New opportunities for secure communication networks using shaped femtosecond laser pulses inducing filamentation processes in the atmosphere

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New opportunities for secure communication networks using shaped femtosecond laser pulses inducing filamentation processes in the atmosphere

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Abstract. The current study discusses new opportunities for secure ground to satellite communications using shaped femtosecond pulses that induce spatial hole burning in the atmosphere for efficient communications with data encoded within super-continua generated by femtosecond pulses. Refractive index variation across the different layers in the atmosphere may be modelled using assumptions that the upper strata of the atmosphere and troposphere behaving as layered composite amorphous dielectric networks composed of resistors and capacitors with different time constants across each layer. Input-output expressions of the dynamics of the networks in the frequency domain provide the transmission characteristics of the propagation medium. Femtosecond pulse shaping may be used to optimize the pulse phase-front and spectral composition across the different layers in the atmosphere. A generic procedure based on evolutionary algorithms to perform the pulse shaping is proposed. In contrast to alternative procedures that would require *ab initio* modelling and calculations of the propagation constant for the pulse through the atmosphere, the proposed approach is adaptive, compensating for refractive index variations along the column of air between the transmitter and receiver.

1. Introduction

Communication networks are nowadays deployed across different media adopting a variety of propagation modalities e.g., wire, optical fibres, microwave or THz links, etc. Recent advances in ultrafast pulse, frequency comb timing standards, and satellite quantum communications technologies may soon enable geostationary satellites to be used as high bandwidth secure communication links. These are paving the way for new global communication modalities beyond the physical confines of the current fibre optics highways. In systematic studies performed by the fibre optics communications laboratories, there has been evidence of a host of linear and no-linear phenomena taking place simultaneously during propagation such as Rayleigh, Mie and Raman scattering, optical Kerr effect, soliton transmission and optical damage (spatial hole burning) even at modest optical powers [1]. The fibre optics communications community has also considered implications of shortening the pulses to the limit of dispersion within a fibre optic network, providing guidelines for the degree of chirping in the transmitted pulse [2], providing also design rules for super-continuum sources for WDM applications [3,4] and calculation of optical phase jitter in dispersion-managed systems [5].

Advances in generating shaped femtosecond pulses are enabling us to re-consider propagation in the higher atmosphere and troposphere assuming these layers may be modelled over a very large bandwidth as dielectrics. This work looks at the physical processes underlying such spatial hole burning and whether we can direct radiation with low losses by harnessing the properties of the super-continuum generated by these pulses. Our aim is to investigate whether we can harness non-linear phenomena through femtosecond pulse shaping techniques in the strong field regime to establish the opening of an efficient secure communication channel from ground to low earth orbit. This is possible because when a laser beam power exceeds a critical value (10^{14} W/cm^2), it starts to self-focus to a point [6-8]. However, the catastrophic collapse is negated due to the ionization of air creating a plasma which in turn defocuses the beam. A self-induced waveguide in air (filament) occurs when the dynamic balance between self-focusing, plasma defocusing and diffraction is met [6-11].

Different layers in the atmosphere as well as the troposphere can be modelled using 2D or 3D networks of resistors and capacitors [12, 13]. In the linear regime, input/output models derived for particular values of time constants [12, 13] can be used to cast propagation phenomena as inverse problems [14]. Such approach is therefore appropriate once steady state conditions through the propagation medium are established, where small fluctuations in atmospheric density may be compensated. The necessary theory for studying propagation under such conditions through layered media is well established [15-21].

The filamentation process, however is more complex and difficult to predict. Although there has been significant progress in understanding discharge as well as filamentation processes by the dielectrics community [16-17], unfortunately the current state-of-the art imaging methods do not enable us yet to fully reproduce filamentation events through different media in a consistent way so as to use results from propagation models as predictors of filamentation events. An alternative method is therefore proposed in the section below.

