Satyameva Jayate
Government of India
Ministry of Human Resource Development

IISc

SPARC
Scheme for Promotion of Academic and Research Collaboration

Virtual Online Workshop - Light-Matter Interactions in Low Dimensional and Topological Photonic Materials

THEME: LIGHT-MATTER COUPLING IN LOW DIMENSIONAL MATERIALS

DAY1: JAN 27, 2022

SPEAKERS	Time (IST/GMT)
Igor Aharonovich (University of Technology Sydney, Australia)	3:30 PM / 10:00 AM
Jaydeep Kumar Basu (IISc. Bangalore, India)	4:10 PM / 10:40 AM
BREAK	
Poster Session	6:20 PM / 12:50 PM
Kausik Majumdar (IISc. Bangalore, India)	7:20 PM / 1: 50 PM
Jie Shan (Cornell University, USA)	8:00PM / 2:30PM

Sessions will be held in online platform "FLOOR"

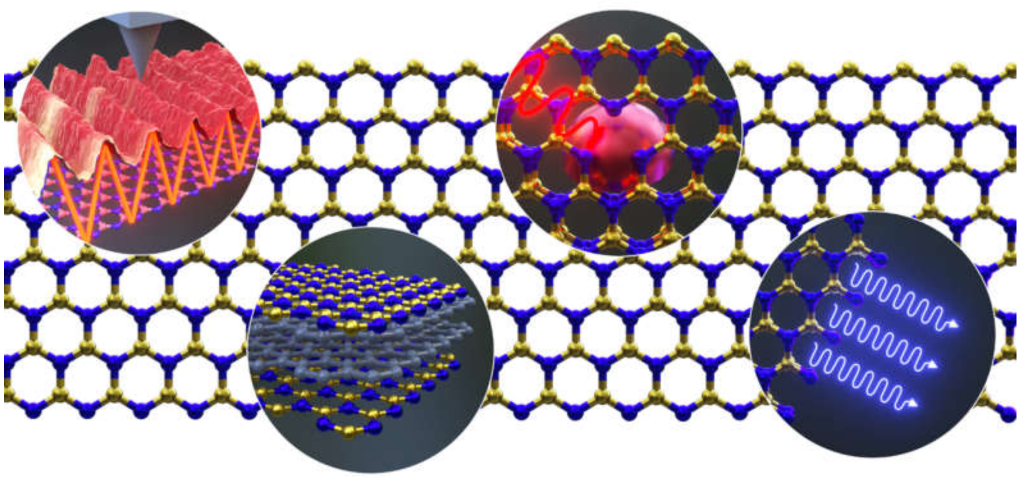
Title: "Hexagonal Boron Nitride – emerging platform for Quantum Photonics"

Igor Aharonovich

[1]*University of Technology Sydney, Ultimo, NSW, 2007, Australia*
[2]*ARC Centre of Excellence for Transformative Meta-Optical Systems*

Engineering robust solid-state quantum systems is amongst the most pressing challenges to realize scalable quantum photonic circuitry. While several 3D systems (such as diamond or silicon carbide) have been thoroughly studied, solid state emitters in two dimensional (2D) materials are still in their infancy.

In this presentation I will discuss the appeal of an emerging van der Waals crystal – hexagonal boron nitride (hBN). This unique system possesses a large bandgap of ~ 6 eV and can host single defects that can act as ultra-bright quantum light sources. In addition, some of these defects exhibit spin dependent fluorescence that can be initialised and coherently manipulated. On top of that, the hBN crystals can be carefully sculpted into nanoscale photonic resonators to confine and guide light at the nanoscale. It hence has all the vital constituents to become the leading platform for integrated quantum photonics. To this extent, I will highlight the challenges and opportunities in engineering hBN devices and will frame it more broadly in the growing interest with 2D materials nanophotonics.



Light-Matter Interactions in Plasmonic Cavity Coupled Quantum Dots: Single Photons to Long range Polariton Transport and Spin-Momentum Locking

Jaydeep K Basu

Department of Physics, IISc, Bangalore

Abstract

We will discuss our recent results on coupling of colloidal quantum dots (QDs), all the way from single to compact assemblies, to plasmonic nanocavity arrays and metamaterials. With single isolated QDs we were able to distinguish quantum coupling to localised surface plasmon and surface lattice resonances modes in plasmonic nanocavity arrays while also suggesting existence of indirect excitation of remote QDs mediated by the lattice modes. Further increase of QD density allows exploration the weak-to-strong coupling transition in in these hybrid devices at room temperature. Using generalized retarded Fano–Anderson and effective medium models it was observed that while individual QD are found to interact locally with the lattice yielding Purcell-enhanced emission, at high QD densities, polariton states emerge as two-peak structures in the photoluminescence, with a third polariton peak, due to collective QD emission, appearing at still higher QD concentrations. We also demonstrate ultra-long-range optical energy propagation in these hybrid quantum photonic devices due to the emergence of extion-polariton states. We provide direct evidence for the detection of an exciton-SLR (ESLR) strongly coupled mode at least 600 μm away from the region of excitation. Finally, we also discuss our recent report on the observation of photonic spin-momentum locking in the form of directional and chiral emission from achiral QDs evanescently coupled to achiral hyperbolic metamaterials (HMM). Efficient coupling between QDs and the metamaterial leads to emergence of these photonic topological modes which can be theoretically explained in terms of rigorous modelling based on photon Green's function where pseudo spin of light arises from coupling of QDs to evanescent modes of HMM. Our results indicate that this highly flexible quantum photonics platform for nanoscale light-matter interactions based on plasmonic array cavity coupled quantum emitters could have various possible applications in sensing and quantum information science.

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2. Yadav Kumar Ravindra, Otten Matthew, Wang Weijia, Cortes Cristian, Gosztola David, Wiederrecht Gary, Gray Stephen, Odom Teri, Basu, Jaydeep Kumar, Strongly coupled exciton – surface lattice resonances engineer long-range energy propagation, Nano letters 20 (7), 5043-5049 (2020).
3. Ravindra Kumar Yadav, Marc R. Bourgeois, Charles Cherqui, Xitlali G. Juarez, Weijia Wang, Teri W. Odom, George C. Schatz, Jaydeep Kumar Basu, Room Temperature Weak-to-Strong Coupling and the Emergence of Collective Emission from Quantum Dots Coupled to Plasmonic Arrays, ACS Nano 14 (6), 7347-7357 (2020).
4. Ravindra K Yadav, Wenxiao Liu, S R K Chaitanya Indukuri, Adarsh B Vasista, G V Pavan Kumar, Girish S Agarwaland Jaydeep Kumar Basu, Observation of photonic spin-momentum locking due to coupling of achiral metamaterials and quantum dots' Journal of Physics: Condensed Matter 33 (1), 015701 (2020).

