RESEARCH ARTICLE OPEN ACCESS

Simulation and designing of Voltage Controlled Oscillator by using C-MOS technology: A review

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Abstract-
"CMOS" refers to digital circuit design, and the processes used to implement that design on integrated circuits. CMOS circuits in VLSI consume less power when static. This paper presents a brief study of various types voltage-controlled oscillator and their function like a complementary metal–oxide–semiconductor (CMOS) ring oscillators and LC-VCO.
The high performance VCO on 45 nm technology to achieve the desired objectives such as both non-linear and linear operations. The circuits used is a modified design of VCO.
The study of an improved design of four-stage CMOS differential ring voltage-controlled oscillator(VCO)withhigh-outputfrequency,lowphasenoise, andlowpowerconsumptionis proposed in this paper. A new differential delay cell has been used for differential ring VCO whichutilising dual-delay-pathtopologytoattainbothhigh-outputfrequencyandlowphase noise. The simulation results have been obtained in TSMC 0.18-μm CMOS process with a supply voltage (Vdd) 1.8 V. The proposed design of VCO exhibits an output oscillation frequency range from 1.619 to 3.712 GHz. The power consumption for this frequency range variesfrom4.628to10.545mWwithcontrolvoltagevariationfrom0.1to1.0V.Theproposed designoccupiescompactlayout areaof0.207 mm2 andachieves –89 dBc/Hzphasenoiseat 1 MHz offset from 3.712-GHz carrier frequency. Improved performance for this design has beenachievedintermsofoutputoscillationfrequency,phasenoise,andpowerconsumption.
Keywords: Voltage control oscillator, ring oscillator, low power consumption, cmos- technology, phase noise, oscillation frequency etc.

Date of Submission: 07-06-2025 Date of acceptance: 18-06-2025

I. Introduction:

Electronicoscillatorsbelongtotheveryfirstelectriccircuitsatthebeginningof thetwentiethcenturyacompletesystematicdesignconceptforthisclassofelectroniccircuits isnotavailableuntil now.Oneofthereasonsisthat thebehaviorofthesedynamicalcircuits depends in an intrinsic manner on the nonlinearities of within the circuit and therefore we areconfrontedwithnonlineardifferentialequations.Theoscillatorycircuitbehaviorisrelated fromamathematicalpointofviewtotheso-calledlimitcycles.Howeverelectronicoscillators arefascinatingcircuitsinmanysensebecausetheprogressinmanufacturingtechnologiesof electronic devices and circuits led to new challenges in oscillator modeling and new mathematical concepts for solving the descriptive equations of oscillators. In certain cases the behavior of an electronic oscillator should be influenced by the behavior of other electronic systemsina desiredmannersuchthat entrainmentandsynchronizationeffects

arise. Therefore driven nonlinear oscillators and their descriptive equations have to be consideredwhereevenchaoticbehaviorcanappear.Fromaphysicalpointofviewelectronic oscillators can be interpreted as such systems where dissipative structures occur. Ilya Prigogine coined this phrase as a name for the patterns which self-organize in far-from- equilibrium dissipative systems and limit cycles are a special case of them; see Nicolis, Prigogine [1]. Such dissipative systems are nonlinear and have to be connected with a DC powersupplyfordeliveringenergyintothesystem.Furthermorethesesystemsinteractwith a heat bath where energy is dissipated.

Accordingly the fluctuations of the heat bath influence Electronic oscillators belong to the very first electric circuits at the beginning of the twentieth century a complete systematic designconceptforthisclassofelectroniccircuitsisnotavailableuntilnow.Oneofthereasons is that the behavior of these dynamical circuits depends in an intrinsic manner on the nonlinearitiesofwithinthecircuitandthereforewearecon frontedwithnonlineardifferential equations.Theoscillatorycircuitbehaviorisrelatedfro mamathematicalpointofviewtothe so-called limit cycles. However electronic oscillators are fascinating circuits in many sense because the progress in manufacturing technologies of electronic devices and circuits led to new challenges in oscillator modeling and new mathematical concepts for solving the descriptive the oscillator as electronic noise. As a result electronic oscillators have to be modeledbydrivennonlinear stochasticdifferentialequationswithlimit cycletypesolutions. In most cases analytical solutions for this type of equations are not available and approximation concepts have to be developed. From this point of view electronic oscillator circuitsareuntilnowasourceofinspirationfornew mathematicaland physicalconcept;see e.g.Guckenheimer[2].Fig.(1).Dissipativestructure.

