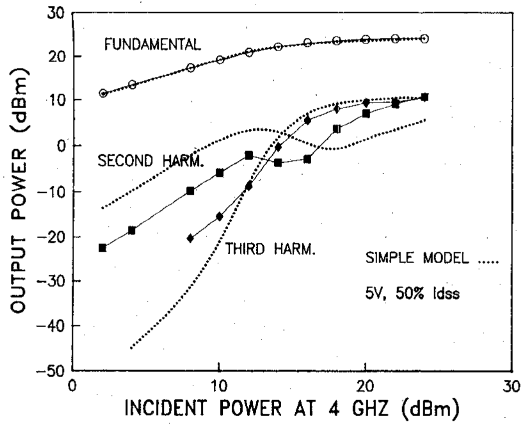

Fig. 6. Output RF powers as a function of incident RF power for the same device as in Fig. 5. Solid lines are data and dashed lines are calculated from FET model not including bias dependencies of C_{gs} and C_{dg}.

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A Low-Noise Microwave Oscillator Employing a Self-Aligned AlGaAs/GaAs HBT

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***Abstract*—This paper studies the application of heterojunction bipolar transistors (HBT's) to low-noise microwave circuits. Design considerations and the low-noise performance of a *Ku*-band free-running oscillator using a self-aligned AlGaAs/GaAs HBT are described. The device has a novel structure in which by utilizing SiO_2 sidewalls the base surface area, which is the main cause of low-frequency noise, is drastically reduced. For a collector current of 1 mA, the fabricated device has base current noise power densities of 4×10^{-20} A^2/Hz, 6×10^{-21} A^2/Hz, and 2.5×10^{-21} A^2/Hz at baseband frequencies of 1 kHz, 10 kHz, and 100 kHz, respectively. The prototype oscillator operating at 15.5 GHz has a measured output power of 6 dBm and SSB FM noise power densities of −34 dBc/Hz at 1 kHz, −65 dBc/Hz at 10 kHz, and −96 dBc/Hz at 100 kHz off-carrier, respectively, without employing any high-*Q* elements such as a dielectric resonator. The results of this study demonstrate the suitability of HBT's for low-phase-noise microwave and millimeter-wave oscillator applications.**

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I. Introduction

With rapid advances in microwave communication technology, there is increasing demand for low-phase-noise oscillators operating at microwave frequencies. Oscillators fabricated with GaAs FET's suffer from a high level of phase noise [1]. This noise results from the baseband noisy characteristics of the device due to large amounts of free-surface, depletion-layer, and channel–substrate interface trap centers.

Oscillators fabricated with Si bipolar transistors, which are only available up to about 20 GHz, show excellent noise behavior [2], [3] since the device has a vertical structure and features a very small number of recombination trap centers. On the other hand, continuing progress in compound semiconductor crystal growth technology has led to the development of heterojunction bipolar transistors (HBT's) which, when compared with GaAs FET's and Si bipolar transistors, promise superior applicability to microwave oscillator circuits with appreciably low noise performance.

The present paper is concerned with the application of AlGaAs/GaAs HBT's to low-phase-noise *Ku*-band oscillators.

II. Phase Noise Generation in Oscillators

The phase noise spectral density $S_\phi(\omega)$ for a microwave oscillator operating at a frequency ω_0 with an RF current amplitude A_0 in terms of the low-frequency noise spectral density $S_{LF}(\omega_b)$, the device impedance $-Z_d(A)$, and the circuit impedance $Z_c(\omega)$ can be given by [4]

$$S_\phi(\omega_b) = \left[\frac{w_b \left| \frac{dZ_c(\omega)}{d\omega} \right|^2_{\omega_0} + (A_0^2/\omega_b) \left| \frac{\partial Z_d(A)}{\partial A} \right|^2_{A_0}}{A_0^2\omega_b^2 \left| \frac{dZ_c(\omega)}{d\omega} \right|^4_{\omega_0} + A_0^2 \left| \frac{dZ_c(\omega)}{d\omega} \right|^2_{\omega_0} \left| \frac{\partial Z_d(A)}{\partial A} \right|^2_{A_0} \sin^2\theta} \right] \cdot S_{LF}(\omega_b) \tag{1}$$

