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Performance of Nonsynchronous Noncommensurate Impedance Transformers in Comparison to Tapered Line Transformers

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Abstract—**Nonsynchronous noncommensurate impedance transformers consist of a combination of high- and low-impedance transmission lines. The present work is dedicated to the synthesis of such transformers. They are analyzed employing wave transmission matrices. The performance of the transformer is compared to a traditional tapered line impedance transformer.**

The increase in bandwidth of nonsynchronous noncommensurate impedance transformers typically leads to shortening the transformer length, which makes the transformer attractive for applications, where a wide operating band and high transformation ratios are required.

Keywords- impedance matching, wave transmission matrices.

I. INTRODUCTION

The design of wideband impedance matching circuits is a challenging task, because the traditional designs based on distributed components exhibit a large circuit size which is highly undesirable in practice. The matching circuits based on lumped elements, however, are compact but suffer from low Q-factor at high frequencies.

Nonsynchronous noncommensurate altering transmission line impedance transformers *(NN impedance transformers)* are one of the promising types of transformers for a broadband matching. They provide a wide bandwidth, comparatively low insertion loss, have a compact size, and exhibit a comparatively low sensitivity to fabrication errors. Contrary to the transformers described in [1], NN impedance transformers consist of the sections of different lengths (*noncommensurate*) with the same characteristic impedances as the impedances of the source Z_0 and the load Z_L which should be matched. The word *nonsynchronous* in the name of the impedance transformer means that the impedance ratio between the steps can be equal or exceed the output-to-input transformation ratio r by a large factor. In some literature NN impedance transformers are also referred as stepped transformers of Class II [2].

The work presented in this paper complements the design data presented in [3] and [4], and the synthesis procedure of a 12-section NN impedance transformer with transformation ratios r = 2 ... 10 and bandwidth ratios χ = 4 ... 20 is given here as an example. The performances of the synthesized NN transformer are then compared to those of a traditional tapered line impedance transformer.

II. ANALYSIS BASED ON WAVE TRANSMISSION MATRICES

For analysis of NN impedance transformers, the approach based on wave transmission matrices (T-matrices) has been employed, allowing to consider multiple reflections from the impedance transformer sections. NN impedance transformer is assumed to be lossless, reciprocal, and antimetric two-port network ($T_{11} = T_{22}^*$, $|T_{11}|^2 = 1+|T_{12}|^2$, $T_{12} = T_{21}$, $Im T_{12}=Im T_{21}=0$). These assumptions simplify the analysis still providing acceptable results. The antimetry yields that the sections' lengths θ_n are symmetric with regard to the transformer center $\theta_n=\theta_{N-(n-1)}$, $n=1\div N/2$, and the partial reflection coefficients from the steps discontinuities ρ_n are also symmetric with regard to the transformer centre $\rho_{n-1}=\rho_{N-(n-1)}$, $n=1\div N/2$, where N is the number of sections. Moreover, the sections' electrical lengths are related to each other linearly $\theta_n=v_n\theta_1$, $n=2\div N$, where θ_1 is the electrical length of the first section at the center frequency f_0 of the matching bandwidth, v_n is the n-th component of the N-dimensional vector defining the electrical lengths of the remaining sections $v=(1, v_2, v_3,…, v_N)$.

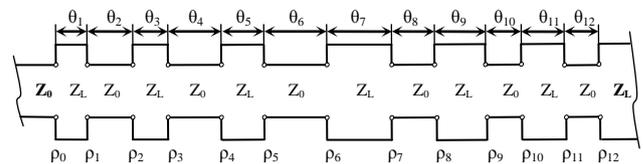A schematic view of a 12-section NN impedance transformer is shown in Fig.1.

Fig.1. A schematic view of a 12-section NN impedance transformer

The transformer consists of altering sections with the electrical lengths $\theta_1=\theta_{12}$, $\theta_2=\theta_{11}$, $\theta_3=\theta_{10}$, $\theta_4=\theta_9$, $\theta_5=\theta_8$, $\theta_6=\theta_7$ and having the same characteristic impedances as the impedance of the source Z_0 and the load Z_L. The model of NN impedance transformer consists of two-port networks formed by two transmission lines with different characteristic

impedances, and the entire impedance transformer is treated as series connected two-port networks.

