A 330-GHz MMIC Oscillator Module

Vesna Radisic, Lorene Samoska*, W. R. Deal, X.B. Mei, Wayne Yoshida, P.H. Liu, Jansen Uyeda, Andy Fung*, Todd Gaier*, and Richard Lai

Northrop Grumman Corporation, Redondo Beach, CA 90278, USA

*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Abstract — **In this paper, a 0.27 mW fundamental oscillator module operating at 330 GHz is presented. The MMIC in the module contains both the oscillator circuit and waveguide probes integrated on the same InP substrate. The oscillator is implemented in coplanar waveguide (CPW) technology and uses advanced high f_{MAX} 35 nm InP HEMT transistor in a common gate configuration. The integrated radial E-plane probe has been designed to operate over a frequency range of 300-350 GHz, using WR2.2 for the input and output waveguide. A free-running frequency of 330.5 GHz has been measured by down-converting the signal to an IF frequency observable on a spectrum analyzer. This is the first oscillator module above 300 GHz and demonstrates that fundamental signal generation at sub-millimeter wave frequencies can be simply and reliably generated.**

Index Terms — **MMIC, Millimeter Wave, HEMT, Coplanar Waveguide, Oscillator, Module**

I. INTRODUCTION

Although mixer based receiver technologies have progressed well past 1.0 THz, fundamental sources have had significant challenges in pushing their operating frequencies into the sub-millimeter wave regime (>300-GHz). Developing reliable sources to complement existing receiver technologies is highly desirable both in propagation based radiometry applications, as well as providing a potential LO source for Terahertz mixers. However, in the past several years, significant progress has been made in pushing fundamental oscillators into the sub-millimeter bands (>300 GHz) [1-6]. Recently, oscillators using InP and SiGe heterojunction bipolar transistors (HBT) in push-push configuration have been demonstrated up to 287 GHz [1-2] and as fundamental oscillators up to 311 GHz [3]. A CMOS oscillator using a linear superimposition method was demonstrated at 324 GHz [4], and fundamental oscillators using high electron mobility transistor (HEMT) have now been reported up to 346 GHz [5-6].

Much of the recent sub-millimeter wave oscillator work has used MMIC technologies and presented on-wafer performance results [1-6]. Waveguide packaging of MMICs at sub-millimeter wavelengths is extremely challenging because dimensional tolerances needed at these frequencies are at the limits of conventional machining technologies. However, for successful system integration, it is essential that these MMICs are integrated into waveguide fixtures, which serve as a practical interface to other electronic components such as mixers, multipliers or waveguide based horn antennas. Waveguide implementation of MMICs at short wavelengths presents a unique set of challenges if approached using conventional lower frequency fixturing techniques. In particular, wire-bonds become impractical at frequencies above 200 GHz due to excessive reactance and the associated mismatch losses. The distributed compensation networks can be incorporated, but limit the bandwidth of the packaged MMIC. For optimum performance at sub-millimeter wavelengths, electromagnetic coupling structures to deliver the signal in/out of the MMIC must be incorporated directly on the MMIC substrate. The first MMIC amplifier designed with integrated E-plane waveguide transitions up to 215 GHz was reported in [7]. The highest frequency amplifier module using integrated waveguide transitions was reported in [8].

In this paper, we report the first oscillator module operating at sub-millimeter wave frequency (>300-GHz). A microphotograph of the MMIC oscillator in the module is shown in **Fig 1**. The oscillator is implemented in coplanar waveguide (CPW) technology and is extremely compact, with dimensions of only 1085 μm x 320 μm for a total die size of 0.35 mm^2. The additional port on the right enables injection locking.

