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Building a Wideband Amplifier and Studying the Impact of Different Substrates on the Strips Elements of Distributed Circuit

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ABSTRACT

This research presents the design of a single-stage collector circuit for a wideband amplifier, which was subsequently transformed into a distributed circuit configuration across various substrates with differing dielectric constants. The impact of these substrates on amplifier performance was systematically analyzed by applying specific mathematical equations and simulation software. Our findings indicate that the optimal performance of the distributed amplifier was achieved using a substrate with a dielectric constant of 4.37, enabling effective operation across a wide frequency range of 14.6 to 16.5 GHz. This study underscores the critical role of substrate material selection in enhancing the efficiency and reliability of wideband amplifiers, providing valuable insights for future developments in high-frequency circuit design. This aligns seamlessly with this work on the wide amplifier, significantly improving the detection of weak reflections in military and aerospace radar systems. With commendable gain, low noise figures, high stability

Keyword: *amplifier, dielectric substrate, lumped, distributed circuit.*

I. INTRODUCTION

Amplifier circuits are essential in modern electronics, enabling amplification across various frequency ranges. Lumped and distributed amplifiers are two fundamental types of amplifier circuits, each suited to different frequency regimes and design requirements. Lumped amplifier circuits are designed with components such as resistors, capacitors, and inductors that are considered "lumped," meaning their dimensions are small compared to the wavelength of the operating signal. These circuits are typically used in low to moderate-frequency applications where the signal's wavelength is much larger than the physical size of the components. Lumped amplifiers are valued for their simplicity and ease of design, making them ideal for many analog and RF applications. The design of lumped amplifiers involves optimizing component values to achieve desired gain, bandwidth, and stability [1,2]. On the other hand, distributed amplifiers are used in high-frequency applications where the wavelength of the signal is comparable to or smaller than the circuit dimensions. These amplifiers utilize transmission line theory, where the reactive components are distributed along the length of the transmission line rather than being lumped at discrete points [3]. This approach provides broad bandwidth and high gain, making distributed amplifiers particularly useful in RF and microwave systems. The design of distributed amplifiers involves carefully considering transmission line parameters and substrate characteristics [4]. The performance of distributed amplifiers is significantly influenced by the substrate material used. The dielectric properties of the substrate affect the impedance, signal propagation speed, and overall efficiency of the amplifier. Key substrate parameters include the dielectric constant (εr), loss tangent (tanδ), and thermal conductivity. Substrate material changes can impact the transmission lines' strip dimensions, affecting impedance matching and signal integrity. Therefore, selecting the appropriate substrate material is crucial for optimizing amplifier performance and ensuring reliable operation, [5]. In this work, a single-stage lumped circuit for an amplifier will be designed. Then, it will be converted into a distributed circuit on several different substrates and studied for its effects on the amplifier's performance. A set of particular equations and the programs (MWO) and (MATLAB) will be used for this work.

II. AMPLIFER DESIGN

The design of a amplifier begins with analytical processes, including choosing the appropriate type of transistor matching circuits, choosing the substrate, and analyzing stability through simulations and calculations.

Selecting the transistor: The transistor choice is crucial for amplifier design, impacting thermal properties, stray inductors, resistors, gain, and bandwidth. Key considerations include [6]

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Operating mode, transistor types such as FET, BJT, MOSFET..; [7], operating resistance of the transistor (0.01Ω–1Ω); [8], drain voltage;[9], and drain current; [10].

Improving performance at high frequencies requires using a transistor with high mobility carriers and a short channel. The JFET with an n channel is preferred, as electrons have higher mobility than holes. When selecting a transistor, it is necessary to consider obtaining: ***i***. The most significant gain of the received signal. ***ii.*** Stability greater than one. ***iii***. The lowest input and output reflectivity is S11 and S22, respectively**.** ***iv***. The lowest possible noise.