Title: Temperature independent, sub-meV linewidth, polarized excitonic luminescence from monolayer semiconductor

Speaker: Kausik Majumdar, ECE, IISc Bangalore

Abstract: The excitonic emission from monolayer transition metal dichalcogenides is usually affected by large inhomogeneous broadening, and one usually requires special substrate treatment and measuring at cryogenic temperatures to achieve low linewidth. Similarly, exciton valley polarization and valley coherence degrade very fast in these monolayers, particularly above cryogenic temperatures. In this talk, I shall discuss about a technique of dual resonance through a single phonon relaxation which helps to suppress the inhomogeneous broadening. Using the technique, we achieve ~ 1 meV linewidth exciton peak (~0.2 meV after laser linewidth deconvolution), with a high (90%/75%) degree of linear/circular polarization of excitonic peak in monolayer WS_2, up to 200 K.

Title: Optical sensing of the strongly correlated states in 2D moiré materials

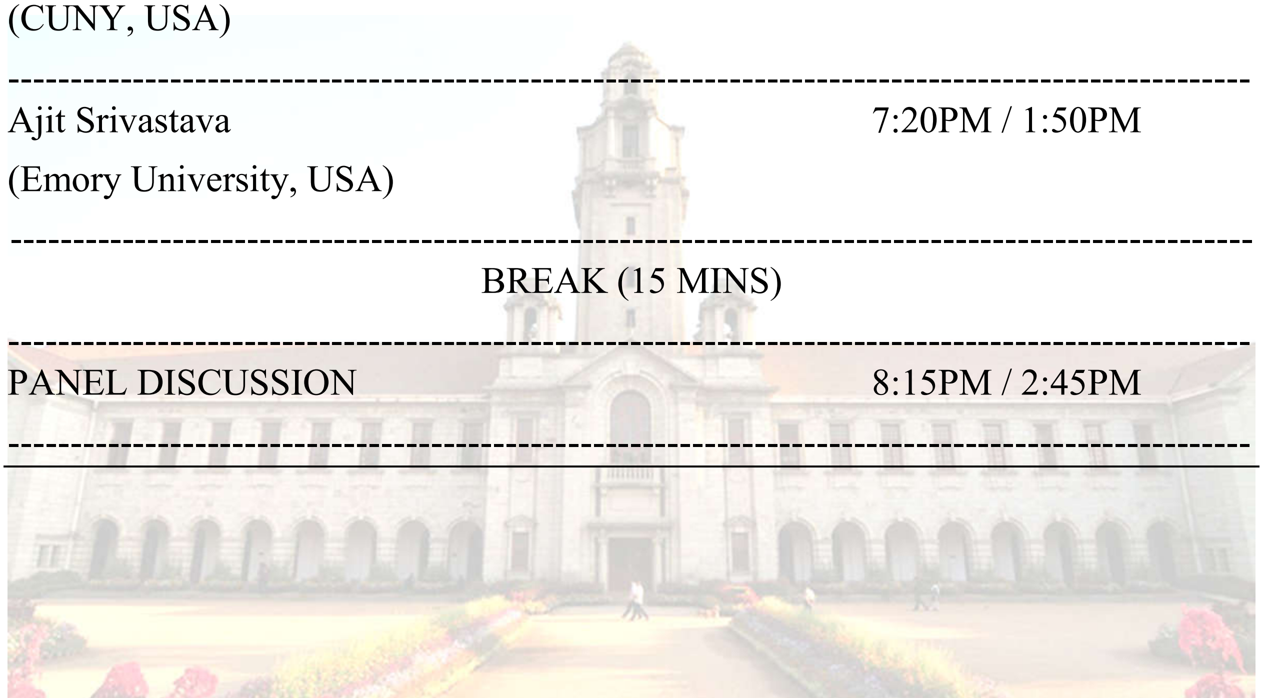
Jie Shan, Cornell University, USA

When two van der Waals materials of slightly different orientation or lattice constant are overlaid, a moiré pattern emerges. The moiré pattern introduces a new length scale, many times the lattice constant of the original materials, for Bragg scattering of Bloch electrons in each layer. This gives rise to flat moiré minibands and rich electronic correlation phenomena. In this talk, I will describe how to use the strong light interaction in atomically thin semiconductors to probe these correlated insulating states.

THEME: LIGHT-MATTER COUPLING IN LOW DIMENSIONAL MATERIALS

DAY2: JAN 28, 2022

SPEAKERS	Time (IST/GMT)
Mandar Deshmukh (TIFR, Mumbai, India)	6:00PM / 12:30PM
Vinod Menon (CUNY, USA)	6:40PM / 1:10PM
Ajit Srivastava (Emory University, USA)	7:20PM / 1:50PM
BREAK (15 MINS)	
PANEL DISCUSSION	8:15PM / 2:45PM



Sessions will be held in online platform "FLOOR"

Title: Berry curvature dipole senses topological transition in a moiré superlattice

Mandar M. Deshmukh, TIFR, India

Topological aspects of electron wavefunction play a crucial role in determining the physical properties of materials. Berry curvature and Chern number are used to define the topological structure of electronic bands. While Berry curvature and its effects in materials have been studied detecting changes in the topological invariant, Chern number, is challenging; particularly changes of valley Chern type. In this regard, twisted double bilayer graphene (TDBG) has emerged as a promising platform to gain electrical control over the Berry curvature hotspots and the valley Chernnumbers of its flat bands. In addition, strain induced breaking of the three-fold rotation (C3) symmetry in TDBG, leads to a non-zero first moment of Berry curvature called the Berry curvature dipole (BCD), which can be sensed using nonlinear Hall (NLH) effect. We reveal, using TDBG, that the BCD detects topological transitions in the bands and changes its sign. In TDBG, the perpendicular electric field tunes the valley Chern number and the BCD simultaneously providing us a tunablesystem to probe the physics of topological transitions.

