On demand spatial beam self-focusing in hexagonal multi-core fiber

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DOI: 10.1109/JPHOT.2009.XXXXXXX
1943-0655/$25.00 ©2009 IEEE

Manuscript received ....

Abstract: Combination of the classical effect of light self-focusing and recently emerged multi-core fiber technology offers new opportunities for the spatio-temporal control and manipulation of high-power light radiation. Here we apply genetic algorithm to design a system enabling self-focusing of light in various fiber cores on demand. The proposed concept is general and can be applied and adapted to any multi-core fiber or 2D array of coupled waveguides paving a way for numerous applications.

Index Terms: Fiber nonlinear optics, nonlinear optical devices.

1. Introduction

Self-focusing of light in a nonlinear medium is one of the fundamental effects in nonlinear optics that occur in various physical problems and applications (see e.g. [1], [2], [3], [4] and references therein). Recent progress in multi-core fiber (MCF) technology [5], including special tapered MCFs [6], and multi-mode fibers (MMF) [7], [8], stimulated by the growing interest from the telecom industry, expanded the possible applications of the self-focusing effect and opened up new prospects for practical implementation of a spatio-temporal wave collapse dynamics in discrete nonlinear systems [9], [10].

One of the potential applications is in the area of laser beam combining. Different schemes of linear beam combining are used to generate high power optical beams [11], [12]. An important requirement in coherent beam combining is the precise phase control of the input beams to maintain output pulse coherence. Coherent beam combining is relatively simple for small arrays, but, combining tens to hundreds of elements with high beam quality can be elusive. More than 20 years ago, it was suggested to use the wave collapse effect for pulsed compression in fiber array [13]. Recently emerged technology of multi-core fibers offers a way for practical implementation of this concept.

Recently, we have demonstrated that coherent high-efficiency pulse-combining can be achieved in multi-core fibers by careful selection of input signal parameters: using numerical simulations, we have demonstrated the possibility of exploiting nonlinear effects in multi-core fibers for the combining and compression of optical pulses [9], [10]. It was observed that in the MCF based

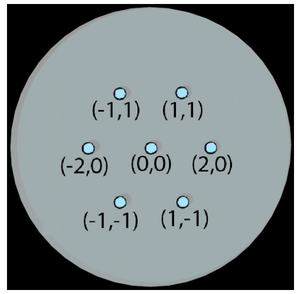

Fig. 1. Scheme of the considered 7-core hexagonal multi-core fiber.

approach, the requirements on the phase control can be weakened compared to the traditional schemes. Unlike conventional optical switch schemes [14], [15], here we vary the input signal parameters, while the characteristics of the fiber remain fixed. The effect of pulse-combining is achieved due to Kerr induced nonlinear signal interactions, which under certain input signal parameters lead to focusing of energy in the central core.

Here we extend this research and show for the first time that one can achieve efficient self-focusing in any core on demand. This can be exploited, for example, in laser-based manufacturing and high-definition design of complex properties of materials, where the surface of the treated metal product is exposed to a periodic sequence of high energy temporal optical pulses, whereby each pulse is focused onto a certain spatial point in the product surface.

We demonstrate the design rules for a special type of self-focusing of light - due to nonlinear interactions of high-power optical pulses - in a preselected core of MCF with a two-dimensional arrangement of the cores (for example, with square or hexagonal lattices). We use a general design of a hexagonal multi-core fiber as the fiber giving the shortest pulse combining distance due to the great number of neighboring cores (see [10] for details), where a genetic algorithm optimizes the parameters of the input signals in each core, so that due to Kerr-nonlinearity at the output of the fiber the light is focused in the given core.

