Summary

- Brief History & Evolution of Laser
- High Power Thermal Lasers
- Modelling Laser/Material Interactions
- High Power Thermal Lasers
- High Power Micro Machining
Brief History and Evolution of Lasers

- 1917 - Albert Einstein developed the concept of stimulated emission, which is the phenomenon used in lasers
- In 1954 the maser was the first device to use stimulated emission (Townes & Schawlow). Microwave amplification by stimulated emission of radiation
Brief History of Lasers

- In 1958 Townes & Schawlow suggested that stimulated emission could be used in the infrared and optical portions of the spectrum.
- The device was originally termed the optical maser.
- This term was dropped in favour of LASER. Standing for Light Amplification by Stimulated Emission of Radiation.

Charles Townes & Jim Gordon at Columbia University in 1954 with their second working MASER.
1\textsuperscript{st} Laser - Ted Maiman 15th May 1960 - working alone and against the wishes of his boss at Hughes Research Laboratories

Electrical Engineer
Maiman’s Ruby Laser - 694.3 nm

New York Times
8th July 1960,
Wrong Ruby Crystal is shown here. The journalist didn’t like the actual stubby crystal. This crystal was used later.

Synthetic pale pink ruby crystal Al₂O₃ containing about 0.05% by weight of Cr₂O₃
Bell Labs & the Laser

1960 Ali Javan, William Bennet, Donald Herriot - HeNe Laser - 1st CW Laser - 1.15 μm

1961 Boyle & Nelson - Continuously operating Ruby Laser

1962 Kumar Patel (front), Faust, McFarlane, Bennet (left to right) - 5 Noble gas lasers and lasers using oxygen mixtures
Bell Labs & the Laser

1964 C. K. N. Patel - High Power Carbon Dioxide Laser - 10.6μm

1964: First Nd:YAG laser 1.06μm (uses neodymium doped yttrium aluminium garnet crystals) by J. F. Geusic and R. G. Smith

1971 Izuo Hayashsi & Morton Panish - first semiconductor laser that operated continuously at room temperature
A Beam Focusing Lens and an Assist Gas Nozzle is required for all but the Excimer Laser.
Dry Laser Etching Ablates Material by Bond Breaking

Chrome on Quartz Mask

Lambda Physik LPX 201i, 125W mean power, 2.5J/pulse, 100 Hz prf, 10 to 50 ns pulse width
Evolution of Industrial Lasers
High Power Materials Processing Lasers

- Carbon Dioxide - up to 100kW more usually 2 to 7kW - 10.6μm
- Carbon Monoxide - not generally available, up to 5kW - 5 to 6μm
- Nd-YAG - up to 4.5kW - 1.06μm
- UV - Argon Ion 2W, HeCd, Tripled YAG 5W
- Diode Lasers 2 kW
High Power Micro-machining Lasers

- Copper Vapour Lasers 511 & 578 nm, 20-30 ns pulses, 2-20 kHz, 50 to 500 kW peak power
- Excimer - pulsed mean power 1 kW – UV – 157 nm, 193 nm, 248 nm, 308 nm, 351 nm, 1000 Hz, 1 kW
- Nd-YVO4 – 355 nm Neodymium Vanadate 38 ns pulses, 10 kHz, 6 W mean
- Ti:Sapphire – 850 nm, 250 kHz, 100 fs pulses, 300 kW,
Our Contribution to the Evolution of CO$_2$ Lasers

- Pulsed lasers give a sharper, hotter knife
- Narrower focus
- It gives greater process control
- High instantaneous power allows processing of highly reflective metals like aluminium
Prototype system that could run for a few seconds

In order to run continuously the first prototype required a transverse gas flow
Computer Simulation was extremely important in establishing the Laser design specification.

