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A Novel Internal NFC/FM Antenna with Parasitic-Patch-Enhanced NFC Interrogation Range and FM Passive Gain

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Abstract—An internal dual-band flexible antenna is described. The antenna employs a rectangular patch to improve the interrogation range (above 100 mm) for near-field communications (NFC), as well as the passive average gain performance (above −20 dBi) for FM radio. A preliminary prototype antenna exhibits an interrogation range of 110 mm at 13.56 MHz and a passive average gain performance from −15.6 to −13.5 dBi in the range 86–108 MHz, while demonstrating an omnidirectional radiation pattern for FM radio applications.

1. INTRODUCTION

In recent years, mobile handset antennas for communication bands including LTE, CDMA, GSM, DCS, PCS, and UMTS, as well as Wi-Fi, have undergone considerable development, and there has been increasing research interest in realizing improved antenna designs that can operate in multiple bands. However, there are no accurate design methods for miniaturized internal dual-band antennas for mobile handsets operating in both near-field communication (NFC) and Frequency-Modulation (FM) radio bands. For such a low-frequency antenna to be easily integrated into a mobile handset, it must be small, and thus it should have low radiation resistance and good passive average gain.

Recently, there has also been increased interest in the use of NFC technology [1], owing to the demand for low-cost, easy-to-use devices operating at 13.56 MHz, for applications including contact-free payments over a range of 100 mm. In the NFC process, information is transferred via electromagnetic induction, using radio-frequency identification (RFID). Several NFC loop-antenna technologies, such as inkjet-printed antennas [2], magnetic coupling antennas for payment applications [3], and small antennas for proximity transponders [4], have been investigated. However, these structures have one major limitation: because of the low operating frequency (13.56 MHz), they are not compact enough for mobile handsets. It should be noted that FM radio service for disaster broadcasts is included as standard equipment in most mobile phones. Various FM radio antennas, such as active antennas [5, 6], chip antennas using magneto-dielectric (MD) materials [7], and monopole antennas [8], have been proposed. These antennas offer the advantages of small volume and high passive average gain. However, integrating an NFC loop, an FM radio monopole antenna, or a chip antenna on an MD substrate consumes considerable space, and optimization of the interrogation range and passive average gain are not straightforward procedures with mobile handset circuitry. Moreover, for handheld wireless systems, a single compact radiator is advantageous because it occupies less space, which is an important consideration for compactness and portability.

In this letter, we propose an internal dual-band flexible antenna that offers enhanced interrogation range for NFC, together with improved passive average gain for FM radio applications, and is compact enough to be suitable for mobile handsets. To obtain NFC and FM operation, the loop and the monopole wire are integrated on a thin MD ferrite sheet substrate. A "parasitic" rectangular patch is inserted

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into the monopole wire to achieve an enhanced interrogation range at 13.56 MHz, together with high passive average gain at FM frequencies. The antenna is designed and analyzed using CST Microwave Studio, and a prototype is fabricated and characterized using a vector network analyzer. The proposed antenna exhibits good feasibility for use in dual-band NFC and FM radio applications, with significantly reduced footprint compared to existing designs [2–8]. The interrogation range is increased from 91.8 to 109.2 mm at NFC frequency (@13.56 MHz), and the passive average gain is increased from −15.6 to −12.1 dBi at FM radio frequency (@ 100 MHz).

2. ANTENNA DESIGN

Figures 1 and 2 show the geometry of the proposed internal dual-band flexible antenna with rectangular patch for use in NFC and FM radio mobile systems. Ferrite antennas have been studied since the 1940s, have been analyzed extensively in the literature [9], and are a popular choice for commercial pocket-sized radios and pagers [10]. The use of material loading to reduce the electrical size of wire monopoles and other antennas is also well known [11], but has previously been regarded as reserved for a few specialized applications.

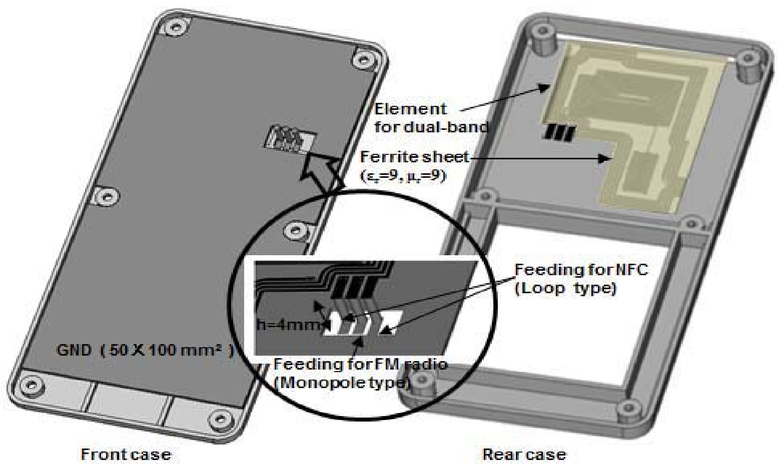

Figure 1. Diagram illustrating the layout of a mobile phone and placement of the antenna.

