Investigation of stripline parametric passive radio transponders

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Abstract. The results of the study of strip parametric passive radio transponders are presented. Stripline parametric passive radio transponders are made in the form of a system of three parametric generators connected to the pump signal strip antenna and the response signal strip antenna. The results of numerical and field experiments are presented for a pump signal frequency of 800 MHz and a response signal of 400 MHz, which are in good agreement.

1. Introduction

Equipping radio responders is one of the possible ways of marking various objects. Sometimes there is no way to access the object to be marked. In this case, it is advisable to use passive radio responders that do not contain internal power supplies. The energy of the request signal to form a response signal (RS).

Due to the re-reflections of the interrogation signal from the interface between the media or surrounding objects, the frequencies of the RS and the interrogation signal for passive radio responders should be different. For this, a nonlinear process of converting the energy of the received request signal into the energy of the RS must occur.

This requirement is met by three types of nonlinear passive radio responders: nonlinear scatterers [1, 2], passive RFID transponders [3], parametric radio responders [4-5].

The parametric radio responder (PR) has the best conversion factor of the interrogation signal in the RS for low levels of the interrogation signal. For this reason, the largest detection range of marked objects can be expected from the PR [6-8].

The study of the possibility of using PR for marking non-serviced objects is carried out in this message.

PRs were proposed in [5, 4]. In the PR, the interrogation signal is converted into the RS due to the parametric generation of the interrogation signal at the half subharmonic. For this, the PR contains a parametric generator for which the request signal acts as a pump signal (PS). The first PRs [4, 5] were a dipole antenna tuned to the PS frequency to which a parametric circuit of a semiconductor diode and inductance was connected. The semiconductor diode in this circuit plays the role of variable capacitance. For this construction, the main properties of the PR were experimentally investigated [4], [5, 9].
At the same time, this PR design is not suitable for marking real objects. Therefore, the task of our research is to search for a PR design for marking non-serviced objects.

On this path, two ideas were investigated: 1) the search for the PR design in which the processes of receiving the SN and the OS radiation are carried out by different antennas and 2) the use of strip antennas in the PR design.

The first idea is related to the transition to PR - a four-port network. The parametric generator in the form of a parametric circuit, proposed in [4, 5], is not suitable for this.

A parametric generator - a four-port network can be implemented based on the use of several parametric circuits in the PR design. The use of strip antennas in the PR design practically means that the parametric generator must be a three-pole. This is due to the fact that the strip antennas ZS and RS should have one common pole - a metal substrate. The general idea of the design is that the PS is loaded on all parametric circuits, and the RS is removed from one of the parametric circuits.

2. Representation of a parametric radio responder by an equivalent circuit

The block diagram of the PR of three parametric circuits is shown in figure 1. Here is a three-circuit strip passive PR, consisting of a stripline antenna PS, a strip antenna RS, an active parametric circuit from which the RS is “removed” and two “cold” parametric contours.

![Figure 1. Block diagram of a three-loop strip passive parametric radio transponder: 1 - pump signal strip antenna, 2 - response strip antenna, 3 - active parametric circuit from which the response signal is “removed”, 4,5 – “cold” parametric circuits.](image1)

\[ f_1 \]

\[ f_2 = 0.5f_1 \]

The principles of PR modelling, proposed in [10], make it possible to create a mathematical model of a three-generator PR. At the first stage, an equivalent circuit of a three-generator PR is built (figure 2), where the PR antennas are represented in the form of a serial LACA electric circuit tuned to the PS or RS frequencies, the resistance RA is equal to the radiation resistance of the PS and RS antennas. In addition, a semiconductor diode is approximated by parallel connected nonlinear capacitance and conductance with known capacitance-voltage and current-voltage dependences. The inductances of the circuits and the loss resistance are assumed constant.

