Vertical Integration of MM-wave MMIC's and MEMS Antennas

Youngwoo Kwon, Yong-Kweon Kim, Sanghyo Lee, and Jung-Mu Kim

***Abstract*—In this work, we demonstrate a novel compact mechanical beam steering transmitter based on a direct vertical integration of a 2-D MEMS-based mechanical beam steering antenna with a VCO on a single silicon platform. By eliminating the long feed lines and waveguide metal blocks, the radiation pattern has been improved vastly, resulting in an almost ideal pattern at every scan angle. The losses incurred by the feed lines and phase shifters are also eliminated, which allows the transmitter to be implemented using only a single VCO. The system complexity has been greatly reduced with a total module size of only 1.5 cm x 1.5 cm x 0.4 cm. This work demonstrates that RF MEMS can be a key enabling technology for high-level integration.**

***Index Terms*—Beam steering, micromachining, VCO, transmitters, V-band**

I. INTRODUCTION

There has been an increasing need for high-frequency beam-steering antennas for various applications such as picocellular communication systems and high-resolution sensors at millimeter-wave frequencies. Phased-array antennas are generally used to direct an antenna beam into a desired direction by introducing electrical phase differences between antenna elements [1, 2]. For the conventional phased array antenna, however, the antenna gain reduces when the beam direction is getting away from the broadside of the antenna. In an effort to overcome this drawback, Baek, et al. [3] proposed a 2-D mechanical beam-steering antenna fabricated using MEMS technology. This V-band antenna is implemented on the polymer platform, which is capable of rotation with two degrees of freedom so that the beam can be steered to any desired directions. However, the measured antenna pattern may show noticeable distortion in the beam shape at a certain steering directions. This is due to the parasitic radiation from the long feeding lines, which were required to bring the signals to antennas from the mm-wave power sources, located apart from the MEMS antennas. Additionally, this antenna module was based on bulky waveguides, and the surrounding metal blocks caused parasitic reflections.

In this work, we designed a V-band VCO MMIC using 0.15-μm GaAs pHEMT technology and implemented a V-band beam steering transmitter module in a planar form using system-on-package (SOP) concept. It is based on a new concept of vertical integration of an MMIC on MEMS antennas. This results in a single-platform mechanical beam steering transmitter, and shows very clean radiation patterns at every scan angle without any distortion effects due to feed lines. Also, the elimination of feed lines and phase shifters allows the whole transmitting system to be implemented without power amplifiers.

II. DESIGN AND MEASUREMENTS

1. V-band VCO Using 0.15-um GaAs pHEMT Techonology

The circuit schematic of the V-band VCO is shown in Fig. 1. It is based on common-source FET (CS-FET)

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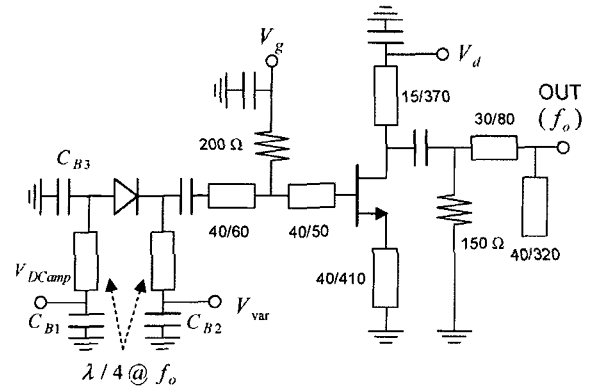

Fig. 1. Schematic of a V-band VCO. Microstrip line dimensions are represented in terms of width/length in um.

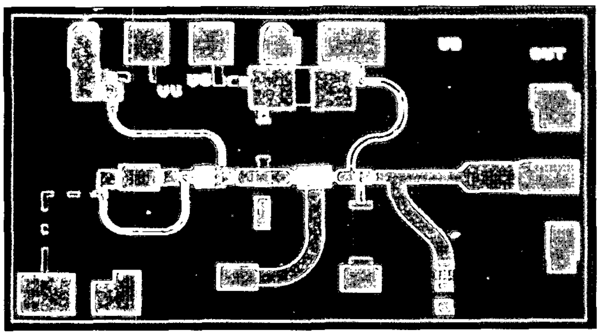

Fig. 2. Photograph of a V-band VCO MMIC. (chip size = 1.45 mm x 0.85 mm)

with series feedback to generate negative resistance, which shows good phase noise performance at mm-wave frequencies [4, 5]. The source series feedback consists of a simple transmission line a little longer than quarter-wave length, providing the capacitive feedback. The parasitic inductance of the via-hole (~30 pH in our case) was also included in the determination of this transmission line length. The resonance circuit at the gate terminal, consisting of transmission lines and varactors, determines the oscillation frequency f_0. The varactor diode is implemented with the gate Schottky contact of the drain-source connected HEMT. The output matching circuit was designed so that the maximum oscillation power could be delivered to the load. The HEMT and varactor diode used in the VCO are 100 μm wide and 80 μm wide, respectively, with the gate length of 0.15 μm. Simulation shows the varactor diode provides a 1:2.5 capacitance variation according to the control voltage, allowing about 10% oscillation range around 60 GHz. The anode and cathode of the varactor diode are biased independently by V_{DCamp} and V_{VAR} as shown in Fig. 1.