A three-dimensional view, including the feed structure of the antenna, is shown in Fig. 1. The proposed dual-band antenna is designed using a loop-type antenna and a monopole-type wire on a ferrite sheet. The front and rear casing material is polycarbonate, and the distance between the ground plane and the antenna is 4 mm when the mobile phone is closed. The two antennas are merged after designing each of them separately, and analyzing their respective resonant frequencies.

As shown in Fig. 2(a), we design an FM antenna as a $\lambda/4$ monopole spiral wire, with half the turns in the center and oriented counterclockwise, and the other half on the outside and oriented clockwise, extending from the feeding pads to the rectangular patch. The number and spacing of the turns are estimated via CST simulation. However, the spacing of the dual-band antenna and the three rectangular feeding pads (including two fixing holes for attaching the antenna to an indentation in the rear case of the cellphone) are specified before designing the antenna for active testing. We use two fixing holes to obtain stable specifications within a narrow tolerance for mass production.

The rear case of a commercial cellphone contains many "bulky" components, including the battery, and lacks sufficient space to accommodate a canonical loop antenna for NFC reading. Consequently, the spacing of the NFC loop wire is specified according to the available space in the rear case of an actual cellphone, and its non-canonical shape (with zigzagging lines) is determined by optimizing the measured interrogation range.

The design requirements are listed in Table 1. In this design, the radiating element has an area of 31.10×38.04 mm, and is printed on a flexible dielectric printed circuit board (FPCB) substrate with a

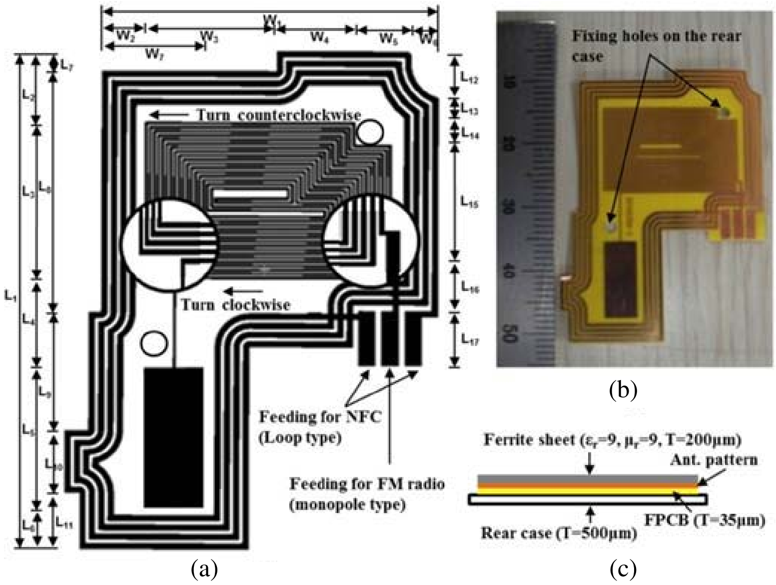

Figure 2. Geometry of the proposed antenna, showing the rectangular patch: (a) Detailed dimensions of the main radiation element. (b) Prototype of the antenna. (c) Side view of the antenna.

Table 1. Design specifications of the proposed dual-band ferrite sheet flexible antenna.

Item	Specifications		Units
	NFC	FM radio	
Frequency	13.56	86–108	MHz
Antenna Type	Loop	Monopole	-
Average gain	-	≥ -20	dBi
Interrogation Range	≥ 100	-	mm
VSWR	-	$\leq 6:1$	-
Radiation pattern	-	Omni-Directional	-
Antenna Position	Rear case		-
Ferrite sheet	$\varepsilon_r = 9$, $\mu_r = 9$		-

thickness of 35 µm and a relative permittivity of $\varepsilon_r = 3.5$. A magneto-dielectric ferrite sheet substrate with a thickness of 200 µm, a relative permittivity of $\varepsilon_r = 9.0$, and a permeability of $\mu_r = 9.0$ (dielectric loss tangent less than 0.01 and magnetic loss tangent less than 0.05) is attached to the antenna pattern for dual-band width. This is required to achieve antenna miniaturization and high passive average gain at low frequencies [12]. The antenna is fed by a 50 Ω coaxial line, which connects the inner conductor directly to the feed in the substrate.

