Prospects of ultrafast pulse shaping

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Availability of femtosecond solid-state lasers around the world has spurred a lot of technological activity in the femtosecond timescale and has also given us a tool to probe and gain more insight into the fundamentals of physics, chemistry and biology. An eventual prospect of controlling and manipulating some of the hitherto impossible tasks, can perhaps now be dreamt of. In this review we give a brief account of some of the promising techniques for ultrafast laser pulse shaping and then list some of the exciting prospects.

ULTRAFAST light pulse can be represented as a coherent superposition of many monochromatic light waves within a range of frequencies that is inversely proportional to the duration of the pulse. The short temporal duration of the ultrafast pulses results in a very broad spectrum. In fact, a 40 fs pulse at 800 nm that is available commercially, has a spectrum as broad as 30 nm. Possibilities of manipulating such an ultrafast coherent broadband source have opened up an extremely exciting field of 'ultrafast pulse shaping' with which, as the name suggests, one can manipulate the individual constituents of the pulse to have a desired shape both in the time and frequency domains. This has in turn led to a spurt of activity in 'coherent control', which is the ability to control the dynamics at various stages of a process as it evolves, under the effect of a coherent source. Many of the frequencies constituting the ultrafast pulse can simultaneously excite many coherent transitions to the excited states, and a capability to manipulate them with the shaped pulses leads to the interesting results. In fact, the recent advances in pulse-shaping technology have been linked with the growth of the coherent control studies. A lot of activity is in progress and one eventually hopes to achieve the ultimate dream of feed-back based quantum control, which has been a desire ever since the birth of quantum mechanics. However the applications are by no means only limited to coherent control technologies, but have spanned numerous applications in optical communications, control of chemical reactions, molecular dynamics, nonlinear optical processes, THz radiation in semiconductors, biomedical applications, quantum computation, etc. In this review, after a brief introduction as to how it is achieved, we concentrate on the exciting prospects of 'ultrafast pulse sha

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Ultrafast pulse shaping

Since the optical pulse that we wish to shape has sub-picosecond temporal duration, we would need a modulator that works on this timescale. This idea of shaping a pulse by sending it through a modulator in real time is referred to as direct pulse shaping. For example, the nuclear magnetic resonance (NMR) scientists have extensively used pulse shaping in the radio-frequency (RF) domain. The pulse lengths in the RF domain are on the order of μs; hence with available electronics, the pulse shaping of the RF pulses could be achieved easily. The advantages of such techniques are evident from the tremendous applications of NMR available today. Thus the natural desire is to extend this technique into the optical domain. However, shaping ultrafast pulses is non-trivial since there are no electronic devices that can work on these femtosecond timescales. Current modulators can operate at 60 GHz, which is much slower than that is necessary to shape a femtosecond pulse. There are several other difficulties which are not encountered in the RF domain. One such example is pulse reshaping. As an optical pulse propagates through an optically dense medium, it will become reshaped. This phenomenon is typically not encountered in NMR spectroscopy that would not be observed in the RF domain, because of the long RF wavelength. Such undesirable phenomena are interesting to study in their own right. Thus shaping femtosecond pulses in the optical domain is more technically challenging then shaping μs pulses in the RF domain.

A creative solution to the problem of slow modulators is the technique of indirect pulse shaping. This approach of ultrafast pulse shaping essentially involves a spatial Fourier transformation of the incident pulse to disperse the frequencies in space and filter the chosen frequency components selectively. A final recombination of all the frequencies into a single collimated beam results in the desired pulse shape. In practice, a grating spreads the pulse, so that each different spectral component maps onto a different spatial position. The collimating lenses and grating pair are set up in a 4F configuration (F being the focal length of the collimating lenses), and in the centre of the 4F system, an element is placed that will modulate the spectrum. With this approach, it is not even necessary to have modulators that respond in the femtosecond timescale to shape the ultrafast pulse.

The first demonstrations of indirect pulse shaping used a fixed spatial mask. The spatial mask can be created

using lithographic techniques as in semiconductor processing. The fact that the spatial mask cannot be changed in real time limits the utility of this technique and hence does not have the capability to be programmed. However, this approach does have the advantage that it is simple, and requires no pulse picker.