In a two-port network, the directions of wave propagation have been chosen so that V_1^+, V_2^- are the voltage amplitudes of the waves entering port *1* and port *2*, and V_1^-, V_2^+ are the voltage amplitudes of outgoing waves from port *1* and port *2*, respectively.

For the chosen directions of propagation, the scattering transfer matrix can be written as

$$\begin{bmatrix} V_1^+ \\ V_1^- \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} V_2^+ \\ V_2^- \end{bmatrix} \qquad (1)$$

The first two-port network of NN impedance transformer is formed by shifting the reference plane of the impedance transformer for a half of electrical length $\theta_1/2$ in the direction of the source. All the following two-port networks are respectively consist of two transmission lines with length $\theta_1/2$ and $\theta_n - \theta_1/2$, $n=2\div N$. For a two-port network between n and $(n+1)$ step, formed by two transmission lines with different characteristic impedances, T-matrix can be expressed as

$$[T]_n = \frac{1}{\sqrt{1-\rho_n^2}} \begin{bmatrix} e^{j\theta_{n+1}} & \rho_n e^{-j(\theta_{n+1}-\theta_1)} \\ \rho_n e^{j(\theta_{n+1}-\theta_1)} & e^{-j\theta_{n+1}} \end{bmatrix} \qquad (2)$$

The impedance transformer has more section discontinuities $(N+1)$ than the number of sections (N), therefore, the last two-port network is formed by combining two transmission lines of length $\theta_1/2$.

The resulting T-matrix of the 12-section NN impedance transformer is found by a consecutive T-matrices multiplication for the impedance transformer sections

$$[T]_{tot} = [T]_1 \cdot [T]_2 \cdot \ldots \cdot [T]_{12} \qquad (3)$$

The parameters of the NN impedance transformer are found solving a mini-max problem for the magnitude of the total reflection coefficient

$$Min|\Gamma|_{max}, |\Gamma|_{max} = \max|\Gamma(\theta_1, v)|, \theta_1 \in [\theta_1(f_1), \theta_1(f_2)] \qquad (4)$$

where $\theta_1(f_1)$ and $\theta_1(f_2)$ are the electrical lengths of the first section θ_1 at the lowest frequency f_1 and the highest frequency f_2 of the assumed matching bandwidth and

$$|\Gamma|_{max} = \frac{|T_{21tot}|_{max}}{\sqrt{1+|T_{21tot}|_{max}^2}} \qquad (5)$$

where T_{21tot} is the scattering transfer coefficient of the overall NN impedance transformer.

III. Design Data for a Synthesis of 12-section NN Impedance Transformer

Figures 2-9 represent the design data for the synthesis of 12-section NN impedance transformer with bandwidth ratios

$r = 2...10$, the transformation ratios $\chi = 4...20$, and the maximum reflection coefficient magnitude $|\Gamma| \le -10$ dB. The data have been obtained by solving (4) numerically.

The given range of bandwidth ratios and transformation ratios has been chosen for practical reasons. *χ > 20* and *r > 10* would lead to poor matching. In most practical cases, this would require implementation of a larger transformer with number of sections of more than twelve. Choosing *χ < 4* would lead to a very low level of reflection coefficient and in most practical cases it would be reasonable to use a shorter transformer (with a number of sections less than twelve).
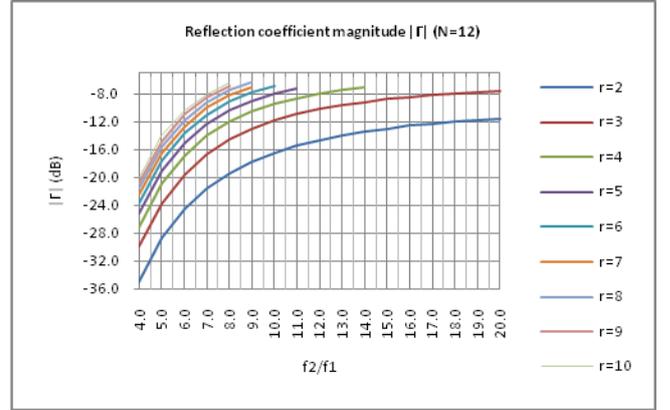

Fig.2. The magnitude of the reflection coefficient for the 12-section NN impedance transformer.

