High Power Optical Pulses through Linear, Nonlinear, and Time-Varying Media and their Applications

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Conclusion and future scope

8.1 Conclusions

This thesis has rigorously investigated the dynamics of high power ultrashort optical pulses in environments endowed with large effects of dispersion, nonlinearity, loss, as well as back-reflection, and an exclusive effect of a time-varying refractive index, targeting towards the control and manipulation of such ultrashort pulses to achieve application-specific robust delivery of light. The entire research work was performed in two classes of photonic structures - waveguides with a spatially-varying refractive index profile, and bulk dielectrics with temporally-varying refractive index profile. Moreover, all the results presented in the thesis have been obtained through analytical study and numerical simulations.

The major part of the thesis has focused on the specialty optical fiber based robust delivery of high power optical pulses. Passive all-solid optical fibers (no gain medium) supporting 1D photonic bandgap guidance of light have been chosen as the waveguide geometry to investigate the behavior of high power ultrashort pulses for their stable delivery at any desired length of propagation. The passive fibers has been chosen in order to eliminate the limitations caused by amplifier bandwidth and noise. Moreover, some targeted applications such as bio-medical surgery and imaging processes demand toxin-free equipment. However, the major factor that ultrashort pulses mostly suffer in such passive all-solid fibers is the dispersion-induced broadening which readily limits their stable propagation length. Moreover, the high power essentially triggers nonlinear interaction which distorts the pulse and sometimes damages the fiber too. In this direction, earlier investigations have revealed that besides optical solitons, pulses with parabolic intensity profile are a robust kind of pulse form to carry high power without wave-breaking. Thus, to achieve stable delivery of high power ultrashort pulses through passive fibers, a pulse reshaping technique has been adapted by suitable counterbalance of normal dispersion and fiber nonlinearity to obtain parabolic pulses with their characteristic linear chirp. It has earlier been observed that parabolic pulses in passive fibers can be realized by exploiting a normally dispersive - decreasing dispersion profile. However, they form an intermediate transient state of propagation for such parabolic pulses which undergo optical wave-breaking due to excessive dispersive and nonlinear phase accumulations. In order to go beyond the transient state of propagation, two specific measures have been implemented.

In chapter 3, an input pulse customization technique has been adapted and implemented since the formation of parabolic pulses primarily depends on the input pulse energy. The input pulse parameter has been customized by using a dark optical pulse of tanh form in the background of any standard bright pulse such as Gaussian or sech pulse form. The bright-dark pulse combination has been allowed to evolve through a dispersion decreasing Bragg fiber designed to operate at 0.98 μm wavelength. Interestingly, the pulse combination has eventually survived over several kilometers of the propagation length with a parabolic shape and linear chirp, and their comparison with single pulse propagation has revealed that the evolution of the pulse-duo has been asymptotic beyond the transient state. It has been concluded that the presence of the dark pulse at the background of the

bright pulse has essentially redistributed the input pulse energy in a way to provide stability over very long distances.

In chapter 4, a novel fiber engineering scheme based on oscillating dispersion profile with an average close-to-zero GVD value has been implemented as the second measure to overcome the transient propagation state. The requirement of such fiber engineering has been essential in a highly dispersive and nonlinear environment mostly experienced while operating at the mid-infrared wavelength range. The chalcogenide glasses that are the most suitable materials at mid-IR are found to exhibit very high dispersive and nonlinear properties which eventually destabilize the formed parabolic pulses. For this purpose, a chalcogenide glass based Bragg fiber has been designed at 2.8 μm comprising of two segments - one decreasing dispersion segment to form the parabolic pulse, and the other has been a multi-section fiber segment exhibiting the oscillating dispersion profile. A stable self-similar evolution of parabolic pulses has been observed through the 8 m long designed dispersion oscillating fiber. Moreover, the varying dispersion with the smallest amount of global average GVD actually has helped to control the broadening of the parabolic pulses which has been extremely suitable for quasi-CW propagation of light with a high repetition rate. Also, a pulse-preserving wide spectrum with spectral width of $\sim$465 nm at 20dB point has been achieved through such dispersion oscillating landscape. However, the effect of third order dispersion in the designed fiber becomes significant due to the presence of several zero-dispersion points, which has further been mitigated by implementing a transverse chirping mechanism in the cladding section only to flatten the dispersion curve followed by the reduction of the TOD effect. Thus, a stable propagation of parabolic pulses in presence of TOD has been achieved up to 4 m in mid-IR and up to 8 m in near-IR range of wavelength. These stable propagation lengths can be further increased by judicious optimization of the fiber core keeping the effectively single mode operation intact.

In chapter 5, the specific challenge of long distance stable delivery of ultrashort pulses through passive fibers due to limited low-loss transmission bandwidth has been addressed. For enhancement of the fiber bandwidth, a novel all-solid 1D bandgap fiber design scheme has been proposed based on effective concentric core formation by selective sets of bilayers in a single geometry. The key has been to overlap the the consecutive photonic bandgaps that corresponds to the optimized bilayer sets, which in turn enhances the overall effective bandwidth of the fiber. A $\sim$1600 nm wide transmission bandwidth with an average confinement loss of 2 dB/km has been achieved from the specialty fiber design. An advanced engineering has also been implemented to lower the confinement loss to $\sim 10^{-2}$ dB/km over a 700 nm wide wavelength range. Solitonic propagation of optical pulses as short as 300 fs have been observed over few kilometers through the designed bandgap fiber. Also, formation of similaritons and their stable propagation have been observed through such fibers with uniform cross-section under the dominant effect of dispersion over nonlinearity.

