Hybrid Integrated HEMT Oscillator with a Multiple-Ring Nonradiative Dielectric (NRD) Resonator Feedback Circuit

Songxin Qi, Ke Wu, *Senior Member, IEEE,* and Zifei Ou

***Abstract*— In this paper, a novel hybrid integrated-oscillator scheme is developed for millimeter-wave sources. A nonradiative dielectric (NRD) multiple-ring resonator is used, not only as a frequency-stabilizing element, but also as a feedback circuit coupled to a planar amplifier through the input and output slots. Such a three-dimensional circuit design indicates that a strong positive feedback can be easily implemented at millimeter-wave frequencies to improve characteristics of the oscillator. A field-theoretical model is derived for accurate prediction of the resonant frequency of NRD multiple-ring structures. The very satisfactory agreement observed between our measured and calculated results validates the modeling approach. Subsequently, a 23.3-GHz hybrid integrated high electron-mobility transistor (HEMT) oscillator has been designed, fabricated, and characterized with a dual-ring NRD resonator. The oscillator exhibits 7.0-dBm output power with 6.4% dc-to-RF efficiency and less than −95.7-dBc/Hz phase noise at 1-MHz offset from the carrier. The attractive electrical performance demonstrates a new approach to the design of cost-effective millimeter-wave sources by the use of an extremely low-cost and low-loss NRD material instead of an otherwise expensive conventional high permittivity (usually ceramic-material based) dielectric resonator.**

***Index Terms*—CAD, hybrid integration technology, nonradiative dielectric, numerical modeling, oscillator, ring circuit.**

I. Introduction

COST-EFFECTIVE and high-performance oscillators [1]–[3] are in great demand due to the rapid growth in the application of microwave/millimeter-wave systems such as high-speed wireless network and collision-avoidance radar. Although a number of oscillator design techniques have been developed to satisfy these stringent demands, the reduction of production costs still remains a challenging issue. In the conventional design of planar oscillating circuits over 20 GHz, the commonly used high-permittivity commercial dielectric resonators becomes miniaturized in size and, thus, it may become very difficult to tune the oscillator circuits through the adjustment of coupling between the dielectric resonator and transmission line. Furthermore, radiation of a dielectric resonator at millimeter frequencies may also become a serious problem and result in undesirable large spurious signals, which may interfere with its neighboring circuits. These problems lead to a number of limitations in the design of high-performance oscillator circuits and suggest that a new appropriate scheme be developed to replace the conventional oscillator design at millimeter-wave frequencies.

The nonradiative dielectric (NRD) waveguide [4]–[9] has been demonstrated to be one of the most attractive building blocks for millimeter-wave circuits because of its simplicity, ease of fabrication, and low-loss nature. Moreover, radiation at curved sections and discontinuities is nearly nonexistent. Various low-loss NRD passive and active components such as filters, couplers, and isolators, as well as NRD-based receivers/transmitters, have been successfully developed. However, there is a fundamental limitation of the spacing between the two metallic plates of the NRD-guide, which may lead to a difficulty in integrating active devices such as FET's, high electron-mobility transistors (HEMT's), and heterojunction bipolar transistors (HBT's) into a planar-circuit mount which should physically fit into the required spacing.

In this paper, a new integration scheme based on the concept of a recently proposed hybrid planar/NRD technology [10] is presented in the design of a new class of high-performance oscillators, making use of the dual slots etched on the ground plane of a planar circuit vertically coupled to the NRD multiple-ring dielectric resonator. Such a topology provides a number of advantageous features over the conventional planar oscillator design. The NRD multiple-ring resonator serves as a feedback circuit, and it is located underneath the planar amplifier circuit, which effectively eliminates potential radiation of the dielectric resonator at high frequencies and also makes it available to use low-cost low-permittivity materials such as Teflon, polystyrene, and highly temperature-stable TMM materials (Rogers' trademark). The low-permittivity allows us to design a sizable dielectric resonator at millimeter-wave frequencies and, therefore, eases the relevant fabrication tolerance. Our previous experience on the design of such a new oscillator is that the coupling strength should be adequately designed [17], and can be achieved through the use of an alternative NRD resonator shape such as a multiple ring instead

Manuscript received October 6, 1997; revised March 31, 1998. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada. The work of K. Wu was supported by the Telecommunication Research Center and by the Department of Electrical Engineering, City University of Hong Kong.

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Publisher Item Identifier S 0018-9480(98)06728-3.

of a cubic form [17]. As opposed to its cubic NRD counterpart used in our first experiment [17], the proposed multiple-ring resonator presents some distinct advantages because the multiple-ring resonator, in fact, presents a set of closed transmission lines. These features may be characterized by effective massive precision fabrication, potentially large electrical size, easy resonance (mode) control, flexible coupling adjustment between the input and output lines, and excellent tuning mechanism with ring-to-ring coupling or other transmission-line techniques. It is also possible to design millimeter-wave oscillator with a high-Q and/or subharmonic resonance using the proposed multiple-ring technique. In this paper, such a multiple-ring topology is studied as an essential resonator element for design of a new oscillator.