The magnitude of the reflection coefficient, $|\Gamma|$, of a 12-section NN impedance transformer can be found from Fig.2. $|\Gamma|$ deteriorates with increasing transformation ratio r and bandwidth ratio χ. Fig.3-8 show the sections' electrical lengths.
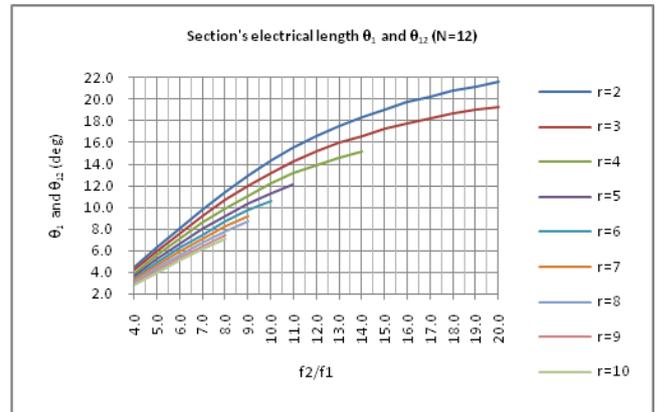

Fig.3. The electrical length of the sections 1 and 12 for the transformer in Fig. 1.

The electrical length of the first and twelfth sections, third and tenth sections, and the fifth and eighth sections of the 12-section NN impedance transformer is increasing while

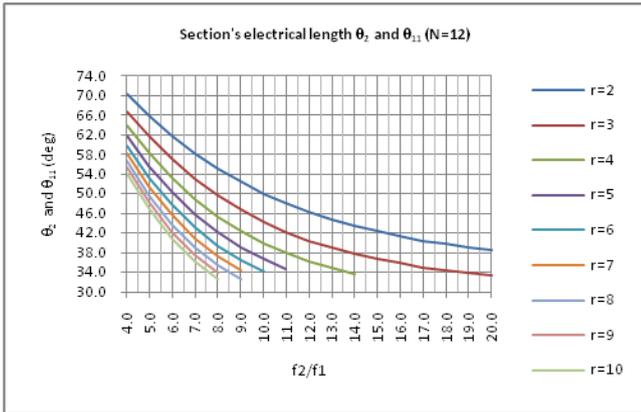increasing the bandwidth ratio and decreasing the transformation ratio.

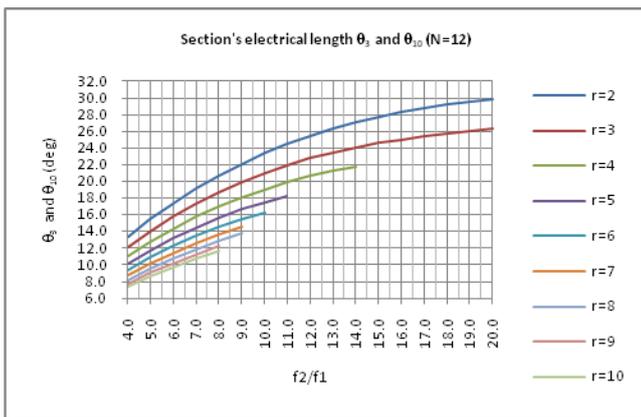Fig.4. The electrical length of the sections 2 and 11 for the transformer in Fig. 1.

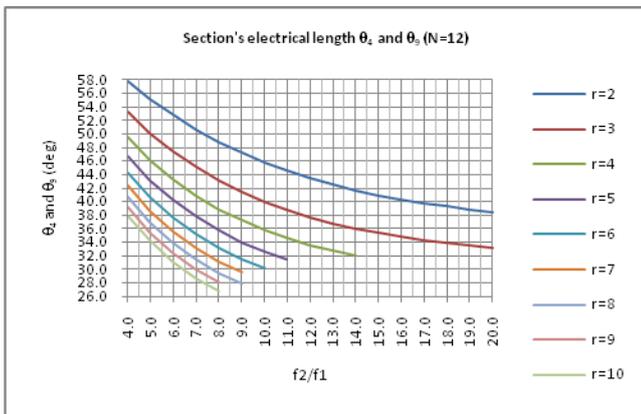Fig.5. The electrical length of the sections 3 and 10 for the transformer in Fig. 1.

