Special Issue on Best Theses and Posters at

20th DAE-BRNS National Laser Symposium (NLS-20)
The images are bright transmission holograms recorded in silver-doped acrylamide based photopolymer recording medium using Nd: YAG laser (532 nm) and Ar’ laser (488 nm). Silver-doped photopolymer system consists of poly (vinyl alcohol), acrylamide (monomer), methylene blue and triethanolamine (photoinitiation system) and silver nitrate (crosslinker). The films were fabricated by spin coating and holographic transmission gratings with 80% diffraction efficiency could be stored in the film. This panchromatic photopolymer system is excellent on account of its wide spectral sensitivity, high diffraction efficiency, good energy sensitivity, high resolution, cost effectiveness, ease of fabrication and real-time imaging capabilities (details on page 11).
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## Membership Form
From the Editor....

20th DAE-BRNS National Laser Symposium was held at Crystal Growth Centre, Anna University, Chennai during January 9-12, 2012. There were 268 poster presentations and 8 Ph. D. thesis presentations during the symposium. Among these 6 posters and 3 theses won ILA best poster and best thesis awards. This issue of Kiran presents the research work reported in these posters and theses. We congratulate the authors and thank them for providing their manuscripts in time. We hope you will find this issue interesting.

We look forward to receiving your suggestions and articles for Kiran.

Manoranjan P Singh
Spectroscopy deals with the interaction of electromagnetic radiation with matter, resulting in absorption, emission, scattering of the radiation, or rotation of the plane of polarization of plane-polarized radiation. It gives information about details of microscopic particles, their interactions with each other, as well as the effect of external factors, such as electric and magnetic fields. The spectral data recorded in spectroscopic experiments help us in understanding the energy level structure of atoms and molecules, as well as their atomic and molecular properties. Since all the elements have distinct spectral signatures, the study is very useful for diagnosis and quantification of atoms and molecules. It has made significant impact on various fields of the basic and the applied sciences, and also led to several technological advances.

Earlier, atomic spectroscopic investigations were carried out by absorption and emission techniques. These methods suffer from serious limitations, such as (i) excited states, having the same parity as that of the ground state are inaccessible, (ii) absorption/emission cross-section becomes smaller, as one goes to higher energy levels, and thus difficult to detect and (iii) often cumbersome vacuum-ultraviolet spectrometers have to be used, if absorption or emission photons happen to lie in vacuum-ultraviolet region. Therefore, it is very difficult to get spectroscopic information by conventional spectroscopic techniques.

In recent times, especially after the advent of tunable lasers, techniques of laser spectroscopy got revolutionized. The high intensity and narrow spectral width of the tunable lasers have not only simplified the resulting spectra but also have opened a new class of spectroscopic techniques. Many experiments, which could not be done before the application of lasers, because of lack of intensity, or insufficient resolution, are readily performed with lasers [1].

In lanthanides and actinides, 4f and 5f shells are progressively filled with electrons. Owing to the high degeneracy of the f shells, a large number of electronic states arise for these elements. The situation becomes even more complicated, because an open s, p, or d, shell frequently accompanies the open f shell. In addition, in most of the cases, these elements have numerous isotopes whose electronic states are shifted by the corresponding isotope shifts, and the odd isotopes have hyperfine structure. Thus, the atomic emission and absorption spectra of these elements are very complex, with a large
number of spectral lines. The ground state of these elements is also multiplet in some cases, and there are many close low-lying metastable energy levels. These elements, being refractory, are not easily produced in the vapor state, which is the requirement for studying their atomic spectra. High temperature operations are required to generate appreciable atomic number densities (~10^3 atoms/cm^3). At these high temperatures, the population is thermally distributed among the various low-lying metastable energy levels and, therefore, the quantum state number density becomes low. These elements are also highly chemically reactive and, hence, handling chemically reactive liquids at higher temperatures is quite difficult. In addition, many of these elements are available only in small amounts, or are radioactive. Elucidation of the spectra of these elements, therefore, requires sophisticated spectroscopic techniques. Laser spectroscopy techniques provide some of the best techniques for their studies. These techniques are generally employed in atom sources such as atomic beams, hollow cathode discharge lamps, flames and plasmas. The spectra from these sources are generally too complex for easy analysis. The tunability, narrow line width and high power of lasers make spectroscopy easy even in these systems by selectively exciting not only the element but also particular quantum state. There are large number of energy levels between the ground state and the continuum. These energy levels can be excited stepwise by using one or more than one photons from tunable lasers. The involved photo-excitation cross-sections for stepwise transitions are significantly large, owing to bound-bound transitions and thus excitations to the excited levels can be easily achieved by available cw and pulsed tunable lasers. The excited atoms are then monitored by detecting fluorescence from the excited levels (LIF), or are detected as ions by further exciting the atoms above continuum. Both these techniques of LIF spectroscopy and RIS have been employed for several elements by various authors [2-4].

For a three-step excitation process, atomic parameters of interest are shown in Fig.1. They are energy levels (E_i, E_j, E), their total angular momentum values (J, J, J), photo-excitation cross-sections (σ_1, σ_2), photo-ionization cross-sections (σ), lifetimes of the energy levels (τ_1, τ_2, τ_3) branching fractions of different decay channels of an excited state (β_12, β_23), isotope shifts and hyperfine structures.

This work mostly deals with use of LIF spectroscopy for measurement of atomic parameters of samarium. Advanced research in areas such as nuclear power programme, high temperature superconductivity, communication and display industry, medical and biochemical applications, material science, fundamental aspects of atomic and nuclear structure etc. requires accurate quantification of these elements, precise structural information of their compounds and detailed knowledge of the interaction of these atoms, and their molecules, with other species. Thus, this work forms the basis of all these high end applications.

**Experimental**

Fig.2 shows the experimental setup used for LIF experiments. The details of the developed effusive atomic beam source of samarium, Nd:YAG pumped dye laser systems, fluorescence collection assembly and detection systems such as photomultiplier tube (PMT) etc. have been described in our published work [5,6]. Many single-colour LIF spectra were recorded in different wavelength regions by scanning the laser and keeping the bandpass of the monochromator fixed. Different decay channels of fluorescence from first excited energy level (resonant and non-resonant) were identified by fixing the laser to the resonant wavelength and changing the bandpass of the monochromator. For two-colour LIF experiments, first-step excitation laser wavelength was fixed either with the help of resonant fluorescence signal or with non-resonant fluorescence signal from the first excited energy level. The second laser was temporally and spatially synchronized and then tuned across the wavelength range to record the two-colour fluorescence spectra. Fig.3 shows the excitation process for finding second-step fluorescence resonances in high-lying energy regions by fixing various first-step excitation wavelengths and varying the second-step laser wavelengths. The two-colour LIF spectra were recorded by varying the bandpass of the monochromator. This was
done by changing the central wavelength of the monochromator. Monochromator, intensified charge coupled device (ICCD) were used for detection of temporally and spectrally resolved fluorescence [6].

Fig. 2: Experimental setup for temporally and spectrally resolved two-colour LIF spectroscopy experiments

Results

Fig. 4 shows the typical two-colour fluorescence spectrum of Sm I when the first-step laser was fixed at 570.68 nm (292.58 cm⁻¹ → 17810.85 cm⁻¹) transition and the second-step laser wavelength was scanned, along with U-optogalvanic signal and Febry Perot etalon fringes. Optogalvanic signal was recorded simultaneously to provide the absolute frequency calibration scale and febry perot fringes to provide dispersion scale. These two spectra were used to find out the exact energy positions of the two-colour fluorescence resonances. Based on the observed resonances in the single-colour and two-colour laser-induced fluorescence experiments, several new highly excited energy levels of samarium in the probed energy regions have been identified. The existence of many of these energy levels has been confirmed when these energy levels were accessed through different intermediate energy levels. Based on multiple excitation pathways and the applicable selection rules of excitation, the ambiguities in values of total angular momentum values were either reduced or removed for some of the proposed new energy levels and for some of the existing energy levels in the literature.

The observed resonances in the two-colour laser-induced fluorescence experiments are compared with the known resonances in two-colour three-photon ionization experiments performed in the same energy region by the earlier researchers [7, 8]. The comparison has revealed that, only a few of the resonances have been observed in both types of the experiments. Some of the resonances observed in two-colour fluorescence spectra are not observed in photoionization experiments, and vice versa. Based on these observations and the plausible explanations it is pointed out that both these techniques of
LIF and RIS should be applied in a complimentary way, for search of optical resonances, and thus identification of energy levels [5].

Fluorescence from some of the high-lying energy levels of samarium has been temporally resolved, using an ICCD camera, to measure their lifetimes. Based on these time-resolved fluorescence experiments, radiative lifetimes are measured for many first-step excited energy levels and also the identified new high-lying energy levels of atomic samarium. The measured lifetimes of

Table 1: Measured radiative lifetimes of step-wise excited even-parity energy levels in atomic samarium using two-colour laser-induced fluorescence

<table>
<thead>
<tr>
<th>Energy level ( (cm^{-1}) )</th>
<th>First excitation wavelength (nm)</th>
<th>Second excitation wavelength (nm)</th>
<th>Fluorescence Lifetime (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34814.4</td>
<td>591.64</td>
<td>567.22</td>
<td>553.4</td>
</tr>
<tr>
<td>34924.0</td>
<td>591.64</td>
<td>563.73</td>
<td>531.4</td>
</tr>
<tr>
<td>34935.5</td>
<td>591.64</td>
<td>563.36</td>
<td>516.2</td>
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<tr>
<td>34972.1</td>
<td>591.64</td>
<td>562.32</td>
<td>571.0</td>
</tr>
<tr>
<td>35072.6</td>
<td>591.64</td>
<td>559.04</td>
<td>543.9</td>
</tr>
<tr>
<td>35092.1</td>
<td>591.64</td>
<td>558.44</td>
<td>494.2</td>
</tr>
</tbody>
</table>

Table 2: Measured branching fractions and transition probabilities of the transitions from the step-wise excited even-parity energy level at 34935.5 cm\(^{-1}\) to various lower odd-parity levels using two-colour LIF with \( \lambda_1 = 591.64 \) nm and \( \lambda_2 = 563.36 \) nm.

<table>
<thead>
<tr>
<th>Energy of lower level (cm(^{-1}))</th>
<th>J-value lower level</th>
<th>Fluorescence wavelength (nm)</th>
<th>Intensity (arb. units)</th>
<th>Branching fraction ( 34935.5 ) cm(^{-1})</th>
<th>Transition probability ( 10^{10} ) s(^{-1})</th>
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</thead>
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<tr>
<td>14380.50</td>
<td>2</td>
<td>486.3</td>
<td>315</td>
<td>0.084</td>
<td>1.1</td>
</tr>
<tr>
<td>14863.85</td>
<td>1</td>
<td>498.1</td>
<td>101</td>
<td>0.027</td>
<td>0.3</td>
</tr>
<tr>
<td>14915.83</td>
<td>3</td>
<td>514.6</td>
<td>177</td>
<td>0.047</td>
<td>0.6</td>
</tr>
<tr>
<td>15567.32</td>
<td>2</td>
<td>516.1</td>
<td>1302</td>
<td>0.346</td>
<td>4.4</td>
</tr>
<tr>
<td>16116.42</td>
<td>2</td>
<td>531.2</td>
<td>321</td>
<td>0.085</td>
<td>1.1</td>
</tr>
<tr>
<td>16748.30</td>
<td>3</td>
<td>549.7</td>
<td>326</td>
<td>0.087</td>
<td>1.1</td>
</tr>
<tr>
<td>17769.71</td>
<td>1</td>
<td>582.4</td>
<td>265</td>
<td>0.071</td>
<td>0.9</td>
</tr>
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<td>17830.80</td>
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<tr>
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</tr>
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<td>18328.64</td>
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<td>602.0</td>
<td>361</td>
<td>0.096</td>
<td>1.2</td>
</tr>
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</table>

Fig. 5: Experimental time-resolved single-color LIF decay signal with an exponential fit. The lifetime for this level \((18225.13 \) cm\(^{-1}\)) was measured to be \( 143 \pm 10 \) ns.

Fig. 6: Spectrally resolved laser induced fluorescence decay channels from step-wise excited even-parity energy level at 34935.5 cm\(^{-1}\) using two step excitation \((\lambda_1 = 591.64, \lambda_2 = 563.36 \) nm\).

Fig. 6: Spectrally resolved laser induced fluorescence decay channels from step-wise excited even-parity energy level at 34935.5 cm\(^{-1}\) using two step excitation \((\lambda_1 = 591.64, \lambda_2 = 563.36 \) nm\).
these second-step excited high-lying even-parity energy levels are listed in Table 1 along with the used excitation wavelengths and the fluorescence wavelength. These measurements are reported for the first time in the literature [6]. Fig. 5 shows the typical time-resolved two-colour LIF decay curve with an experimental fit for the energy level 34814.4 cm⁻¹. The lifetime of this energy level was measured to be 127 ± 13 nsec.

The fluorescence decays from high-lying excited levels have also been spectrally resolved using a 0.5 m monochromator, to provide branching fractions to the different decay channels. Fig. 6 shows the typical spectrally resolved laser induced fluorescence decay channels from stepwise excited even-parity energy level at 34935.5 cm⁻¹ using two-step resonant excitation (?₁ = 591.64, ?₂ = 563.36 nm). Table 2 shows the intensities of different decay channels from 34935.5 cm⁻¹ energy level along with the energies of the lower levels and their J values. The calculated branching fractions are also listed in one of the columns of Table 2.

These lifetimes and the branching fractions measurements have been used to calculate ground-state-to-excited-state and excited-state-to-excited-state absolute transition probabilities of many atomic transitions of samarium. Table 2 also lists the measured excited-state-to-excited-state absolute transition probabilities in the last column. The experimental value of this parameter is of great importance and measured for the first time in the literature.

Based on the total angular momentum values of the lower excited energy level for different decay channels reported in Table 2, the total angular momentum of the second-step excited energy level were assigned. Table 3 shows some of the high-lying even-parity energy levels which were assigned unique total angular momentum values using this spectrally resolved fluorescence technique [9].

