Unconstrained Evolution of Close-to-ideal "LCR" Low-pass filter

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Abstract – **The unconstrained evolution has already been applied in the past towards design of digital circuits, and extraordinary results have been obtained, including generation of more compact circuits with smaller number of electronic components. In this paper the unconstrained evolution method is developed for analogue circuits. At first, the method is probed on the design of analogue low-pass filter with standard transition band. The algorithm produced the best results in terms of quality of the circuits evolved and evolutionary resources required. Then, the new methodology is applied towards more sophisticated task, the close-to-ideal low-pass filter. The new methodology developed differs from previous ones by its simplicity and represents one of the first attempts to apply Evolutionary Strategy towards the analogue circuit design. The obtained results are compared in details with low-pass filters previously designed.**

I INTRODUCTION

Evolvable Hardware (EHW) is one of the most promising areas of today's electronics. Evolutionary Algorithm (EA) applied towards reconfigurable hardware enables to find a solution among global solution space. The EHW where the ultimate goal is a circuit design is also referred as Evolutionary Electronics [3]. The Evolutionary Electronics gives an alluring opportunity for an amateur in the field to reach out the same results as professional one, possessing mostly the knowledge of Darwinian's laws and inspiration. The EA, navigated by a fitness values, provides randomly created and mutated chromosomes. Each chromosome encodes the structure for a circuit and has to be evaluated by a fitness function assigning a fitness value. The last one shows how close the current hardware structure by its behavioral and circuit characteristics to the required one. The circuits evolved may have unconventional designs and less of all depend on personal knowledge of a designer [1]-[9].

For instance, using simulation software (extrinsic EHW), low-pass filters [1]-[6] and amplifiers [2]-[4], [7] are successfully designed with the help of EA. In [11] the unconstrained evolution, both spatially and temporally, has been applied intrinsically towards the digital FPGA-based reconfigurable hardware. By releasing the full repertoire of behaviors that FPGA can manifest, namely, allowing any connections among modules, letting the evolution to evolve the granularity of modules as well as the regimes of synchronization, evolution has been able to find a highly efficient electronic structure, which requires 1-2 orders less silicon area to achieve the same performance as conventional design does. Once fully unconstraining the design methodology rules, the natural behavior of analogue elements started to be exploited inside a circuit [11].

In analogy to this approach, the unconstrained evolution could be applied towards the originally analogue circuits. In this sense, the range of circuit-structure-checking rules at the netlist composition stage, prohibiting the invalid circuit graphs, are regarded as the main constraints for the design methodology. In this paper, we consider unconstrained extrinsic evolution for analogue "LCR" circuit design of low-pass filter with 1kHz transition band. We utilize the simplest oscillating length genotype (OLG) sweeping strategy [2] that together with unconstrained evolution produces much better results that previously achieved. Then, the new developed method is applied towards more sophisticated task, the design of low-pass filter with 0.4kHz transition band.

The paper is organized as follows. The next section gives an overview of previous work in the area. Section III describes the problem to be evolved. Section IV introduces the unconstrained evolutionary technique. Section V describes the experimental results. Section VI compares the obtained results with the filters evolved previously as well as designed conventionally. And, finally, the last section concludes the paper.

II PREVIOUS WORK

As well as in any evolutionary search, in electronic circuit design the freedom of evolutionary search is respected as crucially important for successful results. In [1], [2], [4], [7], [8] the freedom of search is emphasized, but has not been realized completely.

The considerable results were obtained by Koza et al in [1]. They used Genetic Programming (GP) circuit-constructing program trees with four kinds of circuit-constructing functions and automatically defined functions. Last one let them to get as results filters with regular structures within the circuit. They utilized a procedure providing the DC path to ground from each node of a circuit by adding the giga-Om resistance, allowing any kind of connections among capacitors. This let them avoid the most of "node floating" errors and enabled to reach the amount of invalid circuit graphs up to 2%. Later, they simplify each circuit by removing redundant resistances and replacing all series and parallel compositions. The main drawback of this experience is that the technique

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requires large computing power to adopt the same methodology as well as the methodology by itself is very complex for implementation.