2. Results and Discussion

Here without loss of generality we examine a 7-core hexagonal MCF (Figure 1). The discrete-continuous nonlinear Schrödinger equation (DCNLSE) [9], [10]

$$i\frac{\partial A_{n,m}}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A_{n,m}}{\partial t^2} - \sum_{(k,l)\neq(n,m)} C_{n,m,k,l}A_{k,l} - \gamma|A_{n,m}|^2 A_{n,m} \tag{1}$$

was used for the numerical simulation of the optical pulse propagation along MCF and was solved by a generalization of the split-step Fourier method [16]. The input signal was modeled using Gaussian pulses

$$A_{n,m}(z=0,t) = \sqrt{P_{n,m}}\exp\left[\frac{-(1+i\alpha_{n,m})t^2}{2\tau_{n,m}^2}\right]\exp\left(-i\phi_{n,m}\right), \tag{2}$$

where P is the peak power, α is the chirp coefficient, τ denotes the pulse width, and ϕ is the phase shift. We have considered parameters for typical existing MCFs operating at the wavelength of light 1.55 mm. Especially the core radius R was equaled 4 μm, the distance between core centers $d = 10R = 40\mu$m, the Kerr nonlinear parameter $\gamma = 1.35W^{-1}km^{-1}$, $\beta_2 = -15.67ps^2/km$. The coupling coefficients C between neighboring core were 7.348 1/m, the remaining coefficients can be neglected.

The considered model (1, 2) has a large number of optimization parameters calling for application of a machine learning approaches (for example, a peak power, width, chirp and phase for

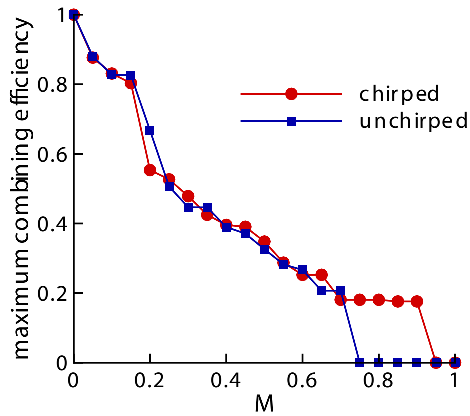

Fig. 2. Maximum combining efficiency of the pulse merged at the peripheral core $(-2, 0)$ that can be obtained by the power modulation approach when peak powers $P_{n,m}$ of input Gaussian pulses differ not more than a factor of M. Red line denotes maximum efficiency when chirped initial pulses are used and blue line corresponds to the maximum efficiency of combining unchirped pulses.

every input pulse). If the machine learning algorithms are combined with adaptive control, it is potentially possible to develop a self-tuning device. We apply here the standard genetic algorithm (GA), which is widely used in optics [17], [18], [19], [20], [21], [22], [23], for optimization of a large number of parameters. We utilized the DEAP package [24] as a software implementation of GA written in Python and supporting parallel execution on computing systems with distributed memory using the SCOOP library [25]. In the GA, the vector of input Gaussian pulse parameters (peak powers, widths, phases and chirps) played the role of a genotype of each individual in the population. Due to the symmetry of a 7-core hexagonal MCF, we can consider the parameters of only 5 pulses for each individual, thus reducing the size of the optimization problem. We aim to obtain the combined pulse at the core $(-2, 0)$, so the pulse parameters for the cores $(-1, -1)$ and $(1, -1)$ equal the pulse parameters for the cores $(-1, 1)$ and $(1, 1)$. The maximum pulse combining efficiency (the ratio of combined energy at the peripheral core to the total energy) that can be achieved by the pulses with specified parameters (genome) along the considered fiber was assigned as the value of the fitness function for each individual. Here it should be noted that the energy in the combined pulse ”wings” was not taken into account in calculating the combining efficiency. We have considered two approaches to determining the Gaussian pulse parameters under which the combined pulse can be obtained in one of the peripheral cores of the 7-core hexagonal MCF.

