Performance enhancement of ground radiation antenna for *Z*-wave applications using tunable metal loads

L. Qu, R. Zhang, H. Shin, J. Kim and H. Kim✉

A ground radiation antenna with tunable metal loads is proposed to improve the performance of a normal antenna at 900 MHz for *Z*-wave applications. The proposed design is comprised of a 5 mm × 5 mm ground radiation antenna and inductor-connected metal loads in a 30 × 50 mm ground plane. The metal loads can take the form of rims, a frame, strips, or wires at the ends of the ground plane and are connected with lumped elements to allow easy adjustment. The proposed antenna was simulated to tune the metal loads, and was then fabricated and measured to verify its improved performance in the *Z*-wave band.

Introduction: With the rapid development of home automation, demand is increasing for compact, high-performance antennas on small PCBs, in particular for *Z*-wave applications. Good performance is difficult to achieve while also miniaturising the PCB to meet the compact volume requirements for antennas in mobile devices, and this is especially true for the low-frequency band. Previous research has proven that strong coupling between the antenna and the ground plane can be achieved when their resonant frequencies (ω_0 and ω_g, respectively) are nearly equal, and that the length of the ground plane should be around half the operating wavelength, which is not practical in most cases [1–3]. Loop-type ground radiation antennas of compact size have been proposed that can effectively excite the ground plane as a dipole-type radiator [4, 5]. However, no previous report has addressed ground radiation antennas for applications below 1 GHz, owing to their narrow bandwidth and low efficiency.

This Letter discusses the design of a small-size ground radiation antenna in a compact ground plane for *Z*-wave applications ($\omega_0 =$ 900 MHz). Its performance is considerably enhanced over a previous design through the use of metal loads, which can increase the effective length of the ground plane and thus improve the radiation efficiency of the antenna. The proposed metal loads can be implemented as rims, a frame, strips, or wires at the ends of the ground plane, and are connected with lumped elements for easy adjustment. By using the proposed metal loads, the resonant frequency of the ground plane can be controlled, as well as the radiation efficiency at the operating frequency; optimal improvement can be achieved when the resonant frequencies of the antenna and the ground plane are equal, as verified herein by means of simulation and measurement. The whole design is tunable and compact, allowing its use in practical applications.

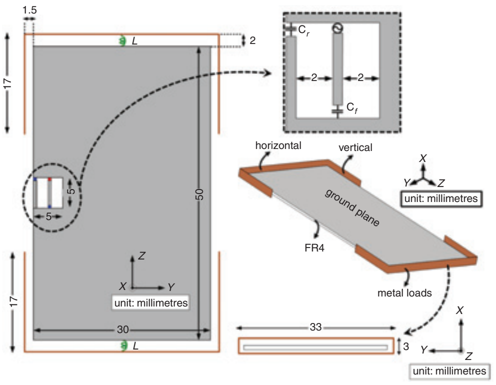

Fig. 1 *Configuration of proposed antenna design with metal loads*

Antenna configuration: The proposed configuration of the ground radiation antenna with metal loads is shown in Fig. 1. A small 5 × 5 mm clearance is adopted for the antenna design in the centre of a 50 mm × 30 mm ground plane, which is printed on a 1-mm-thick FR4 substrate ($\varepsilon_r = 4.4$); both the antenna and the ground plane are very small for 900 MHz applications. The antenna is comprised of a feeding loop with a series capacitor C_f and a radiator loop with a capacitor C_r; this loop-type antenna structure can create a loop-type current mode that couples with the ground plane through magnetic coupling [3–5]. The metal loads are located at the ends of the ground plane, and are connected by the inductors L at the centres of the short sides of the ground plane to extend the effective length of the ground plane; the inductance of L can be varied to achieve easy control over ω_g without any changes in the lengths of the metal loads. The horizontal and vertical sections of the loads are, respectively, 33 and 17 mm in length, with respective gaps of 2 and 1.5 mm from the ground plane; all of them have the x-axis width of 3 mm to achieve compact volume, although the use of a larger volume, especially to increase the gap, can improve the performance. Hereinafter, we refer to the ground radiation antenna without any metal loads as the reference design. In the simulations described below, the values used for C_f and C_r were 1.35 and 3.1 pF, respectively, for the proposed design, and 0.5 and 3.3 pF, respectively, in the reference design; as discussed below, the optimum value of L in the proposed design was determined to be 9.1 nH.

