A fully distributed modeling approach is proposed in this paper that incorporates the wave propagation effects in developing the equivalent circuit and works as a simulation tool for analyzing high-frequency transistors such as GaN high electron mobility devices. The details regarding the device arrangement are discussed and it is explained how the parameter extraction in the proposed modeling approach is developed merely based on the physical structure of the device along with the electrode dimensions and geometry. The governing equations for obtaining the currents and voltages at each time interval and spatial distance are analyzed based on a finite difference time domain method, where an implicit scheme is developed to ensure the unconditional stability of the technique along with reducing the computation time of the developed solution. The obtained results for the current gain and maximum available gain are verified by the measurement results from a 0.1-µm nitrogen-polar oriented GaN HEMT at 0.25-67 GHz frequency range. The results are also generated for wider cases and over higher frequency ranges to show the importance of using a fully distributed modeling technique and demonstrate the convergence of the results. An experiment is also developed regarding the thermal analysis of the high-frequency HEMT device and to discuss the heat transfer phenomenon over the device width and its effects on the distributed modeling approach are analyzed.

**INDEX TERMS** Equivalent circuit, finite difference time domain method, GaN HEMT, implicit scheme, parameter extraction, thermal analysis, wave propagation effects.

**I. INTRODUCTION**

Wireless communication systems have penetrated almost every aspect of our daily lives with applications such as autonomous cars, personalized medicine, monitored healthcare, agricultural sensing, and merchandise inventory, to name only a few [1]. High output power and high operating frequency are the two most critical properties of the devices that embody the future of wireless communication systems in achieving higher data rates. Several examples of these systems can be found in 5G applications that are expected to operate at upper millimeter-wave (mm-wave) bands to meet the broad bandwidths and reconfigurability requirements. In general, all the technologies in this area owe their emergence and advancements to the material properties of gallium nitride (GaN) utilized in high electron mobility transistor (HEMT) devices [2]. High saturation velocity, high electron mobility, high sheet carrier density, and high breakdown voltage are some of these characteristics that make GaN a material that meets the requirements of building high-power amplifiers (HPAs) capable of working at high operating frequencies and temperatures [3].

The subject matter has attracted many research groups to enhance the device performance for various applications [4]. Consequently, developing accurate modeling techniques for these devices is demanded for having a simulation tool that predicts the device behavior and can be used at the design stage [5]. Equivalent circuit approach is the most typical transistor model which is used extensively in characterizing and designing integrated circuits or individual devices.
A common high-frequency model of a GaN HEMT device is comprised of intrinsic and extrinsic sections. The elements for the extrinsic section of the model demonstrate the effects of the electrode material and dimensions, transistor pads, and all the semiconductor layers under the conductors, whereas the intrinsic elements show the innate behavior and characteristics of the transistor when operating.

Many of the reported modeling procedures are based on S-parameter measurement results and I-V characteristics of the devices. These processes are considered along with the gate-forward and pinched-off measurements followed by a de-embedding process to separate the extrinsic section from intrinsic parameters [6]. Some techniques utilize the X-parameter measurements which eliminates the need for DC measurements and better incorporates the nonlinearities in the modeling process [7]. Initially, the parameter extraction techniques used a direct methodology with a very high sensitivity to the measurement results, but these methods were computationally inexpensive [8]. To address the limitations associated with the direct methods, optimization techniques were incorporated which reduces the sensitivity of the method to the measurement, provided that the improved technique yields reliable results for extraction [9]. A newly developed optimization technique is the Particle-Swarm-Optimization (PSO) which is applied to a GaN HEMT device accounting for high-frequency and high-power operations of the device by adding more elements to the model [10].

Developing system-level simulation tools is the direct outcome of the improved accuracy of the circuit models [11]. Most of the contemporary devices in the area of advanced microwave systems are designed based upon highly varied physical dimensions and are operating in various frequency scales. Hence, the topics such as electromagnetic-wave propagations must be addressed in the modeling process [12]. Many of the already developed modeling techniques require the device fabrication and characterization in order to be able to find the element values in the equivalent circuit model for different operating modes, power levels, and frequency ranges [13]. This procedure requires a great amount of processing time and imposes high operational costs, which is considered as one of the main limitations with the already reported circuit models and extraction techniques.

