its top-/bottom-side views are given in Fig. 7. The measured VSWR is plotted in Fig. 8 against the predicted results for the antennas with the finite (actual) and infinite (ideal) ground plane. From the figure, it can be observed that the two predicted VSWR curves of the slotline antennas with finite- and infinite ground planes are almost the same as each other. It is indicated that the finite ground has no effect on the input impedance of this antenna if its overall size is sufficiently large. Over the realized UWB band of 3.2 to 10.8 GHz, the measured VSWR is less than 2.3 and it is slightly higher than 1.8 obtained in simulation. This small discrepancy is mainly attributed by certain unexpected tolerance in fabrication. The simulated and measured antenna peak and average gains at its H-plane are plotted in Fig. 9 as a function of frequency. The peak gains vary from 0.5 to 4.0 dBi in the realized impedance bandwidth whereas the average gains vary from -3.0 to 1.3 dBi. Fig. 10 plots the simulated and measured radiation patterns at three individual frequencies, i.e., 3.5, 6.0 and 10.0 GHz, and they are in reasonably good agreement with each other. At the high-end frequency near 10.0 GHz, the H-plane radiation pattern is split into a few radiation beams and the cross polarization in the E-plane pattern is increased. It is primarily attributed by the fact that the slotline resonator becomes electrically large at high frequencies and many other high-order resonant modes are excited in the wide slotline resonator. This cross polarization can be decreased at high frequencies by narrowing the radiating slot at the cost of narrow impedance bandwidth. This undesired phenomenon can not be abolished in physics and also exists in many other UWB antennas, e.g., a planar monopole antenna [18].

IV. Conclusion

In this communication, a novel UWB microstrip-fed slotline antenna has been presented, designed and implemented under the concept of multiple-mode resonance of a single resonator. Our extensive study has firstly exhibited that its wide bandwidth of 3:1 or $\sim 100\%$ is realized by concurrently exciting the first four resonant modes of a single slotline radiator that is fed by the microstrip line at a proper offset position. With reference to the 160-Ω port impedance, an initial slotline antenna is designed to achieve a wide operating band with a fractional bandwidth of 97.9%. By installing a tapered-line impedance transformer, an actual 50-Ω microstrip-fed UWB slotline antenna has been developed by using four excited resonant modes. Measured results of the proposed antenna are in good agreement with the predicted ones and they have demonstrated a 97.9% operating bandwidth, over which the VSWR is less than 2.3 and the antenna gain varies from 0.5 to 4.0 dBi, as like other UWB antennas.

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A Compact Hepta-Band Loop-Inverted F Reconfigurable Antenna for Mobile Phone

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***Abstract*—A folded loop-inverted F reconfigurable antenna for mobile phone applications is designed and the obtained results are discussed in this communication. It is shown that loop antenna mode and an inverted F antenna (IFA) mode are controlled by only one p-i-n diodes with simple bias circuit. The impedance can be matched by adopting a matching bridge for both the loop and IFA modes. In a compact volume of $60 \times 5 \times 5$ mm^3, the proposed antenna operates in hepta-band, including GSM850, GSM900, GPS, DCS, PCS, UMTS and WLAN, with the return loss lower than 6 dB. A prototype of the proposed antenna is fabricated, measured, and obtained results including return loss, efficiency and gain, are presented.**

***Index Terms*—Handset antennas, impedance matching, Mobile antennas, multiple band antennas, reconfigurable antennas.**

I. Introduction

With the rapid development of wireless communication technology, multi-band and multi-functional antennas are widely studied and adopted for the mobile phone applications. There is a significant demand to integrated more wireless services to small volume mobile handsets. Wide bandwidth and compact structure are important

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requirements for the internal multi-band antenna design, such as monopole antennas [1], [2], IFA [3]–[5], as well as the many other designs described in [6]–[13].