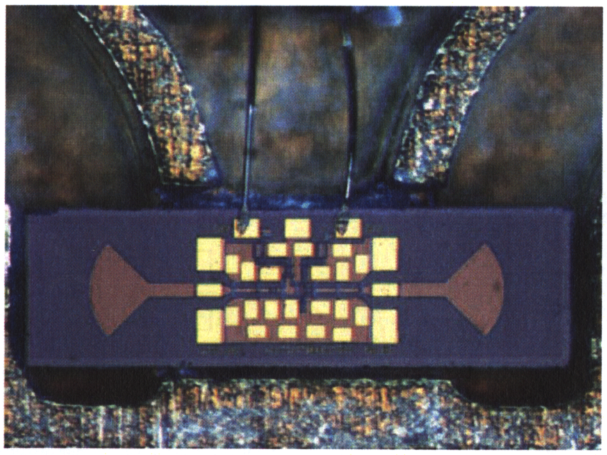

Fig 1. 330 GHz oscillator MMIC installed in split waveguide fixture. The die size is 1085×320 μm^2.

978-1-4244-1780-3/08/$25.00 © 2008 IEEE

II. 35-NM INP HEMT TECHNOLOGY

Fundamental to this demonstration of a 330-GHz oscillator was the development of devices with sufficient gain characteristics at the targeted operating frequency to insure oscillation. The basic device technology in this work is identical to that in [6]. However, the results presented in this work are from a different lot with higher transconductance. The InP HEMT epi wafers were grown by MBE and employ a pseudomorphic In$_{0.75}$Ga$_{0.25}$As channel, a silicon delta-doping layer as the electron supply, an In$_{0.52}$Al$_{0.48}$As buffer layer and an InP substrate. Room temperature electron mobility over 12000 cm^2/V.s has been achieved with a sheet charge of 3.5e12 cm^{-2}. Excellent DC performance has been achieved, including a peak G$_m$ of ~2000-mS/mm and breakdown voltages over 2.5V. The output conductance is also well controlled by a carefully optimized gate recess etch and epitaxial structure design. The 35nm T-gate was formed with over 80% transistor yield and excellent uniformity.

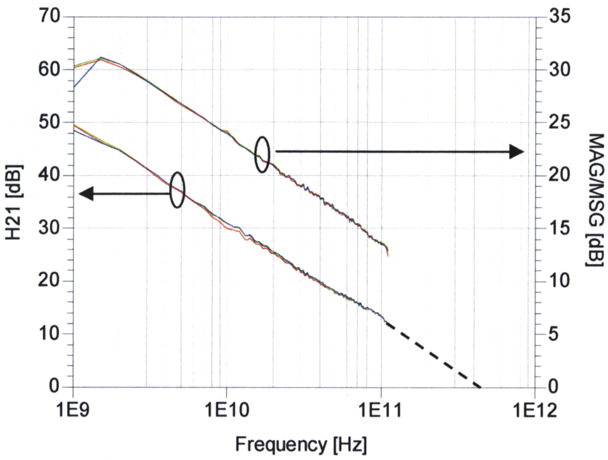

Fig 2. Measured H$_{21}$ and MAG/MSG of a 30-μm device at a drain bias of 1 V and 150 mA/mm de-embedded to reference plane of the device. The dashed line is H$_{21}$ extrapolation at 20 dB/decade.

The result of the high performance epi profile and aggressive gate is a device with excellent RF characteristics. The measured H$_{21}$ and MAG for a two finger device with periphery of 30 μm are shown in **Fig** 2. Measurements were taken with an on-wafer CPW calibration with reference planes placed at the device feeds. f$_T$ extrapolated from the H$_{21}$ trace is > 400 GHz. The measured devices were from the same lot as the measured circuits reported in this paper. However, the device used in the oscillator circuit is a single finger transistor with 20 μm periphery, chosen for ease of layout in a common gate configuration. The performance of this transistor scales as expected to the two finger 30 μm device performance shown in **Fig** 2.

III. OSCILLATOR DESIGN

The circuit topology of the oscillator presented in this work is shown in Fig. 3. The basic oscillator core is similar to that presented in [6], which was on our first dedicated 35-nm InP HEMT mask. The circuit topology consists of a single-finger HEMT transistor in common gate configuration, a CPW resonator connected to the gate, an output power matching circuit on the drain, and an injection locking port connected to the source.

