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Research Article

Evolutionary Algorithm Geometry Optimization of Optical Antennas

Ramón Díaz de León-Zapata,[1,2] Gabriel González,[2] Efrén Flores-García,[1] Ángel Gabriel Rodríguez,[2] and Francisco Javier González[2]

[1] *Instituto Tecnológico de San Luis Potosí, Avenida Tecnológico s/n, 78376 Soledad de Graciano Sánchez, SLP, Mexico*
[2] *Universidad Autónoma de San Luis Potosí, Álvaro Obregón 64, 78000 San Luis Potosí, SLP, Mexico*

Correspondence should be addressed to Ramón Díaz de León-Zapata; ramondz@hotmail.com

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Printed circuit antennas have been used for the detection of electromagnetic radiation at a wide range of frequencies that go from radio frequencies (RF) up to optical frequencies. The design of printed antennas at optical frequencies has been done by using design rules derived from the radio frequency domain which do not take into account the dispersion of material parameters at optical frequencies. This can make traditional RF antenna design not suitable for optical antenna design. This work presents the results of using a genetic algorithm (GA) for obtaining an optimized geometry (unconventional geometries) that may be used as optical regime antennas to capture electromagnetic waves. The radiation patterns and optical properties of the GA generated geometries were compared with the conventional dipole geometry. The characterizations were conducted via finite element method (FEM) computational simulations.

1. Introduction

Printed circuit antennas which have been extensively used in the radio frequency (RF) spectrum have also been used to detect electromagnetic radiation at optical and infrared frequencies. The use of these types of antennas at optical frequencies provides several advantages over traditional optical and infrared detectors; among these advantages are low profile, low cost, faster response times, compatibility with integrated circuit technology, and wavelength and polarization selectivity [1, 2].

Even though several RF antenna designs have been successfully used at optical and infrared frequencies [3], the design of antennas at optical frequencies by using traditional RF antenna design rules can result in nonoptimized antennas due to the dispersion of material properties that can be neglected at lower frequencies [4, 5].

Evolutionary algorithms imitate nature, where all living organisms possess specific genetic material which contains information about each organism that can be transferred to new generations via reproduction. The other organism involved in reproduction also transfers some of its characteristics [6]. These characteristics are encoded in genes stored in chromosomes, which together constitute the genetic material known as a genotype [7]. Genes are modified during the characteristic transfer process as a consequence of the crossover between maternal and paternal chromosomes. Mutation may also occur, altering the information contained within the genes of a given chromosome. Although the newly created individual possesses the information of its parents, the combination of two different organisms makes the individual unique. This organism begins life in an environment that is not significantly different from that of its parents. The new organism develops in a manner that allows it to survive and transfer its genome, permitting the species to persist in a given environment. An individual that cannot adapt to its environment will struggle to survive and transfer its genes to new generations.

These evolutionary processes can be used to optimize the solution of nonanalytical problems assuming that the environment is defined based on known values and characteristics. The evolved individual or the whole evolved population can constitute the potential solution to a given problem [8–11].

An adequate mathematical function must be chosen to define the fitness of any given individual representing how well adapted they are to their environment. Exchange of genetic materials and mutations will occur during the genetic crossover process. Thus, an optimal solution will be created that best suits a given environment.

These algorithmic techniques allow the exploration of unconventional geometries or combination of materials that can be used in the design of nanophotonic circuits and devices for diverse applications [12].

In this work, a genetic algorithm (GA) is used to obtain the geometry that optimally concentrates the electromagnetic field of a dipole-type nanoantenna at a resonance frequency of 500 THz, which can be varied based on the nanostructure dimensions. The nanoantenna radiation pattern was obtained via computational simulations and compared to a classical dipole geometry.

2. Method

The most basic and general type of genetic algorithm called "Holland Genetic Algorithm" proposed by Henry Holland [13] was used. The flow diagram of the genetic algorithm is presented in Figure 1. It starts with an initial random population's chromosomes (population is equivalent to the geometry coordinates and the chromosomes are their values in this work). A loop is implemented to evaluate repeatedly the fitness of chromosomes in the population where only those with better health survive and can combine their chromosomes to produce new individuals. Some genetic operators like random mutation are inserted at this point only to certain percentage of the new individuals, just like in biological specimens. The loop ends when a stopping criterion is achieved; it can be the number of iterations, level of health, and so forth, and this final stage has the best chromosome (or solution).

