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A Detailed Overview of the Technical Analysis of the Designing and Optimization of various Types of Novel Unconventional Lasers

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Abstract

Various types of unconventional lasers including Raman lasers, Spin lasers, Random lasers, macroscopic lasers, Nano lasers, and White lasers. Have recently been the subjects of interest in the research institutes of the world? This Keynote Address is to present some of these results in the fascinating field of unconventional lasers.

Keywords: Spin lasers • Phase conjugated lasers • Quantum cascade lasers • Raman lasers • X-ray free-electron lasers • White light lasers

Introduction

As a result of the success and utility of the conventional lasers a lot of interest has been shown by the Researchers on exploring the various types of Unconventional Lasers. The subject started drawing the serious attention of the academecians and designers engaged in the newer realms of Lasers [1].The quantum of work in this field has picked up ttemendously in the last decade. Chopra has done detailed technical analysis, modeling, and optimization of various types of unconventional lasers including Raman lasers, Spin lasers, Random lasers, macroscopic lasers, Nano lasers, and White lasers. Recently, Walia and Choprahave also made some interesting studies in this field. The purposed this Keynote Address is to present some of these results in the fascinating field of unconventional lasers [2].

Some Types of Unconventional Lasers are: Spin Lasers, Phase Conjugated Lasers, Diode Pumped Er Fiber Lasers, Unconventional Lasers based on Photonic Crystals, GaSb-based Type-I Diode Lasers around 3μm ,Quantum Cascade Lasers, Ultrashort Pulses from Femtosecond Fiber Lasers, Cr: LiSaF and Cr:LiCaF Lasers, Mode-Locked Ti: Sapphire lasers, Mid-Infrared Random Lasers, Raman Lasers, Ultrafast Mid - IR Lasers, X-ray free-electron lasers, Metal-clad semiconductor nanolaser and Subwavelength hybrid lasers,White Light Lasers and the Newly Evolving Conceptual Lasers.

Literature Review

Technical discussion of some results reported in literature

Technical Discussion of some important results reported in Literature, has been presented below.

Principle of spin laser: A spin wave laser is based on the emission of energy in the form of electromagnetic waves by electrons with axial and orbital spin undergoing transition from the higher energy spin states to the lower energy spin state. For a spin wave laser with a population inversion of spin states, the individual spins precess, resulting in the stimulus to drop to a lower energy spin state, in the form of electromagnetic waves, matching the frequency of precession -- the Larmor frequency. Interestingly, the spins are stimulated to emit electromagnetic waves, which are in phase with the stimulating electromagnetic waves.

Spin laser showing the design of laser cavity: Spin Laser Design of Laser Cavity is shown in (Figure 1).

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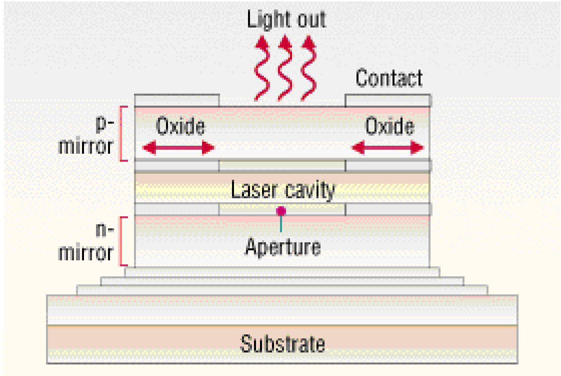

Figure 1. Spin laser showing the design of laser cavity.

Working principle of a high-power GaAlAs laser diode array

The system is based on a high-power GaAlAs laser diode array, which is coupled to a photorefractive phase conjugator. The phase conjugate feedback is rendered frequency selective, which is done by placing a grating in the external cavity between the conjugator and the laser diode array. The frequency selective feedback system makes the multimode laser diode array to oscillate in a single spatial and a single longitudinal mode with a conversion efficiency > 90%. Polarizers and half wave plate are also required for this phase conjugate feedback.

A GaAlAs laser diode array with phase conjugate feedback from a BaTiO3 crystal: A GaAlAs laser diode array with phase conjugate feedback from a BaTiO3 crystal is shown in (Figure 2).

