Quantum Electronics **47** (12) 1150–1153 (2017)

https://doi.org/10.1070/QEL16536

Spatiotemporal multiplexing based on hexagonal multicore optical fibres

I.S. Chekhovskoy, M.A. Sorokina, A.M. Rubenchik, M.P. Fedoruk

Abstract. **Based on a genetic algorithm, we have solved the problem of finding the parameters of optical Gaussian pulses which make their efficient nonlinear combining possible in one of the peripheral cores of a 7-core hexagonal fibre. Two approaches based on individual selection of peak powers and field phases of the pulses launched into the fibre are considered. The found regimes of Gaussian pulse combining open up new possibilities for the development of devices for controlling optical radiation.**

Keywords: *multicore fibre, nonlinear Schrödinger equation, genetic algorithm, nonlinear combining of pulses.*

1. Introduction

One of the modern technologies for increasing the strength characteristics of metal products in manufacturing is the use of short high-power laser pulses. The surface of the processed metal product is subjected to the action of a train of high-power optical pulses. Each pulse irradiates a certain point on the product surface. For the generation of high-power optical beams, various schemes of linear pulse combining are used in practice [1, 2]. An important requirement to such schemes is the need for a precise control of the field phases of the combined beams to maintain the output pulse coherence.

Earlier, using a numerical simulation, a possibility for optical pulse combining and compression using nonlinear effects arising in multicore optical fibres has been demonstrated [3, 4]. Such a nonlinear scheme has several advantages compared to conventional linear schemes [5, 6]. In particular, the requirement to the control of the field phases of combined pulses can be substantially weakened. In this case, efficient combining can be achieved by selecting the parameters of the input pulses, with the fibre characteristics being unchanged.

In this paper, using a hexagonal multicore fibre, we demonstrate a fundamental possibility of developing a device for nonlinear combining of pulses capable of generating high-power optical pulses, each coming out from a chosen core of the multicore fibre. Because in this case the generated pulses are produced as a result of nonlinear combining of optical pulses, this device can be used, for example, for metal product compaction. However, as was shown in previous works [3, 4], when introducing completely identical Gaussian pulses, their combining in a hexagonal optical fibre may only occur in the central core. Therefore, the main task in this case was to determine the conditions ensuring efficient combining of optical pulses not in the central, but in any other core by adjusting the parameters of these pulses.

I.S. Chekhovskoy, M.P. Fedoruk Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; Institute of Computational Technologies, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 6, 630090 Novosibirsk, Russia; e-mail: i.s.chekhovskoy@gmail.com;
M.A.Sorokina Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK;
A.M. Rubenchik Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Received 16 October 2017
Kvantovaya Elektronika **47** (12) 1150–1153 (2017)
Translated by M.A. Monastyrskiy

2. Mathematical model

A 7-core hexagonal fibre of length L was chosen for the studies (Fig. 1). In the numerical simulation of the optical pulses with the fields U_{nm} propagating through the fibre, use was made of a discrete-continuous nonlinear Schrödinger equation (NSE) for normalised values [3, 4]:

$$\mathrm{i}\frac{\partial U_{nm}}{\partial z} + \frac{\partial^2 U_{nm}}{\partial t^2} + (\underline{CU})_{nm} + |U_{nm}|^2 U_{nm} = 0, \qquad (1)$$

where

$$(\underline{CU})_{nm} = U_{n-1\,m-1} + U_{n+1\,m-1} + U_{n-2\,m} + U_{n+2\,m} + U_{n-1\,m+1} + U_{n+1\,m+1} - 6U_{n\,m}.$$

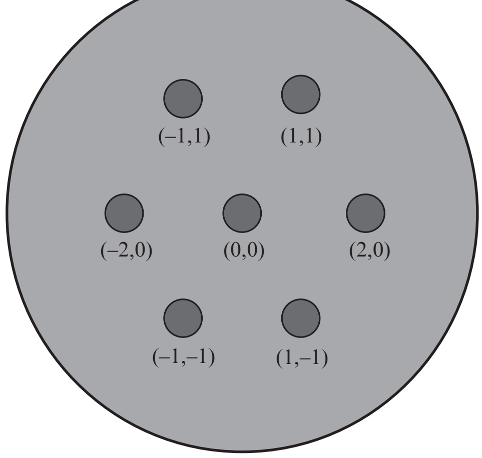

Figure 1. Scheme of the 7-core hexagonal fibre under study.