Various studies, such as [8, 11], have applied this algorithm to multiple problems, where the resulting optimized geometries are different from classical macroscopic antennas, as shown in Figure 2.

Figure 2(a) illustrates a significant electromagnetic field concentration increase, but the active antenna area also increased. Therefore, the obtained geometry efficiencies cannot be directly compared due to the effective antenna area increase. Figure 2(c) represents a series of macroscopic antenna simplifications, which are not applicable at the nanoscale. Thus, this final geometry does not offer a viable alternative for the type of nanoantennas that we wish to analyze and eventually fabricate.

The authors assume a specific preestablished antenna area based on the desired resonance frequency. The geometry is then modified using the evolutionary algorithm as a malleable material. No empty regions are added, and a solid shape is sought which achieves a maximum electromagnetic field concentration at the center of the nanostructure.

This algorithm has been successfully applied to multiple problems; the results show that the resulting optimized geometries are different from classical RF antennas [8, 11].

The genetic algorithm was programmed in MATLAB where a link was made to COMSOL Multiphysics where the electromagnetic simulations were performed and the results were returned to MATLAB where the fitness function was evaluated. Iterative changes or adjustments are then made to optimize the solution, and the new proposed nanostructure is analyzed using COMSOL until a fixed number of iterations was achieved.

The genetic algorithm performs the nanostructure analysis required to suggest a geometry that approaches the optimal design conditions, assuming a (two-dimensional) flat nanostructure. The solution space is constrained to dimensions near the optical wavelength for an antenna irradiated by a normal incident electromagnetic wave. The main parameters required by the genetic algorithm, such as the dimensions of the simulation space (maximum size of the antenna), number of chromosomes (number of individuals to be analyzed), chromosome resolutions (quality), overlap between generations (mortality index), mutation rate (as a percentage), and mating rules, must be input by the user.

Figure 3 illustrates the MATLAB and COMSOL processes, which together comprise the genetic algorithm.

The Bézier curve control points, which are modeled as chromosomes, are used to obtain the optimized geometry of the dipole-type nanoantenna. A total of 10 lines are set, including 4 with two Bézier control points, 4 with only one, and 2 straight lines with no control points. The lines with no control points represent the section where the electromagnetic field is applied to the nanoantenna. The algorithm execution stops if the average loss in the electric field is zero or if the iterative limit is reached, which is based on the number of generations [14].

The fitness function [15] is shown in (1). The function should accept a vector, whose length is the number of independent variables, and return a scalar. This function must accept a vector of length 24, corresponding to the variables (points in x and y coordinates) that conform the geometry (which includes the straight and Bézier lines), and return a scalar equal to the value of the function that represents the value of the electromagnetic power loss density for such geometry. By minimizing this equation (minimizing losses), we can find the strongest electromagnetic field. As an application example, the optimized fitness function calculates the minimum loss (optimization function) of the electromagnetic field at a frequency of 500 THz and is a parameter that COMSOL submits to MATLAB, which then evaluates it using the genetic algorithm function:

$$F_{\text{Fitness}} = \min\left(\frac{1}{2}\operatorname{Re}\left(\mathbf{J}_{\text{tot}} \cdot \mathbf{E}_{\text{tot}}\right)\right), \quad (1)$$

where $\mathbf{J}_{\text{tot}}$ is the total electric current density over the whole geometry shown in