Energy level diagram of a Carbon Dioxide Laser

Predicted Laser Output

Optical resonator design
Output coupling
Electrical pulse shaping
Injection of radiation for pulse shape control
Gas mixture
Second Prototype with Transverse Gas Flow

System CAD Model

Maximum flow rate - 15,000 m³/hr
Maximum laser cavity velocity @ 200 Torr - 104 m/s
Cooling capacity 120kW
Laser cavity length 1 metre, Area - 0.04 m²
Laser Pulsed Power Supply

PRF continuously variable up to - 10 kHz
Peak PFN voltage - 20kV
Maximum pulse duration - 10 μs
Maximum pulse energy - 10 J
Peak pulse voltage - 10 kV
Maximum pulse power - 1 MW
Laser Output Pulse

Typical output pulse

CW laser cutting 1.25 mm thick steel. Mean power 300 W

Pulsed laser cutting

Operated at 5 kHz, Mean power 2 kW, Pulse power 65 kW

To get to 10 kHz at 5 kW the Trigger Wire Pre-ionisation scheme needed to be replaced with Electron Beam Pre-ionisation. This would give 100 kW pulses

Typical Glow Discharge

Anode

Cathode
3.5kW Diffusion Cooled CO$_2$
Laser - CW or 5kHz pulsed

1. Laserbeam
2. Beam shaping unit
3. Output mirror
4. Cooling water
5. RF excitation
6. Cooling water
7. Rear mirror
8. RF excited discharge
9. Waveguiding electrodes

Courtesy of Rofin
Flash Lamp Pumped 2.7kW cw or Pulsed (500 Hz) Nd-YAG Laser

1. Laser beam
2. Output mirror
3. Nd:YAG rod
4. Excitation lamps
5. Reflector
6. Rear mirror
7. Focusing unit
8. Fibre - 600 microns
9. In-coupling unit
10. Beam bending mirrors

Courtesy of Rofin
4.4 kW cw Diode Pumped Nd-YAG Laser

1. Nd:YAG rod
2. Laserbeam
3. Output coupler
4. Diode arrays
5. Collimating optic
6. High-reflectance mirror
7. Cooling
8. Electrical supply
9. 300 micron fibre
Long Pulse Interaction
Nd: Glass Laser Interactions
Nd: Glass Laser Interactions
Streak Photographs of Laser Drilling with an Nd:Glass Laser
Schematic illustrating electron movement inside metals
Electron kinematics

- We need to evaluate the number of electrons which leave element ‘dɛ’ after colliding there.
- Then suffer their next collision in a volume element ‘dV’ a distance ‘s’ away in time ‘dt’.
- The solid conical element subtends an angle ‘ω’ with the ‘x’ axis.
Electron kinematics

- We need to take account of electrons coming from the right of ‘dV’ and electrons that are reflected from the surface and travel along the path BAC.
- To achieve this we can use a mirror image method as shown in the following figure.
Schematic illustrating electron movement inside metals using a mirror image method.
Electrons transported into dV

- Using the mirror image method we must determine the energy transported into ‘dV’ from all electrons in ‘dε’ at ‘ε’

\[ n_{\varepsilon V} = \frac{N' \ z.r \ d\omega \ e^{(-s/\lambda)} \ d\varepsilon \ dV}{2s \ \lambda \ cos \ \omega} \quad (1) \]

- \( N' \) = number of Fermi surface electrons; \( \lambda \) = electron-phonon mean free path; \( z \) = collision frequency in dV; \( v \) = Fermi electron velocity; \( z = v / \lambda \)

- Hence to evaluate the number of electrons arriving in dV which come from dε we must integrate over ‘‘-∞ < ε < ∞’’ and ‘0 < ω < π/2’
The energy carried into the volume $dV$ in time $dt$ by electrons depends upon the specific time at which the electron free path was generated. There are two groups:

i. Those travelling a distance $s < vdt$. Electrons generated within the time interval $dt$ will arrive in $dV$ during the same time interval.

ii. Those travelling a distance $s \geq vdt$. These electrons must be generated in the previous time intervals if they are to arrive in $dV$ during the current $dt$. 
Energy Transported by Electrons into dV

- Therefore the average energy $E$ stored in the electron at $\varepsilon$ is:

$$E = E(\varepsilon, t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial E(\varepsilon, t)}{\partial t}$$

(2)
Schematic to show the photon absorption process from $\varepsilon$ to $x$
Photon Absorption

- Ignoring quantum effects, free electrons are assumed to acquire the laser energy by merely passing through the electromagnetic field of the incident beam.

