# Far IR (FIR) Gas Lasers

- 10 - 1500 microns wavelengths, 300 – 10 THz frequency
- Called Terahertz lasers or FIR lasers
- At this wavelength behaves more like microwave signal than light
- Created by Molecular vibronic transitions
- Requires gases with a permanent dipole moment

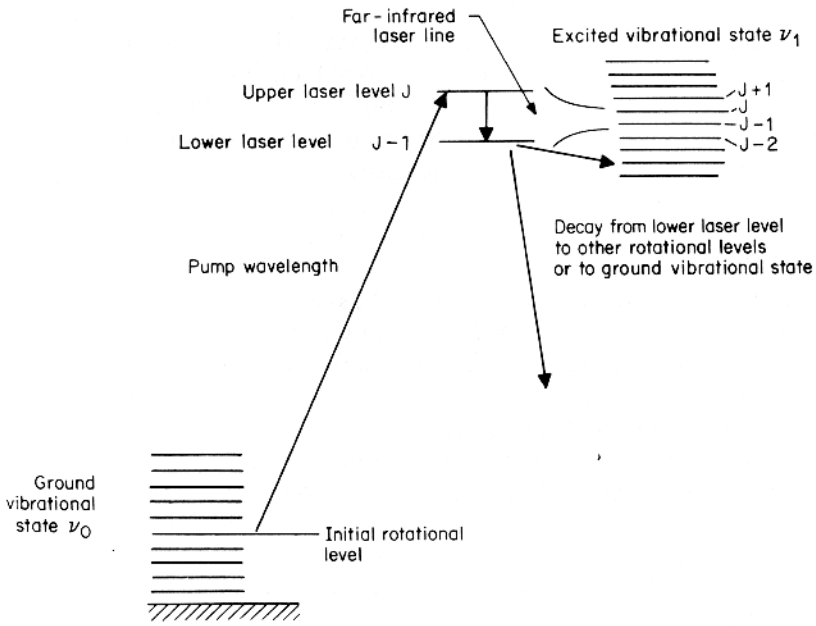



**Figure 15.1** Representative energy-level diagram for a far-infrared laser, showing how optical pumping raises a molecule to an excited vibrational state, where laser action in the far-infrared takes place on a transition between two vibrational levels. The laser levels are pulled out of the series of other rotational levels for clarity; their spacing actually is similar to that of other levels.

**TABLE 15.1 Major Far-infrared Laser Lines Available from Commercial Lasers**

| Wavelength, μm | Gas | Wavelength, μm | Gas |
|---|---|---|---|
| 41.0 | $CD_3OD$ | 255 | $CD_3OD$ |
| 46.7 | $CH_3OD$ | 375 | $C_2H_2F_2$ |
| 57.0 | $CH_3OD$ | 433 | HCOOH |
| 70.6 | $CH_3OH$ | 460 | $CD_3I$ |
| 96.5 | $CH_3OH$ | 496.1 | $CH_3F$ |
| 118.8 | $CH_3OH$ | 570.5 | $CH_3OH$ |
| 148.5 | $CH_3NH_2$ | 699.5 | $CH_3OH$ |
| 163.0 | $CH_3OH$ | 764.1 | $C_2H_2F_2$ |
| 184 | $CD_3OD$ | 890.0 | $C_2H_2F_2$ |
| 198.0 | $CH_3NH_2$ | 1020.0 | $C_2H_2F_2$ |
| 229.1 | $CD_3OD$ | 1222.0 | $C^{13}H_3F$ |

SOURCE: From tabulations by Laser Photonics Inc. and MPB Technologies Inc.

# Far IR Gas Lasers

- Use a Carbon Dioxide laser to pump FIR gas laser
- Was mostly for research but now moving into applications
- Molecular & atmospheric spectroscopy
- Diagonistics of plasmas (plasma fusion)
- Astronomy (sub mm wave amplifiers)
- Strong interest in medical applications – penetrates tissue readily
- Terahertz is non-ionzing radiation hence safe

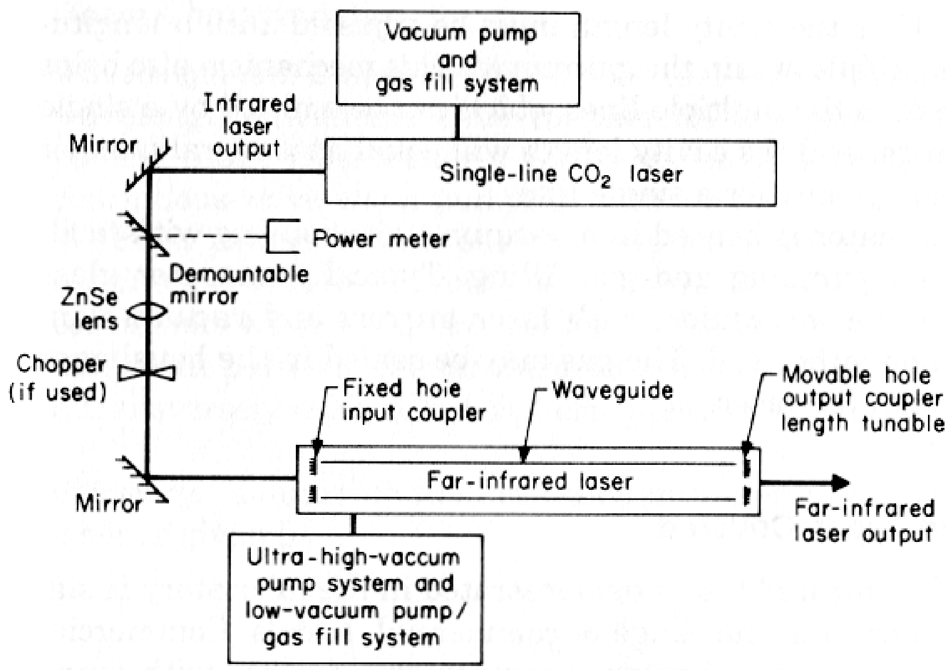
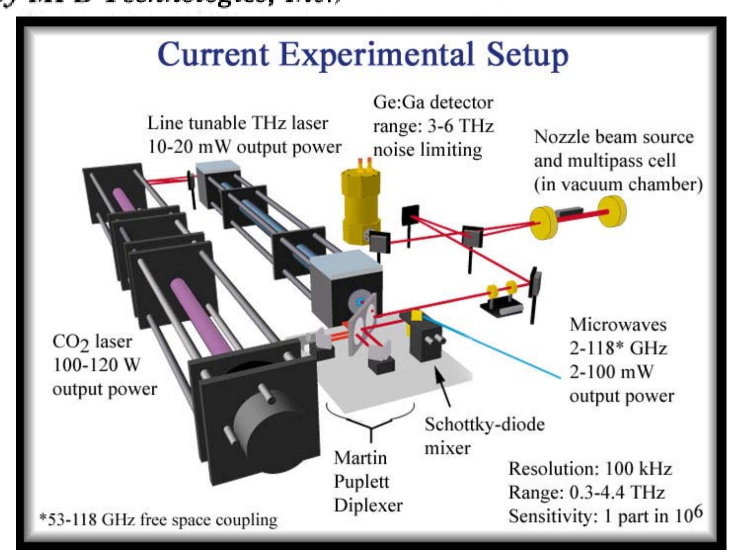
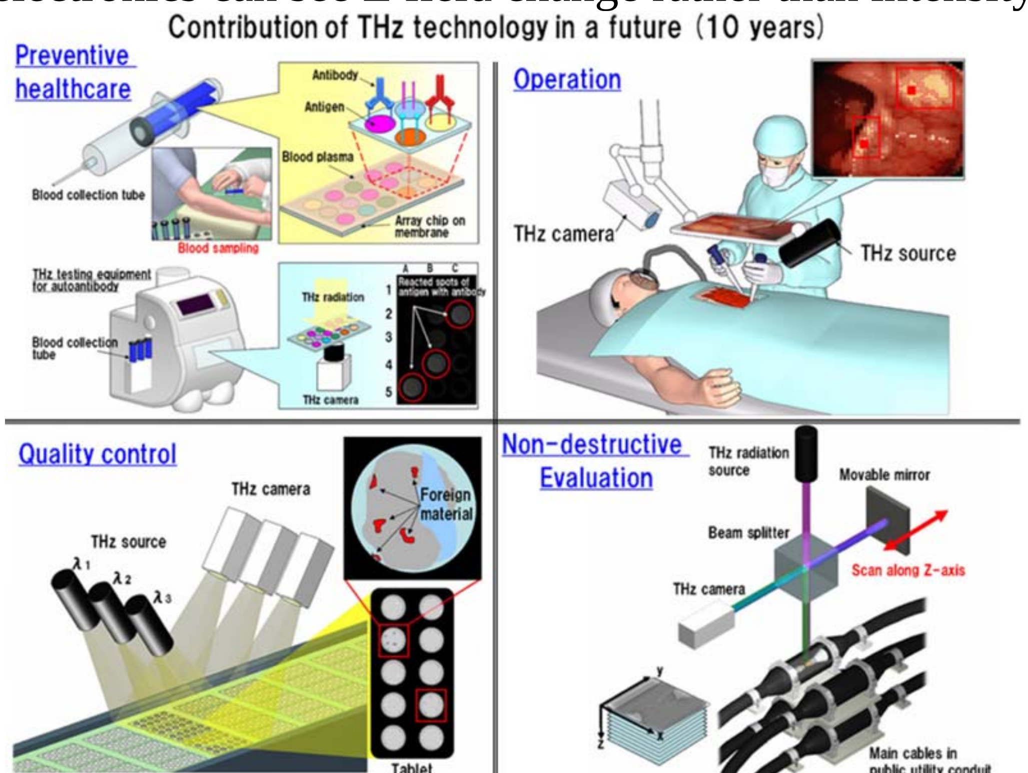