$$\mathbf{J}_{\text{tot}} = \sigma\mathbf{E}. \quad (2)$$

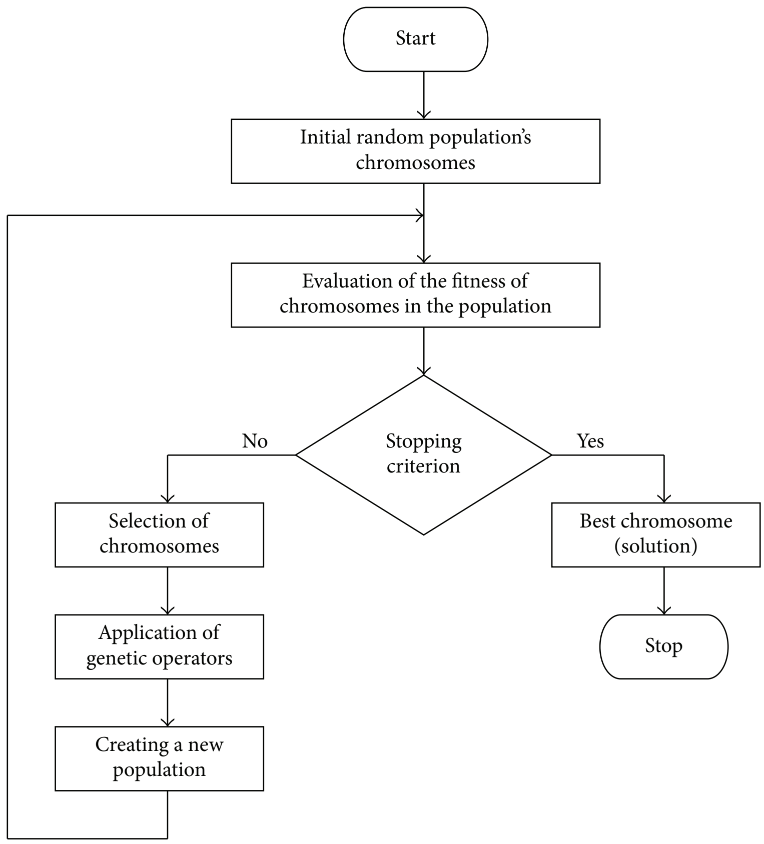

FIGURE 1: Flow diagram of the genetic algorithm.