Femtosecond pulse shaping algorithm

We propose to use femtosecond pulse shaping techniques using adaptive evolutionary algorithms to optimize spatial hole burning and the propagation of pulses in the atmosphere while also preserving phase delay across spectral intervals. In this approach, evolutionary meta-algorithms for pulse shaping of broadband femtosecond duration laser pulses are utilized to achieve this goal. This is not the first time that femtosecond pulse shaping has been considered to provide closed loop control of a physical process [24-27] although to our knowledge it has never been applied to this type of problem.

The genetic algorithm (GA) searching the evolutionary landscape for desired pulse shapes consists of a population of waveforms (genes), each made from two concatenated vectors, specifying phases and magnitudes respectively over a range of frequencies [28]. Frequency domain operators such as mutation, two-point crossover average crossover, polynomial phase mutation, creep and three point smoothing as well as a time-domain crossover may be combined to produce fitter off-springs at each iteration step [29].

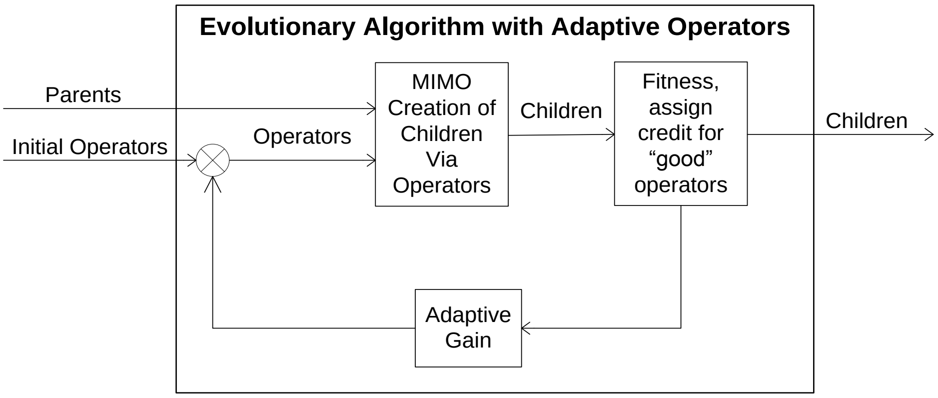

Figure 1. General structure of the proposed evolutionary algorithm for femtosecond pulse shaping where the operators are tuned through an adaptive gain to produce the desirable pulse shape that performs spatial hole burning.

The developed algorithm applies roulette wheel selection, elitists and linear fitness scaling to the gene population associated with the spectral bands associated with the femtosecond pulses. A Differential Evolution (DE) operator that provides a source of directed mutation and wavelet operators are used to speed-up convergence of the pulse to its optimal shape for spatial hole burning. Fast convergence of the algorithm is necessary for maintaining the channel in the presence of changing atmospheric conditions through feedback from the receiving end. Using properly tuned parameters for DE, such meta-algorithm may be used to essentially solve a waveform matching problem in a few generations as shown below.

In the algorithm of Adaptive Operators, any operator that creates a child more fit than the best fit of the previous generation is assigned credit. The credit is then used to update the weights used in choosing the operator that creates future children. While one could theoretically specify an ideal initial set of operators, any static weighting will fail to capture the true dynamic nature of the evolutionary algorithm search space. As the population moves from the initial state to convergence, the ideal set of operators used to create children will change. Adaptive updating not only accounts for the dynamic needs of the search space, but it allows for the inclusion and competition of many different types of operators.

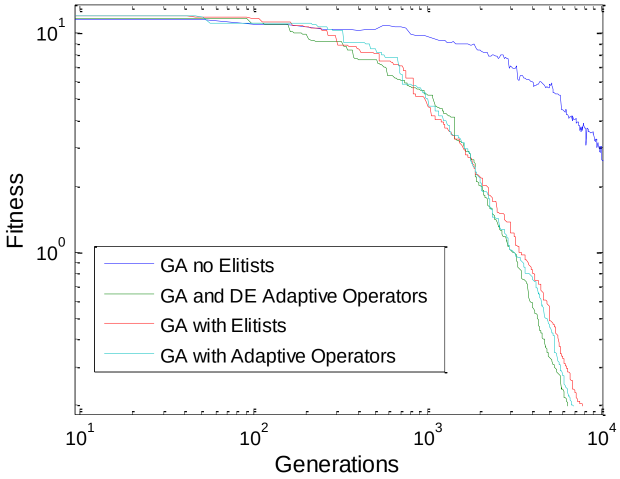

Figure 2. The effect of introducing elitists, differential evolution aadaptive operators to improve the convergence of the algorithm to fewer generators.