Our design procedure consists of several segments since very limited design tools are available. First of all, a field-theoretical model is developed to determine resonant frequency of the NRD multiple-ring structure, considering the fact that there are no results available for the design of such a multiple-ring structure. A good agreement is observed between the calculated and measured results for the fabricated samples, thereby validating the developed modeling technique. Subsequently, the choice of the slot size and distance between the two slots are partially optimized by using the transmission-line matrix (TLM) algorithm [13], [14] to obtain sufficient transmission power (coupling strength) and appropriate transmission phase at the designated oscillating frequency in order to build an appropriate feedback circuit. Note that it is impossible to optimize the complete circuit with the TLM algorithm at this time. A 23.3-GHz hybrid integrated oscillator has been then designed, fabricated, and measured. Experimental results indicate that this three-dimensional circuit configuration possesses the potential possibility in developing high-performance low-cost millimeter-wave oscillators, and it also provides a desired alternative to the conventional oscillator design scheme.

II. Design Technique and Consideration

The proposed structure of a planar NRD-based oscillator is shown in Fig. 1. It consists of a planar amplifier circuit, and an NRD multiple-ring resonator served as a positive feedback circuit as well as a frequency-stabilizing element. The NRD multiple-ring resonator is located under the planar amplifier circuit, which are coupled to one another through the two-slot apertures. The similar logistics of such an arrangement were discussed in [12] and [17], where only a cubic NRD resonator was used. In this paper, the multiple-ring topology is used as an alternative which may provide a high flexibility of coupling control as well as a better adjustment of the two-slot spacing. The resonance of a ring structure is usually easy to control with a better modal description compared with its cubic/rectangular NRD resonator. Instead of a single-ring structure, which provides a limited freedom of designing the oscillator with an adequate operating frequency, the multiple-ring structure may be used to achieve a large frequency-tuning range and also a wanted Q-factor. This can be better illustrated through the example of a two-ring structure, as shown in Fig. 1, in which one ring serves as the principal ring (signal)

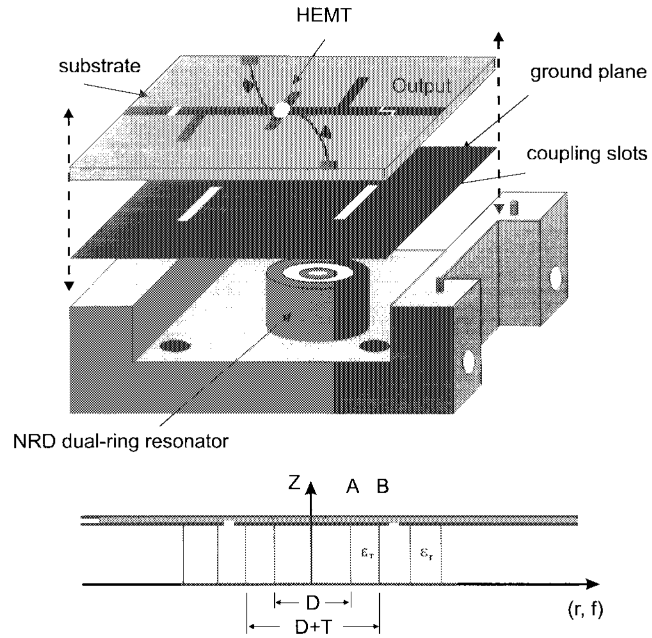


Fig. 1. Schematic diagram of the proposed hybrid integrated oscillator with the new multiple-ring NRD resonator, including the definition of an NRD dual-ring structure.

while the other (auxiliary) is used to adjust the operating frequency and slot coupling through a simple perturbation.

In addition, the ring resonator can also be used to generate dual-mode operation and high-Q resonant modes (e.g., higher order harmonics), which may be useful for advanced oscillator design. High-power output may be also generated by combining multiple oscillators with the ring structure. However, there are several design issues to be addressed for the planar NRD oscillator, among them, the choice of an NRD multiple-ring structure, characterization of a line-NRD resonator-line transition, and the design of a feedback oscillator layout.

In this section, an efficient simple technique based on field expansion is developed to accurately predict the resonant frequency of NRD multiple-ring structures. In addition, an optimized hybrid integrated-feedback circuit is characterized by the use of a TLM algorithm, and the oscillator design procedure is briefly described.

