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Optimal Design of One-Dimensional Photonic Crystal Selective Filters with the Use of Computational Optimization Methods

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Abstract—This paper presents a comparative study that was done using genetic algorithm, improved particle swarm optimization, and hybrid technique genetical swarm optimizer approaches for the design of one-dimensional photonic crystal selective filters. The three evolutionary methods for synthesizing the geometrical parameters of a fiber Bragg grating structure from its layer thicknesses are proposed and demonstrated. The synthesis of the mono-band 1-D PhC selective filters is designed as a mono-objective problem, and these 1-D PhCs are composed of alternate Si and Air layers with thicknesses on micron scale. The main contribution of this paper is formed by the solution to this kind of problems. According to the literature, this hybrid methodology genetical swarm optimizer has been not dealt with before, when 1-D PhCs selective filters are considered. Comparison of the GA, IPSO, and GSO for the selected set of examples revealed an improvement of paramount importance in terms of error lowering and the number of iteration cycles diminution.

1. INTRODUCTION

The one-dimensional photonic crystal finds applications in high-accomplishment fiber optics communication systems, chemical and biological imaging, eye protection glasses, as well as anti-reflecting coating for solar cells and security screening [1]. During the last decade, the researchers in the field of fiber optics have been attracted by the design of photonic filter. The literature about one-dimensional photonic crystal selective filters exposes a wide range of synthesis methods. The 1-D PhC synthesis problem can be defined as that of finding the layer thicknesses to produce the required spectral response patterns [2]. Several methods have been presented for the design of PhC, including, among others, simulated annealing [3], minimax optimization approach [4], particle swarm optimization algorithm [5], hybrid of Tabu Search (TS) and Nelder-Mead (NM) Simplex algorithm [6], layer peeling technique [7], quadratic response surface methodology [8], and a statistical design centering approach [9]. In this work, we show the application of three computational methods, genetic algorithm, improved particle swarm optimization, and the hybrid genetical swarm optimizer to the synthesis of one-dimensional photonic crystal selective filters by acting on the Bragg grating layer thicknesses.

This paper is organized, besides the introduction, in five sections. Section 2 describes the governing equations of the propagated electromagnetic wave, the general structure of 1-D PhC filters, as well as the formulation of the design problem. Brief overviews of the applied well-known algorithms are described in Section 3. Section 4 is devoted to reviewing the obtained results and the comparative study. Finally, conclusions are drawn in Section 5.

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2. 1D PHOTONIC CRYSTAL THEORETICAL MODEL

A one-dimensional photonic crystal is an artificially periodic layered structure which consists of two alternating materials able to possess certain photonic band gap at some frequencies ranges.

To calculate the radiation propagation through a finite one-dimensional layered photonic crystal, we solve the Helmholtz equation depicted below which govern the propagation of the electromagnetic wave [10]:

$$\frac{\partial^2 E_z(x)}{\partial x^2} + \varepsilon_r(x)\frac{\omega^2}{c^2}E_z(x) = 0 \tag{1}$$

Figure 1 depicts a one-dimensional photonic crystal based filter which is modeled as a periodic structure made of two alternating materials, with the index contrast (n_1, n_2) and the layer thickness parameters ($d_1, d_2, \ldots, d_N$).

$$n(x) = \begin{cases} n_1 & 0 \le x \le d_1 \\ n_2 & d_1 \le x \le d_2 \end{cases} \quad \text{With: } n(x+d) = n(x),\ d = d_{1+}d_2$$

The recovered electric field component in the jth layer of the Helmholtz equation can be written as (2):

$$E_j(x) = A_j e^{jn_j k x_j} + B_j e^{jn_j k x_j} \tag{2}$$

where A_j and B_j denote the transmissivity and reflectivity propagation from a layer to another one.

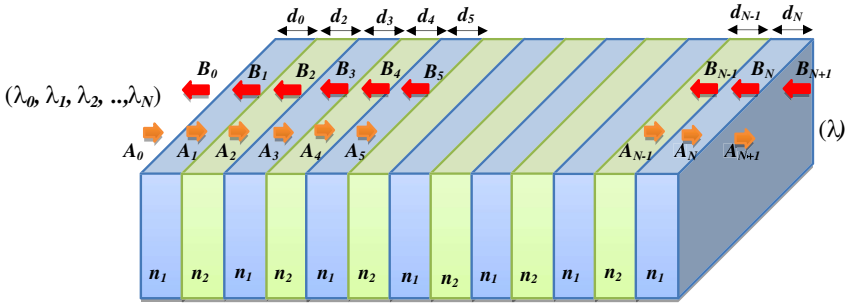

Figure 1. Schematic representation of one-dimensional photonic crystal.