Table 3: Assigned J values to six step-wise excited high-lying even-parity energy levels of atomic samarium along with the used excitation wavelengths.

<table>
<thead>
<tr>
<th>Energy level (cm⁻¹)</th>
<th>First-step excitation wavelength (λ₁) in nm</th>
<th>Second-step excitation wavelength (λ₂) in nm</th>
<th>Total angular momentum value (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34814.5</td>
<td>591.64</td>
<td>567.22</td>
<td>2</td>
</tr>
<tr>
<td>34924.0</td>
<td>591.64</td>
<td>563.73</td>
<td>2</td>
</tr>
<tr>
<td>34935.5</td>
<td>591.64</td>
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<td>591.64</td>
<td>558.44</td>
<td>3</td>
</tr>
</tbody>
</table>

Conclusion

This work has developed LIF based spectroscopic techniques for measurement of atomic parameters of complex atoms. It demonstrates the usefulness of LIF/RIS for generating extensive database of atomic parameters and for investigating photoexcitation dynamics in complex atoms.

References

Coherent sources of short wavelength radiation are much sought after in view of their applications in a variety of fields such as microlithography, XUV spectroscopic studies etc. The interaction of intense fs laser pulses with under-dense gaseous media results in generation of high order harmonics of the incident laser in the soft x-ray region. There are several potential applications of high order harmonic generation (HHG) such as generation of attosecond pulses, study of fast alignment of molecules in strong laser field etc. Some of these applications have not yet become feasible because of rather low conversion efficiency of HHG. Hence it is desirable to increase the conversion efficiency of the HHG process, which in turn, depends greatly on the properties of the nonlinear medium used. Normally, noble gases are used as the HHG medium. However, the use of noble gases restricts the harmonic generation to only a few elements. On the other hand, use of plasma plume as the medium for HHG allows the study HHG in a variety of elements and compounds, and even enables use of nano-particle targets, which was hitherto not possible.

In the present research work, we have experimentally studied the HHG from the interaction of intense ultra-short (τ = 45 fs) laser pulses with preformed plasma plumes of a various target materials, ablated by a low intensity laser pulse. The target materials used may be broadly categorized as a) bulk solids such as: Ag, In, Cr, Mn, C etc. and b) nanostructured targets such as: fullerenes (C_{60}) and nanoparticles of various metals. The setup and the main results are described in following paragraphs.

**Experimental Arrangement**

A chirp pulse amplification based 10 TW, 10 Hz Ti:sapphire laser of 45 fs pulse duration was used in these experiments. The schematic of the experimental arrangement is given in Fig. 1. The harmonics were produced by the interaction of this laser pulse with a low-excited preformed plasma plume. The plasma plumes were created by the interaction of low intensity laser pulse with the target surface. The plasma plume was produced ~60 ns before the arrival of the femtosecond pulse. The introduction of this delay facilitates the expansion and cooling of the plasma plume and helps us in achieving optimum conditions for HHG. The extreme ultra-violet (XUV) harmonic radiation was detected by an in-house developed XUV spectrograph.

**Harmonic Generation from Various Plasma Plumes and their Wavelength Tuning**

Plasma plumes of various targets were used for the generation of high order harmonics. A typical spectrum HHG generated from plasma plume of silver showing the generation of harmonics in intensity plateau is shown in Fig. 2. The spectrum shows the HHG from 21^{st} H (38 nm) to 61^{st} H (13 nm), order. One can see the HHG in intensity plateau of harmonic orders which confirms HHG from essentially a gas like medium. Mainly plasma plumes of silver, indium, chromium, manganese, GaAs, carbon, silicon were used for HHG. Optimization of various parameters such as laser intensity, chirp, delay between the two laser pulses (pre-pulse and main pulse), etc. was carried out in order to maximize the yield and cut-off of the HHG process. The tuning of the harmonic frequencies through the variation of laser chirp was studied. It was observed that the harmonic wavelengths shift toward red (blue) with the introduction of positive (negative) chirp in the main laser pulse. This observation indicates that HHG from plasma plumes essentially comes from the leading edge of the laser pulse.

**Resonance Enhancement of Harmonic Radiation**

It was observed in our study that, in certain plasma plumes, the intensity of particular harmonic orders was
much higher compared to that of their neighbouring harmonics. The phenomenon is termed as 'resonance enhancement'. For instance, the intensity of $13^{\text{th}}$ H ($\sim \text{61 nm}$) generated in indium plasma plume was $\sim \text{200 times}$ higher. A typical spectrum of HHG from indium plasma plume is shown in Fig. 3. It was demonstrated that the tuning of the harmonic radiation with chirp can move a resonantly enhanced harmonic order out of resonance, and can also bring a normal harmonic order into resonance.

**Propagation Effects**

In order to understand the effect various phase-matching factors on the intensity of harmonics, we have studied the scaling of harmonic intensity with medium length. For this study, high order harmonics were generated from an elongated plasma plume of silver. Since HHG is a coherent process, the intensity of harmonics ($I_n$) is expected to increase with medium length ($L$) as $I_n \propto L^2$ (assuming perfect phase-matching). However, in our experiments, this scaling exponent was $\sim 0.7-0.9$ (much smaller than 2) indicating the presence of phase-mismatch in HHG process. Different phase-mismatch factors were identified and their contributions were estimated to explain the observed results.

**Improvement in the Stability and the Cut-off of the HHG**

The improvement in the stability and the cut-off of the HHG is important for their use as a coherent x-ray source for practical applications. It was observed earlier that the HHG intensity reduced to half after about 30 shots were fired on same surface. However, after various optimizations of laser and plasma conditions, one can continuously generate high order harmonics for about 2000 shots fired on the same surface. From Fig. 4 one can observe that the intensity of harmonics is decreased by a factor of 4 after firing 2600 shots on the same surface. Next, a second plateau of harmonics was observed in Mn plasma plumes. It was seen that HHG spectrum from Mn plasma consists of a plateau, followed by a sharp cut-off at $\sim \text{29th order}$. The spectrum again starts at $33^{\text{rd}}$ harmonic and after some optimizations, we could get the 'second plateau' extended up to $73^{\text{rd}}$ H order (Fig. 5).

**Efficient HHG from Nano-particle Targets**

In order to increase the conversion efficiency of HHG process, we have used nano-particle targets. Due to their small size, the nano-particle targets exhibit high optical nonlinearity. Nano-particle targets such as fullerene and metal nano-particles of Ag, Au, etc. were used in our study. These targets were made from the dried mixture of nano-particles of various materials with organic matrix or with simple glue. It was observed that the intensity of the lower order harmonics generated from these targets is quite enhanced compared to that of the corresponding harmonics from bulk materials. For example, the intensity of the $9^{\text{th}}$ harmonic from the plume of silver is much higher compared to that of their neighbouring harmonics. The phenomenon is termed as 'resonance enhancement'. For instance, the intensity of $13^{\text{th}}$ H ($\sim \text{61 nm}$) generated in indium plasma plume was $\sim \text{200 times}$ higher. A typical spectrum of HHG from indium plasma plume is shown in Fig. 3. It was demonstrated that the tuning of the harmonic radiation with chirp can move a resonantly enhanced harmonic order out of resonance, and can also bring a normal harmonic order into resonance.

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The improvement in the stability and the cut-off of the HHG is important for their use as a coherent x-ray source for practical applications. It was observed earlier that the HHG intensity reduced to half after about 30 shots were fired on same surface. However, after various optimizations of laser and plasma conditions, one can continuously generate high order harmonics for about 2000 shots fired on the same surface. From Fig. 4 one can observe that the intensity of harmonics is decreased by a factor of 4 after firing 2600 shots on the same surface. Next, a second plateau of harmonics was observed in Mn plasma plumes. It was seen that HHG spectrum from Mn plasma consists of a plateau, followed by a sharp cut-off at $\sim \text{29th}$ order. The spectrum again starts at $33^{\text{rd}}$ harmonic and after some optimizations, we could get the 'second plateau' extended up to $73^{\text{rd}}$ H order (Fig. 5).

**Efficient HHG from Nano-particle Targets**

In order to increase the conversion efficiency of HHG process, we have used nano-particle targets. Due to their small size, the nano-particle targets exhibit high optical nonlinearity. Nano-particle targets such as fullerene and metal nano-particles of Ag, Au, etc. were used in our study. These targets were made from the dried mixture of nano-particles of various materials with organic matrix or with simple glue. It was observed that the intensity of the lower order harmonics generated from these targets is quite enhanced compared to that of the corresponding harmonics from bulk materials. For example, the intensity of the $9^{\text{th}}$ harmonic from the plume of silver...
nano-particles is ~200 times higher compared to that from plasma plume of bulk silver. A comparison of the intensities of high order harmonics from various nanostructured targets with those from bulk silver and indium is shown in Fig. 6.

**Generation of Broadband Harmonics**

We have shown that the bandwidth of the harmonic orders can be increased by using a spectrally broadened fs laser. The latter was accomplished by passing the fs laser pulse through a 5 mm thick glass plate. The bandwidth of the laser was increased from ~18 nm to ~32 nm by self phase modulation, resulting in the increased bandwidth of the harmonic orders. For example, the bandwidth of the 17th harmonic was increased from ~0.5 nm to ~0.9 nm.

It was also observed that the bandwidth of the harmonics generated from nanostructured targets can be increased by optimizing the intensity of fs laser pulse. For example, the bandwidth of the 11th harmonic generated from plasma plumes of Ag nanoparticles was increased (only towards blue side) from ~1.4 nm to ~5 nm when the intensity of laser was increased from $1.8 \times 10^{15}$ W cm$^{-2}$ to $3.5 \times 10^{15}$ W cm$^{-2}$ (Fig. 7). This phenomenon is a signature of HHG from blue-broadened laser due to its interaction with expanding nanoparticles at resonance phase. A theoretical model was proposed in our earlier study.

![Fig. 7: Broadening of harmonic spectrum with the increase of laser intensity. The bandwidth of 11th H changed from ~1 nm to ~5 nm, when laser intensity was increased from $1.8 \times 10^{15}$ W/cm$^2$ to $3.5 \times 10^{15}$ W/cm$^2$. The harmonic spectrum for higher laser intensity has been shifted up for visual inspections.](image)

**HHG from Two-Colour Laser Pulses**

Due to inversion symmetry of the HHG process, interaction of the femtosecond laser pulses with the plasma plume resulted in the generation of only odd harmonics. However, this inversion symmetry can be broken by mixing a small amount of second harmonic (SH) radiation in the laser (known as two-colour laser). We generated a two-colour laser pulse by passing the laser through a KDP crystal (conversion efficiency ~2.5%). The use of two-colour laser pulses results in generation of both even and odd harmonic orders with comparable intensities. The process could be seen in Fig. 8. Use of single colour radiation would generate only odd harmonics. As observed in Fig. 8 (a) and 8 (c) odd harmonics of fundamental (800 nm) and second harmonic radiation (400 nm) were generated. Whereas use of two-colour pulse generates the 12th H which is even order for both radiations. These observations indicate that a) the HHG from two-colour laser pulses is not the harmonic generation from individual laser pulses but essentially a symmetry breaking process and b) although the relative intensity of the SH pulse was very small, it was sufficient for breaking the symmetry of the HHG process.

![Fig. 8: CCD images of the harmonic spectra generated in C$_{60}$ plasma in the cases of: (a) single-colour fundamental pump (800 nm), (b) two-colour pump (800 nm + 400 nm), and (c) single-colour SH pump (400 nm). The data were collected under similar experimental conditions.](image)

**Papers Relevant to Present Thesis**

**A. Publications in Journals**


B. Publications in Conferences/symposia


A New Metal Ion Doped Panchromatic Photopolymer for Holographic Applications

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Abstract
The research work focuses on the development of an efficient metal-ion doped acrylamide-based photopolymer recording media for holography. Silver-doped methylene blue sensitized poly (vinyl alcohol)/acrylamide photopolymer system was developed and investigations were carried out to ensure its suitability for holographic applications. The photopolymer films were found to have good energetic sensitivity and transmission gratings recorded in the films using He-Ne (632.8 nm), frequency doubled Nd: YAG (532 nm) and Ar’ (488 nm) lasers exhibited high diffraction efficiency. The recorded gratings could be stored for more than three years with good diffraction efficiency. Holographic data page with good image fidelity and bright transmission holograms could be recorded in the developed photopolymer film.

Experimental
Photopolymer based holographic recording media generally consists of a photoinitiator (photosensitizer dye, electron donor), one or two monomers and an inert polymer matrix (host or binder) [1]. In the present study, poly(vinyl alcohol) (PVA) was used as the binder or the host matrix. Methylene blue (MB) was used as the photosensitizing dye and triethanolamine (TEA) was used as the electron donor. Acrylamide (AA) was used as the monomer. Metallic crosslinkers are incorporated to improve the storage life of the recording media since metal ions form ionic crosslinks with the PVA matrix, thereby inhibiting the diffusion of unreacted monomers and stabilizing the recorded grating. Silver nitrate (AgNO₃) was selected as the crosslinker. Gravity settling and spin coating methods were used for film fabrication. Various characterization methods were used to exploit the potential of the developed film for holographic recording. He-Ne laser (632.8 nm), Ar’ laser (488 nm) and frequency-doubled Nd: YAG Laser (532 nm) were used for various studies. Optical absorption studies were carried out to determine the spectral response of the silver doped MBPVA/AA photopolymer film. The optical absorption spectra of silver doped and undoped MBPVA/AA films are shown in fig. 1. From the graph, it can be seen that, even though the maximum absorption is in the red region (peak at 665 nm) for both undoped and silver doped MBPVA/AA films; silver doped films showed another absorption peak in the blue region (425 nm) as well. Even for 532 nm, there is a small absorption. The broad spectral sensitivity of the silver doped film indicates the possibility of using it as a panchromatic recording material.