A. Resonant Frequency of an NRD Multiple-Ring Structure

An NRD multiple-ring structure to be modeled in a cylindrical coordinate system (ρ, φ, z) is shown in Fig. 1. A number of dielectric rings (two rings are described in the figure) are placed between two parallel and perfect conducting plates. The dielectric material is assumed to be lossless and homogeneous in the z-direction. The design of an NRD-ring requires that the spacing between the two metallic plates be smaller than a free-space half-wavelength which corresponds to the resonant frequency. Electromagnetic fields in different homogeneous regions are described by two vector potentials Π^e and Π^h. The vector potentials are supposed to be z-oriented and they are thus reduced to a pair of scalar potential functions ψ^e and ψ^h. The scalar potential functions must satisfy the Helmholtz equation when applied to describe an homogeneous region, such that

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial\psi^{e,h}}{\partial\rho}\right)+\frac{1}{\rho^2}\frac{\partial^2\psi^{e,h}}{\partial\varphi^2}+\frac{\partial^2\psi^{e,h}}{\partial z^2}+\varepsilon_r k_0^2\psi^{e,h}=0 \tag{1}$$

in which k_0 is the free-space wavenumber. This equation is easily analytically solved and its general solution can be simply constructed by a linear combination of Bessel functions of the first and second kinds as follows:

$$\psi^{e,h}=\left[J_n(k_\rho\cdot\rho)A^{e,h}+Y_n(k_\rho\cdot\rho)B^{e,h}\right]\cdot e^{-jk_z z}e^{jn\varphi} \tag{2}$$

where $k_\rho^2+k_z^2=\varepsilon_r k_0^2$ and n is an integer number. To transform the field quantities along the radial direction from one side of an homogeneous region (plane A) to the other side (plane B) defined in the proposed multiple-ring structure, the following simple matrix form is used:

$$\begin{bmatrix}\psi_A^{e,h}\\ \psi_B^{e,h}\end{bmatrix}=e^{-jk_z z}e^{jn\varphi}\cdot\begin{bmatrix}J_n(k_\rho a) & Y_n(k_\rho a)\\ J_n(k_\rho b) & Y_n(k_\rho b)\end{bmatrix}\cdot\begin{bmatrix}A^{e,h}\\ B^{e,h}\end{bmatrix} \tag{3}$$

and its derivative, with respect to ρ, can be expressed by

$$\rho\frac{\partial}{\partial\rho}\begin{bmatrix}\psi_A^{e,h}\\ \psi_B^{e,h}\end{bmatrix}=P_n^{-1}\begin{bmatrix}R_n & 2/\pi\\ -2/\pi & Q_n\end{bmatrix}\cdot\begin{bmatrix}\psi^{e,h}\\ \psi^{e,h}\end{bmatrix} \tag{4}$$

with the following elements:

$$\begin{aligned}P_n&=[J_n(t_A)Y_n(t_B)-J_n(t_B)Y_n(t_A)]\\ R_n&=t_A[J_n'(t_A)Y_n(t_B)-Y_n'(t_A)J_n(t_B)]\\ Q_n&=t_B[J_n(t_A)Y_n'(t_B)-J_n'(t_B)Y_n(t_A)]\end{aligned}$$

in which $t_A=k_\rho a$ and $t_B=k_\rho b$.

In this way, electric- and magnetic-field components are easily derived from the above-described potential functions in the cylindrical coordinate. Following a simple algebraic arrangement in relation to the above equations, the tangential-field components at the cylindrical planes A and B are related to each other through the following matrix equation:

$$\begin{bmatrix}\rho E_\varphi\\ j\eta_0 H_z\end{bmatrix}_{A,B}=\begin{bmatrix}\alpha_{E1} & s_E\\ -s_E & \alpha_{E2}\end{bmatrix}\cdot\begin{bmatrix}\gamma_{H1} & s_H\\ -s_H & \gamma_{H2}\end{bmatrix}^{-1}\cdot\begin{bmatrix}E_z\\ j\eta_0\rho H_\varphi\end{bmatrix}_{A,B} \tag{5}$$

with the abbreviated submatrices

$$[\alpha_{E1}]=\begin{bmatrix}\dfrac{k_z n}{k_0^2\varepsilon_r} & \dfrac{jR_n}{k_0P_n}\\ 0 & j\left(-\dfrac{k_z^2}{k_0^2}+\varepsilon_r\right)\end{bmatrix}$$

$$[\alpha_{E2}]=\begin{bmatrix}\dfrac{k_z n}{k_0^2\varepsilon_r} & \dfrac{jQ_n}{k_0P_n}\\ 0 & j\left(-\dfrac{k_z^2}{k_0^2}+\varepsilon_r\right)\end{bmatrix}$$

$$[\gamma_{H1}]=\begin{bmatrix}-\dfrac{k_z^2}{k_0^2\varepsilon_r}+1 & 0\\ \dfrac{R_n}{k_0P_n} & \dfrac{jk_z n}{k_0^2}\end{bmatrix}$$

$$[\gamma_{H2}]=\begin{bmatrix}-\dfrac{k_z^2}{k_0^2\varepsilon_r}+1 & 0\\ \dfrac{Q_n}{k_0P_n} & \dfrac{jk_z n}{k_0^2}\end{bmatrix}$$

and

$$[s_E]=\begin{bmatrix}0 & \dfrac{2j}{\pi k_0P_n}\\ 0 & 0\end{bmatrix}$$

$$[s_H]=\begin{bmatrix}0 & 0\\ \dfrac{2}{\pi k_0P_n} & 0\end{bmatrix}.$$

By invoking the continuous conditions of the tangential electric–magnetic fields at the specific cylindrical interface, a trivial field-coefficient matrix can be obtained from the null determinant