The larger computational efforts in a circuit evolution required by GP were proven by works of Zebulum et al [3] and Ando et al [5], where they have given the comparison between GP and Genetic Algorithm (GA). The first work was made as analogy to biology concept with comparison of performance among different types of sweeping strategies: Increasing Length Genotypes (ILG), Oscillating Length Genotypes (OLG) and Uniformly Distributed Initial Population. The second work there was intrinsic evolution of real hardware for robustness purposes.

The previous development in evolution of analogue circuits design is summarized in the Table 1. The analysis of Table 1 reveals that all the approaches developed in analogue circuit domain previously are based on the circuit-structure–checking rules for avoiding the invalid circuit graphs. In contrast, the experimental results were promising for evolution of digital circuits in the unconstrained search space [11]. Furthermore, the approaches introduced previously for analogue circuit design provided search with GP and GA, and none of them used purely ES. Also, the majority of algorithms for low-pass filter design used the ILG strategy as a sweeping strategy; however in the work of Zebulum et al [3] the OLG has shown excellent results for analogue circuit design, and the best for the low-pass filter. Finally, there are no any noticeable works in the past on evolution of low-pass filters with shorter transition band.

III PROBLEM STATEMENT

Most of the works in the analogue circuit design start from evolving a passive low-pass filters, that is a convenient tool for probation of evolutionary technique and tuning the EA parameters towards the more sophisticated designs [1], [2]. Low-pass filter circuits have deeply developed theory supported by numerous examples of real-world applications. Moreover, this task can be scaled along the level of difficultness by varying the steepness in the transition band and attenuation requirements. A low-pass filter passes low frequencies fairly well, but attenuates high frequencies. An ideal low-pass filter completely eliminates all frequencies above the cut-off frequency while passing those below unchanged. The transition region is infinitesimal. It can be realized mathematically by multiplying with the rectangular function in the frequency domain or, equivalently, convolution with a sinc function in the time domain.

However, the ideal filter is not realizable for real signals because the sinc function extends to infinity. The filter would therefore need to predict the future and have infinite knowledge of the past in order to perform the convolution. Real filters for real-time applications approximate the ideal filter by delaying the signal for a small period of time, allowing them to "see" a little bit into the future. Greater accuracy in approximation requires a longer delay. Previously the behavior of low-pass filters between frequencies 1Hz and 100KHz, cut-off frequency 1KHz and transition band 1KHz has been actively researched through in [1], [2], [3]. Thus, the performance of proposed evolutionary technique could be evaluated more precise if the evolution target will have exactly the same filter properties. On the other hand, the evolution of analogue low-pass filters with shorter transition band is very rarely regarded in the area.

IV UNCONSTRAINED EVOLUTION OF “LCR” CIRCUITS

A Algorithm overview

The structure of proposed system contains 4 main steps shown on Fig.1.

Step 1: The Start-block provides the start terms such as kind of circuits to evolve (”LCR”), seed for random number generator, the characteristics of filters to be evolved and the list of elements’ parameters to be used by evolution. Last one is set to E-12 series of the totally 51 parameters for each element.

Step 2: ES part sets the particular parameters of ES, such as: mutation rate, population size, selection criteria and termination terms.

It modifies the genotype and produces the population of chromosomes in form of cir-batch-file towards OrCAD Pspice. Unconstrained evolution here applies the special design rules that allow the circuit generation to be unconstrained.

Step 3: Pspice has been used in non-interactive batch simulation mode to reduce the evaluation time.