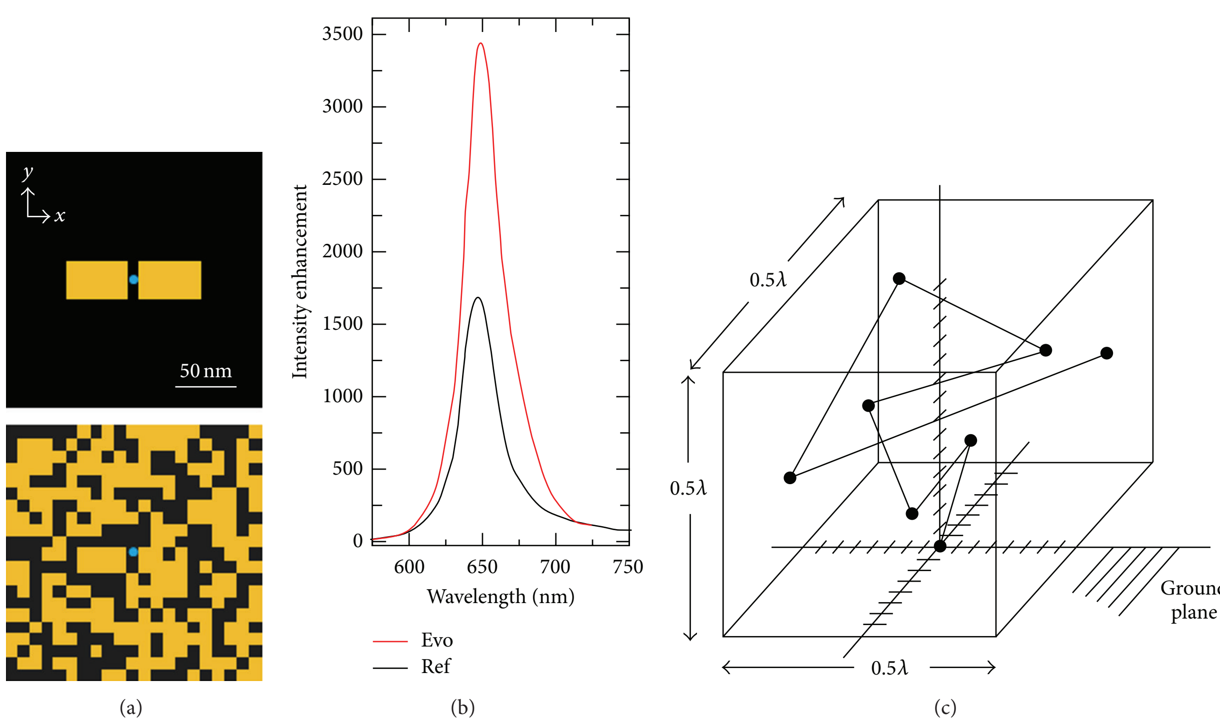

FIGURE 2: (a) Top: reference classical dipole. Bottom: geometry generated by the genetic algorithm. (b) Efficiency comparison between the reference antenna and that generated by the genetic algorithm, taken from [11]. (c) Geometric model obtained using the evolutionary algorithm, taken from [8].

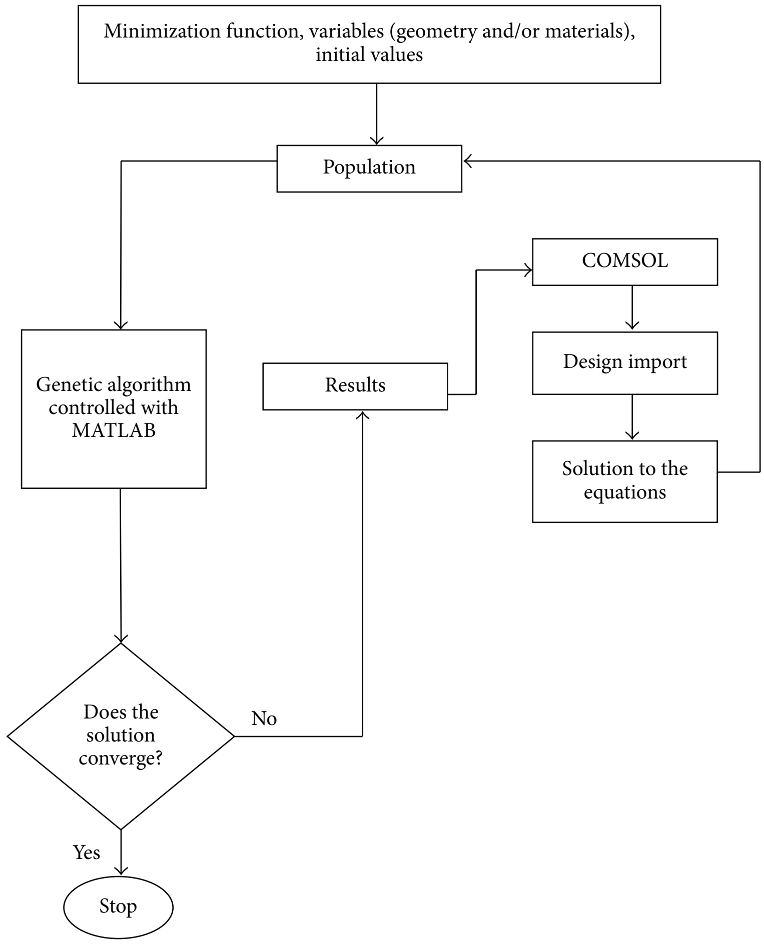

Figure 3: Flow diagram of the application process, noting the links between the COMSOL and MATLAB software packages.

σ is the electrical conductivity and $\mathbf{E}_{\text{tot}}$ is the electric field over the whole geometry shown in

$$\mathbf{E}_{\text{tot}} = \left(\mu_0 \int \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right) d\mathbf{a}\right). \tag{3}$$

The refractive index in the optical regime of operation in the nanostructured materials (metamaterials) becomes a function of frequency [5].

A geometric model with 12 Bézier curve control points, plus 11 fixed points which represent the geometry limits (noting the first point is also the last one to have a closed geometry), is found during the first iteration, based on steady-state initial conditions, 100 chromosomes, a 50% intergeneration overlap, and a 1% mutation rate. In addition, a single crossover point was used, which can occur between any pair of segments in the chromosome with equal probability. Figure 4 shows the superposition of the geometry as it evolves. Figure 5 plots the electric field power loss as it approaches zero. Values after the fourth population generation, which rapidly decrease from $1.3e^{-7}$ nW/m^2 to $8e^{-15}$ nW/m^2, cannot be detected due to scale limitations.

