Active multi-core fibers – photonic platform for development of a topological charge switching device

P. P. Beličev[1], G. Gligorić[1], A. Maluckov[1], Lj. Hadžievski[1] and S. Turitsyn[2,3]
[1] COHERENCE, Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, P.O.Box 522, 11000 Belgrade, Serbia
[2] Aston Institute of Photonic Technologies, Aston University Bitmingham , B4 7ET, UK
[3] Aston-NSU Centre for Photonics, Novosibirsk State University, Novosibirsk 630090, Russia
e-mail: *petrab@vin.bg.ac.rs*

Introduction

Active multi-core fibers (MCFs) represent powerful platform for coding infomation via power, phase, frequency, and topological charge. It supports discrete vortices that carry orbital angular momentum suitable for spatial-division-multiplexing in high capacity fiber-optic communication systems. The main concern of our study has been related to optimization of the conditions capable to ensure transfer of high coherent light through the MCFs w.r.t. the possibility of nonlinearity managed propagation of highly coherent vortices carrying huge power through the passive circular MCFs consisting of small number of periphery cores [1]. In addition, the effects of the presence of central core and material loss/gain of all cores on the linear MCF system eigenvalue commensurability conditions have shown significant impact on the coherent planar and vortex mode dynamics [2]. All these findings stimulated the investigation of possibility to amplify the power transferred through the MCF via vortex carriers by inducing effects of the saturable gain and non-saturable loss in the periphery and/or central cores [3].

We numerically consider three cases of active circular MCFs: 1) active are only periphery cores, 2) solely central core is active, 3) all cores are active. The light propagation is modeled by the generalized nonlinear difference-differential Schrödinger equations with complex coefficients and saturable gain [3]. Results for MCF with 4, 5 and 6 periphery cores have shown that the active periphery is the most promising candidate for topological charge switch of vortices carrying high powers [4].

