GENERALIZED ANALYSIS OF UHF TRANSMISSION-LINES JUNCTION TWOPORT WITH THE WIRE COUPLING ELEMENT

Zakhariya Y. A. and Kobilyanska O. V.

Lviv Polytechnic National University, Lviv, Ukraine
E-mail: anasko12@mail.ua

Abstract

The synthesis problem of UHF transmission line junction twoport with the wire exciting element on the multiport loss-free conditions and known input impedance basis is considered. Graphical analysis results open the possibility for junction structure optimization. General conclusions are for width class of transmission lines and exciting elements type valid.

Keywords: Loss-free conditions; line/waveguide junction (transition).

1. INTRODUCTION

It is well known, that junction twoport of UHF transmission-lines also a wave mode transformer is. For example in a coaxial line/rectangular waveguide junction TEM wave mode into TE_{10} waveguide mode is transformed. Below we consider a case, when the wire radiator as a waveguide exciter is used. Commonly a transmission line junction, in our example coaxial line/waveguide junction, is a loss-free device. The transmission losses through the junction are by refections caused only. Therefore the basic junction twoport parameter is the frequency band width, in what the reflection coefficient from junction is smaller then given.

The junction twoport we can separate in two parts: 1) exciter threeport, and 2) load of one exciter port (Z_H on Fig.1.). Usually exciter threeport is by electrodynamic methods analysed. Initially one calculate the input impedance, *Z*, use corresponding problem modeling. But calculation of exciter threeport scattering matrix elements is complicated and difficult. In the present work on the multiport loss-free-conditions basis a possibility to ovoid these difficulties is proposed. Conditions mentioned above follow from UHF circuit theory and charakterize the UHF multiport, inside of them the active power no wasted is. Therefore the calculation accuracy occur higher as by electrodynamic methods use.

In published papers mainly the exciter threeport input impedance, *Z*, is considered [3]. Below we use this parameter as fundamental in threeport scattering matrix (S-parameters) calculation [1]. Thus the calculation accuracy of input impedance *Z* is important. The problem of *Z* calculation is often noncoordinate electrodynamic problem, whose solution the suitable modeling demands [2], [3]. Such model must give the possibility the singularity of used Green-functions to avoid [1], the possibility accurate longitudinal and lateral current distribution on the exciter element surface to determine, and exciter feed structure to consider [2], [3], [4].

We should know, that every of named above input impedance calculation difficulties finally are not solved today. It causes, that we must the simplified electrodynamic methods with smaller accuracy use, or experimental input impedance to determine. It is to emphasize, that at the input impedance calculation all wave modes are seized, but S-parameter are on fundamental mode based only. Thus the common use of S-parameter and impedance *Z* is possible, if in the structure wave modes of higher order vanish.

2. S-PARAMETER OF EXCITER THREEPORT

We consider below the symmetrical exciter threeport in the junction twoport structure of coaxial line and rectangular waveguide (Fig. 1.).

It is evident, that the structure on Fig.1 is for other line and waveguide type valid. Symmetry conditions are by identity of ports 1 and 2 in threeport structure Fig.1, b provided. Hence we have equality of scattering matrix coefficients: $S_{22}=S_{11}$; $S_{13}=S_{23}$; $S_{31}=S_{32}$. Thus the scattering matrix of exciter threeport contains only four coefficients, if additionally reciprocity condition is used ($S_{12}=S_{21}$; $S_{31}=S_{13}$):

Use following styles for the preamble (from the title till the keywords):

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{11} & S_{13} \\ S_{13} & S_{13} & S_{33} \end{bmatrix}. \quad (1)$$

It being known, that loss-free conditions for multiport follow from absence of active power waste inside multiport. These conditions are through scattering matrix coefficients expressed:

