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SOLITON WAVE GENERATION ON NONLINEAR TRANSMISSION LINES USING A PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

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Abstract: In this article, analysis, designing, and generation of soliton waves are performed using nonlinear transmission lines (NLTLs). As a result of performing mathematical analysis processes, circuit parameters and values are determined. A particle swarm optimization (PSO) algorithm is used to determine the parameters and their values. The parameters obtained from the optimization are used to design a nonlinear transmission line. The circuit designed over the determined parameters is simulated with the LTspice program. Then, experiments of the created circuit design are carried out. The simulation data and the experimental implementation data are compared for the nonlinear transmission line circuit. Simulation and experiment results are found to be compatible.

Keywords: Soliton, electric soliton oscillator, soliton generator, nonlinear transmission line (NLTL), particle swarm optimization (PSO)

Parçacık Sürü Optimizasyon (PSO) Algoritması Kullanılarak Doğrusal Olmayan İletim Hatlarında Soliton Dalga Üretimi

Öz: Bu makalede, doğrusal olmayan iletim hatları kullanılarak, soliton dalgasının analizi, tasarım modellemesi, ve üretimi gerçekleştirilmiştir. Matematiksel analiz işlemlerinin gerçekleştirilmesi sonucu devre parametreleri ve değerleri belirlenmiştir. Parametreleri ve değerlerini belirlemek için parçacık sürü optimizasyonu (PSO) algoritması kullanılmıştır. Optimizasyon sonucunda elde edilen parametreler kullanılarak doğrusal olmayan iletim hattı tasarlanmıştır. Belirlenen parametreler üzerinden tasarlanan devre, LTspice programı ile simüle edilmiştir. Daha sonra, oluşturulan devre tasarımının deneyleri gerçekleştirilmiştir. Doğrusal olmayan iletim hattı devresinin; simulasyon verileri ile deneysel gerçekleme verileri karşılaştırılmıştır. Simulasyon verileri ve deneysel gerçekleme verilerinin uyumlu olduğu görülmüştür.

Anahtar Kelimeler: Soliton, elektrik soliton osilatör, soliton üreteç, doğrusal olmayan iletim hattı, parçacık sürü optimizasyonu(PSO)

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1. INTRODUCTION

Soliton waves produced by using nonlinear transmission lines (NLTLs) can be used for data transfer in communication systems, military radar systems, and advancing humanoid robot studies. In addition; It can be used in communication, modulating the signal and carrying this modulated signal over long distances.

The first observation of the soliton was due to natural phenomena. The first observed soliton was the result of a water wave traveling along a narrow and nonlinear channel (Russell,1845). Another example of soliton formation is fiber optics where nonlinear waves are observed. Soliton production in systems used in fiber optic studies is done with nonlinear optical elements (Hasegawa and Tappert ,1973). Soliton waves produced by electrical soliton systems are implemented using nonlinear transmission lines and nonlinear electronic elements (Ricketts et al.,2006; Yildirim et al.,2009; Yildirim and Ham,2014; Aziz et al.,2020). A self-starting nonlinear circuit is designed using ambient noise to generate a soliton pulse. (Ricketts et al.,2006; Ricketts et al.,2007). Soliton waves are produced by the propagation of a rectangular wave given at the input along a nonlinear line (Neto et al.,2020; Neto et al.,2016; Elizondo-Decanini et al.,2015; Nikoo et al.,2017; Aksoy and Yenikaya,2021). In the NLTL design, soliton wave generation was made for different linear inductor values (Xie et al.,2018). A soliton wave was generated using hybrid NLTL (Rossi and Rizzo,2009; Neto et al.,2018). Soliton generation has been carried out for high power at microwave frequencies (Ikezi et al.,1988; Brown and Smith,1997; Darling and Smith,2008). The soliton wave generation performances of the rectangular, half-sine, and triangle waves given in the introduction were examined and it was seen that the rectangular wave was the most appropriate (Rangel et al.,2016). RF soliton waves with a frequency of 200MHz were produced, and double-backed horn antennas were used to radiate this RF wave (Raimundi et al., 2018). Theoretical analyzes were made for the NLTL line and soliton wave generation was performed using the results of these theoretical analyzes (Nikoo et al.,2017; Nikoo et al.,2018). They modeled a soliton generator design that can generate soliton waves without continuously using the rectangular wave given at the input (Azad et al.,2020).