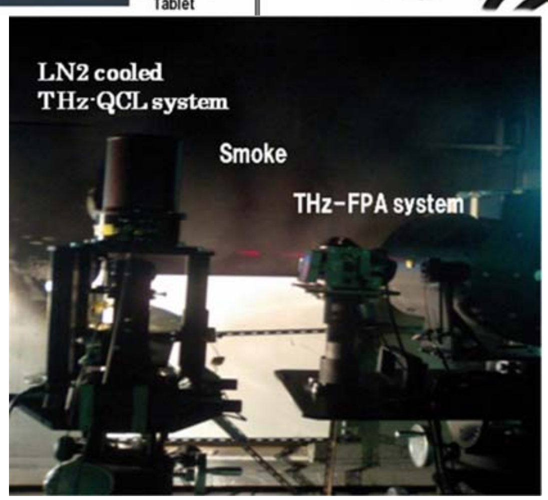

**Figure 15.2** Typical arrangement for pumping a far-infrared laser optically. (*Adapted from diagram by MPB Technologies, Inc.*)



## Terahertz Imaging:

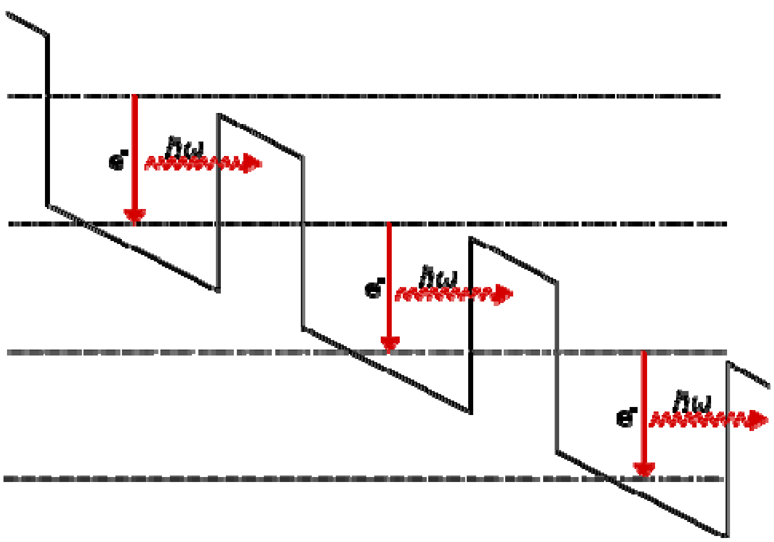
- Non Destructive Evaluation (NDE) for dielectric materials
- Passes through dielectrics: ceramics, organics and wood
- Security – detect hidden items for smuggling/screening
- Medical – can possibly detect cancers better than X-rays
- X-rays not see cancers directly - density cancer same as regular
- Only through calcium created around cancer
- Terahertz different tissues have different absorptions
- Similar for quality control – finding voids in ceramics/plastics
- Difficulty is detectors – best is cooled to 77$^{o}$K
- Fast electronics can see E field change rather than intensity

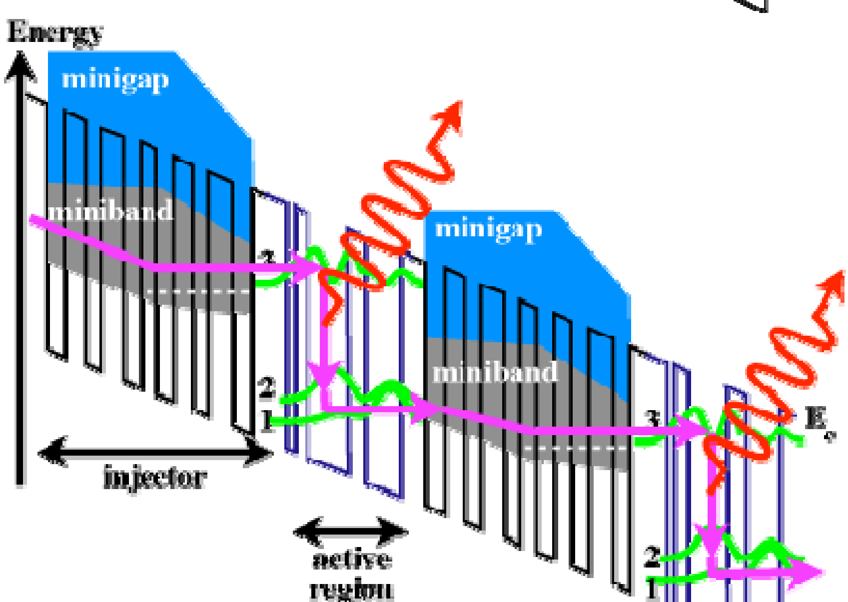


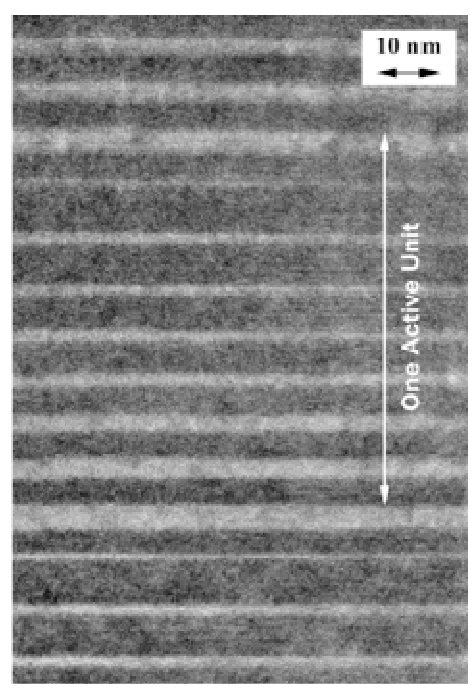



# Quantum Cascade Lasers

QCL are Mid to Far IR diode type lasers
InGaAs/InAlAs on InP substrates often used
Created at Bell Labs in 1994
Uses periodic quantum layers forming a superlattice
Creates a varying electric potential across device
Varies the probability of carriers occupying different locations
1D quantum well confinement
e’s to a inter-subband transition emitting photons
e then quantum tunnels to next sublattice periodic structure
Then emits another photon - hence quantum cascade

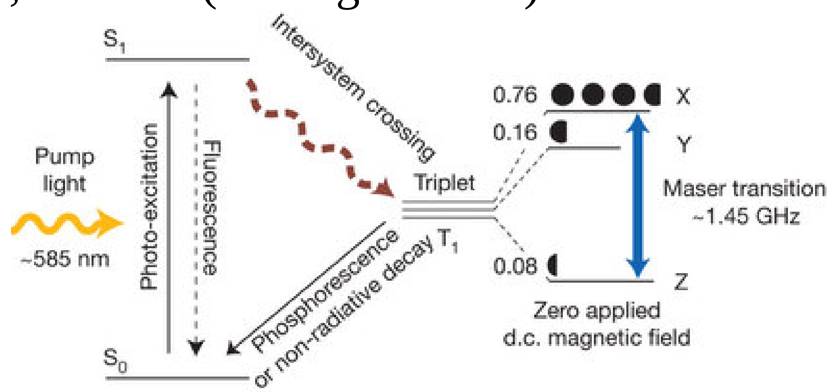


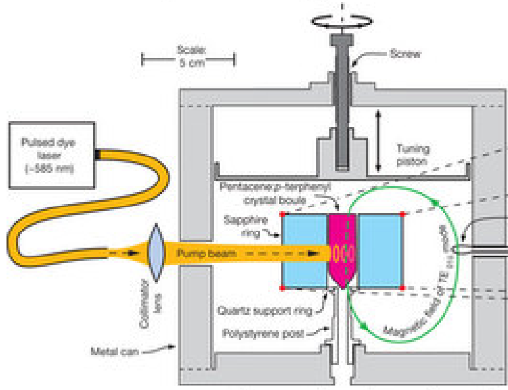


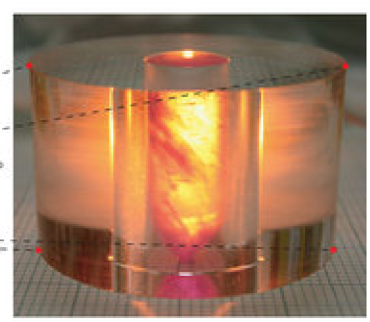



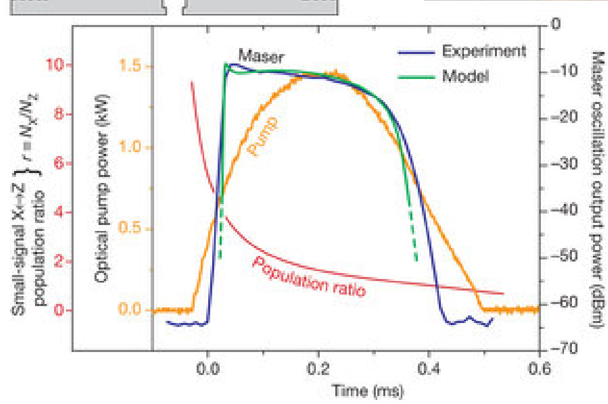
# New Room Temperature Maser

- Original maser required atomic sources, vacuum & magnets
- Solid state (ruby) ones cooled to near 10°K
- Good amplifier but not a beam source
- New solid state maser at room temperature on lab bench
- 585nm (yellow) pumped
- pentacene-doped p-terphenyl (organic crystal)
- Output 1.45 GHz ( 20.7 cm λ): pulsed not CW
- Uses Spin selectivity of triplet state in dopand
- Power -10 dB mW – $10^8$ times atomic maser power
- Oxborrow, Breeze, Alford Room-temperature solid-state maser
- Nature 488, 353–356(16 August 2012)





