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Functional microwave flat antenna using alumina ceramic substrate and piezoelectric actuator

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Abstract

We have demonstrated a new-type microstrip patch antenna on a dielectric ceramic substrate with a mechanism of a variable antenna height using a mechatronics technology. The functional microwave flat antenna with an alumina ceramic substrate was controlled by a piezoelectric actuator, and changed the resonant frequencies. We have confirmed a possible variation of the antenna resonant frequency of 96% from 5.4 to 10.6 GHz.

Keywords: Microwave patch antenna; PZT; Actuator

1. Introduction

A service of radio communications systems will become increasingly prominent in microwave and millimeterwave band regions. Microstrip antennas have a flat structure composed of a compact and lightweight substrate, and is used for various radio connections such as satellite broadcasting and local area network (LAN) and is compatible with mobile communications like an airplane, a car, and a cellular phone, etc. Therefore, functional antennas which operate at various frequencies and polarizations of interest and scan beams are desired. Recently, the research of antennas using a microelectromechanical-systems (MEMS) technologies is attracted for a new radio communication tool. MEMS devices are excellent in loss, cost, and power consumption. Until now, circuit devices such as a filter, a switch, and a phase shifter using a MEMS technology have been reported in both microwave and millimeterwave regions.[1] As regarding antennas using MEMS, we can find beam scanning antennas composed of a dipole antenna in which an piezoelectric actuator is used for the movement[2] and a patch antenna in which magnetic mechanism is utilized for the operation.[3] Moreover, there is also a multi-band antenna using a MEMS switch.[4]

We are advancing the research of a variable frequency antenna until now paying attention to combining antenna and mechatronics technologies. We have already proposed two types of such antennas. One is a patch antenna in which a movable dielectric material is partially loaded in an air gap region and operates at desired frequencies.[5] The variable width $(f_0 - f_m)/f_m$ of the frequency of this type antenna was obtained up to 24%. Here, f_0 is a variable resonance frequency and f_m is a resonance frequency without the loaded dielectric material. The other is an antenna in which a coaxial-fed portion is devised in order to control the height (h) of a conducting patch from the substrate. This antenna has a function of varying two parameters of frequencies and polarizations. The variable width of frequencies was obtained to be 12%.[6] In this case, f_m is the resonance frequency without the air gap, and the dielectric material of a printed circuit board (PCB) in the patch antenna was a fluorocarbon-resin (FR) substrate of the small relative dielectric constant (ϵ_r) of 2.2. A large ϵ_r ceramic material is required to expand the variable frequency region. According to the electromagnetic calculation by the Finite Difference Time Domain (FDTD) method,[7] the variable frequency width of an octave was predicted to be expanded when adoping the large ϵ_r of 9.7.[8]

This paper describes a tunable microstrip patch antenna, in which alumina (Al_2O_3) ceramic was used as a dielectric substrate. Moreover, h of the antenna was continuously changed by the piezoelectric actuator instead of inserting different thick spacers into a substrate and a ground plane.[6]

2. Experimental method

Fig. 1 shows the structure of the proposed and fabricated antenna. This antenna was formed to a coaxial-fed type patch,

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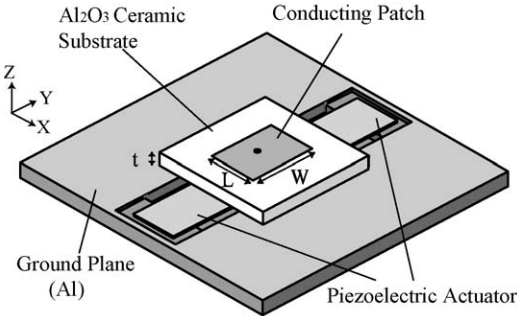

Fig. 1. Structure of the proposed and fabricated antenna.

and it was the structure where a patch antenna produced on the one side copper (Cu) plating PCB and a ground with a coaxial connector were separable. The rectangular patch antenna with length (L) and width (W) was printed on an Al_2O_3 substrate ($\epsilon_r = 9.7$). The thicknesses of the Al_2O_3 substrate were $t = 0.2$, 0.4, and 0.6 mm. The size of the ground plane of aluminium (Al) was 200 mm × 200 mm × 5 mm. The coaxial connector was machined precisely for the desired movement.[6] Thus, the Al_2O_3 substrate with the patch was movable; that is h of the antenna between the patch and the ground plane is variable. By moving up the antenna patch, an air layer appears between the patch antenna portion and the ground plane.

We used a piezoelectric actuator to change h of the antenna. Two actuators made and supplied by Nihon Ceratec Co., Ltd. were fixed to the outside of the hole of the ground and arranged under the patch antenna. The size of each actuator was 60 mm × 20 mm × 0.5 mm. A piezoelectric material used in the experiment was lead zirconium titanate (PZT).