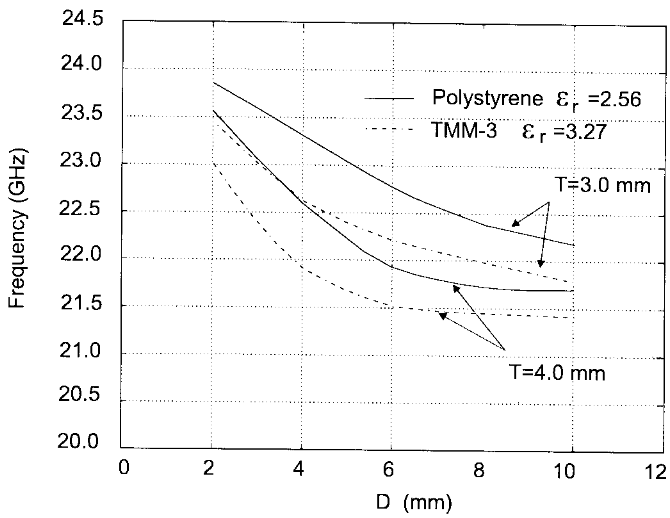
$$\det[Y]=0. \tag{6}$$

Therefore, the unknown resonant frequency can be determined from an indirect eigenvalue approach, namely, a singular-value-decomposition technique. In this way, the interface-field components as well as potentials can also be calculated.

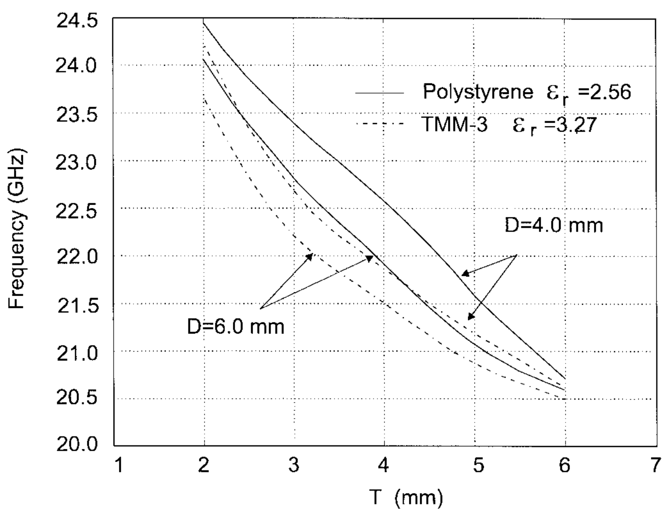
The above-developed model allows designing a multiple NRD ring structure with a specific frequency and other desired features for oscillator applications. In this paper, a coupled dual-ring geometry is considered in the design of a *K*-band hybrid NRD-ring oscillator. Such a choice is largely based on the fact that there is a possibility of generating two different resonant frequencies, and it is also possible to obtain a coherent (or synchronized) resonance with a much higher Q factor. This can be done by adequately choosing geometrical structures of the inner and outer rings. In addition, the spacing and coupling strength between the two slots can be easily adjusted since the design freedom seems to be enhanced while maintaining a wanted resonant frequency. Once a packaged transistor device is selected, the distance between the input and output reference planes of the active device is somewhat fixed, which is related to the feedback loop of a positive coupling. It allows a very limited freedom of realizing a prescribed resonance with an appropriate coupling strength if a single NRD-ring structure is used. The additional NRD ring actually provides an element of perturbation for a designer to achieve the specific goal in connection with the desired resonant frequency and other electrical characteristics.

Since our objective is to design an oscillator operating at 23.3 GHz with the proposed hybrid integration technique, the spacing between the two parallel plates is selected to be 6.4 mm based on the fundamental rule of the NRD-guide that it should be smaller than the free-space half-wavelength. This is done with reference to the Polystyrene dielectric material ($\varepsilon_r = 2.56$). Note that this condition is also valid for a nonradiative operation in the case of using the TMM materials with $\varepsilon_r = 3.27$. To simplify our design of a dual-ring resonant circuit, the radius and thickness of the outer ring are set to be 8.1 and 3.9 mm, respectively, while the inner ring's dimensions can be changed in view of obtaining the desired resonant frequency and other electrical characteristics.

