A V-Band Micromachined 2-D Beam-Steering Antenna Driven by Magnetic Force With Polymer-Based Hinges

Chang-Wook Baek, *Member, IEEE*, Seunghyun Song, *Member, IEEE*, Jae-Hyoung Park, *Member, IEEE*, Sanghyo Lee, Jung-Mu Kim, Wooyeol Choi, Changyul Cheon, *Member, IEEE*, Yong-Kweon Kim, *Member, IEEE*, and Youngwoo Kwon, *Member, IEEE*

***Abstract*—This paper presents a new type of antenna fabricated by micromachining technology for mechanical beam steering with two degrees of freedom of motion. A V-band two-dimensional mechanical beam-steering antenna was designed and fabricated on a single high-resistivity silicon substrate using microelectromechanical systems technologies. A fabricated antenna is driven by magnetic force to overcome the limit of electrostatic actuation, and a polymer-based hinge structure is used to increase the maximum scanning angle to as much as 40°. Simulation result for validating the mechanical beam-steering concept is presented. In addition, mechanical properties such as static actuation angles are investigated together with microwave properties such as the return loss and radiation pattern at the V-band.**

***Index Terms*—Beam-steering antenna, microelectromechanical systems (MEMS), micromachining.**

I. Introduction

THERE HAS been an increasing need for high-frequency smart antennas for various applications such as picocellular communication systems and high-resolution sensors at millimeter-wave frequencies. For this kind of system, both beam-forming and beam-steering functionalities are required. Phased-array antennas are generally used to direct a beam into the desired direction by imposing electrical phase differences between the antenna elements [1], [2]. Although this electronic scanning antenna offers fast scan speed, it requires many phase-shifter circuits, which are expensive in millimeter-wave frequencies. Moreover, radiation efficiency of the phased-array antenna decreases when the beam is directed far away from the broadside of the antenna because only the array factor can be controlled by phase changes, while the radiation pattern of the array antenna depends not only on the array factor, but also on the element factor, which is not constant in all beam directions. A switched beam antenna may be another alternative, but it requires many antennas with pre-fixed beam directions.

A more efficient way to increase the performance of the array antenna is to rotate each antenna element "mechanically" in the desired beam direction. The array antenna using a mechanical scanning antenna unit has advantages in both controlling the beam direction and reducing the cost. It allows constant gain in most of the beam directions by adjusting the mechanical angle of the individual antenna element. Another useful feature of this antenna is that beam focusing in the near-field space would be possible if the individual antenna elements of array system were rotated to point to one spot. This is useful for quasi-optical signal transmission, especially at millimeter-wave frequencies, where the loss of the transmission lines cannot be neglected. It is also very useful for high-resolution millimeter-wave imaging.

Recent development of the microelectromechanical systems (MEMS) technology makes it possible to fabricate the microwave passive devices with low cost by a batch fabrication process. A MEMS device allows reduction of the feature size of the structure so that it can become compatible with the antenna system at high frequencies. It can also provide fast mechanical actuation capability and low-power consumption, which give better flexibility for mechanical scanning. Several approaches to enhance the performance of the antenna using MEMS have been reported. Chauvel *et al.* [3] showed a microstrip patch antenna on the micromachined quartz plate supported by a torsional hinge and driven by electrostatic force, giving one-dimensional spatial scanning capability. However, relatively large voltage (~200 V) is required to actuate the structure due to the inherent limit in the electrostatic driving mechanism, which is not a good choice for obtaining a large static scanning angle. Chiao *et al.* [4] showed a Vee antenna with a movable arm driven by a scratch drive actuator (SDA), having beam-shaping and beam-steering functions, but it requires a multilayer polysilicon process for the structure and further post-processing for metallization. Moreover, all these micromachined "movable" antennas have thus far been limited to one-dimensional movement.

The authors proposed a V-band micromechanical beam-steering antenna with two degrees of freedom of motion in [5]. In [5], a microstrip patch antenna was formed on the polymer dielectric platform supported by a silicon structure frame and glass substrate. It requires various complex processes such as glass micromachining, anodic bonding, and chemical–mechanical polishing, making the total process excessively difficult and, thus, reducing the yield. In addition, only a small scanning angle (<7°) could be realized due to the stiffness of silicon-based hinges. In this study, a single

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The authors are with the Center for Three-Dimensional Millimeter-Wave Integrated Systems, School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea (e-mail: baekrose@chollian.net).

