THz Sources

1. Vaccum Electronic Sources.
   1. Backward wave Oscillator
   2. Free-electron lasers
   3. low voltage virtual cathode Oscillators.
   4. Gyrotrons
2. Semiconductor based THz Sources.
   1. Quantum cascade lasers. (QCLs)
   2. Gunn-like diodes.
   3. Resonant tunneling diodes (RTDs)
   4. frequency multipliers

   } Electronic based THz Sources
3. Photoconduction based THz Sources.
   1. Photoconductive Antennas
4. Non-linearity based THz Sources.
   1. Optical rectification
   2. Difference frequency Generation (DFG)

→ Classical sources of coherent EM radiation rely on the common physical principle of converting the kinetic energy of an electron current into electromagnetic field energy.

Two categories of THz sources.
① Based on Quantum and ② Classical electronic principles.

Vaccum Electronic High Power THz sources - ②

→ Solid state electronic devices works on conduction current.

→ Vaccum electron devices work on the convection current. Convection current stands with ballastic transportation of charge particles, or collisionless transportation.

→ Convection current is suitable for high power generation.

Operating principle →

① → An electron beam containing the accelerated electrons that interacts with EM wave being generated by a slow wave structure.

→ magnets are used for the beam confinement. And, e^- beam is collected at the collector.

→ Finally output as THz radiation can be taken using an antenna or output port.

→ An EM radiation fields are generated by an electronic charges with time varying currents, either due to time varying velocity or current with time varying charge densities or both.

→ Larmor formula can be used for the expression of this principle mathematically.

$$P = \frac{2}{3}\frac{q^2}{c}\gamma^6\left[(\beta)^2 - (\beta\times\beta)^2\right]$$

$$\Rightarrow \boxed{P = \frac{2}{3}\frac{q^2}{c}.(\beta^2)}$$

q → charge, c → speed of light, β → velocity vector normalized by speed of light; γ → relativistic lorentz energy parameter.

→ For a collection of ~~current~~ electrons constituting current, Maxwell's equation shows that a time varying current and/or spatiotemporal variation in electron charge density generate em radiation ~~fields~~ as -

$$\nabla^2 E(r,t) - \frac{1}{c^2}\frac{\partial E(r,t)}{\partial t^2} = \frac{\nabla \rho(r,t)}{\epsilon} + \mu\frac{\partial J(r,t)}{\partial t}$$

E → electric field, r, t → space & time variables, ρ → electric charge density, J → current density, others have their usual meaning.

→ To establish the spatiotemporal charge density and time varying current at high frequency, VEDs require high frequency electric field and static magnetic field.

Gyrotrons use time varying currents are generated by very high intensity magnetic field.

Free electron lasers ~~and~~ or beamline sources - time varying currents are generated by the relativistic electron velocities.

Challenges in design of VEDs -

→ Precision in EM circuit fabrication is required

→ A high quality e-beam generation

→ Control of electron beam

→ high vaccum packaging and mangement.

→ Design complexity.

Categories of VEDs →

① Cerenkov transition based - Slow wave. (moving through an inhomogeneous medium)

② Bremsstrahlung mechanism based - moving through a periodic deflection force.

③ or longitudinal and transverse modulation of current based VEDs

longitudinal current modulation devices

→ use a high frequency electric field to induce the longitudinal modulation to the electron velocities, parallel to the primary axis of the device.

→ The resulting longitudinally modulated current drives EM waves by coupling to the longitudinally polarized component of the wave's electric field.

→ following devices (VEDs) fall in this category -

1. conventional variants of klystrons.
2. Extended - interaction klystrons (EIKs)
3. Travelling wave tubes (TWTs)
4. Backwards - wave oscillators (BWOs)

→ Electron interact with longitudinally polarized electric field,

→ A stream of e⁻s with velocity modulation is produced.

→ In the absence of collisions, faster electrons ballastically catch up the slower electrons.

→ This produces a periodic electron density modulation (bunching) and a strongley modulated electron beam current.