Table 1
Some previous works on the evolution of analogue circuits

	Koza et al, [1]	Lohn et al, [2]	Goh, et al [4]	Zebulum, et al [3]	Grimbleby [6]	Dastidar, et al [7]	Ando, et al [5]	Sripramong et al [8]	Proposed method
Publication year	1997	2000	2000	1998	1999	2005	2003	2002	2006
Type of circuit evolved	LC, LCR, LCRMD	LCR, MR	LCR	LCR, MR	LC	M	LCR	LCRM	LCR
Type of EA	GP	GA	GA	GP,GA	GA	GA	GP,GA	ES+sim. annealing	**ES**
Circuit-structure-checking rules	Partially	Yes	Yes	Yes	N/A	Yes	Yes	Yes	**No**
Parameter optimization	No	No	No	No	Yes: numerical	Yes: GA	Yes: GP,GA	Yes: hill-climbing	No
Sweeping strategy	ILG	ILG	ILG	ILG,OLG, UDIP	ILG	OLG	N/A	Fixed	OLG
Circuit growth method*	1	2	1	1	1	1	1	No	1

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* 1- technique where the place for a new element within a circuit is to be chosen arbitrarily, 2- where the circuit growth is along the way the current/voltage usually goes from input to output. N/A – data is not available. L-inductor, C-capacitor, R-resistor, M-transistor, D-diode.

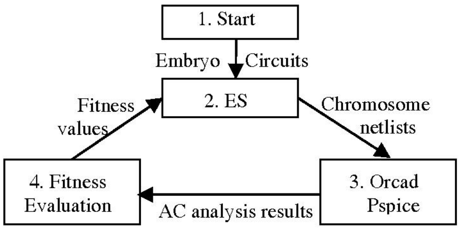


Figure 1
The flowchart of the experiment

Step 4: Fitness evaluation block, as described bellow, fairly assigns the fitness values towards each circuit from AC analysis produced by Pspice in the form of batch out-file and passes the results to ES block.

The PC program written in C programming language describes all 4 parts and unites them in one code. This stage also contains the circuit simplification procedure reducing the redundant elements and uniting the serial and parallel structures.

B The embryo-circuit

The embryo-circuit refers to the elements that are definitely known as essential for the target circuit, stay unchangeable during all the evolution and take place in each circuit netlist. In our case of LCR low pass filter as the target circuit, there are 3 such kind of elements: AC voltage source, source resistance and load resistance. We define the embryo circuit similar to the most popular case [1], [2], [4]-[6], where the circuit is driven by an incoming AC voltage source with a 2V amplitude, has the source resistance R_{source}=1kΩ and the load resistance R_{load}=1kΩ. The output voltage is measured on the pins of Rload.

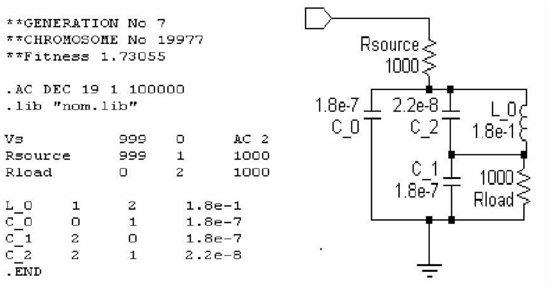
An example of Pspice netlist with correspondent schematic is shown on Fig. 2, where three embryo elements followed by the netlist are shown.

The circuit growth methodology is very simple and is similar to one reported in [4]: adding one gene to each chromosome at the same time.

The improvement of the circuits is driven by evolutionary strategy with disruptive selection scheme [10].

C Chromosome representation

The linear circuit representation is proposed for use, similar to one that exploited in [3]. That is every element of a circuit is represented as a particular gene, and each of 4 element’s features: name of an element, its parameter, and every its pin is represented by particular loci in a gene. The advantage of this chromosome representation is that it directly maps the description of one element in the Pspice netlist. The number of genes in chromosome equals to the number of elements in a circuit. The circuit on Fig.2 contains four elements (apart from embryo-elements). Therefore the chromosome representation contains four genes. Each gene is described by four loci. For instance, the first gene is “L_0 1 2 1.8e-1”, which describes the first inductor with pins N1=1 and N2=2 and with a value of 1.8e-1 Henry. The first loci is reserved for the element’s type (L or C or R), the second and the third loci are reserved for the first and the second pins, and the last loci is for the element’s parameter. Similarly the remaining genes in the chromosome are encoded.