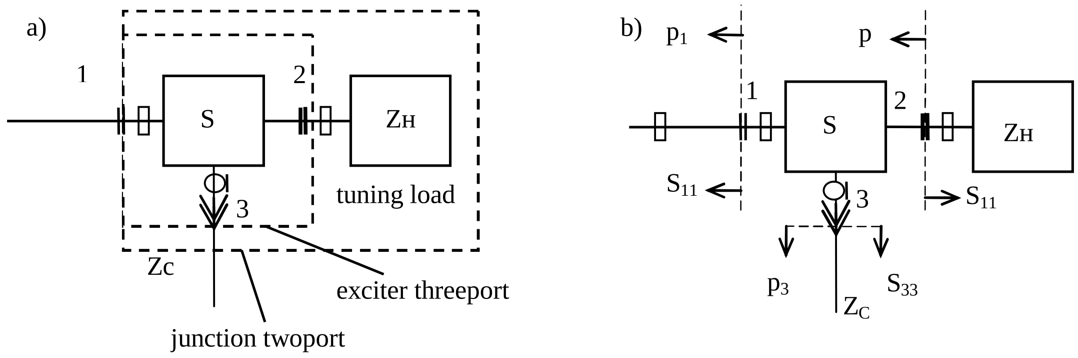

Fig. 1. Block scheme of junction twoport (a); parameter of exciter threeport (b)

$$\begin{aligned}
&\text{a)}\ \left|S_{11}\right|^2+\left|S_{12}\right|^2+\left|S_{13}\right|^2=1;\\
&\text{b)}\ 2\cdot\left|S_{13}\right|^2+\left|S_{33}\right|^2=1; \qquad (2)\\
&\text{c)}\ S_{11}\cdot\overset{*}{S}_{12}+S_{12}\cdot\overset{*}{S}_{11}+\left|S_{13}\right|^2=0;\\
&\text{d)}\ S_{11}\cdot\overset{*}{S}_{13}+S_{12}\cdot\overset{*}{S}_{13}+S_{13}\cdot\overset{*}{S}_{33}=0.
\end{aligned}$$

Above complex conjugate coefficients are used: $\overset{*}{S}_{11}$, $\overset{*}{S}_{12}$, $\overset{*}{S}_{13}$, $\overset{*}{S}_{32}$.

The input impedance $Z=\left|Z\right|\cdot e^{j\cdot\phi_z}$ of the port 3 (Fig.1, b) is determined at matched loads of the ports 1, 2. Known is also the line characteristic resistance, *Zc*. Now we have the possibility to find the reflection coefficient S_{33}:

$$S_{33}=\frac{Z-Z_C}{Z+Z_C}. \qquad (3)$$

Accordingly to the definition of coefficient $S_{13}=\left|S_{13}\right|\cdot e^{j\cdot\phi_{13}}$ the argument ϕ_{13} in the plane *z=0* (plane of exciter axis location) is expressed by formula:

$$\phi_{13}=\pi+\arg(1+S_{33})-\phi_Z. \qquad (4)$$

Use the expression (4) it is posible to find argument ϕ_{33} in general case. This argument is independent from transmission line- and exciter-type. In the expression (4) one can include the diplacement of port-plane. As example we consider the port-plane diplacement from *z=0* to z=*a*, where *a*-radius of waveguide exciter element.

Then from ϕ_{13} - value (4) it is necessary the phase delay, - $\beta_0 a$, to subtract (β_0 - waveguide phase coefficient).

From equation (2, b) we obtain $\left|S_{13}\right|$:

$$\left|S_{13}\right|=\sqrt{\frac{1-\left|S_{33}\right|^2}{2}}. \qquad (5)$$

Equation (2, c) gives the expression:

$$\cos(\phi_{11}-\phi_{12})=-\frac{\left|S_{13}\right|^2}{2\cdot\left|S_{11}\right|\cdot\left|S_{12}\right|}. \qquad (6)$$

Analogous, from equation (2, d) we find the argument θ:

$$\theta=2\cdot\phi_{13}-\phi_{33}-\phi_{11};$$

$$\cos\theta=\frac{\left|S_{13}\right|^2-2\cdot\left|S_{11}\right|^2}{2\cdot\left|S_{11}\right|\cdot\left|S_{33}\right|}. \qquad (7)$$

The last expression determine the limitations of $\left|S_{11}\right|$ value by the conditions: $-1<\cos\theta<1$:

$$\frac{1}{2}\cdot(1-S_{33})<\left|S_{11}\right|<\frac{1}{2}\cdot(1+\left|S_{33}\right|). \qquad (8)$$