The main goal of introducing a modeling technique is to develop a simulation tool that is able to help in optimizing the device performance for different applications and operating frequencies, and this is supposed to be performed before going through the fabrication process. Additionally, the reliability of the results obtained from these techniques is normally satisfied at a specific frequency range and drastic changes are made to either the number of elements or the parameter values when the device is operating at higher frequencies. This is due to the fact that the effects associated with the wave propagation phenomenon are not considered in the process which may render the developed model inaccurate at higher frequency bands. The concept of distributed equivalent-circuit model that was initially introduced by Heinrich for traveling-wave FETs is believed to be the promising modeling approach that addresses the above-mentioned problems [14].

The limitations regarding the distributed effects when the device width is comparable to the wavelength were discussed by El-Ghazaly [15], where an inverted-gate field effect transistor was proposed to avoid the phase-cancellations in a common-gate configuration. The air-bridged gate MESFET was then proposed by Hammadi to reduce the wave propagation effects at high-frequency bands by keeping both the input and output signals in-phase along the device width [16]. Hammadi explicitly discussed approaches to incorporating the electromagnetic-wave effects in full-wave transistor models. Additionally, in [17], Al-Sunaidi proposed a full-wave physics-based model which takes into account the effects of wave-particle interactions on the operation of high-frequency devices. Key observations of the research around this subject and the associated findings suggest that due to the coupling of the passive and active sections inside high-frequency devices and the complexity of the electron dynamics, it is crucial to have the required cognizance to the travelling-wave effects in these devices.

In this paper, the distributed modeling approach is utilized to develop the small-signal equivalent circuit for a recently fabricated GaN HEMT device. This work, which builds upon the prior published research in [18], [19], starts with discussing the details of the device structure. The developed small-signal model is presented and the extraction techniques for obtaining the parameter values for all the elements present in the model are discussed. It is also explained how the structural dimensions of the device is used in the extraction process. The distributed model along with the details of the utilized numerical method and how this model can be a representative of the entire device width are introduced and discussed. For validating the results, different gain parameters of the transistor is used to compare the simulation and measurement results obtained from the presented GaN HEMT device. The necessity of using the distributed model for wider devices operating at higher frequency ranges is also examined. Moreover, a study of the heat transfer phenomena for the distributed model developed for the GaN device on sapphire is presented here. The experiment demonstrates the heat distribution over the device width and it is explained why the distribution of heat is critical to be considered while developing the equivalent circuit model.

II. DEVICE CONFIGURATION AND MODELING PROCEDURE

The cross-section of the 0.1-μm N-polar oriented GaN MISHEMT (Metal-Insulator-Semiconductor HEMT), developed by Zheng et al., is demonstrated in Fig. 1, which describes the different semiconductor layers with specific thicknesses and the associated doping profiles grown on an a-plane sapphire substrate [20]. The main advantage of the nitrogen-polar oriented GaN devices is their potential of providing sufficient power amplification in the W-band.
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FIGURE 1. Cross-section of the N-polar oriented GaN MISHEMT device.

The growth technique for this device is the metal-organic chemical vapor deposition (MOCVD) and the materials used for the electrodes are gold and titanium. The dimensions of the drain and source electrodes are \(0.12 \, \mu m \times 6 \, \mu m\). The gate top and gate stem dimensions are \(0.53 \, \mu m \times 0.45 \, \mu m\) and \(0.22 \, \mu m \times 0.1 \, \mu m\), respectively. The spacing between the gate and source electrode is \(0.3 \, \mu m\) which is relatively small compared to the \(1.6 \, \mu m\) of gate-drain spacing. The attenuation of the signal along the gate electrode was one of the limitations with the initially structured HEMT devices due to the presence of a large parasitic resistance on the gate electrode. This limitation has been addressed in the recent devices by increasing the cross-sectional area of the gate metal strip in T- or mushroom-shaped configurations.

As discussed before, the 5G technology and generally all the wireless communication applications are expected to work at the mm-wave frequency range. Consequently, due to the current limitations on the device fabrication technologies, the dimensions of the active component (specifically the device width) become comparable to the electromagnetic wavelength of the propagating signal inside the device. The input impedance of the transistor (gate electrode) is different than the output impedance (drain electrode), the wave propagation phenomenon affects the behavior of the device and it is essential to include this effect in the modeling process. In consequence, the device electrodes must be considered as transmission lines [15]. This means that the lumped element models will not have the sufficient accuracy to represent the operation of high-frequency devices. Considering the effects of the wave-particle interactions in the developed equivalent circuit is the main contribution of the proposed approach compared to the other distributed techniques, which ensures that the final model is independent of the operating frequency of the device.