Selection of the Substrate: The effective dielectric constant (ε) of the substrate affects device size and electromagnetic field concentration, reducing radiation losses [11].

Matching:

To achieve maximum signal transfer, reflection coefficients (S11, S22) must be optimized, requiring the source impedance to match the complex conjugate of the load impedance [12].

Input Impedance Matching**:** For effective power transfer from a radio frequency source to a transistor, input impedance is crucial. Typically, high-frequency transistors have a small ohmic component, varying from several ohms, influenced by contact resistance and the transistor’s casing and capacitors [12].

Output Impedance Matching**:** The transistor’s output impedance, which includes a capacitor C_{out}, must match the load impedance to maximize power transfer. The AC output voltage is lower than the DC source voltage due to saturation effects at radio frequencies [13]. Impedance measuring devices using S-parameters have been developed for direct measurement

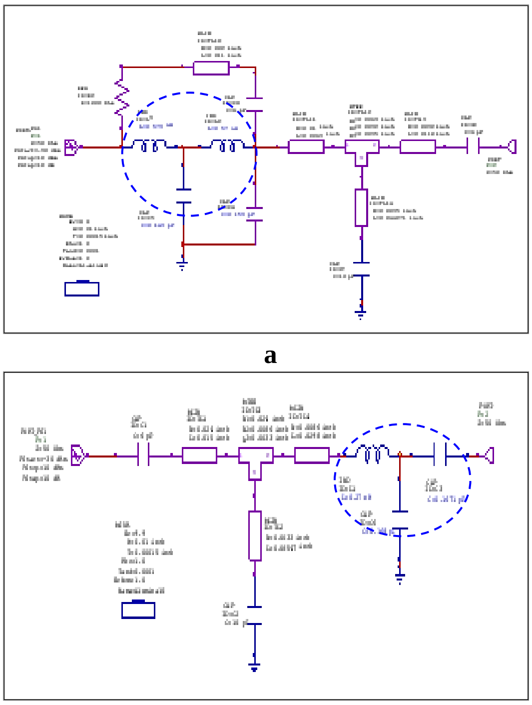
III. MATERIAL and MRTHODS

This work, first it was based on the Microwave Office 2000 (MWO) program, as well as preparing the Matlab program to calculate the mathematical equations related to the dimensions of the chip, then moving to design the model of a (lumped circuit) from the original elements and conducting the required measurements, then in another stage preparing a distributed circuit (Microstrip) from the lumped circuit. The work was divided into three stages: The first was designing the model for the lumped circuit for an amplifier that operates in microwave frequencies and its matching circuits with the help of the (MWO) program. The second part includes converting each circuit element into distributed-strip elements on different dielectric substrate values by calculating the element's dimensions. The third part included designing the distributed circuit in terms of geometric dimensions, extracting the output parameters, and comparing them with the output parameters of that lumped circuit. It also included making a comparison and simulation of previous works and comparing them.

Design of an equivalent circuit for a transistor: Using (MWO), the design of the input and output impedance circuit for the transistor was simulated so that it gives values very close to the fundamental values of the impedances when connected to the transistor and over a wide range of operating frequencies, where initial values for the elements in this model are entered so that the condition is met that the values of the resulting model impedance are precisely equal to the fundamental values of the transistor impedance at all frequencies of the band.

Transistor input circuit**:** Depending on the design, the equivalent of the transistor can be represented by adding inductors, capacitors, and resistors. Figure (1-a) shows the equivalent circuit of the transistor's input impedance after its representation. Also, the best working frequency is at the lowest value of the reflection coefficient S11.

Transistor output circuit**:** Figure (2-b) shows the elements inside the dashed circle representing the transistor's output circuit.



a

b

Figure 1: The input(a) and output (b) of the equivalent circuit of the transistor

The results of the reflection factors (S11) and (S22) at the input and output of the transistor lumped circuit were as shown in the figures (2).