Fig.6. The electrical length of the sections 4 and 9 for the transformer in Fig. 1.

The electrical length of the second and eleventh sections, fourth and ninth sections, and sixth and seventh sections of the 12-section NN impedance transformer is decreasing while increasing the bandwidth ratio and the transformation ratio.
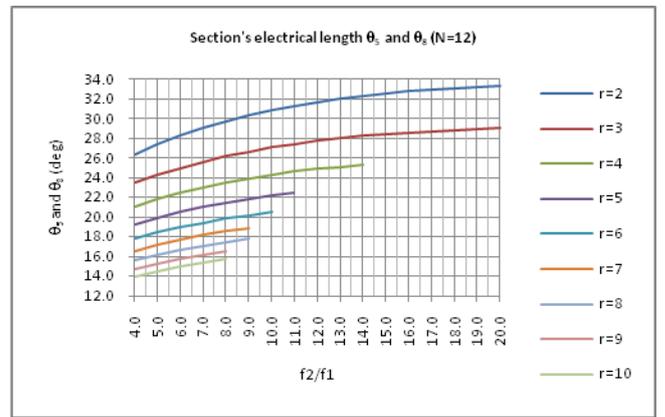

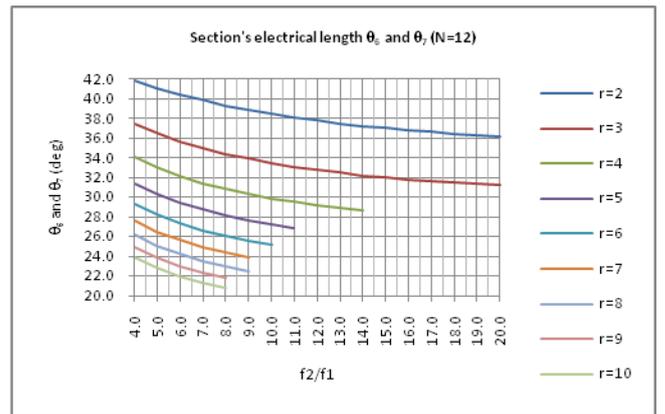Fig.7. The electrical length of the sections 5 and 8 for the transformer in Fig. 1.

Fig.8. The electrical length of the sections 6 and 7 for the transformer in Fig. 1.
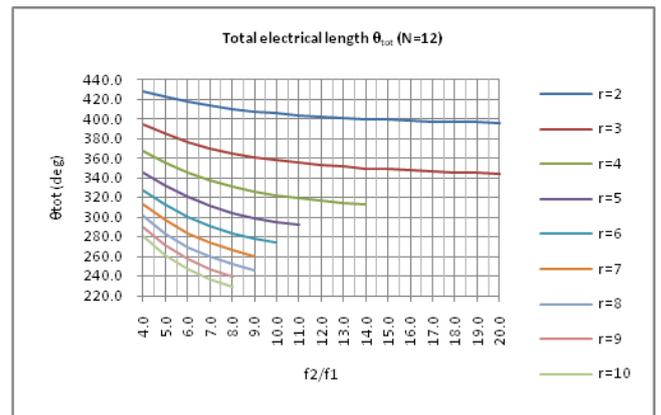

Fig.9. The total electrical length of a 12-section NN impedance transformer.

The total electrical length of the impedance transformer becomes shorter while increasing the bandwidth ratio χ and the transformation ratio r, as shown in Fig. 9.