## Free Electron Laser (FEL)

- Proposed J. Mandey 1971
- Create a laser using high powered electron beams
  tunable over wide wavelength range
- High energy electrons emit bent by magnetic field
- Produce synchrotron radiation (light)
- No energy levels
- Free Electron Laser has array of magnets of alternating polarity
- Called wigglers
- Recall electrons in a magnetic field create circular motion
- Due to electromotive force interaction between moving e & B field

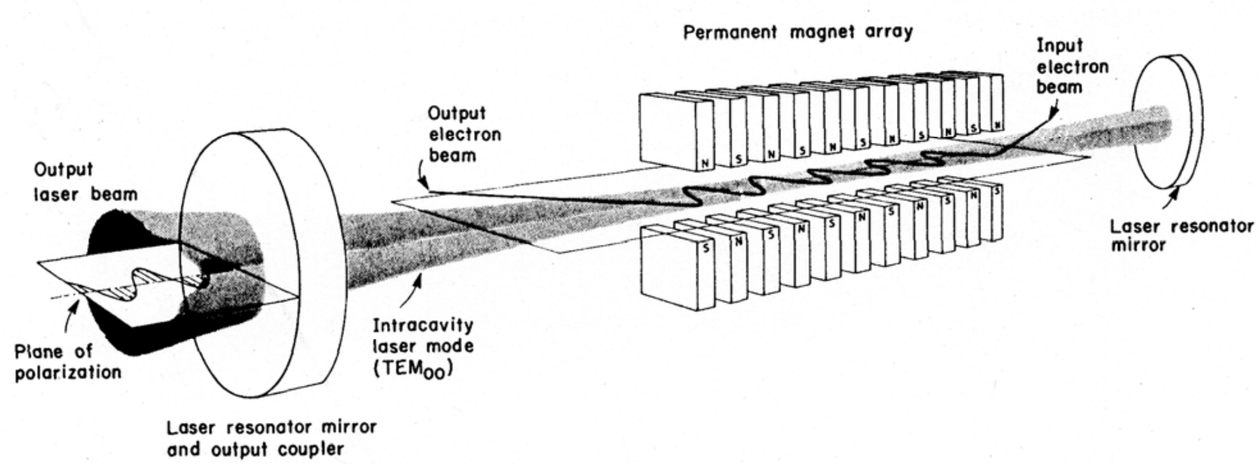
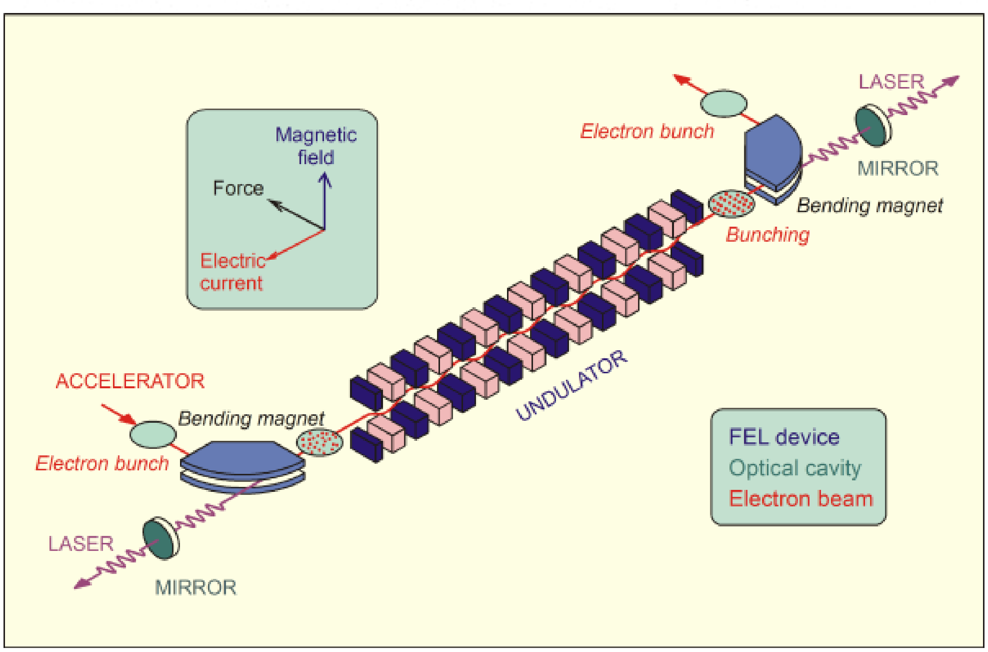



**Figure 28.1** Structure of a free-electron laser. (*Courtesy of University of California at Santa Barbara Quantum Institute.*)

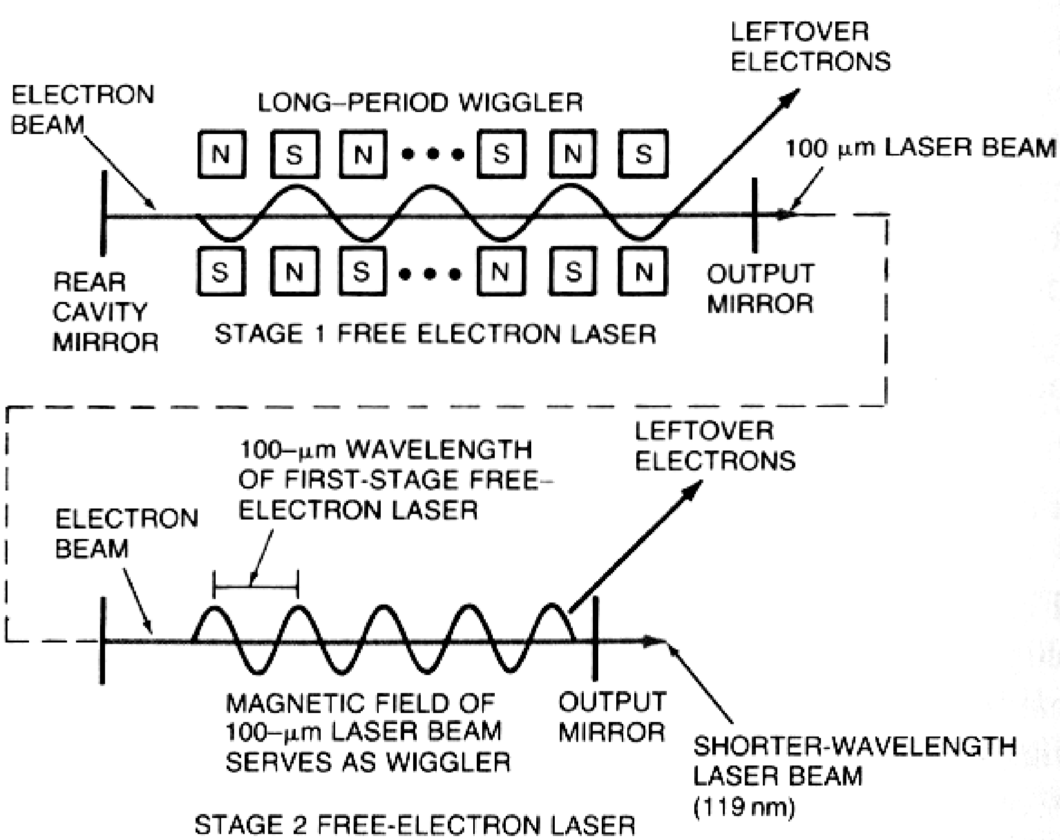


# Free Electron Laser

- Alternating Mag field cause e's path to wiggle (move back an forth) and collect e's into clumps
- Emit synchrotron radiation:
- Radiation create by charges moving in a near circular path
- Wavelength set by energy of e's & radius of curved path
- With line of wiggler magnet emit at same wavelength and in phase
- Emitted energy set e velocity & magnet period p

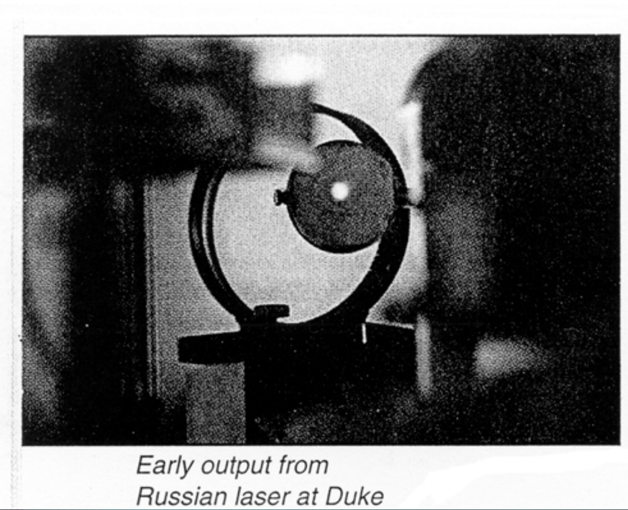
$$\lambda = \frac{p}{2\left[1 - \left(\frac{v^2}{c^2}\right)\right]}$$

