An Efficient 60 GHz Resonator Using Harmony Search

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***Abstract*— In this paper we utilize the newly devised Harmony Search (HS) method to optimize the geometrical profile of a slow-wave tapered coplanar strips (CPS) resonator within a 90nm standard CMOS process for 60 GHz applications. Our results show the merit of harmony search in finding an improved Q-factor of 28.4 which is an improvement of around 90% in comparison with the conventional tapered CPS resonators. Our structure is estimated to be significantly more efficient than the conventional uniform CPS resonator by 220% in Q-factor.**

Keywords-optimization; harmony search; resonator; high-Q; coplanar strip; CMOS

I. INTRODUCTION

To effectively exploit modern CMOS processes in mm-wave circuits, on-chip high quality factor passive components such as capacitors, inductors and transmission lines (TL) are required [1]. Furthermore, because passive components tend to occupy a large amount of on-chip area, it is necessary to reduce the dimension of these components and consequently reduce the cost [2]. With their explicit distributed behavior, transmission lines play a critical role at mm-wave circuits. Moreover, due to relatively small wavelength in the mm-wave regime, quarter wavelength transmission lines can be realized on-chip [2]. These transmission lines can be used not only to carry signals, but also as reactive components and resonators in oscillators and amplifier circuits. As a result, it is important to reduce the on-chip area and aspect ratio of a transmission line resonator while improving its quality factor [2, 3].

Although, coplanar transmission lines (CPTLs) such as coplanar strips have the advantage of low resistive loss, they typically suffer from conductive loss due to the low resistivity of the silicon substrate. This conductive loss is mainly due to the penetration of the electric field of the CPTL into the low resistive silicon substrate. One effective method of shielding a transmission line is use of an array of closely spaced narrow floating strips placed under the coplanar transmission line. These floating strips not only reduce the electromagnetic wave penetration in the lossy substrate, but also reduce the electromagnetic wave propagation speed along the transmission line, hence the name slow-wave transmission line. So using slow-wave TLs is an effective solution of reducing substrate losses in CMOS technologies. A shorted $\lambda/4$ transmission line can be used as a resonator like a parallel LC tank resonator in voltage controlled oscillators (VCO). For a cross-coupled VCO, a balanced transmission line resonator is needed. A quarter wave-length differentials CPS which is shorted at one end exhibits a standing wave mode at its resonance frequency [3]. Keeping this in mind and considering the Q-factor equation (Eq.1, [4]) for a TL one can conclude that to have higher Q-factor, the TL resonator needs to be more capacitive at the beginning of the line, where we have the maximum voltage. Also it needs to be more inductive at the end of the transmission line, where the current is at its maxima. In this equation parameters V, C, I, G and R are functions of position x, □ is the angular frequency, L is inductance, C is capacitance, R is resistance and G is conductance.

$$Q = \omega \frac{E_{\text{stored}}}{P_{\text{diss}}} = \omega \frac{\int_0^l \frac{1}{4}\left(V^2(x)C(x) + I^2(x)L(x)\right)dx}{\int_0^l \frac{1}{2}\left(V^2(x)G(x) + I^2(x)R(x)\right)dx} \qquad \text{Eq. 1}$$

With this explanation, it has been shown in [3] that a maximum Q-factor can be achieved with a numerical optimization of the width and spacing of the two strips of the CPS.

Over the last decade the simulation-based heuristic search methods, having powerful searching abilities, have shown their strength to overcome several deficiencies of the mathematical search methods [5-8]. Among those, Geem et al. [7] developed a basic Harmony Search (HS) heuristic optimization algorithm which was based on the process of music improvisation. The harmony of a piece is analogous to the quality of the solution in HS and the musician's improvisation is analogous to the global and local search schemes. HS has been successfully applied to various optimization problems including the traveling salesperson problem, water supply networks, hydrologic model parameter calibrations and thermal systems optimization [5-8]. In this work we used HS to optimize the geometric configuration of a TL to maximize Q-factor.

The rest of this paper is organized as follows: in section II the newly devised meta-heuristic optimization algorithm Harmony Search (HS) is introduced and the process of its application to the optimization of the slow-wave CPS resonator explained. In section III optimization and simulation results are

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presented and compared with those of previous methods and finally in section V the conclusion is given.