However for the oscillator circuit design not only approximative solutions of certain descriptive equations are needed since at the first stages of a design process only very few circuitparametersareknown.Notethatacircuitdesignconceptconsistsoftwostepswhere it is startingfrom the specifications ofa circuit under design.These specifications areclosely related to the solutions of the descriptive equations of the designed circuit. In a first design step the circuit architecture - circuit shape (O'Dell [3]) - has to be chosen whereas in the secondstepthefreeparametersofthiscircuitshape havetobedetermined.Thereforeifnot all circuit parameters are available it is even not possible to know whether the descriptive equations possess oscillatory or limit cycle solutions.

ForthisreasonMandelstamandPapalexi[4]developedin1931theconceptofparametrized descriptiveequationsforoscillatorcircuitsbasedonideasoftheFrenchmathematicianHenry Poincare. This concept was also the basis for the bifurcation theory of electronic oscillators; today it is called Andronov-Hopf theorem in the theory of dynamical systems. In contrast to the quantitative analysis of nonlinear differential equations this theorem studies these equations from a qualitative point of view. By means of the qualitative analysis we are able to consider the qualitative change of different types of solutions of nonlinear differential equationsindependenceoncertaincircuitparameters.In thecaseoftheAndronov-Hopf

theorem the change from an equilibrium point to a limit cycle is explained. Although this theorem is known in electronic oscillator analysis since 1935 [5] (see Maggio et al. [6] for a more recent publication) it was never used for a systematic design process of electronic oscillators until recently; see Mathis & Russer [7], Prochaska et al. [8]. As mentioned above the circuit description with parametrized equations is well suited for the second step of the designprocessandthereforetheAndronov-Hopftheoremshouldbeusedindesignprocesses for electronic oscillator circuits; a first concept idea was presented by Mathis [9].

II. Literature Review

A-EarlyOscillator Circuits

Sincein1895Marconishowedforthefirsttimethatthelaboratoryarrangementof Hertzcan be used for the wireless transmission of information along larger distances more powerful electrical arrangements were desired. Around 1900 several researchers (e.g. Thompson, Tesla, Slaby, Braun, von Arco and others) suggested improved versions of Marconi's arrangement.ProbablyitwasamilestoneasDuddelpublishedhispaper“Onrapidvariations in the current through the direct-current arc” [10] where he used results of the German physicist Simon [11]. A few years later Poulsen improved Duddel's oscillatory generator substantially from a technical point of view and as a result he presented in 1906 a new powerfularrangementwithanarcaselectronicdevicefor wirelesstransmissionoftelephony signals. For further studies we refer to Blake [12] and Nesper [13]. Although the physical processes in arcs are rather difficult to understand at this time because of their electronic nature reasonable nonlinear models were developed by Kaufman, Duddel, Simon, Wagner andothers.InthedissertationthesisofWagnermanyaspectsofsuchcircuitswerediscussed [14]. Using these results Zenneck [15], a former co-worker of the above mentioned Braun, published in 1914 an interesting paper where he studied the start-up behavior of such RLC circuit including a nonlinear arc device. In contrast to his predecessors he described the behaviorofthecircuitbymeansofanonlineardifferentialequationthatdescribedtheenergy (or power) balance. After solving this equation he got the approximative solution that is similar to the approximative of the vander Pol equation which was discovered several years later by van der Pol in the analysis of triode oscillators. From a mathematical point of view Zenneck'sbalanceequation correspondstoanapproximativefirstintegralofthevander Pol equation. Zenneck's paper was also the first that studied the start-up behavior of oscillatory circuits in more details. Further details are considered in an other publication [16]. Circuits including sparks or arcs were the first successful generators for oscillatory currents. These electroniccircuitshadseveraldisadvantages.Although engineersandphysicistsintheleading industrial companies (e.g. Marconi Comp., Telefunken, AT&T, Western Electric Comp.) tried to improve these circuits by using interesting ingenious ideas the robustness of these arrangements as well as their transmitting power were rather restricted. Therefore a new generation of generators applied and now nonelectronic principle to get high-power oscillatory currents. For this purpose the static frequency doubling effect which was studied by Epstein, Joly and Vallauri was used for the development of rotating alternators (seeKühn [17], Meißner [18]). These generators had much better properties than the spark or arc circuits. Only the frequency of oscillatory waves generated by these electrical machines was restricted. However at thistime transmitting stations worked withlong waves. Around 1925 thesituationwaschangedastheHeavisidelayerwasobservedbynonprofessionalusersusing transmitting stations with short waves. Within this range of frequencies rotating alternators cannotbeapplied.Moreovershortwavesdidnotneedhigh-powertransmittingstationssuch thatthepowercanbereducedforthesefrequencies.Asaconclusionelectronicvacuumtubes were used to build generators with oscillatory behavior for powerful transmitting stations.