- The field is described by Lambert's law:

\[ I(x,t) = I_0(1 - R(t))e^{-\delta x} \]  

- \( I(x,t) \) is the beam intensity at time \( t \) after propagating distance \( x \) in the material. \( I_0(t) \) is the intensity at the surface. \( R(t) \) is the reflection coefficient and \( \delta \) is the absorption coefficient.
Photon absorption by electrons

- Considering the small element $dp$; the power absorbed per unit area by electrons at time $t$ is:

$$I_0(t)(1 - R(t))\delta e^{-\delta p} dp$$  \hspace{1cm} (4)

- The energy absorbed per electron is:

$$\frac{I_0(t)(1 - R(t))\delta e^{-\delta p} dp \Delta t}{N'}$$  \hspace{1cm} (5)

- Where $\Delta t$ is the average time an electron stays in the element $dp$; $\Delta t = \frac{dp}{vcos\omega}$  \hspace{1cm} (6)
Photon absorption by electrons

- It can be assumed that $I_0(t)$ and $R(t)$ are constants in the time required for the electrons to move from $\varepsilon$ to $x$.

- Hence, substituting for $\Delta t$ and integrating. The energy absorbed per electron in moving from $\varepsilon$ to $x$ is:

$$\frac{I_0(1-R)\delta}{N'v\cos \omega} | \int_{\varepsilon}^{x} e^{-\delta p} dp |$$

(7)
Average energy of arriving electrons

- From (2) and (7) the average energy of an electron entering $dV$ at $x$ from $\varepsilon$ after $dt$ is:

\[
E(\varepsilon, t) + \frac{1}{2} \left\{ dt - \frac{2 |s|}{v} \right\} \frac{\partial E(\varepsilon, t)}{\partial t} + \frac{I_0 (1 - R) \delta}{N' v \cos \omega} \int_{\varepsilon}^{x} e^{(-\delta p)} dp \quad (8)
\]

- If $E_p(x, t)$ is the average energy of phonons in $dV$ at $x$, the energy given up by electrons to the phonons on collision is:

\[
f \{ E(x, t+dt) - E_p(x, t) \} \quad (9)
\]

Where $f$ is the fraction of the energy difference between an electron and a phonon given up by an electron on collision with a phonon.
The rate at which electrons loose energy to phonons in elastic collisions

- The fraction $f$ of the average energy difference between electrons and the lattice in any given volume is:

$$f(x, t) = \frac{8m}{3M} \left\{ 1 - \frac{T(x, t)}{T_e(x, t)} \right\}$$

- Where $m$ and $M$ are the masses of the electrons and lattice atoms respectively, $T_e(x, t)$ and $T(x, t)$ are their temperatures at time $t$ and distance $x$. 
Energy of the Lattice Phonons

- The total energy transferred to the lattice from all electrons colliding in $dV$ at $x$ over the time interval $dt$ is equal to the energy increase of the lattice, where $n(x,t)$ is the number density of atoms:

$$\frac{\partial nE_p(x,t)}{\partial t} dV = dV \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ \frac{N' v}{2\lambda} e^{(-|x-\epsilon|/\lambda \cos \omega)} \frac{\sin \omega}{\lambda \cos \omega} \right\}$$

$$\times (f) \times \{ E(\epsilon,t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial E(\epsilon,t)}{\partial t} + \frac{I_0 (1-R) \delta}{N' v \cos \omega} \int_{\epsilon}^{x} e^{(-\phi)} dp \mid -E_p(x,t) \} \ d\omega d\epsilon \quad (10)$$
Energy of the Electrons

- The average energy change of electrons at $x$ equals the energy left in the electrons after collision less the energy carried away by electrons leaving the elemental volume $dV$ during $dt$.

