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# Design of Alternating Magnetic Field Stimulator Using Duty Factor

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**We have developed an alternating magnetic field stimulation system consisting of a switched-mode power supply and a digital control circuit which modulates a duty ratio to maintain a magnetic field intensity of a few mT even while the frequency increases up to 4 kHz with a controllable coil temperature below 30 °C in air. This duty ratio modulation and water circulation are advantageous for cell culture under ac-magnetic field stimulation by preventing the incubator from exceeding a cell-viable temperature of 37 °C. Although the temperature of the coil when subjected to a sinusoidal voltage rapidly increased, that of our system modulated by the duty factor did not change. This is a potentially valuable method to investigate the effects of intermediate frequency magnetic field stimulation on biological entities such as cells, tissues and organs.**

**Keywords :** alternating magnetic field, duty factor, cell stimulation

## 1. Introduction

The development of telecommunications and electronic devices has increased interest in the relationship between electromagnetic fields and human health. Most studies on the effect of alternating electromagnetic field stimulation on vivo and *in vitro* biological have been performed at extremely low frequencies of 50-60 Hz for home electric appliances or radio frequencies of several MHz to GHz used in telecommunications devices [1, 2]. According to the World Health Organization (WHO) definition, the intermediate frequency of electromagnetic fields is in 300 Hz-10 MHz range. The interest in the biological and health effects of intermediate frequencies has rapidly grown with the proliferation of heating, detecting and switching equipment operating at these frequencies. Also, the WHO has reported on the biological effects of magnetic fields at 100 kHz or lower in Environmental Health Criteria (EHC) 238 [3]. A recent review of this information revealed that limited frequency data is available for determining the biological and health effects of intermediate frequency magnetic fields. Further studies are necessary to understand the physiological effects in this frequency range [4, 5].

To study the effects of the intermediate frequency on biological systems, such as cell cultivating systems or animal exposure facilities, a magnetic field exposure system should be designed to control the magnetic field intensity and coil heating induced by changing frequency. Merritt's multiple coil structure has been applied at extremely low frequency magnetic fields in *in vivo* exposure systems [6]. A 20 kHz magnetic field in vivo exposure facility has been developed by Shigemitsu *et al.* [7]. For in vitro studies, 23 kHz and 20 kHz magnetic field exposure systems have been developed [8]. However, these systems had problems with rapid coil heating as the frequency increases and could not generate a strong magnetic field at high frequencies. Therefore, it is very important to develop a magnetic field exposure system with well-controlled coil heating.

In this study, we develop an alternating magnetic field stimulation system consisting of a switched-mode power supply and a digital control circuit which modulates a duty ratio. The voltage applied to the coil with increasing frequency was controlled by the duty ratio to keep a constant magnetic field intensity of a few mT without increasing coil temperature. The coil temperature of our designed system modulated a duty ratio factor that was almost unchanged as the frequency increased, whereas the magnetic coil subjected to a sinusoidal current was rapidly heated.

## 2. Experiment

Commercial alternating magnetic field devices typically

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generate a sinusoidal wave using a coil with limited frequency regulation due to coil inductance. In cell culture incubators, rising coil temperatures above 37 ºC induce cell death. To reduce the coil heating due to the increase in the impedance of $Z = [R^2 + \omega^2 L^2]^{1/2}$ with frequency, we embedded an alternating magnetic field based on a saw wave instead of a sinusoidal wave as shown in Figure 1(c). Our system is designed to generate an alternating magnetic field intensity fixed at 3, 5, and 10 mT while the frequency is varied. We set the generated magnetic field frequencies between 200 Hz and 4 kHz because most biological signals related to external stimuli-induced action potentials are within this range [9]. The generating coil (coil A) used in cell stimulus consists of a single layer wound in 15 revolutions around a hollow 14 × 6 cm rectangle using a flat square, single-stranded wire that is 1 mm thick and 3 mm wide. A 6-well 12.7 × 8.5 cm culture plate can be placed on this coil structure and used with the water cooling system.