B-TubesandOscillators

First ideasfor a new electronic device werepublished by Fleming in 1904. For the invention ofhisthermionicdiode(orFlemingdetector)heusedreseearchresultsintheareaofemission and transport of electrons (Edison effect, Richardson, Wehnelt; see Johannsen [19]) in vacuum although the physical details were not well-known at this time. A modulation of the current in Fleming's thermionic diode was achieved by adding a grid. This was done by de Forestin1906.ThiselectronicdevicewascalledbydeForestasAudion[20].Inthesameyear v. Lieben presented a patent oftriode type ofamplifier valve[21] that was improved by him inapatentfrom1910togetherwithReiszandStrauß[22]. Theaudionaswellasthe"Lieben- valvewerethree-poledeviceswithcathode,gridandanode.IncontrasttodeForest'saudion the"Lieben-valvewasfilledwithmercury.ThereforeLieben'svalve wascalled"gasrelay"and deForest's"electronrelay"(audion).Thisdifferenceremaineduncleear inthefollowing years and led to many discussions; see e.g. Armstrong [23] (p. 220) and Meißner [24] (p. 65). Furtherreferencescanbefoundinapaperof Tucker[25]; seealsoJohannsen[19].Afterthe discovery of these triode valves it lasted further six years until first practical circuits were available. The first two classes of circuits were amplifiers and oscillators. Several groups in Germany, USA, United Kingdom, and Austria were participated in these activities and there were many relationships between thesegroups. Thereforeit isdifficult tosolvethe problem of priority with respect to the different electronic circuits; see e.g. Tucker [25], Johannsen [19], Barkhausen [26](part II, pp.112), Meißner [24], and Skowronnek [27]. In1913Meißner presented a first high frequency transmitter including an electronic oscillator with a von Liebentube(Fig.2).Itshouldberemarkedthattheprinciplesofthermionicconductionwere studied based on physical foundations by Langumir.

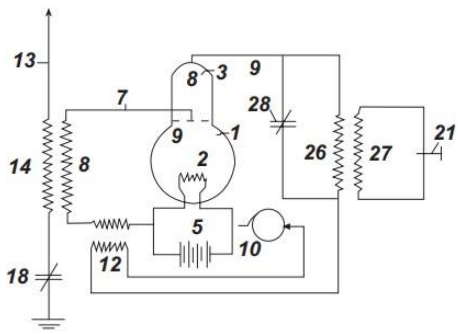


Fig. (2). Meißner's oscillator with a v. Lieben tube.

Afirstexampleofanelectronicoscillatorswithavalvewhichisthemainsubjectofourpaper wasinventedbetween1912and1913wherethedifferencebetweenDeForest'saudionand the Lieben-Reisz valve is not considered (but see remarks of Meißner [24] (p. 65) and Hazeltine[30](p.98)).InagreementwithHazeltine[30]itseemsthatMeißnerandArmstrong hadsimilar ideas atthe same time withrespecttoanoscillating circuitincluding avalve.The corresponding comments of Tucker [25] are a little bit obscure. Since the problem of the design of electronic circuits and especially oscillators with valves in order to transmit electromagnetic waves and receive them wasa main subject in all militarylaboratories in all industrialstateswhichareinvolvedinthefirstworldwar manyinformationbecameasecret. At the end of this war several electrical engineers and physicists published their results with a delay of one or more years (see corresponding remarks in the papers of Hazeltine [30], Barkhausen [26], Meißner [24] and others did not have an opportunity to publish it, just like Colpitts or Hartley). Hazeltine [30] (p. 98) gave some more references to interesting collections of oscillating circuits. Obviously at the end of the first world war many different oscillator circuits were known and several authors began to publish their theoretical results about this interesting class of electronic circuits**.**