- One example tunable from 120 to 800 microns wavelength
- 30% efficiency demonstrated
- Electrons 5 MeV so need an accelerator
- Heavily Supported by Strategic Defense Initiative/Star Wars
- Called Self Amplified Stimulated emission (SASE)

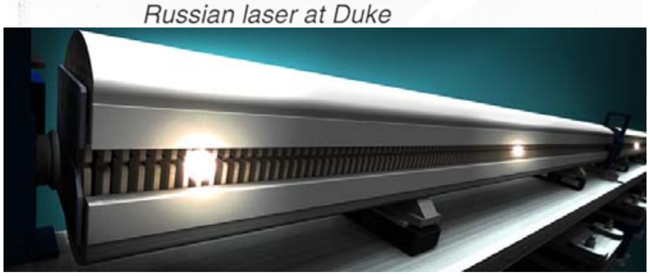


## Current Free Electron Lasers

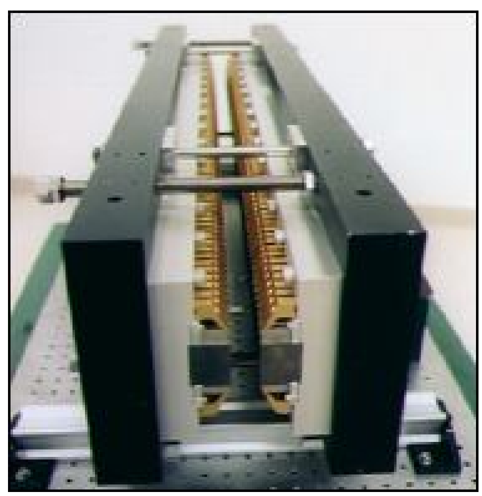
- Russian OK-4 first powerful FEL at Duke University ~ 1992
- Pumped by 1.2 GeV electron storage ring- needs huge accelerators
- Produced 240 nm UV emissions
- 2012 have X-ray lasers with diamond monchrometer
- Linac Coherent Light Source (LCLS) at Stanford
- European X-ray free electron laser (XFEL)Hamburg – 3.4Km long
- Univ of Nebraska XFEL 0.1 nm pulse of $10^{-15}$ sec




Johnson Labs – Harvard



XFEL U Nebraska



Wigglers in Hamberg FEL

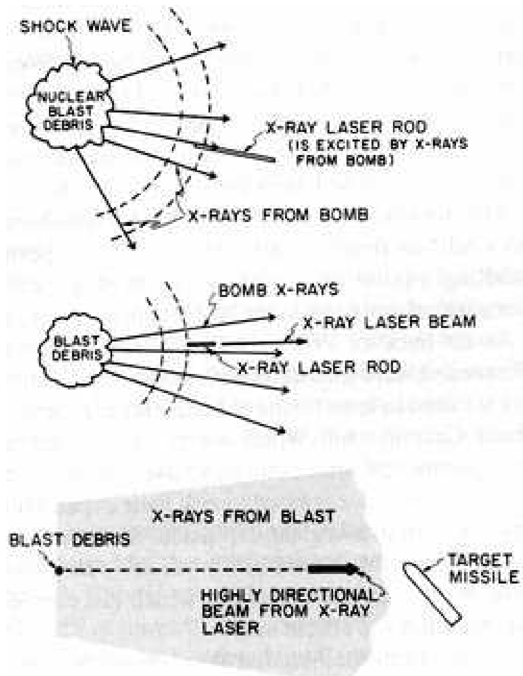
Linac Coherent Light Source: Stanford Linear Accelerator

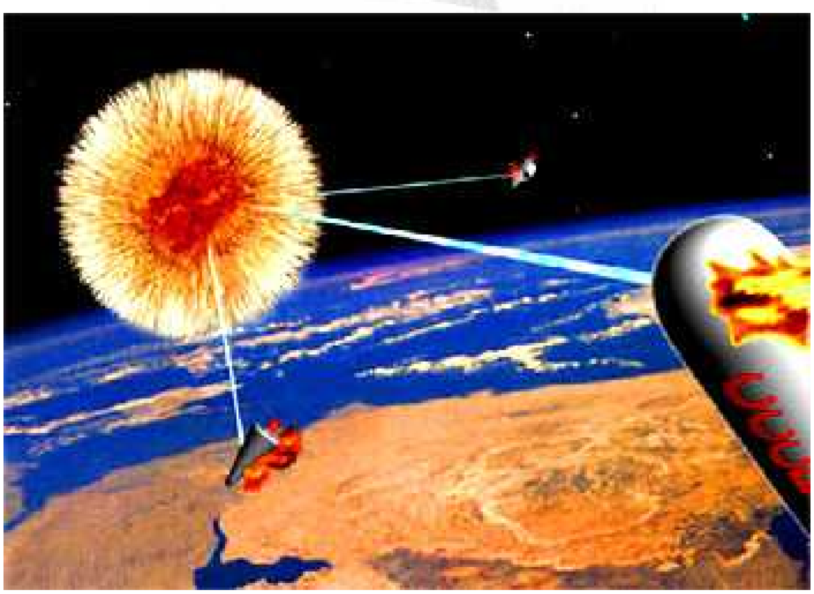
# X ray Lasers

- Use highly ionized materials
- Two basic types: radiation pumped & current pumped

**Bomb driven X-ray Lasers**

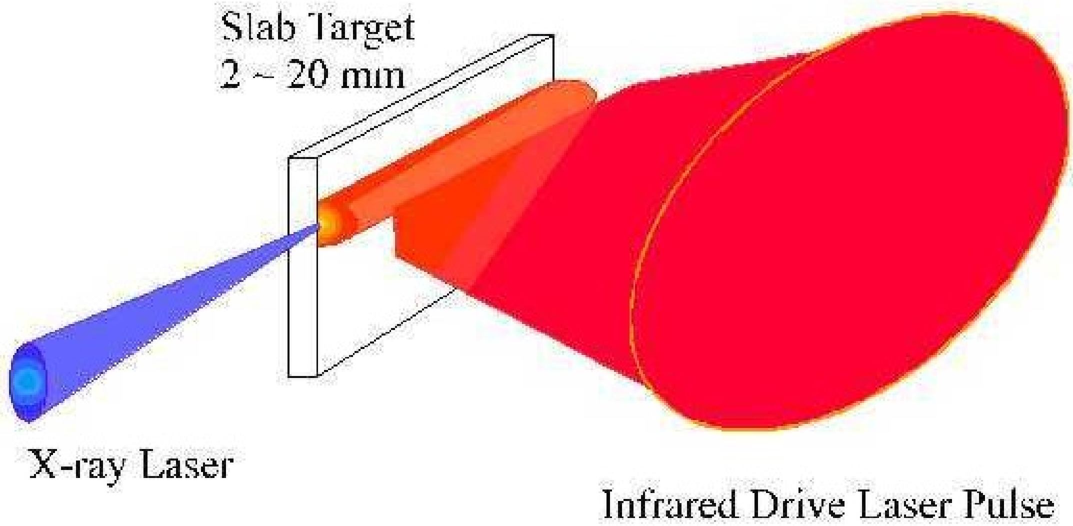
- Use atomic bomb to vaporize rods: form plasma
- Get a population inversion
- 1.4 nm wavelength reported
- Funded by Strategic Defense Initiative until late 1980's
- Done at Lawrence Livermore Labs



## Light Driven X-ray Lasers

- Done at Lawrence Livermore Labs laser fusion source
- Focus laser pulse on metal rod to create plasma
- Use 0.5 nsec pulse, with terawatt ($10^{12}$ W) power
- Selenium rod: $Se^{24}$ ion: 20.6 nm, 20.9 nm
- Shortest published $W^{46+}$ ion: 4.316 nm
- Interest in studying living cells (X-ray holograms)



# X-ray Lasers from Discharge

- Small capillary with Argon gas
- Excited by 40 KA, 60 nsec pulse
- Changes gas to Neon like
- 1 nsec pulse of 46.9 nm wavelength
- Colorado State university