Model

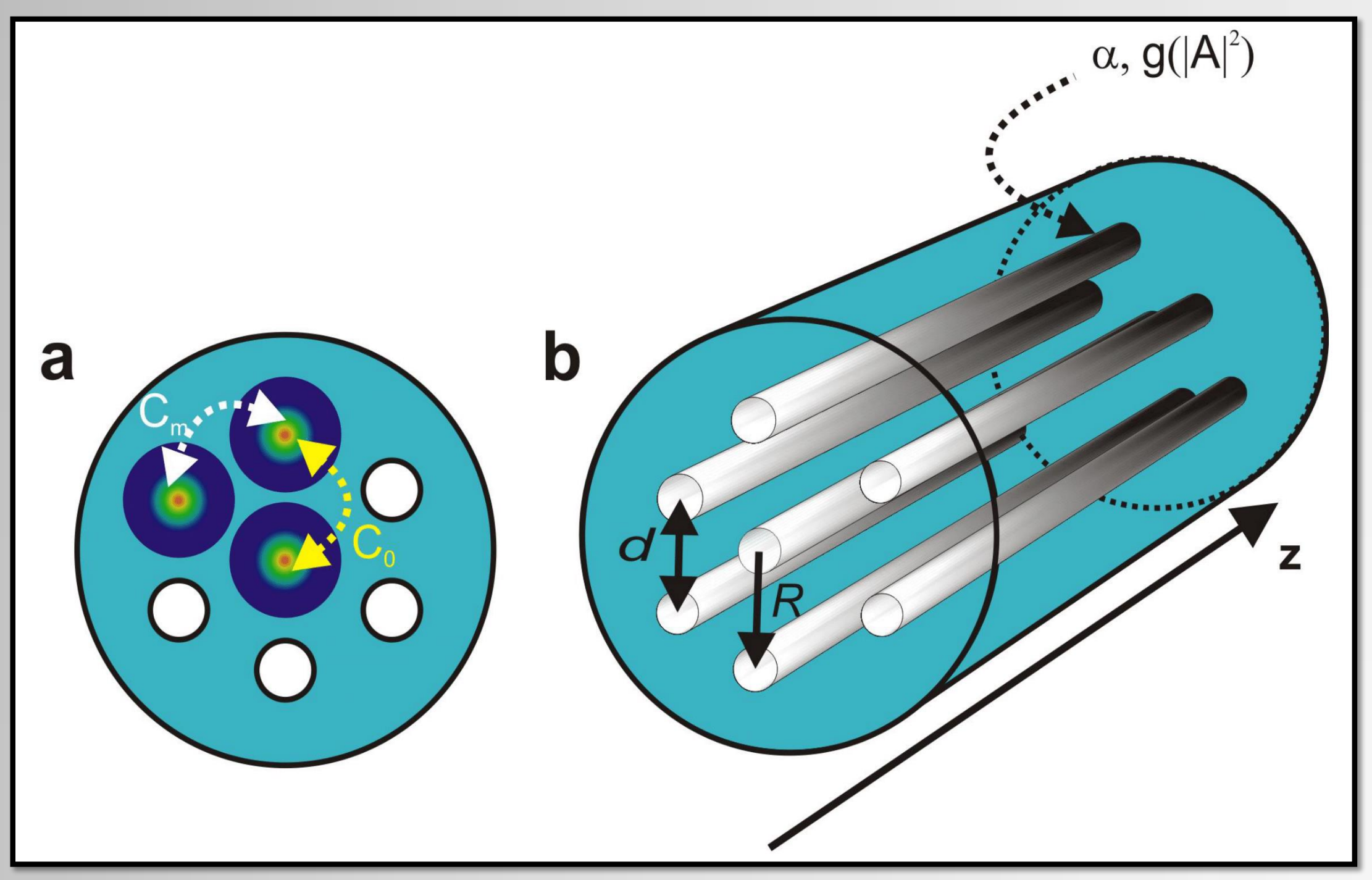

Fig. 1: Schematic representation of nonlinear active MCF system with six periphery cores. (a) Cross-section of hexagonal MCF depicting field coupling between individual cores and (b) three-dimensional perspective. Coupling constants values obey $C_0 = C_m$ as a consequence of equality of geometrical parameters *R* (central-periphery core distance) and *d* (periphery-periphery neighboring core distance). Loss α is constant along the propagation direction *z*. Gain *g* is a function of the MCF mode's power.

Master equation:

$$i\frac{d\Psi_0}{dz} + B_0\Psi_0 + C_0\sum_{m=1}^{M}\Psi_m + 2\Gamma_0|\Psi_0|^2\Psi_0 - i\frac{g_0}{2}\frac{\Psi_0}{1+|\Psi_0|^2} = 0,$$

$$i\frac{d\Psi_m}{dz} + B_m\Psi_m + C_0\Psi_0 + C_m(\Psi_{m+1}+\Psi_{m-1}) + 2\Gamma_m|\Psi_m|^2\Psi_m - i\frac{g_m}{2}\frac{\Psi_m}{1+|\Psi_m|^2} = 0$$

Parameters:

$\Psi_{0,m}$ - Complex amplitude of the light field in the central and periphery cores

$C_{0,m}$ - Coupling constants between central-periphery and periphery-periphery cores

$B_{0,m} = \beta_{0,m} + i\alpha_{0,m}/2$ - Propagation constant in the central and periphery cores

$\beta_{0,m}$ - Linear propagation constant in the central and periphery cores

$\alpha_{0,m}$ - Effective distributed loss in the central and periphery cores

$g_{0,m}$ - Signal gain parameter in the central and periphery cores

$\Gamma_{0,m}$ - Kerr type nonlinear parameter in the central and periphery cores

Stationary solution – vortex with topological charge S:

$$\Psi_0 = 0, \Psi_m = \Psi\exp\left(\frac{i\cdot 2\pi S}{M}\right)\exp(-i\mu z), m \in [1, M]$$