with

$$S_{LF}(\omega_b) \equiv \langle i_{LF}^2 \rangle /\mathrm{Hz} = \frac{\lambda(T) A_0^\alpha}{\omega_b^\beta} \tag{2}$$

where $\langle i_{LF}^2 \rangle$ represents the device low-frequency noise current power spectrum, $\lambda(T)$ is a temperature-dependent proportionality factor, ω_b is the baseband frequency, θ is the device line $Z_d(A)$ and impedance locus $Z_c(\omega)$ intersecting angle at (ω_0, A_0), $\alpha \simeq 2$, and $\beta \simeq$ [5], [6]. With respect to (1) and (2), the oscillator phase noise is an up-conversion of the active device low-frequency noise into the carrier frequency through an interaction of the active device with the passive circuit.

To achieve a low-phase-noise oscillator it is, therefore, of prime importance to employ devices demonstrating low $1/f$ noise. The $1/f$ noise behavior for a microwave transistor is strongly influenced by the device structure and by the factor λ in (2). The principal mechanisms for the generation of low-frequency noise in lateral structure devices such as GaAs FET's are (i) the interaction of carriers with traps in the oxide near the source–gate and gate–drain free surface region, which results in the surface mobility fluctuation; (ii) generation–recombination (G–R) traps in the gate/channel depletion region; and (iii) traps at the channel–substrate interface [7]. In the case of vertical-structure devices such as Si bipolar transistors, $1/f$ noise is generated mainly due to (i) base surface-recombination velocity fluctuation and (ii) carrier recombinations in the emitter–base space charge region [8], [9]. It is, however, understood that in both these device structures the free surface region is the dominant source of $1/f$ noise. This explains why the vertical bipolar devices, which are capable of maintaining an extremely small base free surface area, exhibit superior low-frequency noise performance over their lateral unipolar counterparts, which require relatively large gate–source and gate–drain free surface areas to sustain sufficient breakdown voltages. There are, however, interesting issues, such as the study of the relative frequency of the traps in different materials and also differences in materials with and without native oxides, such as Si and GaAs, respectively which can be beneficial in achieving GaAs MESFET's with considerably improved noise performance [10], [11]. This is, however, out of the scope of the present work.

Recalling (1), for a device with specific low-frequency noise characteristics, oscillator phase noise can be minimized by incorporating a high-Q element, such as a dielectric resonator (DR) or a YIG in the circuit impedance to make $dZ_c(\omega)/d\omega$ as large as possible and by providing a perpendicular ($\theta = 90°$) impedance locus $Z_c(\omega)$ to the device line $Z_d(A)$ to minimize the operating point fluctuation due to the device line vibration [4]. A YIG-tuned Si bipolar transistor operating at 18 GHz has a phase noise of -100 dBc/Hz at 20 kHz off-carrier [3].

In the rest of this paper a self-aligned AlGaAs/GaAs HBT is utilized as a low-noise active device in the development of the first *Ku*-band oscillator employing an HBT with an optimum circuit design for minimum phase noise operation.