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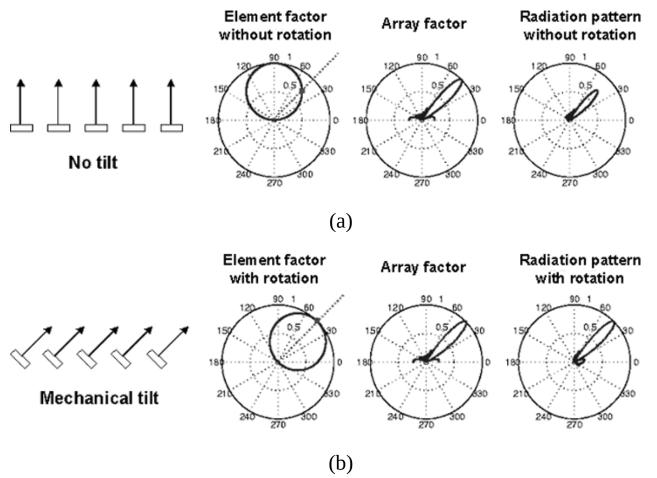


Fig. 1. Simulation results of the element factor, array factor, and radiation pattern when: (a) the antenna elements are fixed and (b) when the antenna elements are mechanically rotated to 45°.

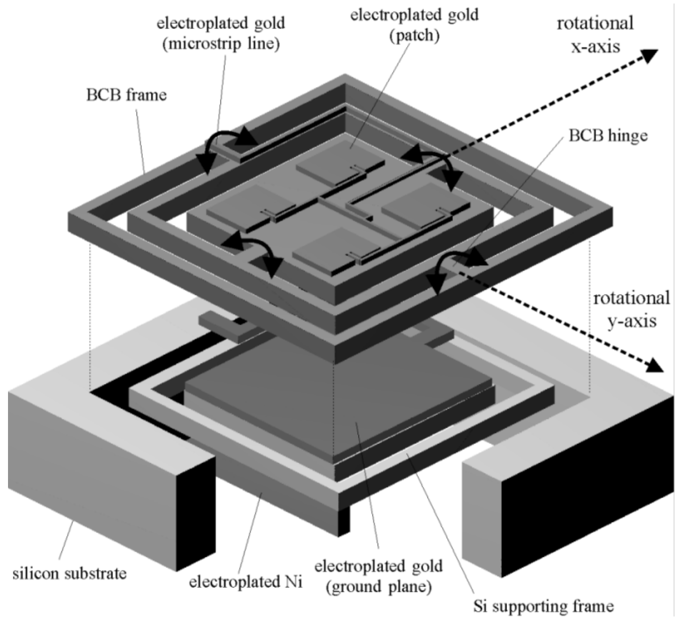


Fig. 2. Schematic view of the 2-D beam-steering antenna.

high-resistivity silicon wafer was used to simplify the process steps while minimizing the substrate losses, and more flexible polymer-based hinge structures were realized by selective removal of the silicon under the polymer to increase the scanning angle of the structure (>30°). Actuation capability by magnetic forces has also been added to avoid the problems of electrostatic actuation. Electrical performance of the beam-steering antenna with a supporting frame and hinges are presented together with the mechanical properties of the antennas. Details of the new fabrication processes to realize the whole antennas on a single silicon frame are also presented.

II. Mechanical Beam-Steering Antenna

In order to verify the effect of mechanical rotation of the antenna elements in the array antenna, simulation has been performed for the case of ten infinitesimal dipole arrays spaced by a half-wavelength. Fig. 1(a) shows the result for the case of conventional fixed planar array. It is clear that the element factor is reduced by 10 dB at 45° compared to the broadside direction (0°), which results in a 10-dB reduction in the total array gain. On the other hand, when the antenna element rotates mechanically by 45°, the element factor also rotates to the same direction, and no loss in overall gain is expected, as shown in Fig. 1(b).

Based upon the theory, we designed a mechanical beam-steering antenna with two degrees of freedom of motion working at the V-band, centered at 60 GHz. The schematic view of the proposed antenna is shown in Fig. 2. High-resistivity silicon is used as an actuating plate on which the microstrip patch antenna is implemented. The actuating plate is located at the center of the whole structure and rotates around the two torsional hinge pairs, and various types of antennas including the microstrip antenna can be placed on this plate. As a substrate material for antennas, low-loss dielectric material is required between the ground and microstrip patch. It should be selected not only by the microwave properties, but also by mechanical considerations such as stiffness and stress. Mechanical property of the dielectric material is especially important in this work since it is also used as a torsional hinge. Polymer material is useful for this purpose because of its flexibility, good durability, and shock resistance [6]. Considering these requirements, we used a benzocyclobutene (BCB), a kind of silicon-containing polymer, as a dielectric material. BCB has good microwave properties such as low dielectric constant ($\varepsilon_r = 2.65$ up to 20 GHz) and low loss tangent ($\delta = 0.0055$ at 20 GHz), as well as a low elastic modulus ($E = 2.9 \pm 0.2$ GPa), which is helpful in obtaining large rotating angles with low driving forces. In our new design, silicon under the hinge part was selectively removed, leaving only BCB as a hinge material in order to maximize the scan angle.