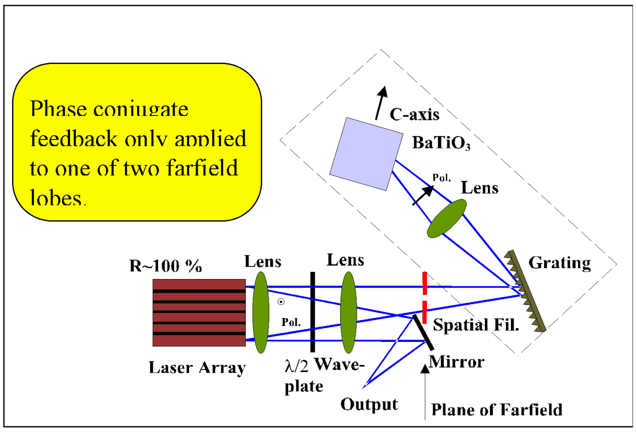

Figure 2. A GaAlAs laser diode array.

Principle of erbium 3 mm fiber laser

ZBLAN a family of glasses with a composition ZrF4-BaF2-LaF3-AlF3-NaF, .having a broad optical transmission window from 0.3μm in the UV to 7 μm in the infrared, low refractive index (1.50), a relatively low glass transition temperature (Tg) of 260 °C, low dispersion and a low and negative temperature dependence of refractive index.

The erbium 3 mm fiber laser in principle operates as a simple four-level laser, based on the pump absorption at 800 nm on the ground-state transition 4I15/2 à 4I9/2 and subsequent fast multiphonon relaxation into the 4I11/2 upper laser level, which lead to the inversion on the laser transition 4I11/2 à 4I13/2 at 3mm. Er:ZBLAN fiber laser has now been established as a very important type of the fiber laser, which is very commonly employed, because of many inherent advantages.

The energy levels of Erbium Doped Fiber, with Er+3 randomly distributed in glass are shown in (Figure 3).

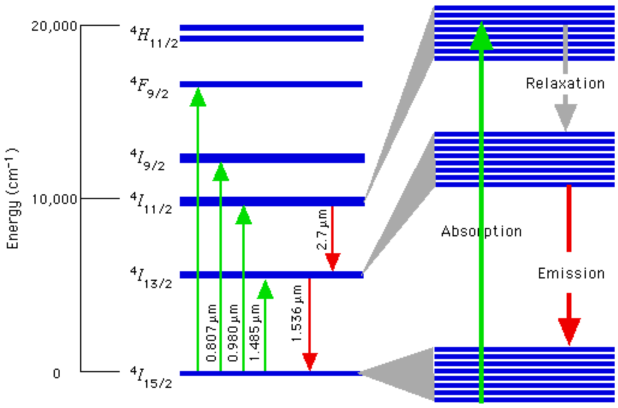

Figure 3. Principle of erbium 3 mm fiber laser.

Optimization of the effective coefficient of absorption: The pump absorption in rare-earth-doped double-clad fibers with chaotic propagation (i.e. the particles become statistically independent when their number becomes large) can be studied and optimized on the basis of the Beer's law of absorption with the effective coefficient of absorption, in terms of the material absorption, the radius of the core, the numerical aperture of the core, and the cladding.

The pump radiation is normally injected into the Er doped fiber active medium through a wavelength demultiplexer supplied by a laser diode, and the pumping radiation wavelength of 980 nm is very commonly considered.

Absortion and Emmission cross sections for the 4I15/2 -> 4I13/2 transition in Er+3 are given in (Figure 4).

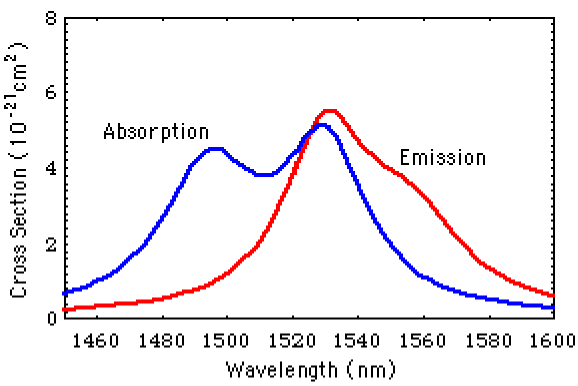

Figure 4. Optimization of the effective coefficient of absorption.

Photonic crystal lasers (PCLs)

Photonic crystal lasers (PCLs) are an important class of unconventional lasers, and are based on nano-structures, for providing the mode confinement and the density of optical states (DOS) structure, required for the feedback, having μm size and tunable on the bands of the photonic crystals.

Classically, the semiconductor lasers are generally in the form of the diode laser; which consists of

(i) an active region in the shape of the quantum wells, and

(ii) The p-n junction, with the properties of the emitted light being determined

(iii) mainly by the semiconductor material , whose band structure decides the energy of the interband transition producing light, and

(iv) to some extent by the physical structure i.e. the well width, and the waveguide geometry.