The first approach is easier for practical realization (in experiment), and it assumes that all pulses have equal parameters and only the peak powers differ. The initial phases of all Gaussian pulses are equal to zero. Thus the total number of parameters in the optimization problem to be solved (the genome size of a single individual in the genetic algorithm) is equal to 7, namely 5 peak powers $P_{-1,1}$, $P_{1,1}$, $P_{-2,0}$, $P_{0,0}$, $P_{2,0}$ and common for all pulses the chirp α and the width τ. The genome values for the initial population are uniformly distributed random variables of the specified intervals. As mentioned earlier, the maximal combining efficiency of input Gaussian pulses obtained after calculating the propagation of these pulses along the MCF acted as the fitness function to evaluate the ”quality” of individuals. Without any additional restrictions on the genomes of the individuals, it is necessary to inject the chirped pulse in the peripheral core with a peak power exceeding the peak power of all other pulses by several orders of magnitude in order to obtain the output pulse in this core, providing maximum combining efficiency. Of course, this solution is trivial and does not use nonlinear pulse combining. Therefore, we have introduced the restriction on the peak power values of input Gaussian pulses:

$$\frac{\min P_{n,m}}{\max P_{n,m}} < M. \tag{3}$$

Using the GA, we have found that if the peak powers $P_{n,m}$ of the input pulses differ from each other by not more than a factor of 2, the maximal pulse combining efficiency that can be achieved is 34.8% (see Figure 2). If the peak powers do not differ by more than a factor of 5 (Figure 3), the maximal efficiency is equal to 55.3%. In this case, the combined pulse was obtained at the distance $z = 7.56$ m along MCF with the following initial Gaussian pulse parameters: $P_{-1,1} = 88.25W$, $P_{1,1} = 88.93$, $P_{-2,0} = 430.0$, $P_{0,0} = 142.96$, $P_{2,0} = 99.03$, $\phi_{n,m} = 0$, $\tau_{n,m} = 6.44$ ps, $\alpha_{n,m} = 37.8092$ $(\forall n, m)$. When the peak power values are allowed to differ by a factor of 10, the maximal efficiency is about 83.1%. Moreover, we note that the chirp parameter α can be neglected in the GA optimization (Figure 2)

The second approach is more complicated from a technical point of view, since it requires control of the initial phases of the input pulses. Here we set the pulse peak powers, widths and chirps to be equal, but change the phase of each pulse individually, and thereby maximize the pulse combining efficiency in the peripheral core by adjusting 8 parameters, namely 5 phases $\phi_{-1,1}$, $\phi_{1,1}$, $\phi_{-2,0}$, $\phi_{0,0}$, $\phi_{2,0}$ and common for all pulses the peak power P, the chirp α and the width τ. However, as in the previous case, we can ignore the chirp parameter $\alpha_{n,m}$. As a result, by using the GA the pulse parameters were obtained giving a combining efficiency about 99.4% at the distance $z = 10.89$ m (see Figure 4). The input Gaussian pulses in this case have parameters $P_{n,m} = 10.50$