Another approach uses a Liquid Crystal Modulator (LCM), which generates a position-dependent transmission function or position-dependent phase shift on applying voltage, which alters the spectrum of the later pulse. The LCM consists of discrete pixels, and the index of refraction can be changed for each pixel. The typical number of pixels is 128. One ramification of the discrete pixels is that there may be inter-pixel gaps that cause undesirable distortions, which restrict the amount and nature of the chirp that can be imposed and make the technique unsuitable for applications where sophisticated and complex frequency modulation is required. This problem has been greatly reduced in recent work through the use of micro-lens arrays and advances in LCM technology. Another point is that with a single LCM, only the phase of a single pulse (in the spectral domain) can be modulated. However, Wefers and Nelson[1] have demonstrated that two LCMs can be used for simultaneous amplitude and phase modulation. They have also stimulated the limitations imposed by the real LCM devices. These limitations include slow update rate (100 Hz), modulator alignment, pixel gaps, pixel calibration, and on–off isolation in the individual pixels.

The AOM (acousto-optic modulator) pulse-shaping technology uses a TeO_2 (visible) or InP (infrared) AOM crystal oriented at a Bragg angle in place of the LCM, at the centre of the 4F system[2]. A shaped RF pulse creates an acoustic wave that propagates through the crystal. The transit time of a femtosecond pulse through the crystal is very short compared to the time the acoustic wave takes to propagate. Thus, the acoustic wave looks like a diffraction grating where the different frequency components of the laser pulse are modulated independently and the diffracted part of the beam is collected. A fundamental difference between AOM and LCM pulse-shaping is that the AOM will diffract the input light, with the diffraction determined by the input RF wave to the crystal. The LCM, in contrast, will transmit the light, and not diffract it. The fact that the AOM diffracts the light will mean that very high contrast ratios can be obtained in AOM pulse-shaping. The contrast ratio will be determined by that of the RF wave. The AOM approach does not have the contrast-ratio problem and has significantly faster update rates compared to the LCM array. The update rate is solely limited by the time it takes the acoustic waveform to travel through the crystal and thus depends on the crystal size. The advantage of minimal discreteness in the imposed shape in case of the AOM approach also enables more modulation features (pixels) to be incorporated in the shaped pulse. Furthermore, in contrast to the LCM

scheme, the AOM shapes the pulses by deflecting the shaped wavelengths in a different path from the transmitted or undiffracted part of the beam. Thus, the isolation in the diffracted beam of an AOM is significantly better than that of the LCM array used in amplitude modulation configuration. The calibration of AOM is simple, and phase and amplitude of RF pulse are directly transferred to the laser beam[3]. However, the AOM technique also has its disadvantages. The travelling acoustic wave results in time-dependent spatial grating, thus the pulses separated by few microseconds will see different gratings. To the first order, this implies that the shape of the output pulse will stay the same, but the centre frequency will change. This may be desirable in some applications[4]; the AOM technique is best suited for applications in which selected or amplified pulses (ranging tens of MHz repetition) are required. A schematic of such indirect schemes of pulse shaping discussed here is summarized in Figure 1.

As discussed here, the choice of the exact pulse-shaping apparatus would depend on the particular application; each technique has different advantages to it. Most often, the shaped pulses only have nanojoule level energies, and for most practical applications in coherent control, higher pulse energies are necessary. Amplification of shaped pulses is not straightforward, since pulse distortion and characterization are critical elements for consideration. However it is worthwhile to mention that the AOM pulse-shaping scheme is the only one where high-fidelity amplification has been demonstrated to hundreds of microjoule levels (200 µJ/pulse)[5].

Various applications of ultrafast pulse shaping

With the current state-of-the-art of ultrafast pulse-shaping technology, it is possible to generate arbitrary shapes of ultra-short pulses that would suit the particular application. Thus, for a given situation we can have the pulses tailor-made for our purposes and this is an important feature of the ultrafast pulse-shaping technology. In this section we list few prospects which hold for this emerging technology using shaped pulses in a variety of fields like ultrafast nonlinear optical fibre optics, optical communications, femtosecond pulse amplification, and coherent control of atomic, molecular, and nonlinear optical processes, biomedical applications, etc.