Interestingly, these quantum wells are either inside a waveguide i.e. an edge-emitter; or between the distributed Bragg reflectors stacks i.e. a vertical-cavity surface-emitting laser.

Conventional edge-emitter viewed from facet (left) and Conventional VCSEL viewed from side (Bottom) are shown in (Figure 5).

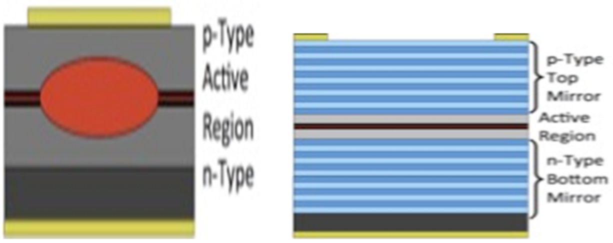

Figure 5. Photonic crystal lasers.

The band structure for the case of a hexagonal lattice of GaN nanowires with a diameter 'd=0.4a' and height 'h=2a', where 'a' is the lattice constant, as calculated, is shown in (Figure 6).

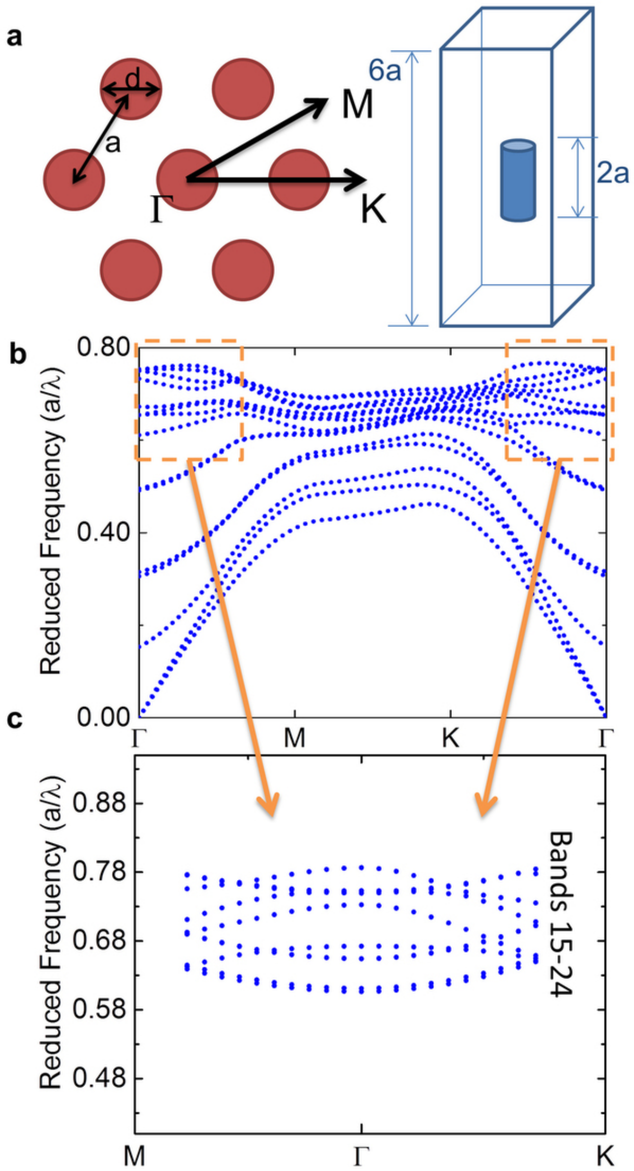

Figure 6. The band structure for the case of a hexagonal lattice.

Spectral characterization of a representative photonic crystal laser is shown in (Figure 7).

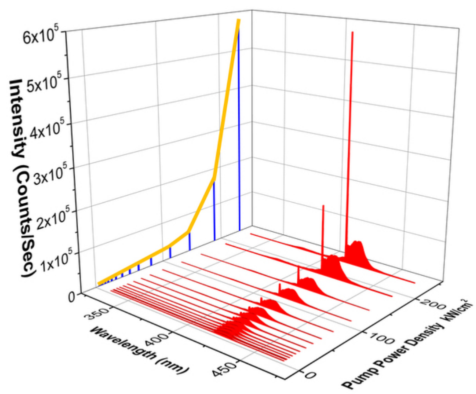

Figure 7. Spectral characterization of a representative photonic crystal laser.