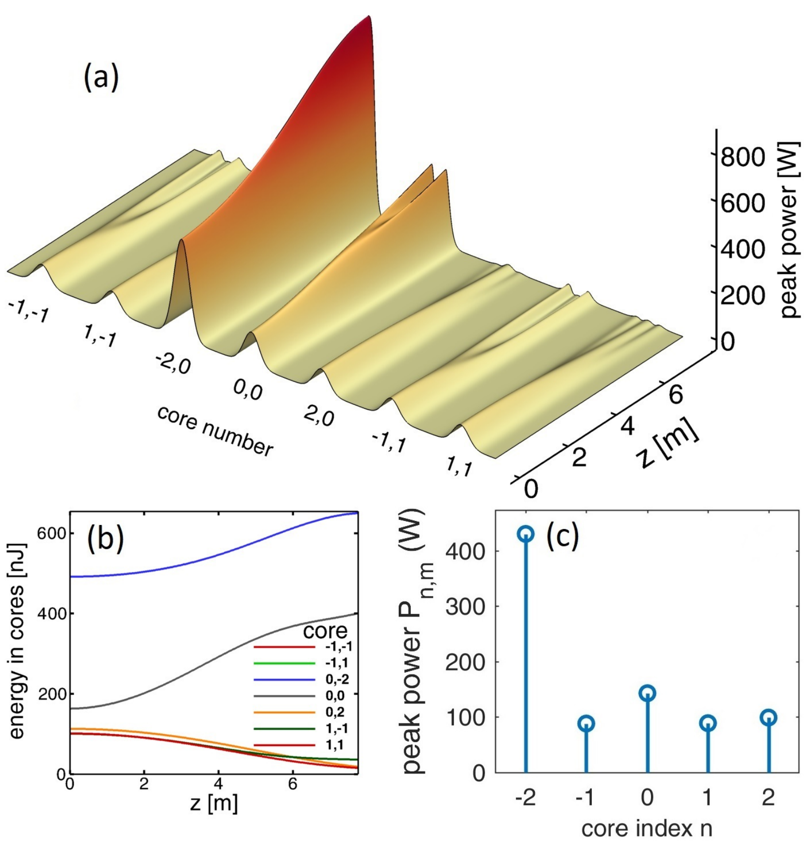

Fig. 3. The pulse intensity dynamics (a), the evolution of an energy by cores (b) for the solution obtained by the genetic algorithm using modulation of peak powers ($M = 0.2$) with the maximum combining efficiency. The peak powers $P_{n,m}$ of the input Gaussian pulses for various cores (c).

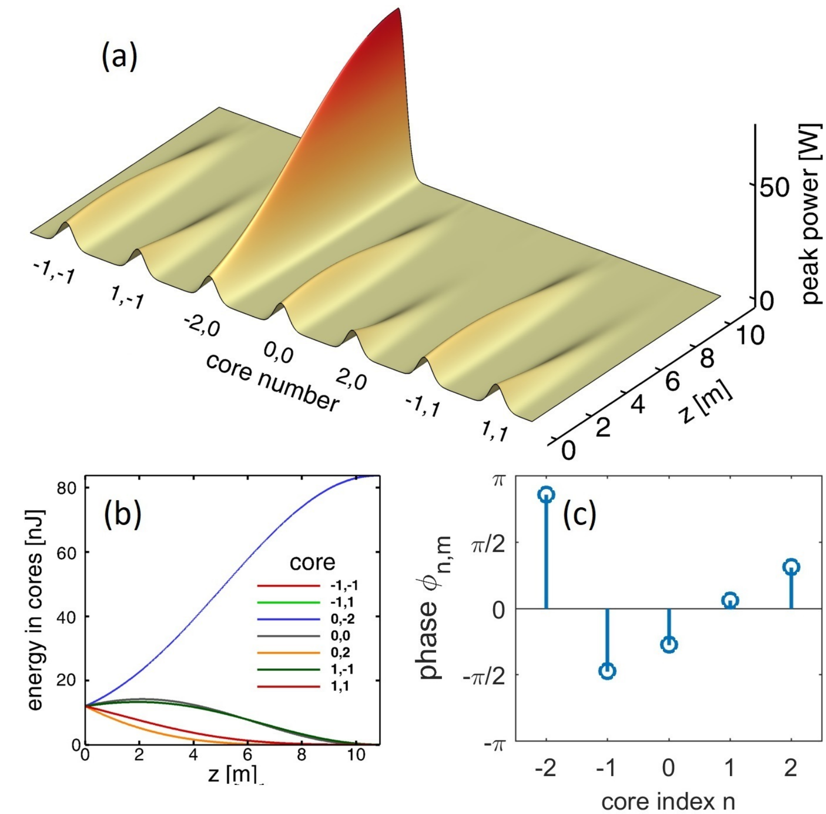

Fig. 4. The pulse intensity dynamics (a) and the evolution of an energy by cores (b) for the solution with combining efficiency about 99.4% obtained by the genetic algorithm using phase adjusting. The phases $\phi_{n,m}$ of the input Gaussian pulses for various cores (c).