In this study; An approach is proposed to predetermine the central frequency value resulting from soliton wave generation in lossless situations in NLTL circuits. Firstly; in NLTL, mathematical analysis results of soliton waves are used for central frequency values. Then, by using mathematical analysis result equations, circuit parameters, and circuit element values are decided, and the PSO algorithm is used for these determinations. Its difference from other studies in the literature is that the PSO algorithm is used and soliton waves can be produced at desired central frequency values. NLTL element values are determined by optimizing the circuit using the PSO algorithm. NLTL line circuits are set up for the determined circuit element values. The simulation applications of the established NLTL circuits are modeled. Then, the experimental application of the nonlinear line circuit is carried out. The compatibility between the simulation results and the experimental application results for the modeled circuit is also clearly seen with the data obtained using the PSO algorithm.

This paper is organized into 6 sections. In Section 2, theoretical analysis has been performed for NLTLs. Section 3, the PSO algorithm used in circuit design is introduced. Section 4, the simulation application of the modeled circuit is performed using the data obtained as a result of the PSO algorithm. Section 5, experiment results are shown for the circuit that is simulated. Finally, section 6 comprises the conclusion.

2. THEORITICAL ANALYSIS OF THE NONLINEAR TRANSMISSION LINES AND ELECTRICAL SOLITON

The basic elements of NLTL circuits are inductors and capacitors. At least one of these two basic elements in the NLTL circuit must be a nonlinear element. Nonlinear capacitors and linear inductors are used in our theoretical analysis.

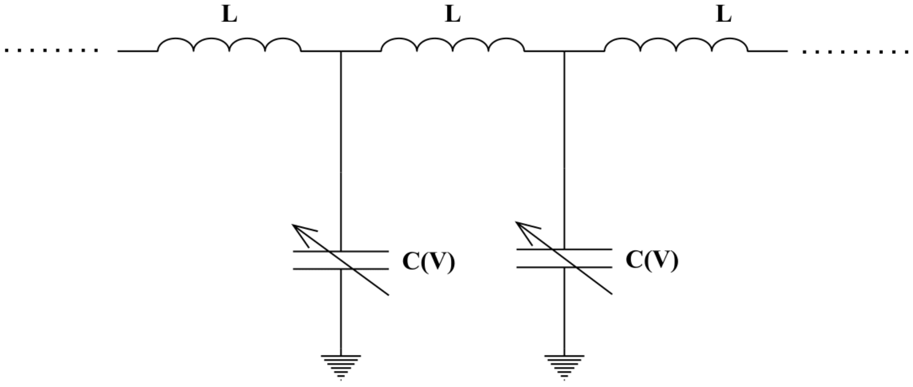

Figure 1:
Basic NLTL design modeling

The model used in the basic NLTL design is shown in Fig. 1. In this circuit, inductors (L) and capacitors (C(V)) are shown, which is formulated in Eq. (1) and Eq. (2). In Fig. 1, the circuit elements used for NLTLs are the linear element inductor, and the nonlinear element is the capacitive diode. This circuit is section of the larger NLTL. The basic characteristic Eq. (1) of the nonlinear capacitor is as follows.

$$C(V) = \frac{C_{jo}}{\left(1+\frac{V}{V_j}\right)^M} \tag{1}$$

In this equation, V; input voltage value, V_j; diode voltage, C_{jo}; unbiased diode junction capacitance, and M; referred to as the nonlinear factor. V_j, C_{jo}, and M are the values found over datasheet for each nonlinear capacitor. The NLTL characteristic impedance formula is as follows (Nikoo and Hashemi, 2017).

$$Z_{NLTL}(V_i) = 0.73\sqrt{\frac{L}{C(V_i)}} \tag{2}$$

In Eq. (2); the characteristic impedance (Z_{NLTL}) formula is given for NLTL, which is shown in its simple form in Fig.1. and its general form in Fig.3. L; is the inductor value, V_i ; is the revised input value, and $C(V)$; is the nonlinear capacitor value given in Eq. (2).

One of the important parameters for the waves produced on the NLTL is the frequency. The central frequency formula for lossless circuit of soliton waves described in Fig. 2 is as in Eq. (3) (Nikoo et al.,2018).

$$f = \frac{0.34}{1+\sqrt{n/220}} \frac{1}{\sqrt{LC(V_i)}} \frac{R_{Load} + 0.33Z_{NLTL}(V_i)}{0.89R_{Load} + 0.49Z_{NLTL}(V_i)} \tag{3}$$

Eq. (3) shows the central frequency formula for load on the NLTL in Fig. 3. Besides, a simple visualization in Fig. 2 is presented for a result of the Eq. (3). L; inductor value, C(V); nonlinear capacitor value, R_{Load}; load impedance, Z_{NLTL}; characteristic impedance found in Eq. (2), n; describes the number of each element. At the same time, this equation is the basic formula used for the optimization algorithm.

