# SPATIO-TEMPORAL ANALYSIS OF NON-COLLINEAR FEMTOSECOND PULSES COMBINATION

Laura IONEL[1]

*Non-collinear coherent combining (NCCC) of ultrashort pulses is investigated in the presence of symmetrical variation of the angle (α°) made by the laser beams propagation trajectory and the horizontal axis in order to determine the optimum conditions to generate higher intensity in the focal region. For this, a 2D model of the electromagnetic field (EMF) distribution in the focal region of the coherently combined pulses have been elaborated using a commercial software that implements the finite difference time domain (FDTD) method for solving Maxwell equations. The sources are Gaussian both in space and in time. The numerical simulations have been done by varying symmetrically the parameter α in the range of 25°-65° with 5° step. A detailed study concerning the intensity evolution of the EMF distribution in the focal area has been performed under the α variation conditions in air, at 2, 5, 10 and 20 cycles pulse duration. The simulation results obtained by this study are relevant for ultrashort and ultraintense pulse laser experiments at laser facilities which employ coherent beam combining to generate higher intensities for different pulse duration, down to few-cycle regime.*

**Keywords**: Gaussian beam; Electromagnetic field; Laser Beam Combining; Femtosecond laser pulses.

## 1. Introduction

Ultrahigh intensity laser systems encountered an accelerated development in the last decades due to the continuous quests in terms of matter and vacuum investigations in strong fields. Following energy up-scaling path, the laser produced fields strength increased exponentially by reducing the pulse duration together with the focal spot area and by increasing the pulse energy [1-3]. The achievement of the very high energies of the laser pulses are in strong relation with the dimension of the optical components, possessing already problems in terms of the technological development for production on large size scale. To avoid these technological limits, plenty of studies have been developed in order to investigate the optimum conditions to improve output power of the laser pulses while the beam quality to remain highly preserved.

Superposition of coherent laser beams was used in many domains like: biology [4], medicine, optical coherence tomography [5], sensing [6], material science [7], holography [8]. For ultrahigh intensity laser beams, the combination of femtosecond laser pulses was used to generate time-dependent polarization pulses [9]. Their superposition is possible at different wavelengths with fringes

[1] Researcher, National Institute for Laser, Plasma and Radiation Physics, Romania, e-mail: laura.ionel@inflpr.ro

formation [10]. To fabricate three dimensional photonic crystals, femtosecond laser combination technique was employed [11].

In this direction, coherent beam combination (CBC) of several ultrahigh power lasers is considered an effective solution to avoid optical limitations related to the damage threshold of the optical components. This method requires a precise control of the beams relative phases to a small fraction of the wavelength. Nowadays, the studies are focused on the optical beam path difference control with spatial resolution corresponding to less than 100 nm [12]. Spatio-temporal aspect of CBC has a very important role in the determination of the extreme electric fields, many approaches being already elaborated in this direction, providing particular schemes and useful computations for high focal intensities experiments [13-19].

This work provides a spatio-temporal analysis of the optimum conditions to generate higher intensities in the focal point by non-collinear coherent combination of two ultrashort pulse laser beams. We determined the maximum field in the vicinity of the focus by varying symmetrically the angle (α) between the laser beams propagation direction and the horizontal axis. The numerical study of the EMF distribution had been done in air, for different pulse durations. This technique aims to provide effective solutions to obtain high laser fields relevant for experiments proposed at multi-petawatt scale laser facilities such as Extreme Light Infrastructure (ELI).

## 2. Theoretical approach: non-collinear coherent ultrashort laser pulses combination

Numerical computations of NCCC were developed in order to investigate the EMF intensity in the focal region in predefined conditions. The 2D numerical simulation had been performed using FullWAVE, a package of the commercial software RSoft by Synopsys Optical Solutions Group [20], which solves the Maxwell equations using FDTD method. In this way, we could investigate the beam intensity evolution at different moments of time and different geometries (for example: the angle between the beams propagation axes).

In this analysis, two aspects have been considered:

1. The spatial analysis of the electromagnetic field in focal region is based on 2D distributions computations at a given moment of time, when the maximum intensity value is achieved.
2. The temporal aspects of the electromagnetic field behavior for different values of α are investigated in the vicinity of the waist of the combined beams by plotting the envelope of the temporal evolution of the electromagnetic field $E_y^2$ (t) by transforming the temporal axis into a spatial one using the Minkowski space relation (1):

$$s = c * \tau \quad (1)$$

where *s* is the spatial extend of the pulse of the collimated beam (given by the number of wave cycles further denoted by *T*), *c* represents the speed of light and τ is the ultra-short pulse duration. Based on this, the temporal analysis is performed in units of c·t, considering that 1 μm corresponds to 3.33 fs.