W, $\phi_{-1,1} = -1.49742$, $\phi_{1,1} = 0.183646$, $\phi_{-2,0} = 2.69176$, $\phi_{0,0} = -0.867763$, $\phi_{2,0} = 0.974319$, $\tau_{n,m} = 6.452$ ps, $\alpha_{n,m} = 0$.

The possibility of obtaining a combined pulse at the same distance along MCF from both peripheral and central cores is an important condition for the functioning of the proposed device. In Figure 5, we show the dependence of the combining efficiency of the Gaussian pulses in the central core of a 7-core hexagonal MCF and the compression factor (the ratio of initial pulse width (FWHM) to the combined pulse width) for obtained pulses (for details see [10]). In these simulations, equal Gaussian pulses with peak powers P and width τ were introduced into all cores of the considered fiber. The white dashed line denotes regimes, in which pulse combining occurs at the distance $z = 10.89$ m, as the most effective regime within the phase selection approach. At this distance in the central core, as one can see, a combining efficiency of 90% of the total energy can be achieved.

Numerical analysis of the impact of the fluctuations of initial pulse phases show that the resulting regimes of both the first and the second approach have a sufficient stability margin with respect to fluctuations of this type. However, the first approach is sensitive to small temporal delays between the pulses. The results of a stability analysis for the two regimes discussed earlier are presented in Figure 6. We consider the deviation of the combining distance, as one of the most important characteristics of the combining scheme.

We modeled the phase perturbations as uniformly distributed on the segment $[-\delta_p; \delta_p]$ with a random function C_{δ_p}, so the initial pulses were

$$\tilde{A}_{n,m}(t) = A_{n,m}(t) \exp\left[-iC_{\delta_p}\right]. \tag{4}$$

The parameter δ_p varied from 0 to π. All computed values were averaged over 2000 launches for each of 100 values of δ_p. The calculations showed that the combining scheme is stable for $\delta_p \in [0; \pi/20]$ in the case of the peak power modulation regime and for $\delta_p \in [0; \pi/5]$ in the case of the phase adjusting. The distance to the combining point along MCF (mean, maximum and minimum values) is shown in Figure 6(a,b).

The random pulse delays were modeled as uniformly distributed on the segment $[-\delta_t; \delta_t]$ with the random function C_{δ_t}, making perturbed initial pulses

$$\tilde{A}_{n,m}(t) = A_{n,m}(t - C_{\delta_t}). \tag{5}$$

The simulations showed the stability of the combining scheme in the case of the phase adjusting approach for $\delta_t \in [0; \tau]$, where $\tau = 6.45$ ps is the obtained width of the injected pulses (see Figure 6(d)). However, the first approach is unstable with respect to fluctuations of this kind (Figure 6(c)). Here $\tau = 6.44$ ps.

In the production of fibers, it is extremely important to preserve the geometry of the fiber cross-section over its entire length. However, slight deviations of the distance between the cores, the core sizes, as well as the refractive index distribution are possible. These ultimately affect the coupling coefficient C between the cores. Therefore we have studied the effect of fluctuations in the coupling coefficient of a 7-core hexagonal fiber on the proposed combining schemes. These fluctuations were simulated using a short segment of the Wiener random process $\Delta C(z)$ (see Figure 7), so the coupling coefficient is represented in the following way:

$$C(z) = C_0 + \Delta C(z), \tag{6}$$

where C_0 is the mean value of the coupling coefficient. This approach allows a relatively smooth change of the value of the coupling coefficient along the fiber. Calculations showed that the proposed regimes are sufficiently insensitive to a variation in the coupling coefficient between the cores. The main characteristics begin to deteriorate significantly when the standard deviation of the coupling coefficients $\sigma_c(z=0)$, normalized by C_0, exceeds 10% for the regime with peak power modulation, and 15% for the regime with phase adjusting. Such a requirement is indeed feasible in practice, since in the production of multi-core fibers, the distance between the cores

