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DESIGN OF PLANAR EBG STRUCTURES USING CUCKOO SEARCH ALGORITHM FOR POWER/GROUND NOISE SUPPRESSION

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Abstract—This paper deals with the application of a meta-heuristic optimization algorithm, namely the Cuckoo Search Algorithm in design of the electromagnetic band gap (EBG) structures. These EBG structures are employed for the purpose of suppressing power/ground noise in printed circuit boards. A design example of 2D planar EBG structure in the specified frequency band is presented and implemented. The measured results are found to be in good agreement with the simulation as well as the analytical results.

1. INTRODUCTION

The propagation of electromagnetic waves is one of the most critical challenges to the electromagnetic interference; compatibility of any system [1]. Simultaneous switching noise (SSN) on the power/ground (PWR/GND) planes is one of the major concerns for the design of high speed mixed signal systems with faster edge rates, and lower voltage level with high current. The SSN is generated by the propagation of unwanted modes in PWR/GND planes of power delivery network (PDN). Several methods [1–3] have been reported in the literature to deal with this problem. The periodic structure such as an EBG structure can be used to prevent propagation of electromagnetic waves in bandgap (stop band) region. The periodic EBG structures can provide good isolation at specified frequencies on a power/ground plane and are used to improve power integrity (PI) performances in

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printed circuit boards (PCBs) design. This isolation is caused by periodic structures of power or ground plane. The periodic pattern determines the EBG characteristics [1]. The mushroom type periodic EBG structures through vias [2] can be employed for reducing the electromagnetic noise, caused by simultaneous switching of ICs and current flow in PCBs. The planar EBG structures on the other hand are simple to implement and their band gap characteristics are dependent upon the dielectric parameters as well as EBG geometry.

EBG structures have become very useful in high-speed system design. EBG structures are introduced to attenuate power/ground noise or simultaneous switching noise in PCBs. Planar EBG structure consists of two metallic layers, separated by a dielectric substrate. One of these two metallic layers is a solid plane and other one is a patterned plane, periodic nature of EBG unit cells. Stop band characteristics and isolation level are dependent on geometrical parameters of an EBG unit cell and number of cells (patches) respectively. Finally maximum number of patches determines the available board space for EBG design [3]. The geometry of this patterned plane consists of 1-D or 2-D EBG structures. In 2-D EBG structures, patches are connected with bridges in both directions. In planar EBG structure patch is modeled with an inductance and capacitance, whereas bridge is modeled with gap capacitance between metal patches and its inductance. The bandgap limit depends on the geometrical parameters of a planar EBG structure [4, 5].

This paper presents the analysis of planar EBG structures using a meta-heuristic optimization algorithm namely the cuckoo search (CS) algorithm. This is for the first time that the analysis of EBG structure is attempted using CS algorithm. Section 2 recalls analytical expressions for EBG structure design. Section 3 introduces CS algorithm to find optimum dimensions of EBG unit cell for a desired frequency band. Finally Section 4 analyzes the full wave simulation, analytical and measurement results.

2. PLANAR EBG DESIGN

Figure 1 shows the typical geometry of a planar EBG structure. Numbers of square patches are connected with each other by small rectangular connections called bridges. The bandgap parameters, f_{low} and f_{high} are associated with the last resonant mode before the bandgap and first resonant mode after the bandgap region respectively. Here f_{low} is determined by considering the whole EBG cavity, whereas f_{high} depends on single patch cavity [5]. The numerical analysis of this structure has been performed by using finite integration technique (FIT) based solver [6].

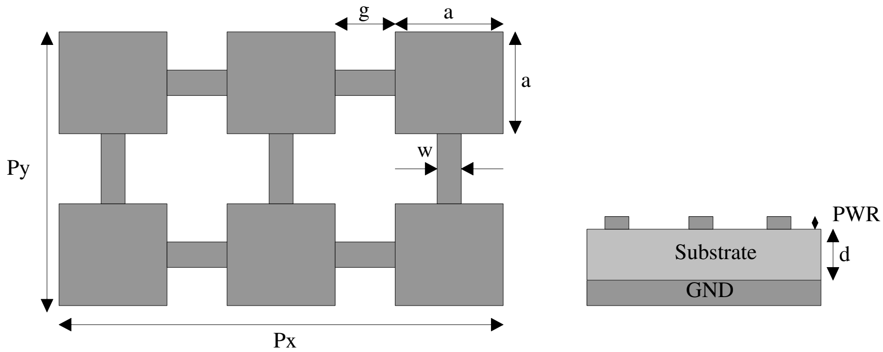


Figure 1. Top and side view of a 3 × 2 planar EBG structure.

