A Dual-Band Tunable Ultra-Thin Cavity Antenna

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***Abstract*—A dual-band ultra-thin cavity antenna with a wide tuning range is designed and fabricated. The overall dimensions are 31 × 15 × 0.5 mm^3. The proposed cavity antenna is realized by making two adjacent side walls of a rectangular dielectric-filled resonant cavity open as radiating ports. The achievable frequency ratio changes from 1.2 to 2.2 with different aspect ratios. With a varactor diode installed at the front open port, the dual frequency bands can be tuned over a wide range. When the applied reverse biasing voltage varies from 3 to 13 V, the realized $|S_{11}| < -6$ dB impedance bandwidth is 420 MHz (12.5%) and 960 MHz (20.5%) for the low band and the high band, respectively. The designed antenna occupies no area on a circuit board, and a 0.5-mm-thin volume inside a device cover is enough for installation. The dual bands can be scaled to other desired bands within the frequency ratio range.**

***Index Terms*—Cavity antenna, dual-band, tunable, ultra-thin.**

I. Introduction

MULTIPLE-INPUT–MULTIPLE-OUTPUT (MIMO) systems use multiantennas to enhance channel capacity and service quality. The antenna units designed for MIMO systems include microstrip patch antennas, planar monopole antennas, planar inverted-F antennas (PIFAs), slot antennas, and so on [1]–[5]. Despite their advantages such as light weight, easy design, and low profile, these antennas generally suffer from narrow bandwidth, which restricts their applications on many occasions. Microstrip patch antennas with E-shaped slot or U-shaped slot, air-fed stacked patch antennas, and varactor-tuned antennas have been proposed to realize broadband performance [6]–[10]. Varactor tunable technique is one of the attractive solutions to extend the operating frequency range, which has motivated a variety of studies [7]–[10].

In [7], two varactor diodes were installed at the radiating edges of a microstrip patch antenna to tune the working frequency. A coplanar patch antenna with a single varactor diode located at one of the radiating edges was designed in [8] to realize frequency tunability. A central square patch surrounded by four trapezoidal patches connected to the central one by varactor diodes and to each other by capacitors was proposed in [9] to allow frequency tuning, polarization agility, and phase shifting while maintaining good impedance matching. A shallow cavity-backed slot antenna using a single varactor diode was demonstrated in [10] to tune the frequency from 1 to 1.9 GHz with reflection coefficient better than -20 dB. A tunable dual-band slot antenna using a single varactor was designed in [11], and a frequency ratio in the range of 1.2–1.65 was realized when its reverse biasing voltage is increased from 1.5 to 30 V. A tunable PIFA covering multibands was proposed in [12] for personal communication handset applications. The common feature of these antenna forms is that they occupy not only a certain area on the circuit board, but also some volume inside the mobile terminals. As more and more functions will be integrated in the limited space of portable MIMO transceivers, it will become quite challenging for the design of these antennas. Besides, these antennas are rather sensitive to the surroundings.

Cavity antennas that radiate through open ports can eliminate the need for areas, and thus provide us a solution for saving space on the circuit board. In this letter, we propose a 0.5 mm-thin tunable dual band cavity antenna which can be integrated with the MIMO devices which adopt full metal cover. The proposed cavity antenna is realized by making two adjacent side walls of a rectangular resonant cavity open as radiating aperture. The advantage of the proposed cavity antenna is that it takes no area on the circuit board, so it can save much space for the multifunctional terminals. A 0.5-mm-thin volume inside a device cover is enough to install the proposed cavity antenna. Meanwhile, it is less sensitive to the environment. The designed structure, resonant modes, achievable frequency ratio and band tunability are first analyzed, and then a dual-band prototype is constructed and measured.

II. Antenna Design

A. Antenna Structure

Fig. 1 shows the geometric structure of the proposed tunable cavity antenna designed for dual-band operation. The overall dimensions in the horizontal plane are 31 (L) × 15 (W) mm^2. The thickness of the proposed cavity antenna is 0.5 mm only, which is filled by a F4B high-frequency microwave dielectric substrate with a relative permittivity (ε_r) of 2.65 and a loss tangent of 0.005. Detailed dimensions of the antenna are shown in Fig. 1. The shorting walls of the cavity antenna are realized by closely spaced vias. The proposed design makes two adjacent side walls of the rectangular cavity short, while keeping the other two walls open so as to radiate energy, as shown in Fig. 1. This configuration makes the resonant frequencies lower and easier to adjust than others. The cavity antenna is excited by a probe with the inner conductor of the feeding cable connected to the upper surface of the cavity, and the outer to the lower. The proposed antenna has a relatively narrow impedance bandwidth because of the high Q-value caused by the ultra-thin