Introduction
Holography is one of the remarkable achievements of modern science and technology. With its widespread applications, holography has the potential to stretch boundaries and impact the society profoundly. Fields of applications include interferometric measurement techniques, image processing, holographic optical elements, holographic memories, security holograms and so on. One of the major challenges in the area of holographic technology has been the development of suitable recording materials. Advances in media and recording methods can further enhance the prospects for holography to become a realizable next-generation storage technology. While many materials have been developed as media for holographic storage, most suffer from disadvantages that prevent their use in practical systems [1]. Photopolymer materials are attractive candidates for write-once read-many (WORM) data storage applications because they can be designed to have large modulations in their refractive index and high photosensitivity, record permanent holograms and are capable of real-time image development [2]. Research work on photopolymer materials is on the rise and efforts are made by scientists worldwide to improve the properties of existing materials and also to develop new materials with better holographic properties [3-6]. Dye-sensitized poly(vinyl alcohol)/acrylamide (PVA/AA) photopolymer films with high diffraction efficiency (DE), high sensitivity and high resolution have an important place among the photopolymer-based holographic recording media [7-9]. The thesis entitled “A new metal ion doped panchromatic photopolymer for holographic applications” focuses on the development of silver doped acrylamide based photopolymer recording media for holography. Efforts were made to develop panchromatic photopolymer recording media with improved holographic properties and investigations were carried out to study its capability for holographic data storage (HDS) applications.
Silver-doped photopolymer system consisting of poly(vinyl alcohol) as the binder matrix, acrylamide as monomer, methylene blue and triethanolamine as photoinitiation system and silver nitrate as crosslinker was developed. Incorporation of silver ions into methylene blue sensitized poly (vinyl alcohol)/acrylamide photopolymer was observed to give better holographic performance compared to other metal-ion doped photopolymer holographic recording media [10]. Silver-doped MBPVA/AA films were found to have good energetic sensitivity and transmission gratings recorded in the film using He-Ne (632.8 nm), frequency doubled Nd: YAG (532 nm) and Ar (488 nm) lasers exhibited high diffraction efficiency (DE) of above 70%. The recorded gratings could be stored for more than three years with good diffraction efficiency. The feasibility of recording bright transmission holograms in the material could be successfully demonstrated. The developed panchromatic photopolymer system is excellent on account of its wide spectral sensitivity, high diffraction efficiency, good energy sensitivity, high resolution, cost effectiveness, ease of fabrication and real-time imaging capabilities [11].
Holographic multiplexing studies were carried out to check the suitability of the film for holographic data storage applications. Angle and peristrophic multiplexing techniques were employed for storing multiple transmission gratings in the films. Angle multiplexing was performed by changing the interbeam angle between the interfering beams during the recording of gratings. This results in the recording of gratings with different spatial resolutions in the same volume of the recording material. Peristrophic multiplexing makes it possible to multiplex many holograms in thin films with same spatial resolution. In this technique, after a hologram is recorded, the recording material is rotated around a certain rotational axis so as to record another hologram [12, 13]. Peristrophic multiplexing has the added advantage that it can be combined with other multiplexing methods to increase the storage density of holographic storage systems [1, 14]. In order to fully exploit the refractive index modulation of the recording material, it is essential to record as many holograms as possible in the same volume of the material. When a large number of holograms are to be recorded, their maximum diffraction efficiency should be as constant as possible in order to make an efficient use of the available dynamic range [1, 14]. Gratings were multiplexed by constant and iterative exposure scheduling methods. The storage capacity of the film was determined by calculating the dynamic range (M/#).

$$M/# = \sum_{i=1}^{N} \eta_i^{1/2}$$  \hspace{1cm} (1)

Where, $\eta_i$ is the maximum diffraction efficiency of each of the gratings recorded and $N$ is the number of gratings recorded. DE and M/# obtained were compared to determine which method enabled the greatest number of gratings to be recorded with uniform DE. By peristrophic multiplexing method, 30 nearly uniform plane wave gratings with M/# equal to 4.7, could be recorded in the developed photopolymer film [15, 16]. The diffraction efficiency of 30 peristrophically multiplexed plane wave gratings recorded with a variable exposure schedule is shown in fig. 4. Recording with a variable exposure schedule resulted in nearly uniform gratings. The range of DE was 0.9 to 5.5% and the average DE was 2.7%. The M/# value obtained while recording 30 gratings in this 130 µm thick acrylamide based photopolymer layer is assumed to be larger than the reported values for multiplexing equal number of gratings in acrylamide-based photopolymer materials with similar composition and layer thickness.

Photopolymer films were also fabricated by spin coating technique and holographic transmission gratings with high DE could be recorded in the film. DE of 80% was shown by the grating recorded with an exposure of 50 mJ/cm² (fig. 5). Even for an exposure of 10 mJ/cm², DE above 70% could be obtained, which clearly indicate the high energy sensitivity of spin coated films. The efficiency was above 70% for exposures in the range 10-150 mJ/cm².

Transmission holograms with good image quality were recorded in the films using He-Ne (632.8nm), frequency
doubled Nd: YAG (532 nm) and Ar⁺ (488 nm) lasers. The photographs of the reconstructed holograms are shown in figures 6 (a), 6 (b) and 6 (c).

In order to study the suitability of the photopolymer film for holographic data storage, image of a checker board pattern was recorded in the spin coated silver doped MBPVA/AA film using frequency doubled Nd: YAG laser (532 nm). Two dimensional data pages are stored as Fourier Transform (FT) holograms in a holographic data storage system. The 4-f architecture with the recording medium placed at the Fourier plane of the objective lens is one of the most commonly used geometries for recording data pages. However in this geometry, a high-intensity DC peak occurs in the Fourier plane of an amplitude modulated data page. These high-intensity peaks require a very large dynamic range from the holographic recording material and result in the saturation of the recording material like photopolymers. This saturation results in non-linear grating formation and an increase in the noise level of the reconstructed data page. Several methods exist to diffuse the high-intensity peaks and redistribute the energy into higher spatial frequencies in order to increase the fidelity of the reconstructed data page [17]. Of these, moving the recording material away from the Fourier plane is the simplest and the most commonly used technique as it does not require any additional optical component as some of the other methods require. Defocusing the recording material away from the Fourier plane distribute light more evenly over the aperture of the hologram leading to high fidelity recording. In the present study, a defocused 4/f HDS system (fig. 3) was employed to record the image of a checker board pattern in the film. The laser beam was split into two beams and then spatially filtered, using a microscope objective lens and a pinhole. Liquid crystal programmable matrix modulator (LCD modulator SLM-M) was incorporated in the path of one of the beams, in order to spatially modulate the intensity of the light beam. The SLM-M provides a resolution of 832 x 624 pixels, each of which can be set to a relative transparency of 0 to 254. The pixel size was 27 µm x 27 µm and pixel pitch was 32 µm x 32 µm. The spatially modulated light beam was then directed to the recording medium by an objective lens. A reference beam mutually coherent with the image bearing beam was also incident on the recording medium. This creates a stationary interference pattern and is stored in the recording medium within a spot area of 0.5 cm².

Parameters like exposure energy, beam intensity ratio and defocusing distance was varied in order to study their effect on the quality of the reconstructed image. It was noted that better image fidelity was shown by the image recorded with exposure energy of 90 mJ/cm², beam ratio (R) equal to 2 and defocused distance (z) of 3 cm. Figures 7 and 8 shows the original and reconstructed images of checker board pattern recorded using these parameters. Hence from the present study, the suitability of the developed film for holographic data storage could be successfully demonstrated.

Conclusions

This research work was a small venture towards the realization of a big goal, a competent holographic recording material with excellent properties for practical holographic applications. As a result of the research work, an efficient panchromatic photopolymer system could be developed and its suitability for recording transmission holograms and holographic data page could be successfully demonstrated. The significance of the developed photopolymer material is that it is very cost-effective and requires no post-development. This photopolymer material is expected to have significant applications in the fields of display holography, holographic storage and holographic optical elements.
Acknowledgements

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References

Simultaneous Observation of Laser-induced Photoionization and Fluorescence Signals in Atomic Uranium

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Abstract
Laser-induced photoionization and fluorescence signals were simultaneously recorded in atomic uranium using a single Nd: YAG-pumped dye laser for two specific cases. The uranium atoms in the ground state were ionized by single-color, three-photon photoionization technique resulting in the photoionization signal. The fluorescence signal was simultaneously obtained from the first-excited state involved in the photoionization process. The photoionization and the fluorescence signals were also estimated theoretically for several values of the photoionization cross-section for the transition between the second-excited state and the autoionization state using density matrix (DM) formalism. From the comparison of theoretically calculated ratios of fluorescence signals in the two specific cases with the experimentally obtained values, the photoionization cross-section for the 33801.06-50701.59 cm\(^{-1}\) transition was obtained.

Introduction
Resonance ionization spectroscopy (RIS), which is based on multi-step resonant photoionization of atoms by laser pulses, is an excellent technique for studying highly excited states of atoms [1]. It has provided very useful information on atomic structures as well as laser-atom interaction dynamics. This technique in conjunction with a mass spectrometer, which is known as resonance ionization mass spectrometry (RIMS), has been extensively used by various groups for studying atomic spectra of uranium and ultra-sensitive detection of trace elements [2-4]. As an alternative to RIS, laser-induced fluorescence (LIF) is another powerful laser spectroscopy technique to study high-lying energy levels of atoms [5-7]. In LIF technique, the resonant absorption of laser photons excites the atoms in the initial state to a final state of higher energy and then the excited state relaxes by spontaneous emission of fluorescence radiation to a lower state which could be the initial state or some other intermediate state. The LIF signal strength is directly proportional to the atomic population left in the excited state. Thus, the observation of LIF signals along with RIS signals indicates incomplete ionization of atoms present initially before laser irradiation [8]. Using LIF, the photoionization efficiency of every step involved in excitation and ionization process can be monitored. Hence, the simultaneous detection of LIF and RIS signals plays an important role for monitoring the photoionization process. In the present work we have monitored the photoionization dynamics by simultaneous observation of RIS and LIF signals in atomic uranium using a single Nd: YAG-pumped dye laser. We have analyzed these signals using density matrix (DM) formalism. We have compared the theoretical ratios of these signals in the two specific cases with the experimentally measured ratios and obtained the photoionization cross-section for the 33801.06-50701.59 cm\(^{-1}\) transition.

Experimental Details
The experimental setup for simultaneous detection of RIS and LIF signals is shown in Fig. 1. It consists of a high temperature atomic vapor source in a vacuum chamber, a dye laser (Quantel TDL 90) pumped by a Q-switched Nd:YAG (Quantel YG 980) laser, a U-Ne hollow cathode discharge lamp (HCDL), a photo-multiplier tube (PMT), a 0.5 m monochromator, a 1.5 m high-resolution monochromator, a pyrometer, a high voltage power supply and an oscilloscope. A pencil-type electron gun of 8 kW power (32 kV, 250 mA) is mounted in the vacuum chamber at an angle of 45° relative to the horizontal axis. The electron beam is turned through another 45° by an external magnetic field so as to ensure normal incidence of electron beam on the surface of the material to be evaporated. The pulse duration, repetition rate and line width of the dye laser were 7 ns, 20 Hz and 0.05 cm\(^{-1}\) (1.5 GHz), respectively. The laser pulse energy in the interaction zone was 2.5 mJ. The laser beam diameter in the interaction zone was 5 mm. The laser beam passed through the atomic beam of uranium in cross-configuration. Resonance and near-resonance excitation was ensured with the help of OG signal which was monitored by passing the laser beam through the HCDL during the experiments. The fluorescence light emitted from the first-excited level was collected in a direction perpendicular to both laser and atomic beams and focussed onto the entrance slit of the 0.5 m monochromator by a suitable lens assembly. The photoion signal was detected using a parallel-plate configuration and applying – 2 kV to the plates across a load of 5 kΩ. The monochromator here is used as a filter. The output slit of the monochromator was coupled with a PMT (gain of 10\(^7\)).
Results and Discussions

The 0-16900.38 cm⁻¹ transition at 591.5 nm in atomic uranium is well studied as it is one of the strongest atomic transitions in uranium in the visible region [9]. This transition also serves as a first-step transition in the RIS of ground-state atoms of uranium using single-color three-photon photoionization pathway to the autoionization state at 50701.59 cm⁻¹. Considering this transition, we have conducted the experiments for simultaneous observation of LIF and RIS signals.

Table 1. Theoretical Ratios of LIF and RIS Signals for Several Values of the Photoionization Cross-Section $\sigma$.

<table>
<thead>
<tr>
<th>$s_i$ (10⁻¹⁶ cm⁻²)</th>
<th>Theoretical ratio</th>
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<tbody>
<tr>
<td>LIF</td>
<td>RIS</td>
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<td>2</td>
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<td>10</td>
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Results and Discussions

The 0-16900.38 cm⁻¹ transition at 591.5 nm in atomic uranium is well studied as it is one of the strongest atomic transitions in uranium in the visible region [9]. This transition also serves as a first-step transition in the RIS of ground-state atoms of uranium using single-color three-photon photoionization pathway to the autoionization state at 50701.59 cm⁻¹. Considering this transition, we have conducted the experiments for simultaneous observation of LIF and RIS signals.

Fig. 1: Experimental setup for simultaneous observation of LIF and RIS signals.

Fig. 2: Energy level diagram for single-color, three-photon photoionization and single-color laser-induced fluorescence when (A) The laser is tuned to resonance in first step transition (0-16900.38 cm⁻¹), (B) The laser is detuned from resonance in first step transition by 0.15 cm⁻¹, so that it became two-photon resonant at 33801.06 cm⁻¹.
observation of LIF and RIS signals in atomic uranium in two specific cases. In the first case, the laser was resonantly tuned to this first-step transition, which excited the uranium atoms in the ground state to the 16900.38 cm⁻¹ energy level as shown in Fig. 2A. Two photons of the same laser further photoionized the excited uranium atoms via a near-resonant intermediate state at 33801.06 cm⁻¹. Both the two-photon photoionization signal and the resonant fluorescence signal have been observed using an oscilloscope. Typical RIS and LIF signals were recorded. In the second case, the laser was slightly detuned from the first-step transition by 0.15 cm⁻¹ so that it became two-photon resonant at 33801.06 cm⁻¹ as shown in Fig. 2B. Typical RIS and LIF signals were also recorded in this case. The RIS signal increased relative to the first case owing to the two-photon resonance transition and its connection to autoionization resonance at 50701.59 cm⁻¹. However, the LIF signal decreased relative to the first case, owing to detuning of the laser from the first-step resonance. All the experiments were done by taking an average of 64 laser pulses. The experimental ratios of RIS and LIF signals were determined by dividing the signal value measured in the first case to that in the second case. These experimental ratios were obtained by repeating the experiments six times for both the cases. The arithmetic mean of the six values of the ratios is represented as the average value of the ratio. We have taken these average values as the measured ratios. We have found the uncertainty in the signal ratios within ± 20% from the spread in the data obtained in the six experiments. This can be attributed to the change in the experimental conditions such as fluctuations in pulse-to-pulse laser power, atomic number density and the optimization of signals for both cases. The measured ratios of LIF and RIS signals are thus deduced as 3.0 ± 0.6 and 0.5 ± 0.1, respectively.