To numerically solve this system of equations, a generalised split-step method was applied, which consists in calculating the matrix exponential in the frequency domain using the Pade approximation [7]. As initial pulses, we used Gaussian pulses with the fields

$$U_{nm}(z=0,t)=\sqrt{P_{nm}}\exp\left[\frac{-(1+\mathrm{i}\alpha_{nm})t^2}{2\tau_{nm}^2}\right]\exp(-\mathrm{i}\phi_{nm}). \quad (2)$$

Here P_{nm} is the peak power of initial pulses; and α, τ and ϕ are the chirp, width and phase shift of the pulses, respectively. Because of the large number of variable parameters, the genetic algorithm which is widely used for solving optical problems served as a search tool [8–14]. Its ready-to-use Python-language software was implemented in the form of a DEAP package [15], which allows parallel computations in the distributed memory systems using the SCOOP library [16]. In the genetic algorithm, a vector of values describing the parameters of Gaussian pulses launched into the fibre (peak powers, widths, chirps and phases) was chosen as the genotype of each individual in the population. Due to the problem symmetry, for a 7-core hexagonal fibre, it is possible to consider the parameters of only five pulses, thus reducing the optimisation problem dimension. As the fitness function value for each individual in the population, we used the maximum value of the combining efficiency [the ratio of the energy fraction located in the peripheral core (–2, 0) to the total energy E launched into fibre] which can be achieved when pulses with the predetermined parameters (genome) propagate through the fibre under consideration. Thus, the energy contained in the pedestal of the combined pulse was not taken into account.

3. Results of modelling

Two approaches to the determination of Gaussian pulse parameters were investigated, in which a combined pulse can be obtained in one of the peripheral cores of a 7-core fibre.

The first approach is simpler in terms of practical implementation (experimentally). Its essence lies in the selection of the peak power magnitude of each optical pulse separately. In this case, the width and chirp for all the pulses are the same, but they are also chosen to maximise the pulse combining efficiency. The initial phases of all the pulses are zero. Thus, the total number of parameters in the optimisation problem being solved, i.e. the genome size of an individual in the genetic algorithm is 7. The values of these parameters for the initial population are uniformly distributed random variables from the specified intervals. As was mentioned above, the combining efficiency of these pulses, obtained after calculation of the propagation of Gaussian pulses through the fibre, served as a fitness function to evaluate the 'quality' of an individual.

If we do not impose any additional restrictions on the genomes of separate individuals, then, in order to obtain a pulse at the output of the peripheral core, which ensures maximal combining efficiency, a chirped pulse with a peak power exceeding the peak power of the remaining pulses by several orders of magnitude must be launched into the core. Of course, this solution is trivial. Therefore, we introduce below a limitation on the spread of the peak powers of initial Gaussian pulses:

$$\frac{\min P_{nm}}{\max P_{nm}} < M, \quad (3)$$

where M is the modulation depth.

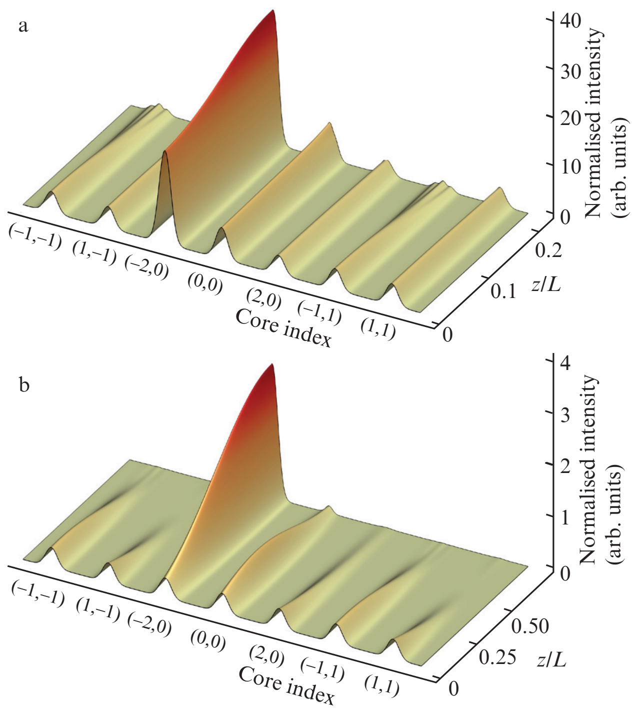

Figure 2. Intensity dynamics of optical pulses for the regime with a maximum combining efficiency, obtained by the genetic algorithm using (a) peak power modulation (M = 0.2) or (b) phase selection.