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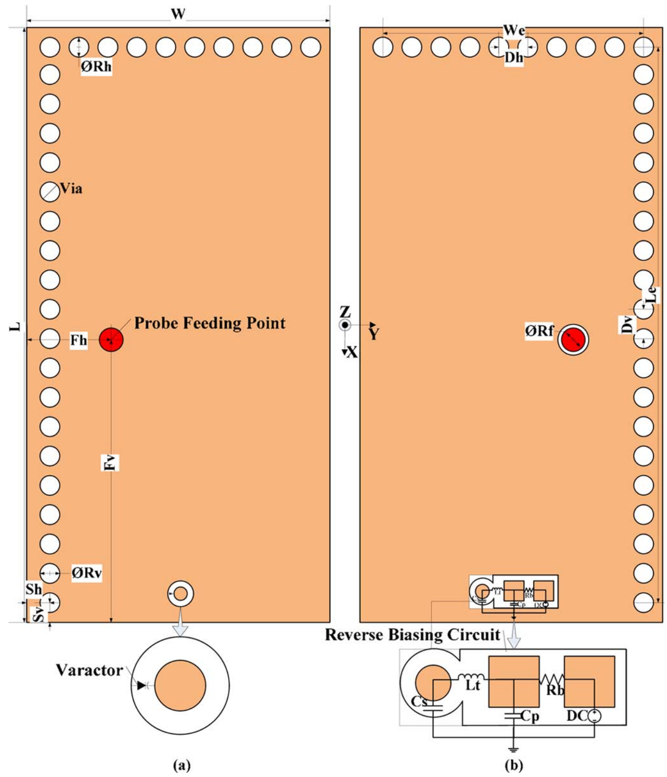

Fig. 1. Geometry of the proposed tunable dual-band cavity antenna: (a) Top view with the varactor position zoomed in. (b) Bottom view with the reverse biasing circuit enlarged. Dimensions: $L = 31$ mm, $W = 15$ mm, $R_\mathrm{v} = R_\mathrm{h} = 1$ mm, $D_\mathrm{v} = 1.5$ mm, $D_\mathrm{h} = 1.4$ mm, $S_\mathrm{v} = S_\mathrm{h} = 1$ mm, $L_\mathrm{e} = 28.5$ mm, $W_\mathrm{e} = 12.6$ mm, $R_\mathrm{f} = 1.2$ mm, $F_\mathrm{v} = 14.2$ mm, $F_\mathrm{h} = 4.6$ mm.

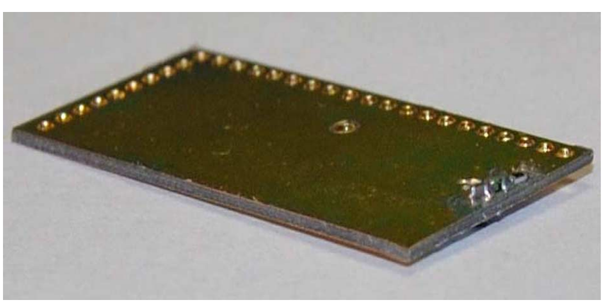

Fig. 2. Photograph of the fabricated prototype.

thickness. To make the antenna operate with wide bandwidth and to reduce the total volume, a varactor diode is installed between the upper and lower surface of the antenna. The antenna can work at a lower frequency and cover a wider frequency band by changing the capacitance of the varactor diode. The varactor diode is installed in the middle of the front open port, which has been optimized to enhance the antenna's efficiency. Fig. 2 shows a photograph of the fabricated prototype.

B. Dual-Mode Resonance

The resonant modes and operating frequencies of the proposed dual-band cavity antenna are simulated by Ansoft HFSS based upon the finite element method (FEM). The field distributions of its basic mode and high-order mode are shown in Fig. 3. At the basic mode, a quarter-wavelength standing wave is formed between the open and short sides along both the length L and width W, as shown in Fig. 3(a). For high-order resonance, a three-quarter-wavelength standing wave is formed along the length L, while the field distribution along the width W remains unchanged, as shown in Fig. 3(b). The resonant frequencies for the two operating modes F_l and F_h can be empirically approximated by