![Figure 2. Equivalent circuit of a three-loop passive parametric radio responder.](image2)
The mathematical model is presented in the form of a system of differential equations [11] describing the relationship between voltages and currents in the elements of the circuit, which is based on Kirchhoff's laws. The specific form of the model depends on the choice of determining functions [11]. This is, first of all, EMF e(t), which characterizes the effect of PS on the PR, antenna currents \( i_{A1}, i_{A2} \); voltages \( V_1, V_2 \) on parametric circuits, supplying currents \( i_k \) and voltage \( V_3 \) at the terminals of the transmitting antenna of the RS. If we use polynomial for \( C(u) \) and exponential for \( g(u) \) approximation [10]:

\[
C(u) = C_0 u + \sum_{n=0}^{\infty} \beta_n u^n; \quad g(u) = g_0 e^{b(u)}.
\]

then the required mathematical model is represented by a system of 5 differential equations of the 2nd order

\[
\begin{align*}
\frac{d^2i_{A1}}{dt^2} &= \frac{1}{L_1} \left( \frac{de(t)}{dt} - \frac{du_1}{dt} - \frac{du_2}{dt} - \frac{Ra_1}{C_{A1}} \frac{di_{A1}}{dt} - \frac{1}{C_{A1}} i_{A1} \right); \\
\frac{d^2i_{A2}}{dt^2} &= \frac{1}{L_2} \left( \frac{du_2}{dt} - \frac{Ra_2}{C_{A2}} \frac{di_{A2}}{dt} - \frac{1}{C_{A2}} i_{A2} \right); \quad \frac{d^2u_1}{dt^2} \\
\frac{d^2u_2}{dt^2} &= \frac{1}{A_1} \left[ \frac{d}{dt} \left( \frac{D_{11}E_1}{C_{01}} + \frac{R_1}{L_1} A_1 \right) + \left( \frac{du_1}{dt} \right)^2 B_1 + \omega_{01}^2 \left( u_1(R_1D_1 + 1) - \frac{L_1}{1} \frac{d}{dt} \left( i_{A1} R_1 \right) \right) \right]; \\
\frac{d^2u_3}{dt^2} &= \frac{1}{A_2} \left[ \frac{d}{dt} \left( \frac{D_{22}E_2}{C_{02}} + \frac{R_2}{L_2} A_2 \right) + \left( \frac{du_2}{dt} \right)^2 B_2 + \omega_{02}^2 \left( u_2(R_2D_2 + 1) - \frac{L_2}{1} \frac{d}{dt} \left( i_{A2} R_2 \right) \right) \right]; \\
\frac{d^2u_3}{dt^2} &= \frac{1}{A_3} \left[ \frac{d}{dt} \left( \frac{D_{33}E_3}{C_{03}} + \frac{R_3}{L_3} A_3 \right) + \left( \frac{du_3}{dt} \right)^2 B_3 + \omega_{03}^2 \left( u_3(R_3D_3 + 1) - \frac{L_3}{1} \frac{d}{dt} \left( i_{A3} \right) \right) \right] \quad (1)
\end{align*}
\]

where \( A_k = \sum_{n=0}^{\infty} (n + 1) \beta_k n u_k^n \); \( B_k = \sum_{n=0}^{\infty} n(n + 1) \beta_k n u_k^{n-1} \); \( D_k = g_0 e^{b_k u_k} \); \( E_k = 1 + b_k u_k \); index \( k \) corresponds to the number of the parametric contour \( (k = 1, 2, 3) \); \( \omega_{0k}^2 = \frac{1}{L_k C_{0k}} \).

The mathematical model in the form of a system of equations (7) allows calculating the dependences between the parameters of the elements of the equivalent circuit in figure 2. At the same time, to solve the problem, it is necessary to know the dependence of the parameters of the RS electromagnetic wave on the parameters of the incident RS wave. In this case, the main difficulty arises when calculating the connection \( \Pi_{C1} \), which characterizes the PS as an external action, and EMF e(t). The problem is that the EMF value \( \alpha_0 \) depends on the matching between the parametric generators of the antenna PS, that is, on the resistance of the parametric generators. In this case, the resistance values of parametric generators also depend on the PS level. Direct calculations are associated with the solution of the laborious problem of solving the Volterra equations [12, 13]. For this reason, in the inversion, the inverse problem was solved, which does not require the involvement of Volterra series.