The resonant behavior of EBG cavity can be characterized by two adjacent planes having perfect electric conductor boundary conditions at top and bottom walls, and perfect magnetic conductor boundary conditions at the side walls [7]. It is well known [8] that the solutions of the Helmholtz's equation give resonant TM modes as

$$f_{\mathrm{TM}_{z,mn}} = \frac{C_0}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{P_x}\right)^2 + \left(\frac{n\pi}{P_y}\right)^2} \tag{1}$$

where P_x and P_y are the dimensions of the cavity along x and y directions as shown in Fig. 1. Here TM_z identifies the constant electric and magnetic fields along the z direction. The upper limit of bandgap, f_{high}, is the first resonant mode of cavity due to single patch and is dependent upon the patch dimension. It can be calculated as [5]:

$$f_{high} = \frac{C_0}{2 * \max(a, b)\sqrt{\varepsilon_r}} \tag{2}$$

where a and b are the dimensions of the patch along x and y directions, respectively. The lower limit of the bandgap region, f_{low}, is associated with the dimensions of planar EBG structure. A loop inductance (L_{patch}) can be calculated for each patch in the x and y directions. The value of L_{patch} of a parallel plate transmission line approximation is given as [5]:

$$L_{patch,x} = \mu_0 d\frac{a}{b}, \quad L_{patch,y} = \mu_0 d\frac{b}{a} \tag{3}$$

For a square patch, $L_{patch,x} = L_{patch,y}$. Here, M number of patches and $(M - 1)$ number of bridges are considered in x direction, whereas N number of patches and $(N - 1)$ number of bridges are considered in y direction. Total inductance (L_{Tot}) along x and y directions can be calculated as [5]

$$L_{Tot,x} = \mu_0 d \frac{P_x}{a} = M L_{patch,x} + (M-1) L_{bridge} \tag{4a}$$

$$L_{Tot,y} = \mu_0 d \frac{P_y}{a} = N L_{patch,y} + (N-1) L_{bridge} \tag{4b}$$

The bridges are connected between patches. Substituting the value of P_x and P_y in Equation (1)

$$f_{flow} = \frac{C_0}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{M-1}{P_x}\right)^2 + \left(\frac{N-1}{P_y}\right)^2} \tag{5}$$

Assuming zero thickness strips, L_{bridge} can be calculated by using bridge length (l), bridge width (w), and dielectric thickness (d) [5]:

$$L_{bridge} = \begin{cases} l\frac{60}{C_0} \ln\left(\frac{8d}{w} + \frac{w}{4d}\right) & \frac{w}{d} \leq 1 \\ l\frac{120\pi}{C_0} \left[\frac{w}{d} + 1.393 + 0.667 \ln\left(\frac{w}{d} + 1.444\right)\right]^{-1} & \frac{w}{d} \geq 1 \end{cases} \tag{6}$$

Conditions for designing a planar EBG structure are: the bridge width (w) can't be equal or greater than the patch dimensions and to calculate L_{bridge}, w must be greater than the metal thickness (t).