The sketch of the system functional blocks is illustrated in Figure 1. This approach implies two identical Gaussian laser sources (central wavelength λ of 800 nm, diameter *D* of 20 μm, linear polarization and symmetrical position relative to the z axis). The numerical simulations have been done for pulse duration values of 5, 13, 27 and 53 fs which correspond to 2, 5, 10 and 20 temporal cycles respectively. The both laser beams are focused by identical optical lenses which have the focal distance *f* of 40 μm and the diameter of 40 μm.

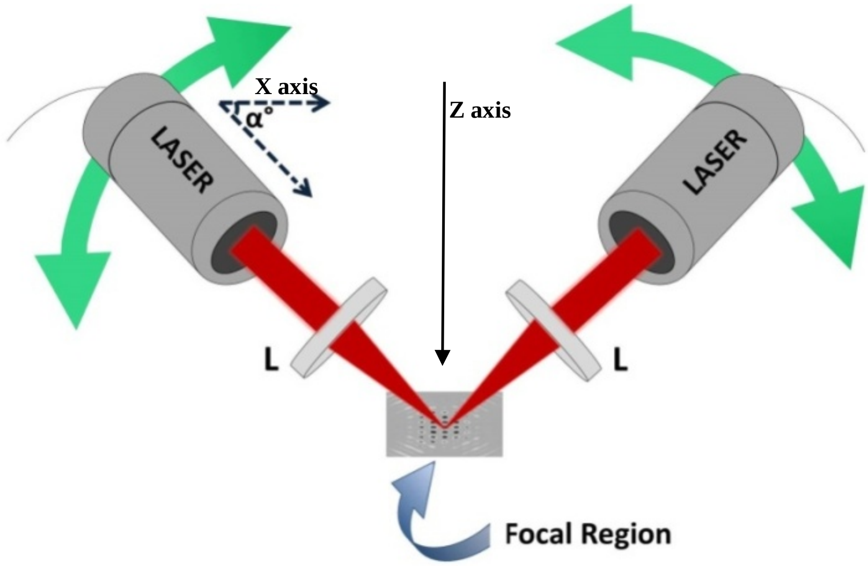


Fig. 1. The sketch of the optical setup for NCCC of two laser beams in the case of symmetrical variation of the angle (α°) between the laser beams propagation directions and the horizontal axis *X*. The EMF distribution is analyzed in the focal region when the angle is set in the range of 25°-65° with 5° step.

The spatio-temporal distribution of the electromagnetic field had been computed in the vicinity of the focal point under the symmetrical variation of the angle α in order to determine the optimum conditions to generate higher intensities in focal region.

## 3. Numerical results and discussions

At first, we investigated the behavior of the EMF distribution in the focal region both from spatial and temporal point of view at twenty cycles pulse duration which corresponds to 53 fs. The spatial extension of the electromagnetic field is represented in fig. 2a at the moment when the intensity of the combined laser beams reaches the highest value. The study has been done for three values of the angle α: 30°, 45° and 60° respectively. The representation of the EMF distribution was made by using false color coded plots in order to indicate the negative and positive values of the field (blue and red colors, respectively) and the zero field which is represented by green color.

One can identify in fig. 2a the rotation of the central spatio-temporal interference lobe in the focal region. This rotation is imprinted by the symmetrical variation of the beams propagation angle α in the previously mentioned range at the moment when the electromagnetic field reaches its maximum. Comparing the cases when α is equal to 30° and 60°, there was observed that the orientation of the central spatio-temporal interference lobes differs by 90° while the electromagnetic field distribution in focus covers similar areas, obtaining comparative intensity values. For the case of α=45°, the superposition of the beams imprints a larger distribution area of the fringes in focus which generates lower intensity values.

To each interference pattern identified across the focal plane for all three cases investigated, we assigned the evolution envelope of the electromagnetic field (fig. 2b). These plots are based on data provided by the temporal monitors positioned in given points from the focal region, where the two ultrashort pulse laser beams are non-collinear combined. The horizontal axis represents the time expressed in c·t units. The comparison in the temporal behavior for all three cases analyzed denotes comparable values of the intensity when α is equal to 30° and 60° while for the intermediary value (45°) the intensity presents a decrease with more than one arbitrary unit.