Discussion

Working principle of laser diode

It is possible to generate a desired modulated laser signal by direct injection of the laser diode with the help of an electric signal of suitable format. Interestingly, the carrier number , and the photon density or optical signal carry the same information as is carried by the modulating electric signal ; which implies that in the absence of current modulation, the laser diode emits a constant-power monochromatic light. However, the application of the current modulation induces a variation of the power and frequency of the beam. Also, the deriving current of a modulated laser diode is the sum of two terms:

(i) the bias current, , which sets a value above the threshold level of the laser, and

(ii) the modulation current , which determines the modulation level.

By adjusting both these currents, it is possible to achieve the desired variable power. Gas-based Type-I Diode Laser around 3µm is shown below in (Figure 8).

Figure 8. Type-I diode laser around 3µm.

Designing the laser diodes: Designing the Laser Diodes is done to optimize the performance of the laser diodes, it is necessary to characterize the laser diode specifications by plotting the L/I curve, where L is the light output, and I is the supplied drive current. Thus laser diode specification is used to determine the current required for obtaining a particular level of light output at a given current. It is observed that the light output is strongly dependent upon the temperature. Laser diode L/I Characteristic is as shown in (Figure 9).

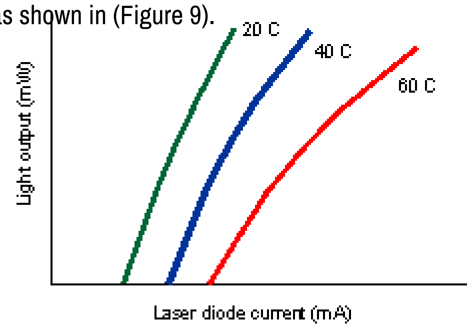

Figure 9. Laser diode L/I Characteristic.

Efficiency of laser diode: The laser diode should be operated to avoid this point for ensuring the reliable operation over the full operating temperature range, as the threshold current rises exponentially with increasing temperature.The efficiency falls with increasing temperature. For a typical laser diode specification, having efficiency around 0.3 mW per mA at around room temperature ~ 25°C, the efficiency is observed to fall by about 0.01 for each 10°C increase. Laser diode V/I characteristic is as shown in (Figure 10).

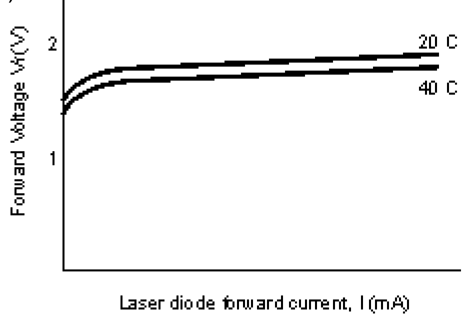

Figure 10. Laser diode V/I characteristic.

The voltage across the laser diode is typically around 1.5 volts, and falls slightly with an increase in temperature. This voltage is largely dependent on the materials used in the diode. The two most important parameters while designing the laser diodes are:

- whether the requirement is for a CW or a Pulse laser diode, and
- wavelength of operation.

Maximizing the net modal gain and quantum confinement in quantum cascade Lasers (QCLs)

QCLs are special kind of semiconductor lasers usually emitting light in the mid-IR spectral region, which operate differently from the conventional semiconductor lasers, as the laser transitions are based on the intersubband transitions in a repeated stack of semiconductor multiple quantum well heterostructures, instead of those between the different electronic bands.

Schematic of the gain region of a quantum cascade laser, showing the electron energy vs. position in the structure, containing three quantum wells is shown in (Figure 11).

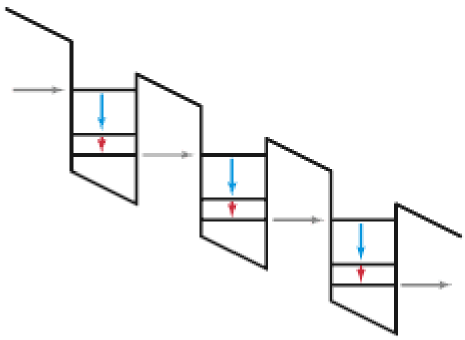

Figure 11. Electron energy vs. position in the structure.

The difference between a conventional interband device (left) and a quantum Cascade device (right) is shown in (Figure 12).