The electric field and its first derivatives applied at the layer interfaces are expressed as (3) and (4):

$$E_j(x_j) = E_{j+1}(x_j) \tag{3}$$

$$\frac{\partial}{\partial x}E_j(x_j) = \frac{\partial}{\partial x}E_{j+1}(x_j) \tag{4}$$

where x_j coordinate represents the jth interface. One has to first replace the global solution (2) to Equations (3) and (4). The response system is expressed as:

$$A_j e^{jn_j k x_j} + B_j e^{-jn_j k x_j} = A_{j+1} e^{jn_{j+1} k x_j} + B_{j+1} e^{-jn_{j+1} k x_j} \tag{5}$$

$$jn_j k A_j e^{jn_j k x_j} + jn_j k B_j e^{-jn_j k x_j} = jn_{j+1} k A_{j+1} e^{jn_{j+1} k x_j} - jn_{j+1} k\, B_{j+1} e^{-jn_{j+1} k x_j} \tag{6}$$

We applied the Cramer's method [1] to obtain solution from the system equations. We can then calculate a set of transmissivity and reflectivity which represent the output response vectors of solution.

$$\begin{cases} A_2 = t_{21}A_1 + r_{12}B_2 \\ B_1 = t_{12}B_2 + r_{21}A_2 \end{cases} \tag{7}$$

Having obtained the output response vectors, the transmittance and reflectance can thus be related through Equation (8):

$$r^2 + t^2 = 1 \tag{8}$$

The design task of selective filter in one-dimensional photonic crystal is to find the optimal set of layer widths such that the synthesized transmission spectra function of the photonic crystal filter $F_s(\lambda_i)$ approximates the desired Gaussian pattern $F_d(\lambda_i)$ in some optimum sense.

In this study, the desired Gaussian function can be set according to the centered filter wavelength as presented in Equation (9):

$$F_d(\lambda_i) = e^{-\left(\frac{15(\lambda_i-\lambda_1)^2}{10^{-2}}\right)} \tag{9}$$

Here the prime objective is to reduce the quadratic error between the desired and actual amplitude responses of the filter.

$$\xi = \sum |F_s(\lambda_i) - F_d(\lambda_i)|^2 \tag{10}$$

Thus, the design of selective filter in 1D photonic crystal is equivalent to the following constrained minimization problem:

$$\text{Minimize } \xi(w) \to w_{opt} \tag{11}$$

Subject to:

$$\begin{cases} \lambda_i \epsilon [1\ 2]\ \mu\text{m} \\ \Delta\lambda = 0.01\,\mu\text{m} \\ \lambda_1 \epsilon \{1.1\ 1.2\ 1.31\ 1.4\ 1.55\ 1.65\ \ 1.71\ 1.85\}\ \mu\text{m} \end{cases} \tag{12}$$

$w = [d_1, d_2, d_3, \ldots, d_N]$ is the filter coefficients used to synthesize a desired pattern.

3. OVERVIEWS OF THE APPLIED ALGORITHMS

The genetical swarm optimizer provides a robust and efficient approach for designing photonic crystal selective filters. The aim of this study is to introduce a hybrid algorithm combining two computational methods, genetic algorithms (GA) and improved particle swarm optimization (IPSO). Our paradigm integrates the merits of both GA and IPSO, and it has two characteristic features. In this section, we briefly present the applied parameters values of the three evolutionary computation algorithms: genetic algorithms (GA) [11, 14], improved particle swarm optimization (IPSO) [12], and the hybrid model genetical swarm optimizer (GSO) [13]. The operators of each well-known algorithm are not reviewed in this section; some references are delivered in [11–13]. The improved particle swarm optimization (IPSO) and genetic algorithm (GA) are combined to achieve the optimal design satisfying a certain criterion. The hybrid model genetical swarm optimizer (GSO) is designed to be the most excellent evolutionary algorithm for mono and multi-objective problems.

Table 1. Parameters of the algorithms used in these simulations.

Algorithms	Parameters	Value
IPSO	Population size	40
	Inertia weight w	0.9 to 0.4
	C_1, C_2	0.57
	$V_{\max}$	1
	T_c	3
GA	Population size	40
	P_m	0.01
	P_c	0.7
GSO	Population size	40
	HC	0.5

We have chosen a suitable fitness function that guides the applied optimization algorithms toward solutions that meet the desired optimal design. The error function to be minimized is described by Equation (10).