We have employed DM formalism to analyze the RIS and LIF signals observed in the two specific experimental cases. The DM formalism for three level open atom interacting with a pulsed narrowband laser relevant to the experiment is discussed in detail in our recent work [10]. From the DM calculations, we have obtained the ratios of photoionization as well as fluorescence signals in the two specific cases, considering several values of the photoionization cross-section as shown in Table 1. By comparing the theoretically calculated LIF and RIS ratios with the experimentally measured values, it is observed that the theoretical LIF ratio (2.9) corresponding to the photoionization cross-section of 5×10⁻¹⁶ cm² matches well with the measured ratio (3.0) within the experimental error whereas the theoretical RIS ratio (0.6) reasonably matches with the measured ratio (0.5) within the experimental error for many values of the

**Conclusion**

We have measured the photoionization cross-section for the 33801.06-50701.59 cm⁻¹ transition in atomic uranium using simultaneous observation of RIS and LIF signals under two specific experimental cases and comparing the experimental results with density matrix calculations.

**Acknowledgments**

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**References**

Coherent Random Lasing from an Array of Amplifying Aperiodic Spherical Scatterers

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Abstract

We demonstrate coherent random lasing from an array of polydisperse and monodisperse microdroplets having gain within. The microdroplets are well separated and act as uncorrelated amplifying scatterers. Ultra-narrow lasing peaks are observed in the longitudinal direction which originates from the entire array. The lasing modes in monodisperse droplets show wavelength sensitivity and larger coherent to incoherent ratio. The origin of ultranarrow modes is attributed to nonresonant feedback within the array. Wavelength sensitivity indicates the participation of Fabry-Perot resonance of an individual droplet. Spectral image and the threshold behavior of emission are also shown to confirm extended mode and random lasing respectively.

Introduction

Lasing is a consequence of a gain medium and a carefully designed resonant cavity. However, randomly distributed elastic scatterers dispersed in an amplifying medium can also provide coherent emission, termed as random lasing [1]. Theoretically, Letokhov [2] proposed the amplification of light via multiple scattering in a disordered amplifying medium. Experimentally, Lawandy et al. [3] observed a significant collapse of emission linewidths with TiO$_2$ spheres in a dye-solvent system. Over the years a variety of material were identified to show random lasing. The system primarily consists of two parts, amplifying medium and randomly distributed scatterers. In most cases, scatterers are separately added to the amplifying medium. For example, when nano-particles like polystyrene or TiO$_2$ are suspended in a laser dye solution, the nano-particles acts as scatterers and the dye solution acts as an amplifying medium. On the other hand, ZnO powders, Nd-doped powders or dye-doped scatterers are different in the sense that both the scattering and amplification are provided by the same entity. In these powder lasers, the scatterers are in a random close-packed formation and hence they are strongly correlated. The inter-scatterer separation cannot be increased as it changes the scatterer density, hence affecting the gain and multiple scattering processes.

Experimental Setup

The experiment deals with the generation of an array of microdroplets (scatterers) and the observation of their emission under laser pumping as shown in Fig.(1). The microdroplets were created from a solution of Rhodamine 6G dissolved in alcohol. The solution is contained in a liquid container with two openings, one for
the gas and another for the liquid solution. The liquid in this container is pressurized using a non-interacting gas. The gas pushes the solution through the micro-capillary (M.C.) with an inbuilt piezo crystal. Under this pressure, the dye ejects in the form of a stream of polydisperse and arbitrary shaped droplets, with a random spacing between them. This stream is irradiated by the second harmonic (532 nm) of a 25 ps Nd:YAG Laser with a focal spot of ~1 mm to pump sufficient number of scatterers (~20 droplets).

Results and Discussions

Two representative longitudinal spectra at pump energy of 10 µJ are shown in Fig. 2[A]. The general characteristic of a coherent random laser like ultra-narrow bandwidth, pulse to pulse intensity fluctuations etc. are observed in the longitudinal emission. The bandwidth of the peaks is measured to be ~0.2 nm, which is limited by the resolution of our spectrometer. We find that every peak in the longitudinal direction has a corresponding vertical bright stripe in the transverse emission which confirms the participation of the entire droplet array in the pumped region.

200 spectra were taken to analyze the frequency fluctuations in these lasing modes. The coherent peaks fluctuate in wavelength over a range of ~ 15 nm as shown in Fig.3[A]. Most of the lasing peaks appear at the emission maximum of dye as expected. The variation of coherent intensity in the longitudinal direction as a function of pump energy is shown in Fig.3[B]. A threshold behavior is observed at $E_p = 0.5$ µJ, after which the output emission grows steadily.

A CCD camera was employed to image the array. This enables the measurement of the size and the spacing distribution of the droplets. Fig.1 (C) shows the distribution of sizes and center to center separation between the droplets. Mirror M2 was placed at about 40º from the vertical axis to redirect the longitudinal emission. Lens L2 was placed on a XYZ translation stage to collect, and focus the transverse and longitudinal emission on the entrance slit of the spectrometer. The emission from the array was analyzed using a 0.5 m focal length spectrometer.

![Fig. 1 : [A]- Schematic of the experimental set-up used for observing random lasing from the stream. M.C. is the micro-capillary to produce microdroplets, Droplets are pumped by a picosecond Nd:YAG Laser, Lens L1 focuses the beam onto the droplet stream. Mirror M2 redirects the longitudinal emission. Lens L2 focuses the redirected emission into the spectrometer. [B]- One of the embodiments of the droplet array. [C]- Distribution of sizes and center to center separation of the droplets.](image)

![Fig. 2 : [A]- Experimentally observed emission spectra from longitudinal direction of the array. [B]-(1): longitudinal spectra, (2) and (3): Simultaneously taken spectral image in the longitudinal and transverse direction respectively.](image)

![Fig. 3 : [A] Distribution of wavelength at which random lasing was observed. [B] Threshold behavior of peak intensity, circles indicate coherent intensity in the longitudinal direction.](image)

To make the droplets monodisperse, the piezo crystal is driven by a periodic square wave and at a frequency of few hundred kHz. The pressure of the chamber and the frequency of vibrating piezo crystal are adjusted such that the liquid jet breaks up into equal sized microdroplets.

Fig. 4(A) shows an image of aperiodic monodisperse scatterer array; [C] is the distribution of center to center separation between the scatterers to confirm randomness. The most probable separation between the scatterers is ~30 µm which is much larger than the emission...
Fig. 4 [A]: The embodiment of the droplet array. [B]: Transverse emission from spherical scatter, black curve is the experimentally observed WGM modes. The red curve is the theoretically calculated Mie scattering efficiency $Q_{Mie}$ curve. [C]: Distribution of center to center separation between the droplets.

To estimate the size of the scatterers we collected the transverse emission. The size of spherical scatterer ($d$) is given by

$$d = \left( \frac{\lambda^2 \pi \theta}{\lambda^2 \pi \theta} \right)^{1/2} \lambda,$$

Where $\theta = \tan^{-1}\left( \frac{(n^2-1) \theta}{(n^2-1) \theta} \right)$. $\theta$ is the separation between two WGMs and $n$ is relative refractive index (for methanol $n = 1.329$). The black curve in fig 4(B) is the experimentally observed WGMs modes with $\theta = 4.75$ nm and central wavelength $\lambda = 558.05$ nm. From Eq.1 this corresponds to a scatterer size of 17.14 $\mu$m. The red curve is theoretically generated Mie scattering efficiency ($Q_{Mie}$) curve, this fits the experimental WGM peaks for a particle size of 17.18 $\mu$m.

Fig. 5 [A]: Two representative spectra obtained in the longitudinal direction. [B]: Probability distribution of lasing wavelength shows a frequency quantization effect.

Fig. 6 [A]: The green and the red circles indicate the calculated the WGMs and FP mode separation respectively, black triangle the experimental measured bunch separation. [B] Threshold behavior of lasing peak intensity.

Two representative longitudinal spectra for monodisperse scatterer are shown in Fig. 5 [A]. The general characteristics of a coherent random laser like ultra-narrow bandwidth, pulse to pulse intensity fluctuation etc. are present in the aperiodic mono-disperse configuration also. But unlike conventional random laser the emission is fully coherent as the incoherent pedestal is absent. The distribution of random lasing peaks at pump energy of 0.7 $\mu$J and for a particle size of 19.6 $\mu$m is shown in Fig. 5 [B]. We observe that lasing peaks occurs only in discrete, specified interval of wavelengths. The bunching in random lasing peaks can be seen whenever the scatterers are mono-disperse and it is confirmed for various particle sizes.

The wavelength quantization can be explained in terms of Fabry-Perot (FP) resonance. Each micro-droplet acts as a spherical FP micro-cavity with opposite spherical surfaces being FP reflectors. Finesse depends on refractive index and size of spherical cavity. For a single scatterer with size 19.6 $\mu$m and $n = 1.329$, the finess of FP mode is $\sim 2.5$ at $\lambda = 560$ nm.

The generation of coherent lasing peak in the longitudinal direction can be understood in the following way. The emission from the scatterers is emitted in all directions.
The fluorescence that propagates along the array undergoes multiple scattering, thus increasing the effective dwell time of photons. The non-resonant feedback due to multiple scattering and the availability of gain in the neighboring scatterers helps in the avalanche amplification of these photons. When the scatterers are mono-disperse, FP modes occur at the same wavelength in all the scatterers. This cavity enhanced amplified photon acquires large intensity in comparison to a photon that lies outside the FP mode. The whole phenomenon can be put forth as amplification helped by the resonant feedback inside a droplet, assisted with non-resonant feedback between the droplets. This is the origin of frequency quantized coherent emission. We have analysed the distribution of coherent random peaks for various particle sizes ranging from 16 to 20 µm. Fig 6 [A] shows the variation of free spectral range (FSR) of FP mode as a function of particle size. The experimental data show excellent agreement with the calculated FSR spacing. Fig 6 [B] shows the lasing intensity of collective emission as a function of excitation energy, a clear threshold is observed at $E_0 = 0.12 \, \mu\text{J}$ which is lower than the threshold of polydisperse scatterer configuration.

**Conclusion**

In summary we have demonstrated coherent random lasing from a linear array of amplifying scatterer. Spectral image shows the co-operative participation of several scatterers. Frequency control is achieved by making the scatterers monodisperse. We believe due to the fluidic nature of our system it can be utilized as a microfluidic optical source. Coherent emission from such an ultra-small system ($\sim 1 \, \text{mm} \times 20 \, \mu\text{m}^2$) is also a motivating factor for deeper study.

**References:**

Study of Strain Propagation in Laser Irradiated Silicon Crystal by Time-resolved Diffraction of K-$\alpha$ X-ray Probe of Different Photon Energies

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Abstract

We present the results of initial experiments on time resolved x-ray diffraction study of strain propagation in laser shocked crystal, carried out using a CPA based Ti:sapphire laser system. The characteristic K-$\alpha$ x-ray line radiation generated by femtosecond laser produced plasmas of two different target materials (iron, and copper) are used as probe; whereas the stretched pulse of sub-nanosecond duration (pump), from the same laser, is used to compress the sample. The use of x-ray probe of different photon energies yields information about the strain over a greater crystal depth. The dynamics of the strain propagation is inferred by monitoring the rocking curve width of the shocked sample as a function of the time delay between the pump and the probe pulse. The shock velocity deduced from these measurements is ~ 1.2 x 10\textsuperscript{6} cm/s, consistent with the velocity in compressed silicon. The observed maximum compression is 0.4 \%, which corresponds to a pressure of 0.8 GPa

Introduction

In the recent years, shock compression of condensed matter has emerged as a subject of considerable importance for a variety of research investigations such as phase transitions\textsuperscript{1} (both structural and magnetic), strain propagation\textsuperscript{2}, etc. X-ray diffraction, although a simple technique, offers great potential in terms of direct observation of lattice distortion because of the inherently large penetration depth of x-rays in matter. Time resolved x-ray diffraction\textsuperscript{3} thus enables real time visualization of atomic arrangement in the sub-ps time scale. The x-ray bursts from sub-ps laser produced plasmas have been utilized for time-resolved study of processes like ultrafast excitation of the crystal lattice non-thermal melting of semiconductors, optical and acoustical phonon excitations etc. In particular, the characteristic K-shell line radiation (K$_{\alpha}$) has generated much interest to be used as a narrow bandwidth and ultrafast probe to study fast processes in matter\textsuperscript{4}. It is generated by the interaction of hot electrons with cold target material behind the plasma. Depending on the interaction parameters, the hot electrons are generated through collective mechanisms such as resonance absorption, vacuum heating, jxB heating etc. These electrons penetrate into the cold target material to generate continuum hard x-ray bremsstrahlung and characteristic K-$\alpha$ line radiation. The photon flux, time duration, and monochromaticity of the K$_{\alpha}$ emission is primarily determined by the hot electrons parameters such as the incident number, energy and its transport into the bulk solid\textsuperscript{5}.