→ The modulated electron beam current induces the high frequency EM fields further downstream in the EM interaction structure.

(i) Travelling waves in wave circuits (slow w) used in TWT & BWOs.

(ii) Standing waves in resonant cavity structures used in klystrons & EIKs.

Transverse current or deflection modulation devices -

→ Here a magnetic field is used to produce transient electron velocities or currents in a direction perpendicular to primary axis of device.

→ The transverse currents drive transversely polarized EM waves.

(i) Gyrotrons employ very strong magnetic field (longitudinal) to induce the transverse gyro-(cyclotron) electron orbit current.

(ii) Free Electron Lasers (FEL) use undulators or wigglers ~~currents~~ having periodic transverse magnetic fields to induce the periodic transverse wigglers current.

→ These transverse wigglers currents also induce longitudinal velocity modulation, which bunches the electrons but the wave polarization is primarily transverse. sourced by the transverse component of the modulated electron beam current.

→ Beamline THz sources can fall into either type of category.

→ pre bunch the ēs at cathode.
→ Then, energy dispersive bending magnets are used to compress the pulses of electron currents into extremly short duration. (ps or fs).
→ finally, these short duration pulses are sent through a thin metallic foil or transverse deflection magnets.
→ Both approaches produce continuous broadband coherent radiation.

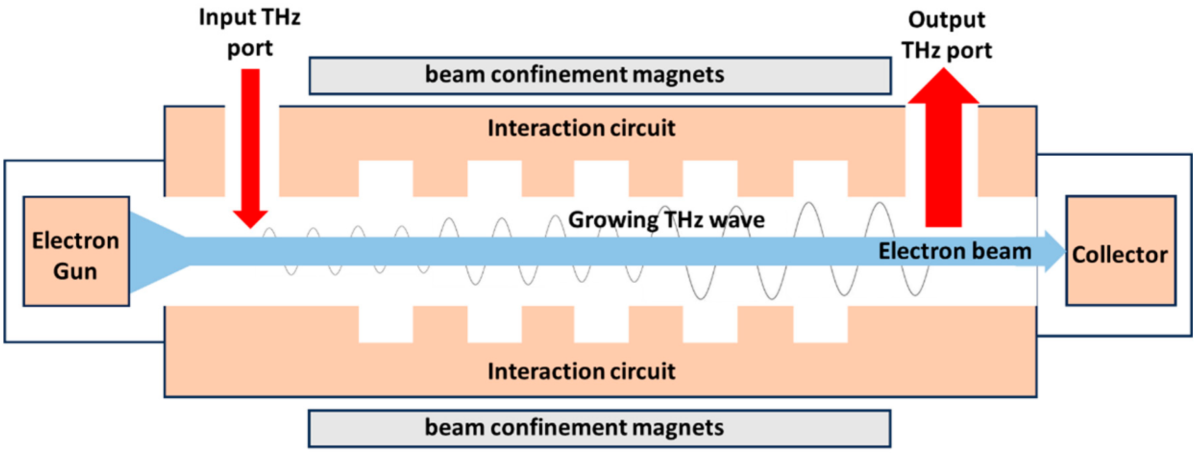

Figure Conceptual illustration of a THz vacuum electron amplifier (oscillator).

Semiconductor based THz Sources-

Quantum cascade lasers - (QCLs)-

(1) Electrons pass through the semiconductor hetero structure consisting of Quantum wells and barriers.

(2): During this movement through quantum wells and barriers e's emit photon at a specific THz frequency.

(3) The phonon light is amplified through optical waveguide structures.

→ QCLs work on the principle of inter-subband transitions of e's in quntum wells created in semiconductor hetero structures.

→ QCLs are fabricated from III - V group materials.