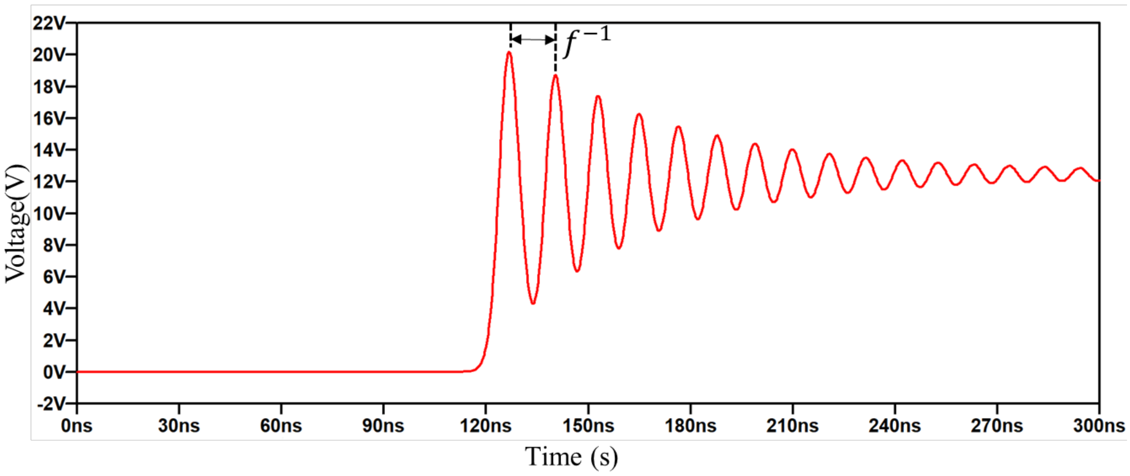

Figure 2:
Sample of a soliton wave generated at the end of the NLTL line

3. NLTL DESIGN USING PSO ALGORITHM

In order to solve different systemic problems in daily life, we may need to try many situations using trial and error methods. In this case, since the use of trial and error methods will cause time and cost less, the use of optimization algorithms will be efficient. There are different optimization algorithms in the literature, which are examples of many studies, some of which are PSO, genetic algorithm (GA), and differential evolutionary (DE) algorithm. The PSO algorithm, which we used in this study and also used in many other studies, has been the reason for preference in terms of its success in problem-solving and ease of implementation.

In previous studies; the NLTL circuit is designed using the trial and error method, taking the theoretically found equations as reference. However, this is inefficient in terms of time and circuit element cost. In this study; before the NLTL circuit is designed, the PSO algorithm is used to determine the circuit element values at the desired frequency.

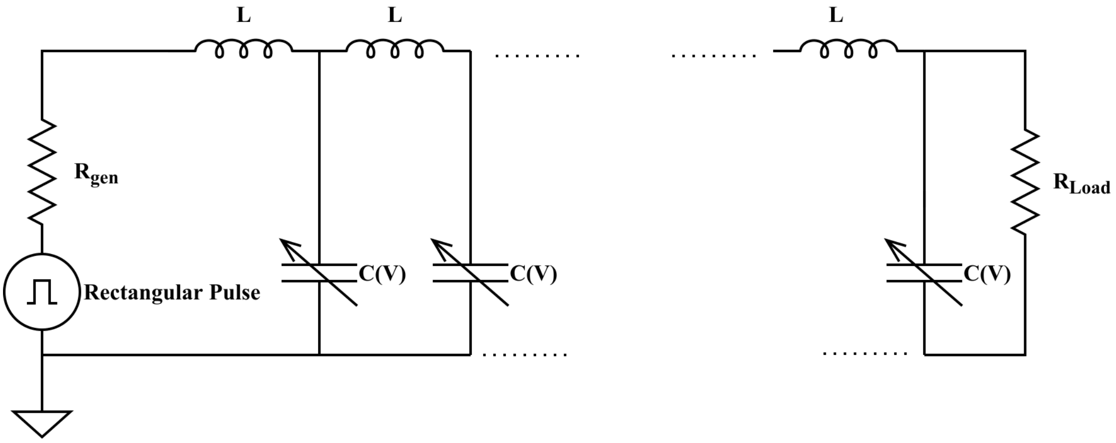

Figure 3:
Standard Nonlinear Transmission Line used to produce for soliton wave.