It is imposed that the temporal phasing condition of the ultrashort pulses in the focal region to be preserved. This implies an absolute optical path difference between the pulses to be equal to zero in focus. The phase of the propagation field along the x axis is computed by the discrete Fourier transform frequency analysis (Fig. 2c) and it describes the position of a particular point in time on a waveform cycle (L), measured as an angle expressed in degrees.

The twenty cycles pulse duration case discussed above corresponds to a rough analysis of the focal region generated by the non-collinear combination of two laser beams. In order to increase the complexity of the study, we investigated another three particular cases of pulse duration, down to few-cycle regime, under similar conditions previously considered. Thus, we decreased the pulse duration T from 20 cycles to 10, 5 and 2 cycles which correspond to 27, 13 and 5 fs respectively. We investigated the behavior of the electromagnetic field of the combined beams in focus for each pulse duration value in the presence of symmetrical variation of the beam propagation angle in the range of 25°-65° with 5° step (fig. 3).

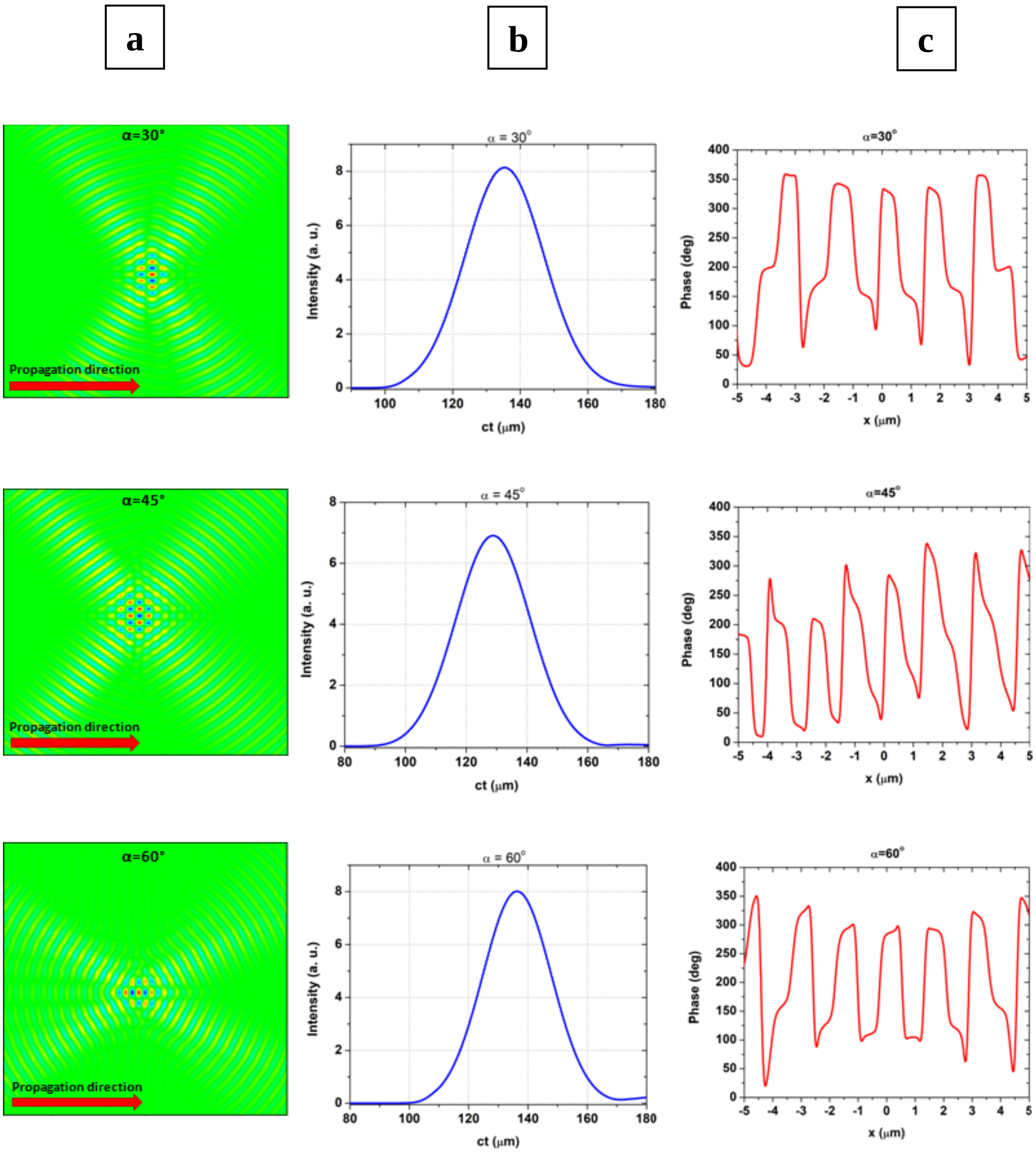


Fig. 2. a) Spatial characteristics in focal region for NCCC of two laser beams in the presence of symmetrical variation of the angle (α°) between their propagation directions. b) Aspects of the laser field intensity measured by a monitor placed in focal point in case of beams propagation angle variation; c) The phase of the propagation field in focus in the moment of non-collinear beams combination process.