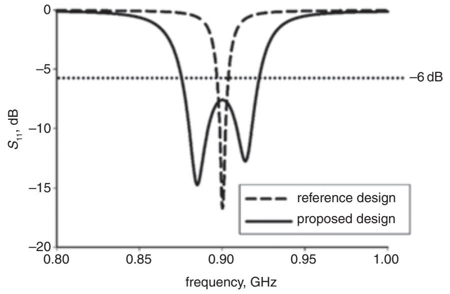

Fig. 2 *Simulated reflection coefficients of reference and proposed designs*

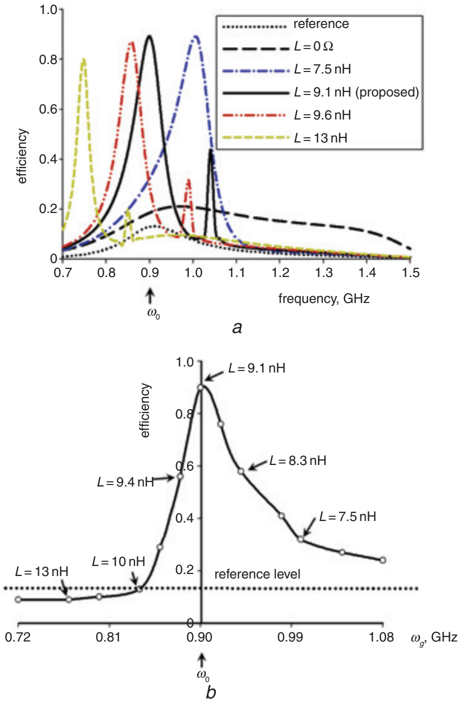

Fig. 3 *Simulated radiation efficiencies of proposed design for various tunings of metal loads*

a Simulated efficiency spectra for various L
b Antenna efficiency at ω_0 against ω_g, with corresponding L values

Controlling mechanisms and simulation results: The reflection coefficients of the reference and proposed designs at 900 MHz were simulated and compared (Fig. 2). The −6 dB impedance bandwidth of the ground radiation antenna without the metal loads was 7 MHz, from 897 to 904 MHz, whereas that with the metal loads is 45 MHz, from 876 to 922 MHz, an approximately six-fold improvement. However, the bandwidth is not an important issue for *Z*-wave applications, so we instead focused on the analysis of radiation efficiency.

The simulated antenna radiation efficiencies were calculated over the region from 700 to 1500 MHz to investigate the variation in efficiency arising from tuning the metal loads, specifically by means of varying the value of L (Fig. 3a). The radiation efficiency of the reference antenna was only 13% at $\omega_0 = 900$ MHz, because both the antenna and the ground plane are very small compared with the wavelength. When the metal loads were included without inductors (i.e. with L of 0 Ω), the radiation efficiency was improved to 19%. When inductors with L of 7.5 nH were included, a radiation efficiency of 32% at ω_0 was achieved, whereas the peak efficiency was 88% at 1000 MHz; that is to say, ω_g shifted to ~1000 MHz. The point of peak efficiency again coincided with the operating frequency of 900 MHz when the inductors were each 9.1 nH; in this case, 90% radiation efficiency was achieved at ω_0. In this case, $\omega_g \approx \omega_0$, yielding maximal radiation efficiency for the antenna at the operating frequency, a finding consistent with that of previous studies [1–3]. As the inductors were further increased to 9.6 and 13 nH, the simulated peak efficiency points were around 860 and 750 MHz, respectively, with the corresponding efficiencies of 29 and 9% at ω_0, respectively.