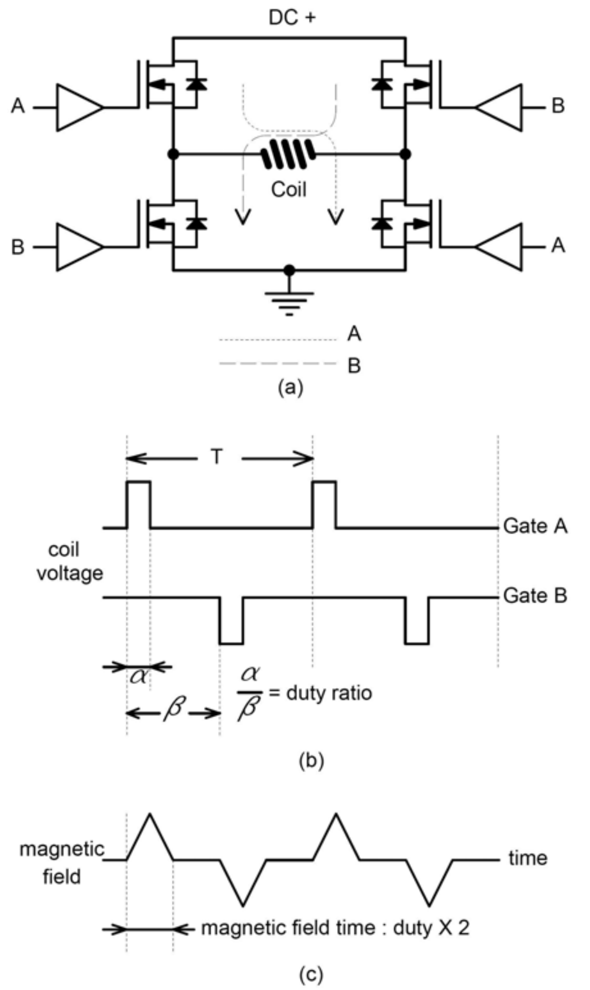


**Fig. 1.** (a) Schematic diagram of our designed circuit consisting of an insulated gate bipolar transistor (IGBT). (b) The coil voltage opened by gate A and B, and (c) the magnetic field of a saw wave type.

Our system enables us to generate a constant magnetic field intensity at varying frequencies by modulating the duty ratio, despite the impedance mismatch between the coil and driving power. The duty ratio is defined as the ratio of pulse width to time duration of the following pulses, β, during a half cycle T/2, as shown in Fig. 1(b). The system uses a switched-mode power supply (SMPS) to provide a maximum current of 40 A and a digital control circuit to generate a magnetic field of alternating saw wave pulses. The circuit consists of four field effects transistors (FET) or insulated gate bipolar transistors (IGBT), as shown in Fig. 1(a). Electric power is alternatively supplied to the coil by opening gates A and B, which provide opposite current flows.

## 3. Results and Discussion

To investigate the effect of temperature on cells under our alternating magnetic field stimulation system, we measured the coil temperatures inside and outside the cell incubator and cultured rat basophilic leukemia cells (RBL-2H3; KCLB, Korea) under various magnetic stimulation frequencies. We reported the in vitro stimulating effect of strong pulsed magnetic fields on RBL-2H3 cells in our previous work [10]. The results will be discussed in our next report.

It is important to compare our newly designed system with commercial sinusoidal power supplies to measure the coil heating as frequency increases. The sinusoidal power supply cannot cause a current flow in coil A with 15 turns due to a low impedance of R = 0.2 Ohm and L = 4.7 μH. We introduce a new coil (Coil B) with a 175 turns, 10 cm radius, and 1mm diameter to compare the coil heating between our system and a sinusoidal one. The resistance and inductance of coil B are 3.0 Ohm and 8.3 mH. The coil temperature in the sinusoidal system increased rapidly up to one hundred degrees.