4. NUMERICAL RESULTS

To evaluate the efficiency and effectiveness of the proposed algorithms in this paper, 1-D PhCs selective filters are used to demonstrate the application of the suggested formulation. The problem formulation has been implemented in Matlab 7 programming software. Our designed photonic filters are required to present a maximum of transmission related to wavelength values located at passband regions of 1.1 μm, 1.2 μm, 1.31 μm, 1.4 μm, 1.55 μm, 1.65 μm, 1.75 μm, and 1.85 μm, and to reject the signals within the stopband regions.

The presented approaches show their abilities to get the optimal design of one-dimensional photonic crystal filter and optimal layer thicknesses of the given filter with a maximum of transmission in the range [1.05 μm–1.15 μm]. The obtained values of the optimization method's errors are as follows: 0.0239, 0.0275, and 0.0333 for the GSO, IPSO, and GA, respectively. According to the results of the simulations carried out depicted in Figure 2, respectively, GSO has lower est error value than IPSO and also GA. Comparing GSO with IPSO and GA, the filters designed by the GSO approach were found to be more effective, and the GSO has higher convergence rate than the IPSO and GA methods. IPSO was found to produce better convergence speed than the GA.

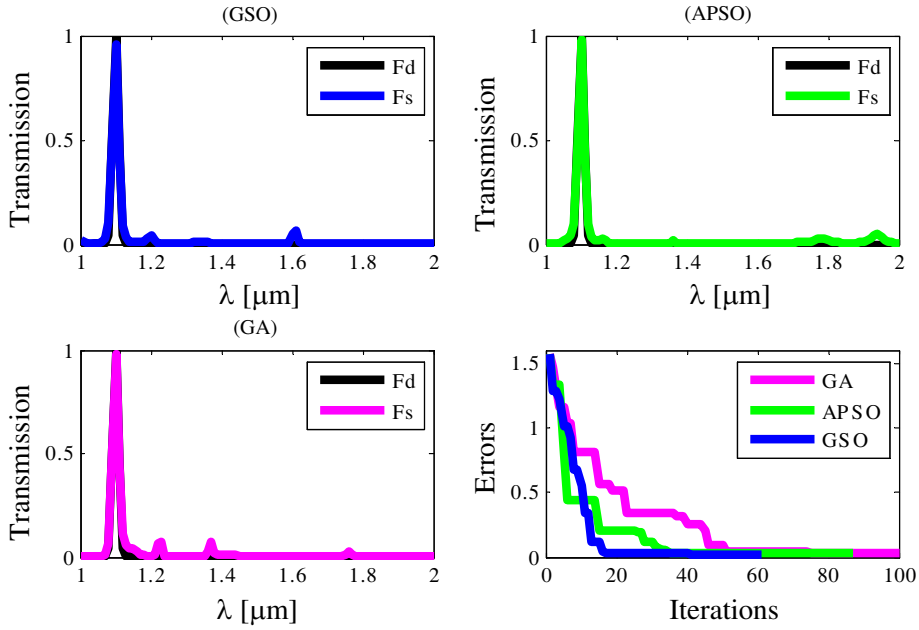

Figure 2. Power transmission spectra at the wavelengths 1.1 μm and their error evolution.

Now, we want to design a photonic crystal which presents a pick of power transmission spectra at 1.2 μm using GA approach, IPSO procedure, and GSO methodology, and the desired and synthesized responses are depicted in Figure 3.

All the applied methods performed well in terms of effectiveness. However, GSO appears to achieve the minimum error value as compared to IPSO and GA. This is due to maintaining the diversity of solutions.

The filters optimized by GSO performed better than the IPSO and GA, however noting that for IPSO and GA, the results of both optimization algorithms were quite similar. The obtained results leading to the conclusion that GSO converged faster than IPSO and GA, and IPSO is more quickly than GA.