II. Optimization and Harmony Search

Over the last four decades numerous mathematical programming paradigms such as linear, nonlinear and dynamic programming have been developed and utilized to solve optimization problems. Despite their efficiency to obtain the global optima in simple models, their ability to find optimum solutions in more complicated problems is very limited. The computational drawbacks of such methods forced researchers to rely on meta-heuristic algorithms mimicking natural behaviors.

In this paper we used Harmony Search (HS) approach, first devised by Geem [9], for design optimization of the transmission lines mentioned in the previous sections. Harmony search imitates the improvisation of musicians and uses a stochastic random search instead of a gradient search eliminating the need to obtain gradient information of a problem set [10].

HS has been extensively used in a number of engineering applications including mechanical, civil and electrical engineering [6, 7, 11, 12] demonstrating its merit to find optimum solutions efficiently in comparison with other heuristic algorithms including particularly Genetic Algorithm (GA) [7, 8]. Over the last decades GA has been used in a number of engineering applications and results are published in a hole stack of articles, yet its high memory cost to keep several solutions at once, the non-trivial operations to generate new solutions and the limitation to code continuous variables [13] are very important measures to be taken to use it.

In this work, to obtain the optimum design parameters of the transmission line the Q-factor introduced in the previous section is used as the fitness criterion. This is done to find the optimal values of geometrical parameters including the discretized TL width, discretized spacing and the whole TL length. To differentiate separate sections of the TL in the resonator, it is divided into 100 equal-length segments each of which having two degrees of freedom width and spacing. This results in a total number of 201 variables including the single variable for the length. Table I presents these variables and their allowable range.

TABLE I. Design parameters, their multiplicity and range of values for optimization

Variable	*Notation*	*Multiplicity*	*Range*
Width of a section	W[i]	100	5-65 μm
Sections spacing	D[i]	100	5-65 μm
Transmission line length	L	1	150-300 μm
	Total number of variables		**201**

Due to the symmetry of the top and bottom TLs, design parameters are just optimized for one of them and to determine the Q-factor both lines are considered identical.

HS generates just a single solution vector at each iteration and the number of solutions called harmony memories kept in the memory is always constant and very limited, usually from 20 to 30. Algorithm parameters used in this work and their values are given in Table II.

TABLE II. Harmony search parameters and their values

Parameter	*Mnemonic*	*Value*
Number of Harmony Memories	*N_HM*	30
Harmony Memory Consideration Rate	R_{accept}	95%
Pitch Adjustment Rate	R_{pa}	50%
Pitch Adjustment Bandwidth	*Band*	0.1
Number of Iterations	*ITR*	2,000,000
Number of Variables	*N_VAR*	201

The pseudo code for Harmony Search in this work is shown in Figure 1.

```
Harmony Search for resonator optimization
begin

  Define design parameters X, X=(x1, x2, ….., x201)
  Define Objective function 1/Q-factor(X)
  Define Harmony Memory Consideration Rate (Raccept = 95%)
  Define Pitch Adjustment Rate (Rpa=50%)
  Define New Harmony Solution Vector Y

  for (i < N_HM)
    HM(i) = Randomly generated solution Xi
  end For
  while (t < ITR)
    while (i<=N_VAR)
      if (rand<Raccept) randomly select a value from HM for Y(i)
        if (rand<Rpa) adjust Y(i) by Band
        end if
      else generate a random value for Y(i)
      end if
    end while
    if ( 1/Q-factor(Y) < 1/Q-factor(HM(worst))
      HM(Worst) = Y,
      Update Worst
    end if
  end while
  find HM(Best)

end
```

Figure 1. Pseudo code of Harmony Search algorithm for resonator optimization

At first, the 30 solution vectors of the harmony memory (*HM*) are generated completely randomly. Through the whole course of optimization this number of solutions (*N_HM*) will not change which is one of the benefits of HS over GA in which the number of solutions kept at the memory is much more. Later on, in each iteration a new solution vector (*Y*), incorporating values for the 201 design variables of the problem, is generated. This could happen either through random value selection among the vectors stored in harmony memory, with consideration rate of 95%, or generated completely randomly, with the possibility of 5%. Then the new values might randomly, with 50% chance, undergo slight pitching determined by value of the *Band* parameter. While generating new solutions, in addition to the cost, their feasibility is also examined and in case of an infeasible solution its chances of rejection out of the harmony memory is increased by increasing the cost by a significant penalty value. In the end, if the quality of the newly generated solution is more than that of the worst solution in the harmony memory, it is replaced with that solution. For cost considerations we use the reciprocal of the Q-factor, so by minimizing the cost maximal Q-factor is sought. Results are presented in the next section.