The geometry obtained at the end of the genetic algorithm execution is shown in Figure 6(a). Figure 6(b) illustrates the data point at which the maximum optical energy absorption-emission is obtained in the terahertz range.

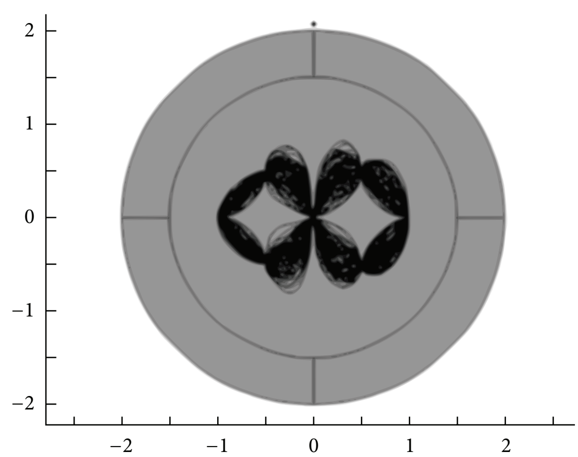

Figure 4: Lines demonstrating the geometry modification process due to mutations when applying the genetic algorithm.

According to the results obtained by [8, 11] and the resulting geometry in Figure 6(b), the geometries obtained

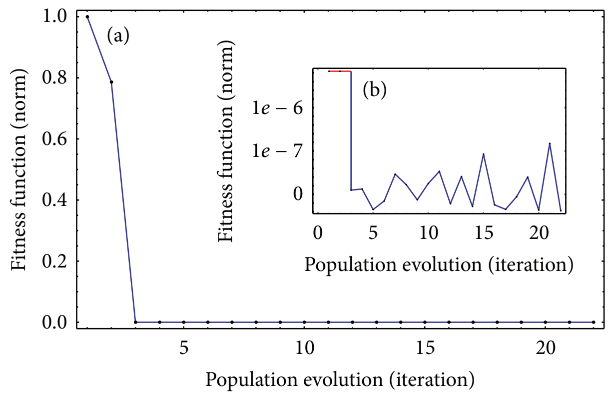

FIGURE 5: (a) Plot showing the trend toward zero of the electromagnetic field loss after each new population generation. (b) Data trends for a zoomed portion of the main plot.

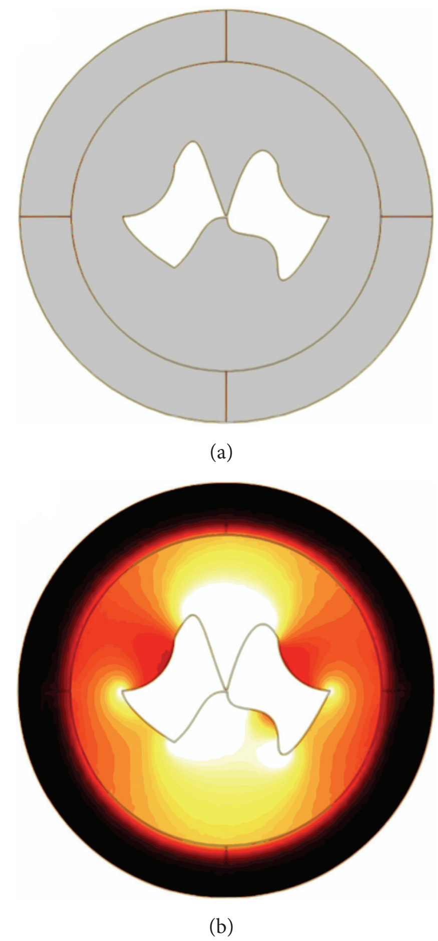

FIGURE 6: (a) Geometry obtained after the genetic algorithm optimization function application. (b) Finite element method simulation of the nanostructure electromagnetic radiation pattern.

by the genetic algorithms represent improvements over the classical or conventional radiofrequency antenna geometries. These geometries were obtained at reduced computer costs and over a shorter processing time compared with traditional analytical processes or trying wide classical RF geometries one by one.