As unknown coefficients we have $S_{11}=\left|S_{11}\right|\cdot e^{j\cdot\phi_{11}}$, and $S_{12}=\left|S_{12}\right|\cdot e^{j\cdot\phi_{12}}$. But for calculation of four parameters ($\left|S_{11}\right|$, ϕ_{11}, $\left|S_{12}\right|$, ϕ_{12}) we have only three equations from loss-free conditions (2). It is necessary to use the additional loss-free condition, formulated on the energy-conservation-law basis: if the wave energy in a isolated loss-free volume falls, completely reflects from them. In order to transform the loss-free exciter threeport in an isolated volume we use the reactive loads in the ports 2 and 3, for example with reflection coefficient: $p=+1$. By aid of signal flow-graph for isolated volume (Fig. 2, a), and use the nontouching-loop rule [1], we find the reflection coefficient $p_1^+=\frac{b_1}{a_1}$:

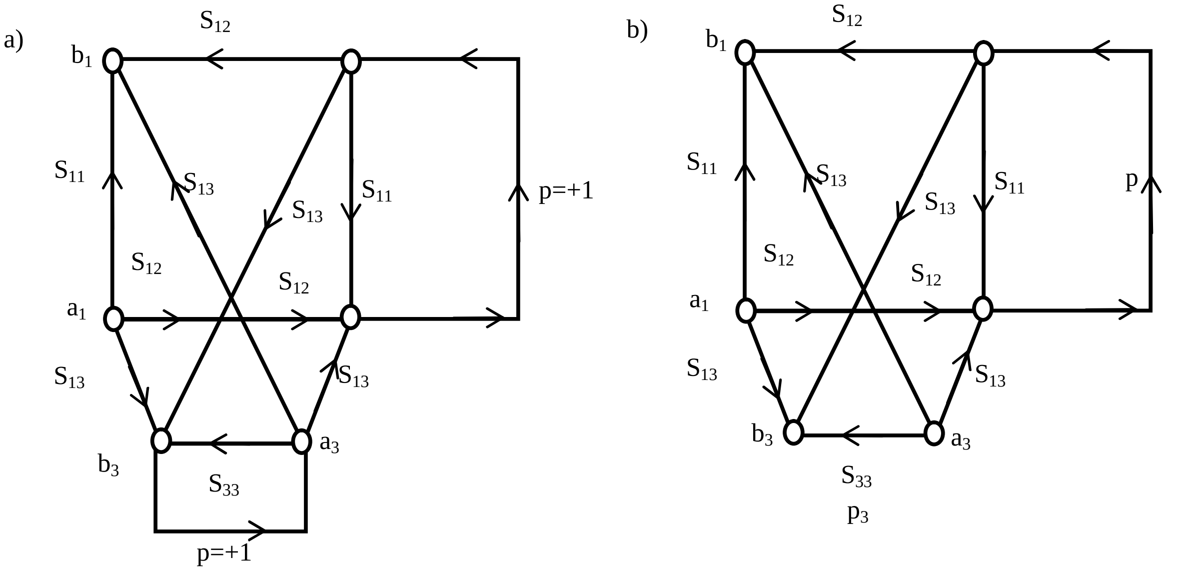

Fig. 2. Signal – flow graph of exciter threeport with loaded ports 2 and 3 (a); signal – flow graph for scheme Fig.1, b (b)

$$p_1^+ = \frac{S_{11}\cdot(1-S_{11}-S_{33}-S_{13}^2+S_{11}\cdot S_{33})}{1-S_{11}-S_{33}-S_{13}^2+S_{11}\cdot S_{33}} + \frac{S_{12}^2\cdot(1-S_{11})+S_{13}^2\cdot(1-S_{11})}{1-S_{11}-S_{33}-S_{13}^2+S_{11}\cdot S_{33}}\,. \quad (9)$$

The additional loss-free condition is expressed now by the equation:

$$\left|p_1^+\right| = 1\,. \quad (10)$$

S-parameter of loss-free exciter threeport must the last equation fulfil. The coefficients S_{13}, S_{33} are known. If to accept the value of $|S_{11}|$, ϕ_{11} - we obtain from formula (7), and coefficient S_{12} - from equation (2, d):

$$S_{12} = -e^{j\cdot\phi_{11}}\cdot\left(|S_{11}|+|S_{33}|\cdot e^{j\cdot\theta}\right). \quad (11)$$

Then are fulfilled also the equations (2, a) and (6). If accepted $|S_{11}|$ the equation (10) don't fulfil, $|S_{11}|$ must be varied. Such procedure may be realized by the program for transcendental equations solution. By aid of that program the equation (10) was solved relative to $|S_{11}|$. Thus all S-parameter fulfil the loss-free conditions (2) and (10).