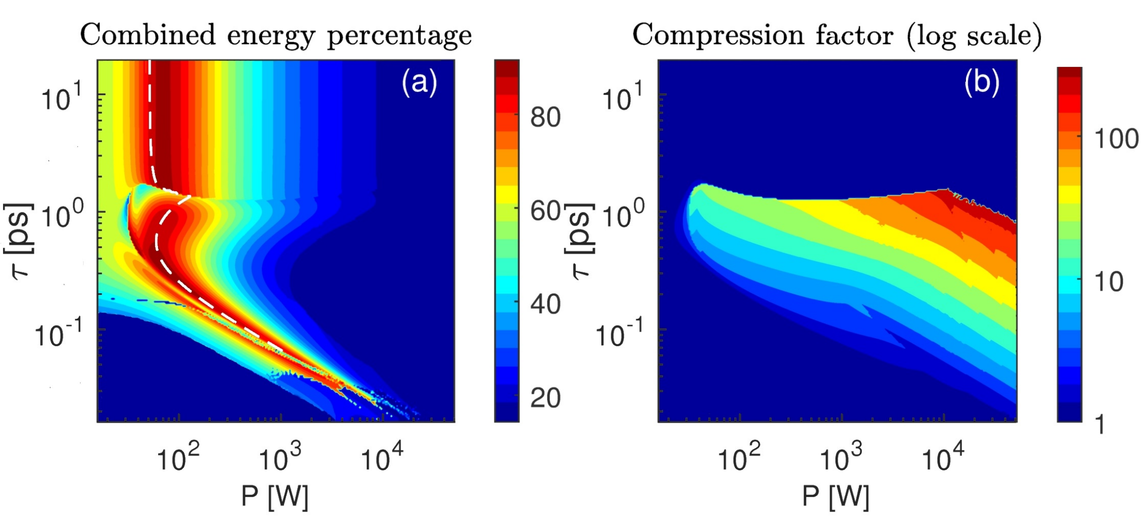

Fig. 5. The combining efficiency of the Gaussian pulses in the central core $(0,0)$ and the compression factor for the obtained pulses in the case of a 7-core hexagonal fiber in dependence of the equal for all pulses peak powers P and widths τ (see [10]). The white dashed line corresponds to the pulses, which are combined at the distance $z = 10.89$ m, as the regime presented in the Figure 4.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JPHOT.2018.2797198, IEEE Photonics Journal