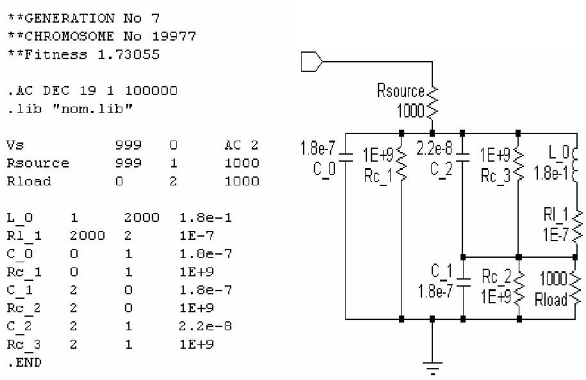


```
**GENERATION No 7
**CHROMOSOME No 19977
**Fitness 1.73055

.AC DEC 19 1 100000
.lib "nom.lib"

Vs          999    0      AC 2
Rsource     999    1      1000
Rload       0      2      1000

L_0    1     2      1.8e-1
C_0    0     1      1.8e-7
C_1    2     0      1.8e-7
C_2    2     1      2.2e-8
.END
```

Figure 2
Chromosome representation at constrained evolution. The typical netlist and the correspondent schematic.

D The essence of unconstrained evolution in “LCR” circuit design domain

We call absolutely *unconstrained evolution* of an analogue circuit the process of a circuit netlist generation during which no any circuit-structure-checking rules applied and all the circuits are counted as valid graphs except ones that have elements with dangling nodes and with isolated subcircuits. There are two main kinds of invalidities that unacceptable for most of simulation software: the nodes that have no DC path to ground (tackled in [1]) and loops that involve inductors and/or voltage source. The most of methodologies in the area (Table 1) just prohibit such kinds of invalidities to appear. In the case of “LCR” circuits, the adding to each capacitor the Giga-Ohm resistance in parallel and the adding to each inductor the Micro-Ohm resistance in series, at the stage of Pspice cir-file generation, allows to avoid these invalidities. We call such kind of resistance as *R-support*. Using R-support and avoiding the dangling nodes makes almost any randomly generated circuit as valid, and indeed becomes an absolutely *unconstrained*.



```
**GENERATION No 7
**CHROMOSOME No 19977
**Fitness 1.73055

.AC DEC 19 1 100000
.lib "nom.lib"

Vs          999    0      AC 2
Rsource     999    1      1000
Rload       0      2      1000

L_0    1      2000   1.8e-1
Rl_1   2000   2      1E-7
C_0    0      1      1.8e-7
Rc_1   0      1      1E+9
C_1    2      0      1.8e-7
Rc_2   2      0      1E+9
C_2    2      1      2.2e-8
Rc_3   2      1      1E+9
.END
```

Figure 3
Chromosome representation at unconstrained evolution. The typical netlist and the correspondent schematic with R-support. The three first elements (Vs, Rsource and Rload) compose the emryo-circuit.

Fig.3 demonstrates how unconstrained evolution generates the circuits with R-support. The circuit depicted on Fig.2 once being processed by unconstrained evolution will have the view shown on Fig.3. Each element line describing inductor (L_0) is followed by R-support element (Rl_1) in series with infinitesimal parameter; and each element line describing conductor (C_No) is followed by R-support element (Rc_No) in parallel with infinite parameter.

If the circuit-structure-checking rules are applied to a circuit after fitness assignment as a part of the simplification procedure, that is, every R-support element is checked whether it could be removed without damage to the current fitness of a circuit, then the circuit could contain a few R-support elements or even does not contain them at all. For instance, the circuit on the Fig.3 after simplification process becomes the circuit on the Fig.2.

E Mutation

The whole process consists of three types of operations over the circuit. Every time the best fitness of a generation is not improved, the population falls into "Add new element mutation" (ANEM) procedure, i.e. one randomly generated gene is added to each chromosome except the chromosome with the best fitness value. At the start the number of nodes in the embryo circuit is equal to three: input, output and earth. The further growth circuit could increase the amount of nodes, if randomly generated node numbers for both pins are equal. In this case a new element splits the elements at the node and comes between them. ANEM procedure could be applied repeatedly, so the real difference in length between the best chromosome and others is *oscillating* and could reach numbers of genes.