In Fig. 3; the circuit is an example NLTL design which is used for soliton generation. The rectangular signal given at the input, the source resistor $\mathrm{R}_{\mathrm{gen}}$, inductor, the diode as the nonlinear element, and the load resistor R_{Load} constitute our NLTL circuit.

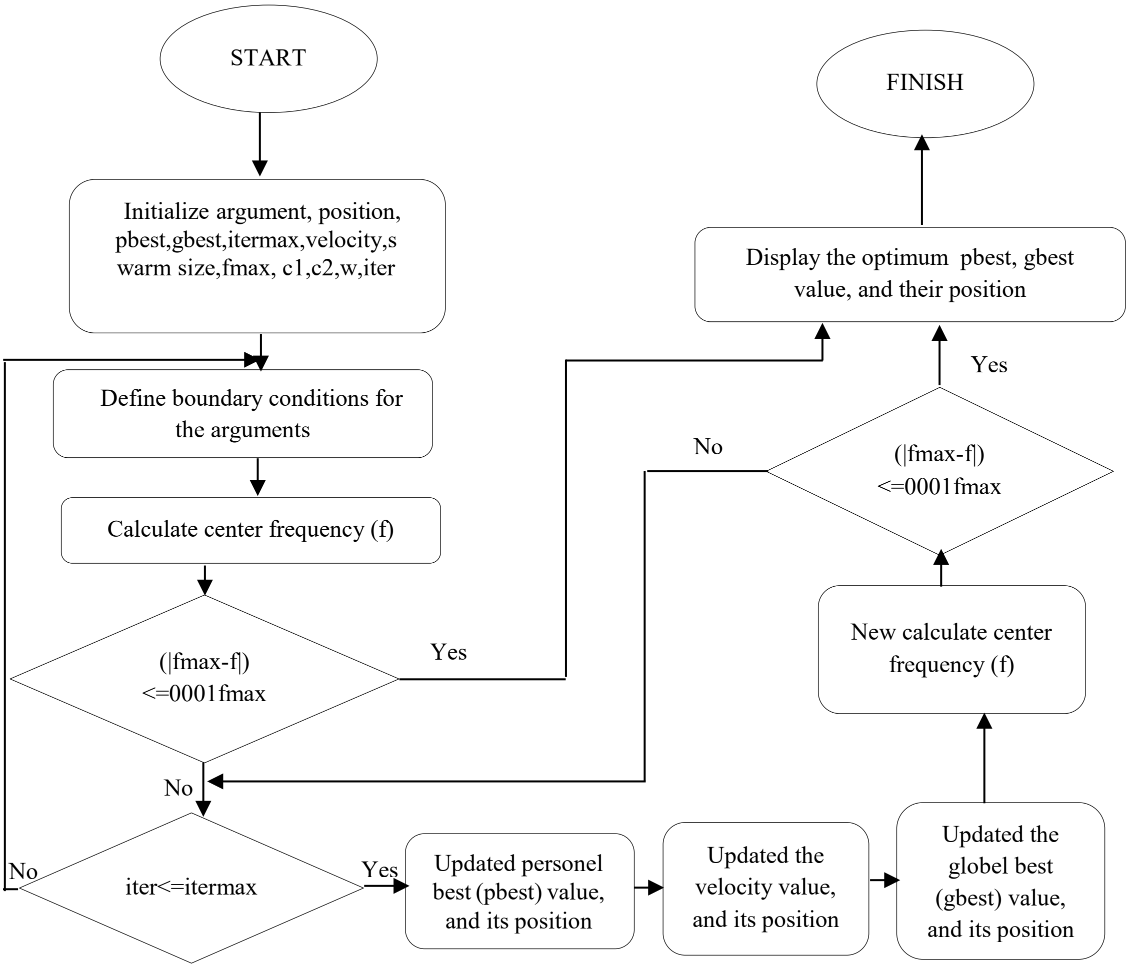

Figure 4:
PSO algorithm used for soliton wave modeling

The flow chart of the PSO algorithm used in this study is shown in Fig. 4. Firstly, in Fig. 4; in the PSO algorithm whose diagram is shown, nonlinear capacitive diode parameters, maximum central frequency value (fmax), personel best (pbest), globel best (gbest), velocity value, maximum iteration (itermax) value, initial values required for optimization are explained. The c1,c2,w values are the constants used for the velocity values in the PSO algorithm, which can be important for faster results. From the initial values required for PSO; c1 and c2; 2, w is chosen as 0.99. The initial velocity is zero, the itermax value is 1000. Initial fmax values are chosen as (17,20,30,70) MHz, respectively. Later on; we created our first version by determining the value ranges of the inductor, input voltage and total circuit elements separately and randomly. R_{Load} value is determined as 1000Ω. Inductor (L) value range is adjusted between 0.1µH and 100µH, revised input voltage (V_i) value range is between 0.1V and 30V, number of circuits element (n) range is from 2 to 40. The central frequency value is calculated in Eq. (3). If the fmax frequency value given at the beginning, and the central frequency value calculated in the Eq. (3) are almost equal, the most suitable parameter values are found. If different; enters iteration. If it does not satisfy the iteration condition; the loop returns to the beginning and the iter value is reset. If it satisfies the iteration condition; firstly, the best value and position of pbest will be updated. Velocity values and positions are updated. Maximum speed values are calculated for 3 different parameter values: these are; inductor value, input voltage, number of circuit elements. The global best(gbest) values and locations are updated. The new central frequency value is calculated according to the updated values. The equality between the maximum frequency value determined at the beginning and the calculated central frequency value is checked and if different, the iteration is repeated. If the values are equal, the most appropriate pbest and gbest values are displayed. The circuit is modeled for the most suitable NLTL design elements found. Thus, there is an inductor, input voltage and a set of circuit elements for the desired center frequency. As a result of PSO; the NLTL design is carried out without any trial and error method.