Fig. 2 shows several sets of curves, presenting the variation of resonant frequency for both materials as functions of geometrical parameters of the inner ring with the fixed outer NRD ring. First of all, the resonant frequency of the NRD



(a)



(b)

Fig. 2. Calculated resonant frequency as functions of various structural parameters for an NRD multiple-ring resonator made of Polystyrene and TMM-3 dielectric materials with a fixed outer-ring topology (its radius and thickness are fixed to be 8.1 and 3.9 mm, respectively). (a) Resonant frequency versus the diameter of the inner ring for its two different thickness. (b) Resonant frequency versus the thickness of the inner ring for its two different diameter.

dual-ring is found to decrease in a monotonous way with the diameter (D), as shown in Fig. 2(a), for two different thickness ($T/2 = 1.5$ and 2.0 mm) of the NRD inner ring. The influence of thickness on the resonance is also plotted for two different diameters ($D = 4.0$ and 6.0 mm). The curve slopes presented in Fig. 2(b) as compared to Fig. 2(a) suggest that the tuning range can be made sufficiently large with the change in thickness (T). In our example, a frequency tuning of 4.0 GHz (approximately 18%) can be easily achieved with a smaller diameter (e.g., $D = 4.0$) for a Polystyrene NRD dual-ring resonator. Therefore, the multiple-ring technique is useful for frequency tuning even though the input/output ports of the planar circuit are firmly defined in this proposed hybrid integration technology. On the other hand, this technique may offer a mechanism in tuning the Q-factor of the resonator and coupling strength of the loop. A further in-depth study is required to confirm these postulations.

B. Optimization of Transition Structure

It is known that the proposed hybrid integration of an NRD resonator and planar structure offers an attractive alternative for designing novel oscillators with low-loss and low-permittivity material. Nevertheless, a successful design of such a scheme critically depends on the optimization of a transition (slot–aperture coupling) between the two dissimilar structures. In particular, the circuit matching over the frequency band of interest is required and an appropriate feedback loop should be designed in conjunction with the planar amplifier circuit. An appropriate field-theoretical technique [13], [14] is used in this paper to optimize the structural parameters of the transition in relation to its coupling slot size, the distance between the two slots, and the position of the microstrip circuit.

To design a hybrid integrated oscillator operating at 23.3 GHz, the NRD dual-ring resonator is designed with a physical layout chosen simply with reference to Fig. 2. Since the Polystyrene material is mechanically easy to process, it is selected in our paper for the design of a dual-ring resonator having $D = 4.0$ mm and $T = 3.0$ mm. This arrangement will give rise to 23.3-GHz operation judging from Fig. 2. An optimized hybrid integrated structure serving as a feedback circuit is then fabricated and measured first of all without mounting the active device. The goal of this experiment is to examine the coupling efficiency (e.g., Q-factor) and also loading effects of the planar circuits on the resonant frequency since our theoretical modeling completely ignores the slots coupling through which the planar circuits are coupled to the NRD resonator. The microstrip line is made on a TMM-3 substrate ($\varepsilon_r = 3.27$) with a thickness of 15 mil. A line impedance of 50 ω is used for the input and output of the oscillator circuit with a strip width of 0.604 mm. The two coupling slots apertures etched on the ground plane of the NRD ring resonator have an optimized dimension of 4.8×0.5 mm^2.

An HP 8510C Vector Network Analyzer (VNA) is used for transmission measurement of the circuit. The measured return loss versus frequency is shown in Fig. 3. It is found that the resonant frequency of the designed NRD dual-ring resonator is 23.28 GHz, which is very close to its prediction, and a good coupling is also obtained. The little effect of the slot apertures on the resonant frequency can be well expected since the coupling is made magnetically and the slots will not disturb the field profile of the resonant mode. The designed feedback circuit presents a relatively narrow-bandwidth behavior. Typically, a bandwidth of 10-dB return loss corresponding to 2% of the center frequency is observed and the peak return loss is 36.2 dB, enabling the coupling strength large enough to build a positive feedback circuit. In this experiment, the unloaded Q-factor of such an NRD resonator is estimated around 2600, considering the dielectric and ohmic losses.

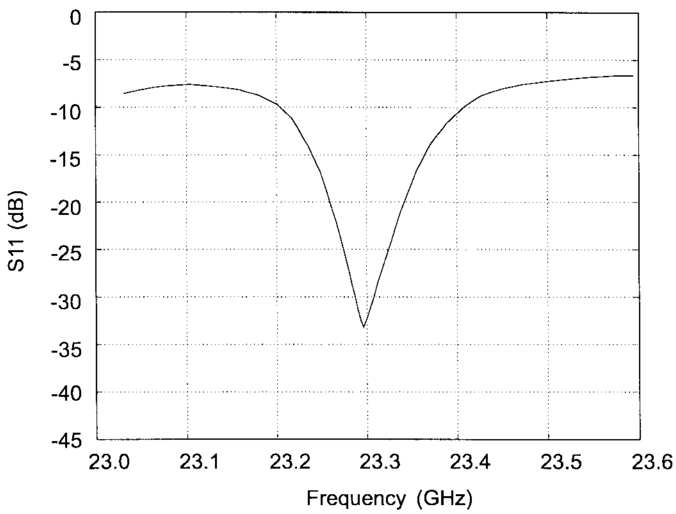


Fig. 3. Measured return loss of the designed polystyrene-based NRD dual-ring resonator for 23.3-GHz application.