In our second mask, a primary goal has been to design a MMIC oscillator suitable for packaging in the module at a target frequency of 340 GHz. This allows the MMIC oscillator to operate as a stand-alone fundamental source at sub-millimeter wavelengths. To achieve this goal, source and drain bias networks have been added to the MMIC using CPW transmission lines connected to a MIM bypass capacitor, and then connected to the DC pad, as shown in Fig. 3. Additionally, the wafer probe pads have been replaced with integrated E-plane probes. The primary purpose of implementing the MMIC in CPW is the low inductance access to ground, which helps maximize the realized transistor gain. The MMIC wafers have been thinned to 2 mil (~50 μm) for dicing and fixturing. We have successfully demonstrated that InP wafers can be thinned to 1 mil for appropriate electrical thickness at 340 GHz for microstrip design. However, our current data indicates that 2 mil substrate thickness is adequate for operation of our CPW designs at the target frequency, and more practical from a yield perspective. The backside processing included via etching to suppress parallel plate modes. The microphotograph of the completed MMIC oscillator is shown in Fig. 1.

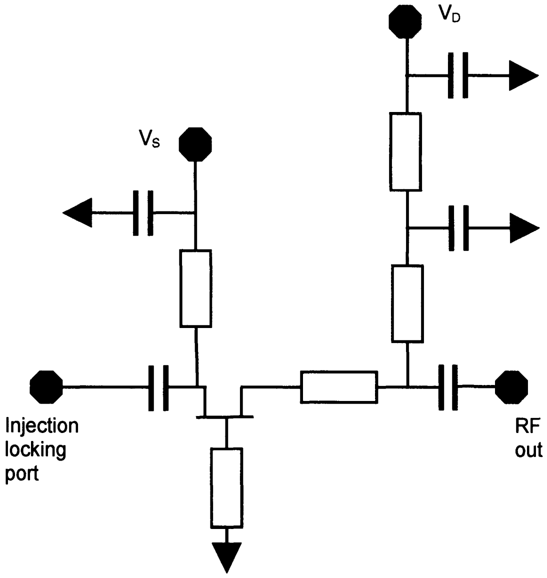

Fig 3. Topology of the common gate oscillator circuit.

In the design of the oscillator, all transmission lines were modeled using the CPW transmission line models included in a standard microwave CAD tool. No electromagnetic simulations were explicitly included in the design other than verifying that the models did a reasonable job predicting the Z_0 and β of the CPW transmission lines at the frequency of interest. The oscillator was analyzed using a linear analysis since only a small signal model was available.

IV. MODULE DESIGN AND ASSEMBLY

E-plane transitions were directly integrated onto the MMIC [8]. The transition was designed with a 3-D electromagnetic simulator, optimized to efficiently couple the dominant TE_{10} mode from the waveguide to the MMIC. Using InP substrate for the E-plane probes causes a large fraction of the channel to be filled with high permittivity material (ε_r = 12.5), in contrast to typical E-plane probe implementation on lower permittivity substrates, such as quartz. Due to the high permittivity, preventing leakage of waveguide TE_{10} mode power in the MMIC channel is a considerable challenge. In this design, the mode is cut-off by limiting the channel width and therefore the MMIC width to 320 μm.

The MMIC oscillator chip was bonded into the module with conductive epoxy, as shown in Fig. 1. Wire bonds from the DC source and drain pads are connected to off-chip 51 pF bypass capacitors, with additional off-chip capacitors and resistors to ensure low frequency stability of the circuit.

V. EXPERIMENTAL RESULTS

The oscillation frequency and output power was measured at the Jet Propulsion Laboratory, California Institute of Technology. The test setup for determining the oscillation frequency is shown in Fig. 4. A WR2.8 sub-harmonic mixer (SHM) is used to down-convert the output signal to a frequency below 50 GHz, capable of being observed on a spectrum analyzer. The 160 GHz local oscillator (LO) signal for the mixer is generated by multiplying a 20 GHz signal from a bench-top synthesizer with commercially available ×4 and ×2 multipliers, as shown in Fig. 4. Although a signal for injection locking can be introduced through the injection locking port, in this case the port was terminated using a WR-2.2 waveguide load to investigate the free-running properties of the oscillator. The down-converted output spectrum of the oscillator was observed on the spectrum analyzer and a sample trace is shown in Fig. 5.