Title: Strong light-matter coupling in 2D semiconductors

Vinod Menon, CUNY, USA

2D semiconductors of transition metal dichalcogenides (TMDCs) have become one of the most attractive optoelectronic materials owing to their extraordinary strength of interaction with light. This property has enabled the realization of robust exciton polaritons – hybrid quasiparticles of light and matter in the TMDCs. In this talk, I will first introduce the concept of strong light-matter couplingin solid state systems. Following this,I will discuss the prospects of realizing highly nonlinear polaritonsfor achieving photon blockade using Rydberg excitons[1] and interlayer excitons[2]. The idea of "strain engineering" as an attractive technique for guiding and controlling exciton flow [3] and nonlinearity in 2D semiconductors will be discussed next. I will conclude with some preliminary results indicating thermalization of exciton polaritons and potential for observing condensation.

[1] J. Gu *et al.*, "Enhanced nonlinear interaction of polaritons via excitonic Rydberg states in monolayer WSe2," *Nat. Commun.*, vol. 12, no. 1, p. 2269, 2021.

[2] B. Datta *et al.*, "Highly non-linear interlayer exciton-polaritons in bilayer MoS2," ArXiv Oct. 2021.

[3] F. Dirnberger *et al.*, "Quasi-1D exciton channels in strain-engineered 2D materials," *Sci. Adv.*, vol. 7, no. 44, pp. 3066–3095, Oct. 2021.

Title: 2D Materials: A New Platform for Interacting Photons

Ajit Srivastava, Emory University, USA

Abstract:
Atomically thin materials,such as graphene and transitional metal dichalcogenides (TMDs),have recently come to the forefront of research in materials physics. This is largely due to the ease with which they can be combined into artificially engineered heterostructures that exhibit emergent electronic and optical properties. Enhanced Coulomb interactions in the truly 2D limit makes TMDs, such as $MoSe_2/WSe_2$, promising to explore correlated quantum phases of matter.

In this talk, I will begin by highlighting some unique properties of optical excitations, such as excitons, in TMDs. Next, I will talk about few-body and many-body interactions amongst them, which can be exploited for realizing on-demand quantum matter in a driven-dissipative setting. Finally, I will show how trapped dipolar excitons can serve as high-resolution quantum sensors of correlated electronic phenomena.

THEME: TOPOLOGICAL PHOTONICS

DAY 1: JAN 31, 2022

SPEAKERS	Time (IST/GMT)
Franco Nori (RIKEN, Japan)	6:00PM / 12:30PM
Moti Segev (Israel Institute of Technology, Israel)	6:40PM / 1:10PM
Girish Agarwal (Texas A&M, USA)	7:20PM / 1:50PM
Sebabrata Mukherjee (IISc. Bangalore, India)	8:00PM / 2:30PM
Poster Session	8:40 PM / 3:10PM

Sessions will be held in online platform "FLOOR"

The quantum spin Hall effect of light:
photonic analog of 3D topological insulators

Franco Nori
RIKEN, Saitama, Japan, and The University of Michigan, Ann Arbor, USA

Maxwell's equations ultimately describe properties of light, from classical electromagnetism to quantum and relativistic aspects. The latter ones result in remarkable geometric and topological phenomena related to the spin-1 massless nature of photons. By analyzing fundamental spin properties of Maxwell waves, we show [1] that free-space light exhibits an intrinsic quantum spin Hall effect—surface modes with strong spin-momentum locking. These modes are evanescent waves that form, for example, surface plasmon-polaritons at vacuum-metal interfaces. Our findings illuminate the unusual transverse spin in evanescent waves and explain recent experiments that have demonstrated the transverse spin-direction locking in the excitation of surface optical modes. This deepens our understanding of Maxwell's theory, reveals analogies with topological insulators for electrons, and offers applications for robust spin-directional optical interfaces. Related work can be found in [2].

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Title: Topological Photonics and Topological Insulator Lasers

Mordechai (Moti) Segev, Technion, Israel Institute of Technology

abstract:
A brief intuitive overview of the principles of topological photonics will be reviewed, emphasizing concepts that have no counterparts in condensed matter physics, and highlighting the hallmark of the field: topological insulator lasers.

ANTI-PT SYMMETRY, ENHANCED SENSING AND CAVITY MAGNONICS-

G S Agarwal*, Texas A&M University

In recent years there has been great interest in the study of the non-Hermitian Hamiltonians and their realizations in physical systems [1,2]. We focus on the characteristics of systems with anti PT symmetry and discuss enhanced sensing [3,4] capabilities of such systems. We discuss realization of the anti-PT symmetry in coupled cavity-magnons system. The cavity magnonics provides a platform to implement many of the ideas, from quantum optics and non-Hermitian physics, like nonreciprocity, exceptional points, level attraction, and level repulsion. We show how the anti-PT symmetry leads to enhanced nonlinear response leading to important applications such as in the inter-conversion between microwaves and optical waves [5], and in realizing low threshold bistability [6].

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Nonlinear Topological Photonics: Observation of Solitons in Floquet systems

Sebabrata Mukherjee
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mukherjee@iisc.ac.in

In the recent past, research on topological systems mostly focused on the linear domain, where nonlinearity and interparticle interactions are negligible. In this talk, I shall discuss the formation of solitons (waves that propagate without diffraction as a result of nonlinearity) in photonic Floquet topological systems consisting of laser-written waveguides. The dynamics of these nondiffracting nonlinear states are governed by the focusing nonlinear Schrödinger equation, which is equivalent to the attractive Gross-Pitaevskii equation describing the mean-field interactions in a Bose-Einstein condensate. I shall present experimental evidence of a family of bulk solitons residing on the topological bandgap and performing cyclotron-like orbits.
I shall then present backscatter-immune unidirectional nonlinear states travelling along the edge of a photonic topological insulator. This soliton-like wave packet forms a long-lived quasi-localized coherent structure that slowly radiates power into the bulk and along the edge. Our results on bulk solitons and soliton-like edge states pave the way to an understanding of nonlinear and interacting topological systems.

