# Synthesis of Filtering Structures for Microstrip Active Antennas Using Orlov's Formula

Fabio Urbani, Filiberto Bilotti, and Lucio Vegni

**In this paper, a synthesis technique for nonuniform filtering structures to be employed in active integrated antenna layouts is presented. The idea is to suppress the higher harmonic contribution due to the presence of nonlinear components through a nonuniform transmission line properly designed via Orlov's synthesis formula. The theory presented is applied here to synthesize an amplifier-based active antenna layout for wireless local area network (WLAN) purposes working at 2.4 GHz. The numerical results presented show the capabilities of the proposed approach.**

**Keywords: Patch antennas, transmission lines, synthesis techniques.**

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## I. Introduction

Active integrated antennas (AIAs) are components in which a passive antenna element and active circuitry are integrated on the same substrate [1]. The integration of both antennas and active circuits is responsible for greater compactness, lower costs, and higher power efficiency with respect to conventional passive layouts [2].

Specifically when active antennas also involve power amplifiers, most of the lost power is due to the amplifier output stage [3]. Therefore, there has been great interest during the last years in maximizing the power added efficiency, which is defined as the ratio between the power at the output port of the amplifier and the input power [3]. In order to achieve this goal, the higher-order harmonic contributions at the output port have to be reflected back to the device. Typical second harmonic tuning exploits a quarter-wavelength (where the wavelength is intended at the fundamental frequency) short-circuited stub connected at the output port, or chip-capacitors exhibiting a self-resonance at the second harmonic frequency.

In AIA layouts, however, the harmonic tuning is usually accomplished by using the inherent frequency response of the antenna element or by using a proper transmission line with a filtering behavior. The approach based on the antenna acting as a filter is very effective in enhancing the compactness of the layout, but leads to a very narrow-band frequency response. Therefore, such an approach cannot be effectively used in communication systems requiring multicarrier broadband CDMA operation.

In such cases, a more complicated layout involving a broad-band filtering structure is more useful. For instance, in [4] Anzellotti and others have proposed the employment of a photonic band gap periodic transmission line in order to obtain a

proper broad-band tuning of the higher harmonic contributions in an AIA layout. The periodicity of the transmission line and the electric/geometric parameters of the periodic cell control the position along the frequency axis, the width and the depth of the stop-band. The incidence of each of these parameters on the stop-band characteristics has been derived and some useful design curves have been provided in [4].

Other filtering structures can be effectively used to achieve the same broad-band tuning behavior. In this paper, we focus our attention on nonuniform transmission lines because of their inherent broad-band behavior as matching and filtering structures [5], [6]. Although the analysis and synthesis of nonuniform transmission lines is an old and well established topic in electromagnetics and circuit theory, to the authors' best knowledge, the employment of such nonuniform structures in active antenna layouts has not yet been proposed in the open technical literature.

The aim of this paper therefore is to develop an efficient and effective design technique to synthesize the electrical and geometrical parameters of a nonuniform transmission line to be used in AIA layouts for higher harmonic tuning purposes.

The structure of the paper is as follows. In section II we describe the circuit equivalent network of the overall active antenna under analysis: the radiating element, the filtering nonuniform transmission line, and the amplifier. Section III presents the proposed design technique of the filtering nonuniform transmission line starting from Orlov's formula. Finally in section IV, some numerical results to show the capabilities and effectiveness of the design technique developed in the paper are reported.

## II. Circuit Equivalent Network of an Active Integrated Antenna

The layout this paper refers to is depicted in Fig. 1. For simplicity, the antenna is considered as a transmitting device, but the same considerations can be also applied by reciprocity to the receiving operation mode.

The approximate equivalent circuit representing the passive radiating component can be obtained through the transmission line model described in [7]. Assuming that the form of the patch is the rectangular one depicted in Fig. 2, and that the patch is fed at one of its radiating edges by a microstrip line, the equivalent network representation for the patch is shown in Fig. 3.

The lumped elements in Fig. 3 take into account the radiation (conductance G) and the reactive effects (susceptance B) at the patch edges.