In a typical time resolved x-ray diffraction (TXRD) setup, a major part of the laser beam energy is focused on to a solid target to generate an efficient, high brightness, sub-picosecond x-ray probe beam. The line radiation emitted is used as a monochromatic x-ray source for probing the transient structural modifications in the crystalline sample induced by the remaining fraction of the laser beam referred as pump laser. For instance, the interplanar spacing is changed due to propagation of shock wave inside the crystal irradiated by pump laser. In such experiments, the rocking curves of the sample are recorded for different time delays between the pump and the probe pulse. Commonly, the experiment is performed in Bragg geometry. It is well known that in the case of Bragg reflection, a large number of layers participate in the process and the diffraction pattern is cumulative contribution of all the participating layers. From the Bragg’s law, the angle of diffraction is related to the change in inter-planar spacing. The lattice strain can be estimated using the relation, \( \Delta d/d = -\cot \theta_s \Delta \theta \), where d is inter-planar spacing, \( \theta_s \) is Bragg angle and \( \Delta \theta \) is shift in Bragg angle. In such experiments, dynamics of the lattice deformation is studied from the shift / broadening of the diffracted x-ray peak and the change in reflectivity of the sample. In addition to this, exploiting the fact that different x-ray photon energies have different 1/e attenuation length in the material, keeping the external excitation source parameters invariant, it is possible to infer about the characteristics of shock wave propagation inside the optically opaque samples.

We present the results of initial experiments on time resolved study of strain propagation in laser shocked Si
crystal conducted using the CPA based Ti:sapphire laser system. The characteristic $K_\alpha$ x-ray line radiation of high brightness, sub-picosecond duration, generated by femtosecond laser produced plasmas of two different target materials (iron, and copper) are used as probe; whereas the stretched pulse of sub-nanosecond duration (pump), from the same laser, is used to compress the sample. The dynamics of the strain propagation is inferred by monitoring the rocking curve of the shocked sample as a function of time delay between the pump and probe pulse. The shock velocity deduced from these measurements is $\sim 1.2 \times 10^6$ cm/s, consistent with predicted velocities and probe depth. The observed maximum compression is 0.4% which corresponds to a pressure of 0.8 GPa.

**Experimental Details**

The experiments were conducted using the 10 TW Ti:sapphire laser system at RRCAT. The schematic of experimental setup is shown in Fig.1(a). The $K_\alpha$ x-ray probe was generated by focusing the 45 fs laser pulses onto solid (iron and copper) targets. A part of the uncompressed (200 ps) pulse was used to irradiate a 500 μm thick flat Si (111) crystal ($2d = 6.271$ Å) at an intensity of 6 GW/cm². The time delay between the 200 ps pump laser pulse and the probing x-ray pulse was adjusted by an optical delay line. A positive delay here means the pump laser pulse is leading the probe x-ray pulse. The diffracted x-ray spectrum was recorded on an x-ray CCD camera. The point x-ray source allowed a direct imaging of a part of the crystal surface onto the x-ray CCD camera. This enables simultaneous recording of the diffracted x-ray spectrum from the laser irradiated and pristine area of the crystal. Figure 1(b) shows the space resolved CCD image of the diffracted iron $K_\alpha$ x-rays from laser irradiated Si (111) surface at a delay of +600 ps. The lower part of the same picture shows the pristine sample where the $K_\alpha$ lines ($K_{\alpha_1}$ and $K_{\alpha_2}$) are clearly identified. The upper part of the picture shows blurring of the $K_\alpha$ lines because of the non-uniform lattice compression attributed to cumulative effects of the laser induced compression wave and the associated thermal broadening of the lattice.

The adjustment of setup to ensure the temporal and spatial overlap is the major challenge. Spatial overlap is achieved by carefully matching the spot of visible He-Ne laser from x-ray probe direction, pump direction and x-ray CCD direction to find the approximate overlap. Next, the position of x-ray on the sample surface is located by covering a part of sample with a thin foil and recording Bragg diffraction by moving sample until the Bragg peaks are appeared. Temporal overlap is first approximated by monitoring the scattered laser radiation (both pump and probe) from sample with a pin diode and fast oscilloscope. Next, Bragg diffraction is observed for scanning negative delay (probe ahead). The position from where no change is observed is taken as zero time.

**Results and Discussion**

The measured rocking curves of Si (111) irradiated by 200 ps laser pulse at a fluence of 2.3 J/cm² for various delay times between -300 ps and +1800 ps are shown in Fig.2. Irradiation by pump laser causes formation of plasma and the expansion of this plasma into the surrounding vacuum drives a shock into the underlying silicon crystal. In this measurement no x-ray optics was used therefore the diffraction pattern is the superposition of the rocking curve of the $K_{\alpha_1}$ and $K_{\alpha_2}$ lines. Nevertheless, diffraction profiles of Fe $K_{\alpha_1}$ (6403.8 eV) and $K_{\alpha_2}$ (6390.8 eV) are well resolved for zero and negative delays. It is observed that the diffraction pattern broadens with increasing time delay up to +1200 ps. After that, the broadening reduces, and finally comes back to original state for delays larger than +1500 ps. The x-ray beam is diffracted from the sample at a particular angle within a thin layer of the crystal where the lattice spacing is such that the Bragg condition is satisfied. The different layers, strained to different extents under the influence of the compression wave, will diffract at other angle leading to the broadening. Furthermore, at early times, the diffraction will occur from both shocked material and the underlying unperturbed crystal. It may be noted that the broadening of the diffracted signals towards higher angles implies lattice compression induced by pump laser beam. The compression of the lattice is either due to the laser ablation of very thin surface of the silicon or due to the stress caused at the front of thermal expansion due to the surface energy deposition. On the other hand, the spread towards lower angles reveals the signature of thermal disordering effect indicating a larger role of thermal wave. Nevertheless, the time evolution of the

![Fig. 1: (a) Schematic experimental setup; (b) CCD image of the diffracted x-rays showing irradiated and pristine parts of the crystal](image-url)
thermal expansion and rarefaction, and thus the
diffraction profile comes close to the pristine level. The
use of x-ray probe of different photon energies can give
information about the strain over a greater crystal depth.
Therefore, rocking curve of silicon irradiated at same
laser parameters (200 ps, 2.3 J cm⁻²) was also measured
with Cu Kα (8.05 keV, θ₁: 14.2°). The profiles of the
rocking curves are similar to those measured with Fe Kα
(4.5 keV, θ₁: 18°). Figure 4 shows the FWHM of Kα line
radiation as function of delay between pump and the
probe pulse for the Fe and Cu. The diffraction profile is
broadened due to change in inter planar spacing.
Diffraction of a beam of x rays incident on the crystal at a
particular angle only takes place within a thin layer of the
crystal where the strain is such that the Bragg condition is
satisfied for the interplanar spacing of that particular
layer. Therefore, the change in measured rocking curve
width gives the direct measurement of strain. This gives a
measurement of the elastic component of the strain since
the lattice spacing is measured for planes parallel to the
shock front. The calculated strain profile is shown in
rocking curve signifies the propagation of laser induced
shock waves inside the crystal. At later times, the
separation of the Kα peak signifies the passing of shock
waves beyond the maximum probe depth inside the
crystal. Figure 3 shows the FWHM of Kα line as a
function of the delay between the pump and the probe
pulse, for two different pump laser fluences. It is
observed that maximum broadening occurs for a lower
laser fluence of 1.2 J-cm⁻² at time delay of 1050 ps
compared to 1160 ps observed at higher fluence of 2.3 J-
cm⁻². The shock pressure is expected to be lower at lower
irradiance and the compression wave will attenuate
before reaching the penetration depth.

The x-ray photons penetration depth inside the sample is
governed by the mean free path of the photons in the
crystal and the Bragg angle. The x-ray photons probe
strained layer upto the attenuation length and the
resultant diffraction pattern is due to encountered
strained layers. The compressed layer relaxes due to

**Fig. 2:** Evolution of Si (111) rocking curve for various time
delays, at a fluence of 2.3 J cm⁻².

**Fig. 3:** FWHM of Kα line as a function of delay between pump
and probe pulse for two different fluences

**Fig. 4:** FWHM of Kα line radiation as function of delay between
pump and the probe pulse for Fe, and Cu

**Fig. 5:** Strain variation as a function of delay between pump
and the probe pulse for Fe, and Cu
Fig. 5. It is observed that the diffraction pattern broadens with increasing delay to reach the maximum. Thereafter, the $K_{\alpha}$ width decreases and come close to the pristine value. Maximum broadening occurs at 1160 ps, and 1870 ps for, Fe, and Cu respectively. The FWHM of the rocking curve of the irradiated sample shows broadening of $3.2 \pm 0.3$ times, compared to that of the rocking curves of pristine sample, for both the probe x-ray lines. The high energy x-rays have longer penetration depth (distance from the surface, governed by the Bragg angle) and are therefore expected to yield information about the strain over a greater crystal depth. The similar nature of the variation of the FWHM of the rocking curve for the two probes is perhaps due to the decay of the compression wave at longer probe delay.

A quantitative knowledge of the velocity of the propagating compression front requires computer simulations based on the dynamical x-ray diffraction theory applied to the strained and laser-shocked crystal. Nevertheless, some important information can be obtained from the delay time at which maximum broadening occurs when the shock arrives at depth equals to penetration depth of the x-ray probe. The attenuation length for Fe and Cu $K_{\alpha}$ are 66 $\mu$m and 17.4 $\mu$m respectively. Taking the penetration depth to be half of the attenuation length, the mean propagation speed of the laser induce compression wave, deduced from the maximum broadening time of the two different x-ray probe comes out to be $1.2 \times 10^4$ cm/s, which is very close to the sound velocity of $9.4 \times 10^4$ cm/s in Si. The derived shock velocity values are in broad agreement with those obtained under similar irradiation conditions. The maximum lattice strain was estimated from the shift (up to which diffraction signal appears) of 0.074, corresponding to a compression of 0.4%. Hironaka et al have reported a maximum lattice strain of 1.05%, corresponding to the maximum pressure of 2.18 GPa. The maximum lattice strain of 0.4% in the present experiment corresponds to a pressure of 0.83 GPa.

In conclusion, time resolved x-ray diffraction is used to measure the rocking curve of the laser irradiated silicon crystal. The $K_{\alpha}$ x-ray line emissions from high-intensity ultra-short laser pulse produced plasmas of two different target materials (Fe, and Cu) are used as probe. The dynamics of the strain propagation is studied by measuring the rocking curve of the shocked sample as a function of delay between the pump and the probe pulse. The shock velocity deduced from these measurements is consistent with the predicted velocities. The observed maximum compression is 0.4% which corresponds to a pressure of 0.8 GPa (8 kbar). The study can be of interest in view of the probing by x-ray pulses of widely different photon energies that can directly give information of shock penetration depth. This makes this technique promising for studying the temporal and spatial strain profile of shocked samples.

References
Abstract
A Shack Hartman wavefront sensor has been fabricated with a lenslet array of 88 lenses for the wave-front analysis of high power Nd:glass laser beams. The wavefront sensor has an input pupil of 130 mm diameter and records the burn pattern data on a photographic paper mounted on the back focal plane. Software is developed for locating the centroid and wave-front analysis. Using the instrument, a 60 mm diameter laser beam from Nd:glass high power laser has been analyzed for aberrations.

Introduction
High peak power Nd:glass laser systems are used for creating high intensities greater than $10^{11}$ W/cm$^2$ for applications in inertial confinement fusion, equation of state (EOS) studies, intense x ray generation etc [1]. This requires the laser beam wave-front quality to be of the order of the diffraction limit. This is achieved by using a master oscillator of low $M^2 \sim 1 - 1.3$, amplifiers with symmetric pump and cooling arrangements, nonlinear phase conjugate mirrors, spatial filters with high $f$/# lenses etc. Apart from these passive methods, adaptive optics (deformable mirrors) are also used as final wavefront correctors.

The large number of optical elements used in these laser systems, if not chosen and assembled properly, leads to aberrations in the laser beam. It is therefore necessary to control the aberrations at the source itself to make it possible to correct the beam to the diffraction limit using the deformable mirror at the end of the laser chain. In order to control the aberrations, the wavefront has to be measured and analyzed. Interferometers, Shack Hartmann (SH) sensors etc. are used for this purpose [2, 3, and 4]. Due to its simpler construction, relative insensitivity to vibrations, Shack Hartmann sensors, along with wave-front analysis software, are used to analyze wavefronts. Generally SH sensors use a matrix of micro-lens lenslets followed by a CCD detector. The commercially available SH sensor has a maximum size of $\sim 20$ mm x 20 mm. For high power laser beam of sizes 50 mm to 100 mm, the device is not available commercially.

At RRCAT, we have developed a SH sensor for handling beam size up to 130 mm. We describe here the design, fabrication, reference generation, recording of the SH pattern of a 60 mm laser beam, analysis software development, and analysis of the wave-front.

The Shack Hartman wavefront sensor (SHWFS) has been developed with a lenslet array for use in the 1054 nm wavelength range. The SHWFS consists of 88 lenses, each of focal length 700 mm, arranged in a square array with 11 mm pitch filled within a circle of 125 mm diameter. The wavefront sensor samples the input beam and records the burn data on the thermal paper which is mounted on the detector plate of the instrument. The grain size of the photographic paper is $\sim 2 - 10$ µm. The SH pattern is then scanned with a flatbed scanner with 1200 dpi resolution. The local tilt of the wavefront across each lens is calculated from the position of the focal spot on the sensor. By sampling the array of lenslets, all of these tilts are measured and the whole integrated wavefront is synthesized and later characterized.

Shack Hartman Sensor fabrication.