TABLE I
THE SPECIFICATIONS OF THE PURCHASED FUJITUS HEMT DEVICE

Items	35LG HEMT
Gate Length	0.25 μm
Gate Width	280 μm
1-dB Saturation Power	14 dBm
Gain-Bandwidth Frequency	35 GHz
Maximum Drain Current	55.0 mA
Gate Turn-on Voltage	0.65V
Saturation Drain Voltage	0.54V
Pinch-off Gate Voltage	-0.55V

Obviously, the transmission phase can be adjusted by changing the distance between the two slots related to the input and output circuits. This electrical parameter can be well accounted for before finalizing the design of the physical layout as to the distance of the two slots. This is because the additional ring can be designed in any case to satisfy the requirement of the expected resonance owing to the potentially large tuning range. This design feature is useful in the design of a hybrid integrated oscillator (e.g., a suitable transmission phase is required to satisfy the initial oscillation criteria).

C. Oscillator Design

In this paper, a low-cost Fujitsu HEMT is purchased for the design of such a hybrid integrated-feedback-based oscillator. Our design begins with a modeling of the HEMT device. Its electrical specifications are described in Table I. Usually, the selection of an active device depends on the maximum allowable operating frequency ($f_{\max}$). Due to the loss of the signal transmission and limited Q-factor, the maximum operating frequency should be at least 1.5–2.0 times higher than the designed oscillating frequency (23.3 GHz) in order to sustain a steady-state oscillation. Parameter extraction and curve fitting are, therefore, carried out using an optimizer available from a commercial microwave circuit simulator with the parameters calculated from the device physical model as the initial guesses.

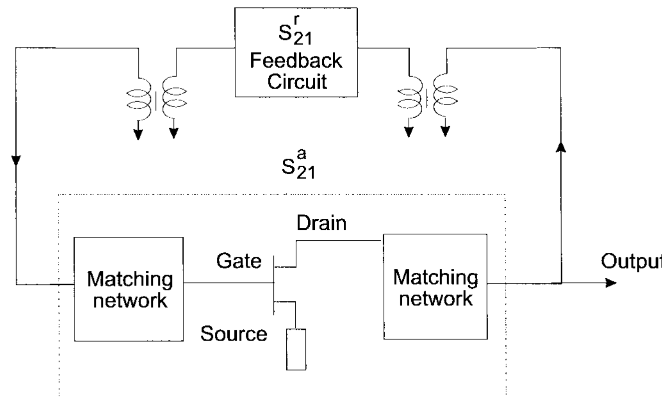


Fig. 4. The equivalent circuit of the proposed hybrid integrated multiple-ring NRD oscillator.

Fig. 4 depicts the equivalent circuit of the developed hybrid integrated oscillator, as shown in Fig. 1, which consists of a planar HEMT amplifier and a feedback circuit using the two slots coupled to the designed NRD dual-ring resonator. It can be seen that the rectangular slot apertures are not coordinately consistently with the NRD outer-ring geometry. The effect of such a problem related to the transition and coupling strength is difficult to estimate, and it thus ignored in this paper. Nevertheless, this problem is not manifested in our experiment.

The drain-related topology is carefully selected to improve the output power of the oscillator since the package of the HEMT device is constructed in the way that a potential heat dissipation is considered, and thus, is difficult to obtain microwave power at the source terminal. A short stub from the source to the ground is used as a series-feedback element. This enables the HEMT to operate with a unconditional stability over a wider range of the frequency. The amplifier and feedback circuits are designed to satisfy the following condition of oscillation:

$$S^a_{21} \cdot S^r_{21} = 1 \tag{7}$$

where S^a_{21} and S^r_{21} are the forward transmission coefficients for the amplifier and feedback circuit, respectively. Input and output impedance matching of the amplifier is achieved by using bandpass matching networks operating near the carrier frequency of the oscillator. The amplifier gain is designed to be sufficiently large in order to compensate for the loss in the NRD dual-ring resonator, and the phase condition in the initial criteria of oscillation is realized by adjusting and optimizing the distance between the two coupling slots. Since the oscillating frequency of the whole circuit is mainly determined by resonant frequency of the NRD resonator, the dimensions of the NRD dual-ring resonator are designed with the modeling results and then fabricated with precision. As shown in Fig. 4(a), the planar part of the assembled hybrid integrated oscillator is fabricated on a 35 $\times$ 32 mm^2 TMM-3 substrate. The microstrip lines are connected to the input and output port of the amplifier, with the distance between the two slot apertures being 18.42 mm.