It turned out that if the peak powers of the introduced pulses differ by no more than twice, the attainable maximum efficiency of their combining is 28%. If the peak powers differ by no more than five times, the maximum efficiency constitutes 53% (Fig. 2a). In the case of a tenfold difference in the peak powers, the maximum efficiency turns out equal to 69%.

The second approach is more complicated from the engineering viewpoint, since it requires the phase control of initial pulses. It is proposed to make the peak power, width and

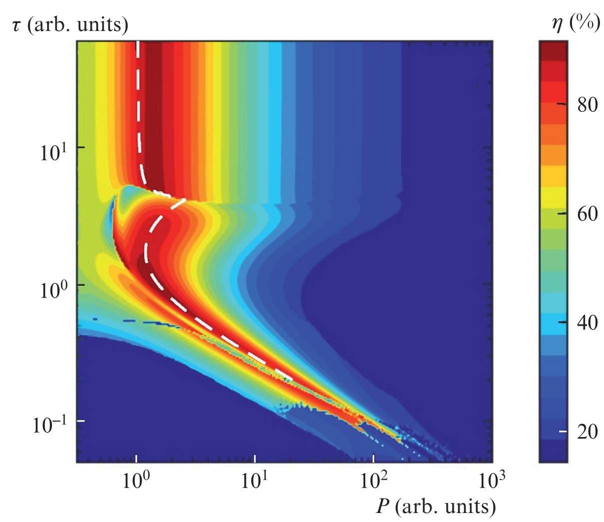

Figure 3. (Colour online) Combining efficiency η of Gaussian pulses in the central core (0, 0) of the 7-core hexagonal fibre as a function of the width τ and peak power P of the initial pulses. The white dashed curve corresponds to the parameters of Gaussian pulses at which their combining is possible at a distance of z/L = 0.8, as in the case shown in Fig. 2b.

chirp equal for all the input pulses, but, in doing so, to select the phase of each pulse separately and maximise the pulse combining efficiency in the peripheral core by selecting eight parameters. As a result, using the genetic algorithm, we obtained a regime allowing 95% of energy of all the injected pulses to be combined at a distance of $z/L = 0.8$ (Fig. 2b).

An important condition for the functioning of the proposed device is the possibility of combining of pulses at the same distance, both in the central core and in the peripheral one. Figure 3 shows the dependence of the combining efficiency of Gaussian pulses in the central core of a 7-core hexagonal fibre [4]. In this case, the dynamics of Gaussian pulses with the same peak power P and width τ was simulated. The white dashed line indicates the regimes in which the pulses launched into the fibre were combined at a distance of $z/L = 0.8$, as in the case of the best regime of pulse combining in the peripheral core, found by means of phase selection. Figure 3 shows that at a distance of $z/L = 0.8$, the pulses can be combined in the central core with an efficiency of about 90%.

Also, we investigated the stability of the found regimes with respect to various fluctuations (Fig. 4). We studied the change in the distance to the point of pulse combining along the fibre as one of the most important characteristics of the proposed scheme of nonlinear combining.

The effect of phase fluctuations of initial pulses was considered, which were simulated using the function C_{δ_p} having a uniform distribution in the interval $[-\delta_p; \delta_p]$. Thus, the initial fields of the pulses had the form