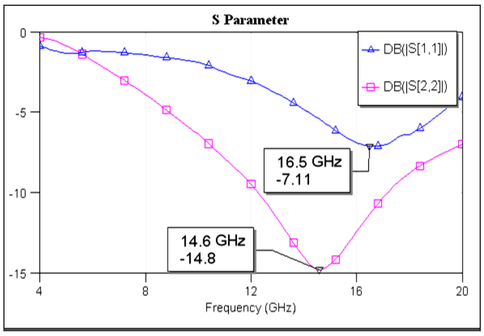


Figure 2:The output parameters for S11 and S22 for the lumped circuit

The above figures clearly show that the lowest value of the coefficients S11 and S22 represents the best value for the amplifier circuit's operating frequency.

A model equivalent to the operation of a transistor in electronic circuits is usually used, and the degree of complexity of the model is balanced with the degree of accuracy and ease of analysis. In general, in the case of small signals, a simple linear model is used to obtain transistors with excellent specifications and results at high frequencies. However, in significant signals, this model cannot be used due to several additional effects, including voltage harmonics and current harmonics resulting from the nonlinear properties of the transistor, so a complex nonlinear model is used to represent these specifications. [14].

Steps to convert the elements of the Lumped circuit to the Distributed circuit:

The process of converting the elements collected in the electronic circuit to the distributed circuit form involves several preparatory steps and calculations for their conversion equations or using programs prepared for this purpose (Matlab) before placing the elements' distributed geometric shape in the circuit, as follows:

A- *Finding the width of the strip for the elements* L, R, and C:

1- Fixe the thickness of the substrate (h=1.5 mm)

2- The range of Z_m values is determined according to the values of W/h used.

3- Choosing the insulating material according to the value of its insulation constant ε_r and the specifications required for the design.

For exact dimensions of the transmission straplines follow these conditions:

i. If W/h < 2 (Skny Strip): The width of the strip W can be found when the impedance is large compared to the load impedance R_L=50Ω to represent an (***inductive***) impedance and is equal to the load impedance, then it represents the resistance impedance, and the following equation is used:[15]:

$$W_L = h \times 4[1/2 \exp(A) - \exp(-A)]^{-1}, \quad \ldots\ldots\ldots\ldots(1)$$

where,

$$A = \pi\sqrt{2(\varepsilon_r + 1)} \times \frac{Z_m}{Z_o} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}(0.23 + \frac{0.11}{\varepsilon_r})$$

ii- For W/h >2 (wide Strip) to find the width of the strip when the impedance is less than the R_L to represent an (***capacitance***) impedance, where the following equation is used: [15]:

$$\int W_C = \frac{\varepsilon_r - 1}{\pi\varepsilon_r}[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}] + \frac{2}{\pi}[B - 1 - \ln(2B-1)] \quad , \ldots\ldots(2)$$

where,

$$B = \frac{\pi}{2\times\sqrt{\varepsilon_r}}\frac{Z_o}{Z_m}$$ since, Z_o=377Ω

B. *Finding the length of the strip elements L, R, and C:*

The strip length can be found using the following equation [16] :

i. For the ***inductance length*** in (micro Henry),

$$L = 0.00508 \times l \times \ln[2 \times l/(W + h + 0.5 + 0.2235 \times (W+h)/l] \quad ,..(3)$$

where, h of the strip (inch), *l* is the length of the strip (inch), and, h is the thickness of the substrate.

ii. For the ***sheet resistance length,*** use this equation, [16]:

$$L_R = (R \times t \times w)/\rho \quad , \quad \ldots\ldots\ldots.(4)$$

iii. For the ***capacitor length,*** use the equation :

$$L_C = C \times d / \varepsilon_r \varepsilon_o w_C \,, \quad \ldots\ldots\ldots.(5)$$

C. Resistance Sheet: The resistance value here depends on the material's specific resistance (Bulk Resistively). Its unit is (µΩ.cm), and it must remain constant for all resistances because the resistance materials are regularly deposited. It can be given as follows [16]:

$$R = R_{sheet} \times Squares, \quad \ldots\ldots\ldots..(6)$$

the quantity w/L represents the number of squares with total resistance.