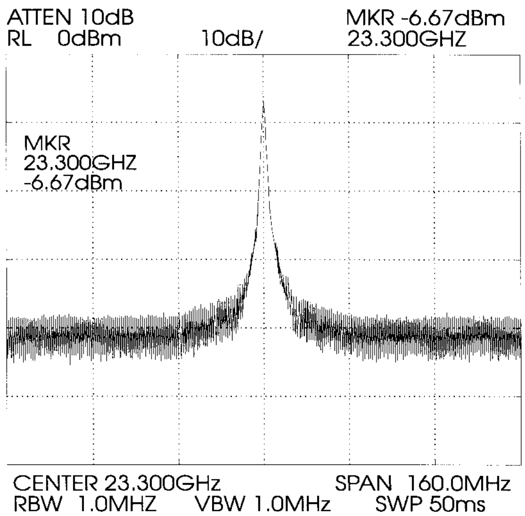


Fig. 5. Spectrum measurement of the hybrid integrated planar/NRD oscillator designed at the central frequency of 23.3 GHz.

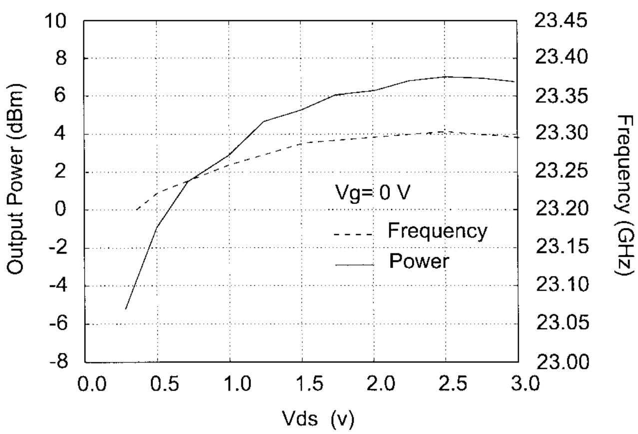


Fig. 6. Measured output power and oscillating frequency of the designed 23.3-GHz planar/NRD dual-ring oscillator as a function of the drain bias voltage for a fixed gate bias.

III. Measured Performance of the Designed Oscillator

In this design, the HEMT device operates with two dc-power supplied bias voltages having different polarity, a positive bias $V_{\rm ds}$ for the drain, and a negative bias $V_{\rm g}$ for the gate. The spectrum measurement is made with an HP-8563A spectrum analyzer. Fig. 5 shows the measured frequency spectrum of the designed oscillator operating at 23.3 GHz under $V_{\rm ds} = 3.0$ V and $V_{\rm gs} = 0.0$ V. It is found that a stable oscillation with clean spectrum is easily obtained at 23.3 GHz. It exactly corresponds to the designed oscillating frequency, i.e., the resonant frequency of the NRD dual-ring resonator.

The measured characteristics of the output power and oscillating frequency are shown in Figs. 6 and 7 as the two bias voltages are changed. It is shown that the output power exponentially increases with the bias voltage $V_{\rm ds}$ and tends to saturate beyond the bias point $V_{\rm ds} = 2.5$ V and $V_{\rm g} = 0$ V. The maximum output power of about 7.0 dBm is obtained, and its dc-to-RF conversion efficiency is 6.4%. Fig. 6 also shows a similar dependence of the oscillating frequency on the drain-to-source voltage. It seems that an increasing $V_{\rm ds}$ leads to a smooth increase in oscillating frequency, but within a very limited range. However, the increase of $V_{\rm g}$ causes a significant decrease of the output power while the oscillating frequency is very slightly increased. In this experiment, phase noise of the designed oscillator is also measured, and is less than -95.7 dBc/Hz at a frequency offset of 1 MHz from the carrier. In a practical use of the microwave oscillator, it is usually required that the initial drift of oscillation is suppressed to be as small as possible. A frequency drift of 58.6 MHz is observed within the initial 4 or 5 m, then the drift completely disappears and the oscillator operates in a very stable manner. In addition, a high dc-to-RF conversion efficiency of the oscillator can be readily obtained by optimizing the output load impedance through a multiharmonic load–pull measurement of the active device under the large-signal condition. This should be studied in the future.

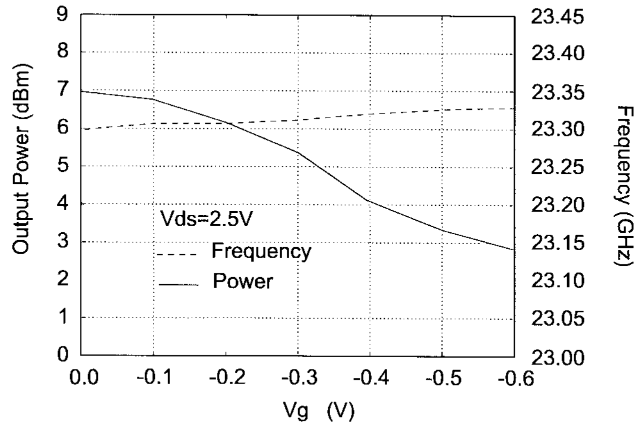


Fig. 7. Measured output power and oscillating frequency of the designed hybrid planar/NRD dual-ring oscillator as the gate bias voltage is changed for a fixed drain bias.