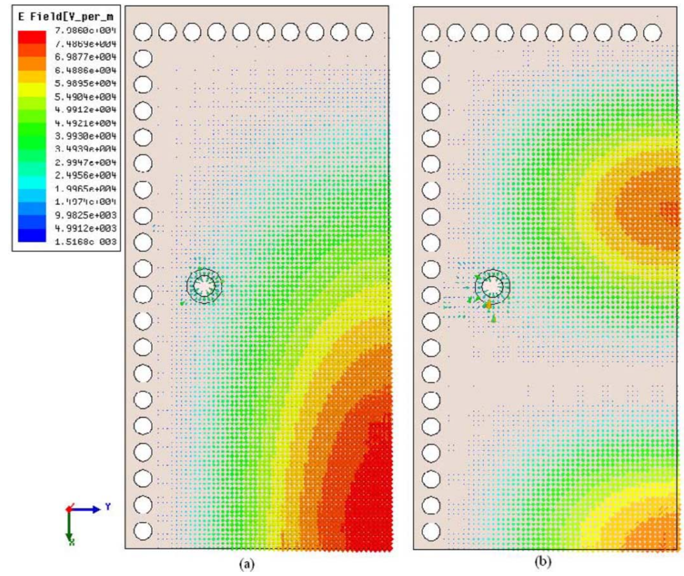

Fig. 3. Field distributions for dual resonant modes of the proposed cavity antenna: (a) Basic mode. (b) High-order mode.

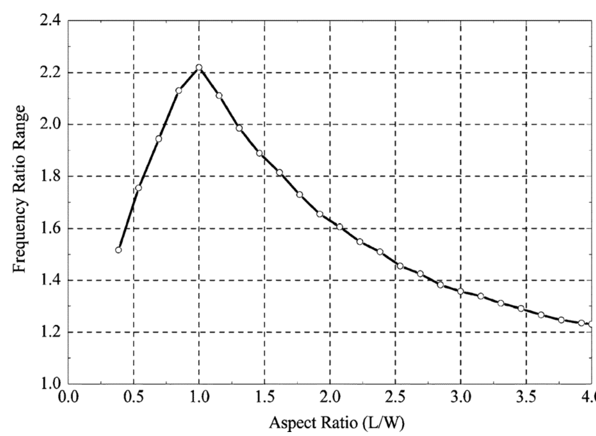

Fig. 4. Achievable frequency ratio with varying aspect ratios.

$$F_\mathrm{l} = \frac{c}{4} \cdot \frac{1}{\sqrt{(\varepsilon_\mathrm{r}+1)/2}} \cdot \frac{\sqrt{L^2+W^2}}{L \cdot W} \tag{1}$$

$$F_\mathrm{h} = \frac{c}{4} \cdot \frac{1}{\sqrt{(\varepsilon_\mathrm{r}+1)/2}} \cdot \frac{\sqrt{L^2+9W^2}}{L \cdot W}. \tag{2}$$

From formulas (1) and (2), we can see that the frequencies of the basic mode and the high-order mode are determined by both the long side L and the short side W, so different dual frequencies can be realized by varying the aspect ratio L/W. Fig. 4 shows the achievable frequency ratio $F_\mathrm{h}/F_\mathrm{l}$ changing with different aspect ratios L/W.

As shown in Fig. 4, the ratio between the high and the low frequency changes from about 1.2 to 2.2 when the aspect ratio

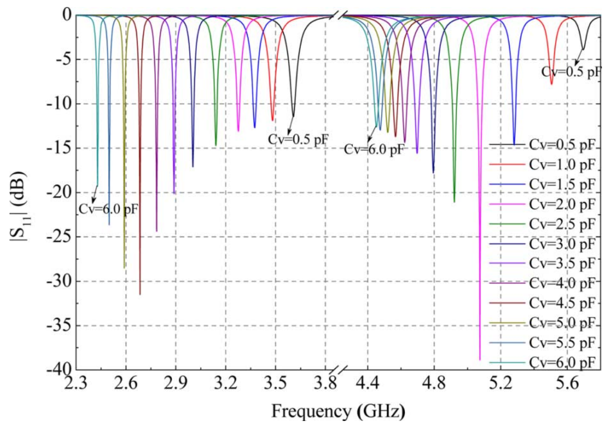

Fig. 5. Simulated $|S_{11}|$ of the dual frequency bands with different shunt capacitances C_{v}.