As a driving mechanism, magnetic actuation is used instead of the electrostatic actuation. In the latter case, a very small gap between the electrodes is required to generate a large electrostatic force and, thus, to reduce the driving voltage. However, small gap limits maximum rotating angle. Moreover, the maximum controllable actuation angle is limited to 1/3 of the gap due to the electrostatic property, which further limits its use for practical rotating antennas. In our study, magnetic material is formed on the backside of the structure for the actuation. If the magnetic field is applied vertically to the plate at the region where the magnetic material is located, magnetic force is generated, downward for this case, and the plate can rotate around the torsional hinges. For this purpose, magnetic materials ("nickel") are placed on the edges of both the center plate and outer frame to independently control the motion to both directions. Since magnetic driving has no theoretical limit of actuation angle, unlike the case of an electrostatic mechanism, we can obtain a much larger scan angle if the hinges can mechanically sustain the torque. Also, if we use a solenoid coil as a magnetic field source, the magnetic force can be controlled by applying the electric signal, which means the tilting angle of the antenna can be controlled electrically as in the electrostatic case. Thus, rotation can be fast enough to be used in the practical beam-scanning systems.

Since the beamwidth of a single microstrip patch antenna was not narrow enough to demonstrate the effect of the beam-steering antenna, a 2×2 microstrip patch array is used as an antenna on the rotating platform. Two types of elementary patch antennas were designed. The first one is the conventional rectangular patch antenna with notches at the feed point, as shown in Fig. 2. The other one is the broad-band patch antenna with improved bandwidth. Parasitic patches were employed in the planar form to increase the bandwidth. Full-wave simulation using a commercial electromagnetic (EM) simulator, IE3D, showed that the directivity of the antenna increases from 7.17 dB for a single patch to 13.96 dB for the 2×2 array. Both types of antennas showed similar gain and directivity, while the bandwidth (defined as the bandwidth showing better than 10-dB return loss) increased from 0.75 to 1.55 GHz. The radiation patterns of the antenna are also simulated and the 3-dB beamwidth is estimated to be approximately 38.4° for narrow-band design and 29.4° for broad-band patch design. The concept of beam rotation by mechanical rotation of the antennas has been verified with the 4-GHz scale-up models, as shown in [5].

III. Fabrication

For the fabrication of a mechanical beam-steering antenna, a hybrid process combining bulk micromachining with surface micromachining was used. Instead of using both glass and silicon wafers as the mechanical platform [5], we have simplified the process by using double-side polished high-resistivity silicon wafers as the only substrate material. Thickness of the wafer is approximately 430 μm and the resistivity of silicon is 20 k$\Omega \cdot$ cm.

The fabrication process flow is shown in Fig. 3. The process begins with the growth of 5000-Å-thick LPCVD nitride on both sides of the silicon wafer as a wet etching mask of silicon. After patterning and nitride etching backside of the wafer, silicon bulk etching is performed in a 30-wt% potassium hydroxide (KOH) solution at 80°C to define the moving space of the antenna plate. Depth of the etched groove is controlled to 300 μm to remain the 130-μm-thick silicon plate for polymer support. After stripping the nitride mask, a Cr/Au (100/1000 Å) layer is evaporated on the front side as an electroplating seed layer, and a thick photoresist (AZ P4620) is coated and developed for an electroplating mold. A 3-μm-thick gold layer is deposited using a commercial noncyanide gold-plating solution to define the ground plane. After etching of the unnecessary seed layer, narrow mesh structures of 20-μm wide are patterned and silicon is etched by plasma etching to form a 10-μm-deep shallow groove. This groove is necessary to prevent the detachment of the subsequent polymer structure from the silicon substrate due to the high stress caused by the electroplated gold and cured polymer.

In the next step, BCB (CYCLOTENE 4026-46, Dow Chemical Company, Midland, MI) is spin-coated on the silicon at 700 r/min and soft-cured at 210°C for 40 min as a dielectric polymer platform material. Thickness of the BCB film is approximately 40 μm after curing. Another Cr/Au layer is evaporated on the BCB surface at 150°C and a photoresist mold is

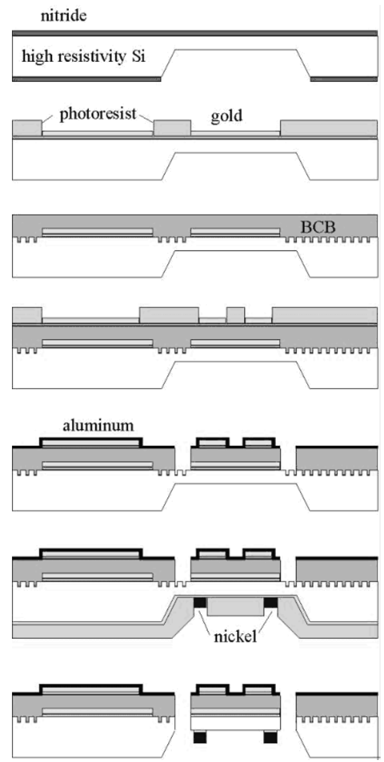
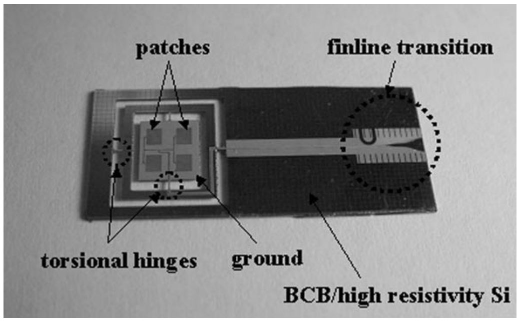


Fig. 3. Fabrication process flow.