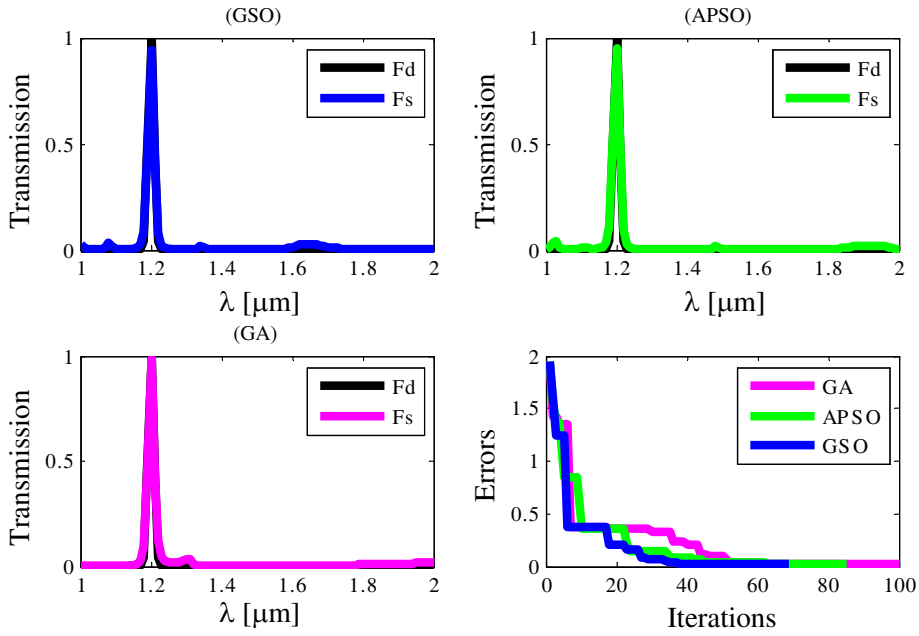

Figure 3. Power transmission spectra at the wavelengths 1.2 μm and their error evolution.

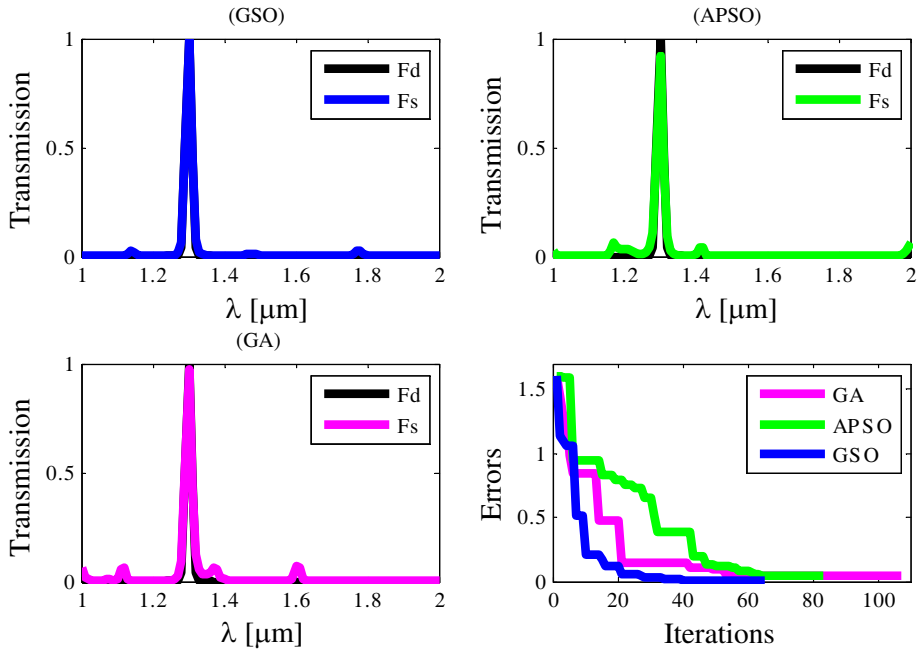

Figure 4. Power transmission spectra at the wavelengths 1.3 μm and their error evolution.

In this studied case, we compare the effectiveness of the three methodologies for the optimal design of 1-D PhCs selective filters with maximum transmission value obtained at the wavelength 1.3 μm.

Figure 4 shows how effectively each algorithm achieved the objective function. The results reveal that the GSO provides an excellent design in terms of lowering undesired picks of transmission levels while maintaining strong transmission in desired wavelengths compared to GA and IPSO. Table 2 shows that GSO converged once again faster than the other two approaches. However, IPSO led to lower iteration value than GA.