C.DescriptiveEquationsforElectronicOscillators

Probablythefirsttheoreticalpaperabout electricaloscillatorswithavalvewaspublishedby Vallauri [31] which was published in German some montha sinusoidal oscillatory behavior already exists. By means of this approach Vallauri got "the exact determination of the conditionsforoscillationsinanaudioncircuit".Afterthe publicationofthispapermanyothe authors presented results that are more or less equivalent. These results were different in modificationsofthevalvemodelorthedecompositionan ditsinterpretationofthelinearized

oscillatorcircuit.Wewouldliketomentiononlythecom prehensivepapersofHazeltine[30], Heising [33] and Barkhausen [26]. The different approaches were compared by Albersheim [34]. Unfortunatelyitwasknownalreadybefore1920thatalin ear theory cannot becompletefor describingallaspectsofelectronicoscillators.Whereast heconditionsofoscillatorybehavior can be derived by a linear model a nonlinear model is essential to determine the amplitude oftheseoscillators.ThisstatementwasgivenbyMöller[29]inaverysimilarmanner(p.331). Based on the idea of the feedback principle for the functionality of electronic oscillators this author developed a theory for these circuits that used again the idea of a power balance equation (just like Zenneck in 1914 for the case of oscillator circuits with an arc). For this purposeMöllerdevelopedaconceptthattakesintoconsi derationonlythefirstharmonicsof the oscillatory behavior and anonlinear differentialequation for the circuit was not derived. As a result he got the method of the "oscillatory characteristic" (in German "Schwingkennlinie") that can be interpreted now as a variant of the harmonic balance or averaging method. Some remarks to the history of this methods can be found in the monograph of Sanders and Verhulst [35] (pp. 181).

Again other authors presented similar approaches that correspond to the fundamental mathematicalproblemofnonlinearoscillatorysystems ornonlineardifferentialequations.In contrasttoMöller'sapproachvanderPol[36]derivedinh isdoctoratethesisforthefirsttime a nonlinear differential equation for an oscillatory electrical circuit and especially for an electronicoscillatorcircuitincludingatriodevalve.Furt hermorehewasabletoapplyaspecial perturbation method that resulted in a solvable nonlinear differential equation. It was a variantofanaveragingmethod(Lagrange'ssecularpertu rbationmethod)thatwasknownto van der Pol from his studies in physics. In his famous paper from 1920 he states that the equationunderconsiderationiscloselyrelatedtosomepr oblemswhichariseintheanalytical treatment of the perturbation of planets by other planets." The differential equation of van der Polbecamean eminentimpact toa newmathematicaldiscipline"nonlinear oscillations" andattheendthemathematicaltheoryofdynamicalsyste ms.Ontheotherhandwehaveto emphasize that although interesting from a theoretical point of view van der Pol's equation wasnotusefulinpracticalsituationsatthistimefortwore asons:1)Graphicaldifferentiations ofhigherorderarise.2)Onlyinthesimplestcasesthepert urbationmethodleadstoasolvable differential equation. In other cases only the steady amplitudes can be calculated. AlthoughMöller'smethodleadsalsototediouscalculati onsansemi-analyticalapproachwas presented by Joos [37]. This author started with a good analytical approximation of the characteristic curves in form of an arctan-function and as a result he got another kind of oscillatory characteristics that didnot include circuitparameters orvalve constants.But also thismethoddidnotbecomepopular.Between1920and1 929onlyveryfewscientificgroups triedtodevelopnewimpactstothetheoryofelectricalosc illators.Oneofthefewexceptions werevanderPolandAppleton.Theypublishedveryinter estingpapersabouttheentrainment problem,forcedoscillationsandonrelaxationproblems aswellasotheraspectsofnonlinear oscillators.