\[
\frac{\partial N'E(x,t)}{\partial t} dV = \int_{-\pi/2}^{\pi/2} \int_0^{\infty} \left\{ \frac{N'v}{2\lambda} e^{-|x-\delta|/\lambda \cos \omega} \frac{\sin \omega}{\lambda \cos \omega} \right\} \times \left\{ E(\varepsilon,t) + \frac{1}{2} \left( \frac{dt}{\nu} - \frac{2|s|}{\nu} \right) \frac{\partial E(\varepsilon,t)}{\partial t} + \frac{I_0(1-R)\delta}{N'v \cos \omega} \left[ \int_0^{\delta} e^{-\Delta \nu} d\nu \right] \right\} d\omega d\varepsilon
\]

\[
- dV \frac{\partial nE_p(x,t)}{\partial t} - dV \frac{N'v}{\lambda} E(x,t) \quad (11)
\]
Continuity equation for electrons

\[
\frac{\partial N'(x,t)}{\partial t} = \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ \frac{N'v}{2\lambda^2} e^{-\frac{|x-\varepsilon|}{\lambda\cos\omega}} \frac{\sin\omega}{\cos\omega} \right\} d\omega d\varepsilon - \frac{N'v}{\lambda} \tag{12}
\]

Assuming that the electron gas is in a state of equilibrium, the participating electrons can be obtained from the ordinary Fermi distribution function:

\[
N' = \frac{NT_e \pi^2}{2T_F} \tag{13}
\]

where \( T_F \) is the Fermi temperature, \( T_e \) is the electron temperature, \( N \) is the number density of valency electrons.
Thermal Properties

- The thermal conductivity ($K$) of the material can be shown to be:

$$K = \frac{N' \nu \lambda k}{3} \quad (14)$$

- The heat capacity is:

$$\rho \ C_p = 3nk \quad (15)$$

- Where $k$ is the Boltzmann constant, $\rho$ is the material density, $C_p$ is the specific heat and $n$ is the phonon atoms number density.
Expressing the equations in terms of electron and phonon temperature - Lattice

- Using equations (13), (14) and (15) in (10), (11) and (12)

\[
\frac{\partial}{\partial t} \left[ \rho C_p T \right] =
\]

\[
f \int_{-\infty}^{\infty} \int_{0}^{\frac{\pi}{2}} \left\{ e^{\left(-|\varepsilon-\psi|/\lambda \omega \cos \omega \right)} \frac{\sin \omega}{\cos \omega} \right\} \times \left\{ T_e (\varepsilon,t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial T_e (\varepsilon,t)}{\partial t} - T(x,t) \right\} d\omega d\varepsilon
\]

\[
+ f \frac{I_0 (1 - R) \delta}{2 \lambda^2} \int_{-\infty}^{\infty} \int_{0}^{\frac{\pi}{2}} \left\{ e^{\left(-|\varepsilon-\psi|/\lambda \omega \cos \omega \right)} \frac{\sin \omega}{\cos^2 \omega} \right\} \left\{ \int_{\varepsilon}^{x} e^{(-\varphi)} dp \right\} d\omega d\varepsilon
\]

(16)
Expressing the equations in terms of electron and phonon temperature - Electrons

\[
\frac{\partial}{\partial t} \left\{ \frac{9K T_e}{2 \lambda v} \right\} = (1 - f) \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ e^{-|x-\epsilon|/\lambda \cos \omega} \frac{\sin \omega}{\cos \omega} \right\} \times \left\{ T_e(\epsilon, t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial T_e(\epsilon, t)}{\partial t} \right\} d\omega d\epsilon
\]

\[
+ f \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ e^{-|x-\epsilon|/\lambda \cos \omega} \frac{\sin \omega}{\cos \omega} \right\} T(\epsilon, t) d\omega d\epsilon
\]

\[
+ f \frac{I_0(1-R)\delta}{2\lambda^2} \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ e^{-|x-\epsilon|/\lambda \cos \omega} \frac{\sin \omega}{\cos^2 \omega} \right\} \left| \int_{\epsilon}^{x} e^{(-\phi p)} dp \right| d\omega d\epsilon - \frac{9K}{2\lambda^2} T_e(x, t)
\]

(17)
Electron Continuity Equation

$$\frac{\partial K}{\partial t} = \int_{-\infty}^{\infty} \int_{0}^{\pi/2} \left\{ \frac{K_v}{2 \lambda^2} e^{(-|x-\varepsilon|/\lambda \cos \omega)} \frac{\sin \omega}{\cos \omega} \right\} d\omega d\varepsilon - \frac{K_v}{\lambda}$$  (18)
Schematic illustrating electron movement inside metals, the material is moving with velocity $V_s$. 

