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Modeling and Studies of Broadband Transmission Line Transformers with Ferrite Toroidal Cores Amidon FT82-43 and FT114-43

Boyan Karapenev
Department of the Communication Equipment and Technologies
Technical University of Gabrovo
4 Hadji Dimitar Str.
Bulgaria

Abstract: This paper presents a method of modeling and results obtained from simulation and experimental studies of Broadband Transmission Line Transformers (BTLT) in the frequency response of their ferrite toroidal cores used with coefficients of resistance ratio nz 1:1, 4:1 and 1:4. Dependencies to calculate the values of model parameters of toroidal ferrite cores used and two models of BTLT containing an ideal transformer and voltage-controlled voltage source are presented. Some transformers are practically implemented with 3 and 5 twists per 1 cm of a pair of copper enamelled wires with ferrite toroidal cores manufactured by Amidon Associates Inc. FT82-43 and FT114-43. The obtained results - characteristics and qualitative parameters have been generalized, presented in graphical and tabular form and analyzed.

Keywords: broadband transmission line transformers; implementation; studies; qualitative parameters.

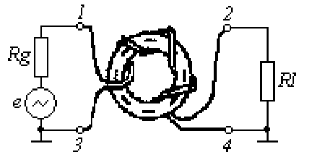
I. Introduction

Broadband coordination and transformation of input and output resistances of a high-frequency amplifier, between two adjacent amplifier stages as well as broadband power aggregation and division can be carried out by transmission line transformers employing an electromagnetic connection between the primary and secondary windings. To provide the necessary transformation coefficient of resistances and minimum decoordination is an important prerequisite for achieving a wide operating frequency band. These transformers have high efficiency and reliability and through them can be made: galvanic dissociation between nodes and units of the equipment [3], transition from asymmetric to symmetric I/O and vice versa, they have small sizes, etc.

II. Implementation of Broadband Transmission Line Transformers

Broadband Transmission Line Transformers (BTLT) are constructed employing appropriately interconnected transmission lines, positioned on a ferromagnetic core which is mostly of toroidal shape [5]. The input signal excites electromagnetic waves whose linear combinations depending on the type of line connection, determine the output signal voltage. Since the resistance transformation of BTLT is associated with changes in the coefficient of voltage transmission Au ($nz=nu^2$) when nz=4:1, nu=2:1 and Au=0,5. For nz=1:4, nu=1:2 and Au=2.
The operating principle of broadband transmission line transformers is illustrated in Fig. 1.

Figure 1 Transmission Line Transformer.



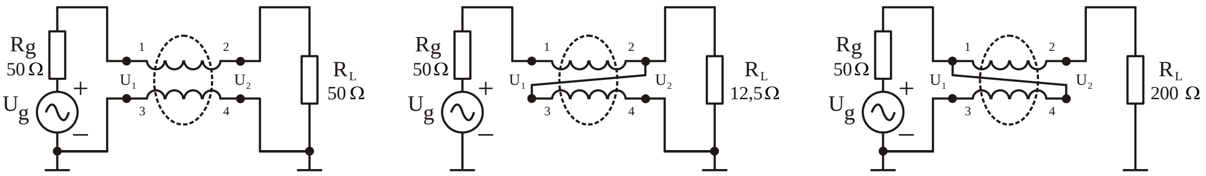
The transmission lines implemented with a pair of copper enamelled wires were most widely used in the frequency range of (0,1÷100) MHz and to ensure the characteristic resistances from 15÷20 to 100÷150 Ω using BTLT [4]. Analytical determination of the geometry of these lines for the necessary characteristic resistance Z_0 is too complicated therefore it is appropriate the construction parameters to be selected experimentally. It is recommended that the wires should be wound with a large number of twists per unit of length, not to change the characteristic resistance along the line [2].
The main component in transmission line transformers is the ferrite toroidal (FT) core used. Some of the most important catalog parameters of ferrite toroidal cores manufactured by the Amidon Associates Inc. FTxx-43 (material 43) are presented in Table I [1].

