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Design, fabrication and operation of a wireless and miniature ignition system

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Abstract

A wireless miniature ignition system has been developed for secure micro ignition applications. The power and data are transmitted using electromagnetic radio frequency waves between two closely coupled coils. The distance between the two coils is of 200 μm. High frequency (13.56 MHz) has been used enabling us to use coils made with PCB technology with only three copper wires with a separation between turns of 120 μm. A fully integrated prototype has been built and tested. It is 3 mm thick and has a section area close to 40 mm^2 (7 mm of diameter). When the command occurs, the system assures the application of enough electrical power (150 mW) to ignite a pyrotechnical powder in contact with the resistor of the ignition system. The measured electromagnetic energy transfer efficiency is up to 50% in normal environmental conditions (air surrounded). The difference between the experimental electromagnetic energy transfer efficiency and model prediction (67%) is due to bad coupling. The implemented solution to increase the electromagnetic energy transfer efficiency is to surround the coils with a magnetic polymer: it increases the energy transfer efficiency up to 72% in the air.

Keywords: Electromagnetic induction; Pyrotechnical micro-igniter; MEMS; Wireless microsystems; Magnetic elastomer

1. Introduction

One important concern, especially in civil applications, is to ensure that pyrotechnical systems must be used only by the authorized person and for the use it has been designed for. Security and safety in any pyrotechnical ignition system is possible with the integration of electronic circuitry to control and command the ignition. For a decade, one other important tendency is the miniaturization of electro-pyrotechnical systems [1–14]. For some applications, to reduce the vulnerability and improve safeness, one could separate the power source from the ignition part containing the pyrotechnical charge. We propose a miniature and secure wireless electro-pyrotechnical system responding to these requirements. It is made of four blocks: two coupled coils and a wireless transmission of power using electromagnetic radio frequency. A control module providing two levels of codes identifications to ensure a good level of security. An electrical resistance made from silicon and a pyrotechnical charge. An LC circuitry for the radio frequency tuning. [21].

Wireless miniature systems have already been developed mainly for sensing application (low power) and for biomedical field [17–21] but not only [20]. Only a few works concern power transmission [21,22]. We present in this paper a wireless miniature system capable of transmitting a minimum of 150 mW (3 V, 50 mA) to ignite a pyrotechnical charge. Our system consists in two parts. First a transmitter part contains the battery, the transmitter coil and the electronic circuitry. The battery is connected to a micro coil via an LC circuitry. The receiver part of the system contains one pyrotechnical igniter [12], one energy transfer module and one electronic chip for the code identification. We have designed and built a prototype of 3 mm thick and with a section area close to 40 mm^2 (7 mm in diameter). With the application of 150 mW, the system can ignite a pyrotechnical charge. Concerning the security aspect, the user is identified by a high frequency coded signal. Two levels of security have been proposed. Once the first code is identified, the igniter resistance and its associated capacitor are connected to the power supply and the capacitor is charged at the required voltage. A second code must be identified to enable the discharge of the capacitor to the igniter's resistance. The paper presents the system design, the fabrication process, the assembling and test of the

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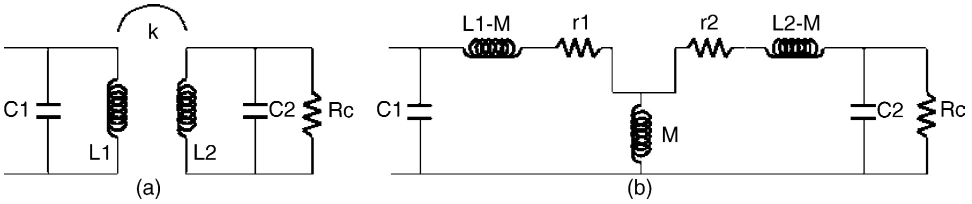

Fig. 1. Circuit with transmitter coil in face to receiver coil (a) and equivalent model (b).

first prototype. The identification circuit has been tested with discrete components, its miniaturization and integration will be published in a later article.