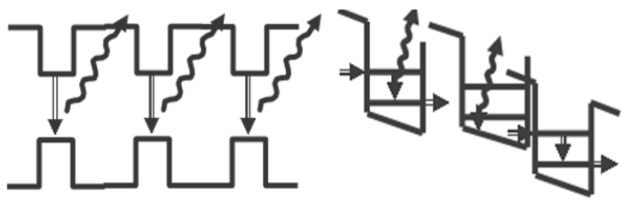

Figure 12. The difference between a conventional interband device (left) and a quantum Cascade device (right).

Discrete energy levels of electrons and holes in Quantum well made of AlGaAs/GaAs/ AlGaAs are as shown in (Figure13).

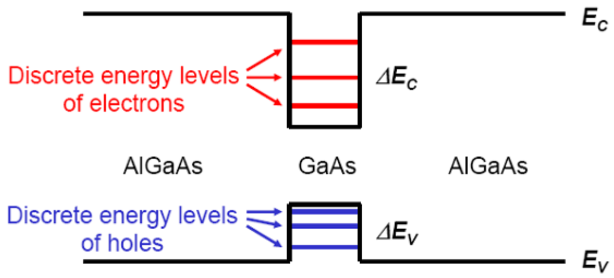

Figure 11. Discrete energy levels of electrons and holes in Quantum well made of AlGaAs/GaAs/ AlGaAs.

Design of Quantum Well Laser (Left) and Design of a Double Heterostructure (Right) are shown in (Figure14).

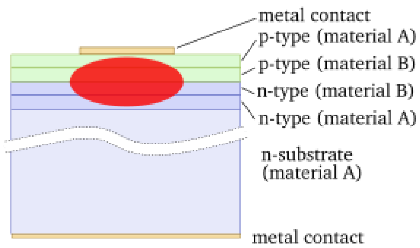

Figure14. Design of Quantum Well Laser (Left) and Design of a Double Heterostructure (Right).

Mathematical modeling of QCLs

The mathematical modeling of QCLs is based on optimizing many parameters namely; threshold current density, reciprocal cavity length (1/L), mirror loss, the facet reflectivity, the gain coefficient, and the overlap factor of the active region. All these parameters are optimized to minimize the waveguide losses αW, which in QC lasers are typically characterised using two independent methods: one based on a plot of the threshold current density versus reciprocal cavity length (1/L) and the other on an analysis of subthreshold emission spectra for different injected currents.

Quantum confinement in quantum wells and quantum dots: Quantum confinement in Quantum Wells and Quantum Dots is explained in (Figure15).

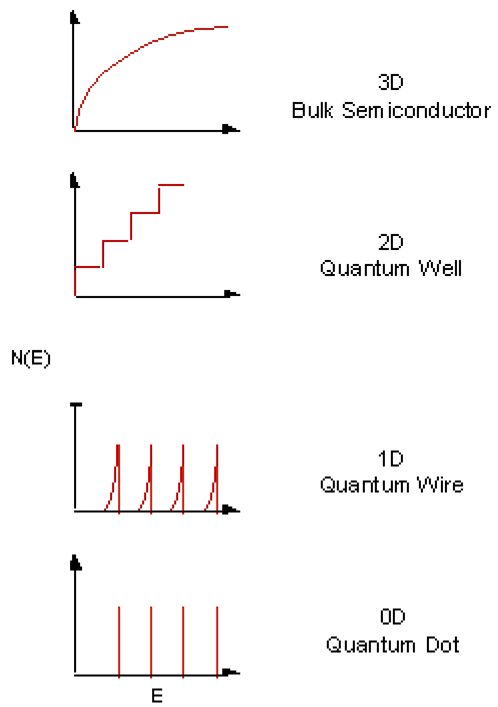

Figure15. Quantum confinement in quantum wells and quantum dots.

Working of the conventional semiconductor laser

The Working of the conventional semiconductor laser is clearly explained in (Figure16).

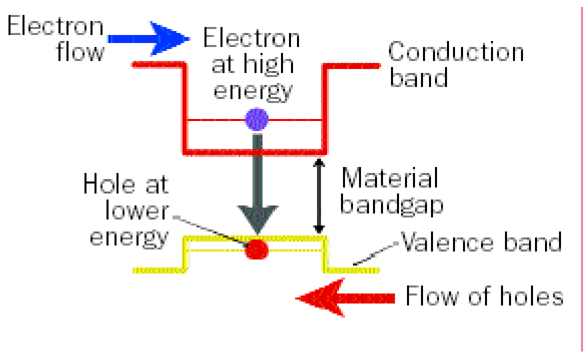

Figure16. The Working of the conventional semiconductor laser.