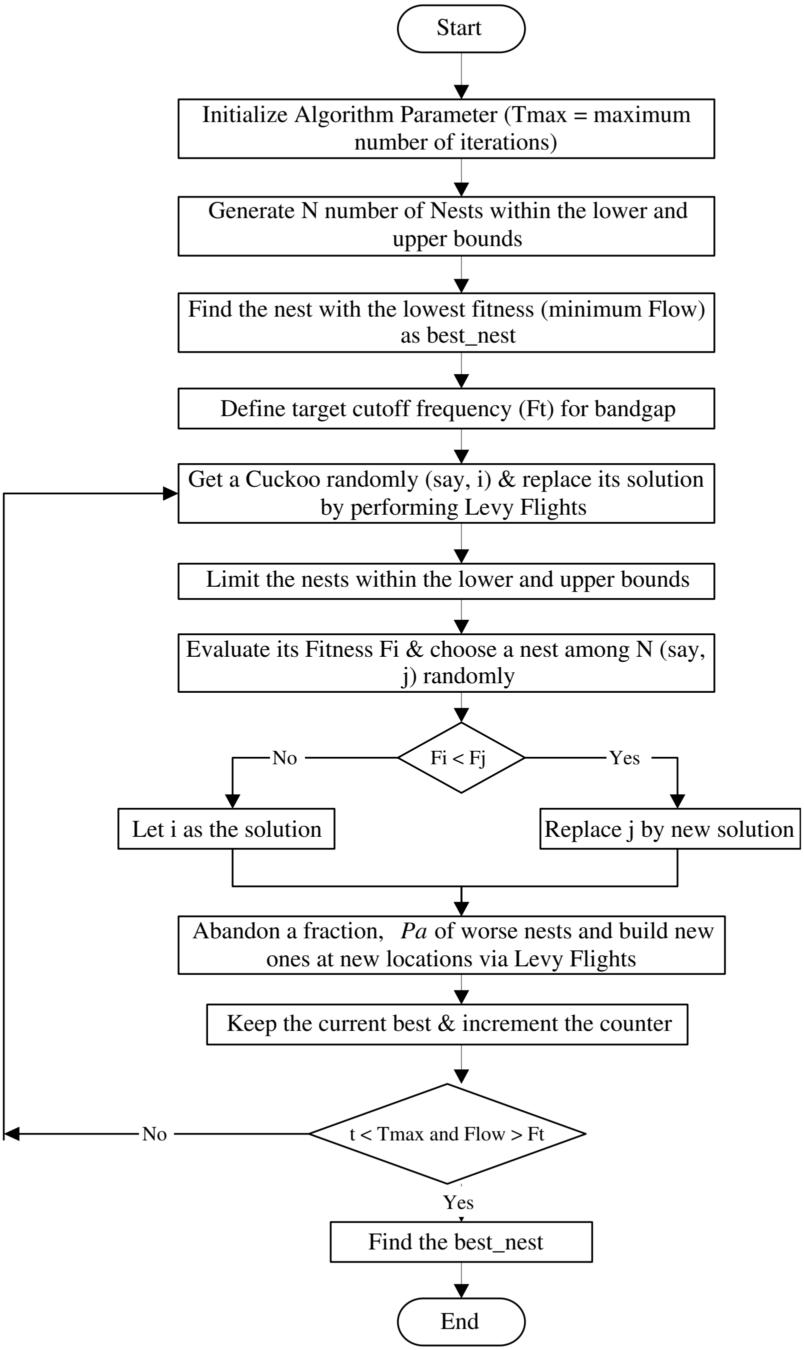
3. CUCKOO SEARCH ALGORITHM

3.1. Theory

Cuckoo Search (CS) is a meta-heuristic optimization technique belonging to Swarm Intelligence (SI) family, developed by X. S. Yang and S. Deb in 2009 [9]. This algorithm is inspired by the cuckoo bird breeding behavior. Generally cuckoo birds lay their eggs in the nest of the host birds. In CS method, cuckoo eggs represent solutions for desired objective function. Yang and Deb discovered Levy flights, a random walk whose step size is determined by Levy distribution. CS is based on three rules [10]:

- Each cuckoo lays one egg at a time, and dumps its egg in a randomly chosen nest.
- The best nests with high quality of eggs will carry over to the next generation.
- The number of available host's nests is fixed, and the egg laid by a cuckoo is discovered by the host bird with a probability $p_a \in (0, 1)$. Discovering operates on some set of worst nests, and discovered solutions are dumped from farther calculations.

