Integrated Planar NRD Oscillator Suitable for Low-Cost Millimeter-Wave Applications

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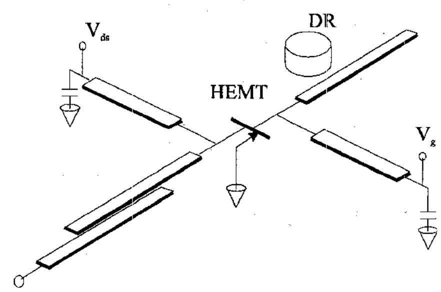
***Abstract*—A class of oscillators are proposed on the basis of a hybrid integration of planar circuits and nonradiative dielectric (NRD) guide. Compared to the existing design procedure and the conventional geometry, the novel oscillator uses an NRD resonator made of low-loss and low-permittivity material coupled to planar oscillator through an aperture. This three-dimensional circuit design allows to have a complete symmetry of circuit and a build-in feedback loop. An HEMT-based experimental prototype shows that the novel scheme of oscillator design is attractive for use in the future low-cost millimeter-wave circuits and systems.**

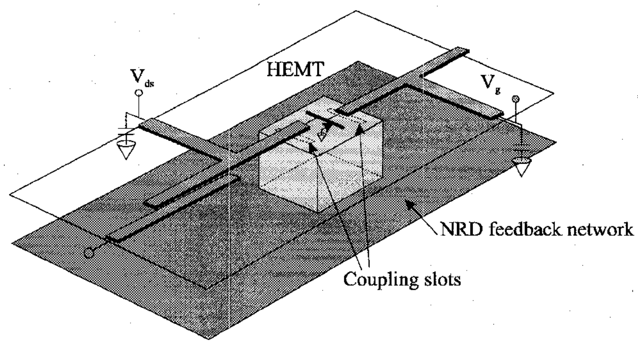
I. Introduction

At MILLIMETER-WAVE frequencies, the conventional design of a high-performance oscillating circuit, as shown in Fig. 1(a), may have some challenging problems. In particular, the commonly used high relative permittivity (>18) dielectric resonators that are in most cases ceramic-based material present an extremely miniaturized size that may be expensive and difficult to handle in the assembly of the device. There is no way to use the extremely cheap low-loss materials such as Teflon, Polystyrene, etc., because the mode confinement is required under such a design. Once fabricated and assembled, it is difficult or even impossible to tune the oscillating circuits through adjusting the spacing between the dielectric resonator in question and its coupled transmission line.

The modeling and analysis of the conventional oscillating geometry are usually tedious due to the fact that the mode profile could be very complicated and the coupling scheme is not coordinate consistent. This coordinate inconsistency can well be reflected by the hybrid structure of a rectangular–coordinate planar line coupled to a cylindrically coordinated dielectric resonator. As such, the field-theoretical modeling and analysis are much more involved. On the other hand, the device makes use of in most cases a single dielectric resonator, leading to an asymmetric configuration. This asymmetry may bring about radiation loss in an open environment or parasitic interference (coupling) in an enclosed package. This could be a serious problem at millimeter-wave frequencies. In addition, the conventional geometry is more and less difficult to provide itself a build-in feedback capacity that is, however, very useful in the design of highly stabilized oscillators or high-quality solid-state power sources. This is a crucial factor in the design



(a)



(b)

Fig. 1. Schematic three-dimensional view of the circuits of (a) the conventional planar oscillator with dielectric resonator (DR) and (b) the proposed planar NRD oscillator with a hybrid integration technique.

consideration since most millimeter-wave circuits and systems are likely to have narrow-band operation for which a high-performance oscillator is strongly desirable. In this way, the noise performance and power efficiency may also be improved.

In this letter, we present a hybrid architecture [1] of planar circuits coupled to a nonradiative dielectric (NRD) resonator for designing a class of oscillators readily operating at millimeter-wave frequencies. The present work aims at proposing a new strategy of developing high-performance low-cost millimeter-wave circuits and providing an alternative to the conventional design procedure.

II. Description of Novel Oscillator and Experimental Demonstration

The NRD guide [2] is known as an attractive technology for microwave and in particular millimeter-wave applications. In contrast to other dielectric waveguides, the NRD guide [3], [4] has virtually no radiation loss and also permits to use a low-permittivity dielectric material. It is therefore permissible

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for one to select high-Q and cheap materials as the NRD strip (Teflon, having a relative permittivity of 2.04, to name an example). In this way, a high-Q NRD resonator can easily be made without resorting to expensive ceramic-based commercial dielectric resonator. Obviously, the NRD resonator can be made relatively large at millimeter-wave frequency owing to its low permittivity. In addition, the shape of NRD resonator can be made in either cylindrical or cubic form for which analytical modeling and experimental characterization of mode resonance and quality factor become much more easy because the symmetry of the resonator is well defined [5]. The low-permittivity material leads also to a low tolerance requirement in view of the mechanic fabrication and shape processing. It is expected that a high-frequency stability of resonator can be achieved if a temperature-stabilized material is used such as the newly commercialized Roger's TMM dielectric materials. In one of our previous works [6], a compact design of resonator excited by microstrip line that is coupled to the NRD resonator through an aperture has been proposed and demonstrated. In that example, the resonator was used to serve as a unidirectional dielectric radiator (UDR) proposed by the first author of this letter [7]. Nevertheless, the unloaded Q of Teflon-based NRD resonator around 20 GHz was measured to have about 8000, which is very suitable for high-performance design of oscillator. Such a performance was achieved at a negligible cost. Note that the resonance property can be very precisely determined by a field-theoretical technique proposed in [5].