Themainresultsoftheseauthorsarecontainedinvander Pol'sreviewpaperfrom1934[38]. A new era of oscillator theory began as the Russian school of Mandelstam and Papalexi entered this area. Although Papalexi had published a book about "The Theory of Oscillators withElectronicValves"in1922andMandelstamwasalr eadyawell-knownscientistwhowas involved also in aspects of wireless transmission of electromagnetic waves they considered electronic oscillators from a new point of view. In 1929 Andronov who had Mandelstam as hisacademicteacherpublishedabriefpaper[39]whereh eappliedPoincare'stheoryoflimit cycles to the van der Pol equation. Another paper together with Witt [40] followed in 1930. Inafurtherpaper[41]thesetwoauthorsshowedthatPoin care'stheoryisusefulforstudying rather difficult aspects ofthe entrainment effect innonlinear oscillations. By means of these resultsitcouldbeshownthatthetheoryoflimitcyclesofP oincarewasasuitableframework tostudyproblemsinnonlinearoscillations.Anotherimp ortantsteptowardsanunifiedtheory of nonlinear oscillations was the introduction of parametrized nonlinear differential equations and again Poincare's ideas were used. Mandelstam and Papalexi showed [4] that first aspects of a theorem that is now called Andronov-Hopf theorem and describes a bifurcationofalimitcyclefromastaticequilibriumpoint. Theseideasbecameabigimpactin Russia for the theory of nonlinear oscillations and several very active groups studied many aspectsofthisproblem.Thereferencesofthefamousboo kofAndronov,WittandChaikin [42]firstpublishedin1937illustratesthisexcitingarea.I nareviewpaperfrom1935 Mandelstam, Papalexi, Andronov, Chaikin, and Witt [5] presented a complete concept of nonlinearoscillationsthatcontainsalreadyalmostallmo dernaspectsofthistheory;seealso Mathis [43] and inparticular the papers of Bissell[44],Aubin,Dalmedico[45] andPechenkin [46].ItshouldbementionedthatatthesametimeKrylova ndBogoliubov[47]developedthe mathematicalfoundationsofaperturbationtheory foroscillatorydifferentialequationsthat is known now as averaging method or harmonic balance. It lasted more than 40 years until this subject was considered by Mees and Chua [48] in 1979. Afterwards Andronov-Hopf bifurcation became an essential subject in the theory of electrical circuits (e.g. Mathis [16]). It should be remarked that in higher dimensional systems ($d > 2$) additional methods are needed.

Example: Design of a 2.4 GHz LC-Tank VCO In this section we show the application of our proposed design concept to a practical oscillator design. The desired specifications are shown in Fig. (5) (a 0.25µm RFCMOStechnologyfrom IHP(SGB25V) is used).An inductor witha series inductanceofLi,s = 11.1nH is chosen for the requested frequency range. Using our proposed model for the voltage dependent varactor capacitance [64] we are able to approximate the varactor dimensions. Fig. (6) shows an approximation of the frequency characteristic of the VCO in dependency of the varactor width Wv. Our calculations show, that as a first estimation a varactor width of Wn = 150µm is an appropriate choice for the requested frequency range (Fig. 5)

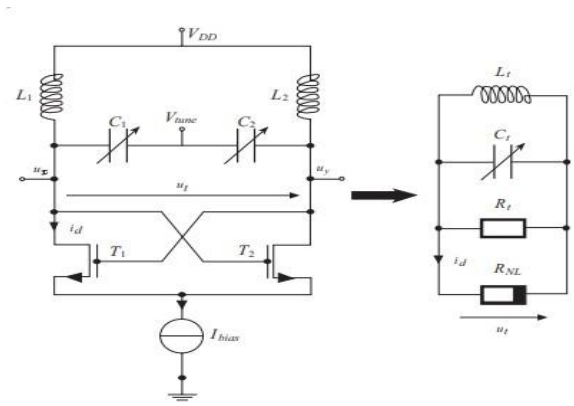


Fig. (4). LC-tank voltage controlled oscillator.

Setting Lv to two times the minimum channel length is a good compromise between series resistance and Cv,max/Cv,min ratio [65]. In order to minimize the parasitic resistance the lengthofthetransistorpairLnissettotheminimumchann ellength.WesetthevalueofIbias to the maximum value allowed by the specifications in order to maximize the output amplitude and optimize the phase noise characteristics of our VCO [66]. All design variables have been determined except the width Wn of the transistor pair. It is guaranteed that a variation of the width of the transistor pair Wn leads to a stable limit cycle as was shown in theprevioussection.Usingexpression(7)itispossibleto calculatetheneededwidthWn.We findthebifurcationpointandthereforethestartingpointo fastableoscillationataparameter valueofWn=2.03µm.IncreasingWnleadstoanexpansi onofthelimitcycleandaccordingly to a rising of the oscillation amplitude (8) (Fig. 6).