Simple approximate formulas for such elements can be obtained in the case of very thin dielectric substrates ($d<\lambda_0/10$),

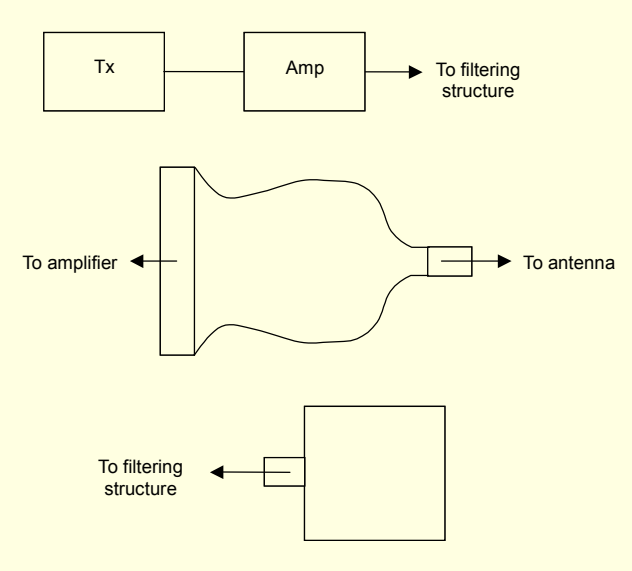



Fig. 1. Schematic layout of the active antenna.

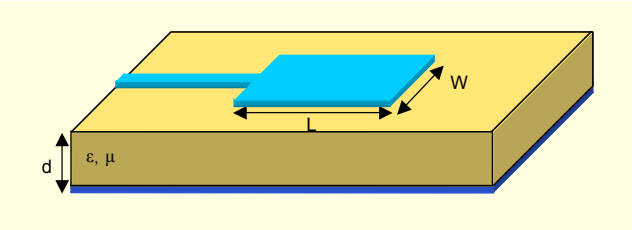



Fig. 2. Basic geometry of the rectangular patch antenna fed by a microstrip line at a radiating edge.

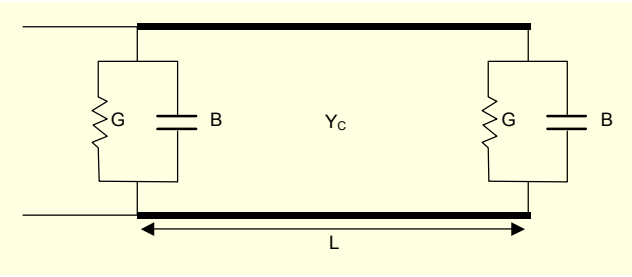



Fig. 3. Equivalent network representation of the rectangular patch depicted in Fig. 2.

and their expressions are given in [7] as

$$G = \frac{W}{120\lambda_0}\left[1-\frac{1}{24}(k_0 d)^2\right], \qquad B = \frac{W}{120\lambda_0}\left[1-0.636\ln(k_0 d)\right], \tag{1}$$

where $\lambda_0$ and $k_0 = 2\pi/\lambda_0$ are the wavelength and the wave number of the vacuum, respectively.

The characteristic impedance and the propagation constant

of the transmission line depicted in Fig. 3 are expressed in terms of the microstrip line parameters as

$$Z_c = \frac{120\pi}{\sqrt{\varepsilon_{r,eff}}\left[\frac{W}{d}+1.393+0.667\ln\left(\frac{W}{d}+1.444\right)\right]}, \quad (2)$$
$$\beta = \omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_{r,eff}},$$

where the effective dielectric constant $\varepsilon_{r,eff}$ is given by

$$\varepsilon_{r,eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{d}{W}\right)^{-1/2}, \quad (3)$$

and $W/d \geq 1$.

Using (1) through (3) and the equivalent network representation given in Fig. 3, it is possible to calculate in closed form the input impedance $Z_{IN}$ of the radiating element as a function of frequency.

Since the output stage of the amplifier is characterized by low output impedance, a matching network between the antenna and the amplifier is required. Such a network can be designed using a nonuniform transmission line (NUTL) as sketched in Fig. 4. The design should also take into account that the NUTL has to behave not only as a matching structure, but also as a filtering structure in order to suppress the undesired high harmonic contributions coming from the amplifier.