In chapter 6, to achieve a robust state of light in fibers for back-reflection free transmission of ultrashort pulses, a novel multi-layered optical fiber geometry based on 1D band topology has been demonstrated. The guidance of light in such fiber has been entirely topology protected, unlike conventional core-clad fiber systems. The systematic procedure has been followed to design the 1D topological lattices, and an interface state has been realized at the junction of the two topologically distinct lattice sections. The robustness of such interface state has also been established by studying the dynamics of the state in presence of perturbations. Furthermore, propagation of ultrashort pulses has been studied through such interface state with the numerically estimated values of dispersion and nonlinearity of the topological light state. Here also, formation of parabolic pulses has been observed with a very high peak power, and it has been anticipated that the robust, defect-immune nature of the interface state would protect the stability of the formed parabolic pulses.

Lastly in chapter 7, dynamics of ultrashort pulses has been presented in-depth through

a bulk-dielectric with a time-varying refractive index profile. It has earlier been observed that an EM wave behaves differently across a time boundary exhibiting certain exotic phenomena. In this thesis, the changes of ultrashort optical pulses propagating from opposite directions across a temporal boundary has been investigated in both the time and the frequency domain. The entire analysis has been done semi-numerically by exploiting the time-transformation method originally curated to study pulse behavior in time-varying media. Pulse propagation in counter-propagating direction through the non-dispersive gain-loss assisted linear time-varying medium has shown an asymmetric transmission of pulses both in temporal and in spectral domain. The presence of gain and loss has found to have high impact on the time-domain output pulse profiles giving an asymmetric pulse dynamics, whereas the change of refractive index with time eventually have shifted the pulse spectrum by a factor defined as the ratio of initial to final refractive index. Moreover, the inclusion of dispersion in such gain-loss assisted time-varying medium has also exhibited the asymmetric behavior not only in the pulse and spectral profile but also in the system's dispersion. For a better understanding, the study of pulse propagation has been performed in a dispersive time-varying medium without considering gain/loss. Owing to the inherent nature of time-reversal symmetry breaking in such time-dependent media, a change in dispersion regime has been observed across the temporal boundary in counter-propagating directions, which in turn led to non-reciprocal transmission properties of the optical pulses. The scattering matrix approach has been implemented to establish the nonreciprocal behavior for the time-boundary problem. Moreover, the shift of the pulse center wavelength in the linear time-varying medium has resulted in spectral nonreciprocity which has been observed earlier only for magnetic photonic crystals.

Since the research carried out in this thesis has been entirely simulation based, it is necessary, as a scientific researcher, to address the feasibility and technicality of the experimental realization of the proposed subjects. The challenge that should be addressed first is the fabrication feasibility of the proposed fiber geometries. The specific choice of 1D periodic layer based photonic bandgap geometry was made so that the fibers can be easily fabricated by using the state-of-the-art technologies such as stack-and-draw or extrusion process for the making of fiber preforms. Moreover, the materials chosen for the fiber design process are commercially available with full specifications for the results to be practical and in good agreement with the experimentation. In addition, special care has been taken in order to optimize the dimensions of the fiber cross-sections such that they are within the tolerance of the fabrication procedure. Besides, the operating wavelengths were also decided on the basis of laser source availability such that the results can be reproduced experimentally. Specifically, for dispersion oscillating fibers, there are well-developed processes for fiber tapering and splicing with negligible loss that can be judiciously exploited. On the other hand, the time-modulation of refractive index can be practically realized by implementing an external drive field to the bulk medium. The precise duration of the modulation can be controlled via pre-designed computerized module, whereas the output pulses can be observed by using commercially available standard auto-correlator and spectrometer with some adaptive optics arrangement.

8.2 Future scope of study

This thesis has presented multiple intriguing domains of research based on theoretical analysis and simulations. The major part of the thesis has focused on optical fiber based pulse reshaping technique for robust transmission of light. For this, various unconventional fiber engineering schemes has been adapted and implemented to achieve the desired outcome. The following domains of research have been identified as immensely interesting and open areas to harness their unique features for development of novel fiber based technologies.

- Experimental verification of the bandwidth enhancement and pulse reshaping through the

fabricated *endless core fiber*, and further study on the bandgap design and optimization process for bandwidth tunability and loss management in presence of bending.

- The domain of *topological fibers* and the use of topologically protected light state for future photonic devices is the rapidly growing field of research. Owing to the defect-immune, robust properties of topological light states, their implementation in fiber like geometries will eventually facilitate the process of developing next-generation topological fiber optic systems. Such topological fibers can be rigorously investigated for developing futuristic telecom infrastructure, as well as in connecting IoT devices. For fundamental research, topological properties of light in fibers may also be amalgamated with non-Hermitian photonics providing new insights on the control and manipulation of light states.

The other part of the thesis has demonstrated the unique propagation dynamics of optical pulses in a time-varying medium. As it has been observed in the thesis that the presence of temporal boundary leads to nonreciprocal light transmission, it would be an important area of research where nonreciprocal light transmission can be achieved without implementing the contemporary techniques. Towards this, the following domains of research can be undertaken.

- Study of time-dependent nonreciprocal devices for next-generation integrated photonics.

- Towards photonic time crystals, and temporal waveguides providing a novel platform for ultrafast chip-based optical/quantum devices.