The 19-element equivalent circuit model of the presented GaN MISHEMT device is demonstrated in Fig. 2. The extrinsic bias independent elements represent the passive section of the device, whereas the active part is formed by the intrinsic bias dependent components. There are specific physical descriptions and explanations associated with the elements of the model. \(R_{GS}\) represents the resistance of the channel and \(R_{GDi}\) is complementary to that element in order to have symmetry in the circuit model. \(C_{GSi}\) and \(C_{GDi}\) demonstrate the charge modulation for the gate electrode when \(V_{GS}\) and \(V_{DS}\) change, respectively. Gate electrode contact is associated with a Schottky barrier and \(R_{Ge}\) shows the resistance to the flow of current along its metal strip. Furthermore, \(R_{De}\) and \(R_{Se}\) demonstrate the resistance of the drain and source ohmic contacts and the access region [22].

As discussed in [18], a systematic approach is developed for obtaining the parameter values of the circuit elements. The extraction procedure is based upon the physical structure of the device, which implies that the process can be applied to other devices with any arbitrary shape in the cross-sectional area of the gate metal strip in T- or mushroom-shaped configurations.

III. DISTRIBUTED MODELING APPROACH AND FINITE DIFFERENCE ANALYSIS

The first step to develop a distributed model is to divide the device width into \(N\) sections. Each of these sections
will be named a unit cell hereafter and has a width of $\Delta z$. It is worth noting that the device width in a high-frequency HEMT device signifies the direction along the electrodes which is perpendicular to the flow of charges. The equivalent circuit model for each unit cell has already been demonstrated in Fig. 2 and for this model to be valid, the value for $N$ and, consequently, $\Delta z$ must be adjusted in a way that the unit cell width becomes much smaller than the propagating wavelength inside the device. All of these unit cells are then cascaded to represent the whole width of the device, as demonstrated in Fig. 3. The boundary and terminal conditions must also be incorporated in this model and this is performed according to the top view schematic of the device is Fig. 4 [21]. The device has two fingers and the width of each finger is 25 $\mu$m. The source pad at the end of the device is grounded and a sinusoidal voltage source is applied to the gate electrode at the input side of the device.

The currents and voltages on the gate, drain, and source lines must be obtained at each temporal and spatial point based on the governing equations representing the properties of the coupled lines and the guided-wave propagations inside the device as demonstrated in (1) and (2). The superscript $t$ denotes the time, $n$ is the representation of the spatial point, and $i$, $j$, and $k$ interchangeably show the gate, drain, and source lines. Due to the coupled nature of the system and since there are no analytical solutions for analyzing the six presented differential equations dominating this system, a finite-difference time-domain (FDTD) approach is utilized. In [18], an iterative explicit scheme was used to analyze the device, where a state of the system at a later time is calculated based on the current state of the system. As the explicit scheme is conditionally stable, there is a limitation associated with the temporal step size in order to satisfy the Courant stability condition. This condition is explained as the smaller value of the numerical time step compared to the time that the wave needs to travel to the adjacent grid point [24]. For analyzing complicated systems, $\Delta t$ must be extremely small to keep the resultant numerical error bounded and this process increases the computation time of the solution. On the contrary, the developed iterative implicit scheme in this study involves both the values for the later time and the current state while solving the equations and, as a result, the scheme becomes unconditionally stable. This scheme allows the usage of larger temporal step sizes and makes the solution computationally efficient [25]. For the same practical circuit simulation, the time step was increased from $10^{-16}$ seconds for the explicit case to $10^{-13}$ seconds for the implicit scheme. It is also worth noting that for the mentioned schemes, the solution starts with an initial condition and then the final response is obtained when the desired convergence is achieved.

$$V_{i(n-1)} - V_{i(n)} = R_i I_{i(n)} + L_i \left(I_{i(n+1)}^{t+\Delta t} - I_{i(n)}^{t}\right) / \Delta t$$  \hspace{1em} (1)

$$-I_{i(n)}^{t} + I_{i(n+1)}^{t} + G_{ij} \left(V_{i(n)}^{t} - V_{j(n)}^{t}\right) + G_{ik} \left(V_{i(n)}^{t} - V_{k(n)}^{t}\right) + C_{ij} \left(V_{i(n)}^{t+\Delta t} - V_{j(n)}^{t} + \Delta t \right) - \left(V_{i(n)}^{t} - V_{j(n)}^{t}\right) / \Delta t + C_{ik} \left(V_{i(n)}^{t+\Delta t} - V_{k(n)}^{t} + \Delta t \right) - \left(V_{i(n)}^{t} - V_{k(n)}^{t}\right) / \Delta t = 0$$  \hspace{1em} (2)