The fabrication of the instrument mainly involves an iterative process of mounting the lenslets on the sampling plate (see Fig.1) and inspection of focal spot of the lenses to be placed in a single plane. The sampling plate consisted of mounting holes for the 88 lenses, each of 10 mm diameter. The lenses were mounted in a square grid of 11 mm pitch and contained within a circular aperture of 125 mm. The lens mount features were fabricated on a 20 mm thick Al-6061-T6 plate, with CNC BARON® 3-axis mill within an accuracy of ±10 µm all over the grid, as inspected with FARO Gauge® CMM. The lenses were mounted on to the sampling plate and then inspected for focus points to be contained in a single plane for a plane wave front obtained using ZYGO® Interferometer. The errant lenses were removed and replaced with fresh ones. This was done iteratively till all the focus points were found to be in a single plane. The focal plane thus obtained was at 700 mm from the sampling plate. The detector plate was then fabricated on a 12 mm Al-6061-T6 plate with square holes pattern matching to the lenslet array, machined with die-sinking EDM process. The two
corresponding shifts in the focal spots at the detector. Let \( \Delta x \) and \( \Delta y \) represent the local displacements of the spots in the back focal plane. The respective \( x \) and \( y \) gradients of the wavefront are \( \frac{\partial \phi}{\partial x} \) and \( \frac{\partial \phi}{\partial y} \) at the center of the individual lens in the lenslet array. Using the displacements \( \Delta x \) and \( \Delta y \) one computes the gradient information with the equation 1, where \( F \) is the back focal length of the lens.

\[
\frac{\partial \phi}{\partial x} = \frac{\Delta x}{F} \\
\frac{\partial \phi}{\partial y} = \frac{\Delta y}{F}
\]

\[
\phi = \int \nabla \phi \cdot dr + \phi_0
\]

\[
= \int \int \frac{\partial \phi}{\partial x} \, dx + \frac{\partial \phi}{\partial y} \, dy
\]

In order to reconstruct the wavefront, one has to carry out a path integration which is expressed as an \( x, y \) integration using the gradient data information. Using the equation 2 on a discrete set we perform the integration to construct the wavefront \( f(r, \theta) \). For analysis, we use an orthogonal basis \( V_j \) to represent this wavefront as a linear combination as expressed in equation 3 where \( B \) are the coefficients of their respective polynomials which are determined using orthogonality condition.

\[
\phi(r, \theta) = \sum_{i=1}^{N} B_j V_j
\]

### Discrete Orthogonal Basis for Zernike Decomposition

The Zernike polynomials are described by \( U(r, \theta) \) functions and they are orthogonal over a unit circle. These polynomials are discretized by sampling them on a rectangular grid and are represented by the set \( U \). To construct a orthogonal basis, we follow the method described by Malacara [5]. The \( V_j \) data set is constructed using the sampled Zernike data set \( U_j \) which obey the orthogonality condition over the unit circle. Here we describe a method in which the sampled data set \( U_j \) is orthogonalized using Gram – Schmit orthogonalization and which results in an orthogonal set \( V_j \). The process begins by computing \( V_j \) which nothing but \( U_j \), then computing \( V_j \) based on the values of \( U_1, U_2 \) and \( D_{1j} \). The first three orthogonal polynomials are illustrated in equations below along with their respective \( \rho \) coefficients. Wavefront coefficients \( D_{\rho} \) define the coefficients of the orthogonal polynomials on the discrete set of the measured data points \( V_j \). The orthogonality condition implies that the dot product of \( V_j \) and \( V_\rho \) should
identically come out to zero, from which we get the individual coefficients $D_j$, as depicted in equation 4, 5.

\[
\begin{align*}
V_1 &= U_1 \\
V_2 &= U_2 + D_{21}V_1 \\
V_3 &= U_3 + D_{31}V_1 + D_{32}V_2 \\
V_j &= U_j + \sum_{i=1}^{i-1} D_{ji} V_i \\
D_{jp} &= \frac{\sum_{i=1}^{N} U_j V_p}{\sum_{i=1}^{N} V_p^2} 
\end{align*}
\] (5)

where $N$ is the number of points of sampled wavefront. $B_j$ are the coefficients of the polynomials to be determined. The wavefront $f(r, \theta)$ can now be expressed as a linear combination of the polynomials $V_j$ and the respective aberration coefficients can be easily computed by taking the dot products of the discrete wavefront set with the discrete orthogonal polynomials $V_j$ which we have constructed with the above method. The coefficients $B_j$ are the aberration coefficients for the sampled wavefront, as in equation 6.

\[
\begin{align*}
\phi(r, \theta) &= \sum_{i=1}^{N} B_j V_j, \\
B_j &= \frac{\sum_{i=1}^{N} \phi V_p}{\sum_{i=1}^{N} V_p^2} 
\end{align*}
\] (6)

Results

The figure 3(a) below shows the results of the wavefront reconstruction from the SHWFS. The figure 3(b) shows the spot recorded on the thermal paper using the SHWFS and its displacement from the calibrated plane wave in the form of arrows. The sampled polynomials have been plotted in the figure 3(c) which form the basis of the wavefront reconstruction. The domain for $\phi = [0, 2\pi)$, $r = [0, 30 \text{ mm}]$ for the plots below.

The results of the above experiment are summarized in the Table 1 below which describes the measured wavefront in terms of $B_j$ coefficients. Apart from the gross tilts which are due to alignment errors of the axis of SH sensor and the direction of propagation of light there are higher order aberrations which are recorded in the form of astigmatism. The typical values of the maximum wavefront errors are tabulated below.

**Table 1: Results of Wavefront characterization with SHWFS.**

<table>
<thead>
<tr>
<th>S No</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peak Wavefront error</td>
<td>57 $\mu$m</td>
</tr>
<tr>
<td>2</td>
<td>Delta Wavefront due to tilt</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>3</td>
<td>$B_i {\text{Coeff. of astigmatism } r^2 \sin (2\theta)}$</td>
<td>-0.003</td>
</tr>
<tr>
<td>4</td>
<td>$B_i {\text{Coeff. of astigmatism } 45\deg. , (r^2 \cos (2\theta))}$</td>
<td>0.002</td>
</tr>
</tbody>
</table>

References

Red-emitting Eu$^{3+}$:R$_2$MZnO$_5$ (R=Y & Gd and M= Ba, Sr, Ca & Mg) Nano Phosphor for Applications in Solid State White Lamps

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Abstract

R$_2$MZnO$_5$ nanocrystalline powders doped with Eu$^{3+}$ ions were prepared via citrate gel combustion method. Their structure and morphology were characterized using XRD and TEM. The structure of these compounds found to be monoclinic with a particle size of ~ 30 nm. Luminescence properties have been characterized using photoluminescence, emission and excitation spectra. A strong charge transfer (CT) band around 250 nm is observed which is due to the Eu-O interaction in the host. Along with the CT band, excitation bands due to Eu$^{3+}$ ions can also be observed in UV and blue regions. From the $^3$D$_0$ level of Eu$^{3+}$ ion, a bright red emission is observed which is comparable to the bulk Eu$^{3+}$:Y$_2$O$_3$.

Introduction

Inorganic phosphors doped with lanthanide (Ln) ions has attracted scientific and technological interest in the fields of solid state lighting (SSL) which is regarded as an emerging technology that will eventually replace the existing normal incandescent and gas discharge lamps. High efficiency, reliability, rugged construction, low power consumption and durability are among the key factors for the development of solid state lighting based on high brightness white light emitting diodes (WLEDs). In order to be excited efficiently, the doped phosphors should have a strong and broad absorption band in the UV or blue regions. With the development of UV and blue light emitting diodes (LED) technology, a renewed interest in novel phosphors that are capable of absorbing such a band and emitting in the visible region has been realized [1].

Amongst various approaches, LED based white light sources are regarded as the next generation SSL technology. In 1996, Nichia Corporation commercialized white LEDs, in which a blue LED chip was combined with Ce:YAG yellow powder phosphors [2]. The luminescence efficiency of the traditional light sources such as incandescent bulbs and linear fluorescent lamp is around 15 and 85 lumens per watt, where as the same is found to be 40 lumens per watt for the commercially available white LED. For white LEDs to cross the efficiency better than the linear fluorescent lamp, which are used quite commonly, it is very important to improve its internal quantum efficiency, the light extraction efficiency and the phosphor efficiency.

Over the past several years considerable effort has been made to improve the internal quantum efficiency and light extraction efficiency from the chip. Although new phosphor materials have been studied, developed and used for the white light generation to improve the color properties, they have not contributed much to the luminous efficiency of these SSL sources. This may be mainly due to the fact that the commonly used Ce:YAG phosphor in white LEDs is very efficient and most of the newer phosphors have added more energy in the red region of the spectrum which is likely to lessen the efficiency [3].

On the other hand, the reduction of particle size of crystalline systems to nano regime leads to important modifications of some of their bulk properties, in particular an increased luminescence efficiency, that are not observed in their bulk counterparts. Taking the advantage of these size-induced changes, the design of enhanced materials for advanced phosphor and photonic applications become possible [4].

The trivalent europium ion (Eu$^{3+}$) is well known as a primary colour (red) emitting activator due to its $^3$D$_{0}$$rightarrow$ $^5$F$_{j}$ (J=0-6) transitions which emits narrow band, almost monochromatic light and have long lifetimes for the $^3$D$_{0}$$rightarrow$ $^5$F$_{1}$ transition at red colour. The ternary oxides of the type R$_2$BMO, (A=Y and Gd, M=alkaline earth metal and B=Cu, Zn) have attracted a lot of attention during the recent years due to their exceptional structural, optical, physical and chemical properties and hence, show unique magnetic and superconducting properties [5]. The synthesis, structural and optical properties of a novel red emitting phosphor based on Eu$_2$O$_3$ doped R$_2$MZnO$_5$ nano particles has been evaluated and are presented. These nano powders were synthesized by a novel citrate-gel
combustion method which resulted in the synthesis of uniform nano particles with high yield.

**Experimental Details**

A novel citrate-gel combustion method was employed to prepare $\text{RMZ}_{2}\text{Eu}^{3+}$ (hereafter referred as RMZ:Eu ($R=Y$ and Gd and $M=$Ba, Sr, Ca and Mg)) nanophosphor. In a typical experiment, all the metal oxides, rare earth oxides and ZnO were dissolved in concentrated nitric acid to form corresponding nitrate solutions. These nitrate precursors were added with citric acid (1:4 molar ratio) dissolved in water, which acts as the monomer to form transparent complex gel upon drying overnight in an oven at 75°C. Further the gel was taken in a quartz boat and introduced in a pre-heated furnace at 800°C for 15 minutes. Initially the citrate complex gel transforms to a black fluffy mass nearly ten times the gel volume and starts decomposing to $\text{CO}_2$ and $\text{H}_2\text{O}$ vapors. After 15 minutes a white fluffy mass of RMZ:Eu nanophosphor is obtained which could easily be crushed to ultra-fine powder used for further characterization. The phase purity and the crystalline phases of the synthesized phosphors was checked by x-ray diffraction (XRD) analysis using Bruker D-8 advanced powder x-ray diffractometer with Cu Ka radiation operated at 35 kV and 30 mA.

**Results and Discussion**

The structure of the RMZ:Eu$^{3+}$ phosphors has been evaluated using the powder XRD patterns, TEM and EDAX measurements. Fig. 1 shows the XRD pattern of $\text{GCZ}_{2}\text{Eu}^{3+}$ nanophosphor at room temperature with x-ray wavelength of 1.54060Å as a representative case. Since most of the lattices in the RMZ series are entirely new lattices and therefore the corresponding JCPDS data cards are not available, and hence we have used WIN-INDEX (ver. 3.08) software for the structure refinement studies and determination of $(h k l)$ values corresponding to the crystalline planes and are shown in Fig. 1. The analysis reveals that the group of RMZ compounds has three different crystal structures: (i) the structure is characterized by isolated square-pyramidal MO$_{5}$ units, (ii) infinite chains of MO$_{6}$ vertex-sharing octahedral running parallel to the axis of unit cell, and (iii) isolated MO$_{4}$ squareplanar units. The monoclinic GCZ compound belongs to the 2nd category and the structure consists of RO$_{4}$, MO$_{6}$, and ZnO$_{4}$ polyhedra. Each Gd (Y) atom is seven-fold coordinated by a monocapped trigonal prism of oxygen atoms. Two such prisms, which have slightly different R-O distances, share edges to form chains parallel to the b-axis with the basic structure motif of R$_{2}O_{4}$. Both the two Gd$^{3+}$ sites have low crystal-field symmetry of $Cs^{[6]}$. Fig. 1(a) shows the transmission electron microscope (TEM) image taken at a magnification of 400 kX. It is observed that the particles have very narrow size distribution and are in the nano-regime (size $<$10 nm). Fascinatingly, the particles are observed to be non-spherical, bit elongated and arranged in chain-like structures, which is due to the processing conditions, chemical environment during the synthesis and magnetism generated by the valence electrons of the RE$^{3+}$ ions. The average diameters of the particles are in the range 4-7 nm with a standard deviation ($\sigma$) of 0.2-0.4. The energy dispersive x-ray analysis (EDAX) of TEM showed that all the elements such as Gd, Eu, Zn and Ca are present in respective proportions and are identified in the EDAX spectrum shown in Fig. 1(b).

The excitation spectra of RMZ:Eu$^{3+}$ powder phosphor were recorded by monitoring a red emission (611nm). Fig.2 shows the excitation spectra of the $\text{Y}_{2}\text{CaZnO}_{5}:\text{Eu}^{3+}$ phosphors prepared using different methods.
samples prepared using solid state reaction method and the citrate-gel combustion method using urea as a fuel. The excitation spectrum consists of an intense and broad excitation band centered at 260 nm, which is a charge transfer band (CTB) due to Eu$^{3+}$ -O$^{2-}$ interactions. The CTB of Eu$^{3+}$ plays an important role due to parity-forbidden transitions of the Eu$^{3+}$ ion and borrows intensity from the lowest strong absorption band. In addition to the CTB, few more excitation bands at around 395 nm corresponds to the $^3F_0 \rightarrow ^3H_j$,$^3D_j$,$^3L_j$ and the other at 465 nm corresponds to the $^3F_0 \rightarrow ^3D_j$ transitions have been observed. It is interesting to note that the excitation peak intensities corresponding to 395 and 465 nm are quite significant in the RMZ nanophosphor system as compared to commercial $Y_2O_3$:Eu$^{3+}$ and $Y_2O_2S$:Eu$^{3+}$ bulk-phosphors used for displays and WLEDs [7,8]. A considerable increase in the intensity of these two peaks is observed in the nano system when compared to the bulk sample. This observation gives the possibility of using the RMZ:Eu$^{3+}$ nanophosphor for the WLED applications.