Higher powers with ultrashort pulses from femtosecond fiber lasers

With the advent of fiber lasers, many research efforts have been made for designing and developing new types of fiber lasers with entirely new capabilities. Thulium and holmium emit in the 2 μm band which is very important, and interestingly, some non-oxide fibers can be useful in the mid-IR.

Some novel fiber lasers

Ytterbium (Yb)- and erbium (Er)-doped fiber lasers have been of great use in applications from high-power materials to femtosecond sources for the routine purposes. In addition, new different types of fiber lasers with novel capabilities e.g. Commercial thulium-doped fiber lasers able to deliver 200 W continuous wave in the 2 μm band, have great utility for the medical and military applications; Holmium-doped fibers can work at 2.17 μm; and Non-silica fibers emit on longer mid-infrared wavelengths.

Mathematical modeling of femtosecond fiber lasers: Obviously, the real electric field of an ultrashort pulse is oscillating at an angular frequency corresponding to the central wavelength of the pulse, which is expressed in the form of the complex field, that can be separated into

- A temporal intensity function , and
- A temporal phase function.

Measured intensity autocorrelation of output pulses (left), and the autocorrelation of the compressed pulses (right) for the Yb-doped Femtosecond Fiber Lasers are given in (Figure 17).

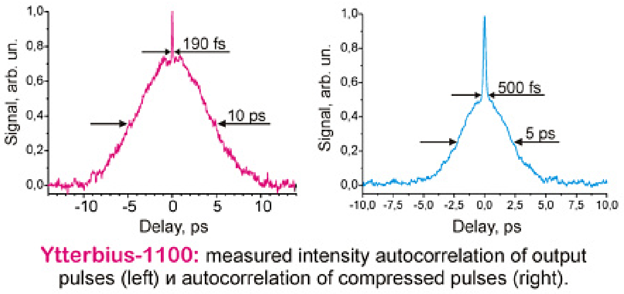

Figure17. Yb-doped femtosecond fiber lasers.

Constructive interference occurrence due to the round-trip phase in the cavity, filled with a medium with frequency-dependent refractive index n(f), on the irradiance with a CW laser are shown in (Figure18).

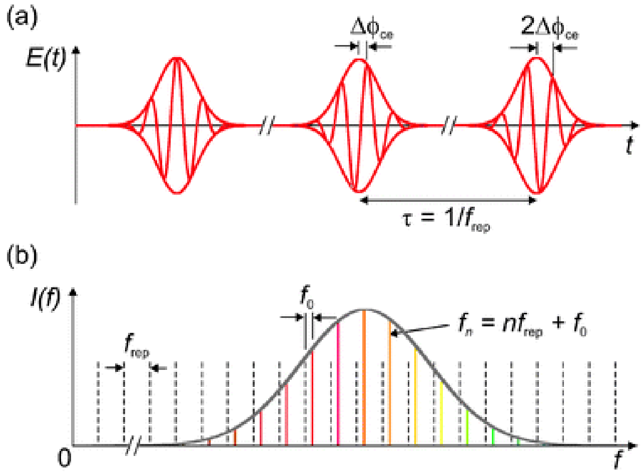

Figure18. Interference occurrence due to the round-trip phase in the cavity.

Cr: LiSaF and Cr:LiCaF lasers: Cr:LiCAF and Cr:LiSAF Lasers have various advantages like - exhibiting broad emission spectra, long lifetime of the upper laser levels, low nonlinear refractive indices, low thermal lensing , and low excited state absorption, which make them the unique sources for tunable or short pulse lasers. In this connection, it may be noted that the Cr: YSO can also be used as a saturable absorber Q switch for the Cr: LiCAF laser near 780 nm, which is the peak of its tuning range.

Modeling and designing of transition-metal vibronic lasers based on q-switching: coefficients and cross-section to the ground state absorption cross-section of the saturable absorber. Modeling a laser passively Q-switched by a solid-state saturable absorber os done by optimizing various parameters like number of levels in Laser, the photon number in the laser cavity, the population inversion of the laser, the ground state population of the saturable absorber, the effective decay rate of the upper laser level, the effective relaxation rate of the saturable absorber, the pumping rate, the cavity decay rate, the coupling the ratio of (the excited state absorption

CW laser output power with output coupling: The CW laser output power with output coupling. For three different cases is shown in (Figure 19).

