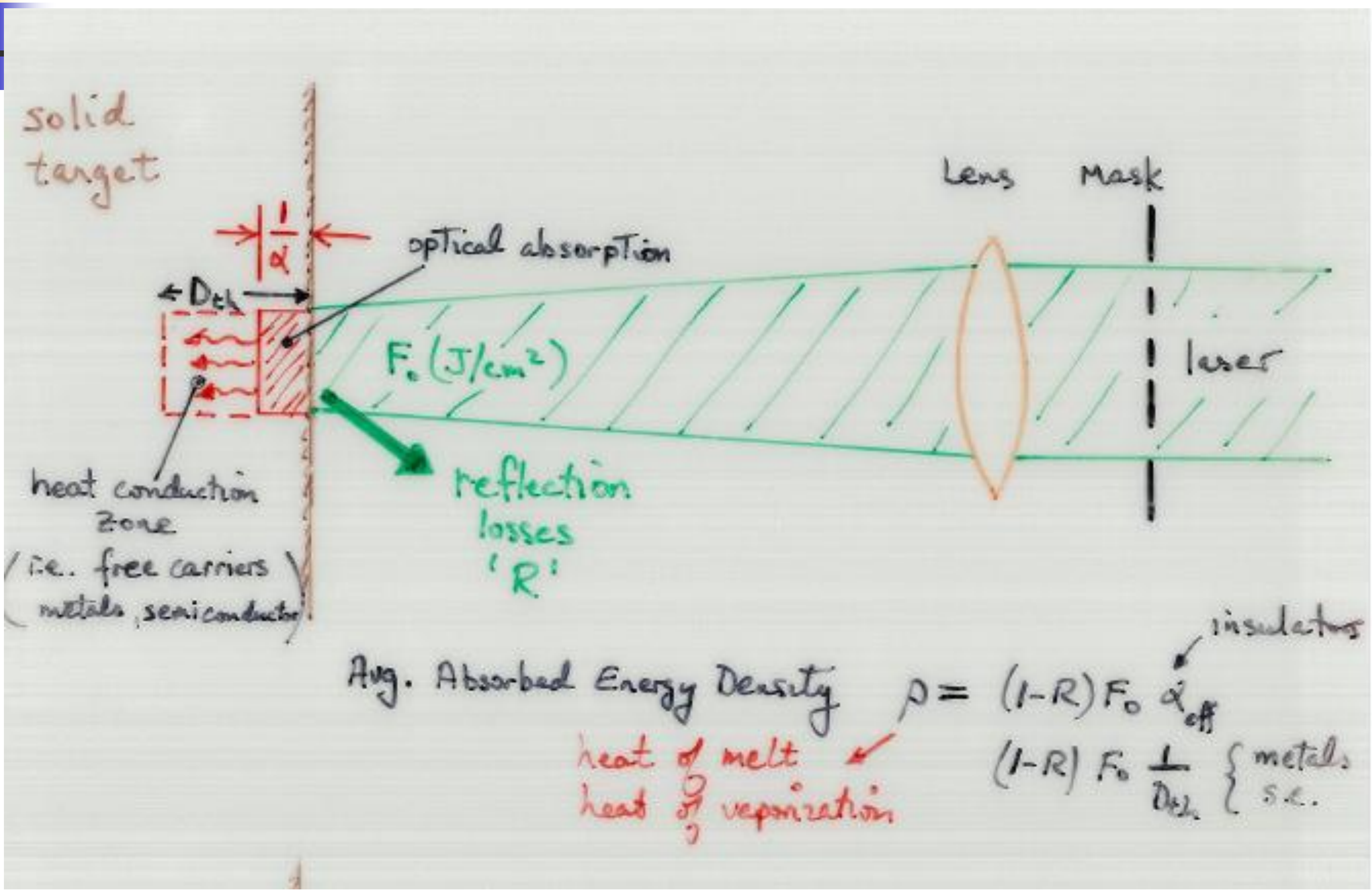
LASER ABLATION

Extremely Weak to Extremely Strong Pulsed Laser-Matter Interactions

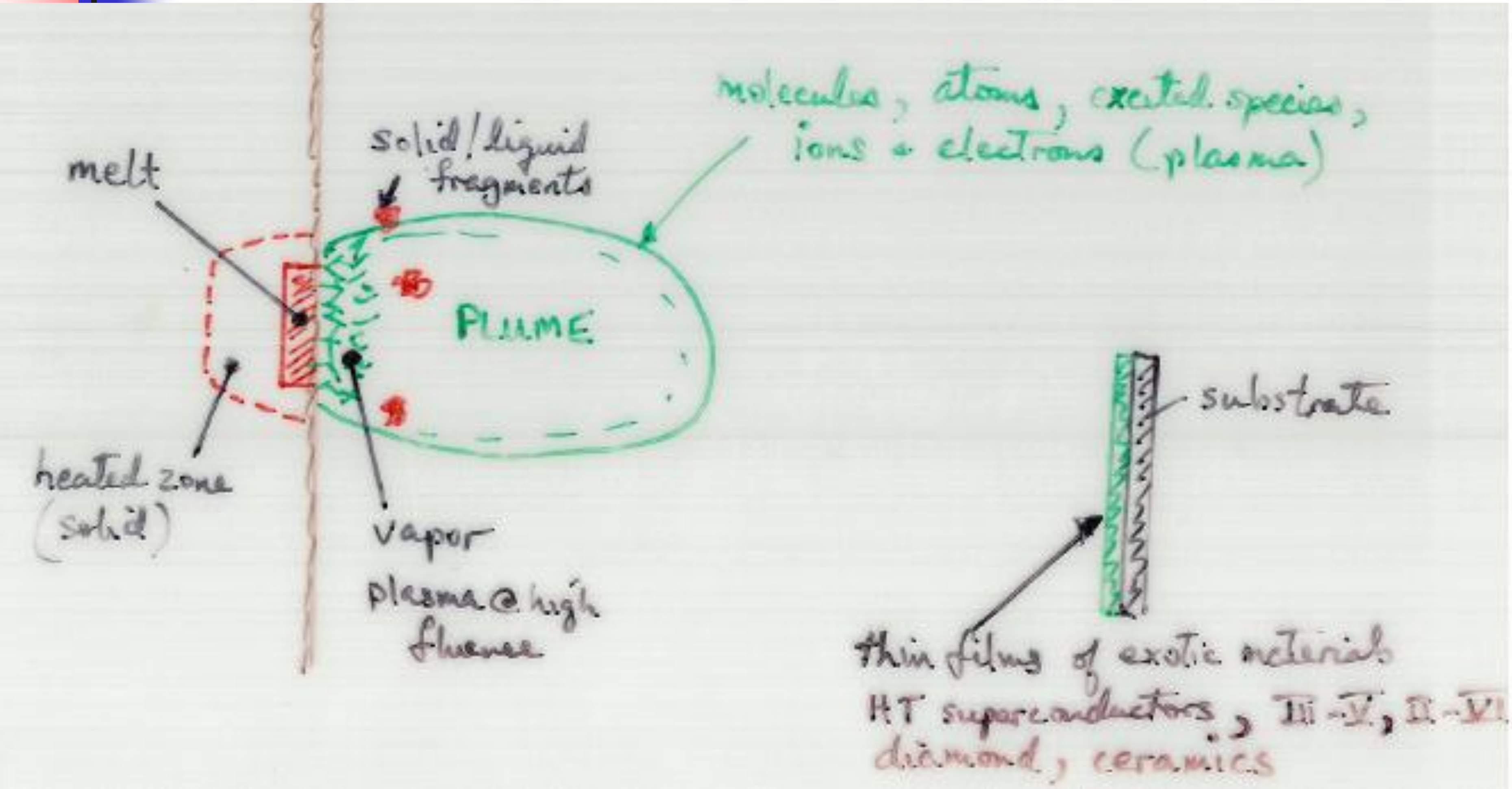
Low Fluence **< 0.01 J/cm^2**	**Moderate Fluence** **0.01 – 10 J/cm^2**	**High Fluence** **> 10 J/cm^2**
Atoms leave surface	> monolayer etching	Deep pits
Little surface heating Solid surface intact	Heating -> melt and vapour Plume forms	Ionization -> Plasma Plasma dominates physics Inverse Bremstraulung absorption
SURFACE SCIENCE	LASER ABLATION	EXTREME PHYSICS x-ray sources, relativistic effects, nuclear fusion
	Concentrate Here	

Observations can vary dramatically with changes in material and in laser type