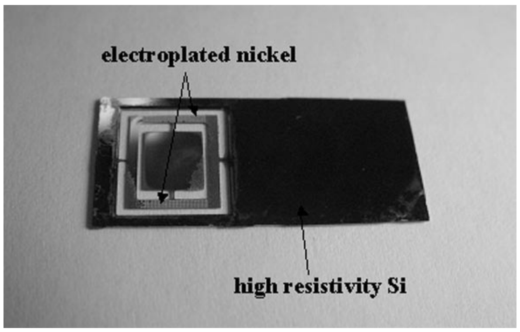
formed for the second electroplating. A 3-μm-thick gold is electroplated again to define the microstrip patch antenna and excitation/measurement structure. For patterning of the polymer platform shape, a Cr/Al (100/5000 Å) layer is deposited and patterned by photolithography and wet etching. Using this layer as a dry etch mask, BCB film is anisotropically etched by reactive ion etching (RIE) using a $O_2/SF_6 = 9:1$ gas mixture. RIE is performed at low pressure below 100 mtorr and plasma power of 150 W to enhance the sidewall profile. Etch rate of the BCB under this condition is 0.4 μm/min.

For the magnetic actuation of the structure, magnetic material should be formed on the backside edge of the antenna plate and outer frame. Cr/Au is evaporated on the exposed silicon surface of the backside and nickel is electroplated to 40-μm thickness. After removing the mold and seed layer, the whole structure is released using deep reactive ion etching (DRIE) equipment. Instead of the conventional vertical etching recipe, a modified isotropic etching condition is used. Since the antenna plate and outer frame are much larger than the hinges, we can selectively remove the silicon under the relatively narrower hinge structure. Structural degradation during the etch process could be avoided since the etch selectivity of silicon to the Al mask and BCB structure was very high. After releasing, an Al/Cr layer on the structure is removed by plasma etching.

Fig. 4 shows the photographs of the fabricated beam-steering antenna after dicing. In this case, an antipodal finline structure is integrated with the antenna for the measurement of the beam pattern. Size of the sample is 1.5×3.5 cm^2, and the large antenna plate is successfully released without deformation. Length and width of the torsional hinge was designed to 1 mm and 150 μm, respectively. SEM photographs of Fig. 5 show that the



(a)



(b)

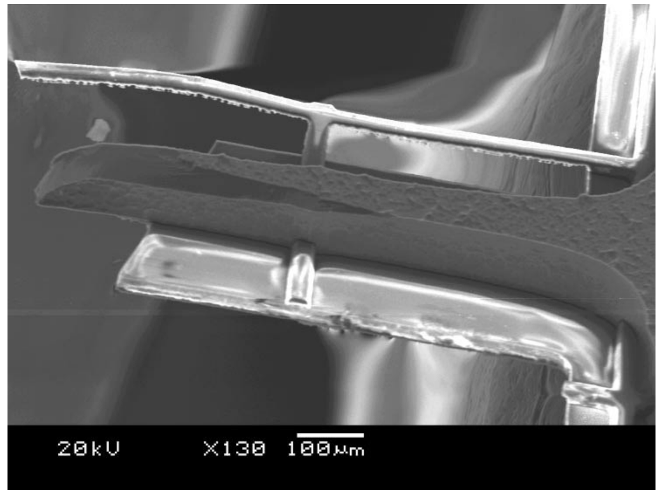
Fig. 4. Photographs of the fabricated antenna samples. (a) Frontside. (b) Backside.

silicon under the hinge is completely removed after the structure is fully released.