→ SiGe structures can be used for developing QCLs,

→

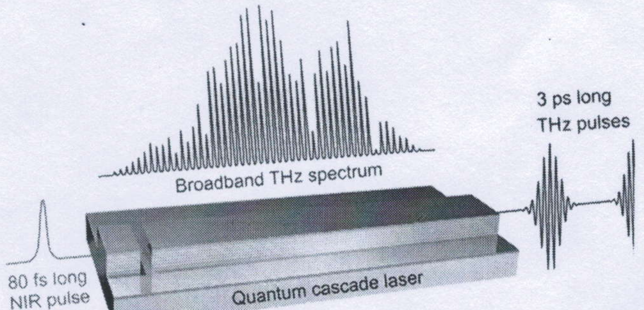

Fig. Broadband THz ampr based on QCL. This generates pulses of width 3PS. (SPIE).

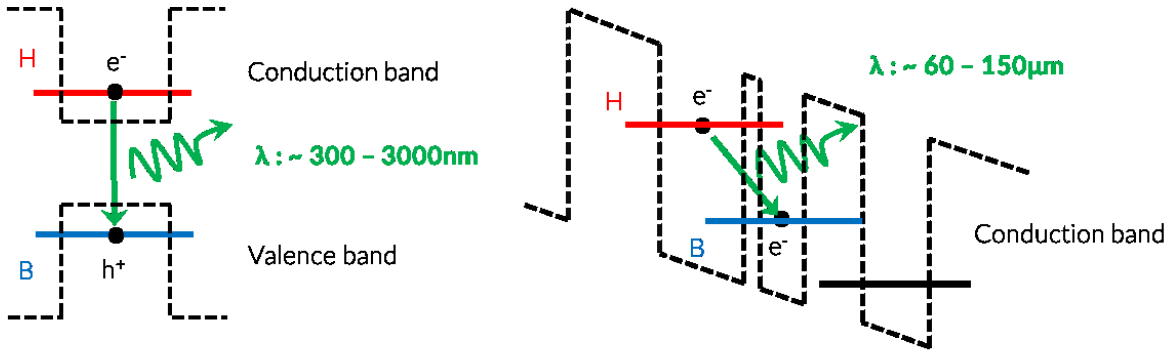

Figure Standard semiconductor laser diode using interband transitions to generate radiation between 300 and 1000 nm (**left**). This range is limited by the energy bandgap difference of the materials used. Schematic (***right***) of a single QCL period exploiting an intersubband transition between two adjacent coupled quantum wells to generate directly THz radiation between 60 and 150 µm (2 to 5 THz).