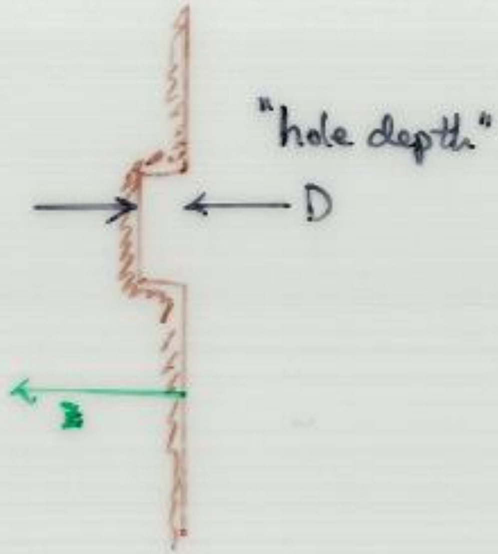
Pulsed LASER ABLATION
Interactions and Etching Rates



Pulsed LASER ABLATION
Interactions and Etching Rates



Ablation Rate



absorbed energy density

$$\rho(z) = -(1-R)\frac{dF(z)}{dz}$$

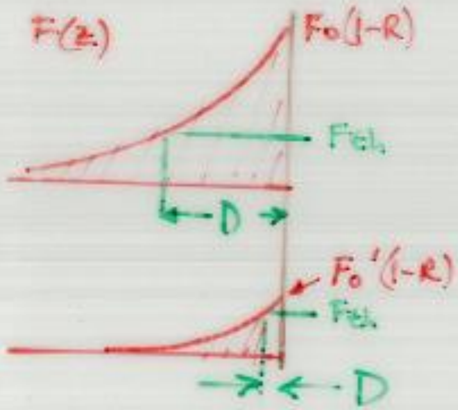
optical absorption

for insulators: $F(z) = F_0 e^{-\alpha z}$

α related to optical absorption

$\propto F$

Then $\rho(z) = (1-R) F_0 \alpha e^{-\alpha z}$



- threshold "ρ" to "evaporate" surface

$$\rho_{th}(z)\Big|_{z=D} = (1-R) F_0 \alpha e^{-\alpha D}$$

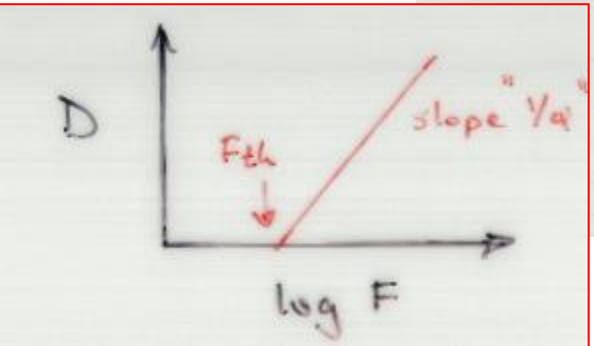
- $F_0 > F_{th} \Rightarrow$ ablation depth D