Comparing to the initial case (T=20 cycles), there were obtained more than two times smaller values for the field intensity in the case of T=2 cycles and intermediate values for the field intensity in the other two cases analyzed. All four intensity slopes corresponding to each pulse duration present the same evolution with a minimum peak registered at α =45° and maximum peaks when α reaches the values of 30° and 60°.

Also, the study has been performed using circular polarized light for non-collinear CBC resulting similar numerical results when compared to linear polarization.

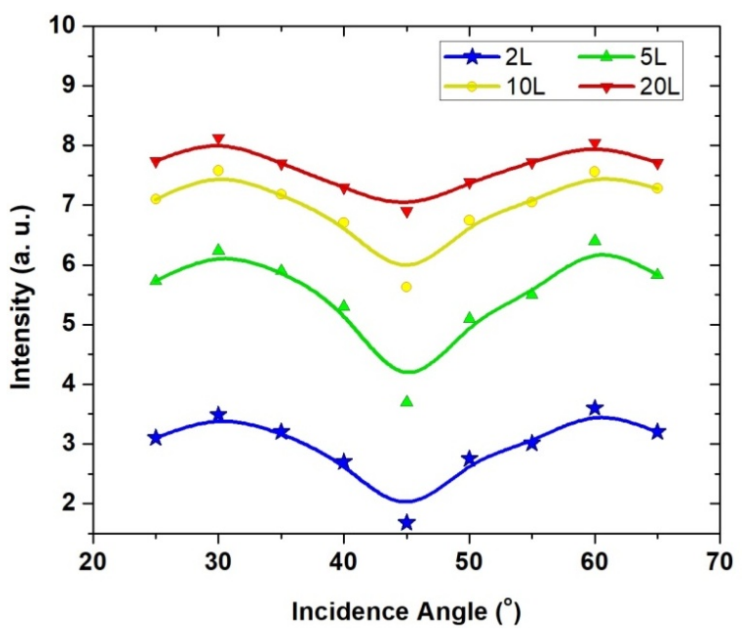


Fig. 3. The evolution of the intensity of the non-collinear combined beams in focal point in the presence of symmetrical variation of their propagation directions angle at 2, 5, 10 and 20 cycles pulse duration which correspond to 5, 13, 27 and 53 fs respectively.

As a general remark, the laser field intensity of the combined beams in focal point decreases with the pulse duration, maintaining a constant ratio between the field intensity values obtained for two particular beam propagation angles at the same pulse duration for all four investigated cases. These results prove good prospects to scale the EMF intensity in the focal region.

## 4. Conclusions

In summary, a 2D FDTD numerical study is presented to analyze the intensity of the electromagnetic field generated by two non-collinear combined laser beams in focal region in the presence of symmetrical variation of the angle between their propagation directions. The spatio-temporal aspects of the EMF distribution had been studied as function of α employing the Minkowski space relation; important details for few-cycles regime experiments had been related. It is shown that in the frame of the non-collinear laser beams combination process, the angle between their propagation directions has a significant influence on the electromagnetic field intensity in focus. Thus, by using this FDTD algorithm, we determined the specific conditions to generate higher intensities for different pulse duration, down to few-cycle regime. Further work involves multiple laser sources in order to solve the actual needs of the ultrashort and ultraintense pulse laser experiments at laser facilities employing coherent beam combining concept such ELI or ICAN. For such high intensity fields, it is necessary to note that non-collinear coherent beam combination requires geometrical configurations based on a single focusing element in reflection in order to create a suitable method for the experiments operating at the waist of the combined beams.

**Acknowledgements**

The author gratefully acknowledges fruitful discussions with Dr. M. Mihailescu and Eng. C. Matei. This work has been financed by the Romanian Authority for Scientific Research and Innovation, contract UEFIS-CDI, PN-III-P2-2.1-BG-2016-0288 No. 45BG/2016, by the National Project Nucleu LAPLAS V 3N/2018 and by the national project PN III 5/5.1/ELI-RO, Project 17-ELI/2016 ("BIOSAFE"), under the financial support of Institute for Atomic Physics – IFA.