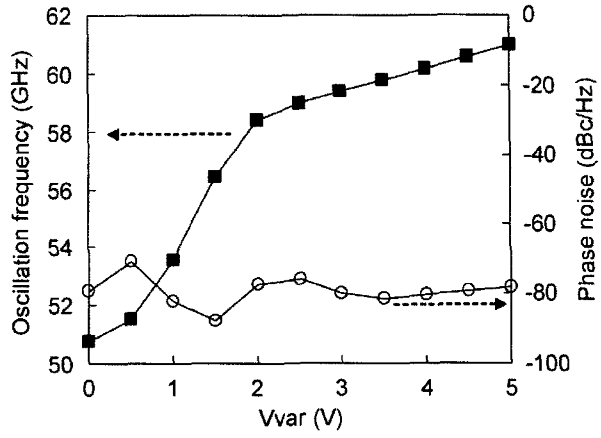

Fig. 3. Measured VCO performance according to the varactor bias: oscillation frequency and phase noise at 1 MHz offset.

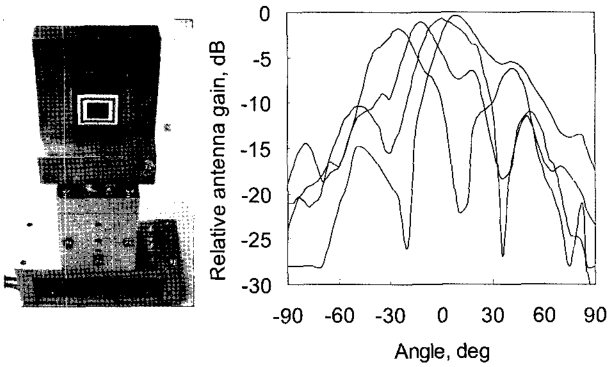

Fig. 4. Photographs and radiation patterns of a waveguide-based V-band 2-D mechanical beam-steering transmitter module.

The designed V-band VCO MMIC was fabricated using a 0.15-μm commercial GaAs pHEMT process (f_t = 90 GHz and f_{max} = 160 GHz, 100-μm-thick substrate). The photograph of the fabricated V-band VCO MMIC is presented in Fig. 2. The chip size is as small as 1.45 mm × 0.85 mm.

Fig. 3 shows the measured VCO performance according to the varactor bias V_{VAR} at a fixed bias condition of V_g = -0.4 V and V_d = 1.5 V (I_d = 28 mA). The free-running oscillation frequency was varied from 50.78 to 60.98 GHz according to V_{VAR} from 0 to 5 V. The phase noise of the free-running oscillator was also measured at 1 MHz offset, which shows the best phase noise performance of -87.7 dBc/Hz.

2. V-band Single-Platform Mechanically Beam Steerable Transmitter

The 2-D mechanical beam-steering antenna module proposed in [3] is based on waveguides and thus requires a waveguide-to-microstrip transition as well as waveguide-based RF signal module. This makes the system bulky and heavy as shown in Fig. 4. Another drawback of this waveguide structure is that the metal jig block perturbs the radiation because the plane of the patch antenna is located much lower than the top plane of the waveguide surroundings. Additionally, when the mechanical antenna is actuated, the moving plate faces the side wall of the metal jig block at a certain angles of rotation. As shown in Fig. 4, the radiation patterns at steered angles are seriously distorted due to this reason.

To overcome these drawbacks, a single-platform 2-D movable antenna concept is devised, in which V-band MMIC chips are mounted on the antenna plate directly as shown in Fig. 5. In this way, waveguide-based signal sources and connections are not needed, and the whole system can be implemented on a single silicon platform without a need for a metal jig block or a PCB plate. Therefore, unwanted reflections and interferences due to jig blocks can be avoided. Also, the losses due to the feed lines and phase shifters can be eliminated, thereby negating the need for a power amplifier.

Fig. 5 shows the detailed schematic of the proposed direct-feeding 2-D beam-steering transmitter module on a single-platform. The bottom silicon plate serves as a substrate of the module as well as a rotating plate of the 2-D mechanically beam steering antenna. The hinges and the antennas are implemented on BCB for flexibility and low loss.