Figure 2 shows the output voltage loaded to coil A and the magnetic field intensity measured by a commercial Hall sensor (A1321) to determine (a) the 500 Hz frequency in the circuit with a ground state, and (b) the 1 kHz without a ground state. In the latter case, reversed pulse currents can be seen in Fig. 2(b). Reverse pulses result from a reverse current flow at the wheel diode and are caused by induced electromotive force voltage in the coil. Fortunately, the induced reverse pulses rapidly decrease to the magnetic field intensity and the circuit without a ground state shows a temperature increase of less than in the circuit with a ground state due to reduced Joule

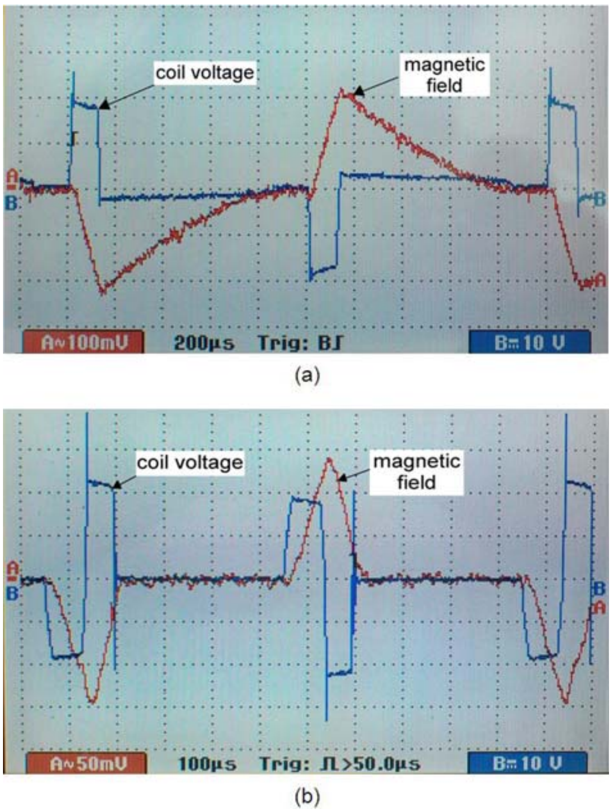


**Fig. 2.** (Color online) Oscilloscope images of the coil voltage and the generated magnetic field in the circuit system (a) with an electrical ground state at a 500 Hz frequency and (b) without an electrical ground state at 1 kHz.

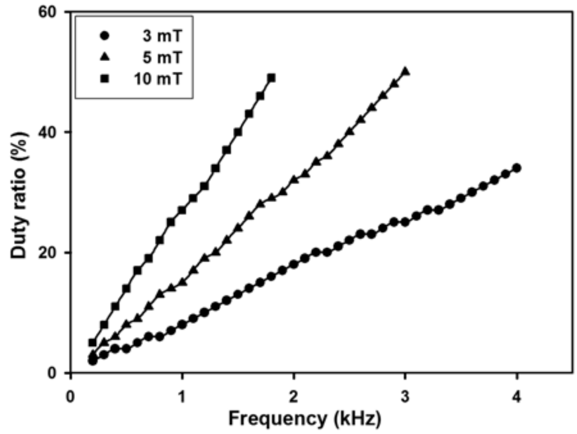


**Fig. 3.** Relationship between stimulating frequency and duty ratio to obtain fixed magnetic fields of 3, 5, and 10 mT.

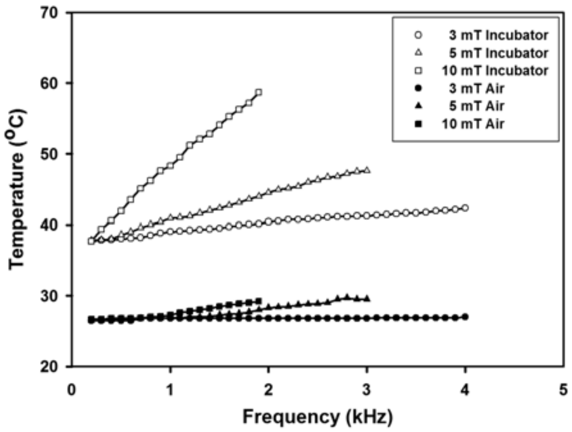


**Fig. 4.** Comparisons of temperature rises with increasing frequency in air (closed symbols) and in the $CO_2$ incubator (open symbols).

heating. In this study, we adopt a control circuit without a ground state to reduce temperature increases in the coil.