3.2. Flow Chart



3.3. Optimization

Planar EBG structures are used in power delivery network (PDN) in PCBs at high frequencies. In the past, several EBG structures are developed for various applications such as mobile phones, GPS and WLAN etc and Genetic Algorithm (GA) and Particle swarm optimization (PSO) techniques have been used for analysis of EBG structures [11, 12]. In this paper, for the first time a meta-heuristic CS optimization algorithm has been employed for designing an EBG structure at desired frequency range. The motivation behind using CS is in many folds. First of all, the CS algorithm is a nature inspired metaheuristic algorithm and is applicable to a wider class of optimization problems. Secondly, in comparison to other metaheuristic algorithms such as particle swarm optimization (PSO), genetic algorithm (GA), fire fly (FA), differential evolution (DE) and ant colony optimization (ACO), it is simplest in implementation as it employs single parameter apart from population size [9]. Lastly, it also has excellent convergence property and capability to offer high quality solution. The comparison of CS, PSO, DE and ACO is very well presented and statistically tested [13] over 50 different benchmark functions to demonstrate the significance of CS. Further the comparison of CS with PSO and FA in terms of convergence and runtime is presented in [14] to obtain global optimum result. For applying CS algorithm, the parameters or variables selected are shown in Table 1.

4. RESULTS

The minimum value of the lower cutoff frequency for bandgap at given frequency range is defined as the objective function in CS algorithm. The dimensions of EBG unit cell parameters and number of patches along x and y directions are found by CS. For 25 iterations of CS

Table 1. Parameters range for EBG design. (All units are in mm.).

	Unit Cell Parameters	Range
1.	Patch size (a)	$\langle 5:25 \rangle$
2.	Bridge length (g)	$\langle 0.2a:0.4a \rangle$
3.	Bridge width (w)	$\langle 0.05a:0.5a \rangle$
4.	Patches in x direction (M)	$\langle 2:10 \rangle$
5.	Patches in y direction (N)	$\langle 1:10 \rangle$

optimization algorithm 25 random entities/nests are considered. A prototype model is developed on FR4 substrate of permittivity ($\varepsilon_r = 4.4$), and dielectric thickness ($d = 1.6\,\text{mm}$) for measurement purpose. Matlab code for CS algorithm has been implemented for the frequency range (1.5 to 2 GHz). Fig. 2 depicts the convergence behavior. After 25 iterations the optimization code gives $f_{low} = 1.53\,\text{GHz}$ and $f_{high} = 3.86\,\text{GHz}$, the dimensions of EBG unit cell are obtained as $b = 18.5\,\text{mm}$, $g = 7.4\,\text{mm}$, $w = 0.9\,\text{mm}$, $M = 2$, $N = 4$.

A planar EBG structure has been implemented using meta-heuristic optimization algorithm, named firefly algorithm (FA) to mitigate SSN in PCBs [15]. Fig. 3 shows the comparison of CS with FA in terms of convergence. The advantage of using CS algorithm over

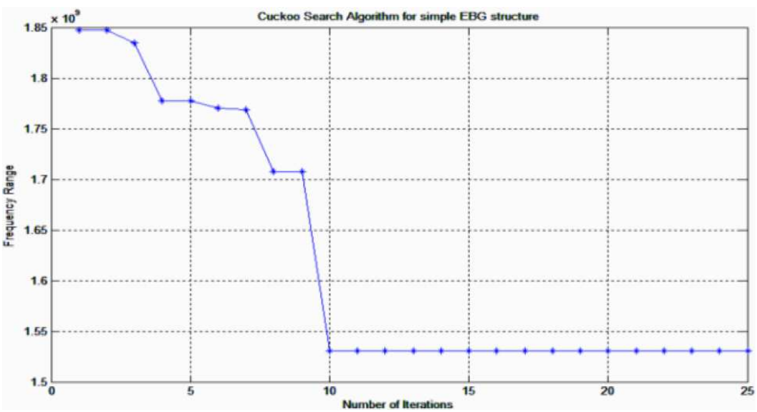


Figure 2. Convergence of cuckoo search algorithm.

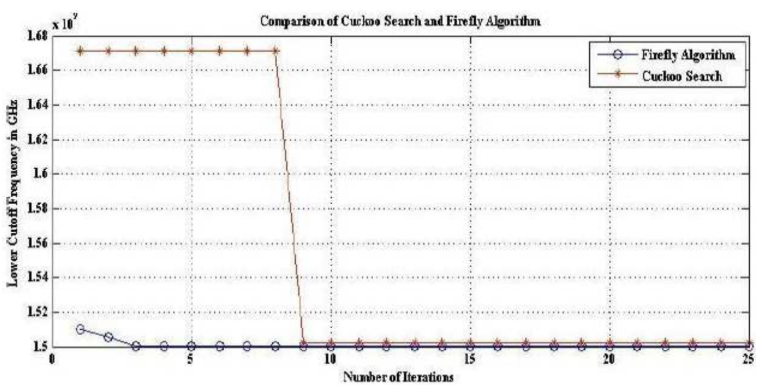


Figure 3. Convergence of CS and FA.