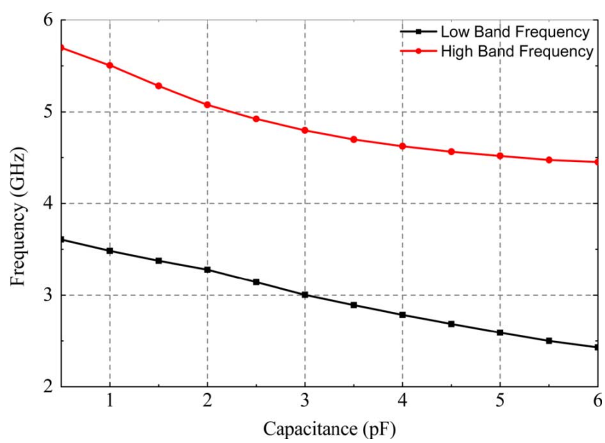

Fig. 6. Simulated dual-band frequencies with different shunt capacitances C_{v}.

varies from about 1 to 4. This result gives us guidelines for designing cavity antennas at the desired dual bands within the frequency ratio range.

C. Tunable Frequency Bands

The proposed cavity antenna without any varactor diode installed can work at dual bands with about 20–30 MHz instantaneous bandwidth each and can apply to some narrowband systems. To make the antenna realize broadband performance, a varactor diode is installed at the front open port along the short side. Simulations with different shunt capacitances are made, and the results are shown in Fig. 5. As shown in Fig. 5, the low frequency band can be tuned from 3.6 to 2.5 GHz, and the high frequency band can be adjusted from 5.7 to 4.5 GHz, when the shunt capacitance C_{v} increases from 0.5 to 6 pF with an interval of 0.5 pF.

Fig. 6 shows the influence of different shunt capacitances C_{v} on the dual-band frequencies with minimum reflection. When the shunt capacitance is small, it causes a big change in the high-band frequencies. However, the high-band frequencies change slowly and the low-band frequencies still change quickly when the shunt capacitance increases.

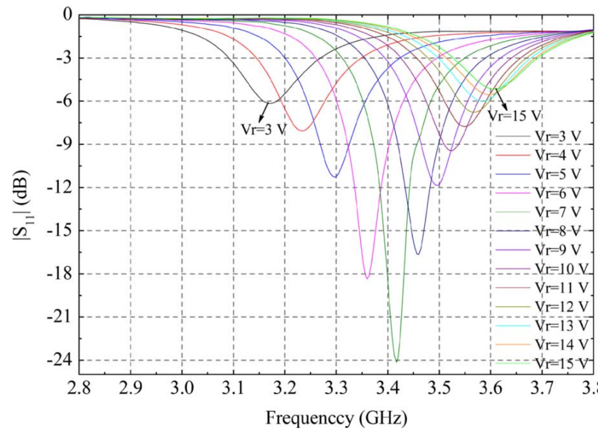

Fig. 7. Measured $|S_{11}|$ of the tunable cavity antenna at low frequency band.

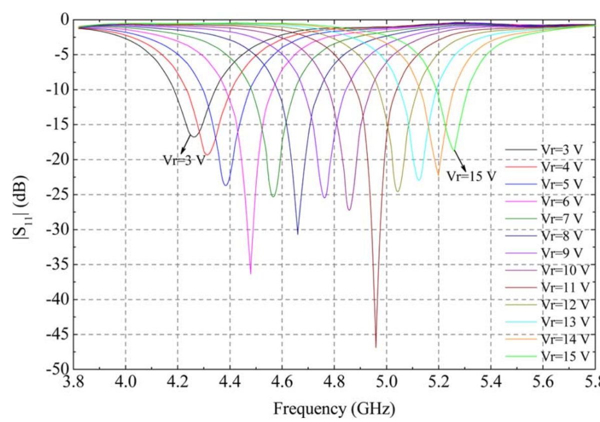

Fig. 8. Measured $|S_{11}|$ of the tunable cavity antenna at high frequency band.

III. Measurements and Discussion

A. Varactor Diode Selection

Simulations show that the cavity antenna can work at two frequency bands when a varactor diode is installed in the front open end. A varactor diode JDV2S71E from Toshiba Company is selected and integrated in the cavity antenna structure for experiment. The capacitance of this varactor diode changes from 10 to 0.5 pF when the applied reverse biasing voltage *Vr* changes from 0 to 25 V. Other varactors with this capacitance range but needing lower reverse biasing voltage are also available on the market. The biasing circuit designed for this varactor is shown in Fig. 1(b) in the enlarged version. The series protection resistor *Rb* is 1 kΩ. The series inductor *Lt* is 4.7 nH to let the direct current (dc) pass and stop the alternating current (ac). The shunt capacitance *Cp* is 100 pF to make the ac short to the ground. The shunt capacitance *Cs* is used to direct the ac passage when the antenna is fed with a coaxial cable.