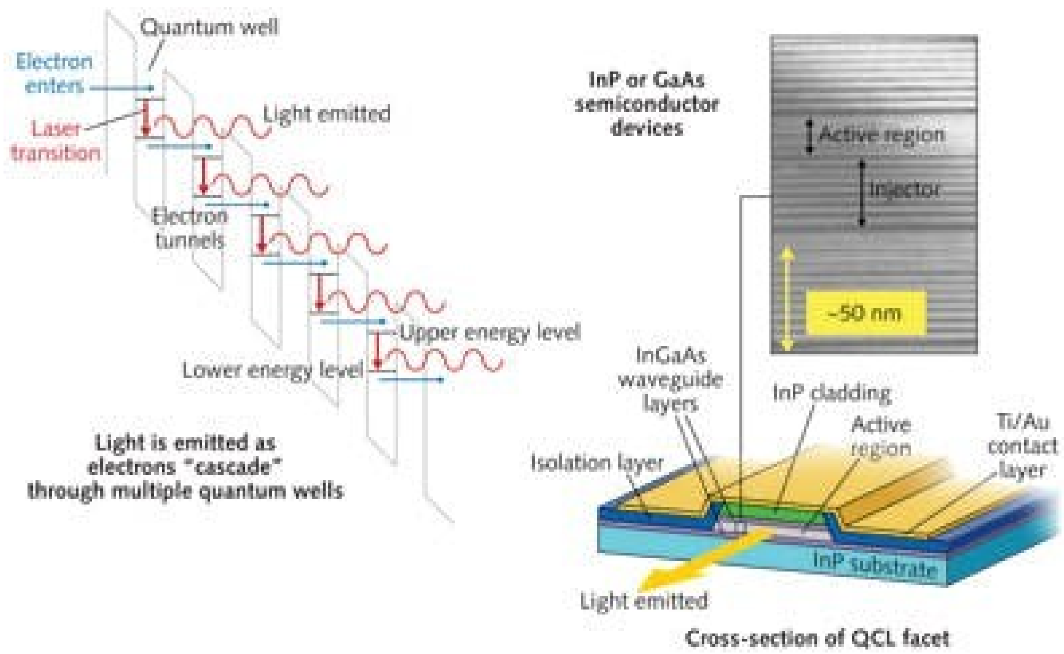

Figure A QCL has multiple active regions through which electrons cascade, each of hundreds of semiconductor layers deposited with nanometre precision.

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Photo conduction based THz sources -

photo conductive antenna (PCA) technology -

Three elements are required in PCAs.

1. Incident optical pulse of duration < 1 ps.
2. photo conductive material in substrate.
3. DC biased dipole antenna.

→ Incident optical pulse is absorbed in the substrate and generates the photo current through