Pulse shaping in optical fibres

It is no secret that even with the current state-of-the-art technology for various electronic devices being pushed to limits, various schemes based on all-optical communication have been pursued aggressively for the inherent advantages they offer. Optical fibres, with their unique properties, have been able to realize various applications. The waveguide nature and near negligible attenuation

of the signal of desired wavelength makes it the backbone for the optical communications. Its long interaction length offered for the light has made it possible to observe various nonlinear optical effects very easily. Also, it has been an extremely useful candidate as a device in all-optical switching, etc. Pulse shaping holds the promise for further extending this limit besides opening up various other new possibilities, right from increasing the speed of the data transfer rate in optical communications to exploring various new nonlinear optical effects, to enhancing the performance of the ultrafast switching and others.

Optical communications: Most of the present-day research effort in optical communication is directed towards achieving extremely high data transmission rate of terabits/s. With the present-day technology available, it has reached data transmission of gigabits/s. Ultrafast pulse shaping holds the promise to achieve the data transmission capacity of a terabit/s. The very high transmission capacity of a terabit can perhaps be appreciated from the fact that about million movies can be transmitted simultaneously. This can be achieved by taking advantage of the various light modulation techniques available, like time-division multiplexing (TDM), wavelength division multiplexing (WDM), and code-division multiple accessing (CDMA).

Communication through optical fibres allows one to use the extremely large bandwidth of about 20 THz sustainable in the fibre, for transmitting data. With the currently available encoding and decoding schemes, one has not been able to exploit this bandwidth fully. Ultrafast pulse-shaping technology can help form ultra-short bit of data streams to be transmitted as short burst of light, thereby allowing an increase in the data transfer rate. This is

essentially TDM[6,7]. It does not demand any ultrafast electronic devices to be operated at this fast speed, nor does it demand much changes in the present day infrastructure available for optical communication.

Another technique commonly used is the WDM, where the broad spectral contents of the ultrafast pulses are wavelength-encoded with an optical pulse-shaper. Normally, to encode the data at various wavelengths, we would require multiple light sources at different wavelengths. Moreover, it also requires all these different sources to be stabilized, which is very difficult. Mode-locked laser can be used as a self-stabilizing source for multiple optical wavelengths. A modulator array placed within the optical pulse-shaper can be used to place independent data on the individual wavelength channels. This avoids the use of stabilized multiple laser sources at different wavelengths, since the entire wavelengths are derived from a single mode-locked laser. The idea of applying pulse shaping to dense WDM was first proposed by Weiner et al.[8] and was later experimentally confirmed by Wegmueller et al.[9].

Finally, in the technique of CDMA[10-13], which essentially utilizes a combination of TDM and WDM techniques, an ultrafast pulse shaper helps to encode and decode signals. Encoding of ultrafast pulses can be achieved by utilizing pseudorandom phase patterns to scramble (encode) the spectral phases. This can be achieved by, say, using a fixed pseudorandom phase mask[14-16]. To reconstitute the original femtosecond pulse, a second, phase conjugate mask is used to unscramble (decode) the spectral phases, thus restoring the initial pulse. If the encoding mask matches the decoding phase conjugate mask, like a key to a lock, then any phase changes introduced by the first mask are undone by the second and the original ultrafast pulse emerges unaffected. And since use is made of both packing the information in
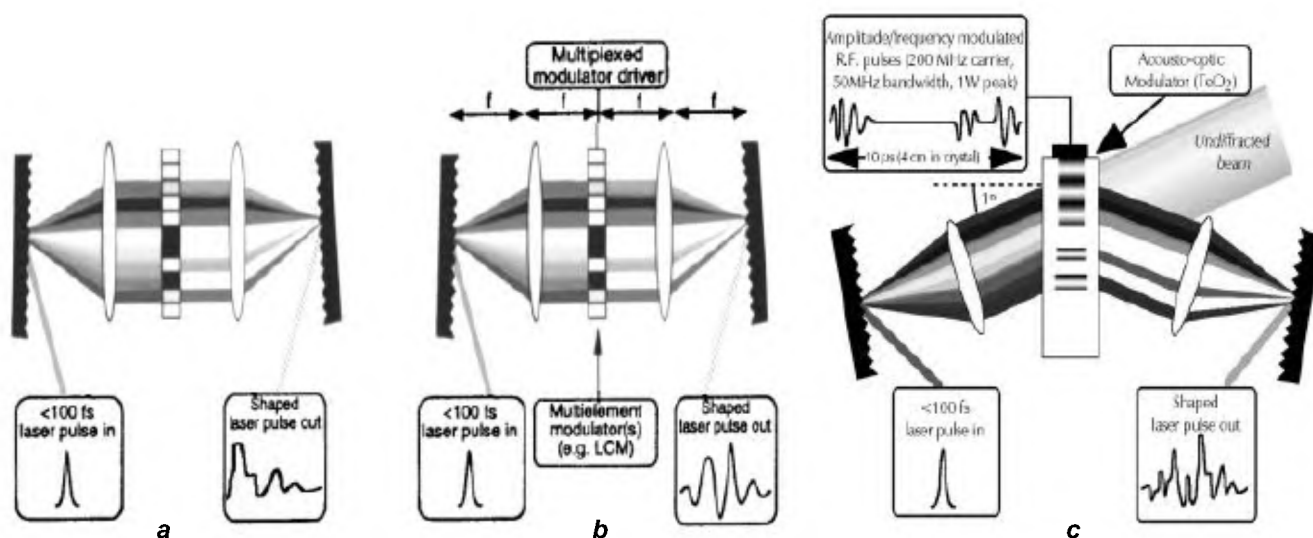
Figure 1. Schematic set-up to achieve ultrafast pulse shaping by 'indirect methods' using (*a*) fixed mask; (*b*) liquid crystal modulator; (*c*) acousto-optic modulator techniques.