[1] S. Mukherjee and M. C. Rechtsman, "Observation of Floquet solitons in a topological bandgap," Science **368**, 856-859 (2020)
[2] S. Mukherjee and M. C. Rechtsman, "Observation of Unidirectional Solitonlike Edge States in Nonlinear Floquet Topological Insulators," Phys. Rev. X 11, 041057 (2021)

THEME: TOPOLOGICAL PHOTONICS

DAY2: FEB 1, 2022

SPEAKERS	Time (IST/GMT)
Da-Wei Wang (Zhejiang University, China)	6:00PM / 12:30PM
Mohd Hafezi (University of Maryland, USA)	6:40PM / 1:10PM
Ritesh Agarwal (U Penn, USA)	7:20PM / 1:50PM
BREAK (15 MINS)	
PANEL DISCUSSION	8:15PM / 2:45PM

Sessions will be held in online platform "FLOOR"

Topological phases of quantized light

Da-Wei Wang
Department of Physics, Zhejiang University

Abstract: Topological photonics is an emerging research area that focuses on the topological states of classical light. Here we reveal the topological phases that are intrinsic to the particle nature of light, i.e., solely related to the quantized Fock states and the inhomogeneous coupling between them.The Hamiltonian of two cavities coupled with a two-level atom is an intrinsic one-dimensional Su-Schriefer-Heeger model of Fock states. By adding another cavity, the Fock-state lattice is extended to two dimensions with a honeycomb structure (Fig.1), where the strain due to the inhomogeneity of the coupling strengths induces a Lifshitz topological phase transition between a semimetal and three band insulators within the lattice. In the semimetallic phase, the strain is equivalent to a pseudomagnetic field, which results in the quantization of the Landau levels and the valley Hall effect. We further construct a Haldane model where the topological phases can be characterized by the topological markers.This study demonstrates a fundamental distinction between the topological phases of bosons and fermions and provides a novel platform for studying topological physics in dimensions higher than three.

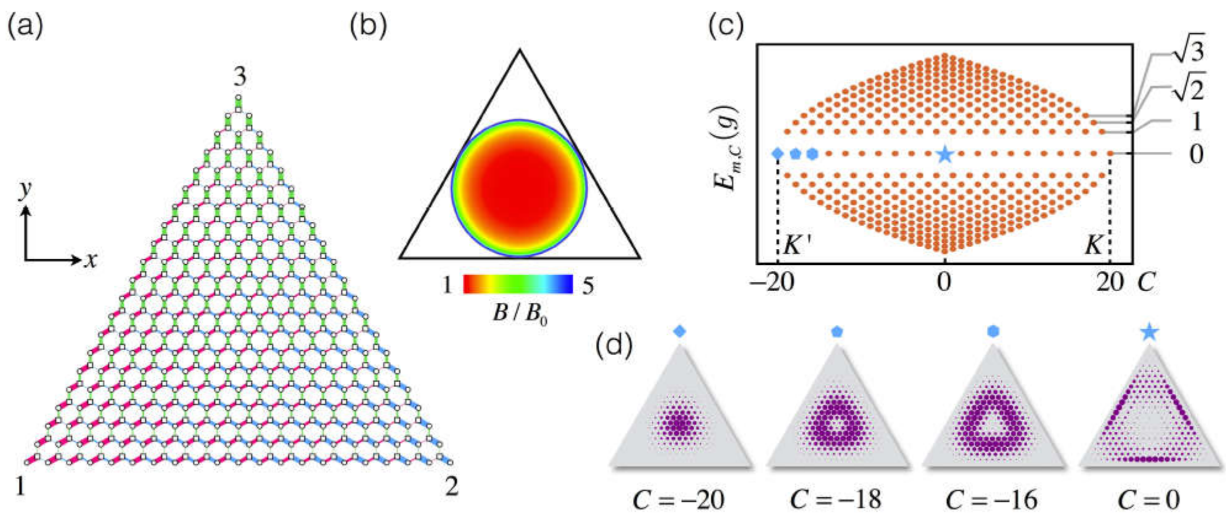

Figure 1: (a) The 2D Fock-state lattice with the line thickness proportional to the coupling strength. (b) The distribution of the pseudomagnetic field in the inner circle. Outside of the inner circle are band insulators. (c) The $\sqrt{n}$-scaling of the eigenenergies of the generalized Landau levels. (d) The wavefunction of the eigenstates.

[1] H Cai and DW Wang, National Science Review 8, nwaa196 (2021).

[2]J Yuan, H Cai, C Wu, SY Zhu, RB Liu and DW Wang, Phys. Rev. B 104, 035410 (2021).

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Recent advances in topological photonics

Mohammad Hafezi, University of Maryland, USA

Helical Topological Polaritons

Ritesh Agarwal
Department of Materials Science and Engineering
University of Pennsylvania

Topological photonics, inspired by the role of topology in identifying and designing states of condensed matter, has rapidly emerged as an important sub-field of optics to explore new photonic phases and to design optical devices that are robust against disorder and defects. Extending these ideas to strongly coupled light-matter systems can further open the possibility for studying new optical phenomena as well as pave the way for fabricating actively controllable topological devices. Owing to the increasing appreciation of the role of topology in both electronic and photonic systems, polaritons, that are half-light-half-matter quasiparticles resulting from the strong hybridization between excitons and photons, can emerge as an important platform for exploring new topological phases of matter. Topological polaritons with non-trivial topology have been proposed in polaritonic lattices with engineered symmetries to demonstrate robust chiral propagation, but their experimental realization had been at cryogenic temperatures and under strong magnetic fields, which makes their potential applications challenging. We will discuss our efforts to engineer and electrically control strong light-matter interactions in 2D semiconductors with plasmonic and dielectric lattices followed by our recent success at generating helical topological polaritons in monolayer WS_2 excitons coupled to a non-trivial photonic crystal protected by pseudo time-reversal symmetry. Helical topological polaritons were observed up to 200K without external magnetic field and verified in both the real and momentum space where polaritons corresponding to opposite helicities were transported to opposite directions along the topological interface. Topological helical polaritons are promising for exploring tunable polaritonic spintronic devices for robust classical and quantum information processing applications. The talk will conclude with our vision towards developing a chiral photonics platform that can generate, transmit and sense information encoded in spin and angular momentum modes of light that are promising for the development of integrated photonic systems with extremely large data processing capabilities.