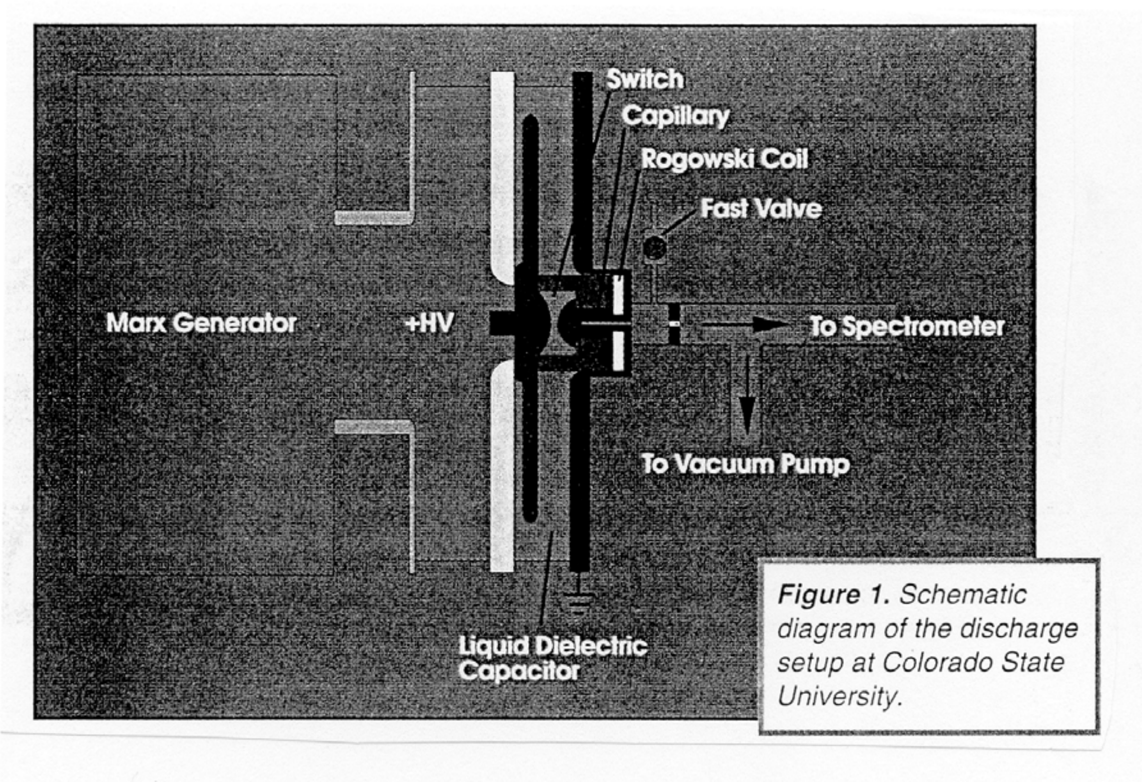



**Figure 1.** *Schematic diagram of the discharge setup at Colorado State University.*

# X-ray Laser Emission from Discharge

- As plasma length grows to 12 get X-ray laser

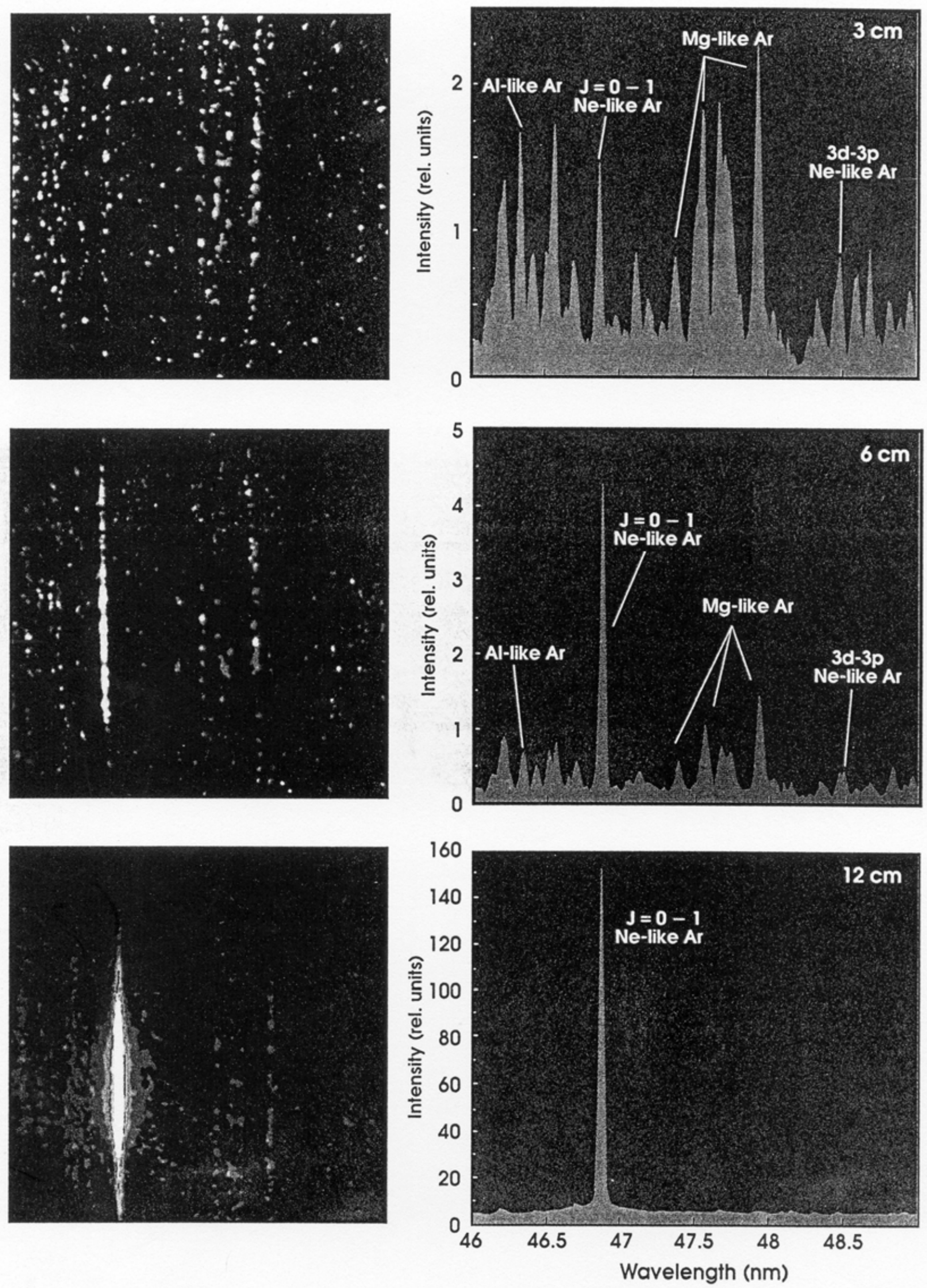



*Figure 2.* Variation of the intensity of the spectral lines in the neighborhood of 47 nm as a function of plasma column length in an argon capillary discharge. For a 3-cm-long plasma, the 46.9-nm laser line of neon-like argon is less intense than the surrounding plasma lines. In the 12-cm-long plasma, the laser line totally dominates the spectrum.

# Microchips and Photolithography

- Integrated Circuits (IC's) created using optical process
- Creation of three dimensional structures
  using photographic techniques

X Derived from creation of printing plates
X Usually start with thin film on wafer (eg $SiO_2$)
X Coat with photosensitive material (photoresist)
X Exposure: to UltraViolet Light through mask of structure
X Development of resist:
  leaves pattern of resist with openings
X Etching: removes film unprotected by resist
X Striping Resist: leave only patterned film

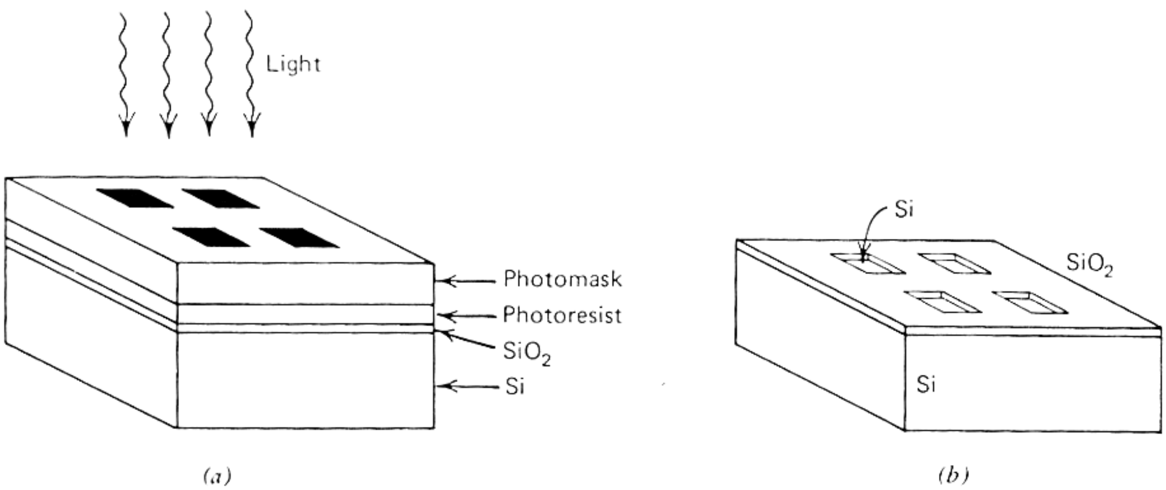
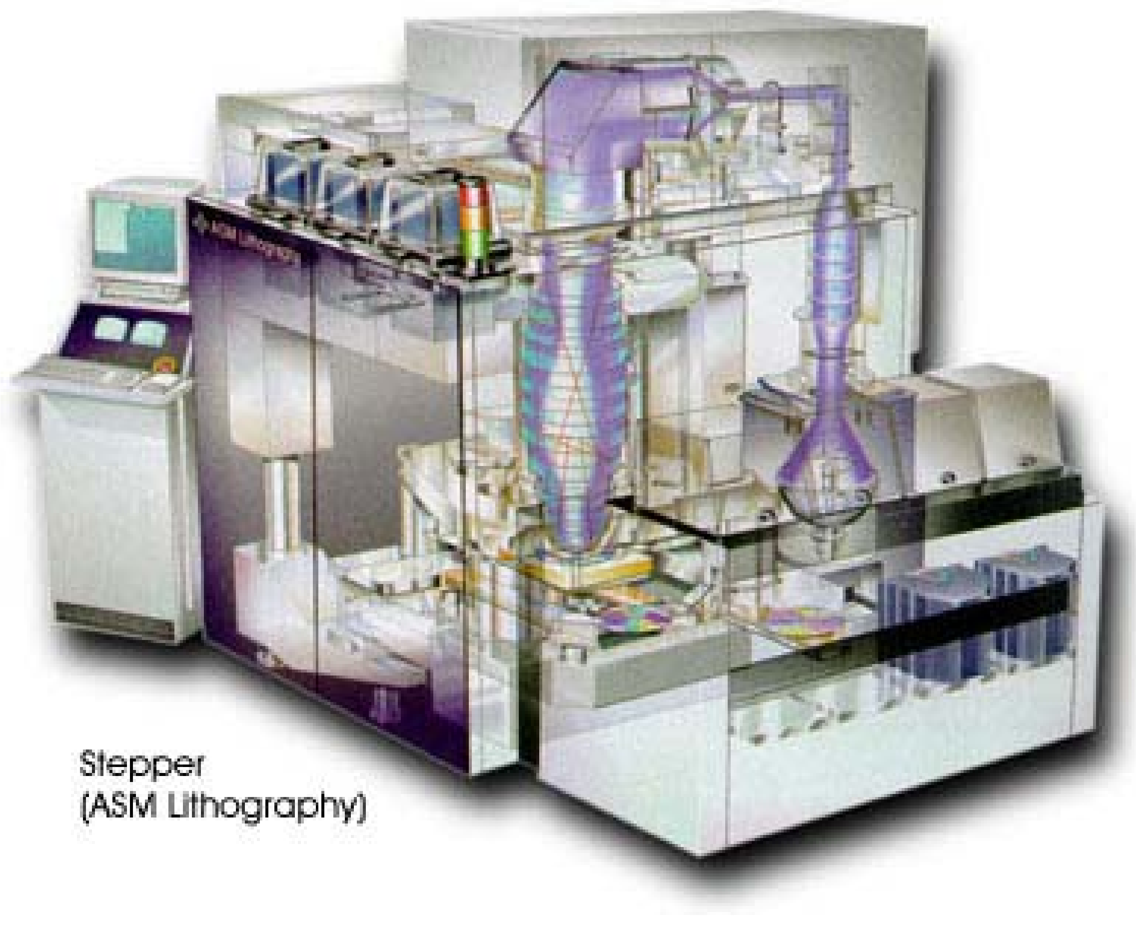