FA is demonstrated here. As seen, CS takes nearly less than half of the time taken by FA to execute optimization algorithm code. Table 2 shows the execution time comparison of CS with FA. For 25 iterations of CS and FA optimization algorithm 25 random nests/fireflies are considered. Both CS and FA have been implemented for the same frequency range (1.5 to 2 GHz).

A full wave solver [6] is employed for designing a 2×4 planar EBG structure. The ports are located at P_1 (8, 8) and P_2 (88, 36) on EBG plane. Fig. 4 shows the top and bottom view of a fabricated planar EBG structure. The simulated S parameter ($|S_{21}|$ in dB) results for the two cases are shown in Fig. 5. A remarkable improvement in reflection loss parameter is obtained in the frequency range from 1.6 GHz (f_{low}) to 3.6 GHz (f_{high}) for EBG structure employed in the power plane.

Table 2. Timing comparison of CS and FA.

Number of times MATLAB code runs	Cuckoo Search Algorithm (time in ms)	Firefly Algorithm (time in ms)
1	68.37	167.52
2	66.93	175.44
3	67.91	178.41
4	67.36	169.19
5	68.67	178.85

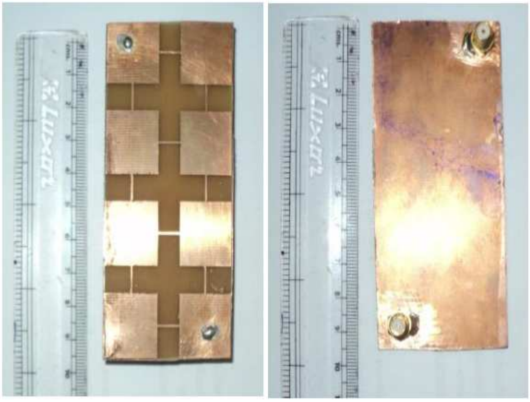


Figure 4. Top and Bottom view of the prototype model (2×4 planar EBG structure).

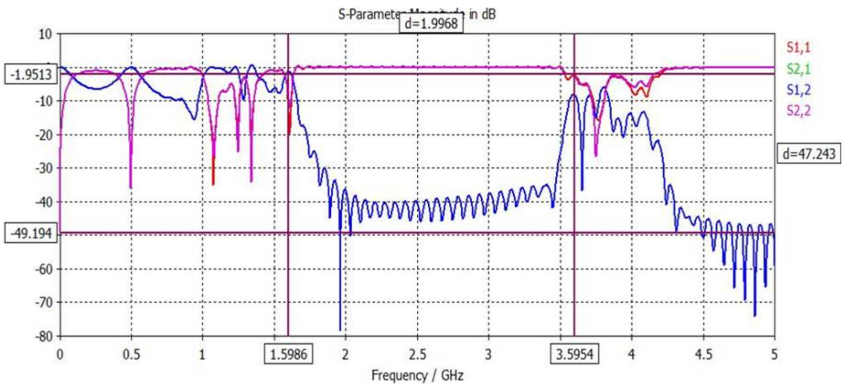


Figure 5. $|S_{21}|$ of a power plane with & without EBG structure.

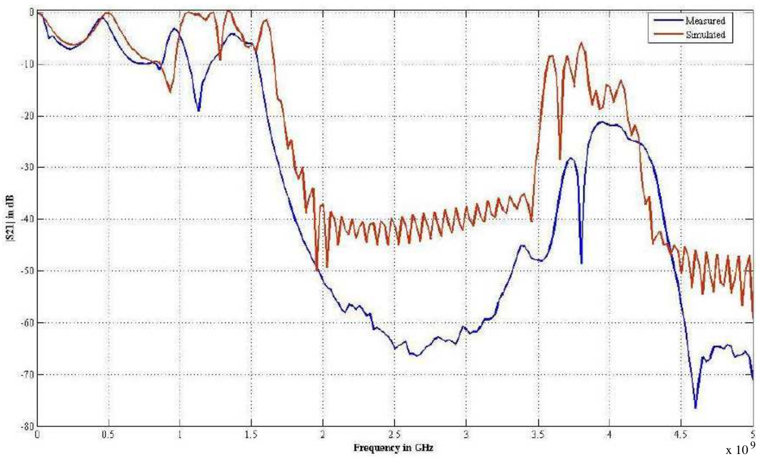


Figure 6. Comparison of simulation and measurement results.