Figure 2 shows a graph of four variants of evolutionary algorithms showing their relative speeds in convergence for solving a waveform matching problem. While all methods will converge, the most efficient algorithm is the Genetic Algorithm (GA) hybridized with Differential Evolution (DE), using adaptive operators to adjust the weights (degree of expression) as well as the operators values. Kohonen maps may be used to evaluate the regions where most benefit to the convergent rate can be gained by tuning the individual operators while searching the evolutionary landscape for the optimal pulses. Because differential evolution and the original genetic algorithm outperform each other in different regions of the search space, their combination to a meta-algorithm leads to faster convergence rates in fewer generations.

Hardware implementation

The current algorithm for waveform matching has mainly been implemented in software with the algorithm running within the Matlab environment. By creating a Labview based front end with the capability of running the Matlab script within it, it was possible to perform some preliminary tests in the lab. For example, it was straightforward to perform dispersion compensation of phase delay across a range of frequencies through 4.0 mm of glass using a dazzler (rf-excited acousto-optic transducer) placed in front of a Mira laser system from Coherent generating 100 fs duration pulses. The dazzler parameters were controlled by the output of the evolutionary algorithm through a digital to analog converter. The amorphous glass medium essentially acted as a multiple input-multiple output (MIMO) channel in the same way that a column of air would act on the propagating pulses, introducing different degrees of phase delay at different frequencies. The experiment has shown that the developed algorithm efficiently flattened the spectral phase of the emerging pulse across the 780-820 nm bandwidth as measured with a spectral phase interferometer (a SPIDER from APE Berlin). Information of the phase flatness was used at each iteration step to change the amplitude and phase delay of the individual genes associated with the genetic algorithm.

This experiment partly validated the proposed approach. For the full implementation of the proposed solution, however, an amplifier based femtosecond system would have to be used in conjunction with a shorter duration seed pulse and a photonic crystal fibre to generate the required super-continuum. The repetition rate of the pulses will generally be lower than the standard 100 MHz associated with most commercially available femtosecond systems due to the requirement for an amplification process. A 10 kHz repetition rate femtosecond pulse laser amplifier produces consecutive pulses spatially separated by 30 Km in the atmosphere. An advantage of the proposed solution, however, is that only a few amplitude and phase genes from the entire population would have to be changed in order to compensate for time-varying atmospheric refractive index variations so that convergence of the evolutionary algorithm can be performed within just a few iterations.

Using pulse shaping, it should be possible to use the leading pulse to induce controlled filamentation and spatial hole burning and consecutive pulses to encode information or alternatively use part of the bandwidth in the white light super-continuum to encode and transmit within the same pulse with another part to perform filamentation. Information encoding can be implemented within the super-continuum over a dedicated spectral band using a spatial light modulator placed in a 4*f* optical system [30]. This is achieved by encoding the time-domain pulse in space through a diffraction grating, then changing the orientation of the individual pixels of the liquid crystal mask accordingly to induce attenuation and phase delay in a binary fashion, thus encoding the information in the modulator's spectral bins. This is quite straightforward using a function generator providing the appropriate information to the mask. A second grating would then be used to re-encode this information in the time domain for the transmission.

Alternative implementations of the proposed evolutionary algorithm where the information can be encoded through radio-vorticity [31-32] are also straight-forward to implement using appropriately modulated masks that control orbital angular momentum [33]. Reducing the dynamics using system identification procedures [34] for the MIMO channel associated with the propagation on the basis of the dielectric properties of the atmosphere is also appropriate and relevant to the implementation of the technique as it would reduce the search space of the evolutionary algorithm.

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