**Figure 2.11** The areas from which the oxide is to be etched are defined by polymerizing a light-sensitive resist through a photographic negative or mask.

## Microchips and Optical Steppers

- Current devices are created by optical projection
- Start with a mask (pattern on quartz) to create the circuit pattern
- Use a Direct Step on Wafer (DSW) or Steppers
- Creates image in photosensitive material called photoresist
- IC created by developing and etching that material
- Devices from 1 μm to now 35 nm
- Project one mask (reticule) print of circuit at a time
- Step to next chip site and repeat over wafer
- Reticules up to 3x3 cm now: may be one or several chips
- Table position uses laser interferometry for < 0.02 micron
- Lens most expensive ~$1M, full DSW ~$5-10M



# Wafer Projection Steppers Limits

- Lenses best every made: diffraction limited
- Important factor in lens is Numerical Aperature

$$NA = n \ \sin(\alpha)$$

- Typical NA 0.16 - 0.5 for steppers
- Smallest object projected set by

$$W_{\min} = k_1 \frac{\lambda}{NA}$$

- $k_1$ depends on resist and other factors ~0.7
- Typical limit is $\lambda/2$

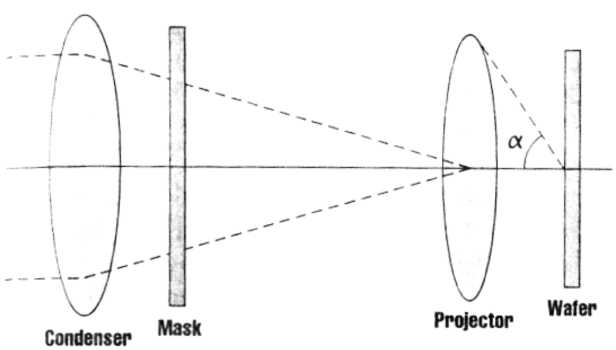
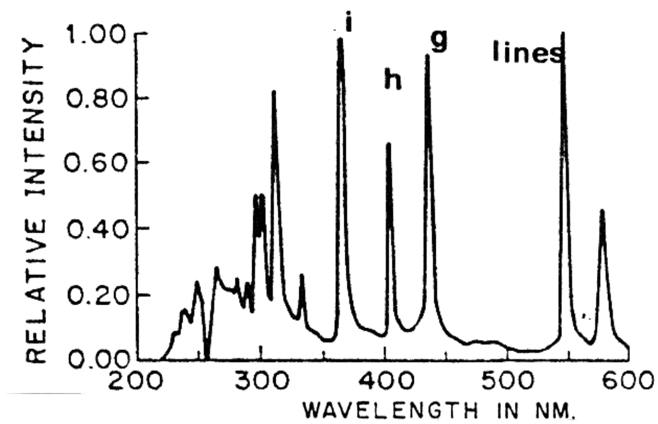
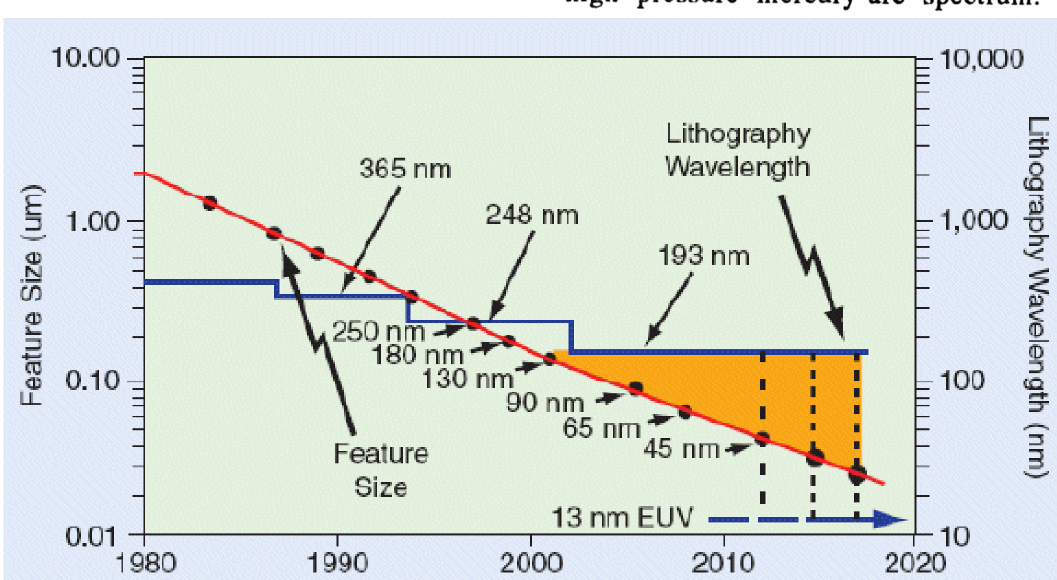



**Figure 7-17** Schematic for the optical train of a simple projection printer.




high pressure mercury-arc spectrum.



## Wavelength and Steppers

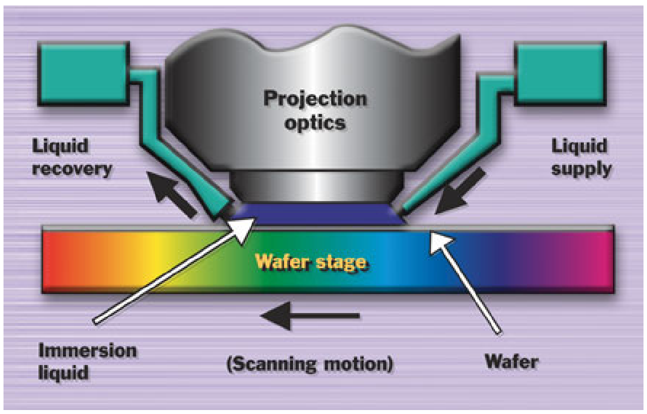
- First Steppers use Mercury Vapour lamp source
- Filters allow single line from source
- 1980: G line (439 nm ) steppers > 0.8 microns
- 1990: I line (365 nm) steppers > 0.3 microns
- Now Excimer laser sources
- ~1994 KrF (248 nm) > 90nm,
- ~2001 ArF (193 nm) down to 35 nm
- Old idea suddenly revived: **Immersion Lithography**
- Immerse lens & wafer in a high index fluid (DI water)
- Effective reduces wavelength of light by n (index of refraction)

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

- Use modified 193 nm steppers: same ArF Excimer & lens
- Now get 133 nm effective source ($n_{water} = 1.44$)
- Effectively increases Numerical Aperature