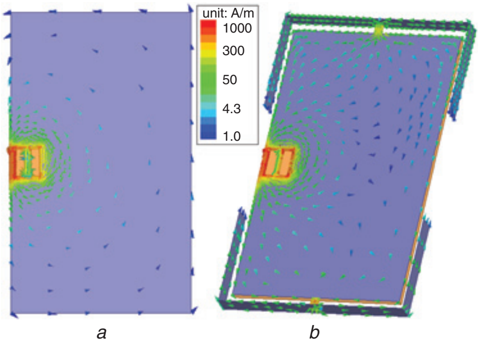

Fig. 4 *Simulated surface current distributions at 900 MHz of reference and proposed designs*

a Reference design
b Proposed design ($L = 9.1$ nH)

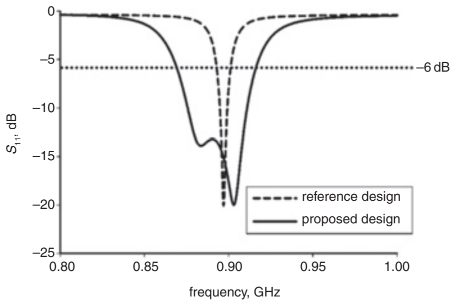

Fig. 5 *Measured reflection coefficients of reference and proposed antennas*

Fig. 3b shows the variation in antenna efficiency at $\omega_0 = 900$ MHz for various ω_g. Improved efficiency over the reference design can be achieved in the proposed design when ω_g is close to ω_0, and the efficiency is maximised when $\omega_g \approx \omega_0$. Also, the efficiency changes faster with changing ω_g in the region of $\omega_g < \omega_0$ than that of $\omega_g > \omega_0$, and larger antenna clearance and/or metal loads (e.g. the gap) can contribute to a gradual change in efficiency.

The surface current distributions of the reference and proposed antennas at 900 MHz were simulated (Fig. 4), showing that currents were induced in the proposed antenna at the ends of the ground plane and within the metal loads, extending the effective length of the ground plane. This represents clear evidence of the effect of the metal loads.

Experimental results: The reference and proposed antennas were fabricated and their reflection coefficients were measured (Fig. 5). The simulated and measured results agreed well: the measured impedance bandwidth was 8 MHz (from 895 to 903 MHz) for the reference antenna and 47 MHz (from 871 to 918 MHz) for the proposed antenna. Both antennas generated omnidirectional radiation patterns on the xy-plane at 900 MHz; the peak gain of −5.1 in the reference design was improved to −0.08 dBi in the proposed design through the use of the tuned metal loads (Fig. 6). The measured efficiencies at 900 MHz of the reference and proposed antennas were 12 and 52%, respectively, indicating greatly improved radiation performance in the proposed design.

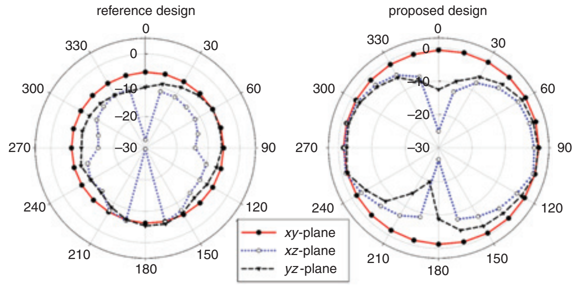

Fig. 6 *Measured radiation patterns at 900 MHz of reference and proposed antennas*

Conclusion: In this Letter, a compact ground radiation antenna in a small ground plane with improved performance has been proposed for Z-wave operation. The proposed design uses inductor-connected metal loads to extend the ground plane, thereby increasing the radiation efficiency. The proposed design was optimised by tuning the resonant frequency of the ground plane to be equal to that of the antenna; better performance can be obtained by enlarging the metal loads and/or the antenna size.

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One or more of the Figures in this Letter are available in colour online.

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