$$\rho_{th}(D) = (1-R) F_0 \alpha e^{-\alpha D} \quad (2)$$

THRESHOLD $D=0$, $z=0$: $\rho_{th}(0) = (1-R) F_{th} \alpha \quad (1)$

insulators

(1) = (2) $\Rightarrow$ $\boxed{D = \frac{1}{\alpha}\ln\left(\frac{F_0}{F_{th}}\right)}$



Heat Transport - Vaporization

Clausius-Clapeyron Eq'n ...follows Phase Changes pg. 10

- **Clausius-Clapeyron Eqn** (Assumes Thermal Equilibrium)

Vapour pressure of material for surface temperature T is very large for $T > T_B$; very small for $T < T_B$

$$p(T) = p(T_B)\exp\left(\frac{L_v}{k}\left(\frac{1}{T_B} - \frac{1}{T}\right)\right)$$

$P(T_B)$ = known vapour pressure at Vaporizing Temp T_B from Gas Law at 1 atm pressure

- **Equilibrium Evaporation Rate:** ν is *velocity* of surface due to vaporization loss

$$v = \frac{\Lambda D_{etch}}{\Delta t} = \frac{p(T)}{\rho}\left(\frac{\overline{m}}{2\pi kT}\right)^{\frac{1}{2}}$$

ρ is density of solid
m bar is avg atomic mass of ablated species
ρ x thermal vel = pressure

These rates are much slower than predicted by D_{etch} in previous notes and observed experimentally, and shows that 'ablation' is not at thermal-equilibrium process.

Do Not Assume Thermal Equilibrium during laser interactions.

Laser Plume

Follow Walt Duley UV Lasers

- begins within ~10ps of appropriate fluence exposure
- plume forms when more than 0.5 monolayer is eject in a laser pulse
- collision of atoms as they try to leave
- directed plume (90degrees to surface), densify gases, ions, plasma, shocks at supersonic velocity.
- plume absorption coefficient which reduces amount of light reaching surface and lowers etch rate (or can raise etch rate if α_p is small/transparent gas)
- e.g.
- $$D = \frac{1}{\alpha_p} \ln\left[\frac{\alpha_p F}{\alpha_{eff} F_{th}} - \frac{\alpha_p}{\alpha_{eff}} + 1\right]$$
- $\alpha_p > \alpha_{eff}$: slows etch rate (shallower penetration/holes)
- $\alpha_p < \alpha_{eff}$: enhance etch rate (deeper holes)

General Concepts:

- melting, then sputtering from defects, then evaporation at low fluence
- liquid hydrodynamics of melt → recast around hole
- gas phase laser heating, shock fronts (faster than speed of sound)
- plasma formation in gas phase and even in ejected material

Laser Plume

Follow Walt Duley UV Lasers

- begins within ~10ps of appropriate fluence exposure
- plume forms when more than 0.5 monolayer is eject in a laser pulse
- collision of atoms as they try to leave
- directed plume (90degrees to surface), densify gases, ions, plasma, shocks at supersonic velocity.
- plume absorption coefficient
  - slows etch rate (shallower penetration/holes)
  - Or…enhance etch rate (deeper holes)

$$D = \frac{1}{\alpha_p} \ln\left[\frac{\alpha_p F}{\alpha_{eff} F_{th}} - \frac{\alpha_p}{\alpha_{eff}} + 1\right]$$

General Concepts:

- melting, then sputtering from defects, then evaporation at low fluence
- liquid hydrodynamics of melt → recast around hole
- gas phase laser heating, shock fronts (faster than speed of sound)
- plasma formation in gas phase and even in ejected material

Laser Plume – Shock Fronts

Section 3.2:

- I_V: intensity threshold for surface vaporization
- I_C: intensity threshold for rapid plasma heating of vaporizing material
- I_D: intensity threshold for detonation wave
- **$I_V < I < I_C$:** significant vaporization, but only low density and high transparent plasma
- **$I_C < I < I_D$: Laser Supported Combustion (LSC) wave** – Fig. 3.2a
  -air shock wave precedes the LSC wave. Some laser radiation can penetrate plume/plasma to reach and heat target. Reverse flow of gas to surface.
- **$I_D < I$: Laser Supported Detonation (LSD) wave** – Fig. 3.2d
  - laser nearly totally absorbed in plasma plume, yielding supersonic expansion of heated gas back toward laser. This LSD wave decouples the laser from the surface,