Recently, a number of publications, however, suggested that the loop antennas could also provide promising solution for mobile phone applications [6]–[13]. To arrange a loop antenna in a small volume with good impedance matching, however, is a challenging task as discussed in many publications. A tuning pad is utilized as described in [8], [9]. The tuning pad shows different effects to different operating modes of the loop and higher modes of operation can be tuned for wider bandwidths. However, integrating more frequency bands to an internal antenna with small volume continues to be still a challenge. Frequency reconfigurable antenna represents an effective solution for multi-band antenna designs. Different operating modes with different frequencies are reconfigured using the same antenna pattern and without extra space. Wide bandwidth is achieved by combing the overall working frequency bands.

In this communication, a folded loop antenna is presented for mobile phone applications. The proposed antenna can be reconfigured to IFA by breaking the loop, using only one p-i-n diode and with a simple bias circuit. Besides adopting the tuning pad proposed in [8], [9], a matching bridge is also utilized in both loop and IFA modes of the proposed antenna to achieve wider bandwidth. Hepta-band coverage is realized in a compact volume of 60 $\times 5 \times$ 5 mm^3, including GSM850, GSM900, GPS, DCS, PCS, UMTS and WLAN. Prototype was also built and the measured results show acceptable radiation efficiency and gain of the proposed antenna, even after considering the effect of p-i-n diode.

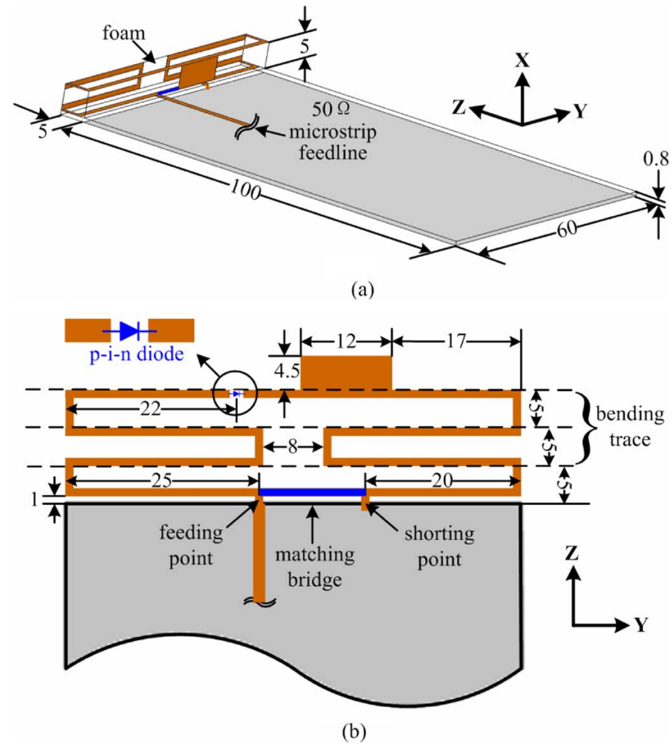

Fig. 1. Geometry and dimensions of the proposed antenna. (a) 3-D view. (b) Detailed dimensions in the planar view.

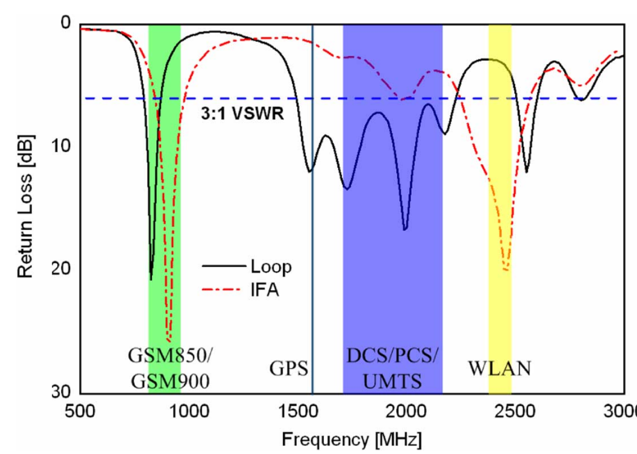

Fig. 2. Measured return loss of loop and IFA modes of the proposed antenna.