Created with PSO algorithm; parametric results obtained for the determined central frequency values; shown in Table 1, Table 2, Table 3 and Table 4 below.

Table 1. PSO algorithm design results for 17MHz frequency

Designed circuit model	Inductor value (µH)	Revised input voltage value(V)	Each of circuit element value	Suitable diode type
D1	L=5.6	8.00	n=7	1N5819
D2	L=7.86	3.02	n=13	MV2109
D3	L=38.0	14.63	n=26	BB910
D4	L=7.80	2.60	n=18	MV209
D5	L=24.0	9.18	n=7	ZC744

Table 2. PSO algorithm design results for 20MHz frequency

Designed circuit model	Inductor value (µH)	Revised input voltage value(V)	Each of circuit element value	Suitable diode type
D1	L=3.10	7.21	n=21	1N5819
D2	L=6.40	5.60	n=13	MV2109
D3	L=5.60	1.40	n=22	BB910
D4	L=8.80	6.78	n=31	MV209
D5	L=7.20	1.21	n=35	ZC744

Table 3. PSO algorithm design results for 30MHz frequency

Designed circuit model	Inductor value (µH)	Revised input voltage value(V)	Each of circuit element value	Suitable diode type
D1	L=4.30	29.75	n=7	1N5819
D2	L=4.50	12.65	n=12	MV2109
D3	L=6.40	3.46	n=8	BB910
D4	L=6.0	8.86	n=17	MV209
D5	L=7.10	12.1	n=28	ZC744

Table 4. PSO algorithm design results for 70MHz frequency

Designed circuit model	Inductor value (µH)	Revised input voltage value(V)	Each of circuit element value	Suitable diode type
D1	L=0.50	20.1	n=22	1N5819
D2	L=0.70	4.72	n=4	MV2109
D3	L=2.70	9.51	n=9	BB910
D4	L=0.72	3.74	n=12	MV209
D5	L=2.13	17.1	n=6	ZC744

In the tables; inductor value, revised input voltage value, element number of each inductor and capacitive diode, nonlinear diode types are explained. Each table is obtained for different center frequency values. Table 1; 17MHz(≈58ns), Table 2; 20MHz(50ns), Table 3; 30MHz(≈34ns), Table 4; 70MHz (≈14ns), shows the circuit element parameters resulting from the PSO algorithm for the central frequency value.

4. SIMULATION RESULTS

Using the PSO algorithm; 4 different table results are shown for different frequency values in NLTL circuits. The circuits are established for the NLTL element values determined by using the results from the tables. NLTL circuits are simulated for each design model.