time domain as well as in the frequency domain, larger rate of data transmission is achieved.

We also note that pulse shaping can be utilized to achieve the dispersion compensation necessary for ultra-short pulse CDMA. One can compensate for a constant (wavelength-independent) dispersion simply by adjusting the grating separation in the pulse encoding or pulse-shaping masks, in order to compensate for cubic or even higher order dispersion.

Also for high-speed communications over a long distance, data are being transmitted in the form of 'soliton' packets, which travel through the optical fibre without changing their shape much. In the subsection that follows, we will see how pulse shaping has helped to produce various kinds of 'solitons' exploiting the non-linear optical technique, helping to undertake various experiments as well as for different applications.

Pulse shaping in ultrafast nonlinear fibre optics: Pulse shaping of ultrafast optical pulses has helped considerably to study various nonlinear optical processes like formation of 'dark' optical solitons, shaping the pulse to avoid the break-up of the high-intensity pulses in the all-optical switching to remove the undesirable frequency compo-nents from the pulse, for producing higher order solitons and so on.

We know that 'bright solitons' are being used for high-speed long-distance communications[17], ever since Hase-gawa and Tappert[18] proposed that the nonlinear refractive index in glass fibres could compensate for group velocity dispersion, resulting in optical solitons, which could pro-pagate in the optical glass fibre. A bright temporal soliton is the result of cancellations between the chromatic dispersion of the material and its self-phase modulation. This is obtained when the material dispersion is ano-malous and when the medium has a positive nonlinear index (or alternatively, with normal dispersion and nega-tive nonlinear index). These solitons are resistant to dispersive effects in the time domain, frequency domain or in space.

For normal dispersion ($\lambda < 1.3$ μm), bright pulses cannot propagate as solitons, and the interaction of the nonlinear index with dispersion leads to spectral and temporal broadening of the propagating pulses. However, 'dark-pulse solitons', which consist of a rapid dip in the intensity of a broad pulse or continuous background, are predicted to exist for normal dispersion[19]. Pulse shaping has played an instrumental role in producing suitable dark input pulses for experiments verifying soliton propagation of dark pulses in fibres. The fundamental dark soliton, also called a black soliton, is an odd function of time, with an abrupt phase shift at $t = 0$. The intensity of the black soliton is completely extinguished at $t = 0$. The phase function of dark solitons was a major obstacle for many years, hindering experimental investigations; only through the use of pulse-shaping techniques has it become

possible to create individual dark pulses with the required phase variation. Weiner *et al.*[20,21] synthesized even- as well as odd-symmetry femtosecond dark pulses, which led to a convincing demonstration of fundamental dark-soliton propagation. Dark-soliton propagation is remarkably robust against perturbations arising from a finite duration background pulse (recall that true dark solitons include a continuous-wave background of infinite duration)[20,22]. Besides this pulse shaping has also enabled the production of 'higher order' bright optical solitons in the anomalous dispersion regime, where the original spectrum and pulse shape have been restored after every integral number of soliton 'periods'.