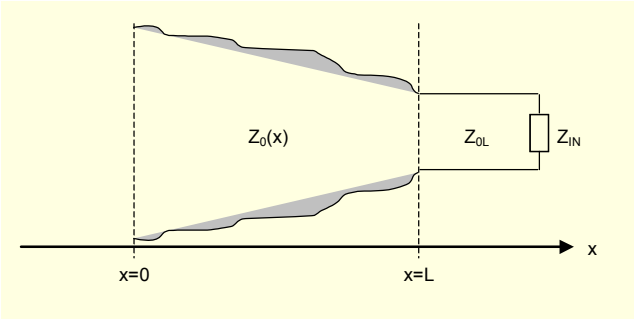



Fig. 4. Equivalent network representation of the matching/filtering structure consisting of an NUTL.

## III. Design of the NUTL Filtering Structure

In this section, we propose an approach based on Orlov's formula [8] to design the NUTL acting as both a filtering and matching structure between the antenna and the amplifier output stage.

The goal therefore is to develop an effective design technique in order to derive the proper impedance profile, $Z_0(x)$ of the nonuniform structure depicted in Fig. 4, capable of both reflecting back the higher harmonics coming from the amplifier and conveying the signal at the resonance frequency to the patch. In order to conduct such a design, we can use Orlov's synthesis formula in [8]:

$$p(x) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{\Gamma(k)[1-|\Gamma_0(k)|^2]-\Gamma_0(k)[1-|\Gamma(k)|^2]}{1-|\Gamma(k)|^2|\Gamma_0(k)|^2}e^{+2jkx}dk, \quad (4)$$

where k is the spatial frequency associated to the spatial variable x, and p(x) is directly related to the characteristic impedance of the NUTL as follows:

$$p(x) = \frac{1}{2}\frac{1}{Z_0(x)}\frac{dZ_0(x)}{dx}, \quad (5)$$

whereas $\Gamma_0(k)$ is the reflection coefficient on the load section reported as x = 0 and expressed by

$$\Gamma_0(k) = \frac{Z_{IN}(k)-Z_{0L}}{Z_{IN}(k)+Z_{0L}}e^{-2jkL}, \quad (6)$$

and $\Gamma(k)$ is the reflection coefficient of the NUTL referred to as x = 0 function of frequency and is given by

$$\Gamma(k) = \frac{1}{1+jQ\left(\frac{c_0k}{2\pi f_0}-\frac{2\pi f_0}{c_0k}\right)^2}, \quad (7)$$

where $f_0$ is the central frequency, $c_0$ is the speed of light in the vacuum and Q is the filter quality factor. The latter formula ensures a stop-band filtering behavior, and its parameters $f_0$ and Q should be designed for reflecting back the higher harmonics coming from the amplifier and for allowing the propagation at the fundamental operating frequency of the patch.

Once the integral in (4) has been solved numerically, the characteristic impedance profile of the nonuniform transmission line placed in between the patch and the amplifier can be finally obtained, solving the first-order differential of (5) as

$$Z_0(x) = Z_{0L}e^{-[2\int p(x)dx]_{x=L}}e^{2\int p(x)dx}. \quad (8)$$

From (8) then, calculating the required profile for the width of the microstrip line conductor is a straightforward matter, using the common microstrip formulas reported in [7].

## IV. Numerical Results

The theory presented in the previous sections is applied here to synthesize an amplifier-based active antenna layout for wireless local area network (WLAN) purposes.

The lower band operating frequency of the Wi-Fi standard for WLAN applications is $f_r = 2.4$ GHz. In order to match this requirement, the rectangular microstrip patch antenna has been designed with the following electrical and geometrical parameters: d = 1 mm, $\varepsilon_r = 2.33$ (RT-duroid) for the substrate, and W = 5 cm and L = 3.9 cm for the patch.

With this ensemble of values it is possible to evaluate the remaining quantities necessary for the synthesis using (1) through (3): $\varepsilon_{r,eff} = 2.19$, $Z_c = 10.87\ \Omega$, and $\beta = 31 f_r\ m^{-1}$. The corresponding input impedance of the rectangular patch is depicted in Fig. 5(a). Please note the higher order modes sustained by the patch geometry. Assuming that the characteristic impedance of the NUTL at the feed section (x = L) is $Z_{0L} = 100\ \Omega$, the corresponding amplitude of the reflection coefficient at the patch input port is depicted in Fig. 5(b).

The NUTL microstrip filter is integrated on the same substrate of the antenna and should suppress the higher order harmonics coming from the amplifier at 4.8 and 7.2 GHz, respectively, which are very close to the resonance frequencies of the higher order modes of the patch.