3. Results

Many studies use analogies between nanostructure geometries and conventional radiofrequency macroscopic antenna geometries based on the assumption that their behaviors can be extrapolated to optical frequencies as in [16]. However, the proposed computational model demonstrated that nanoantenna geometries require further study. The nanoantenna shape analyzed in this study does not feature a conventional geometry, such as those utilized for the radiofrequency range. Figure 7 shows a comparison between the classical dipole (a), the dipole generated by the algorithm after the first iteration (b), and the final geometry, which is based on the lowest electromagnetic field loss at the dipole center (c). Figure 7(a) is a theoretical dipole which fully covers the area proposed to evolve our geometry, demonstrating that increasing area does not increase the electromagnetic field even at their (Figure 7(a)) own resonant frequency.

Figure 8 compares the electromagnetic field intensities of the classical dipole and the geometry generated by the genetic algorithm. The results obtained via the genetic algorithm represent an optimal concentration, and both geometries encompass the same effective area. Compared to Figure 2(b), Figure 8 shows an increase in the electromagnetic signal and the effective bandwidth, with the difference that the area remained the same; as an added advantage, the GA design presented in this work is simpler than the one shown in Figure 2(a); therefore, the fabrication process would also be simpler. The peaks of both plots represent the dipole resonance frequencies. From Figure 8, with an increase from 0.4 for non-GA dipole to 0.93167 for GA dipole at resonant frequency in the antenna response (a difference of about 0.536), we found that the geometries obtained by the genetic algorithm provided a 33% better result than the classic dipole geometry and with the bandwidth for non-GA dipole being about 39 THz (from 481 to 520 THz) and for the GA dipole about 48.7 THz (from 475.6 to 524.4 THz) it was increasing the bandwidth by 25%.

4. Conclusions

The classical or conventional dipole-type antenna geometries (in the radiofrequency regime) do not encompass the maximum electromagnetic field concentration (in the optical regime). This is due to the intrinsic differences between electron and photon behaviors. In addition, many macroscopic antenna assumptions and simplifications are not applicable for nanoscale optical frequency regimes because the electromagnetic wavelength is comparable to or even shorter than the antenna dimensions. Thus, a new refractive index function is introduced which defines the electromagnetic field behavior at such frequencies.

The proposed alternative genetic algorithm was applied to improve dipole geometry while accounting for the nanoscopic scale properties of these structures. Our results

FIGURE 7: Electromagnetic field concentration comparison according to the geometry. Panel (a) shows a classical dipole; (b) shows the first iteration of the genetic algorithm; and (c) shows the final geometry, which is based on the maximum electromagnetic field concentration at the center of the nanostructure.

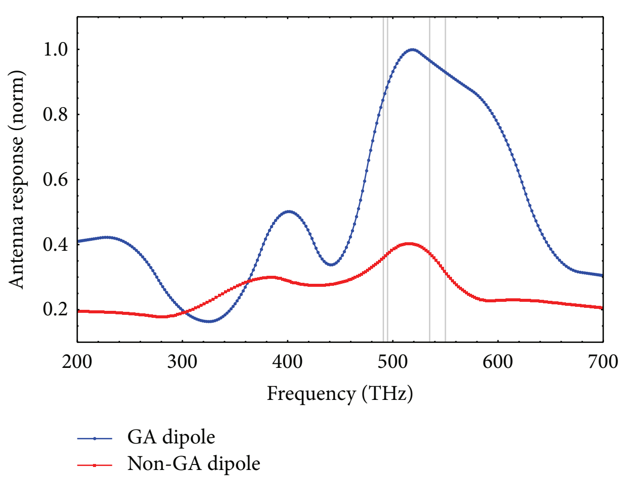

FIGURE 8: Electromagnetic field concentration comparison between the classical dipole geometry and that generated by the genetic algorithm.

demonstrate that the final nanoantenna shape is significantly different than the classical case in the context of providing the optimal electromagnetic field concentration.