II. Antenna Design and Configuration

Fig. 1 shows the geometry of the proposed reconfigurable antenna, the overall dimensions are $60 \times 5 \times 5$ mm^3. The folded loop antenna (uniform width of 1 mm) is supported by foam with the permittivity close to that of air. The antenna structure is arranged just outside the ground plane area and above the main board. The main board is made of FR4 substrate ($\varepsilon_{\rm r} = 4.4, \tan\delta = 0.01$), with the thickness of 0.8 mm. A $100 * 60$ mm^2 metal ground is printed on the backside of the main board, connecting the shorting point of the loop through a via-hole. A 50 Ω microstrip line is arranged on the front side of main board and is connected to feeding point of the loop. A shorting bridge (blue color in Fig. 1), which has the same width as the loop (1 mm), connects the feeding point with the shorting point. The position of p-i-n diode is illustrated in Fig. 1(b). When the p-i-n diode is "ON," the antenna works in a typical loop mode. When the p-i-n diode is "OFF," on the other hand, the loop will be broken into two IFA, and the left part (the one without tuning pad) is the main working branch. As a result, the operating modes of the proposed antenna can be switched by the state of p-i-n diode.

The measured return losses of both working modes are shown in Fig. 2. These data agree well with simulation results as will be shown in Section III. Hepta-band is covered with -6 dB $({\rm VSWR} = 3:1)$ by combining the bandwidths of two modes. For the loop mode (solid line), the achieved bands are 790–870 MHz and 1490–2225 MHz, covering GSM850, GPS, DCS, PCS and UMTS bands. For the IFA mode (dash dotted line), the achieved bands are 845–980 MHz and 2240–2565 MHz, covering GSM900 and WLAN bands. Analysis on the impedance matching of both modes is described in Section III.

III. Working Mode Analysis

A. Loop Mode

Typical loop antennas and their applications in the mobile phones area are systematically discussed by Wong [7]–[10]. Three resonant modes, including 0.5-wavelength mode, one-wavelength mode and 1.5-wavelength mode, are usually utilized. The tuning pad [8], [9] is a good method for impedance matching and with different effects to different modes. The 0.5-wavelength mode is tuned for lower band, and the one-wavelength and 1.5-wavelength modes are tuned together to cover the higher bands. In order to achieve wider bandwidth, a matching bridge is added between the feeding and shorting points of the loop as shown in Fig. 1. The simulated return loss of the loop mode with and without the matching bridge is illustrated in Fig. 3. Simulations were made using the Ansoft High Frequency Structure Simulator (HFSS) software. As it may be seen, the inclusion of the matching bridge resulted in improving the bandwidth, thus covering the GSM850, GPS, DCS, PCS and UMTS bands.

The matching method is shown on the Smith Chart of Fig. 4. The matching bridge works as a shunt inductor at the feeding point of loop. As studied in [14], a shunt inductor is able to move the impedance curve alone the equal admittance circle. The susceptance introduced by shunt inductor is $1/{\rm j}\,\omega\,{\rm L}$, where ω is angular frequency and L is the equivalent inductance of the matching bridge. For the lower band, the susceptance is larger than that of the high band. As a result, the impedance curve moves further away from the matching center and towards the lower frequencies. Similar to the tuning pad in [8], [9], the matching bridge also has different effect that depends on the frequency. For the lower band, shown in Fig. 4(a), the frequency shifts to lower band with similar bandwidth. However, more band moves into the VSWR 3:1 circle is shown in Fig. 4(b) and as a result the bandwidth is enhanced.

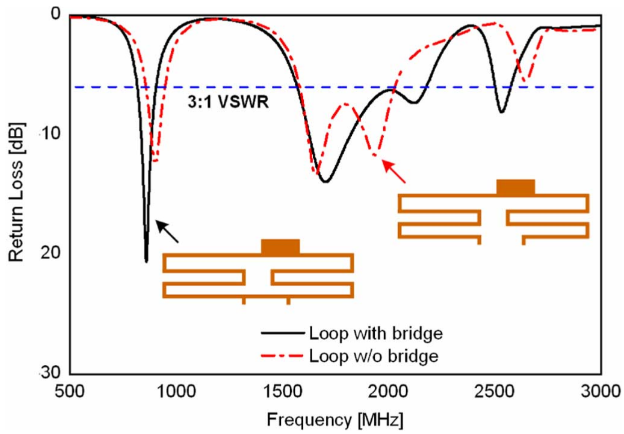

Fig. 3. Simulated return loss of loop mode of the proposed antenna with or without the matching bridge.