Conserved quantities:

$$P = \sum_{m=1}^{M}|\Psi_m|^2 - (vortex\ solution) \rightarrow \frac{dP}{dz} = \left(-\alpha_1 + \frac{g_1}{1+P/M}\right)P \Rightarrow$$

$$P_{sat} = \left(\frac{g_1}{\alpha_1} - 1\right)M$$

Saturated vortex power after transient time

$$H = -\sum_{m=1}^{M}[\beta_m|\Psi_m|^2 - C_m(\Psi_{m+1}\Psi_m{}^* + \Psi_{m+1}{}^*\Psi_m) - C_0(\Psi_0\Psi_m{}^* + \Psi_m{}^*\Psi_0) - \Gamma_m|\Psi_m|^4] \\ -\beta_0|\Psi_0|^2 - \Gamma_0|\Psi_0|^4$$

$$J = i\sum_{i=1}^{M}(\Psi_{m+1}{}^*\Psi_m - \Psi_{m+1}\Psi_m{}^*) \rightarrow \frac{dJ}{dz} = \frac{2g\Psi^2}{1+\Psi^2}\times M\sin\left(\frac{2\pi S}{M}\right) \Rightarrow$$

J* is conserved solely for ineteger values of 2*S/M

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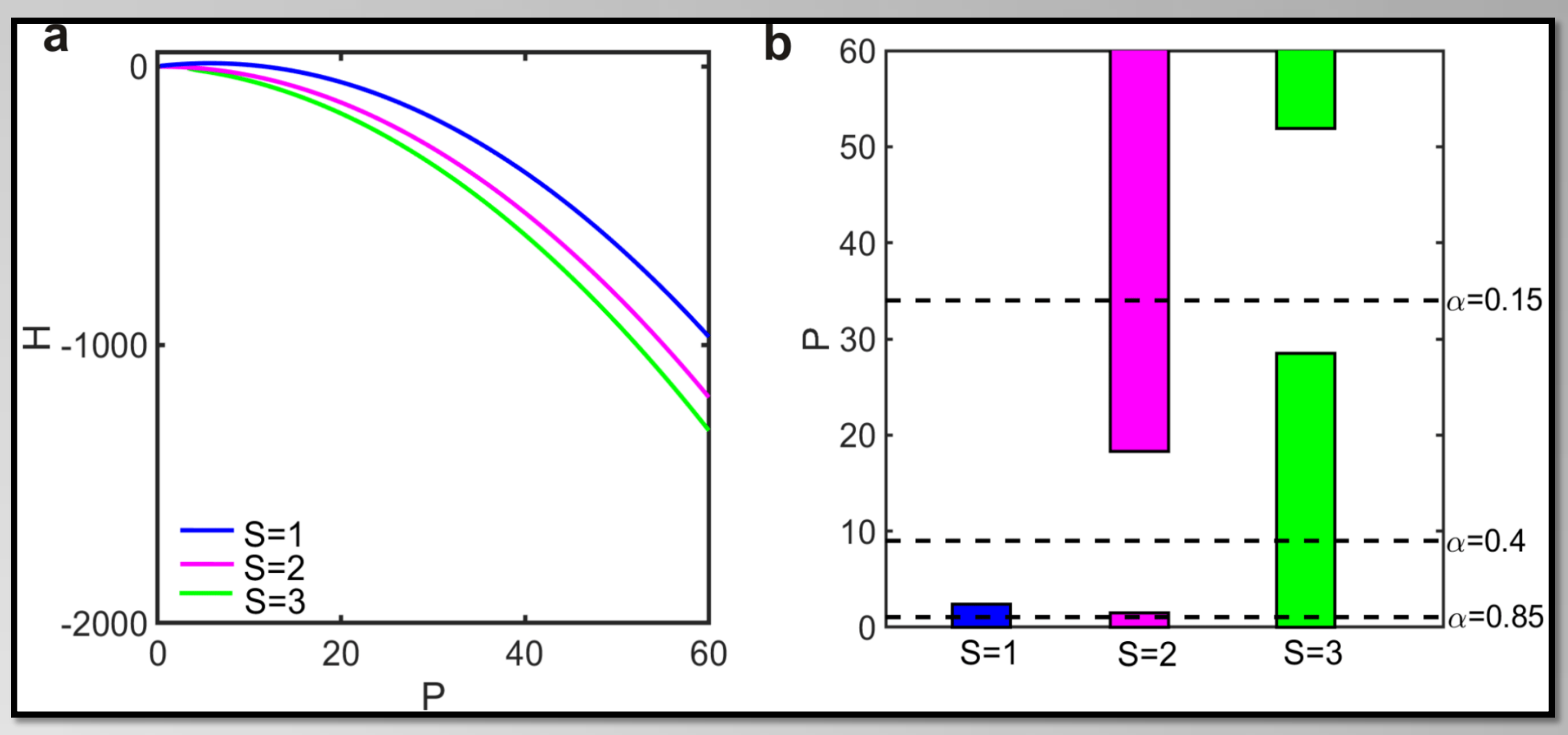
References