The dual-band antenna is situated in the rear cover against the main printed circuit board (PCB) of a $50 \times 100 \times 0.8$ mm ($W \times L \times H$) FR4 substrate, which is the typical size of the circuit boards used in mobile handsets.

By numerical simulation, we are able to optimize the structure of the antenna, and the resulting dimensions (all in mm) are as follows: $W_1 = 31.10$, $W_2 = 5.00$, $W_3 = 10.65$, $W_4 = 8.00$, $W_5 = 6.00$, $W_6 = 1.65$, $W_7 = 12.65$, $L_1 = 38.04$, $L_2 = 4.60$, $L_3 = 12.04$, $L_4 = 6.50$, $L_5 = 10.90$, $L_6 = 4.00$, $L_7 = 2.04$, $L_8 = 13.20$, $L_9 = 10.80$, $L_{10} = 7.00$, $L_{11} = 5.00$, $L_{12} = 4.00$, $L_{13} = 2.00$, $L_{14} = 2.00$, $L_{15} = 10.20$, $L_{16} = 4.00$, and $L_{17} = 5.00$. The NFC loop wire length is 549.50 mm, the width is 0.80 mm, and the spacing between turns is 0.45 mm. The FM radio monopole wire length is 198.00 mm, the width 0.20 mm, and the spacing between the turns 0.15 mm. The antenna is designed for dual-band (NFC and FM radio) applications.

Without further modification, this antenna is not capable of acquiring sufficient bandwidth for passive average gain in FM radio applications, nor can it provide an acceptable interrogation range for NFC applications. Therefore, the antenna also includes a "parasitic" rectangular patch (7.65×10.90 mm) to realize these important design specifications. With the rectangular patch connected to the end of the monopole, a dual resonance is obtained, providing a wider bandwidth in the FM radio band, and a stronger mutual coupling to enhance the interrogation range at 13.56 MHz (NFC).

We carry out a parametric analysis to optimize the design parameters. We are able to cover the entire FM radio bandwidth, including low FM frequencies (above 86 MHz), by combining the two resonant frequencies (92 MHz, 118 MHz) generated by the two effective $\lambda/4$ monopole lengths (single wire, wire plus patch). Moreover, the NFC loop operates as a parasitic loop for the FM monopole. A prototype antenna is fabricated and characterized for dual-band operation. The return loss of the fabricated antenna is measured using an Agilent N5230A vector network analyzer. Its far-field patterns and average gain are measured inside a compact range in an anechoic chamber (exclusive FM band chamber $15 \times 5 \times 5\,\text{m}^3$).

Figure 3 shows the simulated and measured return loss values for the antenna in the FM radio band. The simulated results with a "parasitic" rectangular patch cover the entire frequency range of the FM radio band, since the rectangular patch adds a second resonant frequency, and shifts the lower resonant frequency 6.35 MHz further into the low band. This leads to a significant enhancement of the FM bandwidth. The measurement range is 83.20–123.72 MHz, providing a 3-dB bandwidth of 40.52 MHz, and thus covering all FM radio systems (voltage standing wave ratio $\leq 6:1$). The simulated 3-dB bandwidth is 83.20–122.03 MHz, which corresponds to a bandwidth of 38.73 MHz (VSWR $\leq 6:1$), and is in good agreement with the measurements. The above bandwidth results are calculated and measured for VSWR $\leq 6:1$. VSWR $\leq 6:1$ is acceptable when the antenna will be used only as a receiver, and is almost good enough for urban environments where the FM signal power is high [8].

Figure 4 shows the simulated and measured average gain of the antenna with rectangular patch in the frequency range 86–108 MHz, where the measured average gain ranged from −16.0 dBi to −13.5 dBi. The simulated results throughout this range of frequencies indicate a passive average gain between 2 and 4 dB higher with the rectangular patch than without it. It must be noted that the proposed antenna features a measured average gain that is significantly better than other recently reported internal FM antennas; e.g., it is 9 dB better (@100 MHz) than the antenna reported by Park [7], and 4 dB better (@103 MHz) than the antenna reported by Aguilar [8]. According to [13], the power received by an internal FM antenna is about 20 dB lower than the power received by an external wire antenna under the same measurement conditions. Nevertheless, the signal quality indicator is similar for both antennas. The signal quality indicator value achieved by both antennas guarantees that FM radio channels can be received clearly, without noise or interference. The useful signal that the FM antenna is capable of