IV. SIMULATION AND MODEL VALIDATION

In order to examine the validity of the simulation, the obtained results from the FDTD method is compared with the measurement results from the $2 \times 25 \mu$m N-polar GaN MISHEMT
presented before. Fig. 5 shows the current gain ($h_{21}$) comparison where the load impedance of the model is set to zero. Previously, the comparison results for the maximum available gain (MAG) between the measurement and simulation was presented in [19], in which the input and output impedances are matched to the circuit. Due to the fact that these comparisons are being made over the frequency range of 0.25-67 GHz, considering two unit cells of width 12.5 $\mu$m each is sufficient for this simulation. As demonstrated, excellent agreement is achieved for the case of current gain and there is a negligibly small average error of roughly 1 dB for the MAG results between the measurement and simulation. In consequence, the distributed modeling approach yields accurate results and the validity of the method is proved. Also, based on the developed distributed model for the device, the extrinsic-level S-parameter simulation results are obtained, as depicted in Fig. 6, for the same frequency range and bias point. These S parameters exhibit the typical response expected from high-frequency modern GaN HEMT, and phenomenologically agree with published results [26].

To investigate the necessity of using a distributed modeling approach and illustrate the convergence of the results, a hypothetical device of width 100 $\mu$m is simulated over the frequency range of 70-150 GHz. The width and the operating frequency is considered in this way to ensure that the electromagnetic-wave propagation effects will be significant and observable in this case. The parameter values are adjusted and the boundary conditions are defined accordingly. The current gain and MAG results are obtained for different number of unit cells in the distributed model and the results are shown in Fig. 7 and Fig. 8, respectively. The number of unit cells for each case represents the value for $N$ and the unit cell width is equal to 100/$N$ $\mu$m. For all of the mentioned cases, the device width is kept constant. Only, the number of unit cells and the unit cell width are varied. According to Fig. 7, the one-unit cell case starts to deviate at around 85 GHz and the sensitivity of the current gain parameter to the case of two-unit cells happens initially at 100 GHz [19]. This implies that since the unit cell width for these two cases is not sufficiently small compared to the wavelength of the guided wave at those frequency ranges, and due to the electromagnetic wave-propagation effects, the yielded results are inaccurate. For the cases of three-unit cells and up, the results are consistent and the required convergence is achieved. In other words, to obtain accurate results for a device width of 100 $\mu$m over the frequency range of 70-150 GHz, the distributed equivalent circuit model must have at least three unit cells to ensure that the wave-propagation effects are taken into account.
Similarly, as demonstrated in Fig. 8, the two cases of one- and two-unit cells are totally divergent and inaccurate and the consistency of the results starts from three-unit cells. In conclusion, for developing circuit models for wider devices operating at higher frequency ranges, it is necessary to use a distributed modeling approach and adjust the required number of unit cells accordingly. It is also worth noting that, for the lower frequency range, since the wavelength is large, the electrical behavior of the device is not affected by the wave propagation and the device can be modeled using lumped element equivalent circuits. This is the main reason for observing the device behavior at higher frequency bands.

V. HEAT DISTRIBUTION EFFECTS

Improvements in fabrication technology have been identified as the primary reason for the increase in the speed of semiconductor devices which results in device size reductions. However, the dominant limitation for the speed or reduced size of the devices is the thermal resistance [27]–[31]. For high-power transistors, the ability of the device to dissipate the heat is one of the most important characteristics [32]. To identify this feature, the thermal resistance parameter is utilized which is defined as the temperature increase at the junction divided by the dissipated power [33]. When analyzing the device, the maximum power dissipation must be specified by determining the temperature that the junction can handle [34], [35].

Experiments have shown that for transistors operating at higher frequencies, device failures may occur even below the power levels determined by the thermal resistance. Hence, for a thorough characterization of semiconductor devices, other than the electronic behavior of the transistors, the study of device operations under different temperature ranges is also very vital [36], [37]. In high-power and high-frequency devices, a great amount of heat is generated in the channel layer, which flows through the other layers toward the substrate and affects the underlying physics of the device. The thermal limitations multiply when there are more interfaces in the device structure which makes it more sensitive to the excess generated heat.