## R E F E R E N C E S

[1] *D. Powell*, Europe sets sights on lasers, Nature **500** 2013, pp. 264–265.
[2] *G. Mourou, B. Brocklesby, T. Tajima, J. Limpert*, The future is fibre accelerators, Nature Photon. **7** 2013, pp. 258– 261.
[3] ELI - Extreme Light Infrastructure, White book. http://www.eli-beams.eu/wp-content/uploads/2011/08/ELIBook_neues_Logo-edited-web.pdf.
[4] *M. Mihailescu*, Natural quasy-periodic binary structure with focusing property in near field diffraction pattern, Optics Express **18**(12) 2010, pp.12526-12536.
[5] *A. Al-MujainiA, U.K. Wali, S. Azeem*, Optical Coherence Tomography: Clinical Applications in Medical Practice, Oman Med J. Mar. **28**(2) 2013, pp. 86-91.
[6] *K. Thurner, F.P. Quacquarelli, P. F. Braun, C. Dal Savio, K. Karrai*, Fiber-based distance sensing interferometry, Appl. Opt. **54**(10) 2015, pp. 3051-3063.
[7] *M. Malinauskas, A. Žukauskas, S. Hasegawa, Y. Hayasa, V. Mizeikis, R. Buividas, S. Juodkaz*, Ultrafast laser processing of materials: from science to industry, Light: Science & Applications **5** 2016, pp. e16133.
[8] *E. I. Scarlat, M. Mihăilescu, A. Sobetkii,* Spatial frequency and fractal complexity in single-to-triple beam holograms, Journ. Optoel. Adv. Mat. **12**(1) 2010, pp. 105-109.

[9] *M. Kakehata, R. Ueda, H. Takada, K. Torizuka, M. Obara,* Combination of high-intensity femtosecond laser pulses for generation of time-dependent polarization pulses and ionization of atomic gas, Appl. Phys. B**70** Suppl. 1 2000, pp. S207-S213.
[10] *S. Odoulov, A. Shumelyuk, H. Badorreck, S. Nolte, K.M. Voit, M. Imlau*, Interference and holography with femtosecond laser pulses of different colours, Nat. Comm. **6** 2015, pp. 5866-1-8.
[11] *T. Kondo, S. Matsuo, S. Juodkazis, H. Misawa*, Femtosecond Laser Interference Technique with Diffractive Beam Splitter for Fabrication of Three-Dimensional Photonic Crystals, Appl. Phys. Lett.**79**(6) 2001, pp. 725-727.
[12] *S. Simion, C. Blanaru, and D. Ursescu*, Design considerations for an interferometer for coherent combination of ultrashort laser pulses, Rom. Rep. Phys. **62** 2010, pp. 644–651.
[13] *L. Ionel, D. Ursescu*, Non-collinear spectral coherent combination of ultrashort laser pulses, Opt. Express **24**(7) 2016, pp. 7046–7054.
[14] *D. Ursescu, L. Ionel*, Spatial and temporal dynamics of ultra-short pulses coherent beam combining, PROCEEDINGS OF THE SPIE **7501** 2009, pp. 750103.1-750103.5.
[15] *R. K. Shelton, L.S. Ma, H.C. Kapteyn, M.M. Murnane, J.L. Hall, J. Ye,* Phase-coherent optical pulse synthesis from separate femtosecond lasers, Science **293**(5533) 2001, pp.1286-9
[16] *J. Bourderionnet, C. Bellanger, J. Primot, A. Brignon*, Collective coherent phase combining of 64 fibers, Opt. Express **19**(18) 2011, pp. 17053-17058.
[17] *S. N. Bagayev, V. E. Leshchenko, V. I. Trunov, E. V. Pestryakov, S. A. Frolov*, Coherent combining of femtosecond pulses parametrically amplified in BBO crystals, Opt. Lett. **39**(6) 2014, pp. 1517–1520.
[18] *V. E. Leshchenko, V. A. Vasiliev, N. L. Kvashnin, E. V. Pestryakov,* Coherent combining of relativistic intensity femtosecond laser pulses, Appl. Phys. B**118**(4) 2015, pp. 511–516.
[19] *A. Klenke, E. Seise, J. Limpert, A. Tünnermann,* Basic considerations on coherent combining of ultrashort laser pulses, Opt. Express **19**(25) 2011, pp. 25379–25387.
[20] https://optics.synopsys.com/rsoft/