The modelling technique [10] of the PR response to the external effect of the PS involves two stages: 1) calculation of the dependences of the signal parameters in the equivalent circuit in figure 2 at the frequencies of the RS and PS and 2) transformation of these dependences in dependencies characterizing the relationship between the parameters of the irradiating RS wave and the re-emitting RS waves.

3. Results of mathematical modelling and physical testing of the amplitude properties of the parametric radio responder

The most important dependence of the PR, which characterizes the energy parameters of the conversion of the PS into the RS, is its amplitude characteristic. The amplitude characteristic was introduced in [14, 15], that is, the dependence of the intensity of the RS wave formed by the PR at a distance of 1 meter of the \( P_{RS} \) on the intensity of the signal pumping the \( P_{PS} \) pumping, irradiating the PR:

\[
\Pi_{RS} = \Pi_{RS}(\Pi_{PS})
\]

The task of calculating the amplitude characteristic is the purpose of mathematical modelling of the PR circuit.
When calculating the amplitude characteristic for the PR with known parameters, the problem of matching the PR antennas with the system of parametric loops is of great importance. In the classical formulation of the problem, the best matching is achieved when the active resistances of the antennas and the system of parametric circuits are equal both at the CH frequency and at the feedback frequency. In this case, it is essential that the value of the resistance of the system of parametric circuits depends on the values of the resistance of the antennas and the level of the PS. In this situation, the optimization problem is easier to solve as the problem of finding the best values of the resistances of the PS and RS antennas for a certain criterion, for example, the maximum RS level or the lowest PS level at which the PR is excited, i.e. by the value of the conversion factor $K = \frac{n_{\text{RS}}}{n_{\text{PS}}}$.

The simulation of the amplitude properties of the PR was performed in the LabVIEW environment for the PS frequency of 800 MHz and the RS frequency of 400 MHz.

Studies of the PR model showed that the best value for the input impedance of the PS antenna lies in the range of 60 ÷ 80 Ohm. For the convenience of the hardware tuning of this antenna during physical prototyping, the value $R_{A1} = 75$ Ohm was chosen. For a given value of $R_{A1}$, the results of mathematical modelling showed that the feedback level is maximized in the range of values of the input impedance of the feedback antenna within 600 ÷ 700 Ohm. Therefore, $R_{A2} = 650$ Ohm was chosen for the RS antenna.

Based on the found values of $R_{A1}$ and $R_{A2}$, a physical model of a three-circuit passive parametric radio responder was implemented. A photo of the layout is shown in figure 3.

The geometrical dimensions of the stripline antennas of the model were calculated using the standard procedure [16]. As a dielectric material, a radio-transparent foam with a dielectric constant equal to unity was used. The antenna gains calculated according to [16] turned out to be 6 dB for the PS antenna and 5 dB for the RS antenna.

The results of mathematical modelling and physical testing of the amplitude properties of a three-generator parametric radio responder are shown in figure 4.
It follows from figure 4 that the developed mathematical model of a stripline three-oscillator PR makes it possible to predict rather well its response to an irradiating pump signal.

4. Conclusion
Thus, the current state of the theory of parametric scatterers makes it possible to create designs of strip parametric scatterers based on combining several parametric generators in the form of a four-port network, the poles of which are loaded onto strip antennas tuned to the frequencies of the pump signal and the response signal. Matching the strip antennas of the response signal and the pump signal with the system of parametric generators is possible by numerical calculations using a mathematical model of the equivalent circuit of the strip parametric scatterer.

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