Table I Catalog Parameters of Amidon Ferrite Toroidal Cores FTxx-43.

Grade of Amidon Ferrite Core	Outside diameter D_{dim} mm	Internal diameter d_{dim} mm	Height of ferrite core h_{dim} mm	l_e cm	A_e cm^2	V_e cm^3	Induction factor A_L mH/1000 wind.	μ_r -	Volume resistance ρ Ω.cm	Frequency response Δf MHz
FT 23-43	5,84	3,05	1,52	1,34	0,021	0,029	188	850	1.10^5	1 ÷ 50
FT 50-43	12,70	7,14	4,80	3,02	0,133	0,401	523			
FT 82-43	21,00	13,10	6,35	5,26	0,246	1,290	557			
FT114-43	29,00	19,00	7,00	7,42	0,375	2,790	603			

The connection method and the values of input and output resistances for coordinating *nz*=1:1 and transforming *nz*=4:1 and *nz*=1:4 of the resistance of the broadband transmission line transformers are shown in Fig. 2.

Figure 2 Connection of Broadband Transmission Line Transformer with *nz*=1:1, *nz*=4:1 and *nz*=1:4.



III. Modeling of Broadband Transmission Line Transformers

A. Model Parameter Calculation of Ferrite Toroidal Cores

The equivalent diagram (model) of a ferrite toroidal core consists of resistance *R*, inductivity *L* and capacitance *C* connected in parallel. The model parameter values can be determined by the following dependencies:

- ***inductivity L*** is derived from the condition $B = \frac{\mu_r N.I}{2\pi r}$, hence

$$L_1 \approx \frac{\mu_r N^2 A_e[cm^2]}{2\pi r_{av}[cm]}.10^{-2} = \frac{\mu_r N^2 A_e[cm^2]}{l_e[cm]}.10^{-2}, \mu H \tag{1}$$

where *B*, Tesla is the magnetic field produced, A_e, $cm^2=(r_2-r_1).h_{dim}$, r_{av}, cm is the average radius of the ferrite toroidal core as $r_{av}= [(r_2-r_1)/2]+r_1$.

To determine inductivity *L* of a ferrite toroidal core of BTLT, it is assumed that the number of windings *N* is equal to 1.

If catalogue parameter l_e, cm is given, *L* can be determined by [4]

$$L_2 = 0{,}4\pi N^2 \mu_r \frac{A_e[cm^2]}{l_e[cm]}.10^{-8}, H; \tag{2}$$

- ***capacitance C*** is determined by the geometric dimensions of the ferrite toroidal core following [6]

$$C = 2{,}8\left(1{,}2781 - \frac{h_{dim}}{D_{dim}}\right).\sqrt{\frac{2\pi^2\left(D_{dim} - h_{dim}\right)\frac{h_{dim}}{2}}{4\pi}}, pF \tag{3}$$

where D_{dim} and h_{dim} are in inches (1 inch = 25,4 mm). To calculate *C* in geometric dimensions in millimeters (mm), use (3) divided by 25,4;

- ***ohmic resistance R*** is determined from the catalogue parameter ρ by

$$R = \frac{\rho.l_e}{S} = \frac{\rho.(2\pi r_{av})}{\pi.(r_2 - r_1)^2}, \Omega \tag{4}$$

for dimensions of r_2, r_1 and r_{av} (l_e) in meters (m).

On the basis of (1)-(4) and catalogue parameters of ferrite toroidal cores of the manufacturer Amidon given in Table I, their model parameters have been calculated and presented in Table II.

Table II Calculated model parameters of Amidon FTxx-43.