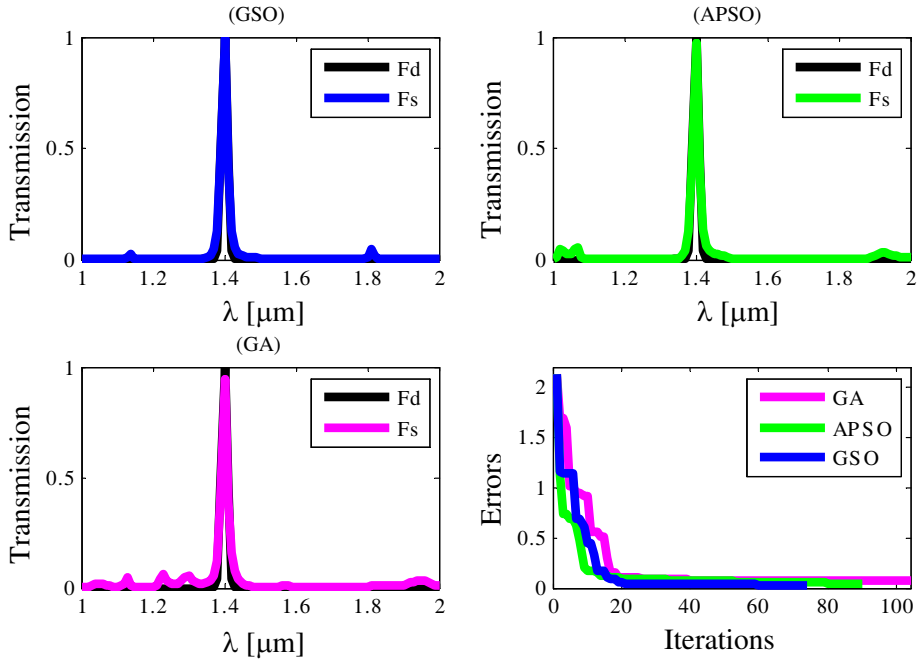

Figure 5. Power transmission spectra at the wavelengths 1.4 μm and their error evolution.

Table 2. Simulation results of algorithm parameters for the studied cases.

		SA [3]	GSO	IPSO	GA
1.1 μm	**Error**	0.4378	0.0239	0.0275	0.0333
	N° Iteration	4092	61	87	98
1.2 μm	**Error**	0.9208	0.0198	0.0225	0.0249
	N° Iteration	4477	69	85	100
1.3 μm	**Error**	1.1104	0.0066	0.0387	0.0474
	N° Iteration	6873	65	83	107
1.4 μm	**Error**	0.8576	0.0288	0.0459	0.0507
	N° Iteration	8939	74	90	104
1.55 μm	**Error**	0.5797	0.0275	0.0296	0.0383
	N° Iteration	2041	47	104	121
1.65 μm	**Error**	0.4871	0.0316	0.0448	0.0505
	N° Iteration	5286	70	82	91
1.75 μm	**Error**	1.1263	0.0544	0.0606	0.0639
	N° Iteration	9047	69	87	100
1.85 μm	**Error**	0.99	0.0419	0.0595	0.0653
	N° Iteration	6849	45	85	106

Comparing GSO with IPSO and GA, the synthesis 1-D PhCs selective filters with the maximum transmission at the wavelength value equal to 1.4 μm by the GSO method were found to be more efficient. According to Figure 5 and Table 2, the GSO exhibite much better performance and a higher convergence rate than IPSO and GA. This can be attributed to GSO's ability to avoid premature convergence and thus produces higher quality solutions, and IPSO is found to provide better results

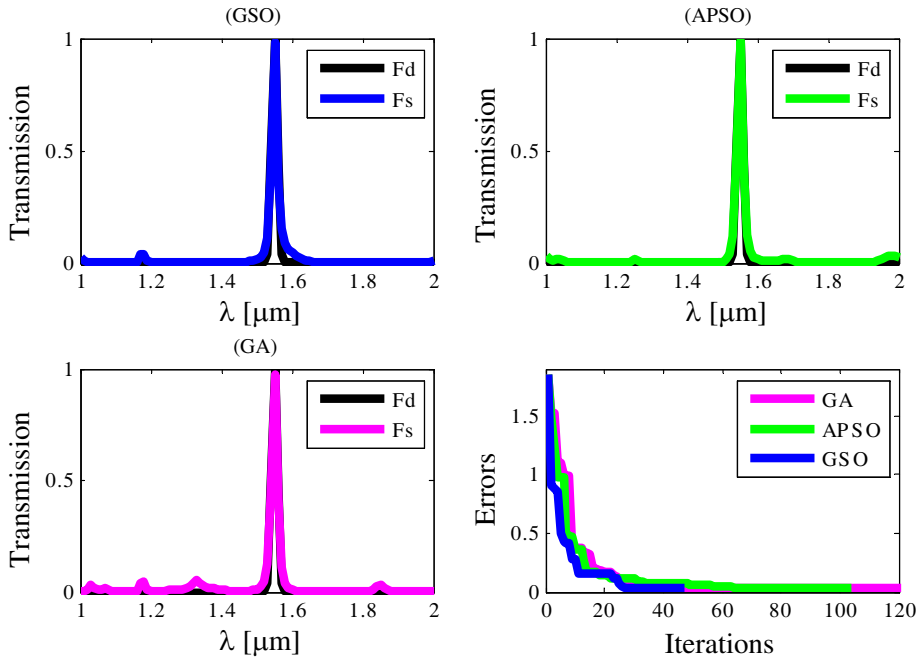

Figure 6. Power transmission spectra at the wavelengths 1.55 μm and their error evolution.