LSC: Laser Supported Combustion Wave

LSD: Laser Supported Detonation Wave

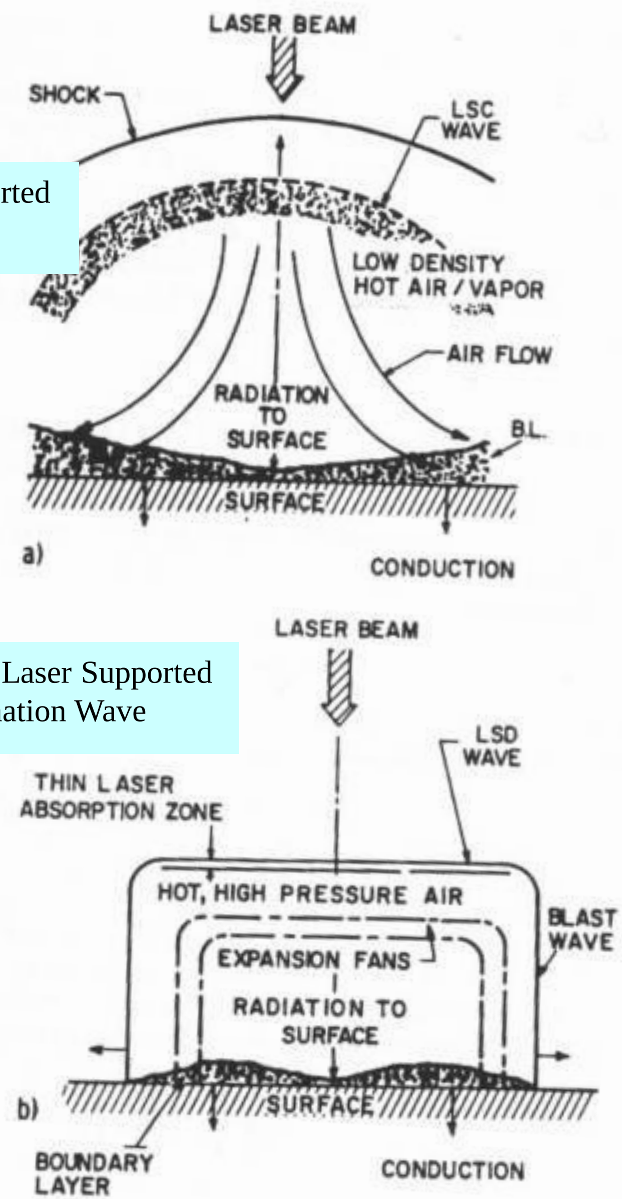


Figure 3.2. (a) LSC wave plasma dynamics. (b) LSD wave plasma dynamics (Pirri *et al.* 1978).

Kherman

Vaporization

(a)