Trade Ferrite	L_1 μH	L_2 μH	C pF	R kΩ
FT 23-43	0,133	0,167	0,254	$2{,}193.10^3$
FT 50-43	0,374	0,470	0,541	$1{,}245.10^3$
FT 82-43	0,398	0,499	0,919	$1{,}074.10^3$
FT114-43	0,430	0,540	1,256	945

From the calculated model parameters of Amidon FTxx-43 presented in Table II it has been found that:
- for each overall dimension of the ferrite toroidal cores inductivity value L varies within a few tenths of μH and it is directly proportional both to its dimensions and to its permeability value μ_r;
- since $tg\delta$ has very small values with ferrites, capacitance C of the ferrite toroidal core depends only on its geometric dimensions - (3). From the obtained values of model parameter C of the FT it has been found that its values vary within (0,3÷1,3) pF, which allows in the general case its averaged value 1 pF to be adopted;
- the ohmic resistance R value is strictly individual and is determined by the geometrical dimensions of FT cores.

B. Model Parameters Calculation of Broadband Transmission Line Transformers

The complete model of BTLT, with secondary side parameters reduced to the primary side is shown in Fig. 3a (Model 1). Resistors R_1 and R_2 connected in series, present the existing losses, respectively in the conductors of the primary and secondary windings. When transmission lines are used – small-length conductors in broadband transformers with ferromagnetic cores, the active loss share in the total losses is negligibly small. C_{11} and C_{22} are the distributed shunt capacitances of the primary and secondary windings respectively, and C_{12} is the distributed capacitance between transmission lines which provides the electromagnetic connection at high frequencies. Capacitance C_{12} can form a transmission line together with distributed inductances L_{S1} and L_{S2}. The characteristic resistance of the transmission line can be regulated by changing the conductor length, number of windings, angle and pitch of twist, location of windings on ferrite core, etc.

Figure 3 Complete Models of Broadband Transmission Line Transformers.

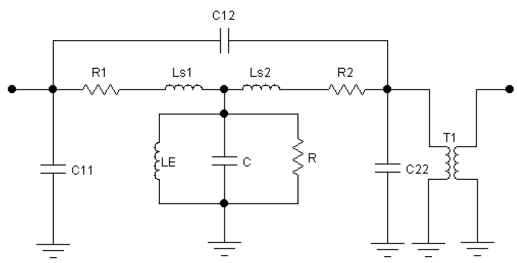


Fig. 3a. Model 1 of BTLT with ideal transformer

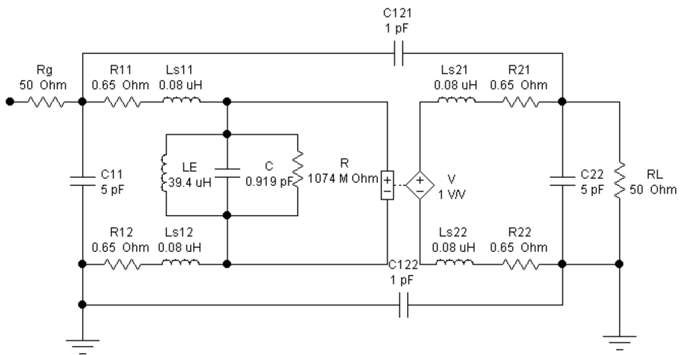


Fig. 3b. Model 2 of BTLT with voltage-controlled voltage source

Model parameters of Broadband Transmission Line Transformers are determined as follows:
- ohmic resistance values R_1 and R_2 of the primary and secondary windings according to (4) are

$$R_1 = R_2 = N.\frac{\rho_{Cu}(2\pi r_{av})}{\pi(r_2 - r_1)^2}, \Omega \qquad (5)$$

when ρ_{Cu}=1,66 μΩ/cm;
- dissipation inductances (leakage) L_{S1} and L_{S2}, whose typical value is 0,5÷1,5 %, is assumed to be 0,8 % of the ferrite core inductance value L when N windings of the primary (L_{11}) and secondary (L_{22}) sides are available, calculated by (1) – $L_{S1}=L_{S2}=0{,}8\%.L$. The model parameter equivalent inductivity $LE=L_{11}+L_{22}+L_1$ ($L_{11}=L_{22}= L$);
- intrinsic capacitances C_{11} and C_{22} have been measured in practice using a passive bridge of BTLT constructed with the preset output data and $C_{11}=C_{22}$=5 pF, and depending on the twist pitch of the transmission lines used (enamelled copper conductors) the inter-winding capacitance value C_{12} is adopted within (0,1÷10) pF.