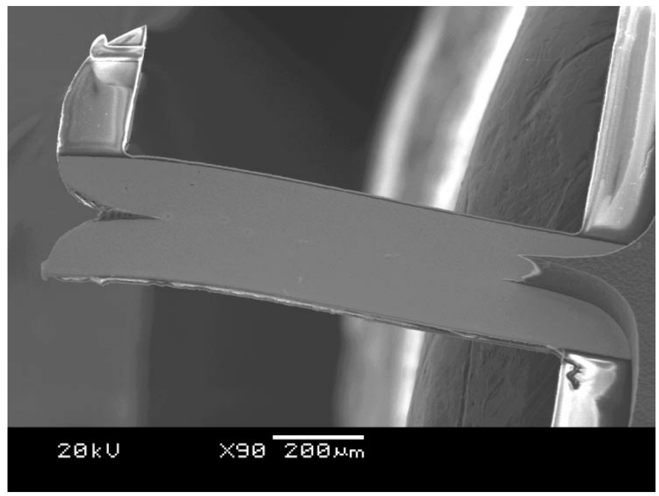
IV. Results

A. Actuation Test

An actuation test of the fabricated antenna has been performed. A simple off-the-shelf solenoid coil without any magnetic core was used for experimental purposes. The coil has an inner diameter of 6.0 mm, an outer diameter of 15.2 mm, and a thickness of 3.2 mm. The number of turns of the coil is 1000 and its resistance is measured to be 63 Ω. This relatively large coil was used to apply an uniform magnetic field to the electroplated nickel array considering the total size of the nickel array of 6 mm $\times$ 0.7 mm. The coil was mounted and wire bonded to the current pad on the PCB board, which was placed underneath the antenna plate. Center of the outer frame of the antenna was placed 2 mm away from the top-surface center of the coil, and the maximum current up to 0.7 A was applied to the solenoid. Through optimization of solenoid coils and core materials, and using better magnetic materials on the backside of the plate such as NiFe, which can also be electrodeposited, the total power consumption of the actuator can be radically reduced. The produced magnetic field was linearly proportional to the input current, and the magnetic field applied to the electroplated nickel was measured to be approximately 38 000 A/m when the current was 0.7 A. Fig. 6 shows the charge-coupled device (CCD)-captured photographs of the rotated structure when the outer frame was rotated statically approximately 0°, 10°, and 20°, respectively. The expected scan angle was calculated from the balancing equation of the magnetic and mechanical torque with the theoretical magnetization curve for nickel [7]. The simulated and measured scan angle as a function of the applied magnetic field is shown in Fig. 7. It is seen that the measured scan angle is larger than the calculated value at a higher magnetic field. It is attributed to the effect of the leakage magnetic field acting on another magnetic material pair formed on the inner plate for two-dimensional (2-D) actuation. Optimization of the driving coil and the use of the experimental magnetization curve can increase the accuracy of the simulation result.



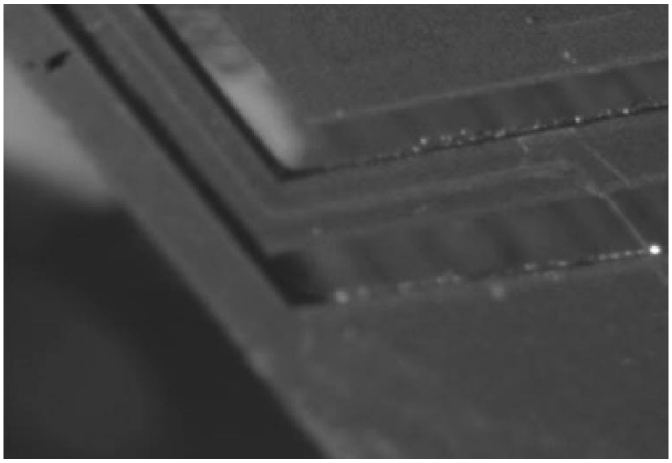
(a)



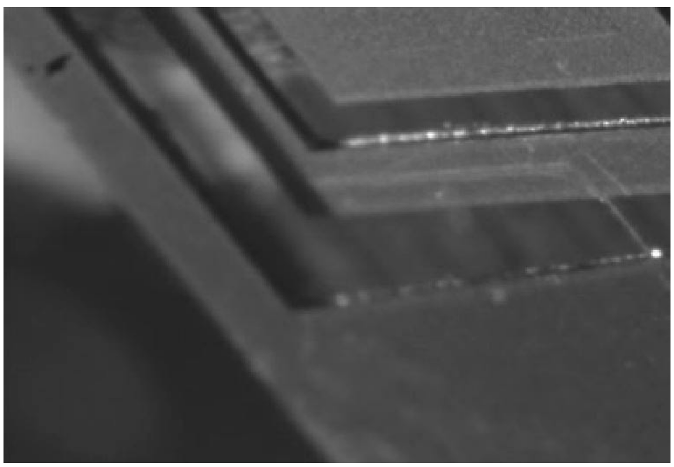
(b)

Fig. 5. SEM photographs of the backside of hinge part after breaking the hinges. (a) Silicon remains under the hinge. (b) Silicon is completely removed after release process is completed.

In this experiment, the scan angle by magnetic actuation was limited from $-20°$ to 20° due to the maximum current capability of the solenoid. In order to determine the failure point, more mechanical load was applied to the structure, and the hinge failure was observed at the rotation angle of approximately 40°. Actuation speed for the applied step input current was also measured using a position-sensitive photodiode. Rising time of the antenna was measured to be as fast as 10 ms, but the settling time to reach the steady state was larger due to the large mass and low spring constant of the fabricated antenna.