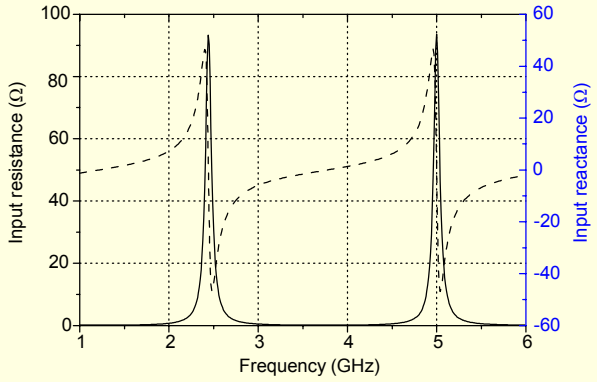
Using (7) and assuming quality factor Q = 1.2 and central frequency $f_0 = 6$ GHz, the reflection coefficient amplitude of the NUTL filter to be designed is shown in Fig. 6. It is worthwhile to point out that the filter parameters Q and $f_0$ have been chosen in order to have a stop-band big enough to include both the second and third harmonics.

The numerical evaluation of the integral in (4) has been performed exploiting the periodicity of the integrand for high k values and the related symmetry properties. Once the function p(x) is known numerically, the line impedance profile can be straightforwardly obtained from (8).

The impedance profile and the effectiveness of the filtering/matching structure designed depend also on the length of the NUTL. This length represents a degree of freedom in the present design and can be chosen to fulfill practical requirements (i.e., space occupancy of the device, etc.) In the following, we present the results for two different choices of the NUTL length. Particularly in Figs. 7(a) and 7(b), the characteristic impedance profiles of the NUTL are shown for the line lengths L = 1 cm and L = 2 cm, respectively, while the output impedance of the amplifier is $Z_{out} = 50\ \Omega$.

The nonuniform microstrip width can be easily computed from the profiles in Fig. 7 by inversion of the common formulas used to calculate the characteristic impedance of the microstrip transmission line [7]. Please note that at x = 0 and at x = L, the matching requirements are satisfied (50 Ω at x = 0 and 100 Ω at x = L).

As a countercheck, the reflection coefficient behavior of the NUTL filters now designed can be determined from the following analysis formula (9) given in [8]:



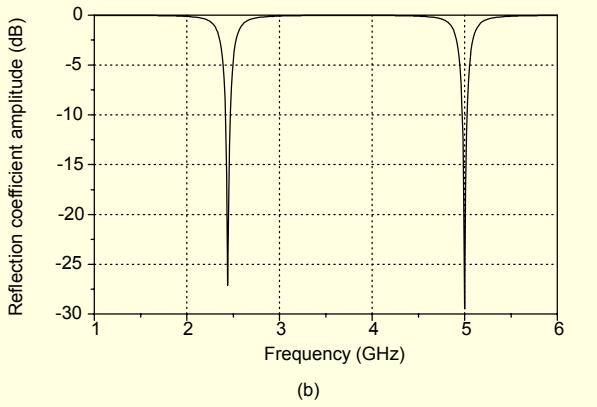




Fig. 5. (a) Input impedance and (b) reflection coefficient of the rectangular patch having the first resonance at 2.4 GHz.

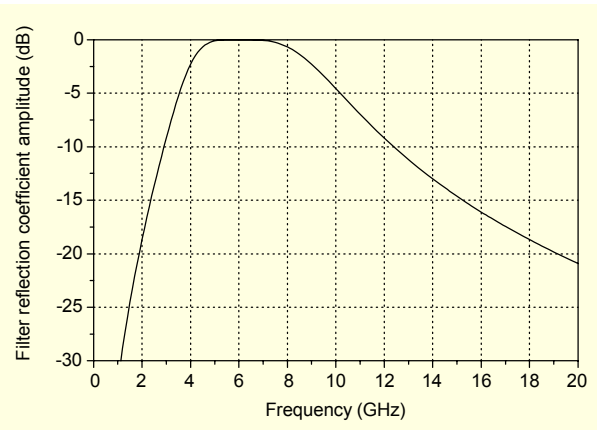



Fig. 6. Reflection coefficient amplitude of the NUTL filter to be designed.

$$\Gamma(k) = \frac{\Gamma_0(k) + \int_0^L e^{-2jkx}\, p(x)\, dx}{1 + \Gamma_0(k) + \int_0^L e^{+2jkx}\, p(x)\, dx}. \qquad (9)$$