Model parameters for the presented complete model of BTLT in Fig. 3a have been calculated using the following output data: ferrite toroidal cores Amidon FT82-43 and FT114-43, nz=1:1, number of windings N=7, diameter of the copper enamelled conductor used d_{Cu}=0,62 mm, given in Table III.

Fig. 3b presents a complete model of BTLT with Amidon FT82-43 ferrite core, containing a dependent voltage-controlled voltage source, in relation to which the calculated model parameters are symmetrical. The dependent voltage source V with transmission coefficient 1 when nz=1:1 is connected between the model parameter values R_1, L_{S1} and R_2, L_{S2} divided by two. Similar modeling of BTLT is closer to its real construction.

Table III Calculated model parameters of BTLT with Amidon FT82-43 and FT114-43.

BTLT	Model parameter values		
	***R*, Ω**	***L*, μH**	***C*, pF**
Ferrite core FT82-43	R=1,074.10^6	L=0,398	C=0,919
Primary side	R_1=1,3	L_{11}=19,50 L_{S1}=0,16	C_{11}=5
Secondary side	R_2=1,3	L_{22}=19,50 L_{S2}=0,16	C_{22}=5
Model parameter LE	-	LE=39,4	-
Inter-winding capacitance C_{12}=2 pF			

BTLT	Model parameter values		
	***R*, Ω**	***L*, μH**	***C*, pF**
Ferrite core FT114-43	R=945.10^3	L=0,43	C=1,256
Primary side	R_1=1,1	L_{11}=21,10 L_{S1}= 0,23	C_{11}=5
Secondary side	R_2=1,1	L_{22}=21,10 L_{S2}= 0,23	C_{22}=5
Model parameter LE	-	LE=42,63	-
Inter-winding capacitance C_{12}=2 pF			

IV. Simulation Studies of Modeled Broadband Transmission Line Transformers

Using Multisim software, a simulation study of amplitude-frequency responses (ARF) of BTLT models (Model 1 and Model 2) with ferrite toroidal cores FT82-43 and FT114-43 with resistance transformation ratios *nz*=1:1, presented in Fig. 4, has been conducted.

Figure 4 Amplitude-frequency responses of BTLT models - Model 1 and Model 2 with *nz*=1:1.