The results of this study will be used in future nanostructure fabrication and characterization studies using two materials with different Seebeck coefficients (one positive and one negative). The materials will generate maximum heating in the region of interest, producing a direct electric current [17] that can be stored in batteries for subsequent use. This will contribute to the creation of renewable energy devices.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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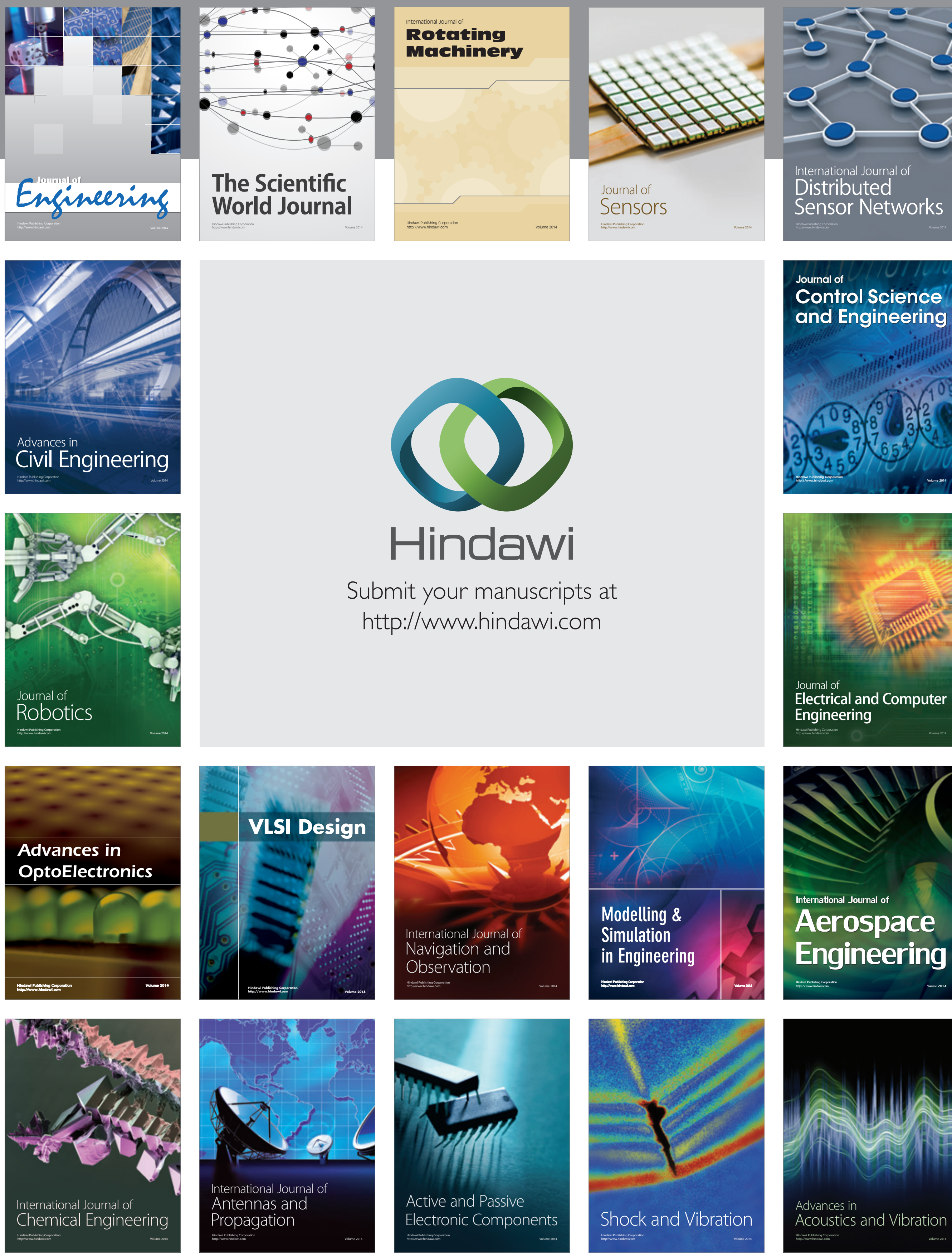
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