HigherDimensionalStateSpaceRepresentation

Ahigherdimensionalstatespacerepresentationallowst heinclusionofotherparasiticeffects and structural enhancements in comparison to the 2-dimensional state space modeling. Examples of possible parasitic effects could be the nonlinear effects of the cross-coupled transistorpairorsubstrateeffectsforinstance.Anexamp leforastructuralenhancementthat couldbeincludedinthemodelingusinghigherdimensio nalstatespaceequationsisafiltering capacitanceparalleltothecurrentsource(Fig.8).Inorder tocarryoutthebifurcationanalysis of an sinusoidal oscillator

Param.	Spec.	Achieved
f_0	2.4 GHz	2.4 GHz
V_{DD}	2.5 V	2.5 V
I_{bias}	≤ 1 mA	1 mA
TR	≥ 20 %	34 %
v_t	≥ 1 V	≥ 1.37 V
C_{load}	≥ 100 fF	100 fF

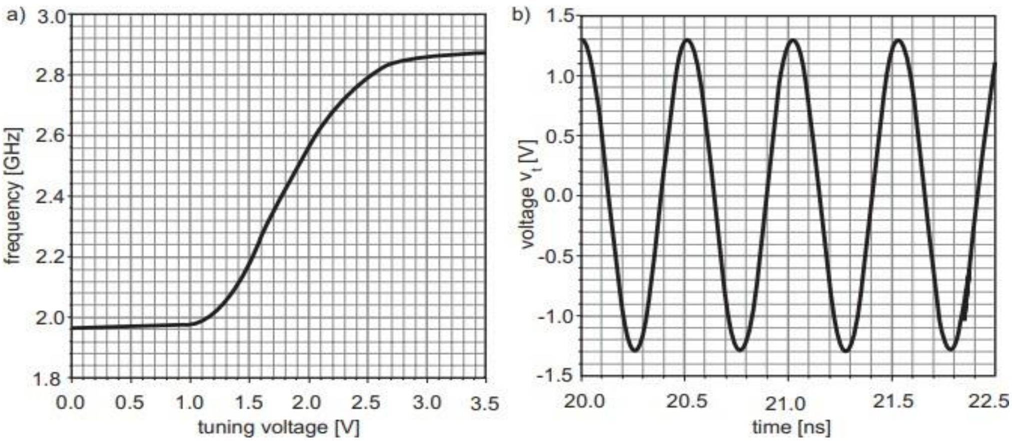
Inductor		
Param.	Maple	Cadence
$L_{l,p}$	11.16 nH	-
$C_{l,p}$	16.6 fF	-
$R_{l,p}$	1824 Ω	-

Transistor Pair		
Param.	Maple	Cadence
W_n	> 2.03 µm	> 3.05 µm
L_n	250 nm	250 nm
R_0	10 kΩ	9.84 kΩ
C_{NMOS}	3.97 fF	3.77 fF

Varactor		
Param.	Maple	Cadence
W_v	150 µm	140 µm
L_v	500 nm	500 nm
$R_{v,p}$	3222 Ω	-
C_{v0}	378 fF	-

Fig. (5). Specifications and design parameters for $V_{tune} = 0$.

Thecentermanifoldapproachforsimplifyingdynamical systemshasa nicegeometricinterpretation. Furtherinvestigationsofthereducedsystemwithanalyticalmethodsarewell-knowninsystemtheory [2]. The following methods are predestinated for the use in common with center manifolds because they are formulated only in the 2- dimensional case or easier to handle in that dimension



III. CONCLUSION:

The essential steps of a systematic concept for the design of electronic oscillator circuits. It can be shown that by means of advanced mathematical methods the intrinsic nonlinear problem of oscillator design is manageable. Using a high-efficient computer algebra system (e. g. MAPLE or MATHEMATICA) semi-analytical expressions for the oscillator design can be derived.

Based on previous work further research will be done in order to develop a computer aided design for electronic oscillators in the GHz area. It is our goal to enable expert analog designerstodesignoscillatorsbymeansofavarietyofwell-adaptedtoolsinsteadofageneral purpose circuit simulator.

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