A comparison of the simulation and measurement results as shown in Fig. 6, depicts good agreement between the two.

5. CONCLUSION

The performances of the PDN impedance in presence of an EBG structure have been studied. CS algorithm is applied successfully to find optimum dimensions of EBG plane at desired frequency range. The planar EBG structure can be employed for reducing PWR/GND noise in PCBs. The measured results have been found to be in good agreement with the simulation as well as analytical results.

REFERENCES

1. Shahparnia, S. and O. M. Ramahi, "Electromagnetic interference (EMI) reduction from printed circuit boards (PCB) using electromagnetic bandgap structures," *IEEE Transactions on Electromagn. Compat.*, Vol. 46, No. 4, 580–587, 2004.
2. Paulis, F. D. and A. Orlandi, "Signal integrity analysis of single-ended and differential striplines in presence of EBG planar structures," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 9, 554–557, 2009.
3. Swaminathan, M. and A. E. Engin, *Power Integrity Modeling and Design for Semiconductors and Systems*, Prentice-Hall, Englewood Cliffs, NJ, 2007.
4. Paulis, F. D., L. Raimondo, A. Orlandi, L. Ren, and J. Fan, "Equivalent circuit models for evaluation of bandgap limits for planar electromagnetic bandgap structures," *IEEE International Symposium on Electromagnetic Compatibility (EMC)*, 770–775, 2010.
5. Raimondo, L., F. D. Paulis, and A. Orlandi, "A simple and efficient design procedure for planar electromagnetic bandgap structures on printed circuit boards," *IEEE Transactions on Electromagn. Compat.*, Vol. 53, No. 2, 482–490, 2011.
6. Computer Simulation Technology, *CST Studio Suite.*, 2011, Available: http://www.cst.com/.
7. Lei, G. T., R. W. Techentin, and B. K. Gilbert, "High-frequency characterization of power/ground-plane structures," *IEEE Trans. on Microw. Theory Tech.*, Vol. 47, No. 5, 562–569, 1999.
8. Pozar, D. M., *Microwave Engineering*, 3rd Edition, John Wiley & Sons, New York, 2004.
9. Yang, X. S. and S. Deb, "Cuckoo search via levy flights," *World Congress on Nature and Biologically Inspired Computing (NaBIC 2009)*, 210–214, 2009.
10. Yang, X. S. and S. Deb, "Engineering optimization by cuckoo search," *Int. J. Mathematical Modeling and Numerical Optimisation*, Vol. 1, No. 4, 330–343, 2010.
11. Kim, T. H., M. Swaminathan, A. E. Engin, and B. J. Yang, "Electromagnetic band gap synthesis using genetic algorithms for mixed signal applications," *IEEE Trans. on Adv. Packg.*, Vol. 32, No. 1, 13–25, 2009.
12. Kovacs, P. and Z. Raida, "Global evolutionary algorithms in the design of electromagnetic band gap structures with suppressed surface waves propagation," *Radio Engineering*, Vol. 19, 122–128,

2010.

13. Civicioglu, P. and E. Besdok, "A conceptual comparison of the cuckoo-search, particle swarm optimization, differential evolution and artificial bee colony algorithms," *Artificial Intelligence Review*, 2011, DOI 10.1007/s10462-011-9276-0.
14. Tripathi, J. N., N. K. Chhabra, R. K. Nagpal, R. Malik, and J. Mukherjee, "Damping the cavity-mode anti-resonances' peaks on a power plane by swarm intelligence algorithms," *IEEE International Symposium on Circuits and Systems (ISCAS)*, 361–364, 2012.
15. Pani, P. R., R. K. Nagpal, R. Malik, and N. Gupta, "Mitigation of simultaneous switching noise on EBG planes using firefly algorithm," *International Conference on Communication, Information & Computing Technology (ICCICT)*, 1–4, 2012.