Poster Presentations

Posters Presented by:

Ashish Soni (IIT Mandi)

Harshavardhan Reddy Kalluru (IISc Bangalore)

Mukesh Pandey (IIT Ropar)

Riya Wadhwa (IIT Ropar)

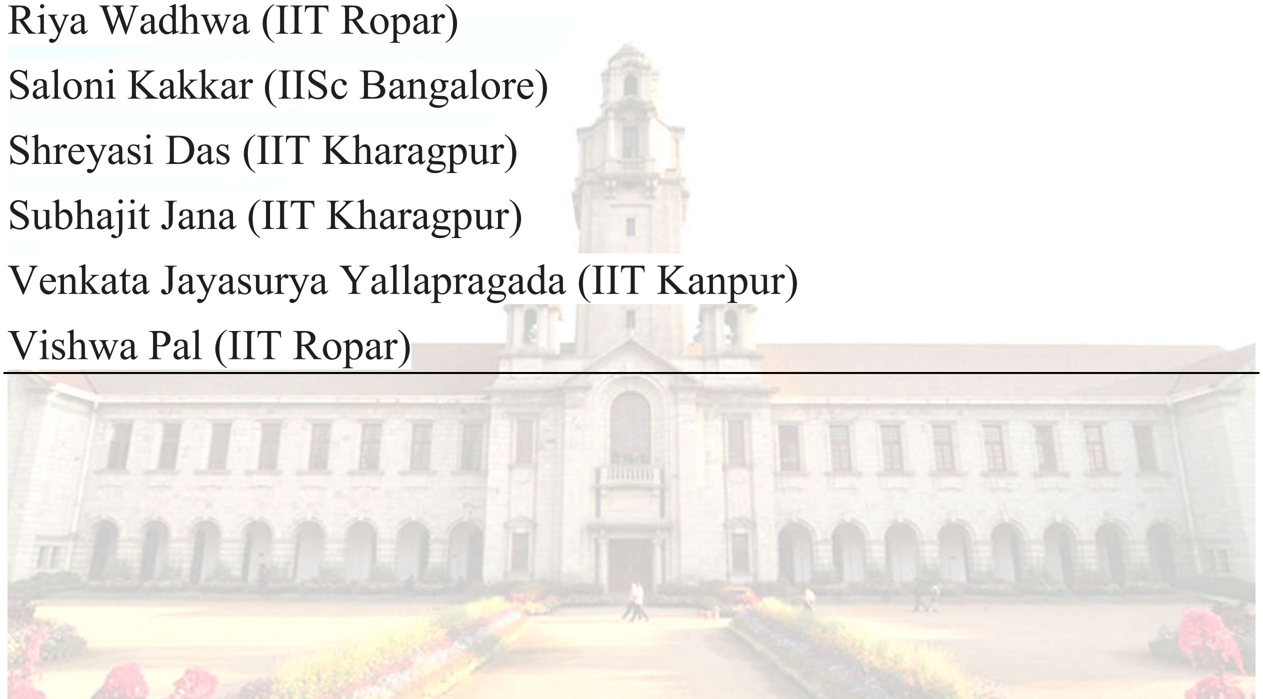
Saloni Kakkar (IISc Bangalore)

Shreyasi Das (IIT Kharagpur)

Subhajit Jana (IIT Kharagpur)

Venkata Jayasurya Yallapragada (IIT Kanpur)

Vishwa Pal (IIT Ropar)



Sessions will be held in online platform "FLOOR"

Understanding the role of exciton-exciton annihilation and exciton trapping on carrier relaxation in large area monolayer WS_2

Ashish Soni[1] and Suman K Pal[1]

[1]*School of Basic Sciences, Indian Institute of Technology Mandi, Kamand, Mandi 175005, Himachal Pradesh, India*

Email: suman@iitmandi.ac.in

Abstract

Transition metal dichalcogenides (TMDCs) have started a new paradigm for the generation of advanced materials which are capable of showing extraordinary optoelectronic properties [1, 2]. Large area monolayer TMDCs could be beneficial for realizing thin and flexible optoelectronic devices. Studying the generation and transport of photoinduced charges is crucial to utilize them for electronic or optoelectronic device applications. Since the last decades, time-resolved spectroscopy is being used to understand the transient behavior of charges in low dimensional semiconducting TMDC materials [3]. Carrier trapping by the defect states that are introduced during the growth process of the monolayer could influence the dynamical behavior of charge carriers. Herein, we investigated some aspects of the ultrafast evolution of the initially generated hot carriers and trapped charges in large area monolayer WS_2 by measuring transient absorption at energies above and below the band gap energy [4]. Our excitation energy-dependent measurements reveal that the photogenerated charge carriers undergo trapping in sub picosecond time scale followed by the formation of defect-bound excitons. The measurements of excitation photon density-dependent transient absorption kinetics show the signature of exciton-exciton annihilation at a higher excitation density (figure 1). Our results could be beneficial for the development of TMDC based semiconducting devices.

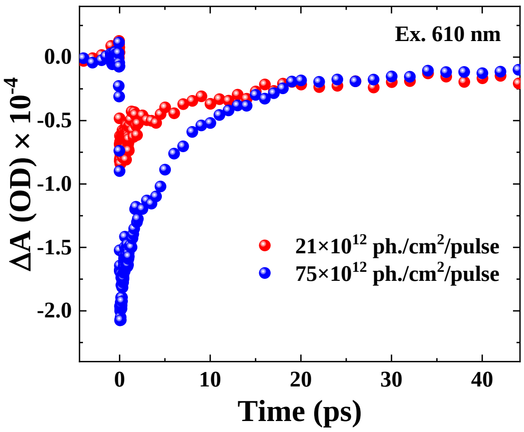


Figure 1 Transient absorption decay dynamics in monolayer WS_2 probed at 630 nm and at different pump fluences (pump wavelength ~610 nm).

References

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[3] Yuan L and Huang L 2015 Exciton dynamics and annihilation in WS_2 2D semiconductors *Nanoscale* **7** 7402-8

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Exciton-Polaritons in monolayer MoS_2 coupled to hyperbolic metamaterial

Harshavardhan R Kalluru[1,*] and Jaydeep K basu[1]

[1] *Department of Physics, Indian Institute of Science, Bangalore 560012, India*