The room-temperature PL spectra were recorded in the wavelength range 575-725 nm under the excitation wavelengths of 248, 395 and 465 nm, respectively. It is distinctly seen that the PL spectra consists of several sharp lines corresponding to the transitions between $^3D_j$ and $^3F_j$ ($J=1, 2$ and $3$) levels. The lines due to $^3D_j \rightarrow ^3F_j$ are most dominating in the spectrum corresponding to 611 nm although other peaks due to $^3D_j \rightarrow ^1F_j$ and $^3D_j \rightarrow ^1F_j$ are comparatively weak. It is interesting to note that the sample with Ca possess highest red emission. Therefore, it can be implied that Eu$^{3+}$ ions occupy non-centrosymmetric sites. The $^3F_0$ and $^3D_j$ levels are non-degenerate and the spectra associated with the transitions between them should indicate as many lines as the number of non-equivalent sites. Therefore, the presence of two-site distribution in the $^3F_0 \rightarrow ^3D_j$ region confirms that the Eu$^{3+}$ ions are introduced in two crystallographic sites of the GCZ lattice.

Conclusions

In conclusion, a novel red emitting phosphors $R_2MZO_3$ (R=Y, Gd, and M=Ba, Sr, Ca and Mg) doped with Eu$^{3+}$ ions were prepared by the simplified citrate gel combustion method. An intense and broad excitation peak is observed at 465 nm in the $R_2MZO_3$ nanophosphor which enables the excitation with a commercial low cost blue chip to realize white colour.

Acknowledgments

One of the authors (CKJ) is grateful to the MoU-DAE-BRNS (No. 2009/34/36/BRNS/3174, dt. 12-02-2010) under MoU between S.V.University, Tirupati and BARC, Mumbai, Government of India for the award of major research project.

References

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Abstract
The effect of swift heavy ion (SHI) irradiation (O, Ag) and low energy implantation (N) on hydroxyapatite (HAp) ceramic - a bone mineral was investigated. The irradiated samples were characterized by XRD, Raman and photoluminescence (PL). XRD analysis confirmed that there is no phase change of HAp due to irradiation. Raman peak shift with increasing fluences indicated stress developed in the unit cell on irradiation. PL studies showed emission in the visible wavelength region. SHI irradiated samples exhibited enhanced bioactivity and there was no significant variation in cell viability.

Introduction
Hydroxyapatite (HAp, (Ca\(_{10}\)(PO\(_4\)\(_6\))(OH\(_2\))\)) is a major inorganic constituent of bone and teeth which belong to the family of apatite’s. Synthetic HAp is used for bone and dental replacement due to its biocompatibility. In addition, it is used as protein adsorbent, gas sensors and as a chromatographic agent [1]. The surface properties of implant materials such as surface roughness, electrical charge and wettability play vital role in binding with the living cells [2]. The properties of the implant surface could be modified by various surface treatments such as laser irradiation, electron, plasma and ion implantation and irradiation [3]. Ion beam irradiation/implantation is employed to modify the surface of thin films and polymers [4]. This method provides selective surface modification for enhancing the osseointegration but not affecting bulk properties of the materials. Further ion irradiation/implantation method could be used to modify the chemistry of HAp by controlling the penetration depth and dose to improve for cell adhesion, proliferation, haemocompatibility and water purification by biomaterials [5]. The SHI irradiation on FAp pellets were explored for nuclear waste storage matrix [6]. Pelletier et al studied that the effect of mechanical properties of nitrogen and argon ion implantation of HAp [7]. Argon and oxygen ion irradiation on HAp revealed enhancement of bioactivity, luminescence, wettability and cell adhesion [8]. In this work, we report in detail the Raman and PL analysis of irradiated HAp.

Experimental Technique
The HAp powder was prepared by gel, hydrothermal and microwave methods [3, 8, 9]. Thin layer of HAp coated over the biocompatible titanium metal substrate by pulsed laser deposition (PLD) technique [10]. The samples having identical thickness (~9 µm) of HAp (10 x 10 mm) thin films were irradiated using silver (Ag\(^{+}\)) ions of energy 100 MeV with a 7 charge state and fluences of 1x10\(^{11}\), 1x10\(^{12}\), 1x10\(^{13}\) and 1x10\(^{14}\) ions/cm\(^2\) at room temperature was carried out at Inter-University Accelerator Centre (IUAC), New Delhi using 15UD pelletron accelerator. Raman spectrum of pristine and irradiated samples was recorded at room temperature in the back scattering geometry using a Jabin Yuov LabRam HR800 spectrometer. Photoluminescence (PL) studies were performed using an excitation wavelength of 325 nm from a He-Cd laser source and Mechelle900 spectrograph.

Results and Discussion

Raman Study
Raman spectrum of pristine and Ag\(^{7+}\) ions irradiated HAp thin films were as displayed in Fig.1 (a-d). The vibration modes of the free PO\(_4\) tetrahedron (point group symmetry) gave rise to four different frequencies \(\nu_1\), \(\nu_2\), \(\nu_3\) and \(\nu_4\). The high intensity peaks at 962 cm\(^{-1}\) correspond to the symmetric stretching of the P-O bonds \(\nu_1\). The peaks at 446 and 430 cm\(^{-1}\) were assigned to the doubly degenerate symmetric O-P-O bending mode \(\nu_2\). The triply degenerate mode involving asymmetric P-O stretching \(\nu_3\) correspond to peaks at 1052 and 1081 cm\(^{-1}\). The peaks observed at 576, 591 and 607 cm\(^{-1}\) was due to triply degenerate of O-P-O asymmetric bending modes \(\nu_4\). In addition to the internal PO\(_4\) bands, several peaks are detected between 100 and 350 cm\(^{-1}\) which are due to translational modes of the Ca\(^{2+}\) and PO\(_4\)^{3-} sub lattices and rotational modes of the PO\(_4\)\(^{3-}\) group. The bond stretching mode associated with the OH\(^-\) group is detected as a sharp peak at 3572 cm\(^{-1}\), whereas, the translational modes associated with the OH sub lattice yield a Raman peak at 328 cm\(^{-1}\) (Table 1). In the case of irradiated films, with increase in Ag\(^{7+}\) ion fluences, the intensity of OH stretch vibration was gradually reduced with increase in ion fluence and its FWHM values were found to increase compared to pristine sample. At 1x10\(^{14}\) ions/cm\(^2\) fluence,
insulator, most probably columnar defects are produced due to ion irradiation. The excitation energy is greater than that of emission; the emitted radiation is of longer wavelength than the exciting radiation. The band gap energy was determined to be 3.52 eV which was consistent with the reports available in the literature [11]. The luminescence intensity considerably increased in the case of irradiated sample due to the combined effect of surface state emission as well as emission from the large defects created by the oxygen ion during SHI irradiation (Fig. 3). With an increase in ion dose, there was no significant shift in the wavelength of the emission. Such surface state emission has been reported earlier in the case of ZnS nano crystallites [12]. The peak position and corresponding energy from PL spectra of pristine and oxygen ion irradiated HAp samples with different fluences were

\[
\begin{align*}
\text{Vibrational Raman Mode (cm}^{-1}) & \quad \text{Assignments} \\
139.74, 153.13, 205.67, 284.92 & \quad \text{Translational mode of Ca}^{2+} \text{and PO}_{4}^{3-} \text{ sub lattices} \\
329.2 & \quad \text{Rotational modes of PO}_{4}^{3-} \text{ and OH sub lattice} \\
430.6, 448.8 & \quad \text{O-P-O doubly degenerated symmetric bending} \\
579.7, 591.3, 607.3 & \quad \text{O-P-O triply degenerated asymmetric bending} \\
962.2 & \quad \text{P-O stretching} \\
1027.8, 1048.8, 1076.4 & \quad \text{P-O asymmetric stretching} \\
3570.1 & \quad \text{O-H stretching of water}
\end{align*}
\]

OH stretching (3572 cm\(^{-1}\)) and phosphate symmetric stretching (962 cm\(^{-1}\)) peaks became weaker and broader due to amorphization. The peak splitting was observed at 960 cm\(^{-1}\) and 958 cm\(^{-1}\) on 1x10\(^{11}\) ions/cm\(^{2}\) irradiation. The peak at 958 cm\(^{-1}\) was ascribed to phonon generation on irradiation. The decrease of intensity in symmetric vibration mode is ascribed to the increasing amorphization and thus distortion of the PO\(_4\) tetrahedral. The 1x10\(^{11}\) ions/cm\(^{2}\) irradiated sample, exhibits only peak broadening features, the separate and sharp modes were absent. In addition, the peak shift was observed from 962 cm\(^{-1}\) to 958 cm\(^{-1}\). The asymmetric stretching vibrations of peak at the range of 980 to 1150 cm\(^{-1}\) also showed similar characteristic feature. The symmetric (400 cm\(^{-1}\) to 500 cm\(^{-1}\)) and asymmetric bending (550 to 650 cm\(^{-1}\)) of peaks showed a decrease in intensity with increase in ion fluence. The translational and rotational modes of Ca\(^{2+}\) and PO\(_4\)\(^{3-}\) peaks also showed increase in FWHM. Hence, as a result of Ag\(^{2+}\) ion irradiation on HAp thin film, there might be degradation of structure of the HAp at higher fluence. The peak below 200 cm\(^{-1}\) corresponding to the parent HAp was absent at 1x10\(^{11}\) ions/cm\(^{2}\) fluence, confirming the structural collapse.

**Photoluminescence**

Ionoluminescence was observed in hydrothermally synthesized samples during irradiation [9]. The presence of phosphorus in HAp is likely to be the origin. The PL spectra of HAp showed in the Fig. 2 (a-d), HAp emission of wavelength ranging from 450 nm to 750 nm. The exact origin of such peaks is still unknown, and further research is in progress to understand this phenomenon. Since the emission is in the visible range (450–750 nm), it is used for practical applications as a phosphor material. They generally require a host crystal structure like ZnS, SnSiO\(_4\), Ca\(_3\)(PO\(_4\))\(_2\), (F, Cl), etc. and activator ions like Mn\(^{2+}\), Sn\(^{2+}\), Pb\(^{2+}\) and Eu\(^{2+}\). These materials are extensively used in fluorescent lamps to emit light. Since HAp is an insulator, most probably columnar defects are produced due to ion irradiation.

The excitation energy is greater than that of emission; the emitted radiation is of longer wavelength than the exciting radiation. The band gap energy was determined to be 3.52 eV which was consistent with the reports available in the literature [11]. The luminescence intensity considerably increased in the case of irradiated sample due to the combined effect of surface state emission as well as emission from the large defects created by the oxygen ion during SHI irradiation (Fig. 3). With an increase in ion dose, there was no significant shift in the wavelength of the emission. Such surface state emission has been reported earlier in the case of ZnS nano crystallites [12]. The peak position and corresponding energy from PL spectra of pristine and oxygen ion irradiated HAp samples with different fluences were
The MG-63 cell viability of pristine and Ag\textsuperscript{7+} ion irradiated films was as shown in Fig. 4. The optical density of the higher fluence (1x10^{12} and 1x10^{13} ions/cm\textsuperscript{2}) irradiated samples had shown around 10% of increment after one day incubation of cells compared with pristine. This result indicated that more number of cells grow on irradiated samples. This may be due to the enhanced wettability of irradiated sample surface assisting the growth of more number of cells. These studies revealed that Ag\textsuperscript{7+} ion irradiated samples are non toxic.

<table>
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<th>Samples</th>
<th>Excitation wavelength λ (nm)</th>
<th>λ\textsubscript{1} (nm)</th>
<th>E\textsubscript{1} (eV)</th>
<th>λ\textsubscript{2} (nm)</th>
<th>E\textsubscript{2} (eV)</th>
<th>λ\textsubscript{3} (nm)</th>
<th>E\textsubscript{3} (eV)</th>
<th>λ\textsubscript{4} (nm)</th>
<th>E\textsubscript{4} (eV)</th>
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<td>467</td>
<td>2.655</td>
<td>538</td>
<td>2.304</td>
<td>638</td>
<td>1.943</td>
<td>741</td>
<td>1.673</td>
</tr>
<tr>
<td>1 x 10^{12}</td>
<td>325</td>
<td>467</td>
<td>2.655</td>
<td>538</td>
<td>2.304</td>
<td>637</td>
<td>1.946</td>
<td>746</td>
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<tr>
<td>1 x 10^{13}</td>
<td>325</td>
<td>467</td>
<td>2.655</td>
<td>540</td>
<td>2.296</td>
<td>638</td>
<td>1.943</td>
<td>736</td>
<td>1.684</td>
</tr>
</tbody>
</table>

# Cell Viability

The paper presents the optical studies of ion irradiated/implanted HAp bioceramics. Ionoluminescence was observed on some of the samples. The PL intensity significantly increased with ion fluence, which could be attributed to the defects caused by the ion beam during irradiation. In addition, these samples have enhanced bioactivity and were non cytotoxic. The photoluminescence exhibited by irradiated HAp could make it suitable for biosensor applications and the monitoring of bone remodeling.

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**Table 2. Photoluminescence emission of pristine and irradiated samples with different fluences.**

**Fig. 4:** Cell viability study of pristine and Ag\textsuperscript{7+} irradiated samples

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**Fig. 3:** PL spectrum of O\textsuperscript{2-} ion HAp prepared by gel method (Insert image represents the pristine)

listed in Table 2. In the case of nitrogen ion implantation, HAp pellets were implanted with 30 KeV of energy with a 1\textsuperscript{st} charge state for a fluence of 10\textsuperscript{14} ions/cm\textsuperscript{2}, have intense peak and blue shift was observed due to the nitrogen ion causing decrement in band gap of E\textsubscript{g} (eV) and increment in E\textsubscript{3} (eV) of electron/hole in sample.
Acknowledgement

The authors thank financial funding of IUAC, New Delhi for irradiation facility provided through the research project No. UFUP 31317. One of the authors (K. T) thanks to UGC-DAE CSR, Kolkata for the award of fellowship.