Group II

Group I

Metal Free Surface

A

B

C

$\epsilon$

$\omega$

$d\omega$

$s$

$dV$

$V_s$

$r$

$dr$

$d\epsilon$

$x$

$0$
Schematic of one dimensional moving boundary problem

Moving Boundary

$\mathbf{x(t)}$

Vapour

$\mathbf{I_0}$
Incorporating Evaporation

- The evaporation rate is given by:
  \[ G = n \sqrt{\frac{kT}{2\pi m}} \cdot e^{-\frac{U_0}{kT_s}} \]  
  (19)

- Where: \( n \) = the atom number density at the surface,
- \( m \) = mass of the atom, \( U_0 \) = latent heat of vaporisation per atom. The velocity of the evaporating surface \( V_s \) is given by:
  \[ G = V_s = n \sqrt{\frac{kT}{2\pi m}} \cdot e^{-\frac{U_0}{kT_s}} \]  
  (20)
Incorporating Evaporation

- At the surface there is a mathematical singularity, this can be handled by changing the coordinate system such that the material moves with velocity $V_s$ towards the origin.

- The problem is then to determine the energy transported into $dV$ at $x$ from all electrons in $d\varepsilon$ at $\varepsilon$, then integrate for $\varepsilon$ to allow for contributions from the whole of the material, bearing in mind that the bulk material is moving through the coordinate system with velocity $V_s$. 
Incorporating Evaporation

- As $V_s << v$ we can neglect the effect of material movement on electron transport.
- The convective heat transfer due to the moving material alters the equations describing the lattice and electron energy distributions.
Incorporating Evaporation - Lattice

\[
\frac{\partial}{\partial t}[\rho C_p T] - V_s \frac{\partial}{\partial x}[\rho C_p T] =
\]

\[
f \int_{-\pi/2}^{\pi/2} \int_{-\infty}^{\infty} \frac{9K}{4\lambda^3} \left\{ e^{(-|x-\varepsilon|/\lambda cos \omega)} \frac{\sin \omega}{\cos \omega} \right\} \times \{ T_e(\varepsilon, t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial T_e(\varepsilon, t)}{\partial t} - T(x, t) \} d\omega d\varepsilon 
\]

\[
+ f \int_{-\pi/2}^{\pi/2} \int_{-\infty}^{\pi/2} \left\{ e^{(-|x-\varepsilon|/\lambda cos \omega)} \frac{\sin \omega}{\cos^2 \omega} \right\} \left| \int_{\varepsilon}^{x} e^{(-\delta p)} dp \right| d\omega d\varepsilon \quad (21)
\]

- With the evaporation term \( \rho L(T_s) V_s \) added at \( x = 0 \)
Incorporating Evaporation - Electrons

\[
\frac{\partial}{\partial t} \left\{ \frac{9KT_e}{2\lambda v} \right\} = (1 - f) \int_{-\infty}^{\infty} \frac{9K}{4\lambda^3} \frac{\pi/2}{0} \left\{ e^{-|x-\varepsilon|/\lambda \cos\omega} \frac{\sin\omega}{\cos\omega} \right\} \times \{ T_e(\varepsilon, t) + \frac{1}{2} \left\{ dt - \frac{2|s|}{v} \right\} \frac{\partial T_e(\varepsilon, t)}{\partial t} \} d\omega d\varepsilon
\]

\[\] + f \int_{-\infty}^{\infty} \frac{9K}{4\lambda^3} \frac{\pi/2}{0} \left\{ e^{-|x-\varepsilon|/\lambda \cos\omega} \frac{\sin\omega}{\cos\omega} \right\} T_e(\varepsilon, t) d\omega d\varepsilon

\[\] + f \left( \frac{I_0(1-R)\delta}{2\lambda^2} \right) \int_{-\infty}^{\infty} \frac{\pi/2}{0} \left\{ e^{-|x-\varepsilon|/\lambda \cos\omega} \frac{\sin\omega}{\cos^2\omega} \right\} \left\{ \int_{\varepsilon}^{x} e^{-\phi} \right\} d\varepsilon d\omega d\varepsilon - \frac{9K}{2\lambda^2} T_e(x, t) + V_s \frac{\partial}{\partial x} [\rho C_p T]