3. Synthesis Problem of Junction Twoport

The transformation of wave modes by junction twoport, as known, is by exciter element-structure realized. It was emphasized above, that the transmission losses through the junction twoport are by reflections from junction ports caused.

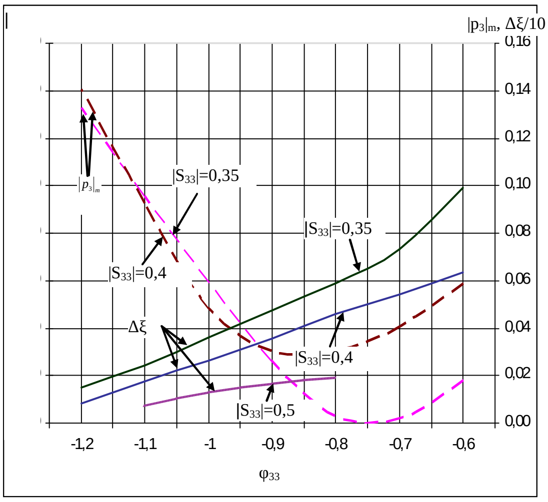

Fig.3. Dependence of junction twoport tuning band width $\Delta\xi$, and reflection coefficient $|p_3|_m$ at middle frequency f_0 - from exciter threeport parameter $S_{33} = |S_{33}|\cdot e^{j\cdot\phi_{33}}$; ($|p_3|_C = 0{,}15$).

Usually junction twoport is characterized by frequency band (Δf), where the reflection coefficient $|p_3|$ is smaller as given admissible coefficient $|p_3|_C$ ($|p_3| = |p_1| \le |p_3|_C$). All S-parameter of exciter threeport are for middle band frequency, f_0, found. Use the impedance Z_H (Fig. 1, a) the minimum of reflection coefficient $\left|p_3\right|_m$ at the frequency f_0 is provided. Impedance Z_H is as input reactance of shorted waveguide piece with length L realized. Thus the reflection coefficient p from reactance Z_H is equal:

$$p = -e^{-j \cdot 2 \cdot \beta_0 \cdot L}, \qquad (12)$$

where β_0 - waveguide phase coefficient is. Use the signal flow-graph Fig 2, b for exciter twoport we determine the reflection coefficient $p_3 = \frac{b_3}{a_3}$:

$$p_3 = S_{13} + \frac{S_{13}^2 \cdot p}{1 - S_{11} \cdot p}. \qquad (13)$$

Now we find the quantity, $p = p_H$, for $p_3 = 0$ at frequency f_0. From the expression (13) we obtain:

$$\begin{aligned} p_H &= \frac{S_{33}}{S_{11} \cdot S_{33} - S_{13}^2}; \\ p_H &= -\left|p_H\right| \cdot e^{-j \cdot \phi_H}; \qquad (14) \\ \left|p_H\right| &= \frac{\left|S_{33}\right|}{\left|S_{11} \cdot S_{33} - S_{13}^2\right|} = \frac{\left|S_{33}\right|}{\left|S_{11}\right|}; \\ \phi_H &= \pi - \arg(p_H). \end{aligned}$$

From the expressions (14) and (12) follows, that:

$$\phi_H = 2 \cdot \beta_0 \cdot L; \; L = \frac{\phi_H}{2 \cdot \beta_0}. \qquad (15)$$

We should to remark, that the quantity $\left|p_H\right|$ may be greater as unity ($\left|p_H\right| \geq 1$), and can not be by reflection coefficient $\left|p\right| = 1$ (12) realized. Such circumstance causes, that at frequency f_0 we obtain $\left|p_3\right| = \left|p_3\right|_m$ instead $\left|p_3\right| = 0$. Simultaneously the minimum of $\left|p_3\right| < \left|p_3\right|_m$ arise at a little diplaced from f_0 frequency. Such effect manifests itself so much the more $\left|p_3\right|_m$ is close to $\left|p_3\right|_C$.