[1] Lj. Hadžievski, A. Maluckov, A. M. Rubenchik, S. Turitsyn, Light Sci. Appl. 4, e314 (2015).
[2] A. Radosavljević, A. Daničić, J. Petrovic, A. Maluckov, Lj. Hadžievski, JOSA B 32, 2520 (2015).
[3] S. K. Turitsyn, Opt. Express 17, 11898 (2009).
[4] P. P. Beličev, G. Gligorić, A. Maluckov, Lj. Hadžievski, S. Turitsyn, Ann. Phys. 2100108 (2021).

Results

Passive MCF (g=0, α=0)

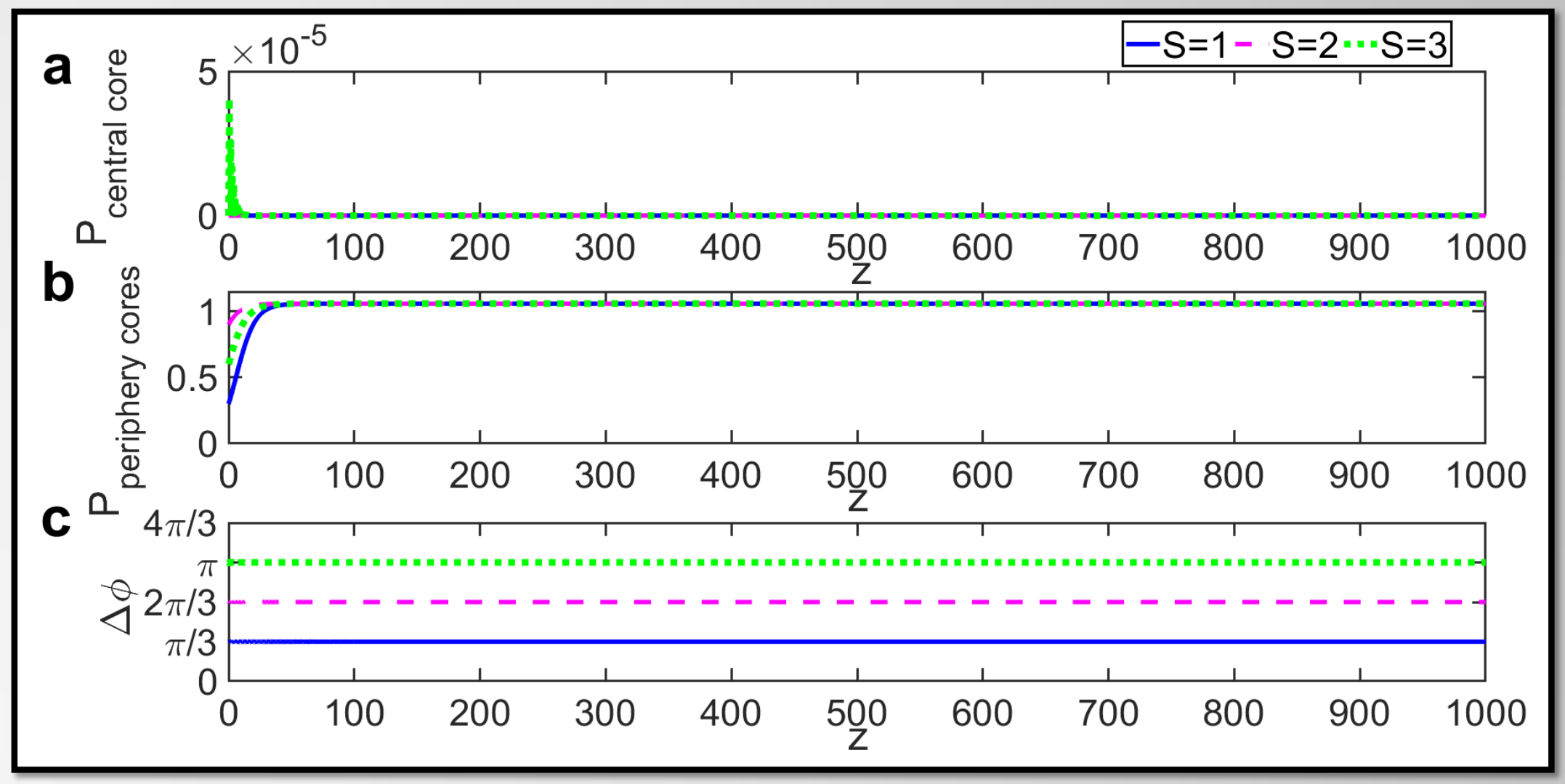
Fig. 2: Optical vortex characteristics in nonlinear passive MCF system with M = 6 periphery cores: (a) H-P diagram for vortex families characterized with topological charge S = 1, S = 2 and S = 3. (b) Parallel overview of stability regions for corresponding vortex solutions. Colored bars depict areas where solution is stable. Horizontal black dashed lines represent output saturation power levels of vortices when gain and loss are included in periphery cores of the system power.