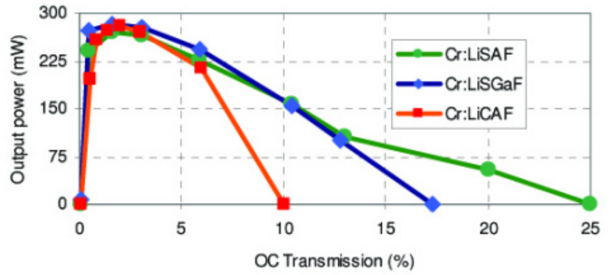

Figure 19. The CW laser output power with output coupling.

Mode-locked Ti: sapphire lasers for maximizing the laser efficiency: Ti:sapphire lasers are popular and important because of the fact that they

- Are tunable lasers, capable of emitting red and near-IR radiations in the spectral region 650nm to 1100 nm, and
- Generate ultra-short pulses. Because of these characteristics, they have become very handy for carrying out scientific research.

Coupling and phase locking of modes resulting in the output in the form of one dominant repeated short pulse: The coupling and phase locking of modes resulting in the output in the form of one dominant repeated short pulse, is as shown in (Figure 20).

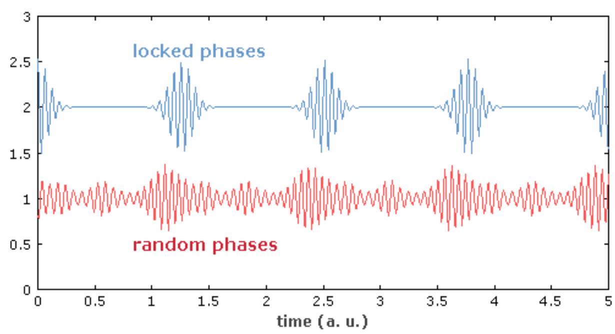

Figure 20. The coupling and phase locking of modes resulting in the output in the form of one dominant repeated short pulse.

Spectra of 46, 53, 64 and 91-fs long pulses from the Cr3+: LiSAF laser: The estimated total cavity dispersion is -30, -110, -190 and -270 fs2,respectively, and the time bandwidth product is ~ 0.35 for all cases, are shown in (Figure 21).

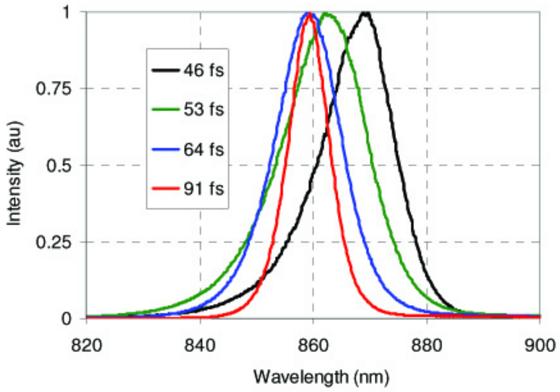

Figure 21. The time bandwidth product is ~ 0.35 for all cases.

Absorption spectrum and emission spectrum of Ti-Sappire: The Absorption spectrum and Emission spectrum of Ti-Sappire are shown in (Figure 22).

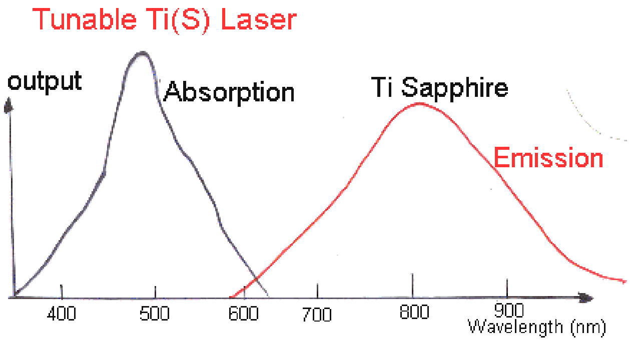

Figure 22. The absorption spectrum and emission spectrum of ti-sappire.

Theory of a random laser: Multiple scattering in amplifying random media Anderson localization of light (Anderson localization is a phenomenon which takes place when electrons become trapped in a disordered metallic structure, due to which the metal goes through a phase transition from conductor to insulator, and these electrons are said to be Anderson Localized.) does not occur, even though the calculations of interferences are required to prove this fact.

There are certain conditions for this localization to occur, which are:

- A high enough density of scatters in the metal (other electrons, spins, etc.) for causing free electrons to follow a single looped path. This is analogous to photons diffusing through a medium scattering off nanoparticles of diameter 10nm - 100 nm.; and
- The Ioffe-Regel criterion, describing the ratio of photon wave-vector k to mean free-path length (of a photon not colliding with anything).