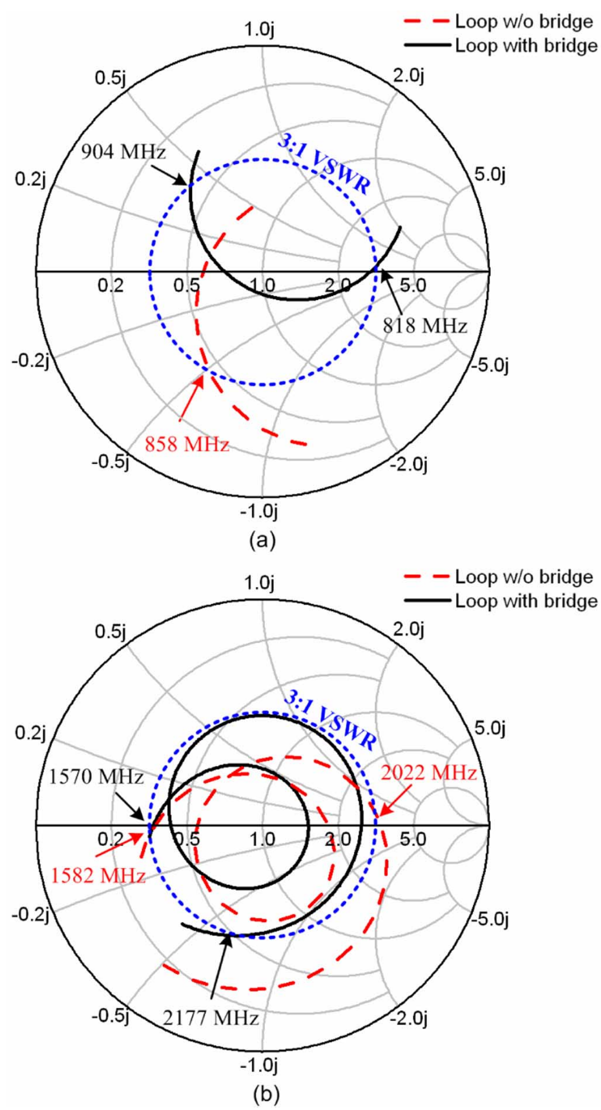

Fig. 4. Smith Chart of the loop mode with or without the matching bridge. (a) Lower band. (b) Higher band.

B. IFA Mode

In order to cover more bands by the internal antenna in the same volume, another mode is developed based on the loop structure. By cutting the loop, the antenna can be divided to two IFAs with the matching bridge, or two monopoles without the matching bridge. The comparison of return loss between two IFAs and two monopoles are illustrated

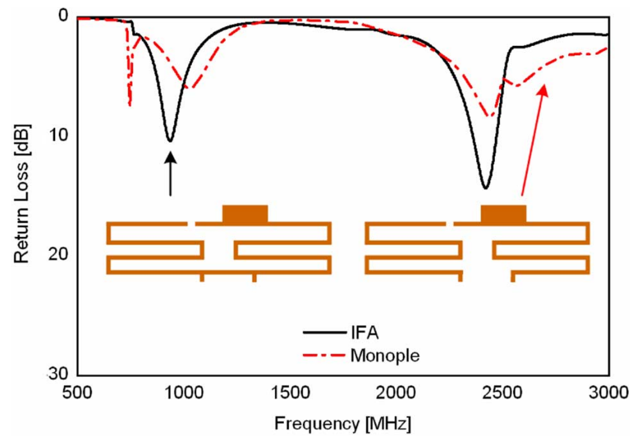

Fig. 5. Simulated return loss of IFA mode of the proposed antenna with or without the matching bridge.