Existence of regimes with stable propagation of vortices carrying huge power.

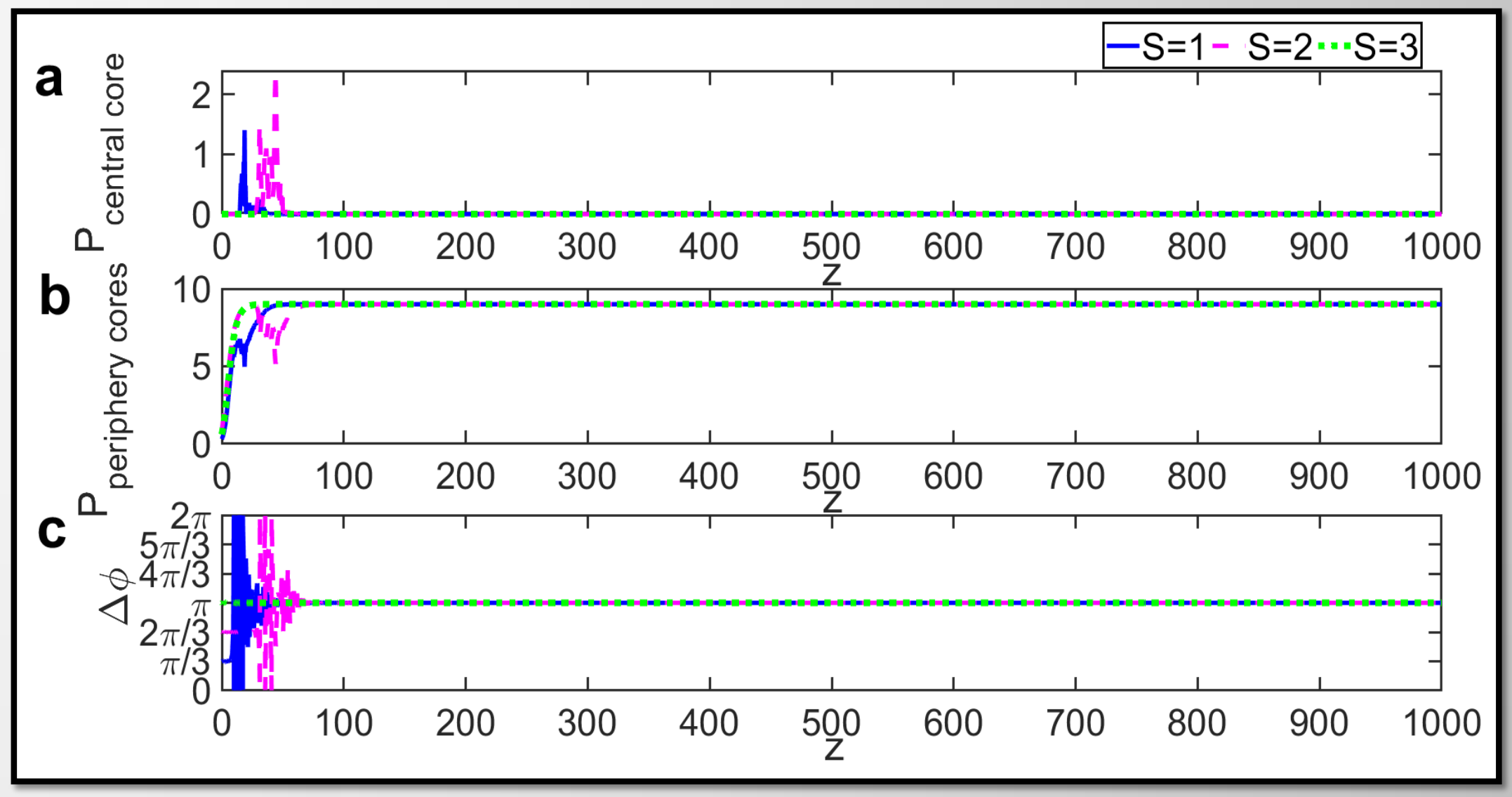
Active MCF (g_0=0, g_1=1, $\alpha_{0,1}$≠0)