IV. COMPARISON OF THE 12-SECTION NN IMPEDANCE TRANSFORMER WITH A TAPERED IMPEDANCE TRANSFORMER

In order to validate the data obtained for the design of NN

impedance transformers, an impedance transformer with a transformation ratio $r=4$ ($Z_L=50$ Ohm, $Z_0=12.5$ Ohm), bandwidth ratio $\chi=5$ ($f_2=2.25$ GHz, $f_1=0.45$ GHz), and the magnitude of the reflection coefficient better than $|\Gamma|\leq-20$ dB has been synthesized based on the design data in Fig.3-8. The calculated S-parameters of the impedance transformer using equation (5) are shown in Fig.10.
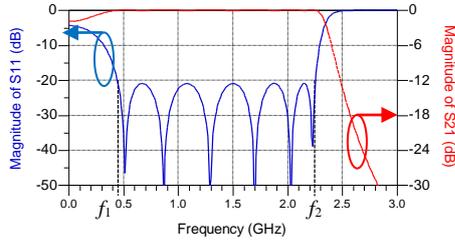

Fig.10. Magnitudes of S_{11} and S_{21} of the 12-section NN impedance transformer.

To compare the performance of a 12-section NN impedance transformer with a tapered impedance transformer, they have been realized using RO4003 substrate with a thickness $h=1.524$ mm, relative dielectric constant $\varepsilon_r=3.55$, dielectric loss tangent tan $\delta=0.0021$, and conductor thickness $t=0.035$ mm. The length of the tapered transformer has been chosen such that it has the same frequency of the reflection coefficient first minimum as an NN impedance transformer.

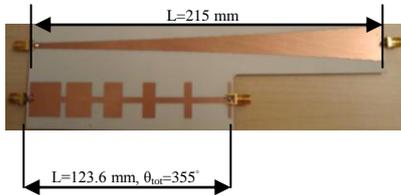The photo of the fabricated transformers is shown in Fig.11.

Fig.11. Photograph of the 12-section NN impedance transformer and tapered transformer manufactured on RO4003.

The impedance transformers have been measured using a vector network analyzer. The actual scattering parameters of the impedance transformer have been obtained through the renormalization and de-embedding.

Simulated and measured S-parameters of the impedance transformers are shown in Fig. 12.

Measurements show that the magnitude of the reflection coefficient of NN impedance transformer deteriorates at higher frequencies. One minimum is not visible compared to the MoM simulations. This is most probably caused by the inaccuracy of the fixture model in the de-embedding procedure. The simulated and measured reflection coefficients of the tapered impedance transformer also differ due to tolerance in fabrication and discontinuity of 12.5 Ohm-to-50 Ohm transmission line step at 12.5 Ohm port. The reflection coefficient magnitude doesn't decrease (improves) continuously while frequency increases, as it was expected.
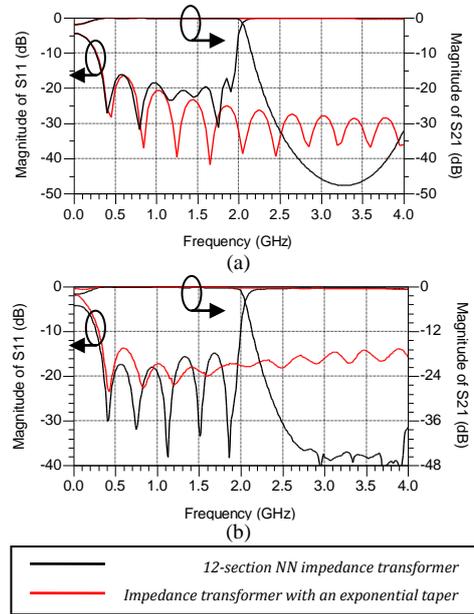

Fig.12 S-parameters of the NN impedance transformers in Fig. 11. (a) MoM simulations. (b) Measurements.

It can be concluded that the NN impedance transformer is more attractive in practice since it provides approximately the same matching level as the tapered impedance transformer in the specified frequency range, but has shorter length. A further miniaturization can be achieved by meandering the high impedance transmission line sections of the transformer [5].

V. CONCLUSIONS

The advantage of NN impedance transformers is that they generally exhibit considerably shorter length than the tapered impedance transformers in a fixed frequency range. It was also found, that the fabrication accuracy of tapered transformer should be high in order to achieve theoretically predicted continuous increase of reflection loss. In practice, however, the reflection coefficient of tapered impedance transformer degrades with frequency. Due to the lowpass behavior, the NN impedance transformers are preferable for matching of power amplifiers, since the higher harmonics exhibited by the amplifier will be attenuated.

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