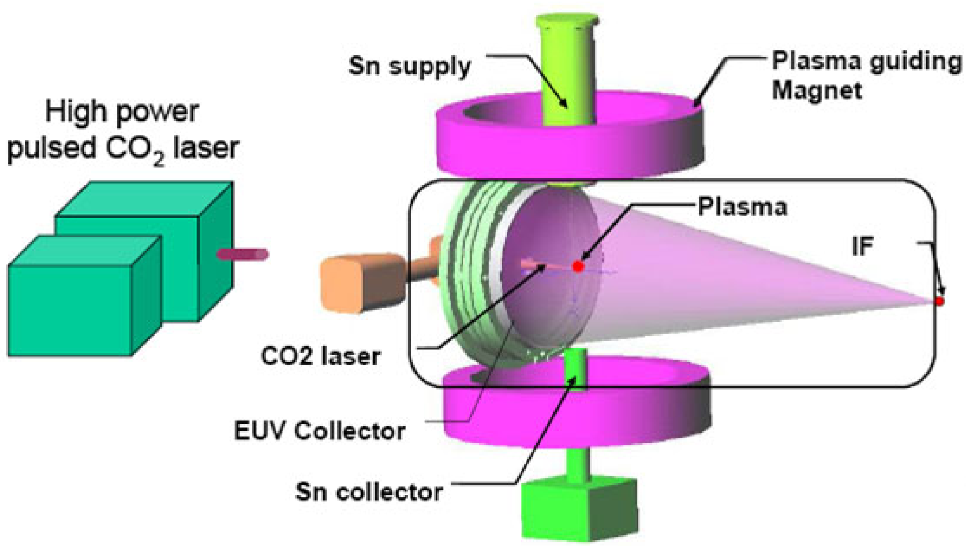
$$NA = n \sin(\alpha)$$

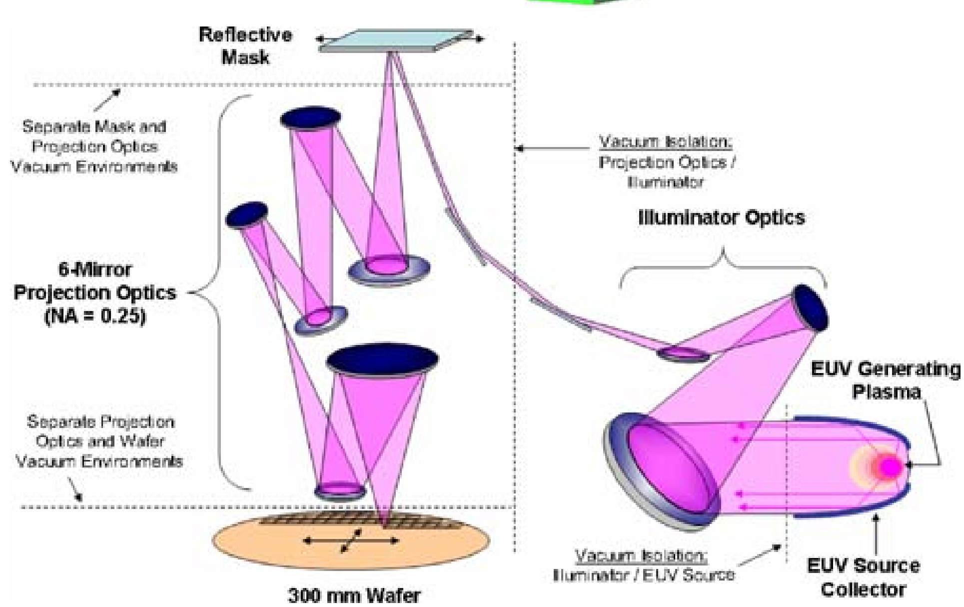
- Problem: lens material limits at short wavelength
- Can produce 0.045 micron devices with these



# Extreme UV Lithography (EUV)

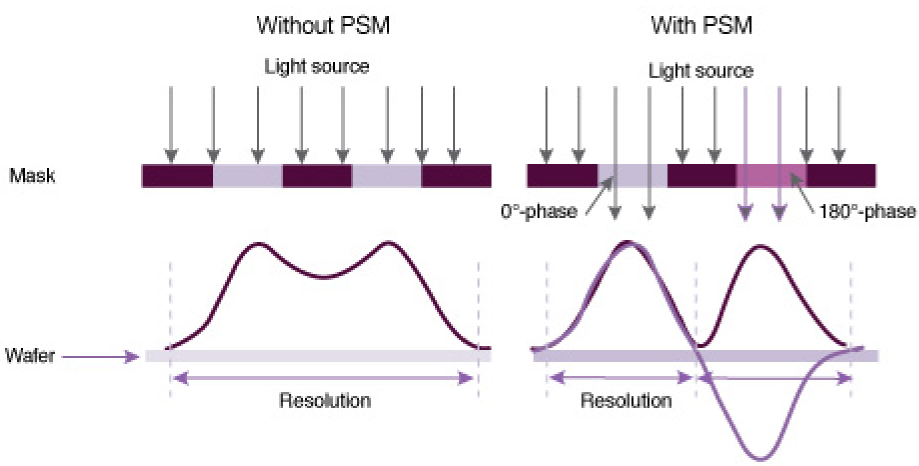
- Next Generation Lithography Extreme UV 13.5 nm
- Under development at Lawrence Livermore Lab since 2000
- Uses Laser Produced Plasma Source (LPS)
- Uses Nd:Yag or $CO_2$ laser focused on copper wire or Xeon gas
- Creates a plasma with 13.4 nm EUV emission
- Near X-ray but acts like light (not too penetrating)
- Must use grazing mirror reflectors for optics in 10X stepper
- Probably will exceed the ultimate transistor limits.
- Problem as of 2014 trouble getting the system to work well
- Not certain if EUV will get to 10 nm devices
- Transistor operation limit in 5-10 nm range

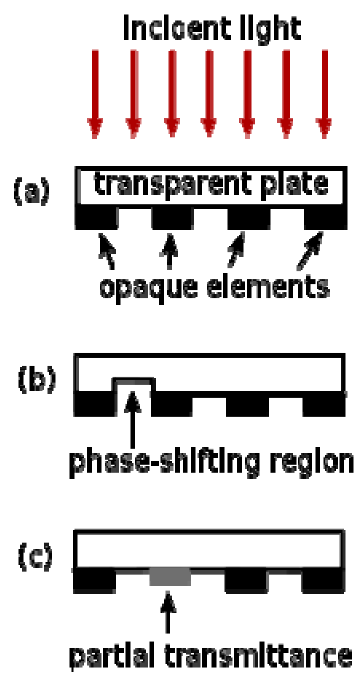


# Phase Shift Mask

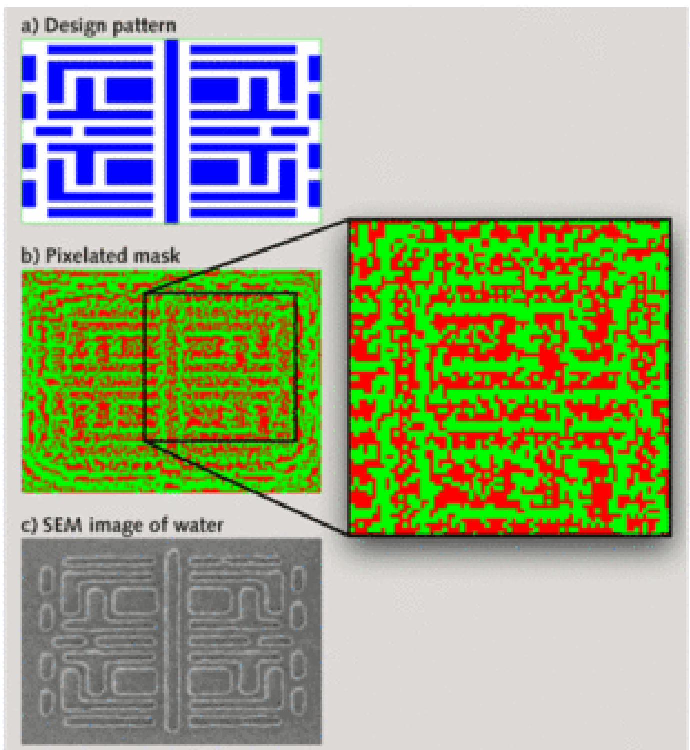
- Regular optical limits is ~λ/2 so 70 nm for immersion
- But what if change masks: add a layer that phase sifts the light
- If invert the phase of light then can make line < diffraction limit
- Get about ~λ/4 or 35 nm structures
- Create phase shift by etching mask glass
- Alternative adding semitransparent