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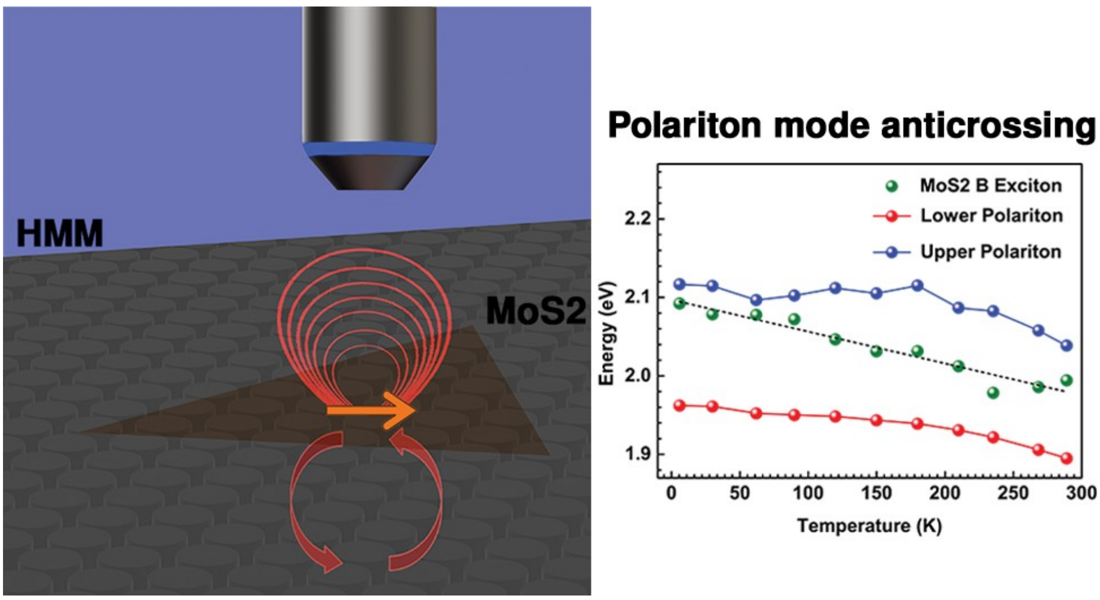
ABSTRACT

A lot of effort in recent years is focused on the ensembles of Polaritons, for developing applications in Quantum Information Systems. An ensemble of Polaritons can form a Bose Einstein condensate, which is the sandbox for building, all optical Polariton qubit states. The Exciton-Polaritons are hybrid light-matter states of the strongly coupled emitter-cavity system.

We demonstrate the Exciton-Polariton modes of a coupled Molybdenum disulphide-hyperbolic metamaterial system. We show that the B excitons of Molybdenum disulphide (MoS_2) strongly couple with the evanescent plasmonic modes of hyperbolic metamaterial (HMM). The A excitons are not strongly coupled with the HMM modes.

The B excitons exchange energy coherently with HMM modes and as a result of the Rabi oscillations, mode splitting is observed. The mode splitting is ≈130 meV at ambient temperature. The mode splitting is visible as a double peak feature in Photoluminescence (PL) emission and Absorption spectra. The Exciton-Polariton mode dispersion is measured by temperature dependent PL emission spectra. The detuning measurement reveals avoided crossing, which is the signature of two crossing quantum states.



The calculated coupling strength shows that the relative coupling coefficient is 70% stronger at B exciton position. The HMM functions as a selective coupler for MoS_2 A and B excitons. The HMM used in this study is made by Anodization of Aluminum sheets and by electrochemical deposition of silver nanowires in the anodized pores. So the system is inexpensive and can be industrially scaled.

Exciton interactions in semiconductor nanocrystals uncovered by spectrally resolved photon counting

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ABSTRACT

Colloidal semiconductor nanocrystals (NCs) have been among the most widely studied nanoscale light emitters during the last three decades. The absorption of a photon by a NC leads to the formation of an exciton. Absorption of multiple photons leads to the formation of multiple excitons, which interact with each other, which leads to shifts in their energies.

Single NC photoluminescence studies using time-resolved single photon counting (TCSPC) have been instrumental in determining the dynamics of the multiexciton states. However, such approaches typically lack the ability to resolve the energy differences between the excitons at room temperature, where most potential applications of NCs lie.

Our recent work demonstrated that this limitation can be overcome using an array of single-photon avalanche detectors (SPADs) at the output of a grating spectrometer. Such a setup enables synchronized TCSPC across multiple channels, where each channel corresponds to a different wavelength. The interaction energies of multiple excitons in NCs can be determined by resolving the spectra of photons emitted at each stage of multiexciton recombination, identified by their order of detection [1]. We have recently used this approach to determine the interaction energy of excitons in doubly excited perovskite quantum dots [2]. In larger NCs, it is also possible to study interactions of more than two confined excitons. Recent experimental results are illustrated in Figure 1.

I will present the state-of-the-art in this emerging form of spectroscopy of few-photon emitters.

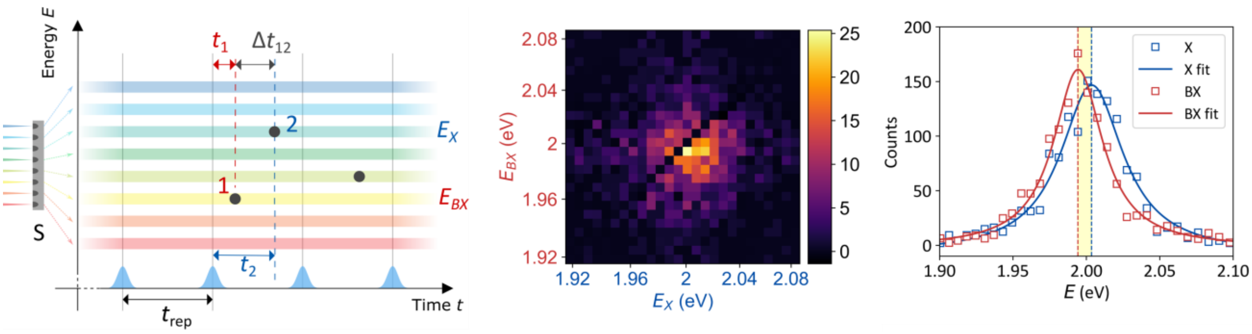

Figure 1 (LEFT) The experimental technique used. A SPAD array is placed at the output of a grating monochromator, so that each pixel detects photons of a specific wavelength. This way, the wavelengths of the first and second photon of a coincidence detection can be recorded. (CENTRE) A 2D histogram of events binned according to the energy of the first photon (y-axis) and the second photon (x-axis). (RIGHT) Spectra of the first and second photons emitted via a biexciton-exciton cascade, illustrating the small binding energy of a few meV associated with biexciton formation.

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Retrieving different morphological and interfacial information of 2D flakes using enhanced optical contrast

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ABSTRACT

Two-dimensional (2D) materials have strain-tunable physical properties. The amount as well as the type of the strain applied to a 2D material, can be investigated using Raman and photoluminescence spectroscopy measurements, which is further correlated with the topographic strain-profile of the strained 2D material. However, an efficient optical imaging of differently shaped (strained) 2D materials or flakes can be advantageous to predict their topographic structure or strain-profile. In this work, we utilize the optical patterns such as interference fringes and Newton's rings[1] observed in the 2D flakes to predict their topography up to a remarkable extent. Further, we developed a polymer assisted technique to get an enhanced optical contrast, which enables the effective characterization of single to few-layers of 2D flakes as a better alternative.