Ultrafast all-optical switching: All-optical switches have much higher operating speeds compared to the electronic or optoelectronic devices. And as the techno-logy for all-optical communication is being pursued aggressively, all-optical switches become very essential, as they would be an integral part of this technology.

Pulse shaping can also play a role in studies of all-optical switching devices, which potentially can operate at speeds much higher than those obtainable with current devices. A number of all-optical fibre switching geo-metries have been reported using glass optical fibres[23] and switching times as short as 100 fs have been demon-strated[24]. Nevertheless, one universal problem arises with nearly every all-optical switching device. Because it is controlled by the instantaneous optical intensity, switch-ing can occur within a pulse, so that the high and low intensity portions of the same pulse are directed to different output ports[24–27]. Such pulse break-up can degrade switching performance in a variety of all-optical switching geometries. Through the use of pulse shaping, problems associated with pulse break-up in all-optical switching can be largely avoided.

Spectral windowing: In fibre and grating pulse compres-sor, the external frequency components generated by self-phase-modulation in the optical fibre are not linearly chirped under some conditions and therefore cannot be efficiently compressed. By placing a band-pass spectral filter or a spectral window into the grating pulse comp-ressor one can eliminate these non-compressible frequency components, which would otherwise contribute to an undesirable pedestal on the compressed pulse. Normally, the self-phase-modulation spectrum is symmetrical, and therefore the band-pass filter is symmetrically placed in the pulse shaper. This simple application of pulse shaping to fibre and grating pulse compressor is referred to as spectral windowing[28].

Chirped pulse amplification

Quest for table-top coherent light sources in the shorter wavelength of extreme ultraviolet or soft X-ray regions of

the spectrum has led to the use of two very promising techniques: lasing in ionized plasma[29] and high harmonic generation from intense femtosecond laser pulses[30]. High harmonic generation essentially involves the nonlinear interactions induced by the strong light in the medium. This allows one to extend the production of coherent light sources at shorter wavelengths. In gases, higher harmonic generation up to several hundreds have been generated from the incident laser pulses, but the efficiency is low and the energy is spread out over many harmonic orders. However by shaping the ultrafast pulse, it is possible to increase the efficiency by an order of magnitude. The generated harmonic can be channelled into a single harmonic order, thereby directing a majority of the emitted energy into it. The output of the harmonic can be further increased if we have intense chirped pulses. As mentioned earlier, chirped pulse amplification[31,32] is not straight-forward. In brief, the pulse to be amplified is first stretched (chirped) in a dispersive delay line in order to reduce the peak intensity. This avoids optical damage and unwanted nonlinear optical effects during the amplification process. After amplification the chirped pulse is recompressed to the bandwidth limit. To date, chirped pulse amplification has yielded the highest level of energy output per pulse, e.g. pulses with durations of 30 fs at energies above 100 mJ[33]. This corresponds to peak powers in the multi-terawatt range.

Ultimate aspects of pulse shaping: Feedback-based quantum control

Most of the control experiments in the past have been on small molecules, usually in gas phase or in molecular beams. Extension of quantum control to large molecules in the condensed phase, which is directly relevant for most of the chemistry and biology, faces major obstacles: the great complexity of such a system and our lack of sufficiently detailed and precise knowledge about them. The traditional time-domain approach to quantum control has been to explicitly calculate the quantum dynamics and optimize the light field using knowledge of the potential energy surfaces of the molecule[34,35]. However, in case of large molecules the optimized fields are often quite complicated and even impossible to create in the laboratory, given the present state of laser technology. These considerations have led to the proposal to use experimental feedback rather than quantum calculations, to find the optimal laser field[36]. In this approach, a computer controls a pulse-shaping device (e.g. AOM pulse shaper discussed earlier in this review) and analyses the output of the experiment. The experimental feedback is then used to modify the subsequent laser pulses for achieving the optimal field required for a particular process. Warren and coworkers[37] used this technique and demonstrated the control of molecular electronic population transfer.