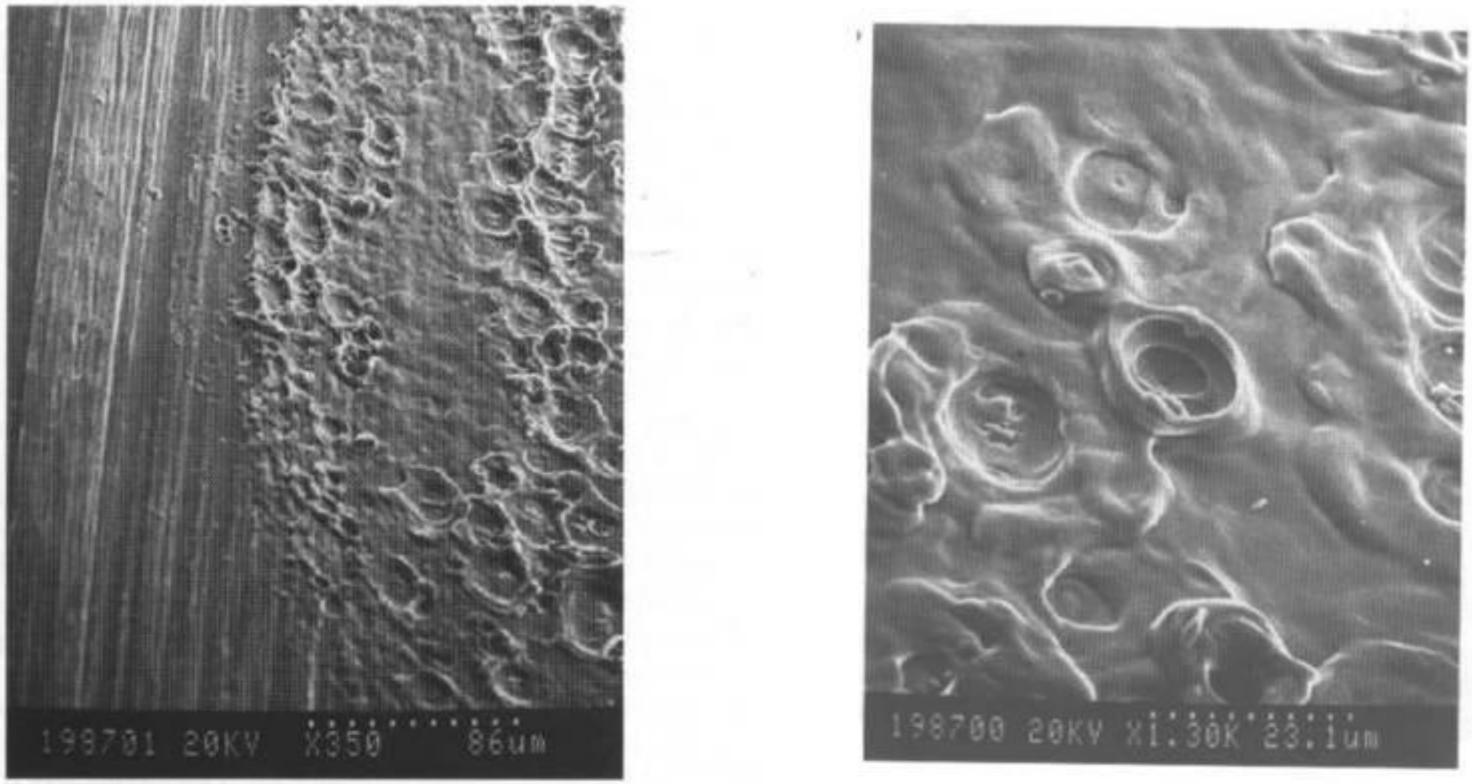


Figure 4.8. SEM micrographs of a Cu surface showing the effect of one pulse at 0.308 μm with $I_0 = 1.3 \times 10^9$ W cm^{-2}. (a) The edge of the irradiation zone. (b) Greater magnification showing evidence of bulk vaporization (Kinsman 1991).

IV < I < IC: significant vaporization, but only low density and high transparent plasma

Note: incubation processes reduce effect of first pulse in 308nm ablation of copper

Laser supported Combustion LSC

120 *Interaction of UV laser radiation with metals*

(a) (b)

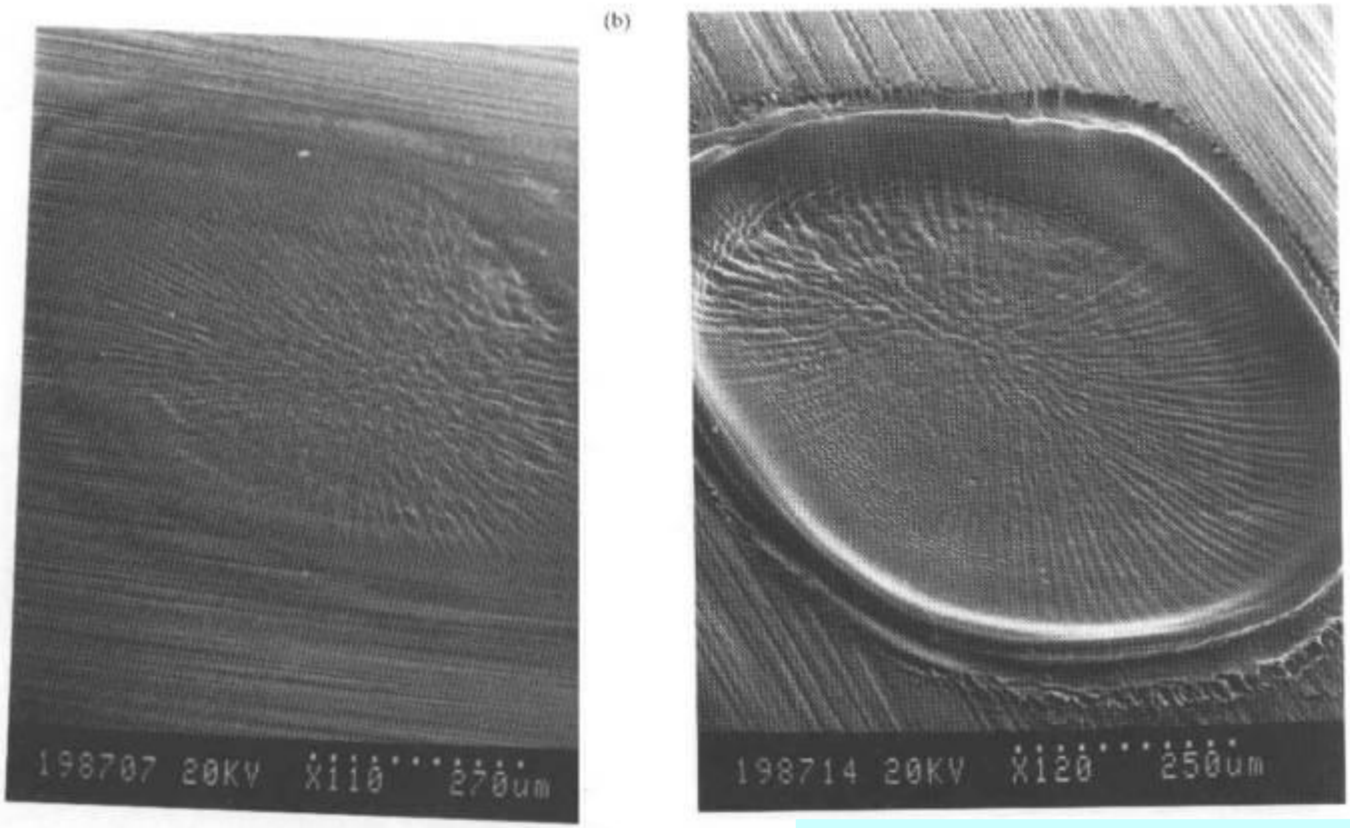


Figure 4.10. SEM micrographs of Cu irradiated at 0.308 μm in the LSC regime at $I_0 \approx 1.3 \times 10^8\ \mathrm{W\,cm^{-2}}$ with the target held stationary: (a) 50 pulses and (b) 500 pulses (Kinsman 1991).

$I_C < I < I_D$: **Laser supported combustion** (LSC) **wave** -air shock wave precedes the LSC wave. Some laser radiation can penetrate plume/plasma to reach and heat target. Reverse flow of gas to surface.