Fig. 3: Evolution of power within central (a) and periphery cores (b). (c) Phase difference between neighbouring periphery cores. Loss α is set to 0.85. Only periphery cores are active. Initially injected vortices are characterized with S = 1 and P = 0.3, S = 2 and P = 0.9 and S = 3 and P = 0.6, respectively. In all cases topological charge has been preserved during propagation.



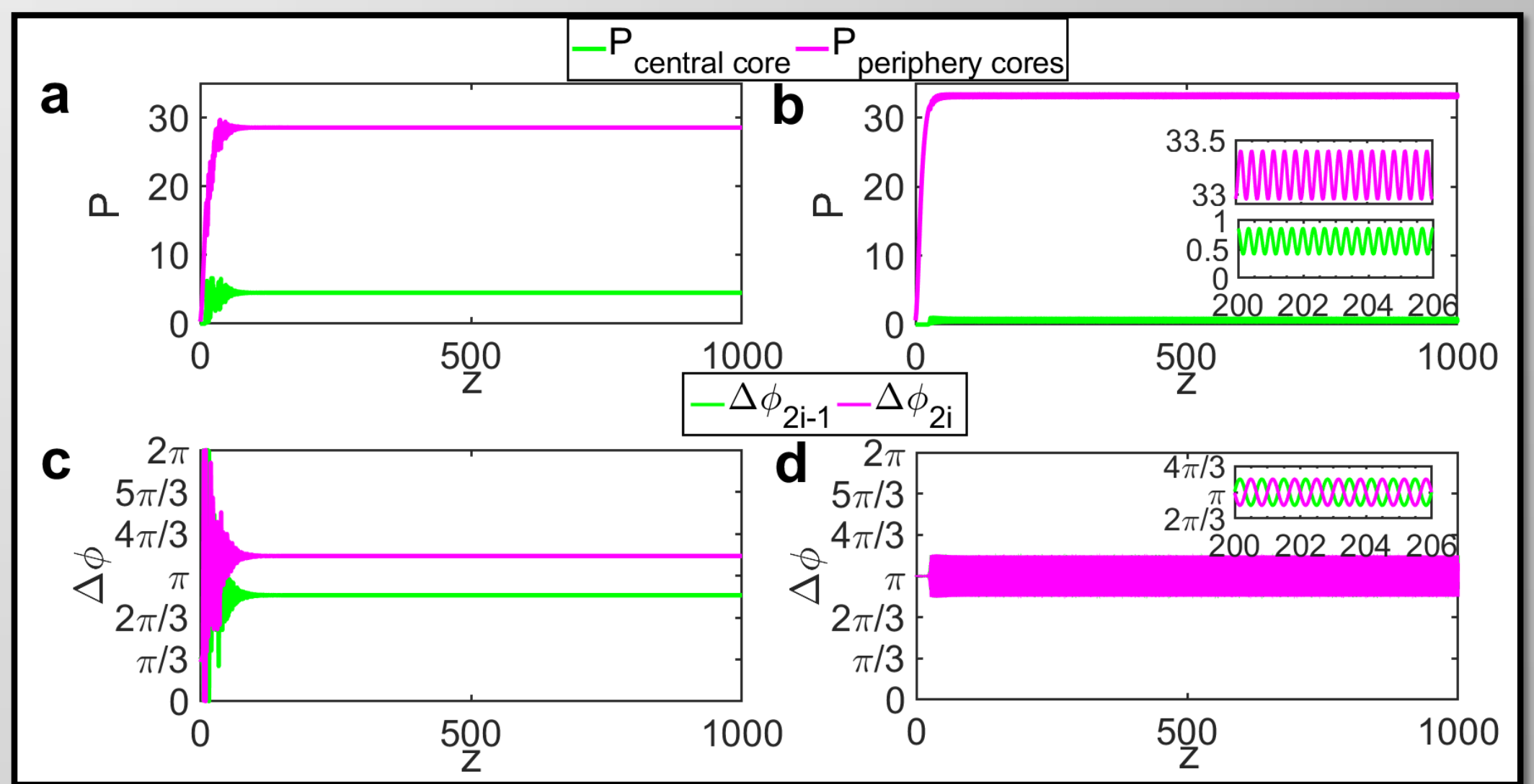
$\alpha_{0,1}$ >0.7 → Preservation of initial topological charge with the increase of input power.