Femtosecond pulses tailored by a computer-controlled acousto-optic pulse-shaper were used to excite fluorescence from laser dye molecules in solution. Fluorescence and laser power were monitored, and the computer uses the experimental data and a genetic algorithm[38] to optimize the population transfer from the ground state to the first excited state of dye molecule IR-125 in methanol solution. In their experiment, the most 'efficient' transfer is the one that maximizes the yield of the excited state population with respect to the given laser power. Similarly, the most 'effective' transfer is the one that maximizes the total amount of excited state population, regardless of the laser power.

The recent demonstration[39] of control of 'chemical reactions' using feedback-optimized phase-shape femtosecond laser pulses, is an important example of this technique. In this experiment, Gerber and coworkers tried to optimize the branching ratios of different organometallic photo-dissociation reaction channels. It was shown that for $CpFe(CO)_2Cl$ sample two different bond cleaving reactions can be selected, resulting in chemically different products. The use of computer-controlled femtosecond pulse-shaper with an evolutionary algorithm and feedback from product yields leads to optimization, without having to deal with electronic population transfer within the parent molecule. The spatial light modulator (SLM) contains pixels whose refractive indices can be changed separately by applying specific voltages. In this way, different optical path lengths can be introduced to the spatially separated spectral components of the laser pulse, resulting in the shift of relative phases. In their experiment, emerging pulses are then focused into a high-vacuum chamber where they interact with a molecular beam, leading to different multi-photon ionization and fragmentation processes. The first simple system $Fe(CO)_5$ was taken and branching ratio of two different exit channels was used as a feedback signal in the optimization scheme. It was observed that maximization is achieved within 30 generations of the evolutionary algorithm and minimization is almost immediate. Further, it is explained that maximization corresponds to very short (bandwidth-limited) pulse, where minimization required long picosecond pulse. The total photo-fragment yield in the minimization experiment was ten times smaller than that in the maximization case, because a long picosecond pulse initiates the multi-photon-induced photo-dissociation with much lower intensity. However, the difference in fragment yield ratio $Fe(CO)_5^+/Fe^+$ by a factor of about 70 in the two experiments is not a mere intensity effect, because the $Fe(CO)_5^+/Fe^+$ ratio increases if the femtosecond laser beam intensity is lowered by attenuation at a constant pulse duration. In the case of a more complex molecule like $CpFe(CO)_2Cl$, there are two product channels leading to $CpFeCOCl^+/FeCl^+$. Their optimized experimental result does not correspond to bandwidth-limited pulses. In fact, in both the cases they get a complex pulse structure and

an increased pulse duration (lower intensity) compared to bandwidth-limited case, thus again confirming that it is the spectral optical phase and not the pulse intensity that is responsible for the optimization results. Considering that the organometallics are widely used as photo-catalysts in many organic reactions and in microelectronics, this experiment represents the first practical example of coherent control of chemical reactions. This is a perhaps an important step towards the synthesis of chemical substances with higher efficiencies, while reducing unwanted by-products simultaneously.

In the demonstrations discussed until now involving feedback loops for both AOM and LCM pulse-shapers, complex algorithms like the evolutionary algorithm[40] and the simulated annealing algorithm[41] have been used and over 1000 iterations were performed in one experiment for optimization. In using such complex schemes, the LCM technique has a disadvantage in the sense that the updating rate of LCD arrays is slow (100 ms). Thus, a large number of iterations can take too long to avoid complications caused by the drifting effects inherent in most laser systems, among other problems. On the other hand, in addition to the unique capability of performing both amplitude and phase modulation simultaneously, AOM-based optical pulse-shapers also have the updating rates that are orders of magnitude faster than LCD-array-based pulse-shapers[42]. Therefore, the AOM-based pulse-shapers are in principle more suitable for applications requiring real-time feedback control over the spectrum in both amplitude and phase. An example of such a feedback scheme AOM-based pulse shaper is shown in Figure 2, which has used a very simple algorithm for amplitude only feedback, and only nine iterations were used to reach the desired goal.

Attempts are being made to combine the manipulation of the centre-of-mass or internal degrees of freedom of the target to achieve molecule-specific coherent control in liquids, that is of relevance to biology[43]. Experiments like picosecond chirped pulse-induced inversion, stimulated emission pumping, and chirped femtosecond three-pulse four-wave mixing have demonstrated that laser chirp can be used to control coherence transfer between the ground and excited states in gas-phase molecules like I_2. Nevertheless, all these experiments are still far from achieving or demonstrating a level of sophistication to take the concept of coherent control to the liquid phase, especially for the reactions in liquid water which is the matrix of life. In condensed phase, an additional control that one would like to achieve (e.g. biomolecular reactions in the liquid phase) is localization of active reactant. Optical tweezers have been shown to have the capability of localizing cells and even large molecules. It is conceivable that the same light field can be used to manipulate the activity of the particular molecule of choice. We discuss these issues relevant to biological systems in the next section.