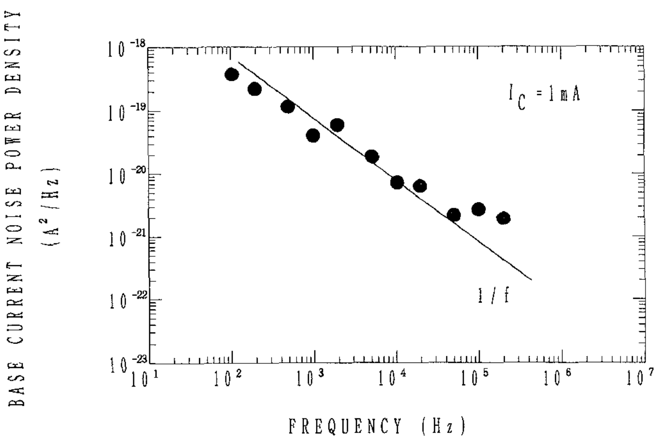

Fig. 1. Baseband noise characteristics for the developed self-aligned HBT.

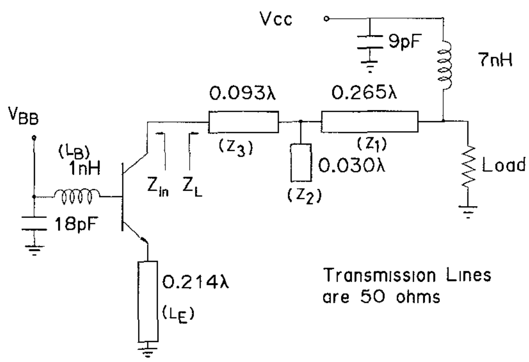

Fig. 2. An equivalent circuit for *Ku*-band HBT oscillator.

III. Device Performance

A full self-alignment technology was applied to fabricate the HBT [12] used in the oscillator circuit. Typical current gain h_{fe} and transconductance g_m for the fabricated HBT with a 1.5 μm$\times$10 μm emitter size were 30 and 30 mS, respectively. Measured small-signal S parameters for the device over the 0.1 ~ 20.1 GHz frequency range resulted in an extrapolated short-circuit current gain cutoff frequency f_T of 50 GHz and a maximum oscillation frequency f_{max} of 27 GHz, which is relatively low since no ion-implantation technique was applied to the extrinsic base –collector capacitance reduction.

To investigate the fabricated device's low-frequency noise characteristics, collector current noise power spectra for a 1.5-μm-emitter HBT were measured using an HP 3585A baseband spectrum analyzer and applied to calculate the base current noise power spectra. Results, for a collector current $I_c = 1$ mA, are represented in Fig. 1 The fabricated device has base current noise power densities of 4×0^{-20} A^2/Hz, 6×10^{-21} A^2/Hz, and 2.5×10^{-21} A^2/Hz, respectively, at 1 kHz, 10 kHz, and 100 kHz.

A direct comparison between the low-frequency input noise level of HBT's and MESFET's is not made here, since the noise characteristics are usually modeled by an "input noise current source" for bipolars, and by an "input noise voltage source" for MESFET's. However, a comparison between the HBT and MESFET oscillators will be presented in Section V.

IV. Oscillator Circuit Design

An equivalent circuit for the *Ku*-band oscillator using the self-aligned 1.5 μm$\times$10 μm emitter HBT is shown in Fig. 2. A series feedback configuration is utilized. In this figure, inductances L_E and L_B are responsible for the realization of a sufficiently large negative resistance at the collector terminal to provide a stable oscillation at *Ku*-band frequencies. The matching network, on the other hand, consists of transmission lines Z_1, Z_2, and Z_3. A Super-Compact CAD program was employed to optimize the oscillator circuit parameters applying the measured S parameters for the device [13]. Simulation results indicated the circuit potential for oscillation at any single frequency in a 14–17 GHz range for the $L_B = 1.0$ nH and $L_E = 1.3$ nH optimum values. To satisfy the oscillation condition at a center frequency of 15.5 GHz and to provide a perpendicular impedance locus Z_l to the device line Z_{in} at the operating point, for minimizing device–circuit interaction effects on the oscillator phase noise, as explained earlier, Z_1, Z_2, and Z_3 were optimized accordingly. The loaded quality factor Q_L for the circuit impedance comprising transmission lines Z_1, Z_2, and Z_3, and a 50 Ω load is estimated to be as low as 10.