IV. Conclusion

A new class of integrated oscillators with an NRD multiple-ring resonator has been proposed under the scheme of hybrid integration technology. This new resonator structures serves not only as the frequency-stabilizing element, but also the feedback circuit. A model has been developed for the accurate indication of resonant frequency of the new NRD multiple-ring structures, and a dual-ring topology is emphasized for our design example. Our experimental results verifies the proposed model very well, and they indicate the importance of optimization with regard to various transition parameters and physical layout in design of the planar/NRD feedback circuit. A 23.3-GHz oscillator has been designed and fabricated with the developed dual-ring technique. A number of design considerations are presented in this paper. The attractive performance of the proposed oscillator indicates that it is possible to develop a novel low-cost high-performance oscillator scheme by using the new three-dimensional design strategy, i.e., the hybrid integration technology of a planar circuit/NRD-guide. This is done by combining the advantageous features of the two dissimilar structures, while effectively eliminating their shortcoming.

References

[1] C. M. Krowne, "Network analysis of microwave oscillators using microstrip transmission lines," *Electron. Lett.,* vol. 13, pp. 116–117, Feb. 1977.

[2] K. K. Agarwal, "Dielectric resonator oscillators using GaAs/(Ga,Al)As heterojunction bipolar transistors," in *IEEE MTT-S Int. Microwave Symp. Dig.,* Baltimore, MD, June 1986, pp. 95–98.

[3] M. E. Tobar, E. N. Ivanov, R. A. Woodeand, and J. H. Searls, "Low noise microwave oscillator based on high-Q temperature stabilized sapphire resonator," in *Proc. IEEE Int. Freq. Control Symp.,* June 1994, pp. 433–440.

[4] T. Yoneyama and S. Nishida, *Nonradiative Dielectric Waveguide* (Infrared and Millimeter Waves Series), K. J. Button Ed. New York: Academic, 1984, ch. 2, pp. 61–98.

[5] T. Yoneyama, "Millimeter wave integrated circuits using nonradiative dielectric waveguide," *Electron. Commun.,* vol. 74, pt. 2, no. 2, pp. 87–94, 1991.

[6] T. Yoneyama and S. Nishida, "Nonradiative dielectric waveguide for millimeter wave integrated circuits," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-29, pp. 1188–1192, Nov. 1981.

[7] F. Kuroki and T. Yoneyama, "NRD guide digital transceivers for millimeter wave LAN system," *IEICE Trans. Commun.,* vol. E79-B, no. 12, pp. 1759–1764, 1996.

[8] H. An, R. G. Bosisio, and K. Wu, "Aperture coupler undirectional dielectric radiator (UDR) and UDR array for microwave/millimeter wave wireless communications," in *Proc. IEEE MTT-S Int. Topical Symp. Technol. Wireless Applicat.,* Vancouver, B.C. Canada, Feb. 1995, pp. 169–174.

[9] J. Huang and K. Wu, "A two path multimode bandpass filters using the nonradiative dielectric (NRD) waveguide technology," in *IEEE MTT-S Int. Microwave Symp. Dig.,* Orlando, FL, May 14–19, 1995, pp. 1547–1550.

[10] L. Han, K. Wu and R. Bosisio, "An integrated transition of microstrip to nonradiative dielectric waveguide for microwave and millimeter wave circuits," *IEEE Trans. Microwave Theory Tech.,* vol. 44, pp. 1091–1096, July 1996.

[11] K. Wu and L. Han, "The hybrid integrated planar NRD-guide technology: A new concept for low cost application of microwave and millimeter wave circuits," in *IEEE MTT-S Int. Microwave Symp. Dig.,* San Francisco, CA, June 18–20, 1996, pp. 90–94.

[12] ——, "Hybrid integration technology of planar circuit and NRD-guide for cost-effective microwave and millimeter wave applications," *IEEE Trans. Microwave Theory Tech.,* vol. 45, pp. 1–8, June 1997.

[13] A. Bacha and K. Wu, "Toward an optimum design of NRD-guide and microstrip line transition for hybrid integration technology," *IEEE Trans. Microwave Theory Tech.,* to be published.

[14] P. M. Frank, N. R. Simons *et al.,* "Exploring the capability of the TLM method on microstrip structures suitable for device integration," in *First Int. Workshop Transmission Line Matrix (TLM) Modeling-Theory Applicat.,* Victoria, B.C., Canada, Aug. 1–3, 1995, pp. 113–117.

[15] G. D. Vendelin *et al., Microwave Circuit Design Using Linear and Nonlinear Techniques.* New York: Wiley, 1990.

[16] Brian C. Wadell, *Transmission Line Design Handbook.* Norwood, MA: Artech House, 1991.

[17] K. Wu, L. Han, "Integrated planar NRD oscillator suitable for low-cost millimeter-wave applications," *IEEE Microwave Guided Wave Lett.,* vol. 6, pp. 329–331, Sept. 1996.

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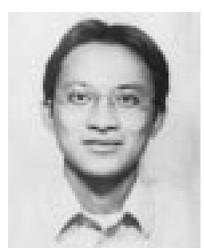

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