(a)



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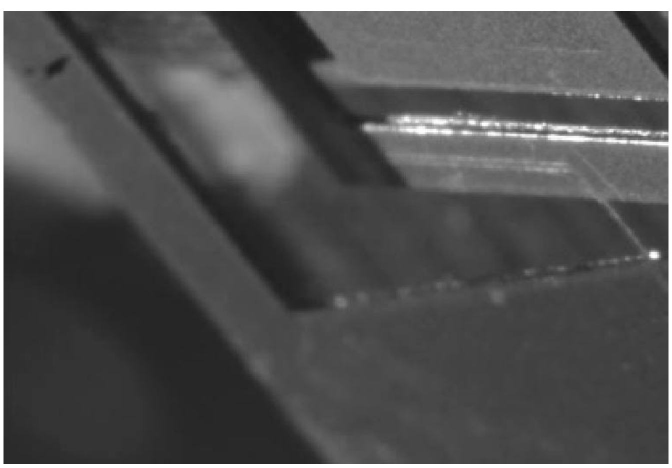

(c)

Fig. 6. CCD-captured photographs of the fabricated antenna when the outer frame is rotated to: (a) 0°, (b) 10°, and (c) 20°.

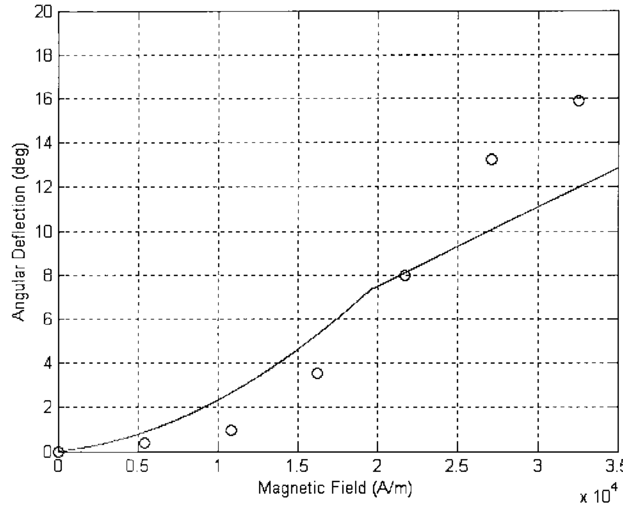

Fig. 7. Simulated and measured static scan angle as a function of the applied magnetic field.

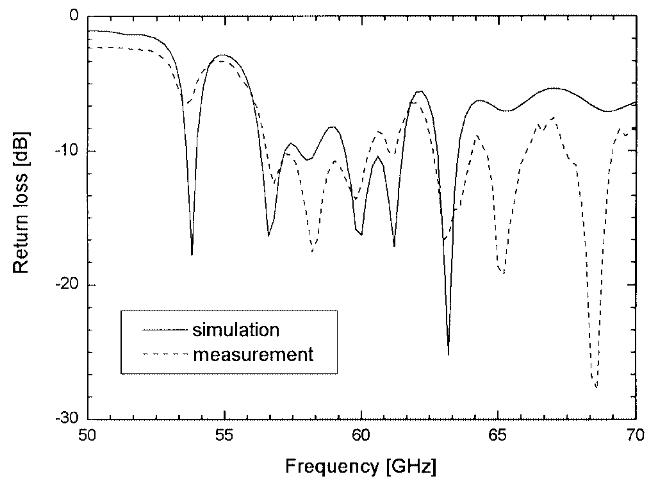

Fig. 8. Simulated and measured return loss of the fabricated antenna.

B. Microwave Properties

Tests have been made to characterize the microwave properties of the fabricated beam-steering antenna structure. The S-parameters of the antenna were measured using an HP 8510XF network analyzer. For on-wafer measurement of the return loss, a microstrip-to-coplanar waveguide (CPW) transition for the V-band was designed and integrated with the antenna. Measured return loss of the transition is better than −17 dB from 50 to 70 GHz. Simulated and measured S-parameters of the 2-D mechanical beam-steering antenna with a broad-band elementary patch design are shown in Fig. 8. Return loss is measured to be approximately 14 dB at 60 GHz, and broad-band characteristics are observed.

The far-field radiation pattern of the fabricated antenna was also measured using the experimental setup shown in Fig. 9. For the beam pattern measurement, a finline transition structure was designed and fabricated with the antenna to perform waveguide-to-microstrip mode conversion. The mechanically tunable Gunn diode source was used as a power source at the V-band. It transmits the power to the antenna element through WR15 waveguide and finline transitions. The fabricated antenna was diced and inserted into the waveguide, forming a transmitting unit at the V-band. This transmitting unit is mounted on the personal computer (PC) controlled rotational stage. Radiated power from the antenna is received by a standard horn antenna, and the received signal is detected by the spectrum analyzer through the harmonic mixer. The receiving horn antenna is mounted on the micro XYZ stage, which enables alignment