Laser supported detonation LSD

118 *Interaction of UV laser radiation with metals* 4.5 SURFACE MORPHOLOGY

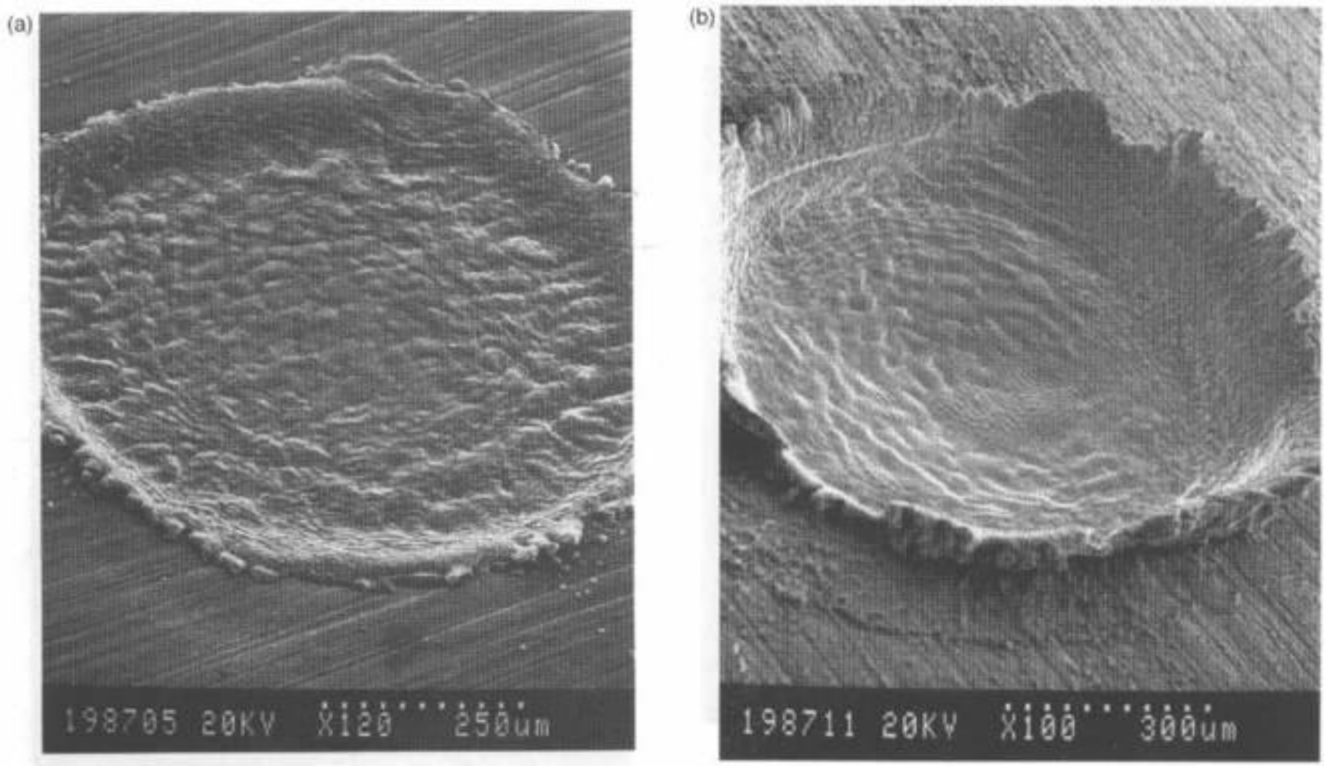


Figure 4.9. SEM micrographs of Cu irradiated at 0.308 μm in the LSD regime at $I_0 \approx 1.3 \times 10^9$ W cm^{-2} with the target held stationary: (a) 50 pulses and (b) 500 pulses (Kinsman 1991).

$I_D < I$: **Laser Supported Detonation (LSD) wave**
- laser nearly totally absorbed in plasma plume, yielding supersonic expansion of heated gas back toward laser. This LSD wave decouples the laser from the surface.