B. Measured Tuning Range

The measured $|S_{11}|$ for the low band and the high band with different applied voltages are shown in Figs. 7 and 8, respectively. The usable impedance bandwidth with $|S_{11}| < -6$ dB is 420 MHz (3.17–3.59 GHz) and 960 MHz (4.26–5.12 GHz) for the low band and the high band, respectively, when the applied reverse voltage changes from 3 to 13 V. The realized frequency

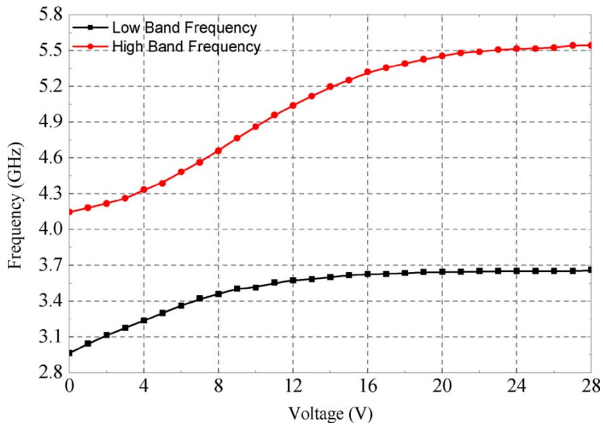

Fig. 9. Measured dual-band frequencies with different reverse biasing voltages applied.

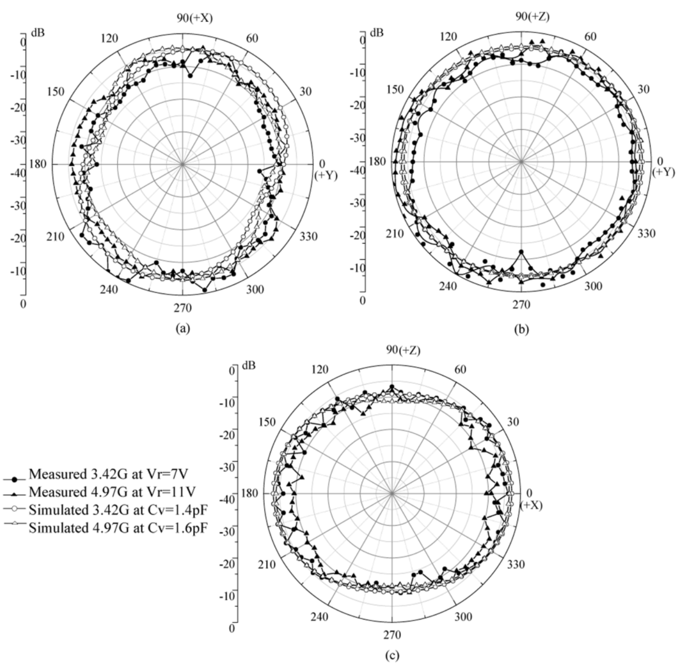

Fig. 10. Measured radiation pattern: (a) *xy* plane; (b) *zy* plane; (c) *zx* plane.

ratio is about 1.5, which is within the achievable frequency ratio range. Fig. 9 shows the frequencies with minimum reflection for both bands when *Vr* changes from 0 to 28 V. This figure implies the variation trends of the two bands with different biasing voltages applied. We can see that when the voltage exceeds 16 V, it will have little tunable effects on the low frequency. The frequency in the high band shows little variation when the applied voltage is above 20 V. The reason is that the varactor capacitance has little change when the reverse biasing voltage is higher than 20 V.

C. Gain and Radiation Pattern

When the applied reverse voltage is 7 V, the antenna operates at 3.42 GHz with a return loss of 24 dB, and the measured gain is −2.95 dBi. When the applied voltage is 11 V, the antenna works at 4.96 GHz with a return loss of 47 dB, and the measured gain is −4.85 dBi. The measured and simulated radiation patterns for these two cases are shown in Fig. 10. The low gain is mainly caused by the high Q-value of the cavity antenna as well as losses caused by these lumped components and the measured system. The discrepancy between the measured and simulated radiation patterns are mainly influenced by the feeding cable and SMA connector, which are relatively large compared to the cavity antenna.

IV. Conclusion

An ultra-thin dual-band cavity antenna with frequency tunability is proposed in this letter. Four units of the proposed antenna can be installed at the four corners of a 0.5-mm-thin device cover to construct a MIMO system. The efficiency and gain of the cavity antenna are not as good as traditional PIFAs, however, and it can be used as auxiliary radiators for MIMO and diversity systems, which work close to the base station and have high data rates. The designed dual-band tunable cavity antenna can be used in time-division schemes where transmissions and receptions operate at the same frequency. The dual bands can operate simultaneously to realize bandwidth aggregation for broadband transmission, high data rates, and spectrum efficiency enhancement.

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