However the "Delete element mutation" (DEM) will delete one gene if the difference between the shortest chromosome and the largest one in the generation greater than 2 genes. Thus the evolution can focus on processing chromosomes of three different neighboring sizes.

The "circuit structure mutation" (CSM) performs mutation over any of four loci of randomly chosen gene. If the mutation comes to a pin connection, the whole structure of a circuit is changed. However the total amount of elements stays unchangeable, the number of nodes of a circuit could be reduced or increased.

At the start the population comes to ANEM for preliminary circuit growth, and, after evaluation, it falls into CSM. The following switching rule between ANEM/DEM and CSM does manage: whenever the mutation within CSM does not bring any improvement in the fitness, the algorithm immediately switches to ANEM/DEM. As experiment shows the fitness of an individual never improves by infinitesimal values, what makes the switch period between two kinds of mutations finite in time. For instance, having the fitness at the second generation 4.6492 and the best fitness 0.0040 at the 80th generation, we have set the value of 1E-5 as the minimum fitness improvement to keep mutation within CSM. Whenever this improvement is less, all the population falls into ANEM/DEM. While CSM searches for the best circuit within the given amount of elements, it unavoidable brings to a fitness improvement stuck. But the adding one element to a circuit during ANEM stage significantly improves fitness reviving the whole process.

F Fitness Function

We perform the AC-analysis along 96 points between 1 Hz and 100 kHz (19 per decade), and measure the absolute deviation voltage between ideal value and produced by Pspice. We set the fitness evaluation in the analogy with [1], that is we distinguish as acceptable a voltage in the passband of between 970 mV and 1 V (i.e., a passband ripple of 30 mV or less) and a voltage in the stop-band of between 0 V and 1 mV (i.e., a stop-band ripple of 1 mV or less):

$$F_1 = \sum_{i=0}^{p} | V^i_{ideal} - V^i_{measured} | ,$$

Where V^i_{ideal} is the voltage in *i*-th point for ideal filter and $V^i_{measured}$ is the voltage in the *i*-th point obtained for evolved filter; *p* is a number of points evaluated in both stop and pass bands.

And we regard any voltage lower than 970 mV in the passband and any voltage above 1 mV in the stop-band as unacceptable, punishing it by multiplier 10:

$$F_2 = 10 \times F_1 .$$

The transition band is regarded as the "don't care" band where the fitness is supposed to be equal zero. In the case of 1KHz transition band it consists of five points between 1 kHz and 2 kHz. In the case of 0.4KHz transition band only 2 points are in the "don't care" band. The error circuits are not analyzed by Pspice and assigned to the worst fitness value that never could be reached by other circuits.

V EXPERIMENTAL RESULTS

A General terms

Population size of 20,000 chromosomes is set in all experiments. Experimentally it has been established that the disruptive selection scheme [10] is the best: only 9% of the best chromosomes and 1% worst ones are to be chosen for the next generation. Being chosen for the next generation each chromosome contributes 10% of the next population size. Static mutation rate of 5% then applied to each chromosome randomly changing with equal probability every loci of a gene. ES is deserved the name of most simple EA among all, because it doesn't content the recombination stage: all the offspring chromosomes are identical to a correspondent parent.

We set as a termination criteria reaching either of the following conditions: the number of circuit elements before simplification 29 (except R-support and embryo elements), the best fitness value 10^{-3}, whole number of individuals (population_size×No_of_generations) 3mln., and the time length of experiment 20 hours. The results presented bellow are the best out of 5 attempts for both experiments performed with 5 seeds for the random number generator.

B Experiment A: Unconstrained evolution of a filter with transition band 1kHz

The purpose of this experiment is to probe the new methodology developed on the example of low-pass filter with transition band 1kHz. We use the same initial data given in subsection V-A. The best result has been obtained at chromosome 9,958 of generations 75 (20,000×74+9,958=1,857,453 individuals), with 28 elements before simplification, with the best fitness value

0.003916, which the best in the area. The schematic after simplification and the voltage response of the best circuit are shown on Fig.4.