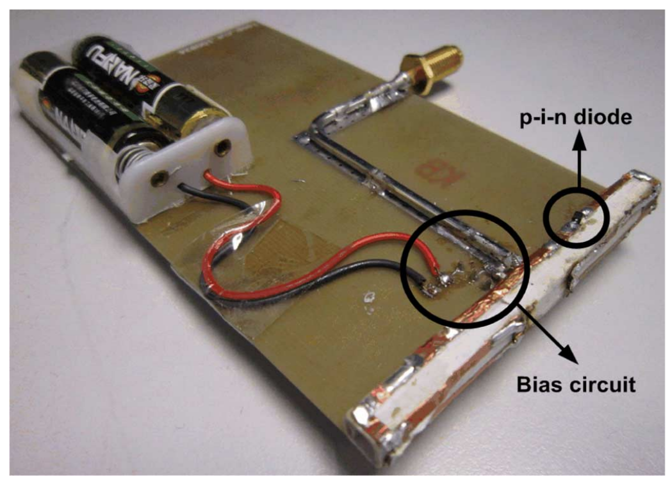

Fig. 6. Photo of the proposed antenna with bias circuit.

in Fig. 5. For the dash dotted line, we can see two resonant frequencies appearing in both lower band and high band, but with unacceptable bandwidth. The narrow bandwidths for two monopoles are mainly due to the compact volume without extra matching structure. For the two IFA results shown in the solid line, one of the two former resonant frequencies has been matched by adding the matching bridge. Therefore, two more bands of GSM950 and WLAN have been achieved based on the matched loop mode.

IV. Antenna Fabrication and Measurement Results

To demonstrate the validity of the presented matching strategy, the proposed antenna with p-i-n diode was fabricated and tested, as shown in Fig. 6. The detailed diagram of bias circuit of p-i-n diode is shown in Fig. 7. The selected p-i-n diode is Philips BAP64-03 silicon PIN diode, with good performance up to 3 GHz [15]. When the p-i-n diode is forward-biased, it works as a series resistance. In the frequency band of 0.5–2.5 GHz, the insertion loss introduced by p-i-n diode is 0.1–0.2 dB at its typical bias current of 10–100 mA. When the p-i-n diode is reverse-biased, it is equivalent to a series capacitance of approximately 0.45 pF, the isolation in the required band is better than -15 dB. Therefore, less number of p-i-n diodes will reduce the insertion loss and improve the performance of the systems. One is the minimum number of diode for two switchable states. In the bias circuit, a capacitor $(\mathrm{C_{b1}})$ is used between the port and loop antenna for DC blocking; another DC block capacitor $(\mathrm{C_{b2}})$ is used between the feeding and shorting points; an inductor $(\mathrm{L_b})$ is used for RF choking; another capacitor $(\mathrm{C_s})$ is used between $\mathrm{V_{contr.}}$ and the ground in order to short the RF signal leaked from $\mathrm{L_b}$; a resistor $(\mathrm{R_b})$ is used to control the bias current. The bias voltage for $\mathrm{V_{contr.}}$ is 3 V, supplied by two AA batteries. The values of each component in the bias circuit are: $\mathrm{C_{b1}} = 120$ pF, $\mathrm{C_{b2}} = 120$ pF,

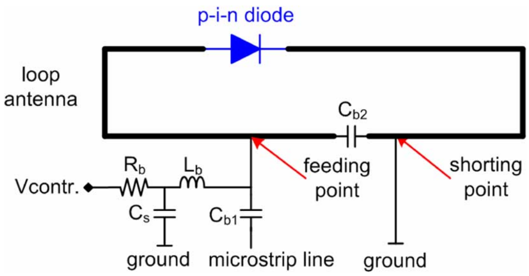

Fig. 7. Diagram of bias circuit of p-i-n diode.

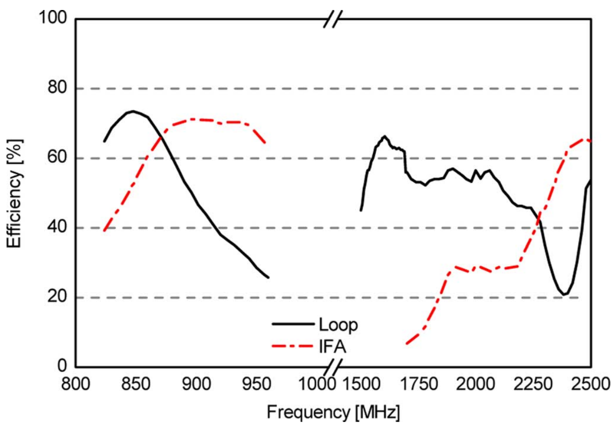

Fig. 8. Measured radiation efficiency of loop and IFA modes of the proposed antenna.