Intensity vs. wavelength (2000nm to 8000nm) curves in the Output of random lasers based on Chromium (1,2,3) and Iron (4,5) doped II-VI powders (1,4-ZnS, 2-ZnSe, 3-CdSe, 5-ZnCdTe) are shown in (Figure 23).

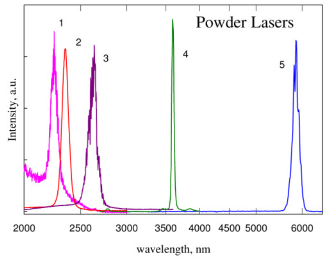

Figure 23. Output of random lasers based on elements.

Raman lasers in various modes

Raman Gain : Raman gain is the optical gain i.e. amplification resulting from the stimulated Raman scattering, which can take place in transparent solid media like optical fibers, liquids and gases by intense pumping of light, and is made use of in Raman amplifiers and Raman lasers.

The optical frequency offset between pump wave and signal wave determines the magnitude of Raman gain, which also depends to some extent, on the pump wavelength, and on material properties.

Three-level atoms + one pump result in 2 photon transition (population inversion) between the two ground states. Raman gain between hyperfine levels with additional scattering can be achieved by sweeping slowly (steady-state) the Raman laser (no probe) around the frequency, where Raman gain is on resonance with the |2> à |1'> transition. These points have been illustrated in (Figure 24).

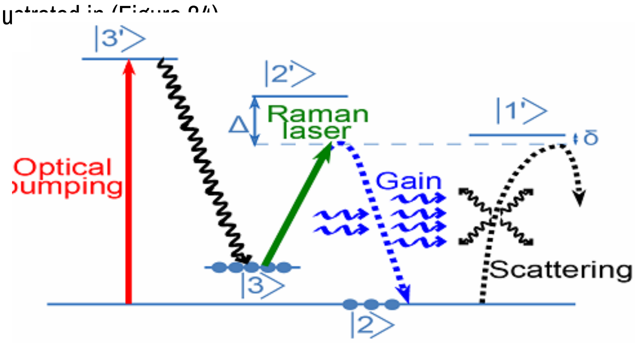

Figure 24. Three-level atoms + one pump result in 2 photon transition.

White light sources: Novel Nanosheet with laser emissions of Elementary colors- Blue (Top), Green (Middle), and Gree (Bottom), have been shown been shown in (Figure 25).

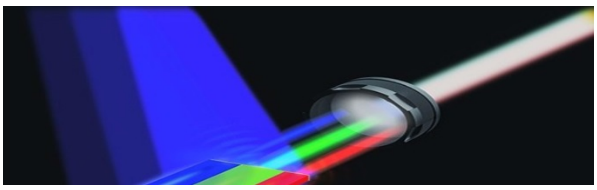

Figure 25. Novel nanosheet with laser emissions of elementary colors.

Formation of the white-laser source: Formation of the white-laser source is explained in (Figure 26).

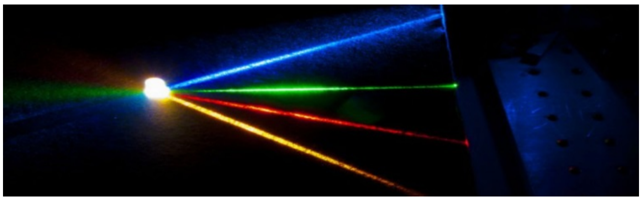

Figure 26. Formation of the white-laser source.

It has to be pointed out here that the figures presented in this Keynote Address are courtesy various Authors and Agencies, as reported in the Monograph written by the Author.

Conclusion

The unconventional lasers have great applications in the Research areas, industry, and medical field. This is the reason that huge financial grants are being given by a number of scientific organizations to various Academic and Scientific Institutions to carry research and development work. Recently, another type of Unconventional lasers - Fibre lasers, especially the Femto- second Fibre lasers have been drawing the attention of various researchers. In view of the recent advances, it can be safely concluded that the field of unconventional lasers is on a firm footing.

Acknowledgements

The author is grateful to Prof. V. K. Tripathi of Physics Department, Indian Institute of Technology, Delhi for motivating to work in this fascinating field. The author is also grateful to many Scientists of Laser Science and Technology Centre, DRDO, Delhi for many interactions and useful discussions culminating in huge improvements in the presentation and concepts of this complex and rapidly evolving field.

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