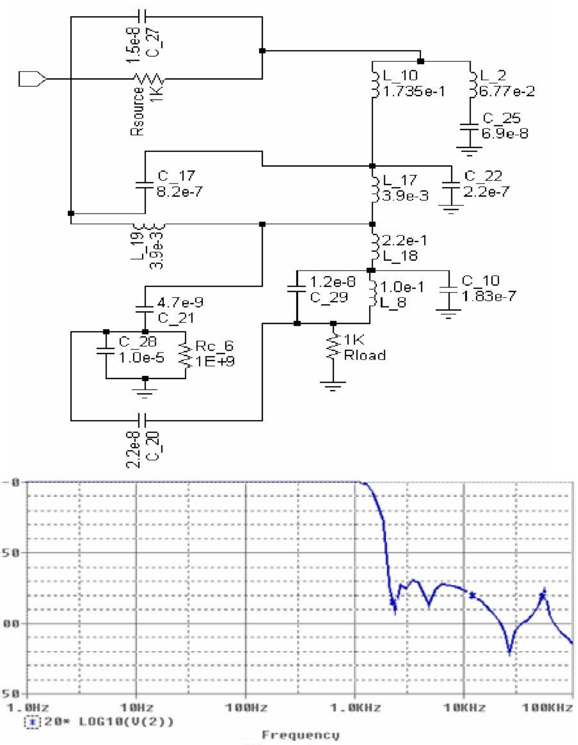


Figure 4
The schematic after simplification and the voltage response of the best low-pass filter evolved at Experiment B.

As could be seen we have got non-monotonic filter consisting of 16 elements (without embryo) among which 1 is R-support and with the following features: the maximum absolute attenuation in passband is 0.0043dB, the maximum attenuation in stopband is -69dB.

C Experiment B: Unconstrained evolution of a filter with transition band 0.4kHz

The purpose of this experiment is to apply successfully tested in Experiment A the methodology towards the low-pass filter with transition band 0.4kHz. We use the same initial data.

The best result has been obtained at chromosome 19,275 of generations 85 with the best fitness value 0.021018. A non-monotonic filter consisting of 29 elements (without embryo), among which 2 R-support elements and 1 resistor shows the following features: the maximum absolute attenuation in passband is 0.01513dB, the maximum attenuation in stopband is -53dB. The schematic after simplification and the voltage response of the best circuit are shown on Fig.4.

VI THE COMPARISON OF RESULTS

During running the Experiment A, the amount of invalid graphs among all randomly generated ones did not exceed in average 0.05%.

In order to provide fair comparison between obtained and previously published results, we validate each result using OrCAD Pspice-10.3. By this we have got filter characteristics for each circuit and its fitness values, all summarized in Table 2. The correct performance of the fitness function is verified by perfect match between the fitness value we have got and the fitness value published in [1] for ladder low-pass filter.