# Computational Lithography

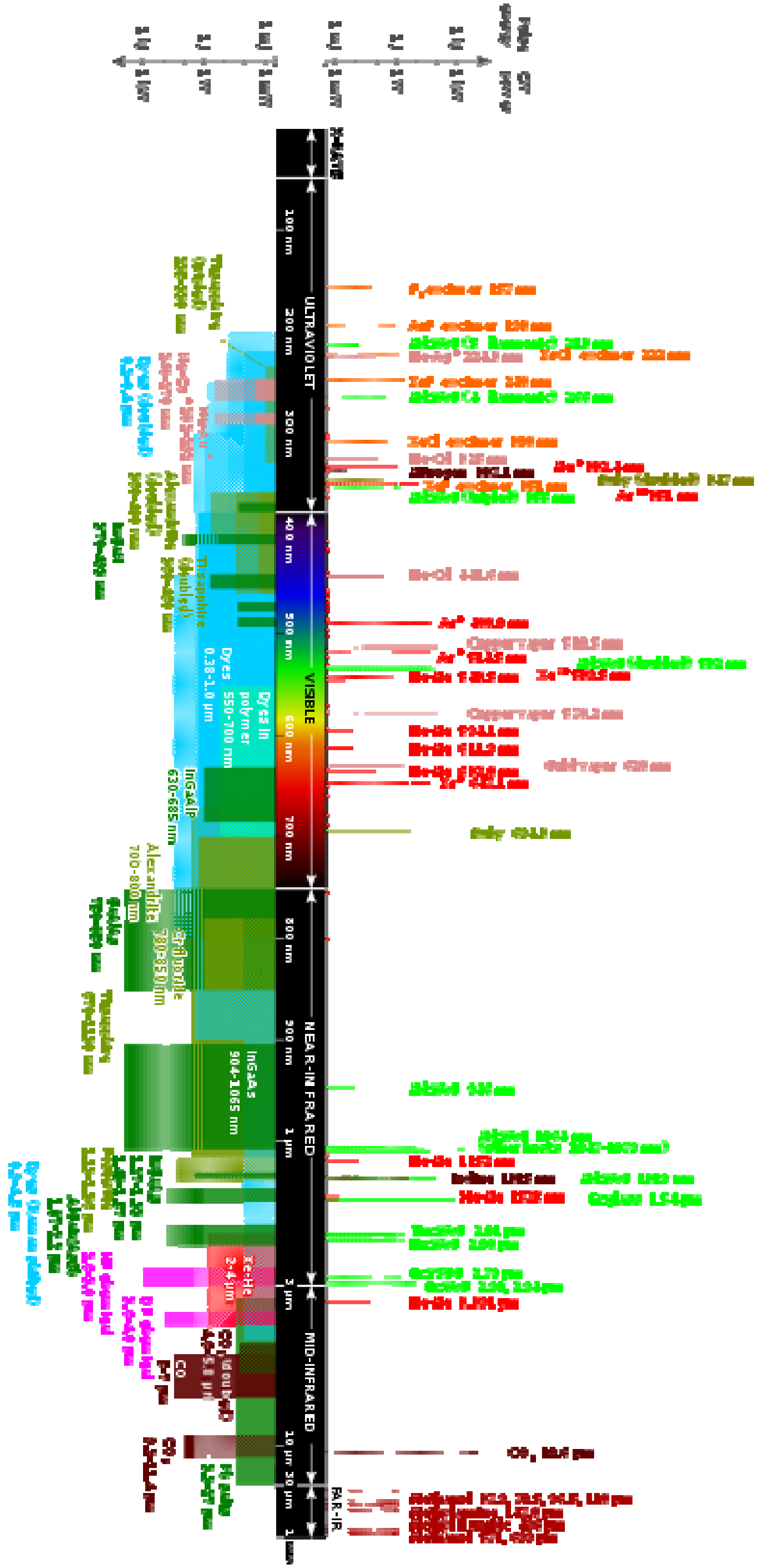
- Failure to get shorter wavelengths than 195 immersion
- To reduce more from Phase shift use Computational Lithography
- Phase shift at limit creates distorted structure
- Instead design the optical pattern you want on the wafer
- Now compute using Emag wave pattern back through stepper
- Find the mask patter to create structure want in resist
- Very compute intensive operation – only on smallest structures
- With this get 20-25 nm structures
- Pushing to get to 15 nm




A portion of the 65nm metal 1 design (a) is converted to a pixelated phase mask design (b), where red represents 180° phase shift pits and green represents 0°, and projected by the stepper forming the resist image in (c).

WaferNews source: Intel Corp.

# Chart of Lasers & Ranges



# Summary of Laser Ranges

Appendix

# Types of Laser

**Commercial Laser Types, Organized by Wavelength**

| Wavelength, μm | Type | Chapter | Output type and power |
|---|---|---|---|
| 0.152 | Molecular fluorine ($F_2$) | 13 | Pulsed, to a few watts average |
| 0.192 | ArF excimer | 13 | Pulsed, to tens of watts average |
| 0.2–0.35 | Doubled dye | 17 | Pulsed |
| 0.222 | KrCl excimer | 13 | Pulsed, to a few watts average |
| 0.235–0.3 | Tripled Ti-sapphire | 24 | Pulsed |
| 0.248 | KrF excimer | 13 | Pulsed, to over 100 W average |
| 0.266 | Quadrupled Nd | 22 | Pulsed, watts |
| 0.275–0.306 | Argon ion | 8 | Continuous-wave (CW), 1-W range |
| 0.308 | XeCl excimer | 13 | Pulsed, to tens of watts |
| 0.32–1.0 | Pulsed dye | 17 | Pulsed, to tens of watts |
| 0.325 | He–Cd | 9 | CW, to tens of milliwatts |
| 0.33–0.36 | Ar or Kr ion | 8 | CW, to several watts |
| 0.33–0.38 | Neon | 8 | CW, 1-W range |
| 0.337 | Nitrogen | 14 | Pulsed, under 1 W average |
| 0.347 | Doubled ruby | 23 | Pulsed, under 1 W average |
| 0.35–0.47 | Doubled Ti-sapphire | 24 | Pulsed |
| 0.351 | XeF excimer | 13 | Pulsed, to tens of watts |
| 0.355 | Tripled Nd | 22 | Pulsed, to tens of watts |
| 0.36–0.4 | Doubled alexandrite | 24 | Pulsed, watts |
| 0.37–1.0 | CW dye | 17 | CW, to a few watts |
| 0.442 | He–Cd | 9 | CW, to over 0.1 W |
| 0.45–0.52 | Ar ion | 8 | CW, to tens of watts |
| 0.48–0.54 | Xenon ion | 16 | Pulsed, low average power |
| 0.51 | Copper vapor | 12 | Pulsed, tens of watts |
| 0.523 | Doubled Nd–YLF | 22 | Pulsed, watts |
| 0.532 | Doubled Nd–YAG | 22 | Pulsed to 50 W or CW to watts |
| 0.534, 0.538 | He–Cd | 9 | CW, milliwatts, in white-light laser |
| 0.5435 | He–Ne | 7 | CW, 1-mW range |
| 0.578 | Copper vapor | 12 | Pulsed, tens of watts |
| 0.594 | He–Ne | 7 | CW, to several milliwatts |

# Summary of Laser Ranges



**Commercial Laser Types, Organized by Wavelength** (*Continued*)

| Wavelength, μm | Type | Chapter | Output type and power |
|---|---|---|---|
| 0.612 | He–Ne | 7 | CW, to several milliwatts |
| 0.628 | Gold vapor | 12 | Pulsed |
| 0.6328 | He–Ne | 7 | CW, to about 50 mW |
| 0.635–0.66 | InGaAlP diode | 19 | CW, milliwatts |
| 0.636 | He–Cd | 9 | CW, milliwatts, in white-light laser |
| 0.647 | Krypton ion | 8 | CW, to several watts |
| 0.67 | GaInP diode | 19 | CW, over 10 mW |
| 0.68–1.13 | Ti-sapphire | 24 | CW, watts |
| 0.694 | Ruby | 23 | Pulsed, to a few watts |
| 0.72–0.8 | Alexandrite | 24 | Pulsed, to tens of watts (CW in lab.) |
| 0.73 | He–Ne | 7 | CW, 1-mW range |
| 0.75–0.9 | GaAlAs diode | 19 | CW, to many watts in arrays |
| 0.98 | InGaAs diode | 19 | CW, to 50 mW |
| 1.047 or 1.053 | Nd–YLF | 22 | CW or pulsed, to tens of watts |
| 1.061 | Nd-glass | 22 | Pulsed, to 100 W |
| 1.064 | Nd–YAG | 22 | CW or pulsed, to kilowatts |
| 1.15 | He–Ne | 7 | CW, milliwatts |
| 1.2–1.6 | InGaAsP diode | 20 | CW, to 100 mW |
| 1.3–1.4 | Overtone HF | 11 | CW or pulsed, to tens of watts |
| 1.313 | Nd–YLF | 22 | CW or pulsed, to 0.1 W |
| 1.315 | Iodine | 16 | Pulsed, to several watts average |
| 1.32 | Nd–YAG | 22 | Pulsed or CW, to a few watts |
| 1.4–1.6 | Color center | 25 | CW, under 1 W |
| 1.523 | He–Ne | 7 | CW, milliwatts |
| 1.54 | Erbium-glass (bulk) | 27 | Pulsed, to 1 W |
| 1.54 | Erbium-fiber (amplifier) | 26 | CW, milliwatts |
| 1.75–2.5 | Cobalt-$MgF_2$ | 24 | Pulsed, 1-W range |
| 2–4 | Xe–He | 16 | CW, milliwatts |
| 2.1 | Holmium | 27 | Pulsed, watts |
| 2.3–3.3 | Color center | 25 | CW, under 1 W |
| 2.6–3.0 | HF chemical | 11 | CW or pulsed, to hundreds of watts |
| 2.94 | Erbium-YAG | 27 | Pulsed, to tens of watts |
| 3.3–29 | Lead salt diode | 21 | CW, milliwatt range |
| 3.39 | He–Ne | 7 | CW, to tens of milliwatts |
| 3.6–4.0 | DF chemical | 11 | CW or pulsed, to hundreds of watts |
| 5–6 | Carbon monoxide | 16 | CW, to tens of watts |
| 9–11 | Carbon dioxide | 10 | CW or pulsed, to tens of kilowatts |
| 10–11 | Nitrous oxide ($N_2O$) | 16 | CW |
| 40–1000 | Far-infrared gas | 15 | CW, generally under 1 W |