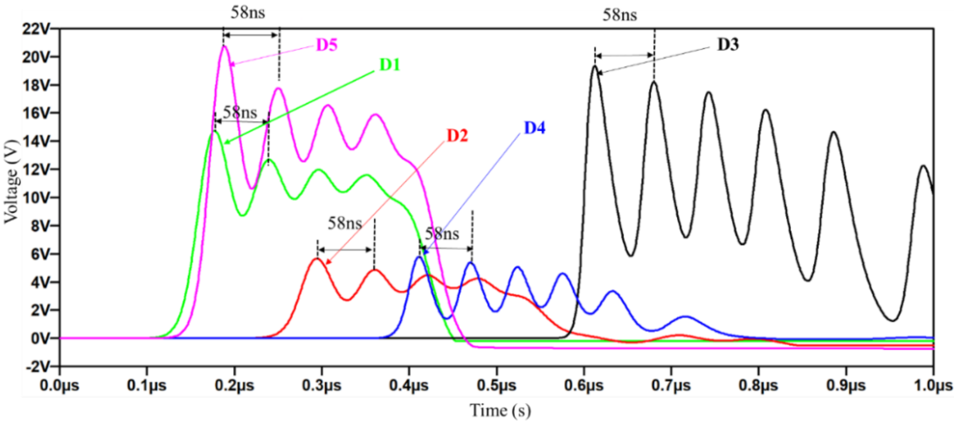

Figure 5a:
Simulation results for alternate designs shown in Table 1

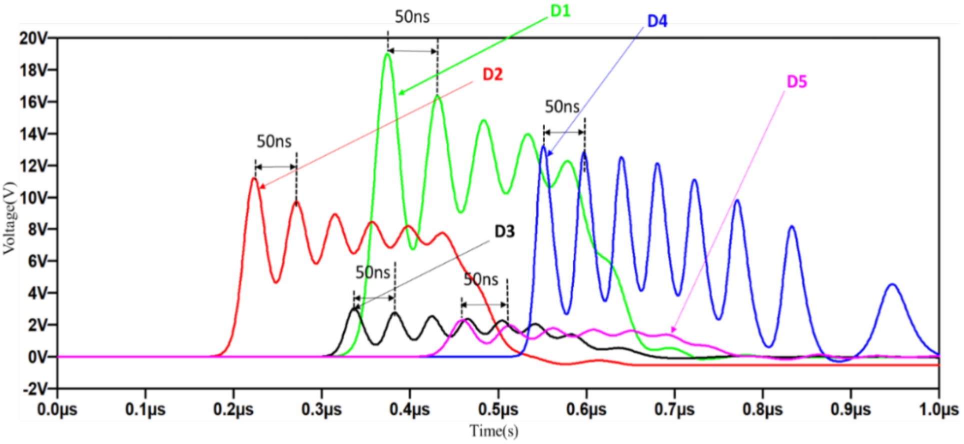

Figure 5b:
Simulation results for alternate designs shown in Table 2

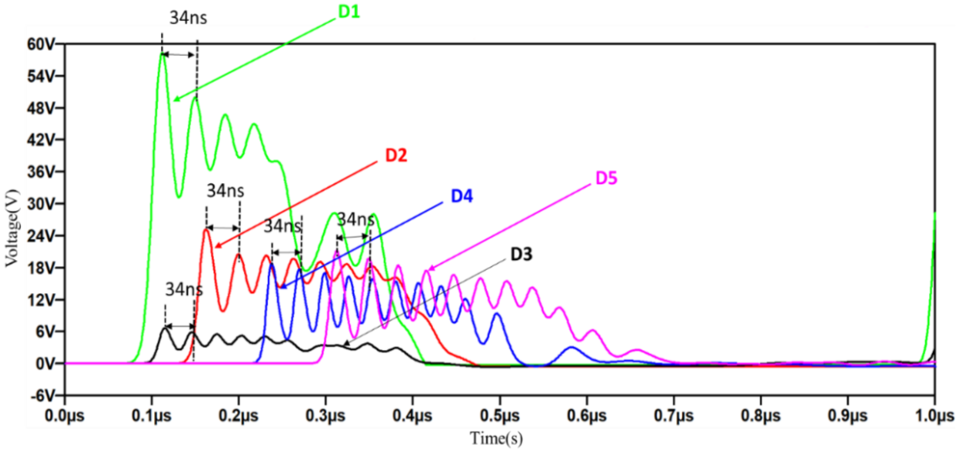

Figure 5c:
Simulation results for alternate designs shown in Table 3

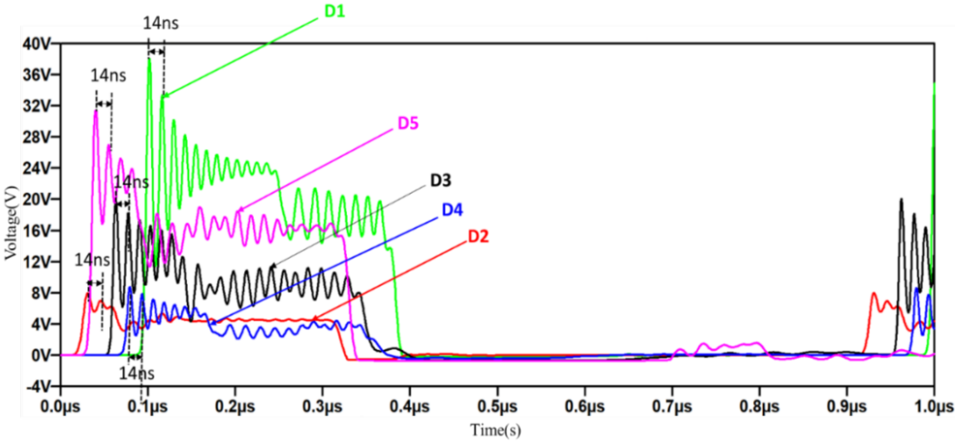

Figure 5d:
Simulation results for alternate designs shown in Table 4

According to the Fig. 5a,5b,5c, and 5d; by using the Eq. (3), simulation results for different center frequency values in the result of the PSO algorithm are shown. Table 1; Fig. 5a, Table 2; Fig. 5b, Table 3; Fig. 5c, Table 4; Fig. 5d are shown the design model figures. Morever; based on the result values of the tables, simulations are carried out for different circuit designs such as D1, D2, D3, D4, and D5 at desired frequencies. Frequencies used for the performed samples; it is selected as 17 MHz(≈58ns), 20MHz(50ns), 30MHz(≈34ns), and 70MHz(≈14ns).

5. EXPERIMENTAL RESULTS

Circuit designs are simulated using the tables given above. Then, one of these circuit designs, experiments were carried out for a model with D1 in Table 1. In this model, 1N5819 Schottky diode, $\mathrm{R_{gen}}$; 50Ω and $\mathrm{R_{Load}}$; 1000Ω resistance values, are used. Gw Instek AFG-2125 signal function generator and Tektronix DPO2014 signal oscilloscope are used to test the circuit**.** The experimental environment in which this oscilloscope, signal generator, and circuit design is used is shown in figure 6.