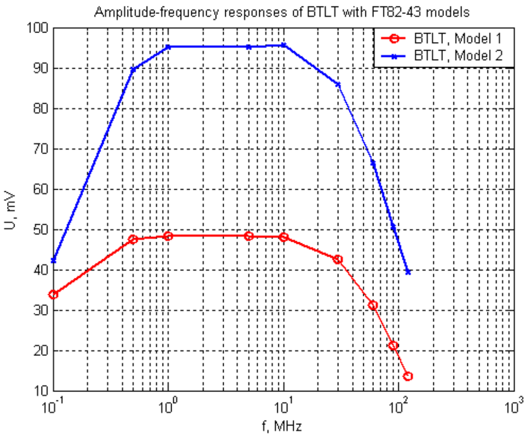


Fig. 4a. AFR of models Model 1 and Model 2 of BTLT with FT82-43

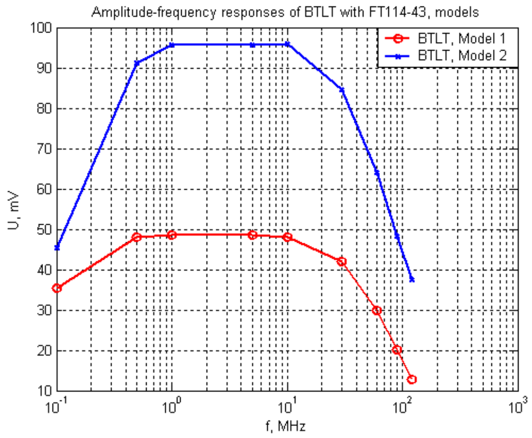


Fig. 4b. AFR of models Model 1 and Model 2 of BTLT with FT114-43

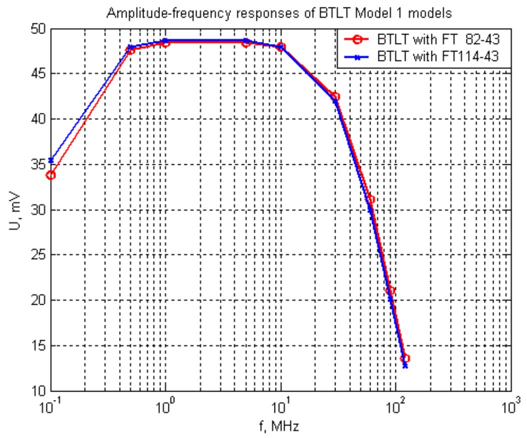


Fig 4c. AFR of Models 1 of BTLT with ferrite toroidal cores FT82-43 and FT114-43

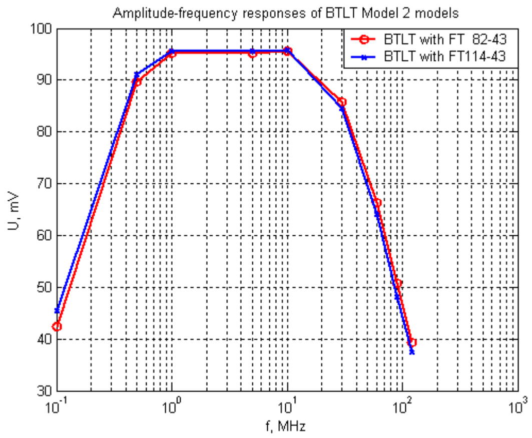


Fig 4d. AFR of Models 2 of BTLT with ferrite toroidal cores FT82-43 and FT114-43

Table IV presents qualitative parameters obtained from amplitude-frequency responses of BTLT models: lower fb and upper fh cut-off frequency and bandwidth Δf.

Table IV Values of qualitative parameters obtained from amplitude-frequency responses.

Model of	Model	fh, MHz	fb, kHz	Δf, MHz
BTLT with FT82-43	Model 1	51,70	130,40	51,57
	Model 2	56,80	206,30	56,60
BTLT with FT114-43	Model 1	49,10	94,04	49,00
	Model 2	52,97	188,50	52,78

The principal difference between the amplitude-frequency responses of Model 1 and Model 2 is the value of the transmission coefficient of voltage Au. In Model 2, containing a voltage-controlled voltage source, Au is approximately equal to 0,96 and it has a value two times smaller for Model 1. It is established that there is a minimum difference in the slopes of decline of amplitude-frequency responses at low and high frequencies which are steeper for Model 2.

From Figures 4a,b,c,d no significant difference is established in the AFR of BTLT Model 1 and Model 2 with different sizes of the toroidal ferrite cores used, i.e. the geometric dimensions of the toroidal ferrite core used has no significant influence on the obtained characteristics and the implemented qualitative parameters. There is minimal difference in the decline of AFR at low frequencies which is of the order of 0,5÷1 % and can be neglected. It is due to the difference in the value of the model parameter equivalent inductivity LE determined mostly by the inductance of the ferrite core in the presence of a coil of BTLT – relation (1) where larger geometric dimensions and hence the value of the cross-sectional area of ferrite core A_e, cm^2 increase the value of L_1 (Table I).