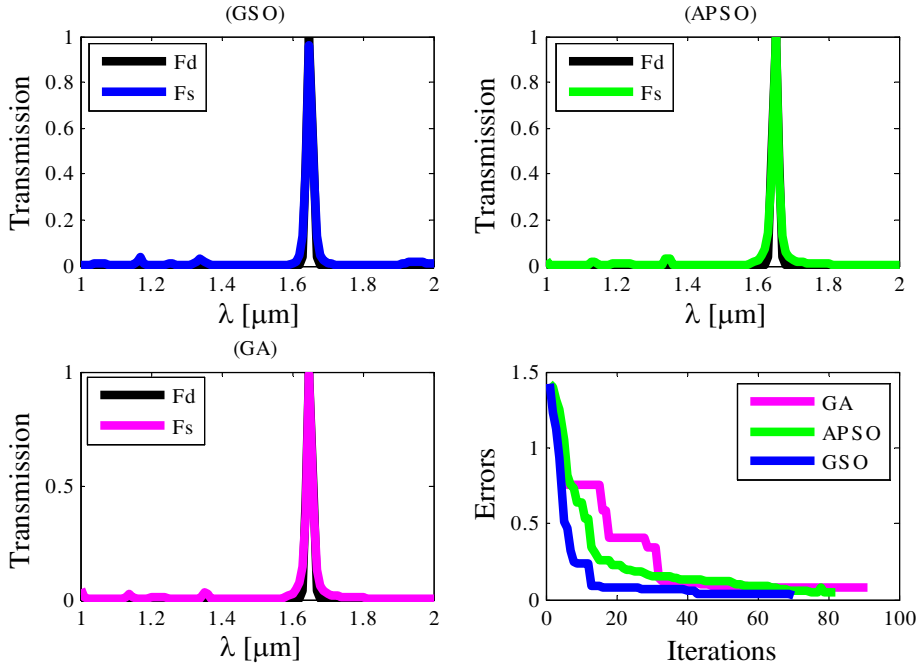

Figure 7. Power transmission spectra at the wavelengths 1.65 μm and their error evolution.

than the GA in terms of error reduction and how fast the algorithm obtained the optimum solution.

For the chosen wavelength λ equal to 1.55 μm, it can be deduced from Figure 6 that the GSO algorithm was the one to provide the lowest error, with IPSO coming a close second. GA produced error an order of magnitude greater than IPSO, so GA produced the worst results.

According to Table 2, GSO is proven to be the fastest among all these algorithms followed by the IPSO and GA.

For the case λ equal to 1.65 µm, GSO produced the lowest error value (0.0316). GA was once again the worst approach with an error equal to (0.0505), and IPSO actually produced the second lowest error value (0.0448). The synthesized function by each algorithm can be seen in Figure 7.

In terms of efficiency, GSO and IPSO performance are higher than GA. GSO is indicated to be the fastest method that converges to the minimum error value, followed by IPSO and then GA.