The operation of the proposed antenna is as below. When h of the antenna is raised, the resonance frequency (f_0) which is inversely proportional to the square root of the effective dielectric constant (ϵ_{eff}) increases according to the air gap between the substrate and the ground[6] because ϵ_{eff} of the patch antenna becomes small with increasing the gap. The amount of the possible variable frequency depends on ϵ_r of the substrate of the patch antenna. The electromagnetic calculation based on the FDTD method[7] for the substrate of the Al_2O_3 showed that the attainable variable width of f_0 was an octave.[8]

The tested antenna was evaluated by measuring the reflective coefficient (Γ) with the conventional network-analyzer (Hewlett-Packard HP8510C). Here, the return loss was expressed with $-20 \log_{10} |\Gamma|$. The measured frequency range was changed from 4 to 10 GHz. The radiation pattern of the tested antenna was measured by rotating the antenna with receiving microwave signal from a standard horn antenna.

3. Results and discussions

Fig. 2 shows motion of the antenna, displacement of actuator, and time duration. Fig. 2(a) shows the cross sections of the antenna with and without voltage applied to the actuators. As shown in the left-hand side for the case of no voltage application, the dielectric substrate of the patch antenna was in contact with the ground. On the other hand, the application of the voltage detached the substrate from the ground and an air gap appeared.

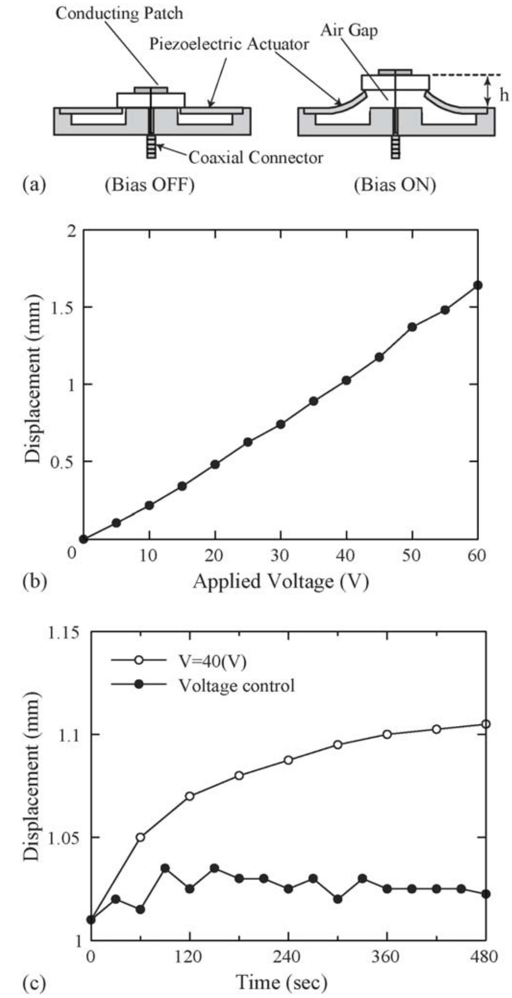

Fig. 2. Motion of the antenna, displacement of actuator, and time duration. (a) Motion of the antenna controlled by the piezoelectric actuator. (b) Displacement of the actuator. (c) Creep phenomenon and its control.

Fig. 2(b) shows the displacement versus applying voltage to the piezoelectric actuator. The result shows the momentary displacement when applying voltage. The displacement of the actuator was increased in proportion to the voltage. For example, when the voltage of 40 V was applied, the displacement was about 1 mm.

Fig. 2(c) shows the time dependence of the displacement of the actuator when applying the constant voltage of 40 V and the time varied voltage considering the upward characteristic of the displacement. Although the certain amount of the height was attainable by applying voltage to the actuator, the creep modification by time and the distortion by change of voltage arose by applying voltage to the ferroelectric PZT material. A displacement was about 100 μm in 480 s. In order to obtain the operational stability of the actuator, the voltage applied to the actuator was then needed to be varied temporally by use of the computer. Although the displacement was controllable within 10 μm in 120 s, the feedback mechanism is required to achieve more precise control.

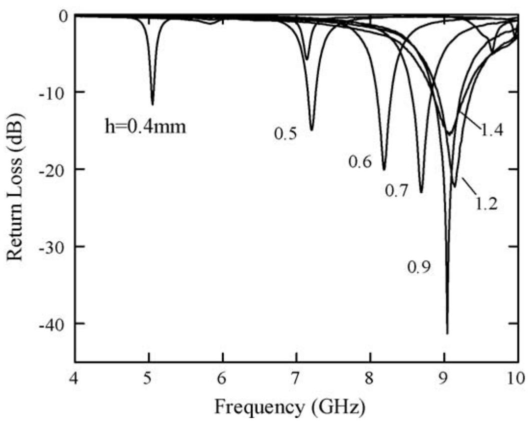

Fig. 3. Return loss of the tested antenna for different antenna heights. Thickness of the dielectric (Al_2O_3) substrate is 0.4 mm.