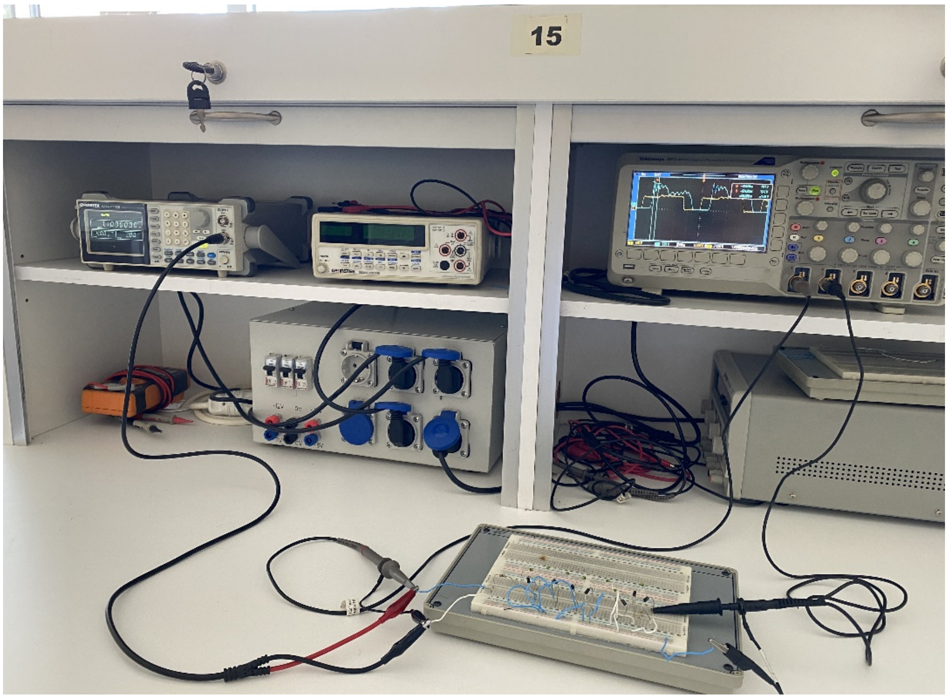

Figure 6:
Example of experimental setup used for soliton wave generation

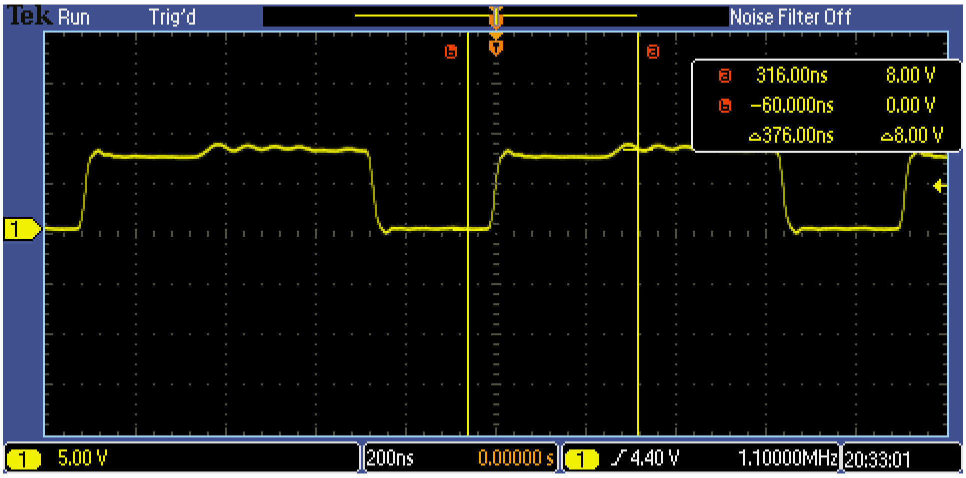

Figure 7:
Input voltage result of D1 design in Table 1

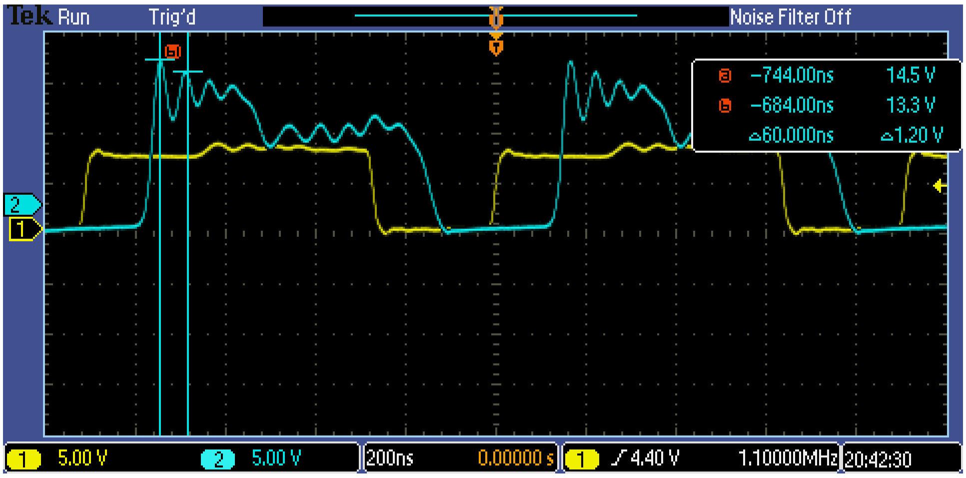

Figure 8:
Experiment results for D1 design shown in Table 1

The experiment results for the 17MHz frequency value are shown in Table 1, showing that the model belongs to the D1 design. In Fig. 7, the input signal of the model, and in Fig. 8, the input and output signals received at the output are shown. The revised input signal is rectangular wave and equal to 8V. The output signal has a soliton wave, a voltage value of 14.5V, and a frequency of approximately 17MHz.

Table 5. Soliton production is described in Table1 for D1 design.

Parameter	**PSO Result**	**Simulation**	**Experiment**
Revised Input Voltage (V)	8	8	8
Output Voltage (V)		14.3	14.5
T (ns)	58	58	60

The results obtained from the PSO algorithm, the simulation, and experimental results are shown in Table 5. As can be seen in the table, the results are consistent with each other. The center frequency value of the simulation results and experimental results are found to be approximately

17MHz. This situation shows that the simulation results and the experimental results are in compatible.

6. CONCLUSION

In this research paper, the production of soliton waves is the primary objective. The first of the steps carried out for this purpose is mathematical analysis, as a result of which the equations are determined. The second stage is the PSO algorithm stage, which is our innovation against trial and error methods in the literature. At the stage of PSO algorithm; firstly, parameters are determined based on mathematical equations. By using the determined parameters, the circuit element values are decided with the PSO algorithm. In the third stage, different circuit designs are made using the results obtained from the algorithm. Later on; the simulations of the designed NLTL circuits for different frequency values are modeled. As a result; PSO algorithm, simulation, and experimental results are found to be compatible.

CONFLICT OF INTEREST

There are no known conflicts of interest or common interests between the authors and any institution, organization, or person.

AUTHOR CONTRIBUTION

Abdullah Aksoy: Theoretical framework, Investigations, Research methods, Numerical methods, and Writing.

Sibel Yenikaya: Investigation, Research methods, Review & editing.

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