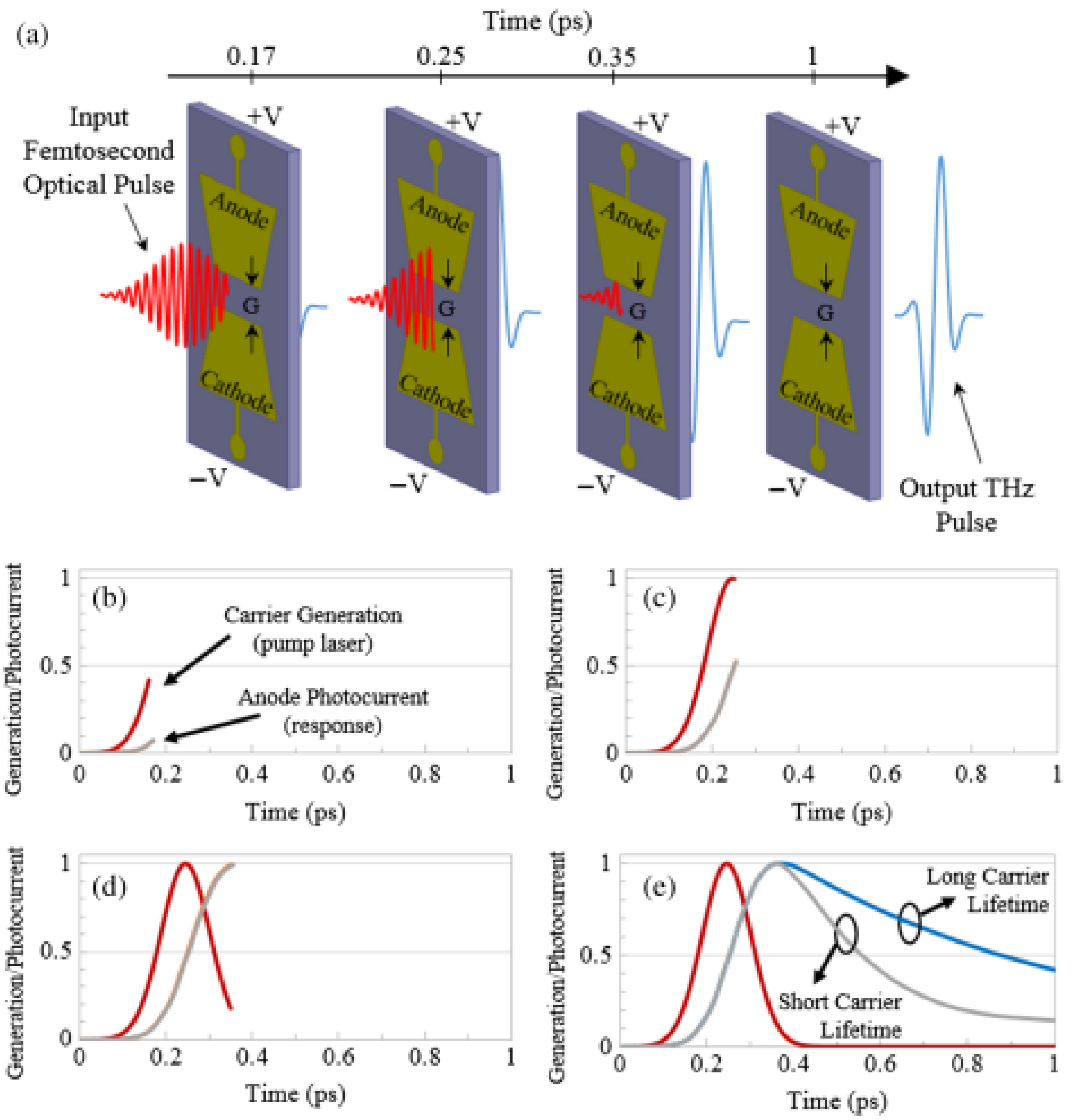

Fig. 1 Illustrative example of pulsed THz generation in a PCA. (a) Femtosecond optical pulse propagates into the photoconductor, generates a transient photocurrent, which drives the antenna, and is re-emitted as a broadband THz pulse. (b–e) Time profile of the carrier generation (red trace) and photocurrent in the antenna gap for photoconductive material (gray trace) for short-carrier lifetime and (blue trace) for long carrier lifetime.