Polyimide PI vs PMMA

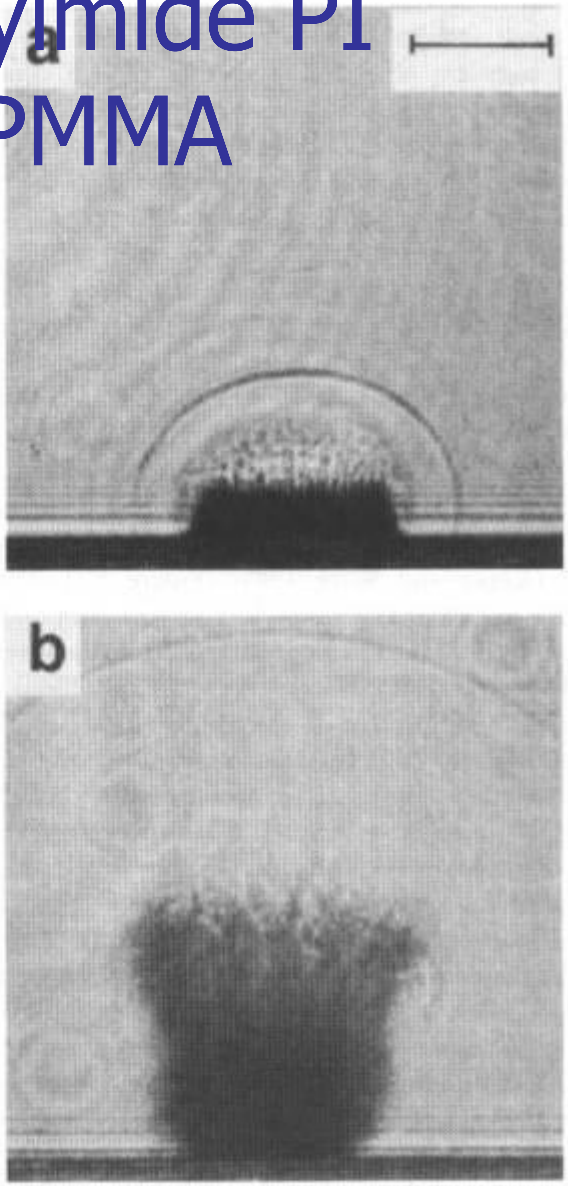


Figure 5.6. Photographs of the blast wave and the ejected material from the surface of a PMMA film on the impact of a single UV (193 nm) laser pulse. Scale bar length 0.5 mm. The time intervals after the start of the laser pulse are (a) 500 ns and (b) 2.9 μs (Srinivasan 1993).

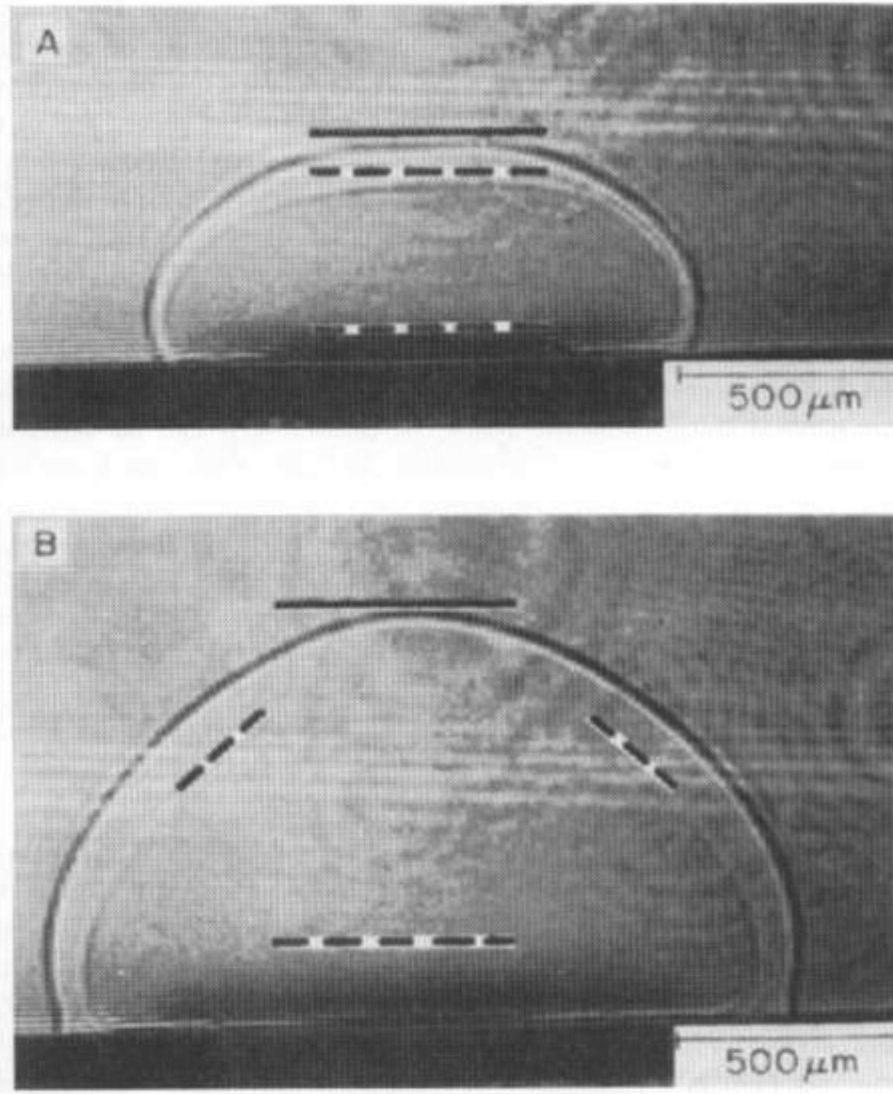


Figure 5.5. PI targets with a thickness of 125 μm were exposed to single laser pulse (308 nm, about 20 ns, pulse diameter 800 μm, 2.3 J cm^{-2}, normal incidence) in air. Th ejecta, contact front, and shock wave were photographed by firing parallel to the targe surface a second ('probe') laser (596 nm, about 1 ns). The imageable limit of the eject and the contact front of the light particles are marked with dashed lines and the shoc wave is marked with a solid line. (a) Delay of 190 ns and (b) delay of 410 ns (Kelly *et a* 1992).

PLUME

What happens to the removed material?