We found our technique as an efficient tool to probe the interfacial behavior of the 2D flake-substrate system. We also model the findings of different fingering patterns under graphene flakes to analyze their generation. The enhancement in the optical contrast is found to be greatly effective for investigating the morphological as well interfacial characteristics of the 2D flakes.

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Plasmon enhanced Pt nanoparticles decorated vertical oriented few-layer MoS_2 broadband photodetector

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ABSTRACT

Two dimensional (2D) layered materials are promising candidate for high speed nanoscale optoelectronic devices, though they suffer from low optical yield. The coupling of plasmonic metal nanostructure with 2D layered materials can further enhance the light-matter interaction. In this regard, plasmon enhanced photodetector is the viable route to improve the device performance. However, previous works are limited to lateral 2D material with conventional metal nanoparticles (NPs) such as Au or Ag, which exhibits narrow spectral resonance range. Contrary to planar structure, vertically orientated layered material can effectively trap the metal NPs and confined strong electric-field within the gap. Here, we design a vertically oriented MoS_2 flakes sensitized with Pt NPs for broadband photodetection. The Raman and Photoluminescence spectroscopy results suggest enhanced electromagnetic field intensity and effective charge transfer due to the strong plasmonic coupling in MoS_2-Pt. The optical absorbance of MoS_2 is enhanced after the integration of Pt NPs, and enhancement in photocurrent is observed. The formation of Schottky junction at Pt-MoS_2 interface inhibits electron transmission, suppressing the dark current and substantially reducing Noise equivalent power. MoS_2-Pt shows enhanced responsivity (432 AW^{-1}, 800 nm) and higher detectivity (1.85×10^{14} Jones, 5V) than pristine MoS_2. Additionally, a theoretical approach is adopted to calculate wavelength dependent responsivity, which matches well with experimental results. Moreover, MoS_2-Pt shows a low response time (87 ms /84 ms) attributed to the faster carrier transport. Thus, present work promotes the growth of 2D vertical structures and consideration of broad localized surface plasmons, for developing high performance multifunctional photodetectors.

Charge back-transfer mediated sensitization of graphene-transition metal dichalcogenide (TMDC) heterostructures to sub-bandgap wavelengths

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ABSTRACT

Binary van der Waal heterostructure of graphene and transition metal dichalcogenide (TMDC) has evolved as a promising candidate for photodetection with very high responsivity due to separation of photo-excited electron-hole pairs across the interface. The spectral range of optoelectronic response in such hybrids have so far been limited by the optical bandgap of the light absorbing TMDC layer. Here, we have utilised the directionality of interlayer charge transfer for detecting sub-band gap photons in graphene-TMDC heterostructure. We have employed Gr/$MoSe_2$ heterostructure to exploit the interlayer charge transfer mechanisms using synchronized visible and NIR photons. Using time dependent photo-response measurements, we have identified a new way to manipulate the charge transfer in Gr-TMDC heterostructure, which allows detection of the low energy photons (less than the energy band gap of optically active TMDC layer). This unique NIR photodetection mechanism provides high photo-responsivity with faster response than trap assisted photo-response. We obtain responsivity as high as 5×10^3 A/W at $\lambda = 1450$ nm close to the communication wavelength which may lead to new device architecture.

Optical tuning assisted many-body phenomena in monolayer two dimensional WS_2 on different dielectric substrates

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ABSTRACT

In monolayer tungsten disulphide (WS_2), efficiently strong Coulomb coupling between electrons and holes engenders tightly bound quasiparticles like excitons, trions etc. As a consequence, the optoelectronic properties of the material have been dominated by these excitonic complexes via many-body interactions. The optical injection of carriers, namely optical doping has significant effect on the Coulomb potential of the photogenerated quasiparticles as well as the many-body properties in two dimensional systems.[1] In this work, the origin of anomalous behavior in excitonic resonance peak-shift and photoluminescence (PL) emission intensity variation via optically tuned many-body effects in exfoliated monolayer WS_2 on two different dielectric substrates: SiO_2/Si and Al_2O_3 substrate have been successfully investigated. In the beginning, exciton resonance energy shows a pronounced red-shift with increasing excitation power, followed by an exceptional blue-shift at Mott transition point. This anomaly is well explained using band renormalization due to interplay between two distinct many-body effects arising due to increasing carrier density: Coulomb screening and Pauli Blocking.

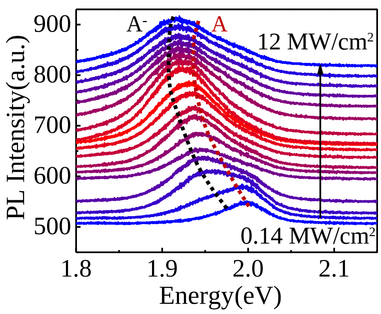

Figure 1: PL spectra of the ML WS_2 for different excitation powers on SiO_2/Si substrates. The colour gradient signifies the intensity variation, i.e. first increases up to a maximum value (from blue to red) and then decreases further (from red to blue.

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Few-layer Phosphorene Nanostructure Silver Nanoparticle Hybrid: Plasmon Driven Enhancement of Broadband Photoresponse

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Black phosphorus (BP) has drawn remarkable interest of researchers for its layer-dependent band gap. BP shows direct band gap nature irrespective of layer numbers in it [1, 2]. On the other hand, integration of plasmonic metal nanoparticles is an easy way to enhance light-matter interactions in these kind of materials by many fold. Here, we report the superior photodetection characteristics of BP nanosheets integrated with plasmonic silver nanoparticles (Ag-NPs) using vertical heterojunction on Si platform [3]. The synthesis of electronic grade BP nanosheets and the Ag-BP hybrid are accomplished through a liquid-phase process. Microscopic measurements have confirmed the exfoliation of bulk BP to few-layer BP nanosheets and the formation of Ag-BP 0D-2D hybrid. The optical properties of the BP nanosheets are significantly impacted by the presence of plasmonic Ag-NPs. The enhancement of broadband photoresponse characteristics is demonstrated using the plasmonic hybrid, where the peak responsivity of the device is shifted to the visible region compared to UV response of the pristine BP nanosheets.