In the proposed design of a NRD-based oscillator, the NRD resonator is placed in a way similar to the hybrid geometry proposed in [6]. Compared to a typical building block of the conventional oscillator as sketched in Fig. 1(a), the new planar NRD oscillator as described in Fig. 1(b) consists of a planar circuit with a three-terminal device, a matching element, and a bias network coupled to the NRD-resonator through a slot aperture. The complete oscillator is designed under the framework of an amplifier together with a positive feedback network. The design of planar circuit part in this work is based on a conventional approach. The major effort in the work is centered on the design of the feedback loop associated with the NRD resonator and coupling mechanism. The aperture coupling is relatively effective for a narrow-band operation, as in this case where frequency is essentially determined by the NRD resonator. The NRD resonator is located under the planar circuit, which shares its ground plane with one of the NRD parallel metallic plates where the aperture is formed.

In addition to some obvious advantages compared to its conventional counterpart, the proposed planar NRD oscillator presents a build-in feedback loop that allows a positive backward coupling between the input and the output of the three-terminal device. In our experimental example, a FHX15X GaAs HEMT transistor was chosen for low-noise applications. In this case, a portion of the output signal goes through one slot aperture magnetically coupled to the NRD resonant mode, and it continue its path of signal flow coupled back to the other slot aperture attached to the input port. The orientation of the slot aperture is designed such that the desired nonradiative resonance mode is excited. A higher loaded Q-value of NRD resonator can be obtained by adjusting the coupling strength of the microstrip line to it. The degree of the coupling strength is made by modifying the distance between the two slots and/or the position of the NRD resonator with respect to the microstrip line. An additional feature of the proposed three-dimensional (3-D) design is that the circuits symmetry with respect to the dielectric resonator can be guaranteed such that the above-mentioned potential radiation or interference due to the asymmetry of dielectric resonance mode encountered in the conventional design can be suppressed.

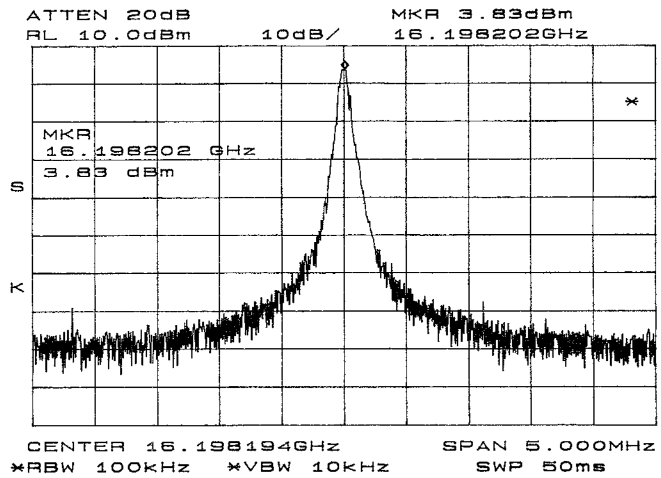

Fig. 2. Spectrum measurement of the proposed planar NRD oscillator together with the experimental demonstration of the output power at the central frequency of 16.9 GHz.

Of course, the design of the optimized distance between two coupled slots requires an appropriate field-theoretical modeling technique. Nevertheless, this is not our primary concern for the design of a preliminary oscillator for our experimental study. Using the proposed scheme, we have designed, fabricated, and tested an oscillator operating at the central frequency of 16 GHz with the Teflon material for NRD resonator and Duroid 5880 (Roger's trademark) substrate with a relative permittivity of 2.22 and a thickness of 15 mil. The spacing between the two parallel metallic plates is 7.12 mm and is obtained by the well-established nonradiative condition. The NRD resonator is dimensioned by $13.55 \times 12.88 \times 7.12$ mm^3. The loaded Q-value of such a kind of resonator together with the proposed coupling mechanism is able to go beyond 1000. This was confirmed by our late subsequent experimental results on the quality of NRD resonator. Nevertheless, the choice of the coupling mechanism is not only determined by the Q-value, but also by the feedback loop design. The design of the feedback loop requires both amplitude and phase matching such that an appropriate positive feedback is achieved. Considering these factors, we have chosen the slot aperture of 5×0.5 mm^2, and the distance between the two coupling slots is 15 mm. The experimental prototype was successfully designed without the first failure. Our measurement results as shown in Fig. 2 suggest that a relatively clean frequency spectrum and stable oscillator are obtained with the proposed scheme. It can be seen that an output power of 5.1 dBm is obtained at 16.19 GHz, which corresponds exactly to the designed NRD oscillating frequency. The noisy background of the experimental prototype, however, was also observed. This can be explained by the fact that a strong coupling was taking place. The strong coupling, which unfortunately lowers the loaded Q-value of the NRD resonator, is made to compensate the insertion loss for obtaining a desired positive feedback. It is suggested that an overall optimization should be made with respect to the dimensions of coupling aperture and the distance of the two slots, such that the possible highest Q-value and the required positive feedback can be satisfied simultaneously. A further theoretical and experimental study is necessary to improve the purity of the oscillating frequency spectrum, and other electrical characteristics such as the phase noise as well as the power-added efficiency should be also investigated.

III. CONCLUSION

Using the recently proposed hybrid integration technique of planar circuits and NRD guide [1], we report in this letter the development of a class of integrated planar NRD oscillators that present a number of attractive technical features and design merits for low-cost millimeter-wave applications. In addition, the build-in feedback loop and other new aspects of the proposed oscillator structure that we believe are the first of their kind promise excellent electrical and mechanic characteristics for use in future circuits and systems.

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