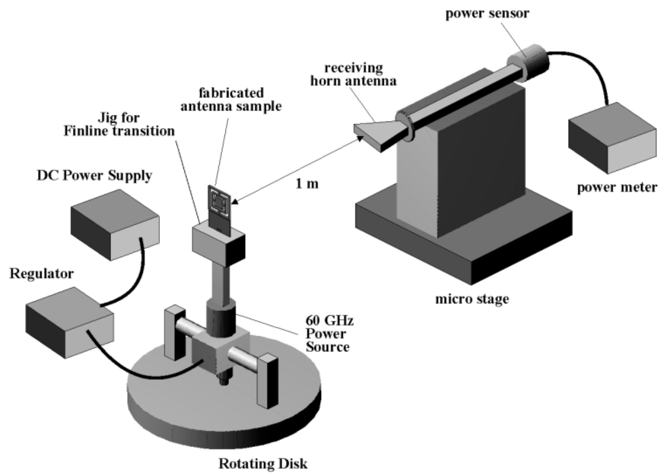

Fig. 9. Schematic view of the experimental setup for the measurement of the radiation pattern.

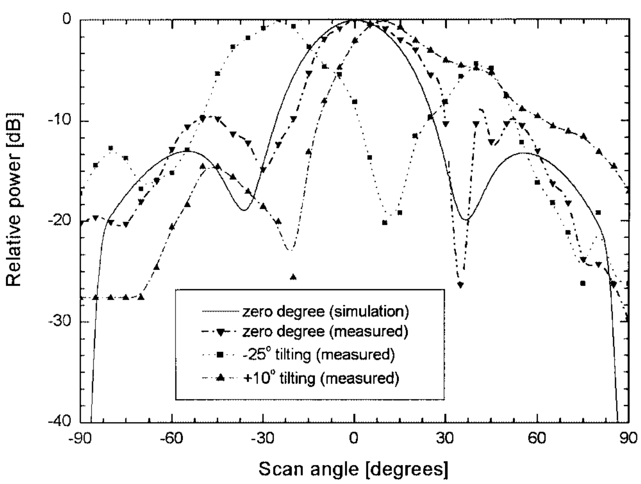

Fig. 10. Measured radiation pattern of the fabricated antenna.

of transmitting and receiving antennas. The distance between transmitting and receiving antenna was set to 1 m, considering the Fraunhoffer region.

Fig. 10 shows the measured radiation patterns when the antenna structure is rotated by magnetic force to -25°, 0°, and $+10^\circ$, respectively. The elementary patch is the broad-band patch type previously described. Pattern shifts according to the rotation of the structure are clearly shown in this figure. The simulated radiation pattern when the patch is at a 0° angle is also compared in Fig. 10. Good agreement is found between the measured and simulated radiation patterns. The radiation pattern is more or less symmetric in the unrotated state. However, as the antennas are rotated, the radiation pattern becomes asymmetric, which is believed to be caused by several reasons such as the interference of the patterns with the surrounding frame structure, and parasitic reflection from the measurement apparatus mounted on the backside of the sample, e.g., the big chunk of driving coils.

V. Conclusions

A magnetically driven polymer-hinged 2-D mechanical beam-steering antenna has been proposed and successfully realized at the V-band using micromachining techniques for the first time. A BCB hinge was used to increase the mechanical scan angle, and the process for the selective removing of silicon at the hinge was developed. EM simulation has been performed on the mechanical beam-steering antenna element including the supporting frame and hinges. The simulation results show that the gain in off-the-broadside direction is maintained to the same value in the broadside direction using mechanical beam rotation. Using a flexible BCB hinge, a static actuation angle up to 20° was obtained by an external magnetic field, and the maximum angle without hinge failure was observed to be 40°, which validates the advantage of polymer hinges for a larger scan angle. Microwave measurements at the V-band showed that the measured result was in good agreement with the simulation. The 2-D movable MEMS antennas of this study can be a promising choice of antennas to realize low-cost electrical/mechanical phased-array antenna systems.

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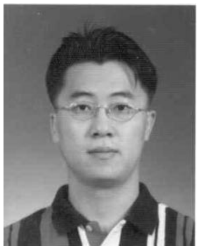
Chang-Wook Baek (S'94–M'95) was born in Korea, in November 1970. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1993, 1995, and 2000 respectively.

In March 2000, he joined the Inter-University Semiconductor Research Center (ISRC), Seoul National University, as a Post-Doctoral Researcher. He also joined the Center for Three-Dimensional Millimeter-Wave Integrated Systems, Seoul National University, as a Member of Research Staff, where he is involved with the development of micromachined millimeter-wave devices. Since March 2002, he has been a Research Assistant Professor with the School of Electrical Engineering and Computer Science, Seoul National University. His current research interests are focused on microelectromechanical/nanoelectromechanical systems (MEMS/NEMS), including the electroplating microfabrication process, material characterization in microscale/nanoscale, and RF/millimeter-wave MEMS devices.