III. Discussion and Results

We implemented the HS code in C++ and to compute the Q-factor in each iteration we implemented a Matlab routine which is invoked within the C++ code. For calculation of Q-factor as the objective of the optimization process, we used ABCD matrices of the tapered TL. As mentioned earlier TL is discretized to 100 pieces. Full wave 3D EM simulator, HFSS [14], was first used for ABCD matrix extraction. 100 µm long differential coplanar strips of varying widths and spacings between 5 µm and 65 µm were simulated at 60 GHz and scattering matrices were saved in a file. Next, Matlab [15] was used to convert S-parameters to ABCD parameters and for the calculation of the total ABCD matrix of the tapered TL. Both programs are run on a dual Intel Xeon 2.8 GHz processor workstation machine. As mentioned in the previous section the algorithm has run for 2,000,000 iterations to get the optimal values for 201 variables. Optimized values of design parameters width and spacing for each segment after the last iteration are demonstrated in Figures 3 and 4 respectively. Due to the discretization of the TL, the final width and length profiles are not very smooth. So, in order to simplify the insertion of data to the HFSS, we fitted polynomials of 6th degree to both width and spacing profiles. Improvement and convergence to the final value of the Q-factor for the best solution vector in harmony memory over iterations of HS is demonstrated in Figure 2.

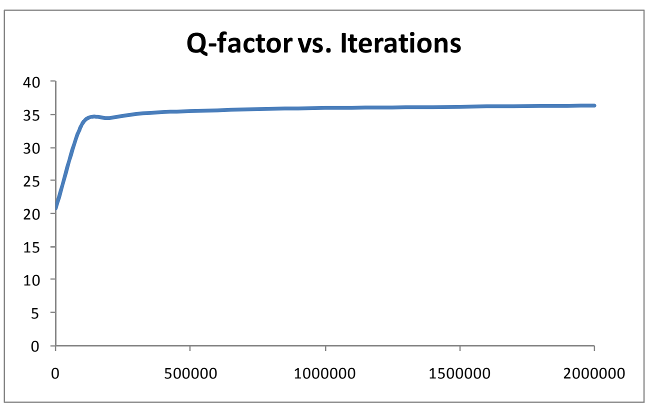

Figure 2. Convergence of Q-factor running HS for 2,000,000 iterations. Vertical axis represents Q-factor. Q-factor reaches the optimum value around iteration number 250,000

As it could be estimated by the figure, the Q-factor reaches its optimum values around the 250,000th iteration and it levels out for the rest of the iterations with trivial changes in the values. This demonstrates fast convergence of HS for a large number of variables relative to the other areas of application where computational cost is very dependent to the number of iterations and as a result references to objective calculation sub-routines. These operations take most of the CPU time in optimization processes as other operations associated with HS in particular are comprised of simple random selection or number generations.

The first four segments of the TL are given a fixed minimum allowable width of 5 µm to comply with the manufacturing regulations for future implementations as well as decreasing inductance effects of input connections.

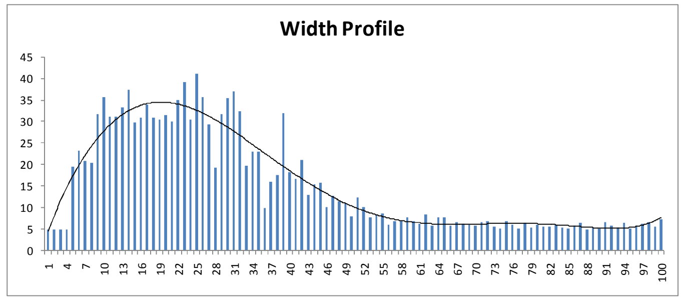

Figure 3. Resultant width profile after optimization. Vertical axis represents width in µm. Bars depict the individual values for each segment and the line is the fitted curve used for simulation

In Figures 3 and 4 the bars show the optimized values of width and spacing for each individual segment whereas the continuous curves are the fitted profiles considered for simplification of fabrication and insertion of data into HFSS.