The measured results for the several antenna heights are plotted in Fig. 3. The resonant frequency was increased from 5.05 to 9.14 GHz as h of the antenna was increased from 0.4 to 1.2 mm. However, when h of the antenna was over 1.2 mm, f_0 was decreased from 9.14 to 9 GHz in addition to the increase of the return loss, and the bandwidth broadened.

Fig. 4 shows f_0 with changing h of the antenna. Thicknesses (t) of the Al_2O_3 substrate were 0.2, 0.4, and 0.6 mm. When t became small, the variable width of frequency expanded. The variable width of the frequency was 62% from 4.93 to 8 GHz for $t = 0.6$ mm, 81% for $t = 0.4$ mm, and 96% from 5.4 to 10.62 GHz for $t = 0.2$ mm. The experimental results were well in agreement with the electromagnetic calculation using the FDTD method.

The radiation patterns of the tested antenna are shown in Fig. 5. In the figure, the solid and the dashed lines indicate for E-plane (*x–z* plane) and H-plane (*y–z* plane), respectively. Fig. 5(a) shows the result for $h = 0.4$ mm and $t = 0.4$ mm. The pattern for the E-plane was affected by the ground edge, and the beam widths of the E-plane and the H-plane were 148 and 96°, respectively.

Fig. 5(b) shows the result for $h = 1.2$ mm and $t = 0.4$ mm. The beam widths of the E-plane and the H-plane were 69 and 68°, respectively. In this case, the antenna patterns of the E-plane and H-plane are symmetrical for all antenna heights. The beam width of the antenna narrowed with increasing the antenna height. The absolute gain of the antenna increased with increasing h. In the case of $t = 0.2$ mm, the absolute gain was within the values between 10 dBi ($h = 1.2$ mm) and 0.3 dBi ($h = 0.2$ mm). For the other values of t, the gain was varied from 9.3 to 3 dBi for $t = 0.4$ mm and from 7.8 to 4.1 dBi for $t = 0.6$ mm.

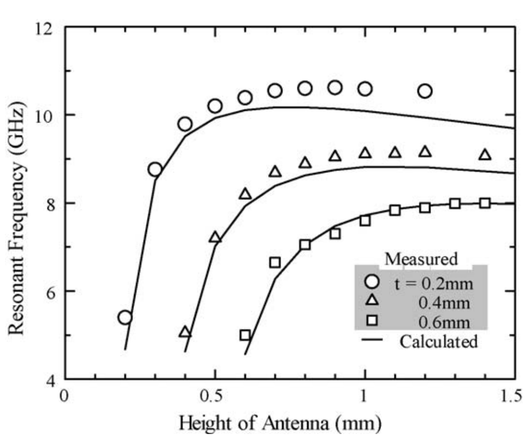

Fig. 4. Measured and calculated resonant frequencies vs. of the height of the antenna.

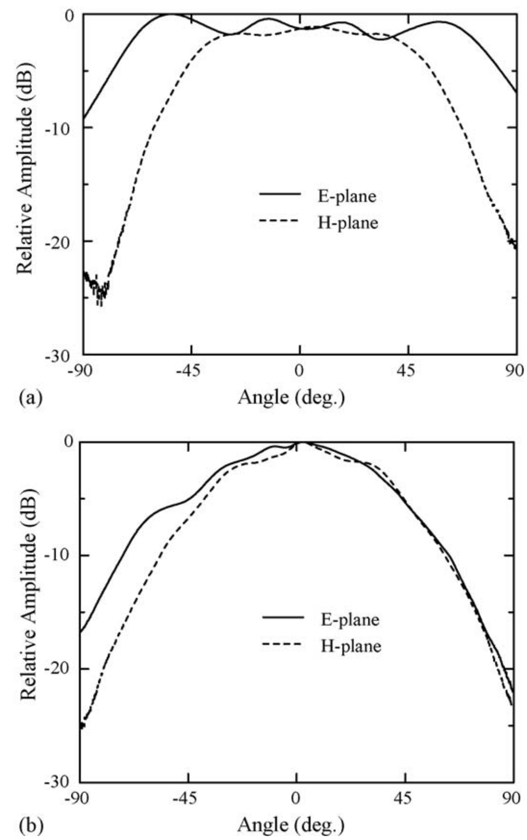

Fig. 5. Radiation patterns of the tested antenna. (a) Operation frequency is 5.05 GHz for the height of the antenna ($h = 0.4$ mm). (b) Operation frequency is 9.14 GHz for the height of the antenna ($h = 1.2$ mm).

The absolute gain and f_0 of the proposed antenna were about the same as the patch antenna loaded with the semiconductor.[9] However, the proposed antenna had an advantage in respect of loss over the latter one.

4. Conclusion

In this paper, a tunable microstrip patch antenna on an alumina ceramic substrate with a mechanism of a variable height of the antenna using a mechatronics technology has been presented. The proposed antenna had a flat structure where the patch antenna portion was movable mechanically. The width of the variable resonant frequency of the tested antenna was attainable to be 96% from 5.4 to 10.6 GHz.

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