References


The 20th DAE-BRNS National Laser Symposium (NLS-20) was held at Crystal Growth Centre, Anna University, Chennai, during Jan. 9-12, 2012. The National Laser Symposium is an annual event sponsored by the Board of Research in Nuclear Sciences (BRNS) of Department of Atomic Energy. It is held in collaboration with Indian Laser Association (ILA).

The inaugural function of NLS-20 was held at the Vivekananda Auditorium of Anna University, Chennai on 9th Jan. 2012. The symposium was inaugurated by former President of India, Bharat Ratna Dr. A.P.J. Abdul Kalam. The function was presided over by Prof. P. Mannar Jawahar (Vice Chancellor of Anna University, Chennai). Presence of Prof. C. Joshi (University of California, USA), the keynote speaker of the symposium, Dr. P.D. Gupta (Director, Raja Ramanna Centre for Advanced Technology, Indore) and Dr. P.K. Gupta (President, Indian Laser Association) graced the function.

In his inaugural address, former President of India, Bharat Ratna Dr. A.P.J. Abdul Kalam talked about the role of lasers in our day to day life. He elaborated on future energy requirements and need to tap the energy from solar radiation in space. He presented visionary ideas on the possibility of laser utilization for energy tapping from space. He motivated young researchers to take career in this challenging area. The inaugural function was followed by inauguration of 'Industry Exhibition of Lasers and related products' organized by ILA. The exhibition was inaugurated by Prof. P. Mannar Jawahar, Vice Chancellor of Anna University.

Prof. C. Joshi, in his key note address titled, 'Making Big Physics Small - Accelerators Using Lasers and Particle Beams', mentioned that the laser beam driven plasma accelerator is one concept that has made spectacular advances in the last few years. He highlighted the possibility of laser beam driven plasma accelerators with very high energy in a small size plasma accelerator.

There were 11 technical sessions with a total of 21 invited talks by several luminaries in the sphere of lasers and laser applications, from all over India and three scientists from abroad. There were two dedicated sessions (six talks) on the second day of the symposium on 'Laser materials and their characterization, these were planned considering the core research area of Crystal Growth Center, Anna University, Chennai, the host for NLS-20. There were 300 papers received for the symposium, out of which 268 were finally accepted for presentation. In line with the tradition of NLS for better and focused interactions among the participants, all these papers were presented in three poster sessions, during the first three days of the symposium. Presentations were given by 8 researchers from Universities and National Labs based on their research work carried out for Ph.D. Two technical sessions were arranged for theses presentations. The total number of participants in NLS-20 was around 450.

ILA plays a key role in the organization of national laser symposium. Like previous years, ILA organized an exhibition of lasers and other related products, where several industries and business establishments participated. The products displayed by the exhibitors and presentations from the industry participants were well appreciated by NLS-20 participants. ILA annual general body meeting was also held after the technical sessions on the first day of the symposium. Six poster presentations were selected as 'best poster paper presentation' and three thesis presentations were selected as 'best PhD thesis presentation'.

The concluding session of NLS-20 on 12th Jan. 2012, was presided over by Prof. S. Shanmugavel, Registrar, Anna University. In his address he appreciated the scientific interactions and overall outcome of the symposium. In this session the best poster and best thesis presentation awards were given by Dr. P.K. Gupta (President, ILA). Shri. S.V. Nakhe, convener, NLS-20, thanked all the participants of the symposium and the members of various committees for the successful organization of the symposium.

By: K.S. Bartwal and S.V. Nakhe
Following the tradition, on 7\textsuperscript{th} and 8\textsuperscript{th} Jan 2012, just before the 20\textsuperscript{th} DAE-BRNS National Laser Symposium, ILA organized two short courses one on Crystal growth and characterization of laser materials and the other on Automation of Physics experiments. Both the courses were conducted for two days and were held in parallel from 9:30 to 17:30 Hrs.

Prof. J. Kumar, Anna University, Chennai coordinated the course on Crystal growth and characterization of laser materials which was attended by 22 participants. The course provided a good overview of the techniques for growth of single crystals and their characterization. The faculty comprised of six well known experts in the field, Prof. H.L. Bhat, Prof. R. Dhanasekaran, Prof. K. Baskar, Prof. S. Moorthybabu, Prof. D. Arivuoli, and Prof. K.S. Bartwal. The participants also visited the laboratories of Crystal Growth Center, Anna University, to have firsthand experience of the different growth techniques. This visit and the interaction with the faculty members of the Crystal Growth Center, Anna University was much appreciated by the participants.

The course on Automation of Physics experiments was attended by 31 participants. This course, jointly coordinated by Shri C.P. Navathe and Shri V. Bhanage of Raja Ramanna Centre for Advanced Technology, Indore, focused on methods for interfacing of different laboratory instruments with a personal computer or microcontroller and covered topics like analog and digital signal conditioning, embedded systems, buses for instrumentation, image acquisition, motion control and software development. The faculty comprised of Shri V. Bhanage, Shri P.P. Deshpande and Shri P. Saxena, all from RRCAT, Indore.

Each registered course participant was provided with a kit which included a CD containing the presentations made by the lecturers and other useful information pertaining to the course. Both the courses were very well received by the participants as evidenced by the feedback provided by them in the concluding session.

ILA will like to thank Prof. S. Shanmugavel, Registrar, Anna University, the chief guest in the inaugural function, and all others at Anna University for providing the infrastructure facilities and volunteers support for the smooth conduct of the various activities required for the organization of the ILA short course. Guidance and help provided by ILA executive committee members and in particular by Dr. P.K. Gupta, President ILA at different stages in the course of planning and execution played a key role in successful organization of these short courses.

By:

\textit{Dr. K.S. Bindra,}
\textit{General Secretary II, ILA}
Best Thesis Awards

Of the eight Ph.D. thesis presentations during the 20th DAE BRNS National Laser Symposium (NLS-20), the following three thesis presentations were jointly selected for the ILA “Best Thesis Award”.

1. A new metal ion doped panchromatic photopolymer for holographic applications, V. Pramitha, Department of Physics, Cochin University of Science and Technology, Cochin.


3. High order harmonic generation from preformed plasma plumes, H. Singhal, Laser Plasma Division, Raja Ramanna Centre for Advanced Technology, Indore.

Each of the three awardees received Rs 5,000 in cash and a certificate. The awards were given by Dr. P.K. Gupta, President, Indian Laser Association, on 12th January 2012 during the concluding session of NLS-20. M/s Laser Spectra Services, Bangalore sponsored the award money.

Best Poster Awards

In the 20th DAE BRNS National Laser Symposium (NLS-20), 268 contributed papers were presented as posters. Of these, the following six papers were selected for the ILA best poster award by a committee of judges.

1. Red emitting Eu⁺:R,MZnO₃ nano phosphor for application in solid state white lamps, R. Rajeswari¹, S.S. Babu², D. Ramachari¹, D. Haranath¹ and C.K. Jayashankar¹, ¹Department of Physics, Sri Venkateswara University, Tirupati, ²Directorate of Laser Systems, Research Centre Imarath, Hyderabad, ³LMD Group, National Physical Laboratory, New Delhi.


5. Coherent random lasing from an array of amplifying aperiodic spherical scatterers, A.K. Tiwari, B. Chandra, R. Uppu and S. Majumdar, Nano-Optics and Mesoscopic Optics Laboratory, TIFR, Mumbai.

6. Study of strain propagation in laser irradiated silicon crystal by time resolved diffraction of K-alpha X-ray probe of different photon energies, V. Arora¹, S. Bagchi¹, M. Gupta², J.A. Chakera¹, A. Gupta¹, P.A. Naik¹, P. Chaddah² and P.D. Gupta¹, ¹Raja Ramanna Centre for Advanced Technology, Indore, ²UGC-DAE Consortium for Scientific Research, Indore.

Each of the presenting author of the above papers were given Rs 2500/- as cash prize money and a certificate during the concluding session of NLS-20 by Dr. P.K. Gupta, President Indian Laser Association. These awards were sponsored by M/s Laser Science, Mumbai and Prof. Vinay Srinivasan memorial award money.

By:
Dr. K.S. Bindra,
General Secretary II, ILA
The website of the Indian Laser Association (whose life membership is now exceeding 1000) continues to have numerous visitors from all nooks and corners of the world. The ILA website continued to follow self-imposed austerity measures, without compromising on the performance and user expectations.

The growth of the ILA website is consistent and is in line with the increasing popularity of the Indian Laser Association. This is depicted in the graphs below.

Visitors' Browser choice: Our visitors have a varied choice of browsers. We strive hard to ensure efficient content delivery keeping in mind the browser diversity.

Visitor Profile: The popularity of Indian Laser Association can be judged by the profile of the visitors from various countries. More than 40% of our visitors are from abroad.

By:
Shri Rajiv Jain
Webmaster, ILA
Science & Engineering Research Council (SERC) of the Department of Science & Technology (DST), Government of India promotes R&D programmes in newly emerging and challenging areas of science and engineering. To selectively promote the general research capability in relevant areas of science and engineering it sponsors Schools on specific topics of research and development. The objective is to encourage young scientists to take up challenging R&D activities. As part of these series of schools, a “School on Laser Physics and Technology” was organized at RRCAT during March, 12-30, 2012. The School was primarily aimed at young researchers interested in pursuing research in lasers.

The response to the advertisement of the School was overwhelming with nearly 120 applicants from various parts of the country. About forty participants were selected based on their previous academic record and relevance of their research work to the topics of the school. Of these 9 were young researchers (Scientists C and D) from various National Labs (DRDO, ISRO, DAE etc), 3 were Assistant Professors from Universities and the remaining 28 were PhD scholars from various parts of the country, all working in lasers and their applications.

The School consisted of 60 lectures covering all important aspects of laser physics and technology. The topics covered include fundamentals of laser physics, laser resonators, Q-switching, mode-locking, chirped pulse amplification, frequency stabilization, non-linear optics etc., which were taught by Dr. P.K. Gupta (RRCAT), Dr. M.P. Joshi (RRCAT) and Dr. S. Raja (RRCAT). Important laser systems such as diode pumped solid state lasers, ultrashort pulse lasers, fiber lasers, semiconductor lasers, gas lasers, free electron lasers, terahertz sources, widely tunable laser systems were also discussed by Prof. K. Thayagrajan (IIT Delhi), Dr. S.K. Mehta (SSPL), Prof. D.N. Rao (Hyderabad University), Dr. K. Dasgupta (BARC), Dr. D.S. Rana (IISER Bhopal), Dr. P.K. Mukhopadhyay (RRCAT) Dr. S.K. Dixit (RRCAT) and Dr. K.K. Pant (RRCAT). Some important applications of lasers in high-resolution spectroscopy, material processing, biophotonics, instrumentation etc. were addressed by Dr. B.M. Suri (BARC), Dr. B.N. Jagtap, Dr. S.V. Joshi (ARCI), Dr. L.M. Kukreja (RRCAT), Dr. P.K. Gupta (RRCAT), Dr. S. Raja (RRCAT) and Dr. Sanjeeb Chaterjee (RRCAT) in their lectures.

Apart from these lectures “hands-on” experiments designed to facilitate understanding of the topics discussed during the School were also arranged. The participants were divided into ten batches, four in each and each batch was given one experiment per day on rotation. These included Diode pumped solid state laser characterization, Yb doped fiber laser characterization, femto second laser pulse characterization, copper vapour pumped dye laser, XeCl excimer laser characterization, laser welding of stainless steel, laser rapid manufacturing, optical coherence tomography, optical micro-manipulation, and magneto-optic Kerr effect.

About five evening lectures were also arranged as part of the School, to provide a perspective of the present status and future prospects for physics & technology of lasers in the country. These lectures were delivered by Dr. L.M. Gantayet (BARC), Dr. D.D. Bhawalkar (Quantalase), Prof. Kankan Bhattacharya (IACS), Prof. Deepak Mathur (TIFR) and Dr. A. Maini (LASTEC). Participants delivered short presentations on preassigned topics towards the end of the school.

By:
Dr. Sendhil Raja S.,
LBAID, RRCAT, Indore
INDIAN LASER ASSOCIATION

MEMBERSHIP FORM

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Type of membership requested : Life (Fee : ` 1,500/- For Indian Residents ; ` 5,000/- For Non Residents) / Corporate (Fee : ` 10,000/-) / Student (Fee : ` 500/-)

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Send completed application form along with payment to : General Secretary II, ILA
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# Make Cheque / Draft payable to Indian Laser Association. Drafts should be payable at Indore.
# For outstation cheque please add Rs. 35 upto 1000/- rupees and additional Rs. 4.5 per extra thousand rupees for bank charges. Combined payment is acceptable.

FOR ILA OFFICE

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Any other remarks : (General Secretary II)
Inauguration of SERC School on Laser Physics & Technology held during March, 12-30, 2012 at RRCAT Indore (From left to right) Prof. Rama Chari, Prof. P.D. Gupta and Prof. P.K. Gupta

Prof. P.K. Gupta of RRCAT is delivering lecture during the SERC School

Group photograph of participants and faculty of SERC School at RRCAT, Indore
A technical session of 20\textsuperscript{th} DAE-BRNS National Laser Symposium (NLS-20).

Inauguration of corporate exhibition during NLS-20 (From left to right) Sri. P. Saxena, Prof. P.M. Jawahar, Prof. P.K. Gupta and Prof. P.D. Gupta.

Lighting ceremony during the Inauguration of 20\textsuperscript{th} DAE-BRNS National Laser Symposium (NLS-20) held at Crystal Growth Centre, Anna University, Chennai during Jan 9-12, 2012 (from left to right) Prof. D. Arivuoli, Prof. Chandrasekhar Joshi, Dr. A.P.J. Abdul Kalam (former president of India), Prof. P.D. Gupta, and Prof. P.M. Jawahar.

Dignitaries present on dais during the inauguration of proceedings of NLS-20 (from left to right) Prof. Chandrasekhar Joshi, Prof. P.D. Gupta, Prof. D. Arivuoli, Dr. A.P.J. Abdul Kalam (former president of India), Prof. P.M. Jawahar, Prof. P.K. Gupta and Sri S.V. Nakhe.

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