The junction twoport frequency band width is usually found use the graphic dependence $\left|p_3\right|$ from frequency f $(\left|p_3\right| = f_1(f))$. For accurate calculation of such junction characteristic one must know exciter threeport S-parameter for every band frequency, and use expressions (12), (13). Also the waveguide phase coefficient β is to calculate for every band frequency ($L = const$). For S-parameters given at frequency f_0 it is possible to have the accurate junction tuning characteristic, it is the dependence $\left|p_3\right|$ from variable length L: $L \pm \Delta L^{\pm} = L \cdot (1 \pm \xi^{\pm})$ where $\xi^{\pm} = \frac{\Delta L^{\pm}}{L}$ - relative variation of shorted waveguide length L, defined at middle frequency f_0. In calculation of junction tuning characteristic $\left|p_3\right| = f(\xi)$ varies the argument ϕ:

$$\phi = 2 \cdot \beta_0 \cdot L \cdot (1 + \xi) = \phi_H \cdot (1 + \xi). \qquad (16)$$

It is to emphasize, that the characteristic $\left|p_3\right| = f(\xi)$ relative to axis $\xi = 0$ asymmetrical is. Therefore the junction tuning band $\Delta\xi$ is a sum: $\Delta\xi = \xi^+ + \xi^-$, where $\xi^{\pm}$ are at $\left|p_3\right| = \left|p_3\right|_C$ found. The junction tuning characteristic may be into frequency characteristic recount use the condition: $\phi(\xi) = \phi(\frac{\Delta f}{f_0}) = \phi(\frac{\Delta\lambda}{\lambda_0})$. One can convince, that $\frac{\Delta f^{\pm}}{f_0}$ approximately one half of $\xi^{\pm}$ equal is. Inaccuracy of such recount is by frequency-dependence of exciter threeport S-parameter caused.

For known junction exciter threeport S-parameter and argument ϕ_H at frequency f_0, we can the junction tuning band $\Delta\xi$ calculate. Quantities ξ^+ and ξ^- it is necessary to find separately. For such purpose we use the equation (13) with $\xi = 0$ ($\left|p_3\right| = \left|p_3\right|_m$), and $\xi = \xi^{\pm}$ ($\left|p_3\right| = \left|p_3\right|_C$):

$$\begin{aligned} \left|p_3\right|_m &= \left|S_{33} - \frac{S_{13}^2 \cdot e^{-j \cdot \phi_H}}{1 + S_{11} \cdot e^{-j \cdot \phi_H}}\right|; \\ \left|p_3\right|_C &= \left|S_{33} - \frac{S_{13}^2 \cdot e^{-j \cdot \phi_H \cdot (1 \pm \xi^{\pm})}}{1 + S_{11} \cdot e^{-j \cdot \phi_H \cdot (1 \pm \xi^{\pm})}}\right|. \qquad (17) \end{aligned}$$

In solution of equations (17) relative the quantity $\xi^{\pm}$ we simplify:

$$e^{\mp j \cdot \phi_H \cdot \xi^{\pm}} = 1 \mp j \cdot \phi_H \cdot \xi^{\pm} - \frac{(\phi_H \cdot \xi^{\pm})^2}{2}. \qquad (18)$$