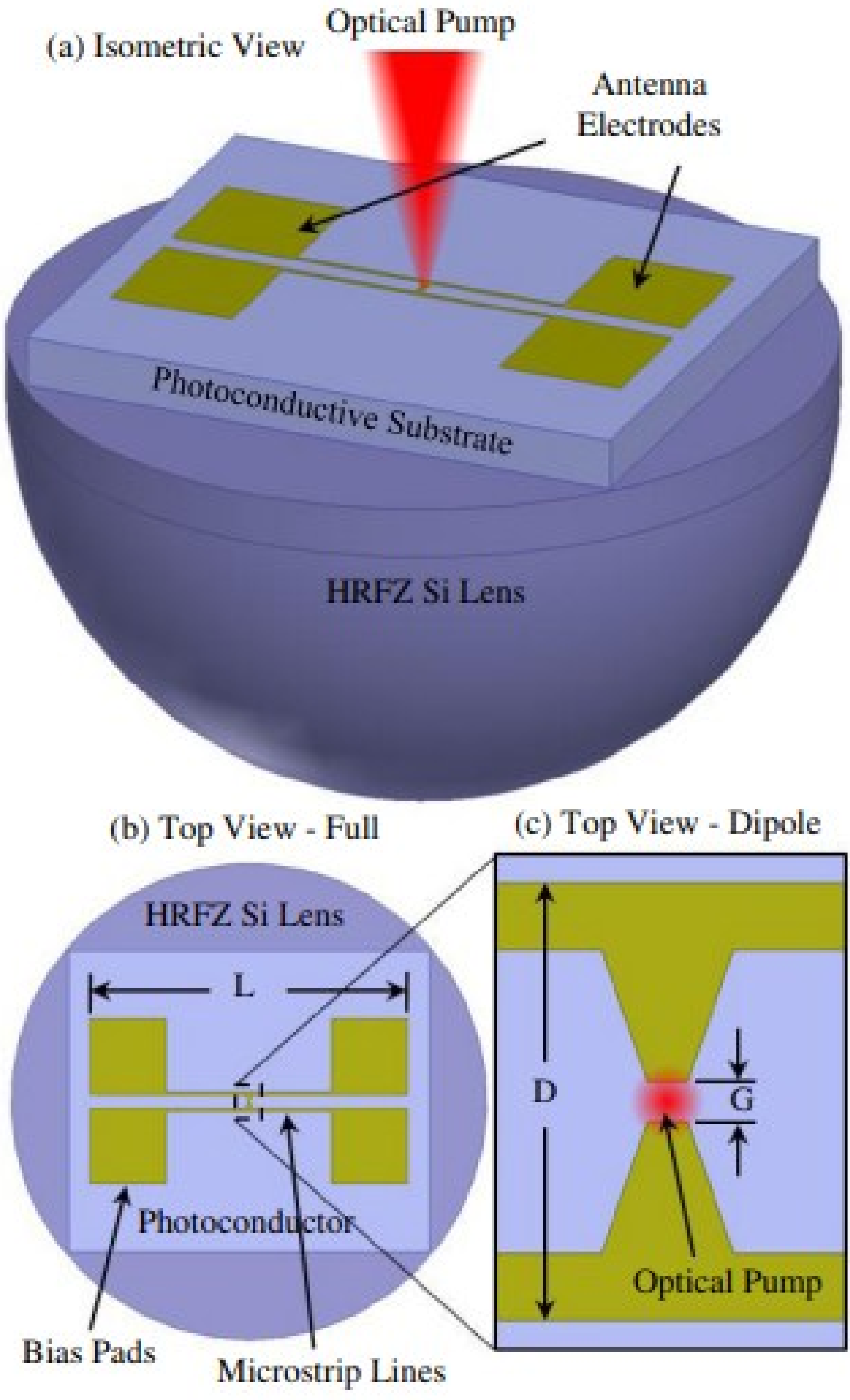

Fig. 2 (a) Isometric view of a typical THz PCA device mounted on a HRFZ Si lens. (b) Full top view of the THz PCA and (c) expanded top view of the centrally located THz dipole structure only showing gap dimension G and dipole length D.

the generation of photo carriers.

→ This photo current drives the dipole and thus re emits the THz pulse.

→ plots are demonstrating that generation of photo current remains in proportion to generation of photo carriers which decays after the incident optical pulse is completely absorbed.

→ The life time of photo carriers depend upon the material used in substrate.

Challenges in PCA –

→ Carrier life-time must be long of duration sub-ps.

→ High carrier mobility..

→ high breakdown voltage.

→ Supression to zero bias photo current.

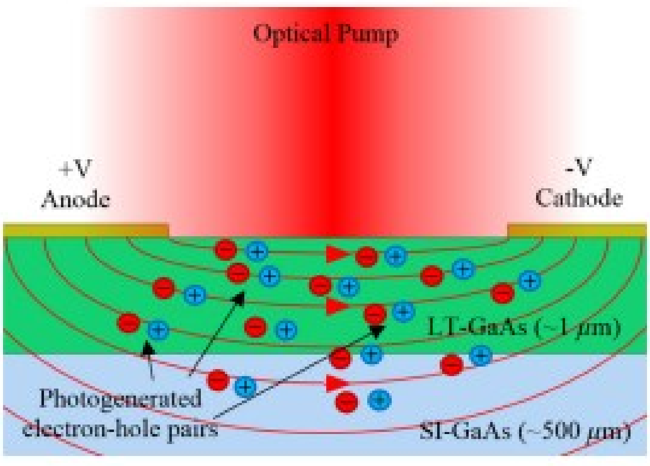

Fig. 4 Cross-section illustration of optical carrier generation at the dipole gap of a LT-GaAs based THz PCA showing the flux lines of the electric field in red arrows.

Materials used in PCAs -

→ Bulk GaAs

→ InGaAs

→ In AlAs

→ III - VI group semiconductors.

limitations.-

→ Saturation at high optical pump power.

→ Under no-illumination, there is a fixed carrier concentration of donor and acceptors. optical illumination changes the carrier concentration that drifts the electrical properties of materialsused in PCA.

→ for optial generated carrier concentration greater than donor concentration, ε'' increases that induces the non-linear increase in surface reflectivity of air-photoconductor interface. Hence O/P power faces a non-linear increase. and reaches the saturation point.

Other techniques used in PCAs.

1. Large area Aperture dipoles.
2. Integrated electrodes
3. Dipole arrays.
4. Plasmonic nano-structures.