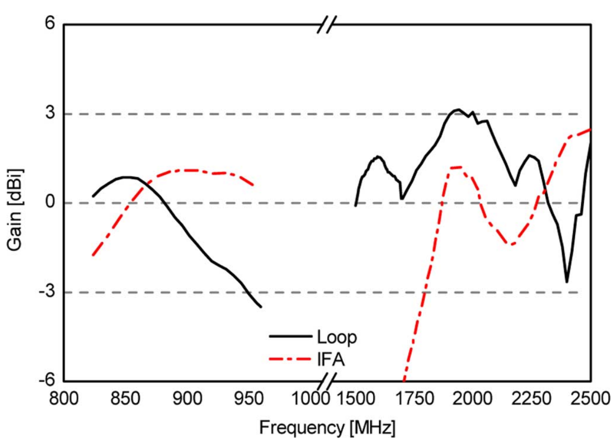

Fig. 9. Measured gain of loop and IFA modes of the proposed antenna.

$L_b = 120$ nH, $C_s = 470$ pF and $R_b = 46\ \Omega$ with bias current is 65 mA. The bias voltage is controlled by a single-pole two-throw switch on the back side of ground plane.

The performance of the proposed prototype antenna is measured, including the return loss, radiation pattern, efficiency, and gain. The measured return loss of both two modes is shown in Fig. 2. By combining the two operation modes, the proposed antenna covers the bands of GSM850, GSM900, GPS, DCS, PCS, UMTS and WLAN with the return loss lower than -6 dB. Especially for GPS operation, linear polarization antenna is adopted instead of circularly polarization antenna in the mobile phone applications, for its unexpected orientation and compact dimension. Circularly polarization antenna is usually utilized in the base station and vehicular environment with a fixed orientation and unlimited volume.

The measured radiation efficiencies for loop and IFA modes are shown in Fig. 8. By combing the curves of two modes, the improvement of efficiency is clearly observed. For the GSM band, the efficiency is better than 64.7%; for the GPS, DCS, PCS, and UMTS bands, the efficiency is better than 47.4%; and for the WLAN band, 62.8% efficiency is achieved. The efficiency can be improved by using high quality diodes in the practical applications. The gain is also measured and shown in Fig. 9. For the GSM band, the gain varies in the range of 0.22–1.10 dBi; for the GPS, DCS, PCS, and UMTS bands, the gain ranges from 0.43 dBi to 3.13 dBi; and for the WLAN band, gain of 2.12–2.41 dBi is achieved. The results indicate the performance improvement by adopting switching mechanism.

V. Conclusion

A folded loop antenna with reconfigurable characteristic is proposed in this communication for multiband applications for mobile phones applications. Two strategies are designed for bandwidth enhancement. The first one is the implementation of the loop-IFA modes switch. The IFA mode is achieved by cutting the loop structure without other changes. Another two resonant frequencies are added for wider bandwidth. Only one p-i-n diode is utilized for modes switching, thus avoiding the complex bias circuit and additional insertion losses. The second one is the matching bridge between feeding and shorting point. For loop mode, different effects take place for lower and higher bands; but for IFA mode, both lower and higher modes are matched. By adopting the matching bridge, the bandwidths of two modes are both improved. As a result, for a typical mobile phone with the ground size of $100*60\ \text{mm}^2$, hepta-band coverage is achieved in the compact volume of $60 \times 5 \times 5\ \text{mm}^3$, including GSM850, GSM900, GPS, DCS, PCS, UMTS and WLAN bands. The proposed antenna shows good radiation performance including the efficiency and gain. The insertion loss of p-i-n diode is also discussed. High quality switch is a promising solution for reconfigurable antenna designs for mobile phone applications.

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