Correspondingly we neglect the quantity $\phi_H \cdot \xi^{\pm}$ in higher degrees then 2. Testing of used simplyfications in tuning band width calculation show the error of some per cent. For accepted above conditions from equations (17) we obtain a quadratic equation relative ($\phi_H \cdot \xi^{\pm}$):

$$(\phi_H \cdot \xi^{\pm})^2 \pm b \cdot (\phi_H \cdot \xi^{\pm}) + d = 0, \qquad (19)$$

where: $$b = 2 \cdot \frac{Ci - t \cdot Ai}{\left|C\right|^2 - Cr - t \cdot (\left|A\right|^2 - Ar)};$$

$$d = \frac{1-t}{\left|C\right|^2 - Cr - t \cdot (\left|A\right|^2 - Ar)}; \; t = \left(\frac{\left|p_3\right|_m}{\left|p_3\right|_c}\right)^2;$$

$$C = Cr + j \cdot Ci = \frac{S_{11} \cdot e^{-j \cdot \phi_H}}{1 + S_{11} \cdot e^{-j \cdot \phi_H}}; \qquad (20)$$

$$A = Ar + j \cdot Ai = \frac{(S_{11} \cdot S_{33} - S_{13}^2) \cdot e^{-j \cdot \phi_H}}{S_{33} \cdot (1 + S_{11} \cdot e^{-j \cdot \phi_H}) - S_{13}^2 \cdot e^{-j \cdot \phi_H}}$$

Solution of equation (19) should have the positive sign.

In junction twoport synthesis problem a great importance has the choice of parameter S_{33}. As is proved above, for given reflection coefficient S_{33} loss-free conditions allow to find other parameter of junction twoport. Correspondingly to expression (3), it is possible to vary the value of S_{33} by choice of line characteristic resistance Z_C. Here we want the dependence of junction tuning band width from $\left|S_{33}\right|$ and ϕ_{33} to find. For tuning band width determination we accept the reflection coefficient $\left|p_3\right|_C = 0{,}15$. Additionally we accept the limitation: $\xi < 1$. The loss-free conditions simultaneously serve as limitation for S_{33}. Calculated results are on Fig.3 shown. These results are only for TEM/TE wave type transformation valid. But here absent frequency limitations, limitations associated with exciter element structure, with line and waveguide type.

The dependences on Fig.3 confirm the known tendency: to accept the low value of $\left|S_{33}\right|$. Such tendency allows a greater junction twoport tuning band, and corresponding greater frequency band, to obtain. The argument ϕ_{33} should be negative and limited: $\phi_{33} = -0{,}4 \div -1{,}2$. So demand loss-free conditions. But minimum of $\left|p_3\right|_m$ lie in boundaries $\phi_{33} = -0{,}4 \div -0{,}8$, and at $\left|S_{33}\right| < 0{,}4$. Increased $\left|S_{33}\right|$ causes narrowing of boundaries of ϕ_{33}. Outside of boundaries (8) the calculation gives the complex value of arguments.

4. Conclusion.

Use the junction loss-free conditions it is a method for structure S-parameter calculation proposed. The corresponding calculation algorithm contains the program of transcendental equations solution. For such calculation only the input impedance of exciter threeport must be known. Found S-parameter give the possibility the tuning reactance for junction twoport to establish. Graphical analysis results open also the possibility for junction structure optimization. Use of loss-free conditions high junction twoport synthesis accuracy in comparison with electrodynamic methods of problem solution is provided. Proposed here algorithm is from frequency, from exciter element structure and transmission line type independent. Remains a problem of accurate input impedance calculation, where it is necessary exciter element structure peculiarities to consider.

References

1. Захарія Й.А. Методи прикладної електродинаміки. – Львів, 2003, 352 с.
2. Захарія Й.А. Вплив структури живлення на випромінювання збуджувачів електромагнітних хвиль / Вісник НУ «Львівська політехніка» - № 534, «Радіоелектроніка та телекомунікації», Львів, В-во НУ «ЛП», 2005, с. 69-73.
3. Jarem J.M. A multifilament method-of-moments solution for the input impedance of a probe-excited semi-infinite waveguide/ IEEE Trans. on Microwave theory and techniques, vol. MTT-35, №1, January 1987, p. 14 – 19.
4. Williamson A.G. Coaxially feed hollow probe in rectangular waveguide driven from a coaxial line/ Proc. IEE., №10, H.132, August 1989., p.273–282.
5. Yehuda-Leviatan, Der-Hua-Shau, Arlon T. Numerical study of the current distribution on a post in rectangular waveguide/ IEEE Trans. on Microwave theory and techniques, vol. MTT-32, №10, October 1984, p.1411-1415.