Model 2 represents the real essence of high-frequency transformers with transmission lines more accurately, as Au is approximately equal to 1 required for modeling of *nz*=1:1, it provides a wider AFR compared to Model 1 having steeper slopes of decline at low and high frequencies. By setting the value of the transmission coefficient of voltage-controlled voltage source V, Au is modeled for the transforming Broadband Transmission Line Transformers.

V. Experimental Studies of Implemented Broadband Transmission Line Transformers

Broadband transmission line transformers with ferrite toroidal cores manufactured by the Amidon FT82-43 and FT114-43 with 7 windings of twisted pair of copper enamelled wires with diameter *d*=0,62 mm when the number of twists is equal to 3 and 5 per 1 cm are implemented practically. The same design implementation of the broadband transmission line transformers with a small (FT82-43) and large (FT114-43) ferrite core is used, and the corresponding coefficient of transformation is provided with the necessary transmission lines connection to the source and load, and their corresponding values (Fig. 2). The experimental studies were carried out employing two values of input voltage Ui.

In Fig. 5a and Fig. 5b are presented amplitude-frequency responses of BTLT with ferrite toroidal cores Amidon FT82-43 и FT114-43 when the number of twists is equal to 3 per 1 cm and *nz*=1:1, 4:1 and 1:4, respectively when Ui=136 mV and Ui=55 mV.

Figure 5 Experimental Amplitude-Frequency Responses of BTLT with Amidon FT82-43 and FT114-43.

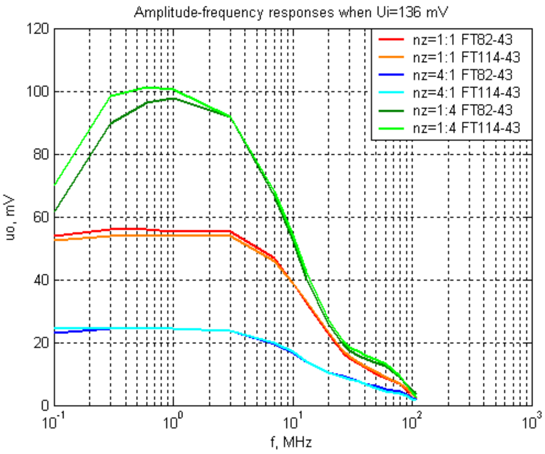


Fig. 5a. AFR of BTLT

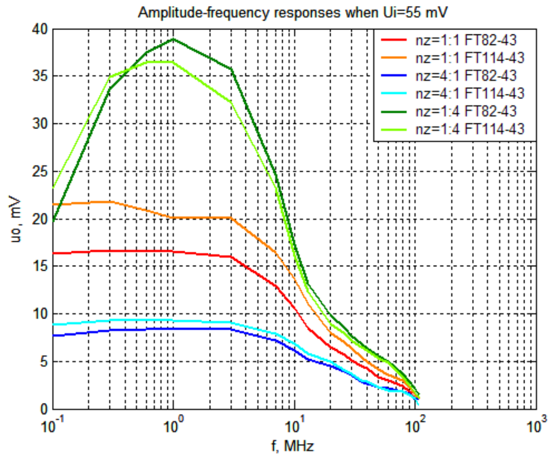


Fig. 5b. AFR of BTLT

The Amplitude Performances (AP) of the studied BTLT are linear and the implemented coefficients of transmission Au for *nz*=1:1, 4:1 and 1:4 almost coincide with their theoretical values. In Tables V and VI are presented the values of qualitative parameters of BTLT obtained. The parameter Dynamic range *D* is equal to Uimax/Uimim.