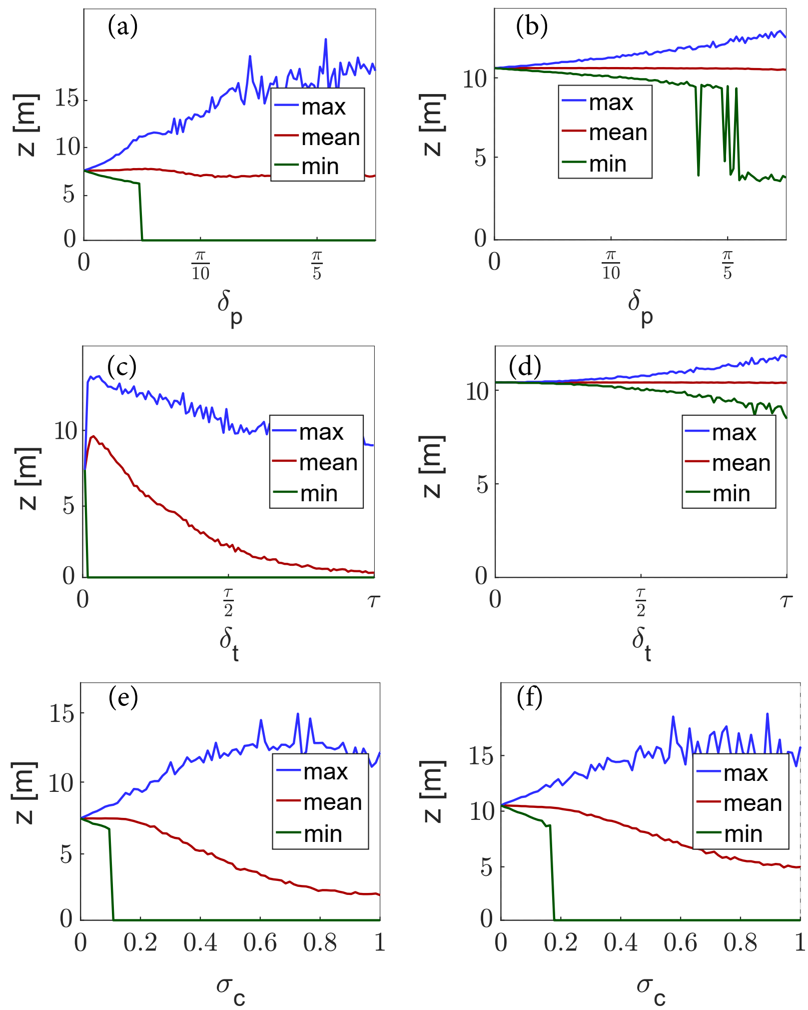

Fig. 6. The influence of phases mismatches (a,b), pulse delays (c,d) and coupling coefficient variance (e,f) on the distance to the combining point of the Gaussian pulses in the peripheral core $(-2, 0)$. Left figures correspond to the regimes with peak power modulation ($M = 0.2$) and right figures refer to the regime with phase adjusting. The mean of the distance to the combining point was averaged over 2000 launches.

fluctuates by an amount not exceeding 3–5%. The characteristic length of such deviations is about 10 meters. Thus, using a sufficiently short (up to 10 meters) optical fiber, the proposed scheme will be resistant to possible inhomogeneities in the structure of the fiber.

3. Conclusions

To conclude, we have demonstrated a self-focusing and light combining in a pre-selected core on demand. The method can be used in any multi-core fiber or 2D array of coupled-waveguides. By optimization the light modulation using genetic algorithm we demonstrated efficiency of the light combining: over 80% when varying signal power and over 99% when optimizing phases. The stability analysis was also performed proving the potential of the method for a feasible range of parameters. The technique can find applications in signal processing, fiber lasers, manufacturing, cryptography and many others.

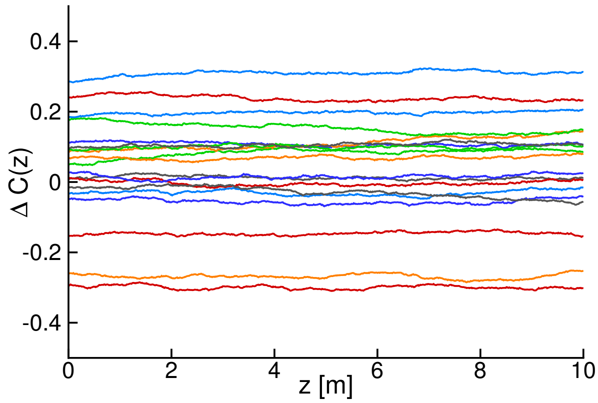

Fig. 7. An example of the realization of the random processes $\Delta C(z)$ for modeling the coupling coefficient fluctuations (standard deviation $\sigma_c = 0.15$ for $z = 0$, normalized by the mean value of the coupling coefficient C_0). Each process corresponds to one of the coupling coefficient.

Acknowledgements

This work was supported by the Russian Science Foundation (Grant No. 17-72-30006) and by the European Office of Aerospace Research and Development (grant FA9550-14-1-0305). The work was partially performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 (work of A.M.R).

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