D. Capacitance Sheet: It is the capacitance used in (MMIC) circuits. It depends on the type of insulator, its thickness, the capacitor's composition, and the capacitor's area. It is given by the following relationship [16]:

$$Capacitance = C_{sh} \times A \text{ (Pico-farads)} \,, \ldots\ldots(7)$$

The previous equations were used to convert the elements of the lumped circuit Figure (3-a) into a distributed circuit as shown in Figure (3-b).

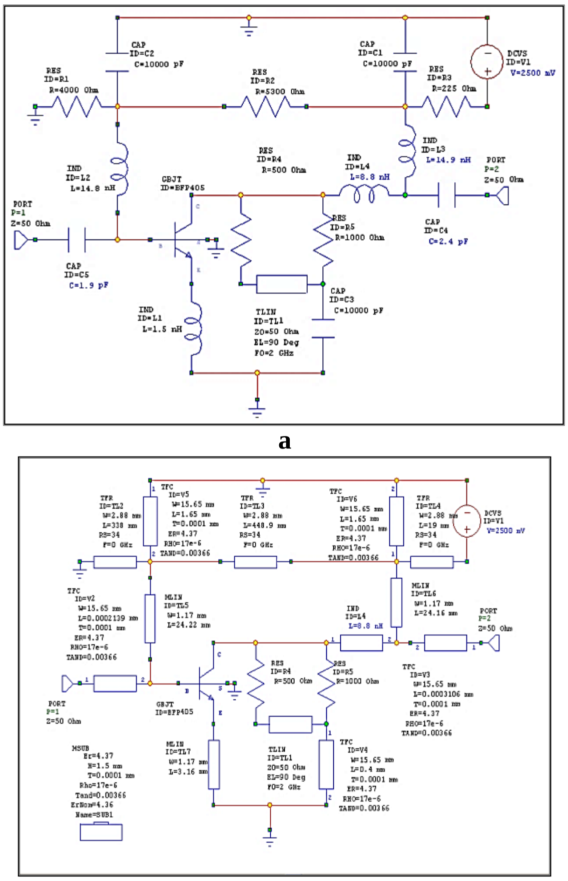


Figure 3: The amplifier lumped circuit(a) and distributed circuit(b)

IV. RESULTS and DISCUSSION

Figure (4) illustrates the relationship between inductance values (L) and the corresponding expected inductance length (*l*) after conversion. This graphical representation is crucial as it provides a visual tool for designers to estimate and refine the dimensions of inductive components based on empirical data. The trial-and-error approach, while effective, could be further enhanced by integrating simulation tools such as our MWO. Prior studies have demonstrated that simulation can significantly reduce the time spent on manual adjustments by providing predictive insights into circuit behavior.

Table (1) below shows the conversion values for several values of inductance L and the insulation constant ε_r for the circuit converted to a distributed circuit.

