

Study of mesoscopic behaviour of light in disordered and gain-loss assisted systems from application point of view

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Conclusions

6.1 Summary:

This thesis looks closely at the mesoscopic behavior of light from an application point of view. Disorder is introduced to an otherwise periodic photonic lattice in order to explore the behavior of light in the mesoscopic domain. Such a lattice can be fabricated using laser writing technique or lithography. Disorder causes multiple scattering of the light, as a result of which various unusual events involving the interaction of light and matter is observed. Here, the impact of both spatial and refractive index disorder on light dynamics is investigated. Additionally, the impact of complex coupling by the intentional application of uniform or selective gain or loss to the lattice is also investigated. In this thesis, diverse light dynamics are observed and investigated as a result of the interaction between applied disorder and complex coupling.

The dynamics of a light beam passing through a disordered lattice with a complex refractive index profile is examined in the second chapter of this thesis. It is shown how light propagation changes from the ballistic to super-diffusive domain, suggesting a broadening of the beam's wavefront. In contrast to earlier assertions, where the distribution of scatterers had to adhere to Lévy statistics inside the material, here we have demonstrated that by introduction of deliberate and controlled disorder in presence of optimum gain, super-diffusive state of light can be generated from a test-bed based on coupled wave-guide lattice. Lévy distribution of the ensemble averaged intensity profile is obtained in this regime by the interaction of introduced disorder and complex coupling. Therefore it can be concluded that a little gain is just enough in presence of adequate disorder in the formation of Lévy distribution of super diffusive light state. We are certain that the results will contribute to a better understanding of how gain and disorder-affected random lasers function from fundamental as well as device application point of view. Additionally, intentional and tailored loss in wave-guides (instead of gain in bulk) should produce almost equivalent light dynamics with Lévy tail characteristics. Thus, the key parameters that control the dynamics of light propagation through an optical lattice are the degree of disorder, the amount of gain or loss, and the lattice aspect ratio.

In the third chapter of this thesis, a novel glass based platform is suggested where light propagates by forming branches, also called as "Branched flow". The platform is a smoothly varying weakly disordered lattice whose length scale of variation is significantly greater than the wavelength of light propagating through it. As a result of the formation of branches, the transverse intensity profile of the lattice attains a heavy-tailed distribution. Under the regime of branched propagation, the photons also undergo Lévy walk. To establish these claims various quantitative studies have been performed including the variance, probability distribution of transverse intensity profile, stability parameter α as well as the scintillation index denoting the

approximate distance of formation of caustics, along with an evidence of achieving long and stable branches of light. Further, presence of gain has been found to be an essential tuning element for regulating the branching of light. It is also demonstrated that, when gain is added to the bulk over a threshold amount, filament-like branches are created that propagate a length proportional multiples of wavelength. Additionally, the branches formed through the proposed lattice have very small beam width ranging within $2\mu\text{m}$. This filament like propagating nature of the formed branches does not depend on the characteristics of input beam. Generation of the branched pattern, as well as the width and location of the most prominent branch created, are observed not to differ significantly even when the width of the input Gaussian beam is doubled. Additionally, the branches have a very high intensity because of the filament-like structure. The light propagation under the regime of branch formation can therefore be leveraged to idealise a new class of nano-lasers as a result of the compact beam width and high intensity. On the other hand, such disordered platforms can be exploited to study various natural phenomena involving branched flow. The tsunami waves propagating through oceans can be categorized under the regime of branched flow. Additionally, the flow of electrons through electron gas is also reported to undergo branched flow. Therefore, such natural events can be generated and studied by creating analogous platforms mimicking a smoothly varying environment. In this way, different geophysical events can be recreated within the vicinity of the lab. It could give us a better understanding of phenomena that happen in the transient regime, if carefully recreated and investigated.

Prototype of a specialty topological lattice comprising of two topologically dissimilar periodic sub-lattices is proposed in chapter IV of this thesis. A loss-less light transmission mechanism through the junction of the two topologically different sub-lattices is demonstrated here. The method entails the transition of a trivial lattice to a non-trivial one by tuning the band-topology which depends on the bi-layer dimension. The transition of the topological nature is verified by estimating the *Zak* phases of the respective bands. For a particular choice of bi-layer dimension, we have encountered a gap-less point in the photonic band-structure during the transition process. Investigations have proved that the topological properties of the analogous photonic lattices are radically different on either side of this gap-less point. Based on these observations, we have combined the topologically trivial and non-trivial lattices to create a specialty topological lattice. The existence of the loss-less topological interface state has been demonstrated by the studying the dynamics of light propagation through this specialty lattice. It is also established that the nature of loss-less propagation is demonstrated by the lattice over a range of wavelength. On the other hand, robust propagation of topological interface state despite lateral dislocation of the junction is also demonstrated. The findings may open up a new way of controlling the flow of light in wave-guide based devices including optical interconnects towards high-speed information-processing capabilities.