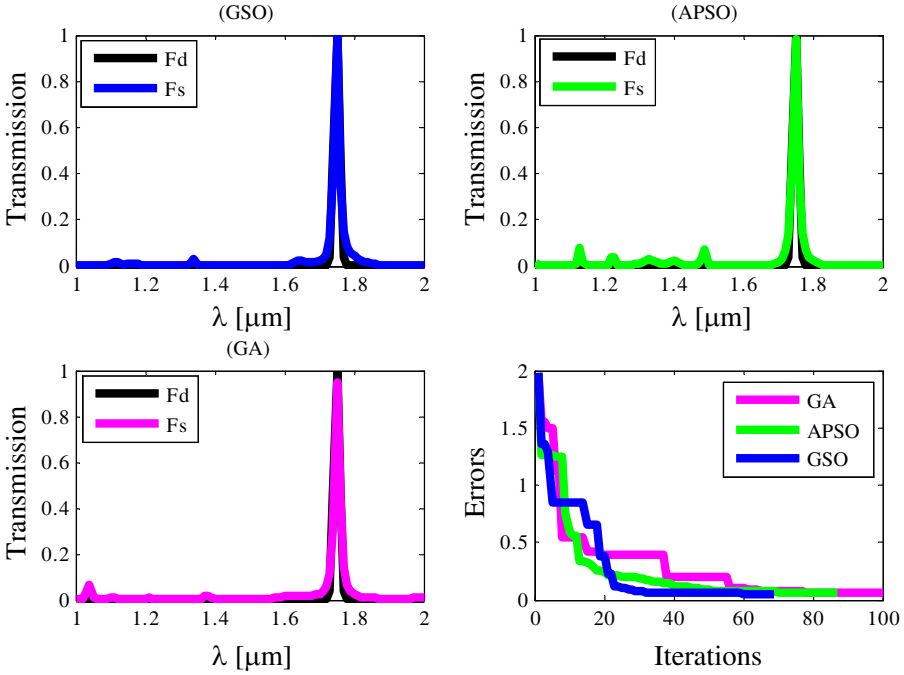

Figure 8. Power transmission spectra at the wavelengths 1.75 µm and their error evolution.

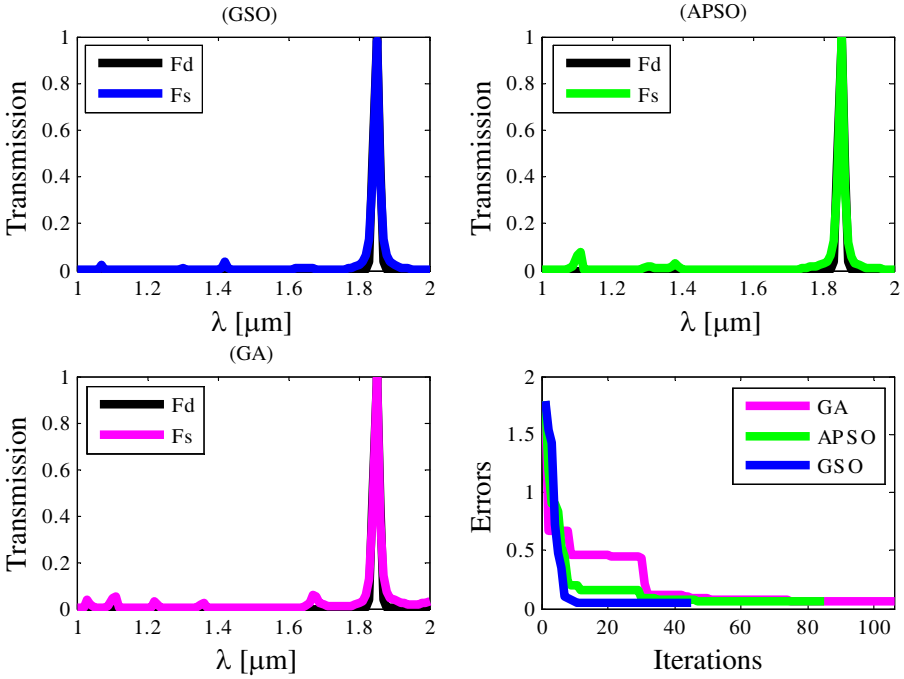

Figure 9. Power transmission spectra at the wavelengths 1.75 µm and their error evolution.

The best performing algorithm for the synthesis of another filter, which must resonate at wavelengths of 1.75 µm, GSO, produced the lowest error value (0.0544). The IPSO algorithm performed quite similarly to GA (0.0639) with an error value equal to (0.0606).

GSO appears to achieve the minimum error value rapidly as compared to IPSO and GA. It was found that IPSO converged faster than GA. Power transmission spectra of the synthesized filters are drawn in Figure 8. The transmission peak amplitude exceeds 99.37%, 98.47%, and 94.50% at 1.75 µm for GSO, IPSO, and GA, respectively, indicating good agreement between obtained and desired results.

Analyzing the results plotted in Figure 9 in this case, the desired wavelength is fixed at 1.85 µm. In this situation, GSO's performance is still much better than other algorithms. Otherwise, GSO uses less running iteration than IPSO and GA. It is observed from Table 2 that optimized error is lower for IPSO than GA. The maximum number of iterations for IPSO is also less than the maximum number of iterations of GA.

In order to evaluate the performance of the proposed algorithms, we compare the numerical results obtained by the applied evolutionary approaches and the simulated annealing [3].