2. Key elements of design

Power and data transmission using electromagnetic radio frequency waves between two closely coupled coils is widely used in wireless transmission. In our case, the wireless ignition systems must satisfy several requirements. First, sufficient power must be transmitted (150 mW minimum) to the pyrotechnical igniter to ensure a good ignition reliability. Secondly, the wireless link should be adaptable so it can satisfy the needs of different applications. And finally, the size of the coils must be small enough to be integrated into a microsystem (size up to 1 cm^3).

2.1. The electromagnetic transfer module

In the field of electromagnetic transmission, several papers discuss on power transmission through coils with several centimeters in diameter. We also find a lot of papers on miniature coils for low power and data transmission for biomedical or chemical application. [15–19]. We are facing different challenges: transmitting up to 150 mW during few milliseconds using coils being lower than 1 cm in diameter and to be integrated into microsystems. The design of the coupled coils is a key step that fixes the feasibility in terms of performance and cost. To design the coils, we have considered two possibilities: either to work at low frequencies thus limiting Foucault losses or at high frequencies leading to a better coils integration. We have chosen the high frequencies to have transmitter and receiver coils with only a few turns (<5). Thus, IC technology can be used for the coils fabrication. 13.56 MHz has been selected because it is one of the band recommended for industrial, scientific and medical (ISM) applications [23–25] and are used frequently in RF identification (RFID) [26,27].

2.1.1. Theoretical laws

From Ampere's law, when a current passes through a conducting material, it generates a magnetic field around the material. For a circular loop, the field reaches its maximum amplitude in the plane of the loop [26]. From Faraday's law, when a time-varying magnetic fields acts over a surface enclosed by a conducting path, it generates a voltage around the loop. The voltage is proportional to the number of loops and the time variation of the magnetic flux [26]. This magnetic flux is the total magnetic field that passes through the coil surface. It reaches its maximum value when the two coils surfaces are parallel to each other. This can be expressed in terms of the mutual inductance (M) [26]:

$$V=-\left[\frac{\mu_0 N_1 N_2 a^2(\pi b^2)}{2(a^2+r^2)^{3/2}}\right]\frac{\mathrm{d}i}{\mathrm{d}t}=-M\frac{\mathrm{d}i}{\mathrm{d}t} \tag{1}$$

The subscripts 1 and 2 represent the transmitter and receiver coils respectively, i is the current flowing in the transmitter coil, a and b are the coils loop radius for the transmitter and receiver respectively, r is the distance of field measurement from the loop's center, μ_0 is the permeability of the free space. This expression for the induced voltage can be found in the typical transformer quadripole models [28–30]. In order to obtain a better coupling from Eq. (1), the number of turns in both coils can be increased as well as the permeability μ using a magnetic material (e.g. ferrite). To enhance the quality factor ($Q = L\omega/r$), the transmitter and receiver circuits must be tuned at the same frequency with the aid of capacitors. Including this factor in Eq. (1), we obtain [26]:

$$V=2\pi f N_2 S_2 Q B \tag{2}$$

where N_2 represents the number of turns in the receiver coil, S_2 represents its surface.

2.1.2. SPICE model

Fig. 1 presents the equivalent model of the electromagnetic energy transfer between two closely coupled coils. Subscript 1 stands for the transmitter part, subscript 2 stands for the receiver part. Orcad Pspice software[1] is used for the simulations. In this model both coils are supposed to be the same. The goal of these simulations is double:

- First, to calculate the right capacitances needed in the transmitter and receiver parts to tune the circuit at the right frequency.
- Then, list the parameters influencing the energy transfer efficiency and evaluate the performances of the prototype.

We can define the electromagnetic energy transfer efficiency by the ratio between the energy produced over the igniter, represented in Fig. 1 by the resistance R_c, to the energy produced by the battery over the transmitter, that is, the energy over the capacitance C_1:

$$\text{energy transfer efficiency}=\frac{\text{energy over } Z}{\text{energy over } C_1}. \tag{3}$$

First the energy transfer efficiency is calculated as a function of the quality factors. $Q_1 = Q_2$ because the coils are supposed

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[1] PSPICE is a circuit simulation program from Cadence.