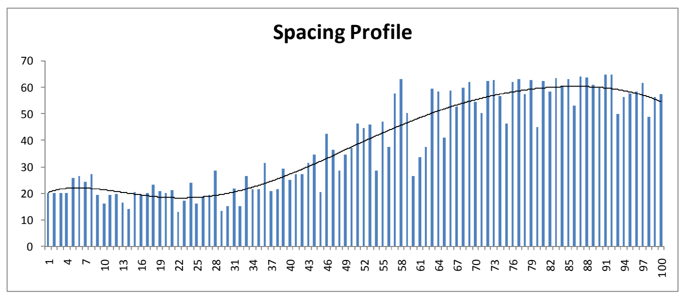

Figure 4. Resultant spacing profile after optimization. Vertical axis represents spacing in µm. Bars depict the individual values for each segment and the line is the fitted curve used for simulation

The two width and spacing polynomial profiles used for simulation are given in Table III.

TABLE III. FITTED WIDTH AND SPACING PROFILE EQUATIONS

Profile	*Fitted polynomial*
Width	$2.12e-0.9x^6 - 5.62e-7x^5 + 4.55e-5x^4$ $-2.55e-4x^3 - 1.17e-1x^2 + 3.83x + 1$
Spacing	$-1.75e-0.9x^6 + 6.14e-7x^5 - 8.3e-5x^4$ $+5.12e-3x^3 - 1.28e-1x^2 + 1.02x + 1.95$

Calculated quality factor by our cost function associated with the original optimized parameters and the fitted profiles are given in Table IV or comparison. As it is shown the fitted profile does not affect the quality factor significantly and just by a trivial factor of 2.5%.

TABLE IV. HARMONY MEMORY PARAMETERS AND THEIR VALUES

Width and spacing profile	*Q-Factor*
Original	37.509
Fitted (Matlab)	36.71
Fitted (HFSS)	34

To further investigate the reliability of our results, we simulated the resulting TL in the EM simulator, HFSS. As Table IV suggests the final results in HFSS are in good match with that of optimization cost function (Matlab).

Both the optimized tapered slow-wave CPS and uniform slow-wave CPS resonators were simulated with 3-D full wave method. Results of our work compared with that of the previous ones are given in Table V. All the given designs are to operate at 60 GHz. It is important to note that in the optimization process we used the Q-factor definition as in Eq.1, yet for comparability of results with those of the previous publications we used the $Q=F0/BW$ definition as used by [4].

TABLE V. COMPARATIVE RESULTS OF Q-FACTOR, OPERATING REQUENCY AND LENGTH OF QUARTER WAVE-LENGTH CPS RESONATORS

Resonator	*Length*	*Frequency*	*Q-factor*	*Improvement*
Uniform [4]	635 µm	57.9 GHz	8.8	-
Tapered [4]	498 µm	54.4 GHz	15	70.4%
Slow-wave uniform [16]	222 µm	60.5 GHz	16	81.8%
Slow-wave Tapred (current work)	320 µm	59.6 GHz	28.4	220%

For the first and base reference in our comparisons we used the conventional uniform CPS resonator results given in [4]. The Improvement column in Table V presents the improvement of Q-factor in each case compared to the first row. The conventional uniform CPS resonator has a length of 635 µm to resonate at 57.9 GHz which gives a Q-factor of 8.8. The second design belongs to a conventional tapered CPS resonator [4]. This had a length of 498 µm and Q-factor of 15 which is a 70% improvement. Here we also presented the results associated with slow-wave uniform CPS resonator discussed in [16] for closer comparison. This resonator has a length of 222 µm and an associated Q-factor of 16 with 81.8% improvement.

Our optimal structure has a length of 320 µm which is relatively short and reasonable for on-chip implementations. The Q-factor from extensive simulation results is 28.4 which proved to be a significant improvement in Q-factor by 220% compare to the conventional uniform resonator. This shows the merit of HS in finding the optimal geometric profile of the resonator in our study and also shows its performance in optimization problems incorporating large number of variables.

IV. CONCLUSION

We used Harmony Search optimization method in this work to determine optimal geometric characteristics of a quarter wave length slow-wave CPS resonator operational at 60 GHz using standard 90nm CMOS technology. We used Q-factor as the objective of the problem and simulated the results with EM simulator HFSS for comparison. Our significant improvements in Q-factor by 220% compared to a conventional uniform resonator and 89% compared to the previously optimized conventional tapered resonator demonstrate merit of HS for such applications. In addition, fast convergence of HS makes it a viable search method in applications with relatively large number of variables, in this case 201.

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