Figure 3 displays the duty ratios as a function of stimulation frequencies at 3, 5, and 10 mT. To maintain a fixed magnetic field intensity while increasing the stimulation frequency from 200 Hz to 4 kHz, the duty ratio necessarily varied linearly by up to 50%, at which the maximum frequencies are limited with the fixed intensity, this can be seen in the curve of 10 mT in Fig. 3. The acceptable maximum frequency at 5 mT is obtained up to 3.4 kHz. Changing the number of coil turns will result in a higher magnetic field intensity.

In general, the coil temperature in the stimulation of sinusoidal waves increases as the stimulating frequency increases. It is very important to control the coil temperature in order to maintain a cell-viable ambient temperature of 37 °C during in vitro cell stimulating. Figure 4 shows the coil temperature dependence of applying frequency in air and in the incubator for our designed system. Using a duty ratio control system, all temperatures measured reached saturation below an air temperature of 30 °C as indicated by the solid symbols of Fig. 4 (or 60 °C in the incubator, open symbols), even at a magnetic field intensity of 10 mT at 2 kHz, this temperature is significantly smaller than that of commercial sinusoidal system.

To compare the coil heating between sinusoidal and duty modulated power supply in detail, coil B with a high inductance of 8.4 mH was introduced. To get 10 mT in coil B, a sinusoidal current of 2.45 A was applied. While increasing the frequency up to 500 Hz, the applied voltage was increased up to 44 V. The starting voltage is 6.3 V at 50 Hz to keep a constant current of 2.45 A. In this case, the coil temperature rapidly increased to 40 °C within 325 sec, and increased up to about 120 °C, the breakdown temperature of the insulating coating.

Figure 5 shows the increasing rate of coil temperature as a function of frequency (50-550 Hz) to compare between the sinusoidal driving system (solid symbols) and the duty modulated system (open symbols). As mentioned in the previous paragraph, the coil temperature in the

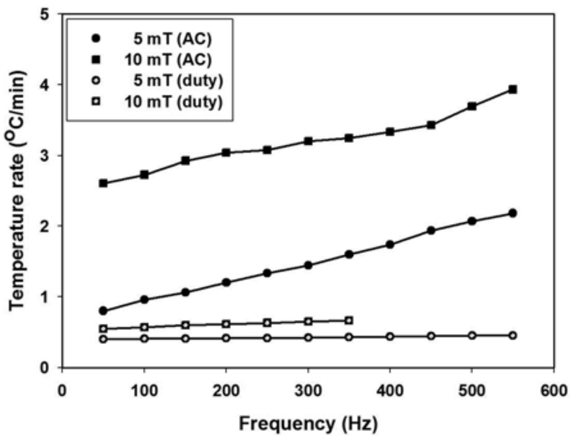


**Fig. 5.** Comparisons of temperature rises as frequency increases to 550 Hz in the sinusoidal driving system (solid symbols) and the duty modulated system (open symbols).

sinusoidal system continuously increases, but that of the duty modulated system did not increase. Therefore, our suggested system using a duty factor is useful for investigating the effects of intermediate frequency magnetic field stimulation on biological entities such as cells, tissues or organs.

## 4. Conclusions

We designed an alternating magnetic field stimulator that modulates the duty ratio and maintains a stable coil temperature as frequency increases. The magnetic field intensity was maintained at 3, 5, and 10 mT in a frequency range of 200 Hz to 4 kHz without any coil heating. The alternating magnetic field stimulator modulated by the duty ratio modulation has the advantage of preventing the incubator from exceeding a cell-viable temperatures of 37 °C.

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