V. Circuit Fabrication and Oscillator Performance

Based on the simulation results, an oscillator circuit was constructed using the microstrip circuit on a 0.26 mm alumina substrate with a dielectric constant $\epsilon_r = 9.7$. The feedback elements as well as the matching network were realized using 50 Ω transmission lines. Oscillator performance versus collector voltage is shown in Fig. 3. Oscillations started at a collector voltage V_{cc} as low as 2.0 V and an output power as high as 6 dBm was achieved in a 50 Ω load at 15.5 GHz with an efficiency of 13 percent.

To investigate the oscillator phase noise performance, the single sideband frequency modulation (SSB FM) noise, normalized to 1 Hz bandwidth, was measured. Results for off-carrier frequencies up to 200 kHz are shown in Fig. 4. The figure

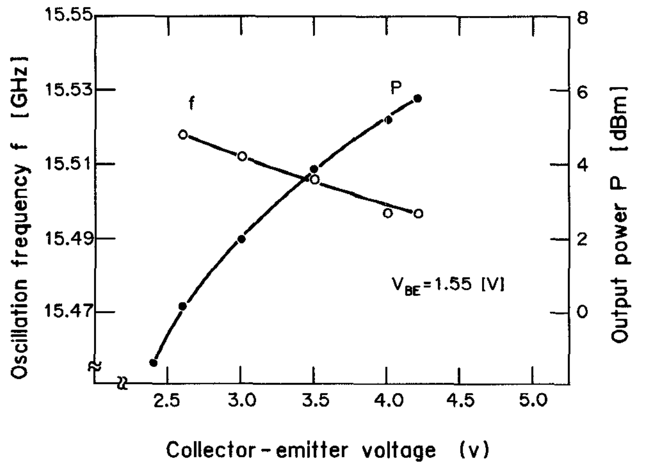

Fig. 3. HBT oscillator power and frequency variation with collector voltage.

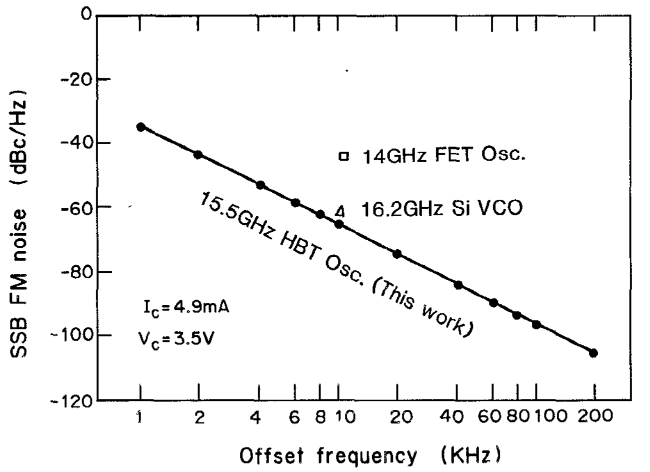

Fig. 4. SSB FM noise behavior for the 15.5 GHz free-running HBT oscillator. For comparison, noise performances of Si VCO (Δ) and GaAs FET (□) oscillators are also shown

indicates SSB FM noise levels of -96 dBc/Hz, -65 dBc/Hz, and -34 dBc/Hz, respectively, at 100 kHz, 10 kHz, and 1 kHz off-carrier. These results for the free-running HBT oscillator are comparable to those of a 16.2 GHz silicon VCO [2], giving -63 dBc/Hz at 10 kHz off-carrier, which might have been degraded by a few dB due to application of a varactor diode, and are about 24 dB lower than the phase noise of a 14 GHz GaAs FET oscillator [1], giving -41 dBc/Hz at 10 kHz off-carrier, as shown in the same figure.