The fifth chapter of this thesis examines the impact of complex coupling and transverse refractive index disorder on light propagation dynamics through the specialty topological lattice. It has been proven that the introduction of optimal disorder allows for the simultaneous hosting of a topological interface state and a *TAL* state in the specialty topological lattice. By simultaneously passing a light beam through the *TAL* state and the topological interface state, light carrying capacity can be enhanced. The studies are also conducted at four distinct wavelengths, ranging from the band center to the pass-band. It is observed that only the trivial sub-lattice exhibits the effect of transverse localization of light as expected and the topological interface-state remain unaffected by the applied disorder over the operational window. Thus, the interplay of transverse refractive index disorder on the specialty topological lattice allows the simultaneous hosting and propagation of two non-overlapping states of light.

The discoveries would pave the way for the development of novel light-manipulating tools that concurrently leverage topological and transverse localization phenomena. On the other hand, it is found that a minimum of 10^{-4} gain or loss is necessary to be applied to the specialty topological lattice to perturb the topological interface state. It is found that application of loss to bulk have similar effect on the light dynamics as introduction of gain to wave-guides. Light is seen to seep into the trivial sub-lattice when homogeneous gain is introduced to wave-guides together with homogeneous loss to the bulk. On the other hand, light escapes into the non-trivial sub-lattice if homogeneous gain is applied to bulk along with homogeneous loss to the wave-guides. However, the topological interface state completely disappears when loss is only introduced to the bulk. Additionally, light escapes into the trivial sub-lattice when gain is added to wave-guides. However, the light beam is significantly attenuated when loss is added to wave-guides. The most interesting outcome of this study from application point of view is the robust amplification of topological interface state due to the introduction of gain to the bulk. The light is amplified nearly hundred times without leaking into any of the sub-lattices. We believe that this robust amplification scheme can revolutionize the technology of optical amplification in near future.

6.2 Future perspectives:

Though various interesting studies have already been reported, plenty of work is yet to be accomplished in this particular domain to get a better insight regarding the light-matter interaction in mesoscopic regime. In this respect, the possible extensions of our work can be quantified as follows.

In the second chapter we have demonstrated Lévy walk of super-diffusive state of light. This project require investigations in the following directions:

- Minimum distance needed for the transition from ballistic to super-diffusive regime in this platform.
- How length dependent application of gain can affect the phenomenon so that size of the lattice can be customized.
- How the selection of wavelength and the band-structure of the considered periodic lattice effect the generation of super-diffusive light.
- A complete fabrication feasible design of one-dimensional random laser can be proposed.
- The presence of deliberate local non-linearity may trigger some unconventional light dynamics.

In the third chapter, we have demonstrated and investigated the branched flow of light through a smoothly varying weakly disordered lattice. Further work in this domain requires investigations in the following directions:

- What is the physical essence of non-integrability and how is it relevant for our system.
- It is observed that within the system there are many locations where a sudden dip in the intensity is observed. These phenomena occurs adjacent to the branches. We anticipate

that the phenomena may be due to the formation of cavity in the disordered platform. But the curiosity arises from the fact that the dip in intensity occurs only for some specific value of gain introduced to the bulk. Therefore, it is necessary to find a concrete reason behind the sudden dip of intensity.

- How the dynamics of the branch formation and its stable propagation is affected by the existence of purposeful local non-linearities.

In the fourth chapter we proposed the design of a specialty topological lattice and demonstrated the robust propagation of topological interface state through it. This investigation can be further extended in the following directions:

- How topological phase transition from trivial to non-trivial and vice-versa is linked to the overall symmetry of the lattice.
- The design should be optimized to have optimum width of trivial and non-trivial lattice governed by the number of bi-layers required on either side of the junction so that multiple junctions can be created to host interface states which do not interfere with each other even after multiple dislocations.
- The light propagation dynamics through this specialty topological lattice in presence of bending.
- Design of an optical interconnect can be optimized for proof of concept study.

In the fifth chapter we have studied the effect of disorder and the complex coupling on the specialty topological lattice. This study can be further extended to:

- Investigate the effect of interplay between disorder and complex coupling on specialty topological lattice.
- Investigate the effect of deliberate non-linearities on the specialty topological lattice.

In a nutshell, this thesis have proposed various specialty photonic lattices and investigated the exotic light propagation dynamics through them. It has given a physical explanation to most of the exotic light dynamics which have been revealed. Though few more questions remain unanswered.