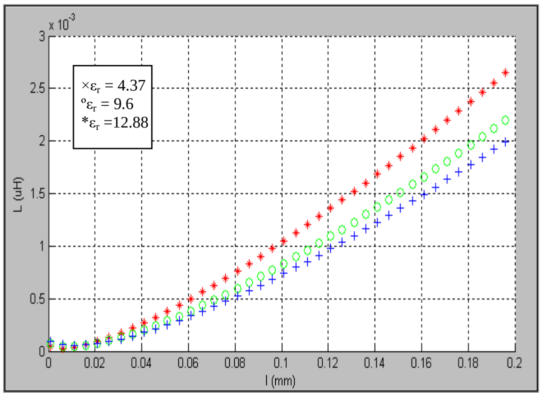


Figure 4: The inductance vs. the length of the geometric shape l for several εr

Table 1: The length and width of the inductance strip for distributed circuit

ε_r	L=14.9 (nH)	L=14.8 (nH)	L=8.8 (nH)	L=1.5 (nH)
ε_r =4.37 w_L=1.17(mm)	**(mm) *l*=22.3**	**(mm) *l*=22.22**	**(mm) *l*=14.85**	**(mm) *l*=4.15**
ε_r =6 w_L=0.838 mm	*l*=21.53	*l*=21.59	*l*=14.47	*l*=3.048
ε_r =9.6 w_L=0.460 mm	*l*=20.75	*l*=20.82	*l*=13.84	*l*=3.81
ε_r =12.88 w_L=0.292 mm	*l*=20.32	*l*=20.44	*l*=13.58	*l*=3.75

Table (1) presents conversion values for various inductances and insulation constants (**ε_r**). The significance of selecting appropriate insulation materials cannot be overstated, as the dielectric properties directly impact the performance and efficiency of high-frequency circuits. Several research highlights how variations in **ε_r** can alter impedance characteristics, potentially leading to mismatches that adversely affect signal integrity. Thus, careful consideration of these parameters in the design phase is critical.

To calculate the length of the strip resistance, Table (2) shows the calculated values for several values of R for different values of ε_r.

Table 2: Calculated L_R values from the expected R values at different ε_r

ε_r	W_R	L_R R=225 Ω	L_R R=500 Ω	L_R R=1000 Ω	L_R R=4000 Ω	L_R R=5300 Ω
4.37	**2.88**	**19**	**42.35**	**84**	**338.82**	**448.94**
6	2.25	14.889	33.088	66.176	264.70	350.73
9.6	1.49	9.88	21.95	43.91	175.65	232.73
12.8	1.10	7.37	16.29	32.588	130.35	172.71

Figure (5) shows the relationship between the resistance R and the expected L/w ratio at different specific resistances for several materials (ε_r).

The conductor thickness ($t \leq 0.5\mu m$) was chosen according to most previous research and within our field of work. At the same time, the specific resistance (ρ) of the copper material was $\rho = 1.7 \times 10^{-6}$ (Ω.cm). This decision aligns with findings from prior works, such as those by Chen *et al.* [17], who observed that thinner conductors can help minimize skin effect losses at higher frequencies.

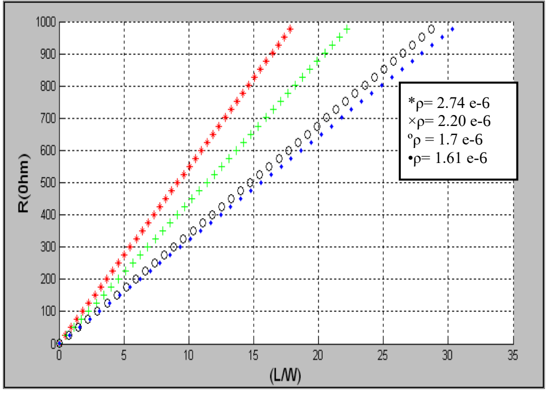


Figure 5: The resistance R vs. L/w ratio for a number of different materials

The values of L_C was also calculated from different ε_r values to for expected Wc values at different C which are listed in Table (3).

Table 3: The L_C capacitor for several C capacitors

ε_r	L_C (C=1.9pF)	L_C (C=2.4pF)	L_C (C=10000pF)
ε_r =4.37 W_c= 15.65mm	**0.0003139**	**0.000396**	**1.65**
ε_r= 6 W_c= 16.37mm	0.000218	0.000276	1.15
ε_r =9.6 W_c= 19.68mm	0.000113	0.000143	0.598
ε_r=12.88 W_c= 23.53mm	0.0000708	0.0000894	0.3728