From an accomplished comparative assessment between the amplitude-frequency responses obtained from the simulation and experimental studies it has been found that:

- the difference between the AFR graphical relationships and qualitative parameters (Table V) of practically implemented BTLT when the number of transmission line twists is equal to 3 and 5 per 1 cm is minimal;
- the implemented amplitude-frequency response from Model 1 is closer to the experimentally obtained in form and qualitative parameters;
- the practically implemented amplitude-frequency responses are narrower (Δf is in the range of 10 MHz) and are displaced in lower frequency range;
- the amplitude-frequency responses obtained by simulation cover more precisely the specified by the manufacturer operating frequency range of the ferrite toroidal cores used.

Table V Values of qualitative parameters from experimental Amplitude-Frequency Responses obtained.

Number of twists per 1 cm	Ui, mV	nz	BTLT with ferrite core FT82-43			BTLT with ferrite core FT114-43		
			fb, kHz	fh, MHz	Δf, MHz	fb, kHz	fh, MHz	Δf, MHz
3 twists	136	1:1	100	10,0	9,90	100	9,9	9,80
		4:1	100	9,0	8,90	100	9,9	9,80
		1:4	150	6,5	6,35	120	5,6	5,48
	55	1:1	100	7,5	7,40	100	8,0	7,90
		4:1	100	6,0	5,90	100	11,0	10,90
		1:4	180	6,0	5,82	140	5,5	5,36
5 twists	136	1:1	100	10,0	9,90	100	11,0	10,90
		4:1	100	9,0	8,90	100	10,0	9,90
		1:4	150	6,5	6,35	110	6,0	5,89
	55	1:1	100	7,2	7,10	100	8,6	8,50
		4:1	26.10^3	56,0	30,00	100	9,5	9,40
		1:4	170	5,5	5,33	130	5,6	5,47

Table VI Values of qualitative parameters from experimental Amplitude Performances obtained.

Number of twists per 1 cm	*f*, MHz	*nz*	BTLT with ferrite core FT82-43				BTLT with ferrite core FT114-43			
			Uimin, mV	Uimax, mV	Au	D	Uimin, mV	Uimax, mV	Au	D
3 twists	1	1:1	0,85	53,74	1,0	63,2	0,53	53,74	1,00	101,40
		4:1	0,71	46,67	0,5	65,7	0,74	46,67	0,50	63,08
		1:4	0,98	49,50	2,0	55,5	0,92	50,20	2,00	54,60
	10	1:1	0,56	38,89	1,0	69,4	0,54	39,95	1,00	74,00
		4:1	0,35	35,07	0,5	100,2	0,60	36,42	0,50	60,70
		1:4	0,42	36,42	1,4	86,7	0,53	53,74	1,40	101,40
5 twists	1	1:1	0,71	53,03	1,0	74,7	0,63	53,74	1,00	85,30
		4:1	0,65	46,67	0,5	71,8	0,64	46,70	0,50	73,00
		1:4	0,57	49,50	2,0	86,8	0,85	50,91	1,96	59,90
	10	1:1	0,60	37,83	1,0	63,1	0,71	39,59	1,00	55,80
		4:1	0,53	35,07	0,5	66,2	0,78	36,06	0,50	46,20
		1:4	0,56	37,48	1,6	66,9	0,64	53,74	1,60	84,00

VI. Conclusion

Practically implemented BTLT show the effect of bandwidth only in the exact coordination between input and output resistances unlike the modeled ones.

The values of BTLT model parameters are optimized using the obtained results of experimental studies and hence the results of simulation studies. After the optimization of the AFR a difference is found only in the steepness of the decline in performances at high frequencies. The relative error between the optimized values of the model parameters and experimentally obtained is in the range of 15÷16 % and taking into account that the manufacturing tolerances of manufactured toroidal ferrite cores are ± 25 %, it can be ignored.

The presented results: model parameters, characteristics and qualitative parameters of toroidal ferrite cores and broadband transmission line transformers with Amidon FT82-43 and FT114-43 as well as those obtained from the experimental studies can be used for modeling of broadband amplifier modules, broadband amplifiers, adders and dividers and in other circuits which are applied in radio communications.

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