For comparison, eight 1D Photonic crystals are considered. We show the comparison of the power transmission spectra responses for the PhCs-1D filters operating at the desired wavelengths and convergence speed among the three proposed techniques' simulation results and the simulated annealing results in [3]. The simulation results of Table 2 illustrate that GSO, IPSO, and GA produced the best optimization results for all studied cases. In other words, it provides the optimum design and small number of function evaluations compared to those of obtained by the simulated annealing algorithm.

5. CONCLUSION

In this contribution, three evolutionary approaches are introduced and compared to obtain an optimal design of 1D PhCs selective filters. In order to investigate robustness and efficiency of the proposed methods, eight different design specifications are considered. The superiority of the applied algorithms is convincingly shown by comparing the obtained results to the corresponding simulated annealing results. From the achieved results it could be concluded that the genetical swarm optimizer GSO technique seems more efficient and has much better convergence rate than IPSO and GA. On the other hand, the IPSO is better than GA and takes fewer iterations than GA to find the optimal design. Moreover, the hybrid algorithm achieves high effectiveness and efficiency simultaneously.

REFERENCES

1. Qiang, H., L. Jiang, W. Jia, and X. Li, "Design of one-dimensional dielectric and magnetic photonic crystal filters with broad omnidirectional filtering band," *Optica Applicata*, Vol. XLI, No. 1, 63–77, 2011.
2. Chaker, H., H. Badaoui, M. Abri, et al., "Efficient synthesis of dual-band selective filters using evolutionary methods in a 1D photonic crystal slab for near-infrared applications," *J. Comput. Electron.*, Vol. 19, 353–358, 2020.
3. Badaoui, H. A. and M. Abri, "One-dimensional photonic crystal selective filters design using simulated annealing optimization technique," *Progress In Electromagnetics Research B*, Vol. 53, 107–125, 2013.
4. Abdel-Karim, S. O. H., A. S. A. Mohamed, M. M. T. Maghrabi, and N. H. Rafat, "Optimal design of one-dimensional photonic crystal filters using minimax optimization approach," *Applied Optics*, Vol. 54, No. 6, 1399–1409, 2015.
5. Mescia, L., A. Giaquinto, G. Fornarelli, G. Acciani, M. De Sario, and F. Prudenzano, "Particle swarm optimization for the design and characterization of silica-based photonic crystal fiber amplifiers," *Journal of Non-Crystalline Solids*, Vol. 357, Nos. 8–9, 1851–1855, April 15, 2011.
6. Teoh, C. W. and F. A. Rahman, "Synthesis of fiber bragg grating parameters using hybrid optimization algorithm," *Conference on Innovative Technologies in Intelligent Systems and Industrial Applications*, 428–433, Sunway Campus, Malaysia, July 2009.

7. Skaar, J., L. Wang, and T. Erdogan, "On the synthesis of fiber bragg gratings by layer peeling," *IEEE Journal of Quantum Electronics*, Vol. 37, No. 2, 165–173, February 2001.
8. Yang, H., S. Meng, G. Wang, and C. Huang, "The optimization of the dielectric layer photonic crystal filter by the quadratic response surface methodology," *Optica Applicata*, Vol. XLV, No. 3, 369–379, 2015.
9. Hassan, A.-K. S. O., A. S. A. Mohamed, M. M. T. Maghrabi, and N. H. Rafat, "Statistical design centering optimization of 1D photonic crystal filters," *Progress In Electromagnetics Research M*, Vol. 49, 153–165, 2016.
10. Sukhoivanov, I. A. and I. V. Gurye, *Photonic Crystals: Physics and Practical Modeling*, Springer Edition, 2009.
11. Bäck, T., D. Fogel, and Z. Michalewicz (eds.), *The Handbook of Evolutionary Computation*, Oxford University Press/IOP Publishing, New York, NY, 1997.
12. Xie, X.-F., W.-J. Zhang, and Z.-L. Yang, "Adaptive particle swarm optimization on individual level," *IEEE International Conference on Digital Signals Processing*, 1215–1218, Beijing, China, July 1–3, 2002.
13. Grimaccial, F., M. Mussettal, P. Pirinoli, and R. E. Zichl, "Genetical Swarm Optimization (GSO): A class of population-based algorithms for antenna design," *IEEE International Conference on Communications and Electronics*, 467–471, October 2006.
14. Badaoui, H., M. Abri, and H. Chaker, "Optimal selective arbitrary-spaced filters optimization using GA synthesis in one-dimensional silicon photonic crystal," *Silicon*, Vol. 11, 789–795, May 2018.