A single VCO MMIC is directly placed on the bottom metal by selectively removing the BCB underneath the chip, creating a tub for the IC. Planarity is guaranteed in this way. Four bias lines to feed the VCO pass along the edges of moving frames and hinges. No unwanted radiation or interference is expected even at the hinges since only DC signals flow through the bias lines. Fig. 6 is the photograph of the fabricated direct-feeding single-platform MEMS-based V-band transmitter module. The module is extremely compact in size, measuring only 1.5 cm x 1.5 cm x 0.4 cm including all the external bypass capacitors and bias lines.

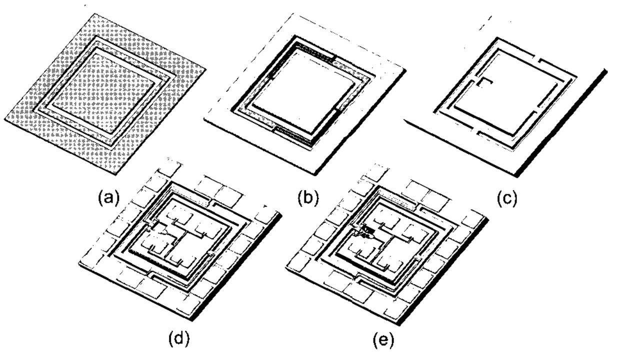

Fig. 5. Schematic views of the direct-feeding single-platform V-band transmitter module in the order of material accumulation from bottom. (a) Silicon frame, (b) bottom metal pattern, (c) BCB substrate pattern, (d) top metal pattern and (e) mounted VCO MMIC.

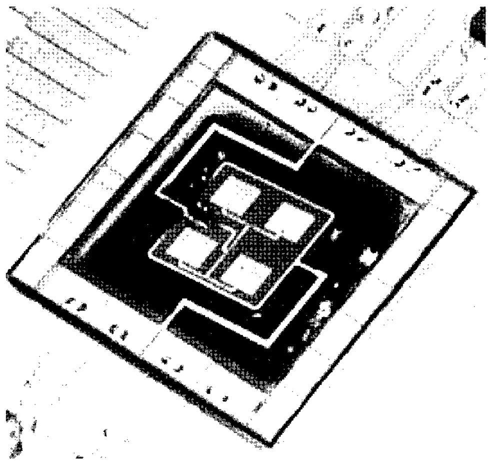

Fig. 6. Photograph of the direct-fed single-platform V-band transmitter module. (module size = 1.5 cm x 1.5 cm x 0.4 cm)

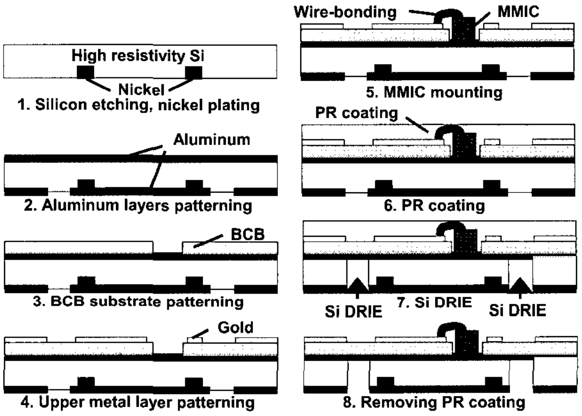

Fig. 7. Fabrication process of the direct-feeding single-platform V-band transmitter module.

The fabrication process of the module follows that of the 2-D mechanical beam steering antennas [3] with modifications to accommodate the vertical integration steps. The fabrication process flow is shown in Fig. 7. The first step is the aluminum layer patterning on both sides of a silicon wafer. The backside aluminum layer is to form a silicon etch pattern (release step) and the front-side one is to form a etch stop pattern in the final silicon etch step. After the top metal is electroplated on the BCB substrate, the wafer is diced to be divided into several unit transmitter module bodies. Then, a MMIC is mounted on the diced MEMS antenna chip. Next, the mounted MMIC is coated with a photoresist in order to protect MMIC against chemical attack of aluminum etchant. Finally, the aluminum layer on the front side of silicon is removed using aluminum etchant (PAN solution) after the backside silicon etch step, and the coated photoresist is also removed using acetone.