Biomedical application

General applications of lasers for biomedical purposes are well known for diagnostic tools, surgical tools and for imaging purposes[44]. The immediate extension of ultra-short pulse-shaping technology for biomedical applications holds a lot of promise, to further necessitate looking into its domain of influence. Though very few applications of ultrafast pulse-shaping technology are currently in use, there are very strong indications as to where it would lead.
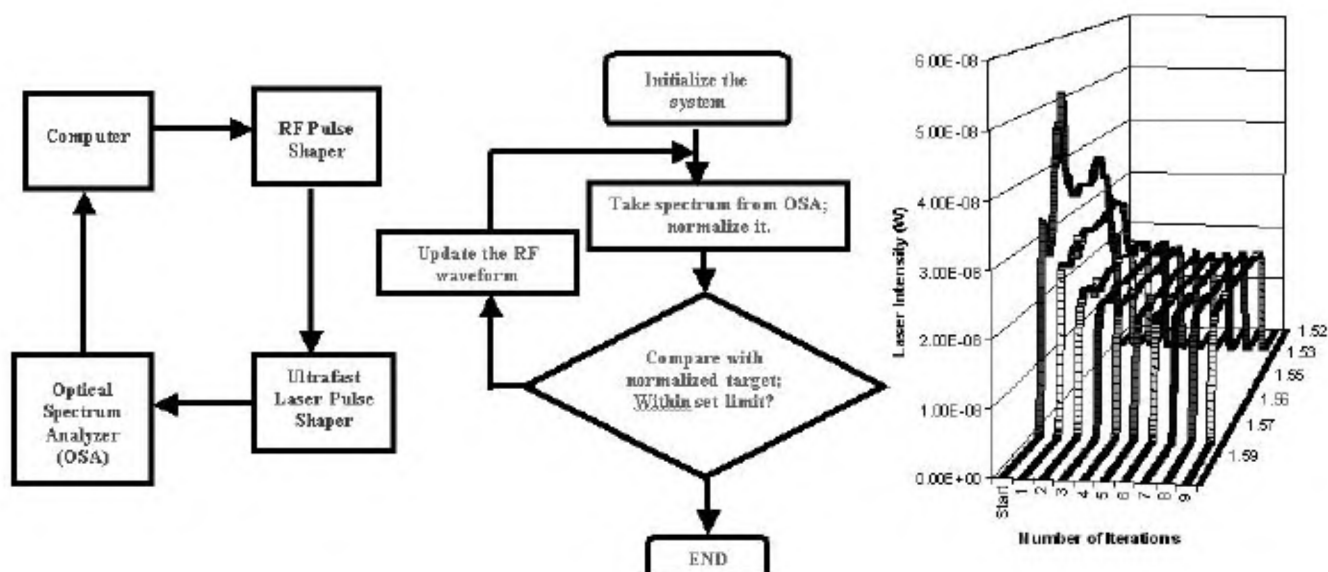
Figure 2. Schematic of feedback loop for computer-controlled AOM pulse-shaper for ultrafast pulse shaping. Here rectangular profile of pulse is obtained within ten iterations.

One of the most commonly adopted methods, for imaging, in recent times for three dimensional profile measurement is optical coherence tomography[45,46] or a white light interferometer, which uses a broadband, low-coherence light source. Recently the principle of femtosecond pulse shaping by spectral modulation has been used in conjunction with the joint transform correlator, to make a spatio-temporal joint transform correlator[45]. The advantage of such a technique has been that it essentially removed the need of 1D depth scanning and thereby avoided the long measurement times involved. Consequently, this eliminates the electronic computation needed to obtain the object image, and so it can be implemented as an all-optical set-up. Initially, this was demonstrated as a surface measurement set-up; however, as a natural extension, it was easily extended for providing tomographic sectioning of biological samples. In fact, with the use of principles of pulse shaping, a depth resolution of 70 μm was achieved[45]. Furthermore, since there is no contact between the probe and the tissue, it is a useful non-invasive technique which provides the physician with near-histological resolution imaging of sub-surface tissue morphology, potentially aiding in biopsy site selection and thus approaching the goal of 'optical biopsy'[47].