The oscillator performance represented in Fig. 3 corresponds to the minimum phase noise operation, as explained. No significant deterioration of the phase noise was observed when impedance Z_2 was readjusted for maximum output power operation: 6.5 dBm power and -60 dBc/Hz phase noise at 10 kHz off-carrier. Fig. 5 summarizes the phase noise behavior of reported GaAs MESFET and AlGaAs/GaAs HBT oscillators at 100 kHz off-carrier, over the 4–16 GHz frequency range [14]–[18]. These oscillators, which apply a microstrip line structure, have a loaded Q, Q_L, of about 10 to 20. The last two [17], [18], which apply a varactor diode, may have a somewhat smaller Q_L. Extrapolating the results, the phase noise of HBT oscillators is about 20 to 30 dB lower than those of MESFET oscillators. This implies that, assuming the oscillator phase noise is an up-conversation of the device's low-frequency noise into the carrier

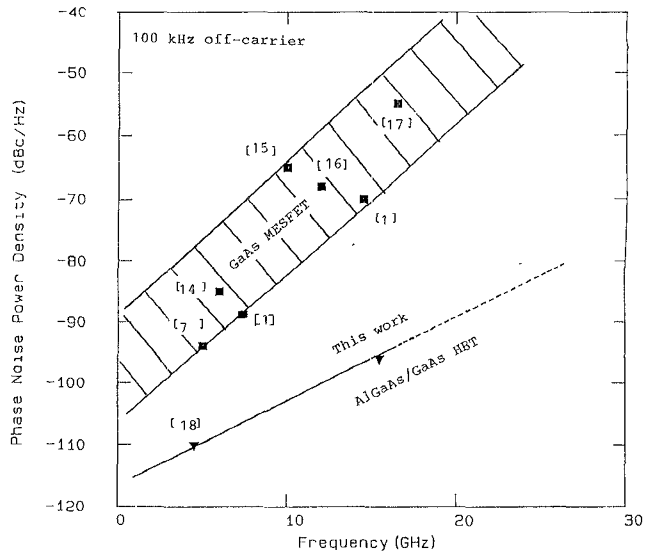

Fig. 5. Phase noise characteristics for GaAs MESFET and AlGaAs/GaAs HBT oscillators over 4 to 16 GHz frequency range, at 100 kHz off-carrier.

frequency, the HBT's are expected to have about 20 to 30 dB lower $1/f$ noise than the MESFET's.

VI. Conclusions

Feasibility of the AlGaAs/GaAs HBT's for low-noise microwave and millimeter-wave circuit applications was described. The importance of employing full self-alignment techniques to reduce the device surface recombination area and parasitic resistances for achieving, respectively, low-noise oscillators and amplifiers was emphasized. A prototype 15.5 GHz free-running oscillator implemented using a fully self-aligned HBT, with a 1.5 μm$\times$10 μm emitter size and a base–emitter electrode separation less than 0.2 μm, has successfully exhibited a phase noise power density of -65 dBc/Hz at 10 kHz off-carrier. Phase noise levels below -100 dBc/Hz (at 10 kHz off-carrier) are expected for the fabricated 15.5 GHz oscillator by employing a high-Q dielectric resonator coupling. Our experimental results give an indication of low-phase-noise microwave and millimeter-wave oscillator performance available with HBT's.

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Integral Numerical Technique for the Study of Axially Symmetric Resonant Devices

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Abstract —**A numerical technique is proposed which is based on the coupling of Kirchhoff's integral formulation and the moment method and is suitable for application to the study of a wide class of axially symmetric resonant devices. Numerical results are presented and compared with corresponding theoretical data for two systems which allow an analytical treatment. In this way the validity of method has been confirmed.**

I. Introduction

This paper presents a numerical technique which is based on Kirchhoff's integral formulation for the electromagnetic field and which is valid for the study of a wide class of axially symmetric resonant devices.