(22)
Electron Continuity Equation

\[
\frac{\partial K}{\partial t} = \int_{-\infty}^{\infty} \int_0^{\pi/2} \left\{ \frac{Kv}{2\lambda^2} e^{-|x-x'|/\lambda \cos \omega} \frac{\sin \omega}{\cos \omega} \right\} d\omega d\varepsilon - \frac{Kv}{\lambda}
\]  (23)

This gives a system of nonlinear integro-differential equations which are solved using numerical methods.
Surface Temperature Variation in Aluminium using the Kinetic Theory

Graph showing the variation of reduced temperature and laser input power with time.

- **Reduced Temperature**
  - Y-axis: Reduced Temperature
  - X-axis: Time (μs)

- **Laser Input Power**
  - Y-axis: Laser Input Power (W/m² x 10^{11})
  - X-axis: Time (μs)

Lines represent:
- Red line: Electron
- Blue dotted line: Lattice
Surface Temperature Variation in Copper using the Kinetic Theory

Reduced Temperature

Laser Input Power \( \frac{W}{m^2} \times 10^{11} \)

Electron

Lattice

Time \( \mu \text{s} \)
Lattice Temperature Profile in Aluminium

- Reduced Temperature
- Depth in Microns

1. $t = 2.5 \, \mu s$
2. $\delta = 0.84 \times 10^8 \, m^{-1}$
3. $\lambda = 0.149 \times 10^{-7} \, m$

1) Kinetic theory
2) Fourier theory
Temperature Profile in Copper Using the Kinetic Theory

\[ \Delta t = 0.6 \mu s \]
\[ \delta = 0.75 \times 10^8 \text{ m}^{-1} \]
\[ \lambda = 0.4 \times 10^{-7} \text{ m} \]
Surface Temperature Evolution for Aluminium

1) Experimental
2) Electron – Kinetic theory
3) Lattice - Kinetic theory
4) Electron / Lattice – Fourier theory
5) Laser Power

![Graph showing temperature evolution over time and laser power]
Surface Temperature Evolution for Nickel

1) Experimental
2) Electron – Kinetic theory
3) Lattice - Kinetic theory
4) Electron / Lattice – Fourier theory
5) Laser Power
Surface Temperature Evolution for Copper

1) Experimental
2) Electron – Kinetic theory
3) Lattice - Kinetic theory
4) Electron / Lattice Fourier theory
5) Laser Power kW

Laser Power kW

Reduced Temperature

Time μs
CO\textsubscript{2}/CO Laser Facilities in Engineering

AF8P - 8kW Carbon Dioxide Laser can run CW or Pulsed up to 3.3kHz

AF8P-CO/01 - 2.5kW Carbon Monoxide Laser can run CW or Pulsed up to 3.3kHz

MFK 1 kW CO\textsubscript{2} Laser

- Knowledge Based Process Control
- Rapid Prototyping and Tooling
  - Laser cutting and Stacking CO\textsubscript{2}/CO
- Welding, Cutting, Drilling,
- Laser Bending
- Heat Treatment
- Surface Engineering
  - Cladding
  - Surface alloying
  - Surface texturing
  - Laser vapour deposition
Laser Cutting

Inert gas ($N_2$) cut samples of 10 mm stainless, 5 mm stainless, 6 mm aluminium

25mm Armour Plate
YAG laser trimming of pressings & CO$_2$ laser cutting
Laser Cutting Nd-YAG & CO$_2$

Laser cutting of sheet metal is now widely accepted, up to 20 mm thick

Laser cutting of tubes

Laser cutting and scribing of ceramics, eg. alumina
Nd-YAG Laser Drilling of Refractory metals

Jet-engine turbine blade
- Nimonic alloy

0.5 mm holes at 20 degrees to the surface in a jet engine combustion chamber
Excitech Lithographic Micro-machining System 8000