- If volatile: pollute the air
- Atoms: Coats nearby materials
- Particulates: melt debris splatters optics; collateral damage, etc., nano-particle generation (exotic materials)
- Pulsed Laser Ablation PLD: scientific method of growing thin novel films; contamination free transfer
- LIFT: laser induced forward transfer (electronic material on tape is moved to coat nearby substrate)
- MALDI: matrix assisted laser deposition (embed biological or other species of interest into a bulkd ablation medium

Application Example: Laser Marking (huge market)

Non-contact, no wearing parts, no ink contamination or damage to parts

- product specification
- addition of functional elements
- product identification
- to guarantee product traceability
- to protect from imitation
- for color and design considerations
- for graining and scything lines
- Workstation or integrated into assembly

- *What process causes the marks to form?*

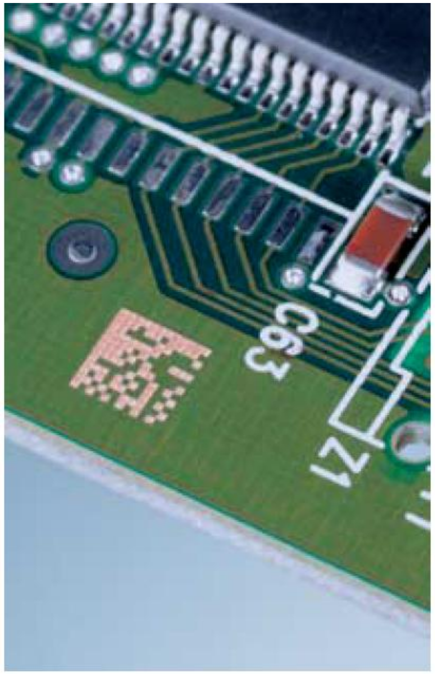
Fiber Laser Video (lots on utube)

Laser Marking (2)

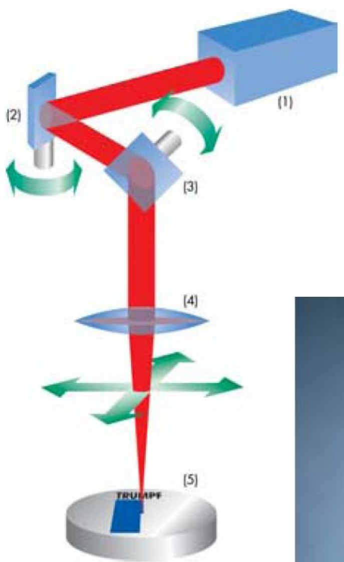
- Galvo or projection: pros and cons?

Tempered metals can be marked permanently and with high contrast.

Functional day and night: automobile component.



Product identification in the smallest of spaces: electronic components.



High quality, even on bent surfaces: marking around an artificial hip joint.

Essential: Product marking on medical parts.

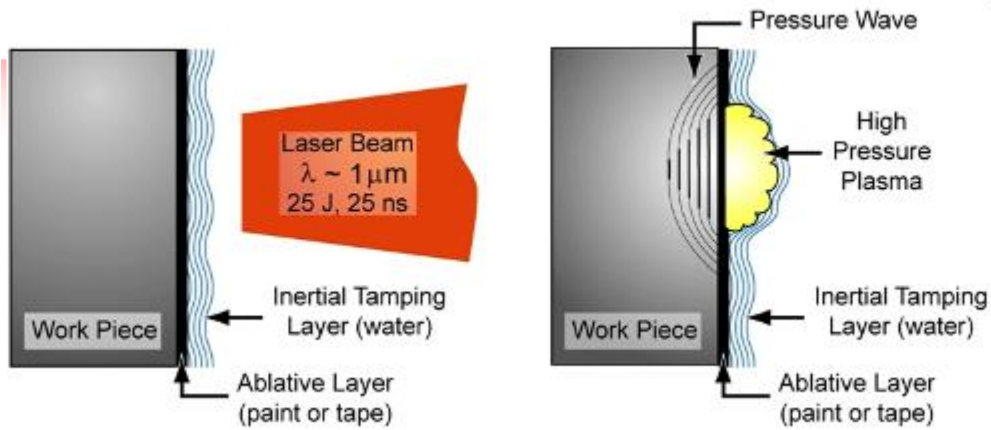
Appliance specific marking: front panel on an electricity meter.

[Laser Marking VIDEO lots on youTube/google]

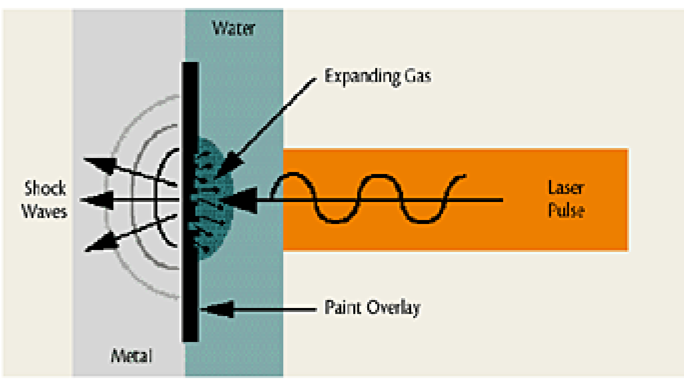
Laser Marking – direct write

- Video *(download from Course Web Site)*

Laser Shock Hardening / Peening



In the Metal Improvement Company laser peening process, technicians fire the laser at the surface of a metal part to generate pressure pulses of one million pounds per square inch, which send shock waves through the part. Multiple firings of the laser in a pre-defined surface pattern will impart a layer of residual compressive stress on the surface that is four times deeper than that attainable from conventional peening treatments. Deeper levels of compressive stress provide greater resistance to fatigue and corrosion failure.



Schematic of laser shock processing. A laser pulse is focused onto a paint overlay vaporizing a small portion, which creates an explosive pressure. Water is used to physically constrain the gas release and the shock wave is directed into the metal.

Fatigue life of peened and non-peened 6061-T6 Aluminum SAE Key Hole Specimens demonstrates a 10X improvement when Laser Peened