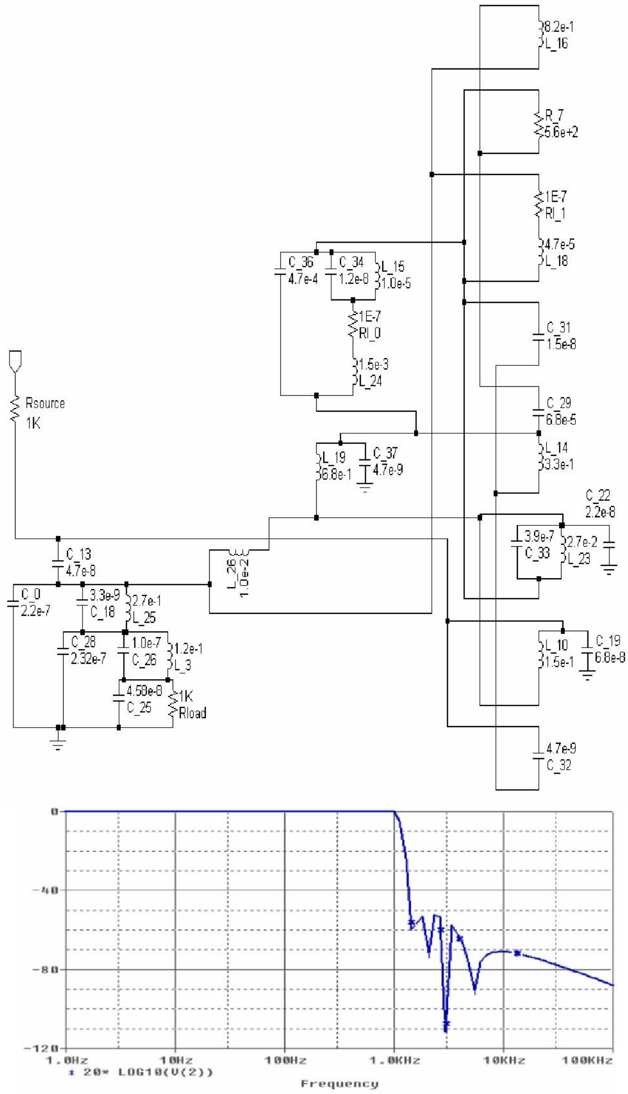


Figure 5
The schematic after simplification and the voltage response of the best low-pass filter evolved at Experiment B.

As could be seen from a Table 2, having only 16 elements the filter from Experiment A exceeds all previously developed by filter and evolution characteristics. The fitness value improved the best previous one almost twice. In comparison with the best filter from [1], the fitness is improved by 82% at lower evolution attempts (generations) by 37%.

Table 2
Comparison table of filter and evolution characteristics among works published before and present.

	Ideal filter	10order Chebyshev filter [12]	Koza 1 et al, [1] elliptic	Koza 2 et al, [1] ladder	Koza 3 et al, [1] bridge-T	Lohn et al, [2]	Goh, et al [4]	Zebulum et al [3]	Experiment A	Experiment B
Filter Characteristics										
Pass band, V	1	1	1	1	1	1	1	2	1	1
Stop band, V	0	0	0	0	0	0	0	0	0	0
Transition band, KHz	0	1	1	1	1	1	1	1	1	0.4
Maximum absolute attenu-ation in the pass-band, dB	0	0.035	0.179	0.0175	0.137	0.0144	0.042	0.188	**0.0043**	0.0151
% of improvement	-	714%	4063%	307%	3086%	235%	877%	4272%	-	
Maximum attenuation in the stop band, dB	- ∞	-83	-72	-61	-60	-59	-34	-24	**-69**	-53
% of improvement	-	-20%	-4%	**12%**	**13%**	**14%**	**51%**	**65%**	-	-
Evolution characteristics										
Fitness value	-	0.0259	0.0805	0.0071	0.0502	0.0134	0.1858	585.7665	**0.0039**	0.021018
% of improvement		**564%**	**1964%**	**82%**	**1187%**	**244%**	**4664%**	**1.5e+8%**	-	-
No. Elements		10	25	14	15	24	12	10	16	29
No. Individuals		-	N/A	2,048,000	N/A	997,000	20,200	320,000	1,489,958	1,699,275
Circuit simulator			MicroSim			SPICE	MicroSim	SMASH	OrCAD	

The value "% of improvement" shows the correlation between the value above in the same column and the correspondent value in the column "Experiment A". N/A means that the data are not available.

VII CONCLUSION

The process of extrinsic evolutionary design of analogue circuits before always been constrained to generation only the valid circuit graphs. However the introduction of R-support elements can significantly release these constraints.

The proposed technique based on Evolutionary Strategy in combination with oscillating length genotype sweeping strategy demonstrates the superior behavior over the methods developed before, which enables to apply the same methodology towards more sophisticated tasks, as close-to-ideal filter.

The instinctive wish to reduce the potential solution space for evolutionary search, by which usually the circuit-structure-checking rules are justified, is not always the best strategic maneuver for reducing the search time and obtaining good results.

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