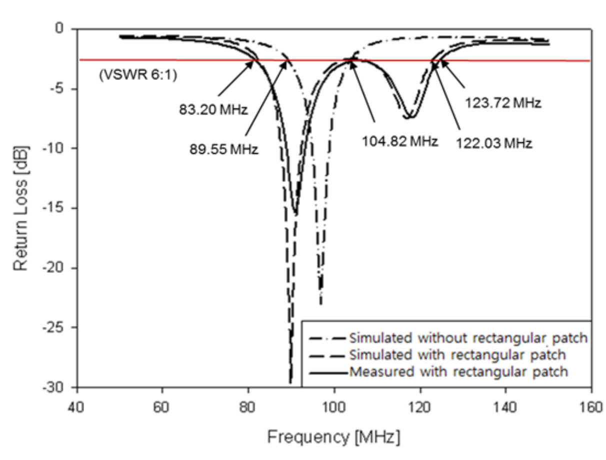

Figure 3. Simulated and measured return loss of the antenna in the FM radio band.

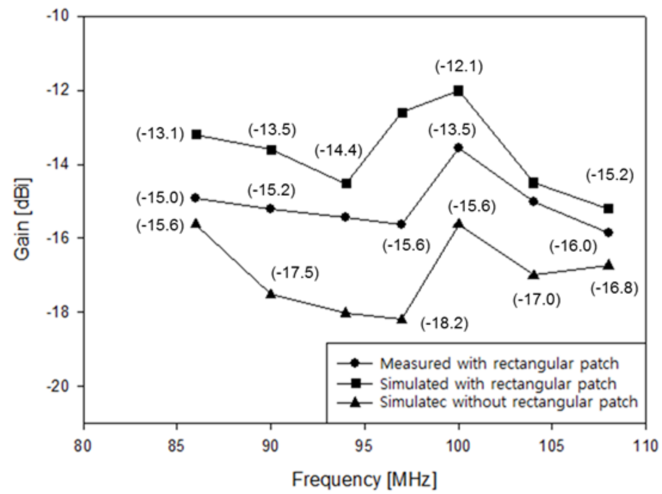

Figure 4. Simulated and measured average gain of the antenna in the FM radio band.

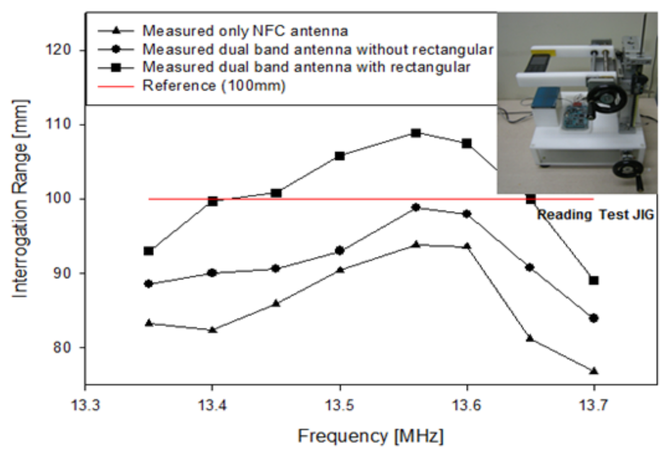

Figure 5. Measured interrogation range of the antenna at NFC frequencies.

receiving has a low power level, but the noise is also much lower. Therefore, even when the gain is only about -30 to -50 dB, the internal antenna can still be used to receive FM signals. In addition, the broadcast FM radio receiver chip (Si4730/31/34/35) of Silicon Laboratories Inc. has a high sensitivity (2.2–3.5 µV) under ideal conditions.

According to the NFC Forum standard [1], an interrogation range at least 100 mm is required for NFC operation. Figure 5 shows the reading test jig and the enhancement of the interrogation range when the rectangular patch is inserted. We used an RC-S461C Felica Reader test jig, which is moved vertically utilizing a circular hand lever, to measure the interrogation range. The inclusion of the rectangular patch resulted in an increased interrogation range. The NFC loop and the FM monopole with rectangular patch derive a significant mutual coupling from the correlation of their magnetic near fields, as verified by an experimental active interrogation range test. The measured interrogation range of the dual-band antenna with rectangular patch is as much as 10 mm higher than that of the dual-band antenna without the rectangular patch. The proposed antenna is measured without other assembly of a cell phone. However, we obtain the performance of the interrogation range for NFC as the commercial cell phone specification.