Among the numerous methods that exist for finding approximate solutions to the field problem in various devices [1], there are some that offer greater accuracy when determining resonant frequencies and other characteristic parameters, an accuracy which today is a technological necessity (e.g. satellite communications). Among these sophisticated methods we can mention those based on a dielectric waveguide model [2]–[4], a mixture of the magnetic wall and dielectric waveguide models [5], finite elements [6], a variational method [7]–[9], and, lastly, Green's function techniques [10], which are very powerful given that they can be applied to very different situations.

With regard to the Green's function methods, those which incorporate the free-space Green's function and which are based on a surface integral approach stand out for their simplicity. Usually these methods consider bound systems and use equivalent currents as a starting point (Glisson and Kajfez [10]). The method presented in this paper is based on Kirchhoff's integral formulation with the free-space Green's function (field components are the basic entities involved) and allows the approximate study of unbound systems.

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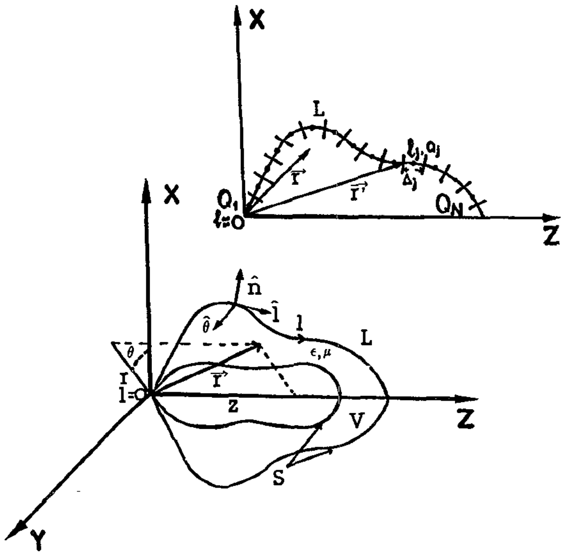

Fig. 1. Geometry and cylindrical coordinates for a body of revolution and the orthogonal right-handed triad of unit vectors n, θ, l defined within the boundary. Discretization of generating arc for body of revolution.

II. Numerical Method

Fig. 1 shows the kind of systems which we are interested in. They are composed of different lossless homogeneous regions with axial symmetry along the Z axis. This symmetry allows special modes to be defined, which correspond to diverse (and usually complex) resonance frequencies of the structure and whose components (in cylindrical coordinates (r, θ, z) associated to the system) would be as follows:

$$f(r,z)\cdot[a\cos(p\theta)\pm b\sin(p\theta)], \qquad p=0,1,2,\cdots. \tag{1}$$

For each mode we use Kirchhoff's integral equation in every dielectric region of the structure and integrate with respect to the angular variable, θ, (taking points $\boldsymbol{r}$ in the half-plane $\theta=0$ (Fig. 1)). This results in a line integral equation extending to the boundary L $(\theta=0)$ of the considered region involving only the $f(r,z)$ part of each field component:

$$\frac{\Omega(\boldsymbol{r})}{4\pi}\psi(\boldsymbol{r})=\int_L A(\boldsymbol{r},l')\varphi(l')\,dl' \tag{2}$$

where

$$\psi(\boldsymbol{r})=\begin{bmatrix}\begin{vmatrix}e_r\\h_r\end{vmatrix}\\\begin{vmatrix}e_\theta\\h_\theta\end{vmatrix}\\\begin{vmatrix}e_z\\h_z\end{vmatrix}\end{bmatrix}\qquad \varphi(l')=\begin{bmatrix}\begin{vmatrix}e_\theta\\h_\theta\end{vmatrix}\\\begin{vmatrix}e_l\\h_l\end{vmatrix}\end{bmatrix}$$

$$A(\boldsymbol{r},l')=\begin{bmatrix}A^{r\theta} & A^{rl}\\A^{\theta\theta} & A^{\theta l}\\A^{z\theta} & A^{zl}\end{bmatrix} \tag{3}$$

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