KrF 248 nm wavelength
ArF 193 nm wavelength

Capable of machining PCB track widths 2 microns wide

CNC controlled and linked into CAD/CAM systems

Structuring of most polymer, ceramic and glass materials

Precise etch depth control to 0.1 microns

Lateral resolution <0.5 microns

Volumetric material removal rate up to 1mm³/sec

Microstructures in polycarbonate

Mask projection

Mask dragging
Example of Fine Processing With Excimer Lasers

- Hair diameter: ~50 microns (2 thou)
- Hole diameter: ~5 microns (0.2 thou)
- Illustrative of the resolution that can be achieved with a standard excimer laser using the mask-imaging technique and good quality beam delivery optics.
Excimer Laser Micro-Machining - Exitech

- PCB Drilling
- Printer Nozzles
- 720 dpi nozzle holes
- Micro-Fluidic Systems

- Biomedical Devices
- Microstructuring
- Fibre Gratings
- Diamond Smoothing

- DUV Lithography
- A-R Surface
- Tapered micro-via
- Sensors
Lab on a Chip
Blind and Micro-via drilling

Multi Laser (CO\(_2\)/Nd: YAG)
Drills both copper and dielectric
High speed - up to 60,000 holes/minute
The pulsed frequency tripped 3 Watt YAG (355nm) laser is used for drilling metals
A wavelength tuned pulsed 80 Watt CO\(_2\) (9.6 microns) laser is used for removal of dielectric

High speed drilling of blind and microvias in all types of multilayer printed circuit boards (PCB's), and multichip modules (MCM's) for panel sizes up to 24" x 28".
Blind and Micro-via drilling

200 µm blind via - 18 µm top copper - 125 µm FR4 - laser cleaned bottom copper

Array of 125 µm blind vias in 25 µm polyimide - pre-patterned top copper

Through holes and annular rings

Circuit board blind vias

25 µm blind vias
Femtosecond Laser Beam Characteristics

Ti:sapphire lasers with output centred at 800nm have the ability to machine features as small as 70nm. With multi photon absorption, laser power scales as \((\text{laser power})^N\) where \(N\) is the number of photons simultaneously absorbed. \(N\) ranges from 3 to 10.

Courtesy of Marco Arrigoni - Coherent
Ultra Fast Pulse Interaction

- No surface debris
- No recast layer
- No melt zone
- No microcracks
- No shock wave
- No heat transfer to surrounding material
- No damage caused to adjacent structures

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Femtosecond Laser Machining Ti:sapphire - Exitech

Aluminium

Stainless Steel

Silica

Glass

100 micron diameter hole drilled in stainless steel using a 355 nm nanosecond pulse Nd: vanadate laser

Ti:sapphire laser; $\lambda_0 \sim 800$ nm, $\Delta \tau \sim 110$ fs, $E \sim 1$mJ/pulse, Rep Rate $\sim 3$–$5$kHz, $M2 \sim 1.2$
Photograph shows a 22,000 hole array of 5μm diameter holes. Material is stainless steel, 100 μm Copper Vapour Laser, 511 & 578 nm, 10kHz, 20 to 30 ns pulses, 50 to 500 kW
## CVL Hole Drilling Capability Table

**Oxford Lasers**

<table>
<thead>
<tr>
<th>Diameter – laser exit side (μm)</th>
<th>Taper (μm)</th>
<th>Thickness (μm)</th>
<th>Exit Side Diameter Tolerance (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 – 15</td>
<td>+ (5 – 10)</td>
<td>10 – 100</td>
<td>+/- 1</td>
</tr>
<tr>
<td>15 – 500</td>
<td>+ (5 – 10)</td>
<td>10 – 200</td>
<td>+/- 0.25 to +/- 1.5</td>
</tr>
<tr>
<td>40 – 500</td>
<td>+10 to 0 to -10</td>
<td>200 – 1000</td>
<td>+/- 2 to +/- 4</td>
</tr>
</tbody>
</table>
Photograph: An array of precision drilled holes of 230μm diameter on a 295μm pitch in 250 μm thick synthetic diamond.

(Photograph courtesy of GEC-Marconi, Materials Technology Ltd.)
References


References


The End