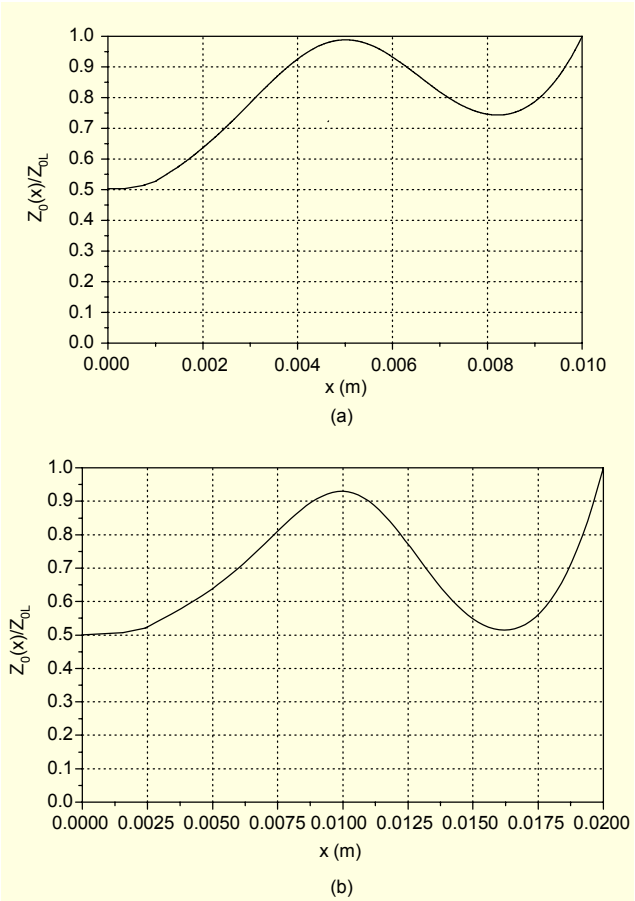



Fig. 7. Normalized characteristic impedance of the NUTL acting as a filter to cut off the higher harmonics coming from the amplifier: (a) L=1 cm and (b) L=2 cm.

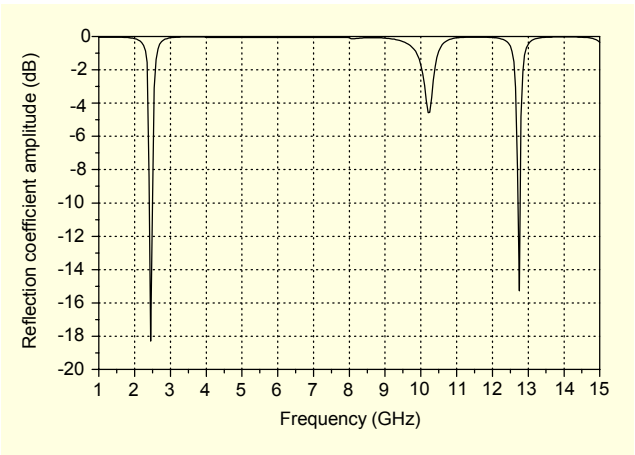



Fig. 8. Reflection coefficient at the input port of the NUTL filter considering the microstrip patch antenna as load.

Plugging in (9), the result obtained for p(x) from the numerical integration in the previous design, and plotting the amplitude of the reflection coefficient as a function of frequency, we should find a good transmission around the antenna working frequency (2.4 GHz) and a high rejection at both 4.8 GHz and 7.2 GHz (frequencies of the 2nd and 3rd harmonics coming from the amplifier).

This behavior is amply confirmed in Fig. 8 for the case L = 2 cm, where the frequency range of analysis has been extended up to 15 GHz to show that the patch modes with resonant frequencies higher than 8 GHz are not affected by the NUTL when the antenna operates as a receiving device.

## V. Conclusions

In this paper, a synthesis technique for nonuniform filtering structures to be employed in active integrated antenna layouts has been presented. A higher-harmonic microstrip suppresser has been designed via Orlov's synthesis formula. In order to demonstrate the capability of the approach, it has been applied in the design of a nonuniform filtering/matching transmission line for a Wi-Fi active integrated antenna working at 2.4 GHz. The numerical results presented support the proposed theoretical approach.

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