Fig. 4: Evolution of power within central (a) and periphery cores (b). (c) Phase difference between neighbouring periphery cores. Only periphery cores are active. Initially injected vortices are same as in Fig. 3, while value of loss is set to α = 0.4. Solutions S = 1 and S = 2 experience topological charge switch and transform to vortex mode S = 3 characterized with Δϕ=π.
For α<0.25, S=2 vortex family is stable according to Fig. 2, thus no topological charge switch will occur for these solutions.



0.18 < $\alpha_{0,1}$ <0.7 → Topological charge switch regime: with the increase of input power initial vortices switch to S=3 vortex.

Fig. 5: Evolution of total power within periphery (magenta solid line) and central core (green solid line) for initially injected vortex with a) S = 1 and P = 0.3, and b) S = 3 and P = 0.6. Corresponding evolution of phase difference among periphery cores are given in (c) and (d), respectively. Loss α is set to 0.15. Only periphery cores are active. Insets in plots (b) and (d) represent enlargement of related quantities.



$\alpha_{0,1}$ <0.18 → Energy transfer to all cores of a system: Preserved stays only S=2 vortex family.

Conclusion

Numerical study of the propagation of phase vortex modes through proposed nonlinear MCF system with constant (linear) loss within all cores and saturable gain distributed solely in periphery cores gave following conclusions:

- amplifying peripheral cores while keeping a passive central core can provide conditions suitable for topological charge switch, i.e. transition between different vortex states.
- presented system supports topological charge switch function between non-counterpart vortices by proper tailoring the ratio between gain and loss in periphery., whereas the key condition for this phenomenon is existence of the central core which appears to play role of mode dynamics moderator.
- the central core, being the singular phase point of the vortex, contributes in energy redistribution between the periphery cores supporting coherent light amplification.
- depending on the gain distribution between periphery and central core, system can support multiple functions in applications: from high-power fiber lasers and beam combiners to carriers and selective topological charge switchers of vortex beams.
- MCF technology is actively developing in telecom for optical spatial division multiplexing, therefore, such fibres are available and non-expensive.