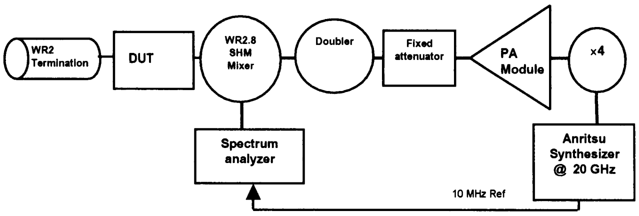

Fig 4. Test setup for determining the oscillation frequency.

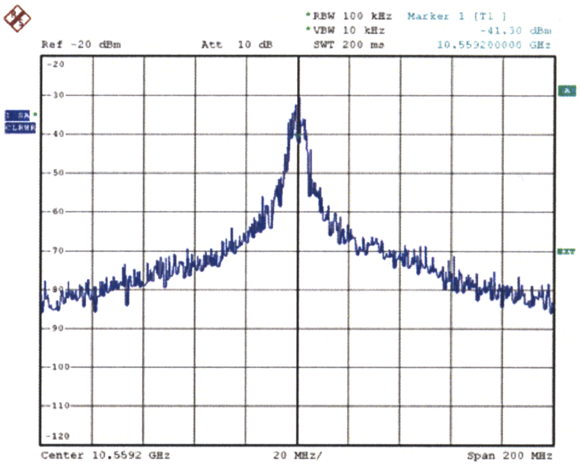

Fig 5. Measured spectrum of the down-converted oscillator with a drain-source bias of 1.8-V and drain current of 8.8 mA.

Since the spectrum is down-converted using a sub-harmonic mixer with a harmonically generated LO driver, it is critical to correctly identify the down-converted spectrum from the multitude of undesired mixing products. By shifting the synthesizer frequency and observing the resulting shift in the down-converted spectrum, the oscillation frequency was determined to be summation of the 320 GHz LO and the frequency observed on the spectrum analyzer, shown in Fig. 5. Therefore, the oscillator frequency of the module is ~330.56 GHz for the drain-source bias of 1.8 V and drain current of 8.8 mA. It should be noted that the oscillator was designed for a 340 GHz operation, only 3 % from the measured frequency.

The oscillator module output power was measured using the setup shown in Fig. 6. The module output is connected to a WR-2 to WR10 transition, and then to Erickson PM2 calorimeter. The bias conditions and injection port termination are similar to those described previously. The measured output power was 0.27 mW, corresponding to RF to DC efficiency of 1.7 % for the module. The accuracy of this power measurement set-up is ~ ±0.5 dB. In [6], we reported 25 μW of power for a 346-GHz oscillator. The 10 times higher output power achieved at 330GHz by this design iteration is attributed to improved power matching networks, improved transconductance of the transistors in our developing sub-millimeter wave MMIC process, and moderately lower operating frequency. It should be noted that the result in [6] was measured on a full-thickness wafer (25 mil), while this result is for a thinned (2 mil) wafer. In the case of the thick wafer, some of the energy may have been potentially coupled into the substrate. Additionally, the test setup in [6] used a WR-3 to WR-10 transition, while a WR-2.2 transition was used in this work.

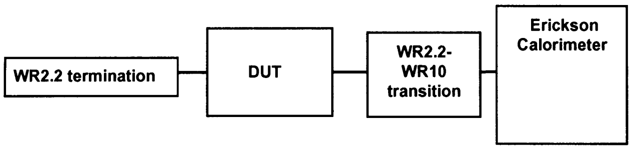

Fig 6. Test setup for the oscillator module output power measurement.

VI. CONCLUSION

In this paper, we report the first fundamental sub-millimeter wave oscillator module. The 330 GHz oscillator module produces 0.27 mW of output power and features WR-2.2 waveguide input and output ports. The MMIC uses a 35 nm InP HEMT transistor and is realized in coplanar waveguide. To avoid wirebonds in the RF path, E-plane transitions have been integrated onto the InP substrate to couple the sub-millimeter wave energy directly to the waveguides. Furthermore, the oscillator demonstrated 1.7% DC-RF efficiency measured at the module level.