In order to examine the heat distribution on the GaN HEMT device, an experiment is designed based on the configuration explained in Fig. 9. The cylinder represents the sapphire substrate that the device is grown on, with a circular base radius of 500 $\mu$m and a height of 100 $\mu$m. The cuboid on top of the cylinder is made of GaN to roughly represent all the semiconductor layers grown on the substrate. The cross-section of the cuboid is a 200 $\mu$m $\times$ 200 $\mu$m square and the height of that is equal to 2 $\mu$m. A rectangular area of 10 $\mu$m $\times$ 100 $\mu$m is considered on the top surface of this cuboid as the section representing the gate electrode and its vicinity, where the majority of the internal heat is generated along the device width while operating. A convection boundary condition is defined for all the surfaces except the bottom face of the cylinder. Since a heat sink is generally mounted on that side of the substrate, the internally generated heat reaching that surface is dissipated to the environment. Hence, that surface is defined with a temperature boundary condition set to the ambient temperature. To show the effects of heat distribution on the distributed model, another arrangement is considered in which the rectangular area on top is divided into five equal sections with a unit cell width of 20 $\mu$m. This configuration is shown in the inset of Fig. 9. All the other device dimensions, materials used, and boundary conditions are defined similar to the typical case.

Fig. 10 shows the cross-section of the simulated model, not drawn to scale, and the assumed cut lines for which the temperature distribution is desired to be observed. CL1 (cut-line 1) is along the device width and CL3, CL4, and CL5 are drawn along the depth of the device. A power of 1 W is uniformly applied to the rectangular section of the typical case and 0.2 W to each unit cell of the distributed model. The temperature distribution at CL1 is depicted in Fig. 11, which shows the temperature for all the points through the device width. Based on this figure, the distribution for the two cases are in good agreement which proves that the distributed modeling approach offers consistent results from thermal point of view.
The unit cells at the two ends of the device show a distinctly different distribution compared to the middle unit cell and the temperature difference between the coldest and hottest points of the device is about 118 K. In order to elaborate on this, the temperature distribution is also observed on CL3, CL4, and CL5, which are the cut lines over the first, second, and third unit cells. The obtained results are shown in Fig. 12 and, accordingly, the equivalent circuit model for each unit cell will be differently affected based on the thermal properties of the device. This phenomenon must be incorporated in extracting the extrinsic and intrinsic parameter values of the distributed model.

Another experiment is also designed to show the effect of the difference between the thermal conductivity of GaN and sapphire and how GaN semiconductor layers involve in distributing the generated internal heat. The thermal conductivity parameter for sapphire is 25.2 W/m.K, whereas for GaN, with either a Wurtzite or Zinc Blende crystal structure, is 130 W/m.K. The GaN layer on top of the substrate in Fig. 9 is removed and the power of 1 W is applied directly to the same section on top of the sapphire substrate. The temperature distribution results on CL2 comparing the case when the power is applied to GaN and the other case when it is directly applied to sapphire substrate is demonstrated in Fig. 13. Despite the fact that the GaN layer compared to the sapphire substrate is very thin, due to the notable difference between the thermal conductivity of the two materials, the temperature distribution is markedly different. The temperature difference of the hottest points between the two cases is 155 K.

Based on the fact that the width of the discussed GaN HEMT device in previous section, for which the electrical behavior was simulated, is relatively small, there was no need for parameter adjustments regarding the thermal properties. However, in other devices, the distributed model allows for semiconductor device properties to be adjusted at each segment to reflect the change in temperature. This is generally performed by either modifying the element values in the extrinsic and intrinsic sections of the equivalent circuit or by adding some elements to account for the changes.

VI. CONCLUSION

The studies conducted in this research explained the significance of using a distributed approach in developing an accurate equivalent circuit model valid for various devices operating at any frequency range and power level. Moreover, the thermal analysis of the presented device demonstrated that incorporating the heat distribution effects is a vital stage when developing the modeling techniques for simulating the electrical behavior of the devices. As discussed, the presented model is developed solely based upon the physical structure of the device and as long as the quasi-TEM approximation is valid, the device is capable of being expanded over all the dimensions. It is worth noting that this approximation holds true for all the Microwave and mm-wave devices for the current and future applications. The distributed modeling approach can also be expanded to account for different bias conditions by including the large signal analysis and all the typical nonlinearities inside semiconductor devices.

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