$$\tilde{U}_{nm}(t) = U_{nm}(t)\exp(-iC_{\delta_p}). \quad (4)$$

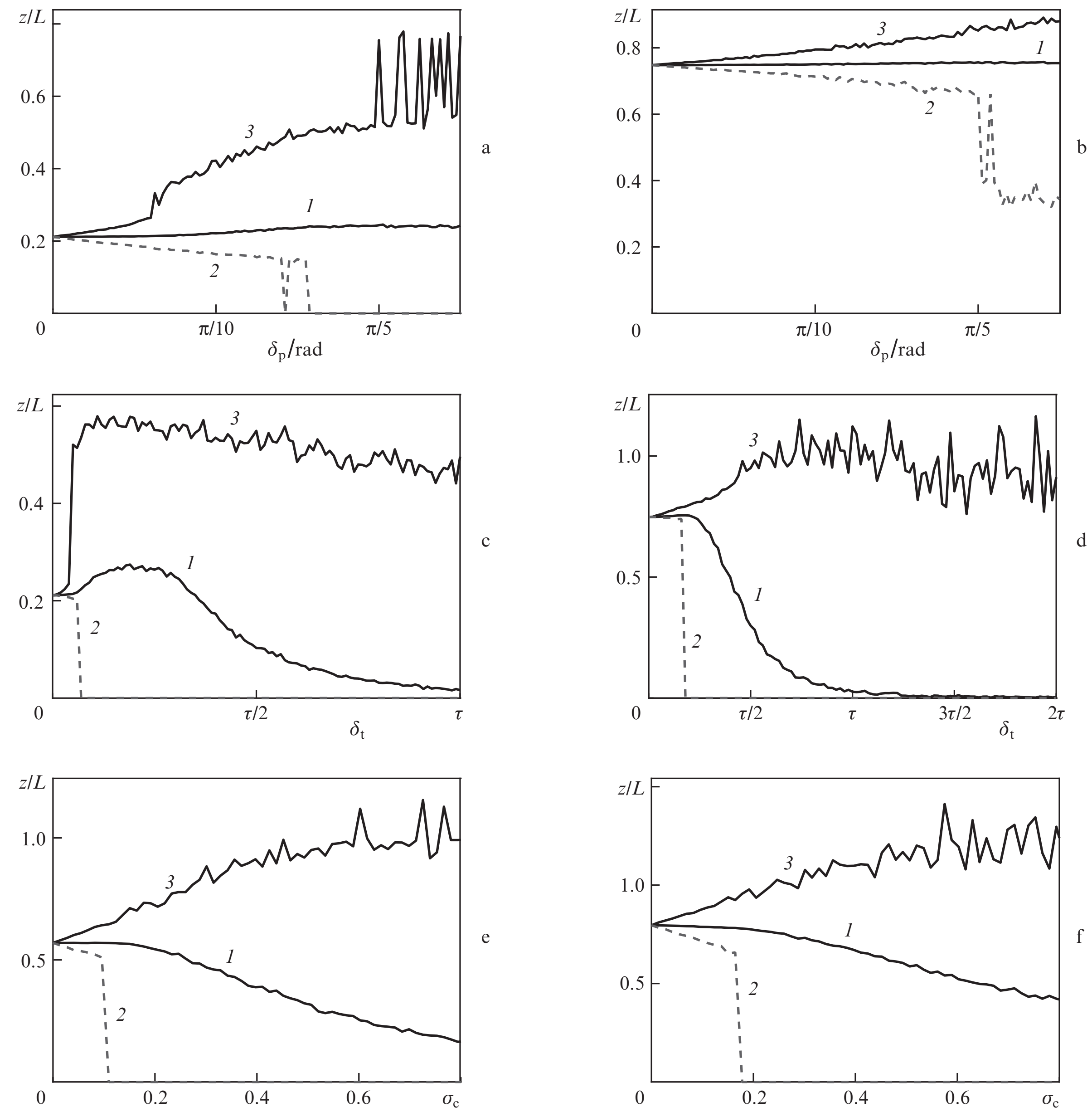

Figure 4. Impact of (a, b) the phase spread δ_p, (c, d) time delays δ_t and (e, f) coupling coefficient fluctuations σ_c at the distances (*1*) z_0, (*2*) z_{min} and (*3*) z_{max} to the point of Gaussian pulse combining in the peripheral core (–2.0). Plots in (a), (c) and (e) correspond to the regime obtained by the selection of peak powers ($M = 0.2$); plots in (b), (d) and (f) correspond to the regime obtained by the selection of phases. The characteristics are found by averaging over a set of 2000 simulation results.

The parameter δ_p was varied from 0 to π. For each of its 100 values, 2000 calculations were performed. Based on these calculations we obtained an average value of the distance to the combining point z_0, and also its minimum (z_{min}) and maximal (z_{max}) values. Calculations showed that the combining scheme remains stable at $\delta_p \in [0; \pi/20]$ in the case of the regime previously considered, in which the peak powers were simulated, and also at $\delta_p \in [0; \pi/5]$ in the case of phase selection (Figs 4a and 4b).