This oscillator module can be easily integrated with mixers, multipliers, and amplifiers for building high frequency transmit and receive systems at sub-millimeter wave frequencies. Since it requires only a DC bias, it is a simple and reliable source for power at sub-millimeter wave frequencies. With this first demonstration of a packaged fundamental sub-millimeter wave source relying on HEMT transistor technology, we expect that future work will be directed to further improving the applicability of HEMT transistors to sub-millimeter wave and terahertz applications.

ACKNOWLEDGEMENT

This work was supported by the DARPA SWIFT Program and Army Research Laboratory under the ARL Contract no. W911QX-06-C-0050 and the authors would like to thank Dr. Mark Rosker (DARPA) and Dr. Alfred Hung (ARL). The authors would like to thank members of the Northrop Grumman Corporation (NGC) for MMIC layout support by Jeff Coakley and Stella Makishi, MBE material growth led by Patrick Chin and Mike Lange, MMIC wafer fabrication by Jane Lee, Danny Li, Linh Dang, Jennifer Wang, Keang Kho, Pat Oliver, John Kane and Tim Naeole, HEMT engineering by Young-Min Kim and Dave Farkas, and project oversight and support by Aaron Oki (NGC) and Reynold Kagiwada (NGC). This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Y. Baeyens, N. Weimann, V. Houtsma, J. Weiner, Y. Yang, J. Frackoviak, P. Roux, A. Tate, and Y. K. Chen, “Highly efficient harmonically tuned InP D-HBT push-push oscillators operating up to 287 GHz,” in *IEEE MTT-S Intern. Microwave Symp. Dig.*, pp. 341 – 344, June 2007.

[2] R. Wanner, R. Lachner, G. R. Olbrich, and P. Russer, “A SiGe monolithically integrated 278 GHz push-push oscillator,” in *IEEE MTT-S Intern. Microwave Symp. Dig.*, pp. 333 – 336, June 2007.

[3] V. Radisic, D. Sawdai, D. Scott, W. R. Deal, L. Dang, D. Li, J. Chen, A. Fung, L. Samoska, T. Gaier, and R. Lai, “Demonstration of a 311-GHz fundamental oscillator using InP HBT technology,” *IEEE Trans. Microwave Theory Tech.*, N vol. 55, issue 11, Nov. 2007, pp. 2329-2335.

[4] D. Huang, T. LaRocca, L. Samoska, A. Fung, and F. Chang, "324 GHz CMOS VCO using Linear Superposition Technique," accepted at the *2008 International Solid State Circuits Conference*, to be held in San Francisco, CA, Feb., 2008.

[5] S. E. Rosenbaum, B. K. Kormanyos, L. M. Jelloian, M. Matloubian, A. S. Brown, L. E. Larson, L. D. Nguyen, M. A. Thompson, L. P. B. Katehi, and G. M. Rebeiz, “155- and 213-GHz AlInAs/GaInAs/InP HEMT MMIC oscillators,” *IEEE Transactions on Microwave Theory and Techniques*, Volume 43, Issue 4, April 1995, pp. 927-932.

[6] V. Radisic, X.B. Mei, W.R. Deal, W. Yoshida, P.H. Liu, J. Uyeda, M. Barsky, L. Samoska, A. Fung, T. Gaier, R. Lai, “Demonstration of sub-millimeter wave fundamental oscillators using 35-nm InP HEMT technology,” *IEEE Microwave and Wireless Components Letters,* Volume 17, No. 3, March 2007, pp. 223-5.

[7] S. Weinreb, T. Gaier, M. Barsky, Y.C. Leong, L. Samoska, “High-gain 150-215-GHz MMIC amplifier with integral waveguide transitions,” *IEEE Microwave Guided Wave Lett.*, Vol. 7, July 1999, pp. 282– 284.

[8] L. Samoska, W. R. Deal, G. Chattopadhyay, D. Pukala, A. Fung, T. Gaier, M. Soria, V. Radisic, X. B. Mei, and R. Lai, “A submillimeter-wave HEMT amplifier module with integrated waveguide transitions operating above 300 GHz,” submitted to *IEEE Trans. Microwave Theory Tech.*