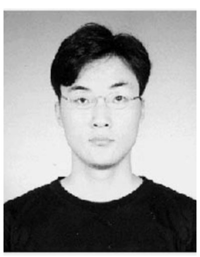
Seunghyun Song (S'98–M'02) was born in Seoul, Korea, on Nov. 22, 1970. He received the B.S. and M.S. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1994 and 1996, respectively, and is currently working toward the Ph.D. degree at the Seoul National University.

Since September 2001, he has been with Samsung Electronics, Suwon, Korea. His research concerns the numerical modeling of passive microwave devices (transmission lines, antennas, filters, etc.) and signal integrity at high-speed integrated circuits.



Jae-Hyoung Park (M'02) was born in Korea, in 1975. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1997, 1999, and 2002, respectively.

He is currently a Post-Doctoral Researcher with the Inter-University Semiconductor Research Center (ISRC), Seoul National University. He is also a Member of Research Staff, where he is involved with the development of micromachined millimeter-wave device with the Center for Three-Dimensional Millimeter-Wave Integrated Systems, Seoul National University. From 1997 to 1998, his main research activities were the manipulation of microparticles. Since 1998, his research interests are focused on the design and fabrication of RF/millimeter-wave MEMS devices.



Sanghyo Lee received the B.S. degree in electrical engineering and M.S. degree in electrical engineering and computer science from the Seoul National University, Seoul, Korea, in 2000 and 2002, respectively, and is currently working toward the Ph.D. degree in electrical engineering and computer science at the Seoul National University.

He is currently with the Three-Dimensional Millimeter-Wave Integrated Systems (C3DM) Group, Seoul National University. From 2000 to 2002, his main research activities were active device modeling and RF MEMS device development. His current research interests are mainly focused on the design of RF MEMS devices and the embodiment of three-dimensional (3-D) millimeter-wave beam-steering sub-systems integrated with active monolithic microwave integrated circuits (MMICs).

Jung-Mu Kim received the B.S. degree in electrical engineering from Ajou University, Suwon, Korea, in 2000, the M.S. degree in electrical engineering and computer science from the Seoul National University, Seoul, Korea, in 2002, and is currently working toward the Ph.D. degree in electrical engineering and computer science at the Seoul National University.

He is currently with the RF MEMS Group, Micro Sensors and Actuators (MiSA) Laboratory, Seoul National University. From 2000 to 2002, his main research activities were the surface modification for RF MEMS devices. His current research interests are mainly focused on the design and fabrication of RF MEMS devices, including surface modification and wet-release process.

Wooyeol Choi was born in Korea, in 1979. He received the B.S. degree from Yonsei University, Seoul, Korea, in 2001, and is currently working toward the M.S. degree at the Seoul National University, Seoul, Korea.

His current research activities include the design of spatial power-combining circuits in the millimeter-wave region and RF MEMS.

Changyul Cheon (S'87–M'90) was born in Seoul, Korea, on April 5, 1960. He received the B.S. and M.S. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1983 and 1985, respectively, and the Ph.D. degree in electrical engineering from The University of Michigan at Ann Arbor, in 1992.

From 1992 to 1995, he was with the Department of Electrical Engineering, Kangwon National University, Chuncheon, Korea, where he was an Assistant Professor. He is currently an Associate Professor of electrical engineering with the University of Seoul (UoS), Seoul, Korea, where his group is currently involved with the design and analysis of microwave and millimeter-wave passive device using the finite-element method (FEM), finite-difference time-domain (FDTD), and method of moments (MoM) techniques. He is also interested in designing of packaging and module structures using low-temperature co-fired ceramic (LTCC).

Yong-Kweon Kim (S'90–M'90) received the B.S. and M.S. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1983 and 1985, respectively, and the Dr.Eng. degree from the University of Tokyo, Tokyo, Japan, in 1990. His doctoral dissertation concerned the modeling, design, fabrication, and testing of microlinear actuators in magnetic levitation using high critical temperature superconductors.

In 1990, he joined the Central Research Laboratory, Hitachi Ltd., Tokyo, Japan, as a Researcher, where he was involved with actuators of hard disk drives. In 1992, he joined the Seoul National University, where he is currently an Associate Professor with the School of Electrical Engineering. His current research interests are modeling, design, fabrication, and testing of electric machines, especially MEMS systems, microsensors, and actuators.

Youngwoo Kwon (S'90–M'94) was born in Seoul, Korea, in 1965. He received the B.S. degree in electronics engineering from the Seoul National University, Seoul, Korea, in 1988, and the M.S. and Ph.D. degrees in electrical engineering from The University of Michigan at Ann Arbor, in 1990 and 1994, respectively.

From 1994 to 1996, he was with the Rockwell Science Center, where he was involved in the development of various millimeter-wave monolithic integrated circuits based on high electron-mobility transistors (HEMTs) and HBTs. In 1996, he joined the faculty of the School of Electrical Engineering, Seoul National University. His current research activities include the design of MMICs for mobile communication and millimeter-wave systems, large-signal modeling of microwave transistors, application of micromachining techniques to millimeter-wave systems, nonlinear noise analysis of MMICs, and millimeter-wave power combining.