Default values of ε_o =0.00885 F/mm^2, were imposed while the distance between the capacitor plates was assumed to be d=0.0001mm. The relationship between the values of the capacitor C and the calculated strip cross-sectional area A was shown for several rε values, as shown in Figure (6). This aspect is essential in wide-band applications, where bandwidth and capacitance are crucial in maintaining signal fidelity. Yang *et al.* [18], findings underscore the importance of optimizing the strip cross-sectional area (A) to achieve desired capacitance while managing parasitic effects, which can detrimentally affect circuit performance. As demonstrated by Gupta et al. [19], even minor alterations in the distance between capacitor plates can lead to significant shifts in capacitance, emphasizing the necessity of precision in fabrication processes

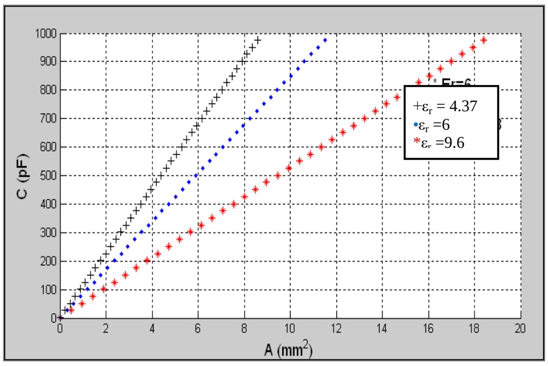
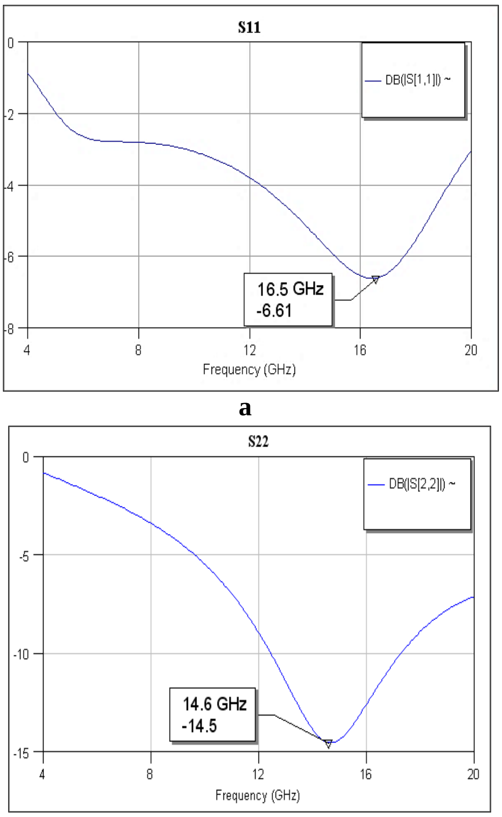


Figure 6: The Capacitor vs. the area A for several ε_r

As evidenced by the reflection coefficients (S-parameters) shown in Figure (7), the testing outcomes validate the distributed circuit's performance across a wide frequency range. This empirical data is vital for confirming the theoretical predictions made during the design phase.



b

Figure 7: Input reflection coefficient S11 and output reflection coefficient S22 for distributed circuit

However, elaborating on the specific frequency ranges tested and discussing the implications of the S-parameter values, such as return loss and VSWR, would provide a more comprehensive understanding of circuit behavior.

V. CONCLUSION

The design and simulation of the wide-band amplifier exemplify a successful fusion of theoretical principles and empirical validation, particularly in its effective performance across a frequency range of 14.6 to 16.5 GHz. The optimal results achieved on a substrate with a dielectric constant of 4.37 highlight the importance of substrate selection in enhancing circuit functionality. Additionally, a comprehensive understanding of high-frequency circuit design evidenced by the careful consideration of inductance values, insulation materials, conductor thickness, and capacitor properties has been validated through S-parameter analysis. This aligns seamlessly with this work on the wide amplifier, significantly improving the detection of weak reflections in military and aerospace radar systems. With commendable gain, low noise figures, high stability, and linearity, this amplifier solution is poised to deliver reliable performance for precise target detection and measurement.

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