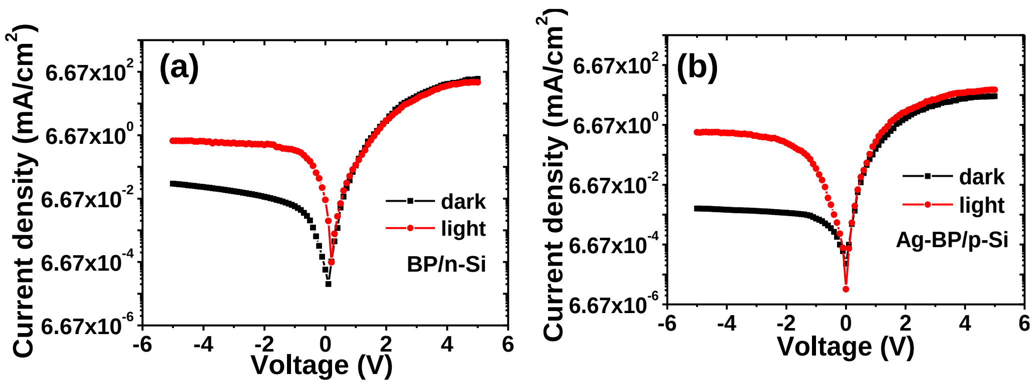

Figure 1: Variation of current density–voltage (J–V) of the devices under different conditions in (a) and (b) for pristine BP nanosheets/Si and Ag-BP hybrid/Si vertical heterojunctions, respectively.

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Generation of discrete vortex with phase-locked lasers

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Topological photonics has emerged a new exciting field of research, where the application of topology is creating a range of new opportunities throughout the photonics [1]. The topology has emerged as another degree of freedom which opens a new door for the discovery of fundamentally new states of light and possible revolutionary applications. For example, potential practical applications of topological photonics include photonic circuitry that is less dependent on isolators and slow light that is insensitive to disorder. Few demonstrations of topological effects were realized in photonic crystals, coupled resonators, laser networks, waveguides, metamaterials and quasicrystals.

Furthermore, laser beams with topological charge (also called optical vortex) have attracted considerable interest, due to their helical wavefront, in various light matter interaction applications, such as in exploring molecular chirality, optical tweezing, guiding and manipulating microparticles, microscopy, molecular spectroscopy, sensing and metrology [2]. There have been several efforts to realize such topological charge beams in both linear and nonlinear systems, and generated either directly at the source or externally. For various applications such as in optical communications, material processing, and laser ablation, high-power optical vortex is required. Recently, new methods for realization of high-power optical vortex has been proposed based on coherent beam combining/phase-locking of lasers. We have investigated the formation of discrete optical vortex with different topological charges by phase locking of lasers in a degenerate cavity [3]. A spatial Fourier filtering mechanism is employed to force the lasers in a steady-state phase-locked state that represents a desired discrete vortex. Further, we have also compared the propagation properties of discrete vortex with a conventional continuous vortex (Laguerre-Gaussian/Bessel-Gauss/circular Airy vortex beam). We have shown that for a given system size (number of lasers) and fixed distance between nearest neighbor lasers, the size of a discrete vortex and its divergence upon propagation do not depend on the topological charge, as opposed to a continuous vortex. We have also found that the discrete vortex possesses good self-healing abilities.

Figure 1(a) shows a discrete vortex with topological charge *l*=1, which is generated by phase-locking of N=20 lasers. Each spot represents a laser with Gaussian (TEM_{00}) intensity distribution, and color represents the phase of the lasers. As evident, the phase circulates from one laser to the next in a clockwise direction, indicating a vortex behavior. With a proper choice of spatial Fourier filters, we can obtain the discrete vortex with different positive and negative values of *l*. Figures 1(b-e) show intensity distribution of a discrete vortex (N=20 and *l*=1) at various propagation distance z, indicating the formation of a ring pattern with a dark spot in the center. The pattern remains stable, however, due to diffraction the size of rings increases with z. To check the self-healing abilities, we have truncated the central part of the beam using an amplitude mask, after propagating a distance *z*=10 m (Fig. 1(f)). The self-healing is quantized by overlap integral (C), which calculates the similarity between ideal and truncated beams. In Fig. 1(f), the truncated beam shows a reduced value of C=78%. Figures 1(g-i) show the intensity distribution of truncated discrete vortex at various propagation distance. As evident, during the propagation the intensity redistribute from inner rings and truncated part re-appears. The increased value of C=98% indicates the self-healing of truncated part (Fig. 1(e)). For longer values of z >18 m, the value of C remains the same. To check the dependence of self-healing on *l,* we have calculated the overlap integral as a function of z for truncated discrete vortex with different *l,* as shown in Fig. 1(j). It is found that the discrete vortex with small *l* value self-heals faster.

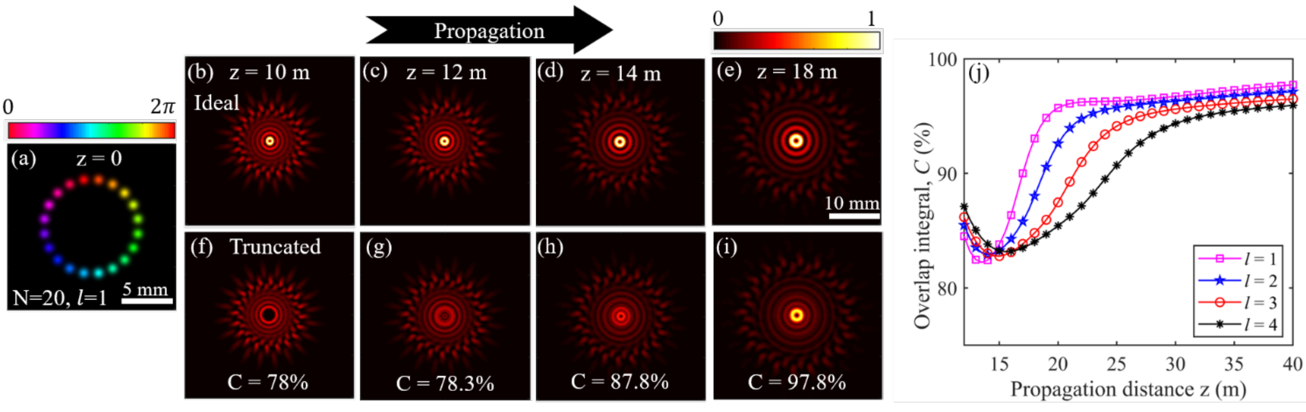

Figure 1. (a) Discrete vortex with l=1 and N=20 lasers. (b-e) Intensity distribution of discrete vortex at different propagation distance z. (f-i) Intensity distribution of truncated discrete vortex at different z. (j) The overlap integral as a function of z for different values of *l.*

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