Optical trapping and manipulation of viruses and bacteria[48] have been demonstrated long ago. Such optical tweezers are used for localizing larger cells and observing the biomechanics[49] of each individual constituent of such a cell. It is possible to manipulate the activity of a particular molecule which responds to the incident light, with the help of the pulse-shaping technology. As this technology has proved its potential in chemistry in the coherent control of the chemical reaction, it is not very difficult to visualize that in near future similar attempts would be possible, with the use of optical tweezers, to isolate a particular constituent of the cell and induce some reaction or regulate an activity of this constituent[50]. Using a broadband source of light it has been possible to identify the pre-cancerous cells[51], especially the ones which are epithelial in origin. This approach essentially looks at the abnormal size of the nucleus to identify whether it is cancerous or not. Once this is identified, then maybe we can use shaped pulses to trigger some photo-reaction in the nucleus, which would prevent the pre-cancerous cells from becoming cancerous. Thus, we can foresee that ultrafast pulse shaping may not only be used as a diagnostic tool, but also for therapeutic purpose. In fact, the use of optical tweezers along with pulse-shaping techniques would perhaps be our first window for attempting molecule-specific coherent control in liquids, which is of relevance to biology.

All these discussions of using shaped pulses for inducing specific coherent controlled processes in biological samples essentially rely on delivering such pulses through optical fibres. However, ultra-short pulses propagating through the optical fibre get reshaped, which would be undesirable. Here again, the pulse-shaping technology can come to the rescue, as discussed earlier. In fact, in all such applications where ultra-short pulses have to be delivered through the optical fibre, this is a serious problem. Knowing the optical characteristics of the fibre through which they propagate is essential, so that one can shape the pulses at the input and as they propagate they would compensate for the dispersive effects resulting in the desired pulse shape at the terminal end. This would enable the desired pulse to be delivered at the target without distortion.

Semiconductors

Semiconductor quantum dots are nano-sized quantum structures that allow electronic properties to be tailored through quantum confinement. These nano-structures are known to have atom-like spectra with discrete and sharp spectral lines. The similarities between atoms and quantum dots suggest the possibility of using coherent optical interactions for wave function engineering. In contrast to higher dimensional semiconductor systems, quantum dots suggest the possibility of using coherent optical interactions for wave function engineering in a similar way to that achieved in atoms, but with the technological advantages of a solid-state system. Thus, the results of coherent control in atoms can well be applied to localized quantum states of quantum dots, to enable wave function engineering of specific target states. In an experiment on similar lines, Steel and coworkers[52] used picosecond optical excitation to coherently control the excitation in a single quantum dot on a timescale that is shorter compared to the decoherence timescale. Two pulse sequences were applied to manipulate the excitonic wave function by using the polarization of laser and by controlling the optical phase through time delay between the pulses. Such experiments promise the future possibility to implement various schemes for quantum computation and coherent information processing and transfer, where it is important to address and coherently control individual quantum units.

Novel optoelectronic devices like optical switches based on undoped quantum-well structures using pulse-shaping techniques have been predicted. Neogi et al.[53] have demonstrated that besides the relaxation time of the system, tailoring the properties of the coupling pulsed laser fields via pulse shape, delay or peak power can also be used to manipulate the interband transitions of the undoped semiconductor quantum well to enhance the switching performance, which depends on the optical nonlinearity. They have also shown how the optical nonlinearities of the interband transitions of semiconductor quantum well are controlled by the induced optical inter sub-band transitions with the coupling laser fields, which results in sharp resonances and ultrafast interband nonlinear response.

Conclusions

Ultrafast pulse-shaping technology has seen a phenomenal growth in the last decade. It has wide and far-ranging applications in the study of some of the fundamental issues in physics like light–matter interactions, to the control of intramolecular vibration rotation problem in chemistry, to manipulating the cell constituents in biology, to holding the promise of achieving terabit/s in optical communications. Each of these applications would require a suitable scheme for pulse shaping, according to the demands of the application. As the technology matures further, it is also opening up exciting new application avenues in areas as diverse as biomedical research to quantum computation.

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