Fig. 8 shows the measured radiation patterns of the fabricated direct-feeding single-platform V-band transmitter module. As expected, the radiation pattern is extremely clean far better than that available from the external-feeding transmitter shown in Fig. 4. When the moving plate rotates along the vertical-direction hinges, the scan angle was about -18° ~+18°. Due to the weak driving capability of the magnet on the reverse side of the module, just 5 H-plane radiation patterns are measured at -18°, -9°, 0°, +9° and +18° scan angles as shown in Fig. 8(a). We can simply extend the scan angle range by narrowing the hinge width. When the moving plate rotates along the horizontal-direction hinges, the scan angle was about -9° ~+9°. The reduced scan angle was due to the smaller rotational radius of moving plate at the horizontal direction, which requires much higher torque. Fig. 8(b) shows the E-plane radiation patterns measured at -9°, 0° and +9°. The measured pattern shows that the antenna gain is almost identical at every steered angle. The variations of antenna gain are just 0.4 dB and 0.2 dB for each rotation along the vertical and horizontal axis, respectively. The uniform HPBW and the bisymmetry of the beam shape verify our design approach.

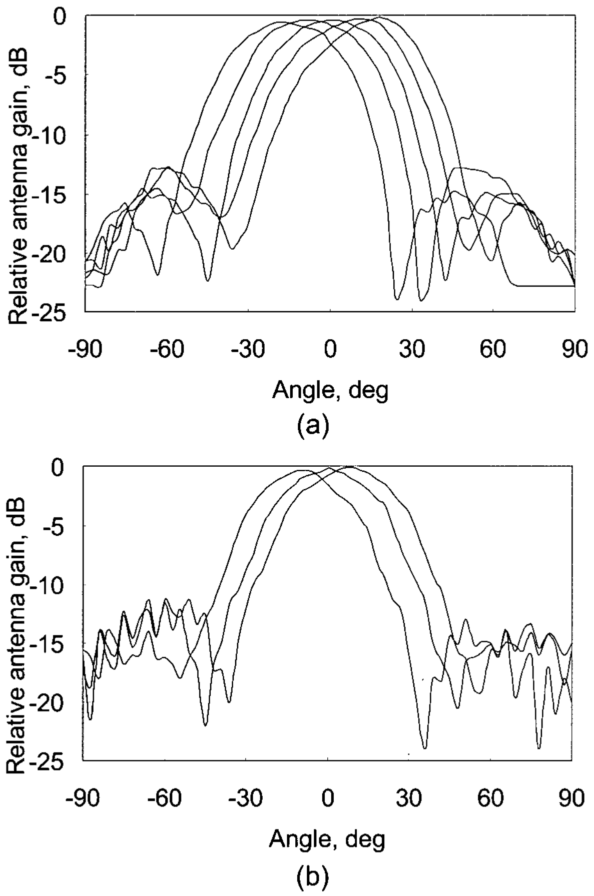

Fig. 8. Measured radiation patterns of direct-feeding single-platform V-band transmitter module when the moving plate rotates along (a) the vertical axis and (b) the horizontal axis.

III. CONCLUSIONS

In this paper, a novel mechanical beam-steering V-band transmitter based on a single silicon platform has been designed and fabricated in order to improve the radiation patterns and reduce the system complexity. This module has a small size of 1.5 cm x 1.5 cm x 0.4 cm and showed almost ideal radiation patterns. The system complexity has been vastly reduced by eliminating the need for phase shifters, beam forming network, feed lines and, most importantly, power amplifiers. This work demonstrates successful vertical integration of MMIC's on MEMS components used as a platform, and shows its clear advantage at mm-wave frequencies.

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REFERENCES

[1] R. J. Mailoux, *Phased Array Antenna Handbook.* MA: Artech House, 1994.

[2] R. C. Johnson, *Antenna Engineering Handbook*. New York: McGraw-Hill, 1993.

[3] C. W. Baek, S. Song, J. H. Park, S. Lee, J. M. Kim, W. Choi, C. Cheon, Y. K. Kim and Y. Kwon, "A V-band micromachined 2-D beam-steering antenna driven by magnetic force with polymer-based hinges," *IEEE Trans. Microwave Theory & Tech.*, vol. 51, no. 1, pp. 325-331, Jan. 2003.

[4] P. J. Garner, M. J. Howes, and C. M. Snowden, "Ka-band and MMIC pHEMT-based VCOs with low phase-noise properties," *IEEE Trans. Microwave Theory & Tech.*, vol. 46, no. 10, pp. 1531-1536, Oct. 1998.

[5] B. Piernas, K. Nishikawa, T. Nakagawa, and K. Araki, "A compact and low-phase-noise Ka-Band pHEMT-based VCO," *IEEE Trans. Microwave Theory & Tech.*, vol. 51, no. 3, pp. 778-783, Mar. 2003.

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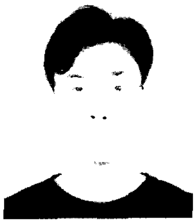

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