We investigated the effect of time delays between the pulses given by the function C_{δ_t} having a uniform distribution in the interval $[-\delta_t; \delta_t]$. The perturbed initial fields of Gaussian pulses were taken in the form

$$\tilde{U}_{nm}(t) = U_{nm}(t - C_{\delta_t}). \quad (5)$$

The simulation results showed that the scheme stability in the case of phase selection is only observed for $\delta_t \in [0; \tau]$, where $\tau = 19.755$ is the width of initial pulses (Fig. 4d). However, the regime found by selecting the peak powers turned out extremely sensitive to the fluctuations of this type (Fig. 4c) and requires that the time difference between the pulses should not exceed the value of $\tau/20$.

In the fabrication of multicore optical fibres, it is extremely important that the fibre cross section geometry remains constant throughout its length. However, small fluctuations in the distance between the cores, in the radii of cores, and also in the refractive index distribution are unavoidable. All that strongly affects the value of the coupling coefficient C between the cores; therefore, this aspect was also studied. The coupling coefficient fluctuations were simulated using the Wiener random process $\Delta C(z)$. The coupling coefficient in this case was represented in the form

$$C(z) = C_0 + \Delta C(z), \quad (6)$$

where C_0 is the average value of the coupling coefficient ($C_0 = 1$ in the model under consideration). This approach allowed a relatively smooth change in the coupling coefficient along the fibre. Calculations showed that the proposed scheme of optical pulse compression and combining is sufficiently stable to a change in the coupling coefficient between the cores. The main characteristics start to significantly deteriorate when the standard deviation σ_c ($z = 0$) of the coupling coefficient exceeds 10% for the regime with the peak power selection and 15% for the regime with phase selection. This requirement is feasible in practice, since, in the production of multicore fibres, the distance between the cores fluctuates by a value not exceeding 3%–5%. In this case, the characteristic length at which these changes occur constitutes ~10 m. Thus, using a sufficiently short (up to 10 m) optical fibre, the proposed scheme will be resistant to possible nonuniformities in its structure

4. Conclusions

In this paper, we have proposed the use of a genetic algorithm for finding the parameters of optical Gaussian pulses, which allows their effective nonlinear combining in one of the peripheral cores of a 7-core hexagonal fibre. Two approaches based on individual selection of the peak powers and phases of the pulses launched into the optical fibre are considered. The values of peak powers of Gaussian pulses are determined, at which the combining efficiency in peripheral cores reaches 69%. When selecting the field phases of the pulses introduced into the fibre, the combining efficiency of about 95% was obtained. The found regimes of Gaussian pulse combining open new possibilities for the development of optical radiation controlling devices. This technique may find application in the problems of signal processing, fibre lasers, cryptography, and in many other problems.

Acknowledgements. This work was supported by the Russian Science Foundation (Grant No. 17-72-30006).

1. Fan T.Y. *IEEE J. Sel. Top. Quantum Electron.*, **11** (3), 567 (2005).
2. Hanna M. et al. *J. Phys. B: At. Mol. Opt. Phys.*, **49** (6), 062004 (2016).
3. Rubenchik A.M. et al. *Opt. Lett.*, **40** (5), 721 (2015).
4. Chekhovskoy I.S. et al. *Phys. Rev. A*, **94**, 043848 (2016).
5. Zheng W. *Proc. ECOC* (London, 2013) OM3I.4.
6. Zhou J. *Opt. Express*, **23** (17), 22098 (2015).
7. Chekhovskoy I.S. et al. *J. Comput. Phys.*, **334**, 31 (2017).
8. Kerrinckx E. et al. *Opt. Express*, **12** (9), 1990 (2004).
9. Rosen S. et al. ArXiv preprint arXiv:1506.08586 (2015).
10. Askarov D. et al. *J. Lightwave Technol.*, **33** (19), 4032 (2015).
11. Da Silva J.P. et al. *Microwave Opt. Technol. Lett.*, **55** (2), 281 (2013).
12. Ivorra B. et al. *Int. J. Comput. Sci. Eng.*, **2**, 170 (2006).
13. Arteaga-Sierra F.R. et al. *Opt. Express*, **22** (19), 2451 (2014).
14. Rosa L. et al. *Proc. ECOC* (Torino, Italy, 2010).
15. Fortin F.A. et al. *J. Mach. Learning Res.*, **13**, 2171 (2012).
16. Hold-Geoffroy Y. et al. *Proc. ICPS* (Austin, USA, 2014) p. 60.