Figure 6 shows the simulated and measured radiation patterns of the antenna in the FM radio band, covering the 86–108-MHz range. Good agreement is obtained between the simulated and measured results. Also, an omnidirectional radiation pattern, suitable for mobile phone handsets, is observed in the xz-plane at all operational frequencies.

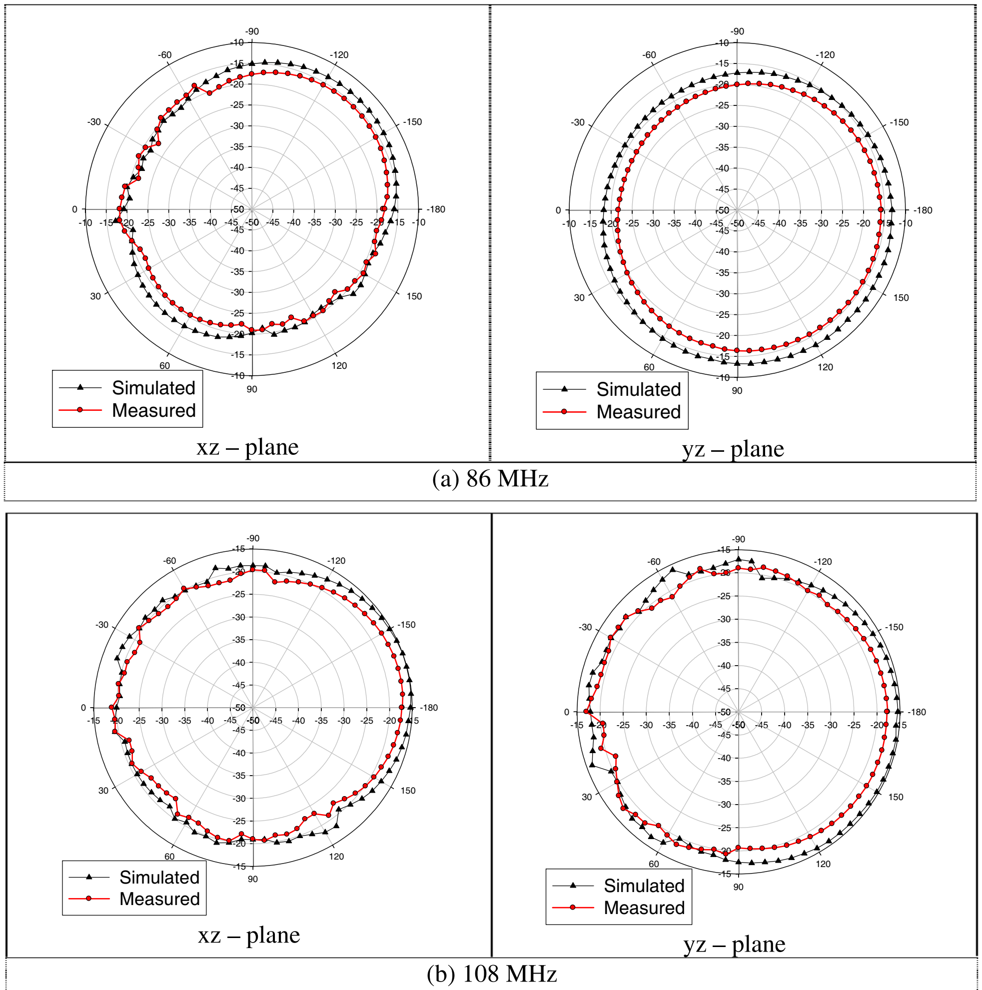

Figure 6. Simulated and measured radiation patterns of the proposed antenna in the FM radio band.

3. CONCLUSION

We design, fabricate, and experimentally characterize an internal dual-band flexible antenna, using a "parasitic" rectangular patch to enhance the interrogation range for NFC, as well as to provide enhanced passive average gain performance for FM radio in mobile phone handset applications. A benchmarking prototype antenna exhibits a 3-dB bandwidth of 40.52 MHz (83.20–123.72 MHz), which covers the entire FM radio bandwidth (86–108 MHz). The antenna has an omnidirectional radiation pattern and a passive average gain ranging from −16.0 dBi to −13.5 dBi, which makes it compatible with FM radio specifications. The maximum interrogation range for NFC applications is 110 mm at 13.56 MHz. These results demonstrate that the antenna can be applied to dual-band NFC/FM radio mobile systems. The overall size of the antenna is 31.10 × 38.04 mm, making it suitable for compact mobile handset applications.

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